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THERMAL AND TRANSPORT CHARACTERIZATION OF RFP PLASMAS FROM ELECTRON TEMPERATURE DATA

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Abstract

The research activity I have carried on during the three years of my Ph.D. course is described in this thesis. I attended my PhD Physics Department "G. Galilei" at the University of Padua, while research and results were mainly developed at the Consorzio RFX (www.igi.cnr.it).

The Consorzio RFX is a joint venture between CNR, the Italian Agency for Alternative Energies (ENEA), University of Padova, the National Institute for Nuclear Physics (INFN) and a private company, Acciaierie Venete s.p.a.. Its main goal is to perform education and research activities in the field of controlled thermonuclear fusion, within the framework of a contract with the European agency Euratom.

Consorzio RFX operates in research and development activities in the field of magnetically confined fusion. In my specific case, I was involved in the RFX-mod experiments, the largest fusion experiment in the Reversed Field Pinch (RFP) configuration. The RFP, together with the Tokamak and the Stellarator, is one of the main configuration used to confine plasmas in toroidal devices for studying controlled thermonuclear fusion as an energy source.

Research activity

I started my PHD experience at the beginning of 2007, carrying on the commissioning and optimization of the Edge TS diagnostic. The system started its operations in February 2008, providing first measurements of density and temperature in the outer edge region (last 10 cm) of the RFX-mod plasma. After few months it was clear that the intensified CCD camera the Edge TS spectrometer was based on, was not able to discriminate the TS signal from spurious signals (plasma light and line emission from plasma wall interaction) limiting the system operation to narrow operational range (particularly in terms of density). I successfully modified the system moving from CCD to avalanche photodiodes to detect signals and waveform digitizers to record their trace. Now the Edge TS usually run during RFX-mod discharges; despite it provides only one or two pulses per plasma discharge, I demonstrated that its proper combination with other T_e and n_e diagnostics enhances the accuracy and the reliability of edge transport analysis.

Contemporarily, I followed the development and installation of an impurity injection system based on Laser Blow-Off. The system exploits the same laser of the Edge TS: after entering the Torus Hall 50% of the beam is

deflected towards the LBO input window and focused on a glass target with the impurity layer. I implemented the entire optical path, and developed the remotely controlled target holder. This system was successfully commissioned and started to operate in 2008, giving informations on the impurities diffusion within the plasma

Contemporary to this experimental activity, I carried on confinement and transport analysis relying mainly on the temperature and density measurements obtained with the Main and Edge TS diagnostics. This work was addressed in particular to the characterization of enhanced confinement states in RFP plasmas, referred to as QSH. I analyzed profiles in terms of gradient position and steepness, both at the edge and in the core, studying their correlation with magnetic configuration (i.e. safety factor $q(r)$ profile) and turbulence (i.e. the amplitude of secondary modes). I have also improved the electron heat diffusivity studies: combining Te and Ne diagnostics I implemented the $\chi_e(r)$ 1D model to time resolved $\chi_e(r, t)$ model first and to $\chi_e(r, \theta)$ 2D model then.

During 2009 I was also involved in an experimental campaign of a week at the MST experiment (Madison, Wisconsin), aimed at comparing the features of helical states in similar regimes to those of RFX-mod. I spent in MST 2 months in three successive visits.

Thesis Outline

The work presented in this thesis is divided in two main topics: the description of the experimental activity on RFX-mod on the Edge TS (Chapter 3 and 4) and on the Laser Blow off system (Chapter 5), and transport analysis in RFPs helical states; the analysis on RFX-mod is in Chapter 6, that on MST is in Chapter 7. Chapters are organized as follows:

- *Chapter 1* is a brief introduction to the magnetic confinement approach to fusion, with particular highlight on the RFP physics and the RFX-mod machine. The crucial role of electron temperature and density, and their measurement, in determining the performance of magnetically confined fusion devices is described.
- *Chapter 2* describes the most common methods for temperature measurements, focusing on the theory of Thomson scattering applied to electron temperature evaluation; finally, a brief overview of a diagnostic setup is presented, carrying as an example the Main TS diagnostic in RFX-mod.
- *Chapter 3* reports the commissioning and the development of the edge

TS of RFX-mod, which implied a deep modification in the optics and in the acquisition system of the diagnostic to make it work reliably.

- *Chapter 4* is an overview of the most significative results obtained with edge TS data in plasma edge characterization. The main physics topics related with Edge TS operation are shortly discussed and the relative measurements are presented.
- *Chapter 5* describes the development and the commissioning of the Laser Blow off system, used in RFX-mod for metal impurity injection, with particular care for the laser optical path, the target holder and bench tests to characterize the system.
- *Chapter 6* shows the analysis carried on temperature and density profiles coming mainly from the two Thomson scattering system. The analysis is focused on helical states (QSH) of the plasma, describing their typical phenomenology; a quantitative analysis of transport is presented, highlightning the confinement improvements measured in QSH. Finally some results on particle transport obtained with the LBO system are presented.
- *Chapter 7* closes the work with the characterization of helical states in the MST experiments. A comparison with RFX-mod in the QSH phenomenology in terms of occurrence and energy transport will be given.

Introduzione

Nel presente lavoro di tesi viene descritta la mia attivita' di ricerca svolta durante i tre anni di corso di dottorato in Fisica presso il Dipartimento di Fisica dell'universita' degli studi di padova. Tale lavoro si e' svolto prevalentemente presso il consorzio RFX (www.igi.cnr.it), una collaborazione tra CNR, ENEA, Universita' di Padova INFN e capitale privato rappresentato dalla societa' Acciaierie Venete. L'obiettivo del consorzio e' la promozione di attivita' di formazione e ricerca nell'ambito della fusione nucleare controllata; in particolare, ha curato la costruzione e gestisce l'esperimento RFX-mod, la piu' grande macchina a configurazione Reversed field pinch (RFP) attualmente in operazione.

Attivita' di ricerca

La mia attivita' di ricerca e' iniziata nel 2007 continuando le operazioni di commissioning e ottimizzazione della diagnostica di thomson scattering di bordo, che nel corso del 2008 ha iniziato a funzionare restituendo misure di temperatura e densita' al bordo esterno del plasma. Dopo alcuni mesi era chiaro che lo spettrometro a CCD su cui era basata la diagnostica non era in grado di discriminare il segnale Thomson dal background (luce di plasma e luce laser diffusa), limitando notevolmente il range operativo del sistema. Ho modificato con successo la diagnostica adottando uno strumento ad APD collegato a un'acquisizione veloce; adesso il Ts di bordo funziona normalmente durante le operazioni, e nonostante possa fornire un solo profilo per impulso, e' in grado di integrarsi con altri strumenti, dimostrando di poter migliorare l'accuratezza e la risoluzione spaziale e temporale delle misure a bordo plasma.

Contemporaneamente ho curato la costruzione e l'installazione sulla macchina di un sistema di iniezione di impurezze attraverso Laser Blow Off, che ha iniziato a funzionare nel 2008 permettendo di tracciare la diffusione di impurita' metalliche all'interno del plasma. Il sistema sfrutta lo stesso laser del Thomson di edge: il 50% del fascio viene deviato su un target in vetro coperto da un film metallico, quest'ultimo e' vaporizzato e iniettato nel plasma; il sistema e' stato commissionato con successo nel 2008, restituendo informazioni sul trasporto delle impurita' nel plasma.

Parallelamente all'attivita' sperimentale ho portato avanti analisi di confinamento e trasporto basandomi sui dati di temperatura elettronica del thomson principale e dell'edge, analisi volte in particolare alla caratteriz-

zazione di stati di plasma a confinamento migliorato (QSH). Ho caratterizzato i profili nella posizione e nel valore dei gradienti di temperatura, collegandoli alle caratteristiche della configurazione magnetica e del plasma stesso; ho migliorato il modello di calcolo della diffusività elettronica e della pressione, da un approccio 1D a uno 2D.

L'attività di analisi mi ha portato anche a seguire una campagna sperimentale su un altro esperimento RFP, l'esperimento MST a Madison (Wisconsin), sempre focalizzandomi sulla caratterizzazione di stati elicoidali. Complessivamente ho trascorso a MST circa 2 mesi nel corso di tre visite distinte.

Outline della tesi

Il presente lavoro di tesi è diviso in due filoni principali: i capitoli 3, 4 e 5 trattano la descrizione dell'attività sperimentale sull'esperimento RFX-mod, sul sistema di Edge Thomson Scattering per la misura della temperatura elettronica a bordo plasma, e sul sistema di laser Blow off per l'iniezione di impurezze metalliche. Il lavoro di analisi viene presentato nei capitoli 6 e 7, con particolare riferimento agli stati elicoidali negli RFP; il capitolo 7 tratta delle misure ottenute sull'esperimento MST. L'analisi è stata portata avanti anche grazie agli strumenti sviluppati, cioè la diagnostica di Thomson Scattering di bordo e il sistema di laser Blow Off.

I Capitoli sono organizzati come segue:

- il *Capitolo 1* è una breve introduzione al principio del confinamento magnetico nella ricerca fusionistica; vi si tratta più in dettaglio della fisica dell'RFP e dell'esperimento RFX-mod.
- Nel *Capitolo 2* vengono elencati i metodi più comuni per la misura della temperatura nei plasmi; si passa poi alla descrizione del Thomson Scattering applicato alle misure di temperatura elettronica nei plasmi di laboratorio; infine, una breve presentazione, come esempio pratico di implementazione, è dedicata al Thomson principale di RF-mod,
- Il *Capitolo 3* descrive il lavoro di sviluppo e commissioning operato sulla diagnostica di Thomson scattering di bordo in RFX-mod, che ha implicato modifiche ottiche, meccaniche e nell'acquisizione per consentire un funzionamento corretto.
- Il *Capitolo 4* espone alcuni risultati ottenuti dalla diagnostica di Thomson di bordo nella caratterizzazione della zona di bordo del plasma; i principali argomenti di fisica dell'RFP collegati alle misure sono brevemente introdotti.

- Il *Capitolo 5* conclude la parte squisitamente sperimentale della tesi, con la descrizione della costruzione e commissioning del sistema di iniezione di impurezze attraverso Laser Blow Off installato su RFX-mod; l'iniezione di impurezze e' uno strumento potente nella caratterizzazione del trasporto di particelle all'interno del plasma.
- Nel *Capitolo 6* viene sviluppata l'analisi sui profili di temperatura e densita' ricostruiti dalle due diagnostiche di Thomson scattering e da altri strumenti. In questo capitolo, l'analisi e' mirata alla caratterizzazione degli stati elicoidali del plasma, e ne descrive la fenomenologia tipica. Un'indagine quantitativa sul trasporto elettronico viene presentata allo scopo di evidenziare i miglioramenti ottenuti nel confinamento dei plasmi a quasi singola elicit'. La parte finale del capitolo integra l'analisi con alcuni risultati ottenuti grazie al sistema di Laser Blow-Off descritto nel capitolo precedente.
- Il *Capitolo 7* chiude il lavoro con una caratterizzazione principalmente fenomenologica degli stati elicoidali nell'esperimento MST (University of Wisconsin, Madison), che ho visitato in tre differenti periodi durante il mio dottorato. Sono messe in evidenza le analogie nel comportamento dei plasmi nei due esperimenti, in particolare per quanto riguarda la temperatura e il confinamento dell'energia.

Contents

1	Nuclear fusion and RFP configuration	1
1.1	Fusion and lawson condition	1
1.2	Magnetic confinement	6
1.2.1	MHD model: plasma as an electrically conducting fluid	7
1.2.2	Static MHD equilibrium	8
1.3	Axisimmetric toroidal configurations: Tokamak and RFP . .	10
1.3.1	Brief elements of MHD stability	12
1.4	Dynamo and RFP configuration	13
1.5	Helical states in RFPs	15
1.6	The RFX-mod experiment	20
2	Electron temperature measures with Thomson Scattering diagnostic	23
2.1	Temperature measurements in a plasma	23
2.1.1	Electron temperature	24
2.2	Incoherent Thoson scattering and T_e measure	25
2.2.1	Incoherent Scattering	28
2.3	General Layout of a TS Diagnostic	32
2.3.1	Temperature evaluation	33
2.3.2	Rotational Raman Scattering and density evaluation .	35
2.4	A Ts diagnostic example: the main TS in RFX-mod	37
3	The Edge TS diagnostic in RFX-mod	43
3.1	Diagnostic description	43
3.1.1	Laser and Mechanical layout	43
3.1.2	Collection optics and acquisition system	46
3.2	Commissioning: from CCD to fast digitizer	49
3.2.1	Problems with CCD in stray and background light suppression	49
3.2.2	First attempts with digitizers and final setup	52
3.3	Opto-mechanical modifications	54
3.3.1	Design problems and signal loss	54
3.3.2	Optics Modifications	55

3.4	Signal processing and data analysis	58
3.5	Alignment and Calibration procedures	59
3.5.1	Spectrometers	60
3.5.2	Alignment & Raman Calibration	61
4	Measurements from Edge Thomson Scattering	65
4.1	First analysis	65
4.1.1	Scalings	67
4.2	Density limit and topology of the $m=0$ island	70
4.2.1	Detection of $m=0$ related structures	72
4.3	Pellets injection	74
4.3.1	Effect on the edge profile of pellet injection	75
4.4	Dynamo Relaxation Events	77
4.4.1	Modification in the profile during a DRE	78
5	Laser Blow off	81
5.1	Laser Blow off principle	81
5.2	The laser blow off system on RFX-mod	82
5.2.1	Layout	82
5.2.2	Commissioning	83
5.2.3	Laboratory tests	86
5.2.4	Final setup	90
5.2.5	Acquired signals in case of succesful injection	92
5.2.6	Upgrades	94
6	Transport in RFP helical states: RFX-mod	97
6.1	Examples of electron temperature profiles in helical states	97
6.2	Core electron temperature and pressure	101
6.2.1	Statistical characterization: ensemble averaged 2D profiles	101
6.2.2	Beyond ensemble averaging: helical remapping for single temperature and pressure profile	102
6.2.3	Correlation between core temperature gradients and helical magnetic shear	106
6.3	Edge electron temperature characterization	112
6.4	Electron energy transport characterization	114
6.4.1	Cylindrical approach	114
6.4.2	Diffusivity at the edge	115
6.4.3	Time evolution of χ_e during a QSH cycle with the 1D model: experimental evidences and limitations	116
6.4.4	2D Approach: explanation of the technique	118
6.4.5	Comparison with the 1D method and results	121
6.5	Edge impurity transport investigations in LBO experiments	122

7	T_e and X-ray analysis in the MST experiment	129
7.1	The MST machine	129
7.2	The experimental campaign	130
7.3	The diagnostic setup	133
7.3.1	Fast TS	133
7.3.2	SXR Tomography	134
7.3.3	Others Tools	135
7.4	Experimental results	136
7.4.1	PPCD results	136
7.4.2	Standard Discharges results	139
7.4.3	Transport and confinement in standard discharges . .	142
8	Conclusions and future work	149
8.1	Conclusions	149
8.2	Developments and future work	150

Chapter 1

Nuclear fusion and RFP configuration

In this chapter the challenge and problematics of nuclear fusion will be introduced. Some examples of configurations for the magnetic confinement of fusion plasmas will be described, focusing in particular on the RFP configuration and the RFX-mod device.

1.1 Fusion and lawson condition

The mass of an atomic nucleus is not the sum of the masses m_p of the Z protons and the masses m_n of the $A-Z$ neutrons of which it is composed [1]. The stable nuclides have a mass defect

$$\Delta = [Zm_p + (A - Z)m_n] - Am_z$$

this mass defect is conceptually thought of as having been converted to energy ($E = \Delta c^2$) at the time that the nucleus was formed, putting the nucleus into a negative energy state. The amount of externally supplied energy that would have been converted to mass in disassembling a nucleus into separate particles is known as the *binding energy* of the nucleus, $B_E = \Delta c^2$; the binding energy per nucleon B_E/A is minimal for deuterium, grows to a maximum for Fe and then decreases for heavier nuclei.

Any process, which results in nuclides being converted to other nuclides with more binding energy, will result in the conversion of mass into energy; the combination of low A -nuclides to form higher A nuclides with a larger B_E/A is the basis for fusion processes which release nuclear energy. On the other side, the splitting of very high A -nuclides to form lighter elements lies at the basis of fission processes, which is also a source of nuclear energy.

The fusion of two light nuclei forms a compound state, which lies in an excited state and then decays into reaction products; the process can be represented schematically by:

$$a + b \rightarrow (\text{compound nucleus}) \rightarrow c + d.$$

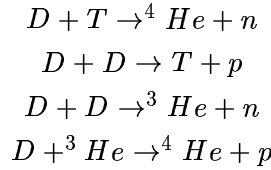
The mass difference

$$\Delta m = (m_a + m_b) - (m_c + m_d) > 0$$

is converted to kinetic energy of the product according to $\Delta E = (\Delta m)c^2$. In order for the fusion reaction to take place, the two nuclei must overcome the long-range Coulomb repulsion force and approach sufficiently close that the short range nuclear attraction can lead to the formation of a compound nucleus; for fusion occurring as a result of random encounters between light atomic nuclei, they must be made sufficiently energetic to overcome the electrostatic repulsion. The rate at which fusion reactions between the species a and b take place can be expressed as:

$$n_a n_b \langle \sigma v \rangle_f = n_a n_b \int_{v_a, v_b} f_a(v_a) f_b(v_b) |v_a - v_b| \sigma_f(|v_a - v_b|) d^3 v_a d^3 v_b$$

where $n_{a,b}$ are the densities, $v_{a,b}$ the velocities and σ_f the fusion cross section. $f_{a,b}$ represents the velocity distribution function, and for hot plasma (which is the environment of the fusion experiments) is often well approximated by a Maxwellian distribution. In these conditions, the two species are thermalized and so the number $\langle \sigma v \rangle_f$ can be written as a function of temperature; its values are shown in fig 1.1 for the three reactions with the lower temperature threshold and hence of technological interest; these reactions can be summarized as:



where the two branches of the D-D reaction occur with almost equal probabilities. The D-T reaction is the easiest to obtained and the only which as the moment is considered for a rectorial use.

The plasma must be heated to thermonuclear temperature (10^8 to 10^9 K) and confined sufficiently long that the thermonuclear energy it produces significantly exceeds the energy required to heat the plasma. Let's name E_f is the energy delivered by a single fusion reation and $\tau_E = W/P_{loss}$ the energy confinement time, as the ratio between the plasma internal energy and the losses per time unit.

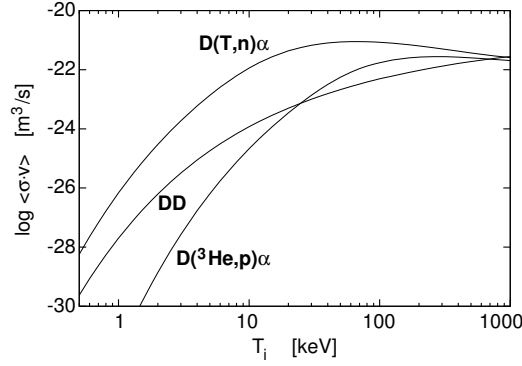


Figure 1.1: reactions rates for the three considered fusion reactions as a function of temperature

For the energy balance of a fusion reactor to be positive, the energy produced by fusion reactions has to exceed that required to create and sustain the plasma itself. One form of energy loss for a D-T plasma with electron density n ($n_{D,T} = n/2$) and temperature T is brehmsstrahlung radiation. The power lost per unit volume due to brehmstrahlung emission is $P_b = bn^2T^{1/2}$, where b is a function of the effective charge Z_{eff} . In addition, power losses due to confinement degradation, e.g. through collisional and turbulent transport phenomena, have to be considered in the power balance. We make a simple estimate of the energy losses due to mechanisms different from brehmsstrahlung as $P_t = 3nT/\tau_E$, where the energy confinement time τ_E is introduced.

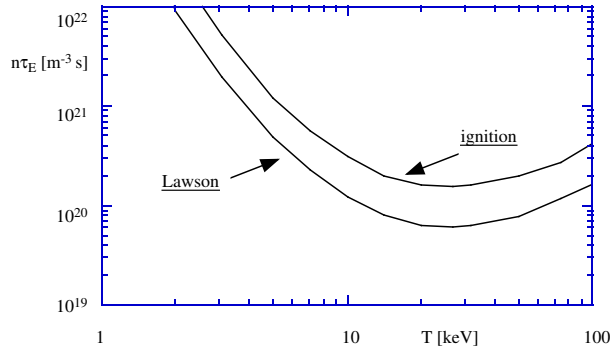


Figure 1.2: Lawson and ignition conditions as a function of plasma temperature

On the other hand, the power generated by fusion reactions can be written as $P_n = W_{DT}n^2\langle\sigma v\rangle_T/4$, where $W_{D,T}$ by a single D-T reaction and $\langle\sigma v\rangle_T$ the reaction rate at temperature T . Let us assume that the reaction power balances the enrgy losses with an efficiency η . The self sustainement condition is thus:

$$P_b + P_t < \eta(P_b + P_t + P_n)$$

which can be rewritten as:

$$n\tau_E > 3T \left(\frac{\eta}{1-\eta} \frac{W_{DT}}{4} \langle \sigma v \rangle_T - bT^2 \right)^{-1} \quad (1.1)$$

This last expression is also known as *Lawson's criterion*. Since the right end side of the previous depends only on temperature, hence the product $n\tau_E$ which satisfies the condition can be plotted as function of T (fig1.2). The curve has a minimum at $T \approx 20keV$ for typical values of η around 30 %; equation 1.2 evaluated for this value of temperature becomes:

$$n\tau_E > 0.6 \cdot 10^{20} m^{-3} s$$

The most probable scenario is one in which the α particles produced by fusion reactions are confined by magnetic field and transfer energy to the plasma, whereas neutrons escape the plasma volume and their energy is converted to electric energy. In this case the Lawson criterion has to be modified, leading to the *ignition criterion*:

$$P_b + P_t < P_o$$

which can be expressed as:

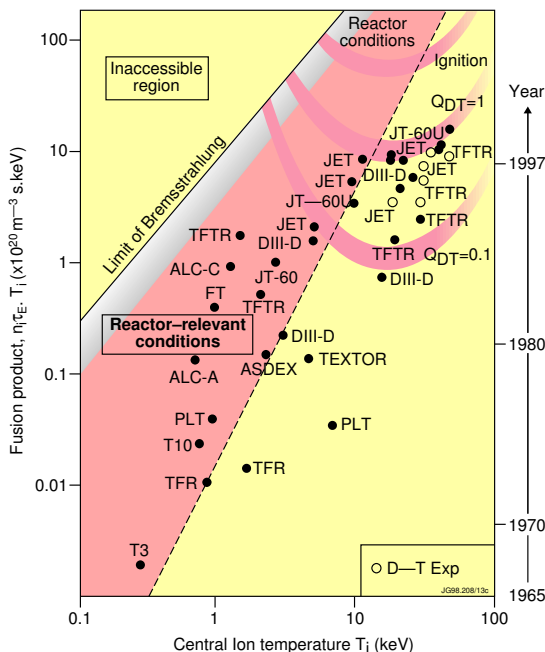


Figure 1.3: Performances of fusion experiments in terms of the $n\tau_E$ T triple product

$$n\tau_E > 3T \left(\frac{W_\alpha}{4} \langle \sigma v \rangle_T - bT^2 \right)^{-1} \quad (1.2)$$

if $W_\alpha = W_{DT}/5$ is the energy of a single alpha particle. As the Lawson's criterion curve, (fig1.2) has a minimum at about 20 keV, where confinement time and density have to satisfy:

$$n\tau_E > 1.5 \cdot 10^{20} m^{-3}s$$

The last result can also be written in the form of the so called *triple product*

$$n\tau_E T > 3 \cdot 10^{21} m^{-3} s \text{ keV}$$

For temperatures of 20 keV and electron densities of $10^{20} m^{-3}$, which in laboratory experiments are limits due physical and technological constraints, the energy confinement time τ_E must be greater than 1s. Conditions approaching ignition have been achieved in recent years in different tokamak experiments, as it is reported in fig.1.3.

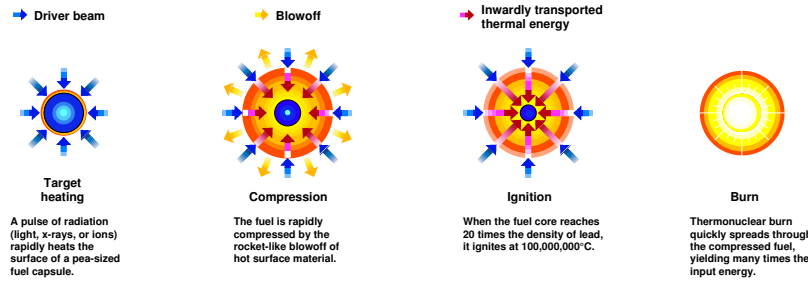


Figure 1.4: Inertial fusion principle

Two methods appears up to now to be rather promising to realize fusion conditions in the laboratory: magnetic confinement and inertial fusion.

- *Magnetic confinement* [2], which is the main focus of this thesis, uses strong magnetic fields to confine matter in the plasma state. It is well known that a charged particle in a strong magnetic field has a spiraling motion around the magnetic field lines. In the absence of collisions, and by using magnetic fields with closed geometry, it is thus possible to confine plasmas for relatively long times.
- *Inertial fusion* [3] represents the other extreme solution maximizing the density, by strong, symmetric heating of a small $D - T$ pellet (see fig. 1.4). The heating can be produced using lasers or particle beams and leads to ablation of an external layer causing implosion due to

momentum conservation. It is clear that the energy confinement time is extremely short in this concept: it is the timescale of the stagnation phase, after the implosion process and before the target re-expansion. Since the fuel is confined only by the inertia of its own mass, this approach to fusion is often called *inertial fusion*. The density required is about 1000 times the density of liquid $D - T$ and the temperature reaches $10keV$. This kind of confinement is not considered in this thesis and will not be dealt with further.

1.2 Magnetic confinement

Plasma magnetic confinement is based on the nature of charged particle motion in the presence of magnetic fields: due to the Lorentz force, ions and electrons are bent into a circular path by the component of magnetic field which is perpendicular to the velocity, with a gyration radius defined as the *Larmor radius*, $r_L = mv_{\perp}/|q|B$ (m is the mass, q the charge and $v_{\perp}$ the velocity perpendicular to the magnetic field $\mathbf{B}$). In the absence of a parallel electric field and for uniform $\mathbf{B}$, any motion parallel to the magnetic field will be unchanged by it, so the general motion would be a helical motion. Several magnetic field geometries have been investigated to seek the best conditions for plasma confinement, reaching the conclusion that, since particles are free to move along field lines, non-periodic or open magnetic configurations will exhibit poor confinement properties [2, 4]. In linear configurations the end losses are by far too large to reach the necessary energy confinement time τ_E ; these end losses can be completely avoided in a toroidal system.

In Fig. 1.5 we define the toroidal coordinates (r, θ, ϕ) , which will be used in the rest of the thesis: r is called the radial coordinate, θ and ϕ are respectively the poloidal and toroidal angles, R_0 and a the major and minor radius of the torus.

In a simple toroidal system with a purely toroidal magnetic field, the magnetic field curvature and gradient result in a vertical drift which is in opposite directions for ions and electrons. The resulting electric field causes an outward $E \times B$ drift of the whole plasma, and therefore such a simple magnetic field configuration would not be viable. It is necessary to twist the magnetic field lines by additional magnetic field components; hence, in toroidal experiments there are both a poloidal component B_{θ} and a toroidal component B_{ϕ} . The magnetic field can be produced both by external coils or by currents flowing in the plasma, depending on the particular magnetic configuration. Magnetic field lines are thus helices, which are wound around the torus lying over toroidal surfaces called *magnetic surfaces*. Helical magnetic field lines are described by the so called *safety factor* q , which is defined as a function of radius as follows:

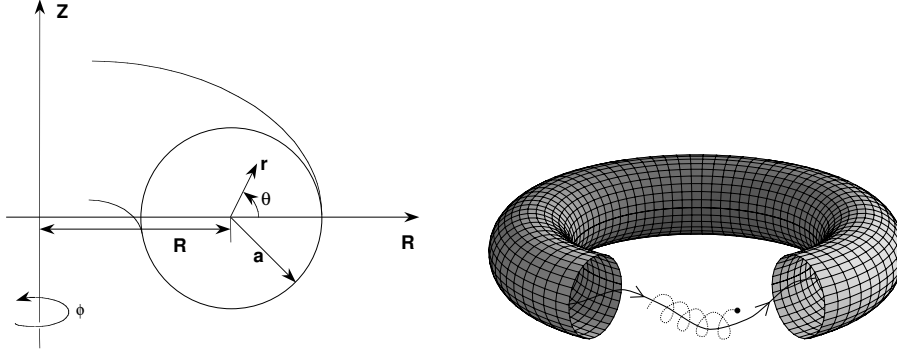


Figure 1.5: On the left, the system of toroidal (r, θ, ϕ) and cylindrical coordinates (R, ϕ, z) . On the right, a scheme showing the principle of toroidal confinement: a charged particle gyrates around a helical magnetic field line and it is thus confined inside a toroidal vacuum vessel.

$$q(r) = \frac{rB_\phi(r)}{R_0 B_\theta(r)}. \quad (1.3)$$

The inverse of this quantity represents the number of poloidal turns done by a helical field line per one toroidal turn.

1.2.1 MHD model: plasma as an electrically conducting fluid

The theoretical description of a plasma system may be undertaken using different approaches, depending on the level of accuracy required in the description, and on the level of complexity desired in the analysis: one method consists in thinking of the plasma as an electrically conducting fluid. This allows the use of the relatively simple equations of hydrodynamics, adding the effects specific to an electrically charged current-carrying fluid, such as electric and magnetic forces [4].

Let's consider here for simplicity a Hydrogen plasma (it would be trivially possible to extend the present description also to multiple species plasmas). Plasma will be considered as a fluid containing positively charged particles (ions) of mass m_i and charge $+e$, distributed with density n_i , and negatively charged ones (electrons), with mass m_e , charge $-e$ and density n_e . We will moreover assume that charge neutrality will be at least approximately satisfied on macroscopic scales, so that $n_i \approx n_e \approx n$.

Since we want to describe the plasma as a single neutrally charged fluid, we need to define the mass density¹ $\rho = n_i m_i + n_e m_e \approx n m_i$, the charge density $\sigma = (n_i - n_e)e$, the mass velocity, $\mathbf{u} = (n_i m_i \mathbf{u}_i + n_e m_e \mathbf{u}_e) / \rho \approx$

¹Ion's mass is much larger than m_e , hence $m_i + m_e \approx m_i$

$\mathbf{u}_i + (m_e/m_i)\mathbf{u}_e$ and the electrical current density $\mathbf{j} = e(n_i\mathbf{u}_i - n_e\mathbf{u}_e)$. Equations are then derived starting from the usual mass and momentum continuity equations, involving quantities just described and connecting them to electric and magnetic fields. The calculation requires some approximations. The gyration radius of particles around field lines can be neglected if compared with the characteristic length of fluid motion. Also σ is usually very small, allowing some terms involving charge density to be neglected. Hence MHD equations are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad \text{mass continuity} \quad (1.4)$$

$$\nabla \cdot \mathbf{j} = 0 \quad \text{charge continuity} \quad (1.5)$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \mathbf{j} \times \mathbf{B} - \nabla p \quad \text{momentum continuity} \quad (1.6)$$

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{j} \quad \text{Ohm's law} \quad (1.7)$$

We must add to this system of equations, the Maxwell equations:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \nabla \cdot \mathbf{B} = 0$$

where the displacement current $\epsilon_0 \mu_0 \partial \mathbf{E} / \partial t$ can be neglected in most cases of interest. The pressure p should be considered as a tensor, since it describes the momentum flux in a generalized direction in space; anyway, in the MHD model, pressure is often considered a scalar. The needed closure in order to obtain a complete and coherent ensemble of equations can be provided by an equation of state for p . To this purpose, an equation of state for pressure is often used of the form $p \propto n^\gamma$, where $\gamma = 1$ represents isothermal compression and $\gamma = 5/3$ adiabatic compression. A different closure scheme can be provided by introducing a continuity equation for energy.

By combining Faraday's law with Ohm's law, it is simple to derive the following equation, which describes the coupled dynamics of the magnetic and fluid velocity fields in the resistive MHD framework:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B} \quad (1.8)$$

The first term on the r.h.s. in Eqn. (1.8) describes the convection of the magnetic field with the plasma, and its change due to motions perpendicular to the magnetic field. Starting from this equation, it is possible to show that, in the ideal MHD limit, i.e. in the case where the resistivity η is negligible, the magnetic field lines move as if they were “frozen” in the plasma [5]. The second term describes instead the resistive diffusion of the field across the plasma.

1.2.2 Static MHD equilibrium

The steady state condition is described by zeroing time derivatives (stationary, $\partial/\partial t = 0$) and considering zero flow (static, $\mathbf{u} = 0$). The MHD

equilibrium equation becomes the so called *force-balance equation*:

$$\mathbf{j} \times \mathbf{B} = \nabla p \quad (1.9)$$

that describes the balance between the magnetic force and the thermal expansion force in a plasma. In the equilibrium condition, the force exerted on the fluid element, by a current flowing perpendicular to the magnetic field, balances the plasma kinetic pressure, so that everywhere in the plasma the local pressure gradient is balanced by the Lorentz force. Note that, since ∇p is perpendicular to both magnetic field and current density, surfaces of constant magnetic flux are also isobaric surfaces. The balance described in Eqn. (1.9) is even more explicit if we introduce an expression for $\mathbf{j}$ using Ampere's law, so obtaining the *pressure balance condition*:

$$\nabla \left(p + \frac{B^2}{2\mu_0} \right) = \frac{1}{\mu_0} (\mathbf{B} \cdot \nabla) \mathbf{B}. \quad (1.10)$$

On the r.h.s. of the equation, a term coming from both bending and parallel compression of the magnetic field (i.e., respectively, coming from the changes of the direction of $\mathbf{B}$ and of its magnitude along the field line) is balanced by the gradient of the sum of kinetic pressure p and magnetic pressure $B^2/2\mu_0$. The ratio between p , averaged over the plasma volume, and the magnetic pressure defines the β parameter, $\beta = \langle p \rangle / (B^2/2\mu_0)$. β measures the economic efficiency of the confinement because the fusion power output roughly scales as p^2 , while B is the magnetic field which has to be externally provided, and represents therefore an energy cost. Since poloidal or toroidal magnetic field components alone could be used in the above definition, the β parameter is also called poloidal β_θ or toroidal β_ϕ , respectively. Usually, β is limited by the occurrence of MHD instabilities, and laboratory plasmas tends to have values of about 10% at most.

For an axisymmetric system, it is convenient to re-write the force balance equation, providing a useful analytical tool for equilibria calculation in the case of toroidal configuration. Using the coordinates (R, ϕ, z) (see Fig. 1.5), the axisymmetric equilibria can be described by a two-dimensional non-linear elliptic partial differential equation, called Grad-Shafranov equation (GSE) [5]. The GSE can be written as

$$\Delta^* \psi_p = -2\pi F \frac{dF}{d\psi_p} - 2\pi\mu_0 R^2 \frac{dp}{d\psi_p} \quad (1.11)$$

where Δ^* is an elliptic operator defined as

$$\Delta^* = R \frac{\partial}{\partial R} \left(\frac{1}{R} \frac{\partial}{\partial R} \right) + \frac{\partial^2}{\partial z^2}. \quad (1.12)$$

Eqn. (1.11) specifies the toroidal equilibrium (magnetic field and flux, current density, and pressure profiles) when the two free functions $F(\psi_p) =$

$RB_\phi(\psi_p)$ and $p = p(\psi_p)$ are given. Here ψ_p is the poloidal magnetic flux, which is used to label the magnetic flux surfaces in a toroidal system.

1.3 Axisymmetric toroidal configurations: Tokamak and RFP

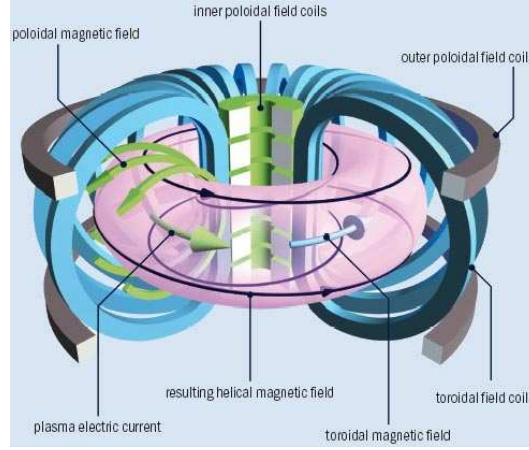


Figure 1.6: layout of a tokamak experiment showing the main components

Different toroidal configurations are characterized by different magnetic field and safety factor profiles, instability behavior and maximum attainable β values at comparable input power. We will focus here on two configurations, the Tokamak and the RFP; the latter will be extensively treated in this thesis. These are similar under many respects, in particular in both a toroidal current is inductively driven by an external circuit, and generates a poloidal magnetic field that confines and compresses the plasma. On the other side, a part of the toroidal field is generated by external coils [6].

Tokamak and RFP configuration present also some important differences, both in the basic physics processes and in more technological aspects. Typical magnetic field and safety factor profiles in the tokamak and in the RFP are compared in Fig 1.7. The tokamak is characterized by a relatively toroidal field, that can reach values of several T in high field machines, and much weaker poloidal magnetic field. On the other side, in RFP the strength of the components is comparable; a point to remark is that the toroidal field at the edge is much lower for RFP, and hence this kind of machine has less demanding technological issues. Moreover, the condition $B_\phi \gg B_\theta$ limits in tokamaks the toroidal current and the related Ohmic heating of the plasma. To reach thermonuclear conditions it is hence necessary to adopt additional heating systems such as neutral beam injection or RF launching, with the result of increasing the cost and complexity of the machines.

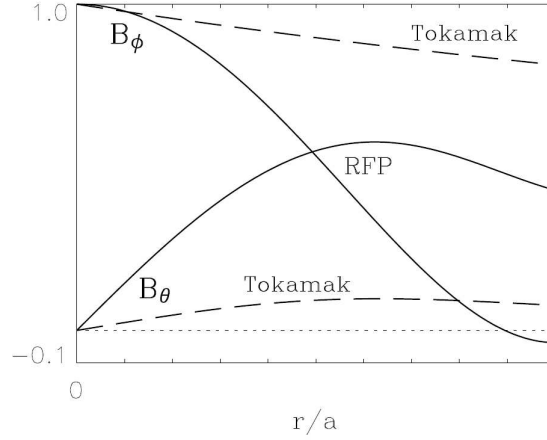


Figure 1.7: magnetic field components in a tokamak and in an rfp

here we introduce two dimensionless parameters that are often used to describe pinch equilibria like the tokamak and the RFP. These are the so called *Pinch parameter* Θ and the *Reversal parameter* F , and are defined as follows:

$$\Theta = \frac{B_\theta(a)}{\langle B_\phi \rangle}, \quad F = \frac{B_\phi(a)}{\langle B_\phi \rangle}$$

where the brackets indicate the average over the plasma poloidal section. In terms of these quantities, the tokamak is typically a low- Θ device with $F > 0$, while RFP is a relatively high- Θ configuration, with $F < 0$.

Tokamaks and RFPs are characterized by very different safety factor profiles, as shown in Fig. 1.8. For stability requirements, tokamak operation is preferable at $q > 1$. The condition $q \approx 1$ is called *Kruskal-Shafranov limit* and is related to the possibility for a strong ($m=1$, $n=1$) kink instability to become unstable. This can bring in some cases to violent current disruptions, with possible damages in the vessel components. In its standard operation, the tokamak safety profile increases monotonically with the radial coordinate r and it reaches typically values $q(a) \approx 3$ at the edge. Other types of safety factor profiles have been studied in advanced tokamak operation, e.g non monotonic dependencies, but here this we will not further enter this issue.

The RFP is intrinsically a low safety factor device, $q < 1$, due to its toroidal magnetic reversal. In fact in the RFP the current is driven well above the Kruskal-Shafranov limit; this fact has many consequences on its stability features. In its standard operation, the RFP is in fact characterized by a broad spectrum of resonant MHD instabilities the presence of these instabilities has a great impact both on the dynamics of this configuration and on its transport properties. Low safety factor operation in RFP does not lead to dangerous disruptive behavior, because of the combined action of a

conducting shell surrounding the plasma and of the magnetic shear at the plasma edge; these two effects produce a passive stabilization of magnetic instabilities.

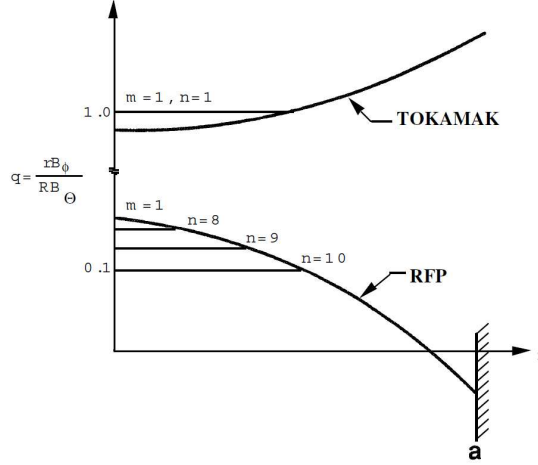


Figure 1.8: safety factor profiles for a tokamak and a RFP experiment; the resonant surfaces for instabilities, identified by rational values of q , are enlightened

1.3.1 Brief elements of MHD stability

As seen in the previous section, the developping of MHD instabilities is one of the most common phenomena in magnetically confined plasmas. A perturbation $\tilde{\mathbf{A}}$ of a quantity $\mathbf{A}$ in a toroidal plasma can be fourier analysed as follows:

$$\tilde{\mathbf{A}}(\mathbf{r}) = \sum_{\mathbf{k}} \tilde{\mathbf{A}}_{\mathbf{k}}(r) e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} = \sum_{\mathbf{k}} \tilde{\mathbf{A}}_{\mathbf{k}}(r) e^{i(m\theta + n\phi - \omega t)}$$

where $\mathbf{k} = (k_r, k_\theta, k_\phi) = (k_r, m/r, n/R)$ is the wavevector in toroidal coordinates, and m and n are respectively the poloidal and toroidal mode number. Each couple (m, n) represents a helical perturbation, or mode. the angular frequency ω is in general a complex quantity $\omega = \omega_R + i\omega_I$, of which the real part describes the propagation velocity and the imaginary part represents a growth ($\omega_I > 0$) or a damping ($\omega_I < 0$) of the perturbation amplitude.

A helical magnetic perturbation with wavevector $\mathbf{k}$ can become unstable if it fullfills the resonance condition $\mathbf{k} \cdot \mathbf{B} = 0$, where $\mathbf{B}$ is the equilibrium magnetic field. in fact, a perturbation with $\mathbf{k} \cdot \mathbf{B} \neq 0$ would bend the mean magnetic field, and thus it would have an energetic cost. The above resonance condition can be written as follows:

$$\mathbf{k} \cdot \mathbf{B} = \frac{m}{r} B_\theta + \frac{n}{R} B_\phi = 0 \rightarrow q(r) = \frac{r}{R} \frac{B_\phi(r)}{B_\theta(r)} = -\frac{m}{n}$$

This shows that helical instabilities can grow only at radial positions where the safety factor assumes rational values. For this reason, these positions are called *rational* or *resonant* radii; this explains why the safety profile behavior is so important when dealing with axisymmetric machines.

Plasma instabilities can be driven by various factors, such as thermal or pressure gradients; an important example is given by the *tearing mode*, which is driven unstable by a gradient in the current density [4, 7] parallel to the magnetic field. The name of this instability comes from the fact that the magnetic field lines tear and reconnect during the instability evolution. The result of magnetic field reconnection is the development of a magnetic island; in toroidal plasmas, such islands have an helical structure, since they follow the pitch of the magnetic field. Magnetic islands characterization in RFP will be one of the main topics of this thesis.

1.4 Dynamo and RFP configuration

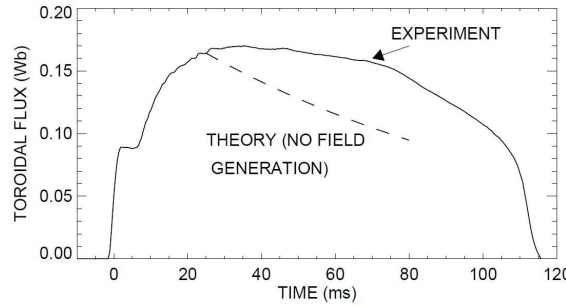


Figure 1.9: Example of experimental evolution of the toroidal flux and expected behavior without the presence of MHD dynamo

If a RFP equilibrium was governed only by resistive diffusion, the characteristic reversal of the toroidal magnetic field would be lost very soon and the discharge terminated. The magnetic field in static cylindric conductor with minor radius a , subject to resistive diffusion, is described by:

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$$

The toroidal component of magnetic field is expected to decay exponentially in time with a time constant $\tau_R = \mu_0 a^2 / \eta$ (fig 1.9), where η is the resistivity of the conductor. It is generally observed that the RFP configuration lasts as long as the plasma current is sustained, which is usually

longer than the resistive diffusion time. Some mechanism must be present that regenerates the magnetic field continuously lost through diffusion; this mechanism is called dynamo. let us consider the paralele component of the mean-field Ohm law:

$$E_{\parallel} = \frac{\mathbf{E} \cdot \mathbf{B}}{B} = \frac{E_{\phi} B_{\phi}}{B} = \eta j_{\parallel} \quad (1.13)$$

Since E_{ϕ} and B are always positive throughout the radius, $E_{\parallel}$ at each radial position is proportional to B_{θ} , which changes sign near the edge. Respect to what happens in the experiment, the current appears to be over driven in the plasma core and under driven at the edge; the discrpepancy is accounted precisely by the dynamo effect. The origin of the dynamo lies in the magnetic activity peculiar of RFP (1.3) and in particular in the non-linear interaction of $m=1$ modes, which are continuously excited according to the shape of the safety factor profile. The standard operation in RFP, where many modes resonate in the plasma interior, is commonly referred as *Multiple Helicity* (MH) regime and the excited $m=1$ modes textitdynamo modes.

The result of having a wide spectrum of excited tering modes is the magnetic stochasticity related to the overlap of many small islands, to high values of the Chirikov criterion [8] s^2 as well as to a turbulent plasma flow. In this situation, it is useful to write the velocity field $\mathbf{V}$ (flow) and the magnetic field as a sum of unperturbed and perturbed terms :

$$\mathbf{B} = \mathbf{B}_0 + \tilde{\mathbf{b}}; \mathbf{V} = \mathbf{V}_0 + \tilde{\mathbf{v}}$$

The perturbation terms are supposed to be responsible of the poloidal electric field via a dynamo mechanism; the 0 order quantities sum to zero for simmetry reasons and:

$$\mathbf{E}_{dyn} = \mathbf{V} \times \mathbf{B} = (\mathbf{V}_0 + \tilde{\mathbf{v}}) \times (\mathbf{B}_0 + \tilde{\mathbf{b}}) \approx \tilde{\mathbf{v}} \times \tilde{\mathbf{b}}.$$

Since $\mathbf{E}_{dyn}$ must have a poloidal components, it follows that $\tilde{\mathbf{v}}$ and $\tilde{\mathbf{b}}$ have a finite radial component which at the end is responsible of the confinement detriment of the RFP configuration. The dynamo term has to be added to eq. 1.13 to get finally the correct expression for the Ohm law:

$$E_{0\parallel} + E_{dyn,\parallel} = E_{0\parallel} + \langle \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} \rangle_{\parallel} = \eta j_{\parallel} \quad (1.14)$$

Since the dynamo mechanism has as a consequence the magnetic field to become stochastic, the main contribution to particle and heat transport is due to parallel diffusion of electrons along stochastic field lines; actually,

²the stochasticity of magnetic field can be quantified with the Chirikov criterion s : $s = \frac{1}{2} \frac{w_{m,n} + w_{m',n'}}{r_{m,n} - r_{m',n'}}$, with r the renonance radius of the m,n mode and w the width of the relative island.

It can be described in the Rochester-Rosenbluth approximation, where the electron diffusivity is related to the magnitude of magnetic perturbations [9]:

$$\chi_e(r) \propto \frac{(\tilde{b}_r)^2}{B(r)^2}$$

The excitation of many magnetic instabilities has other consequences: in MH regime, $m=1$ modes interaction one with another is responsible to an overall, toroidally localised plasma deformation, due to constructive interference of the $m=1$ radial components; phase differences tends to stabilize thanks to viscous torque transfer, and the resulting structure, commonly referred as *locking* or *slinky* pattern [10], causes the field lines to intersect the first wall and there release a huge amount of thermal power.

Moreover, non linear interaction of $m=1$ modes has been proved to excite the resonance of $m=0$ modes; according to the shape of the safety profile q , $m=0$ modes resonate at the reversal; the resulting $m=0$ islands tend to lock each other and with the $m=1$ ones, following the relation $\alpha_{0,n} = n\phi_0 - \Delta_0$, being $\Delta_0 = \pm\pi/2$ and ϕ_0 is the toroidal location of the $m=1$ interference pattern. The presence of the $m=0$ islands chain influences deeply the confinement features in the edge region; here the temperature gradients are steep and, practically, almost all the confinement takes place.

Though the exact reconstruction of the current pattern in RFP should account for the dynamo contributions, for common applications such as the equilibrium reconstruction a mean-field approach is used, based on Taylor's modellization of RFP [11]. This modellization is based on the conservation of magnetic helicity in a force free condition ($\nabla \times \mathbf{B} = 2\lambda\mathbf{B} = \mu\mathbf{B}$) for the magnetic field; a spatial solution, in cylindrical geometry, is described by the Bessel functions J_0, J_1 :

$$B_z = B_0 J_0(\mu r); B_\theta = B_0 J_1(\mu r) B_r = 0;$$

and known an "Bessel Function Model" (BFM). Practical models based on the BFM, such as the μ & p model [12] used for equilibrium reconstructions in RFX-mod, don't consider μ as a constant but as a function of radius, to account for the resistivity increase as one moves toward the chamber wall ($r=a$) μ & p accounts also for the presence of pressure gradient, solving:

$$\nabla \times \mathbf{B} = \mu(0) \left[1 - \left(\frac{r}{a} \right)^\alpha \right] + \left(\frac{\beta_0}{2B^2} \right) \mathbf{B} \times \nabla P$$

β_0 being the value on the axis of β

1.5 Helical states in RFPS

In the last years, the description of RFP's as an axisymmetric device, as reported in the previous section, has been found to be no more adequate.

The standard paradigm of a turbulent dynamo driven by a wide spectrum of tearing modes has to face the experimental detection of states in which one single tearing mode (which is typically the $m=1$ inner resonant) is excited and grows to saturation, while the level of the other remains significantly lower. These states are referred as Quasi Single Helicity (QSH) and, at the present, can be obtained only in transient way. QSH states have been so far identified in various RFP experiment: EXTRAP T2R in Stockholm (S), TPE-RX in Tsukuba (JP), MST in Madison (USA) [13]. They can be detected as asymmetric peaking in the temperature profile or presence of bright SXR island in the tomographic inversions (fig. 1.10)

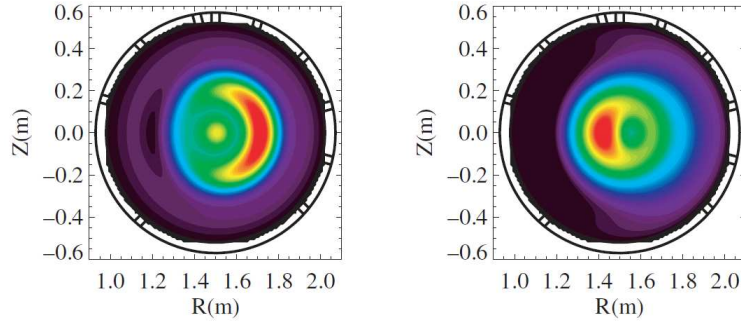


Figure 1.10: Experimental detection of an bright emissivity island in the MST machine; the island develops at the resonant surface for the inner resonant mode

In all cases the QSH is clearly evident in the magnetic spectrum of $m=1$ modes fig.1.11, showing a single mode which grows while the other remain constant or decrease.

However, the discharge fraction interested by a QSH state and the duration itself of QSH scale positively with the Lundquist number S (fig.1.12), while the normalized amplitude of secondaries scales negatively [14,15]. According to spitzer formula for resistivity:

$$\eta_p = 1.65 \cdot 10^{-9} Z_{eff} T_e^{3/2} \ln \Lambda \quad (\ln \Lambda \text{ is the Coulomb logarithm})$$

the Lundquist number, which is the ratio of resistive to Alfvén times, can be written as

$$S = \frac{30 I_\phi T_e(0)^{3/2}}{0.4 + 0.6 Z_{eff} \ln \Lambda \sqrt{m_i \langle n_e \rangle}}.$$

QSH states in RFP machines are characterized by topological and thermal changes in the plasma core: Poincaré plots (made ORBIT particle tracing code [16]) show that, if the secondary mode spectrum is weak enough, conserved surfaces emerges around the magnetical island related to the dominant mode. As a term of comparison, in MH states, the plasma core is

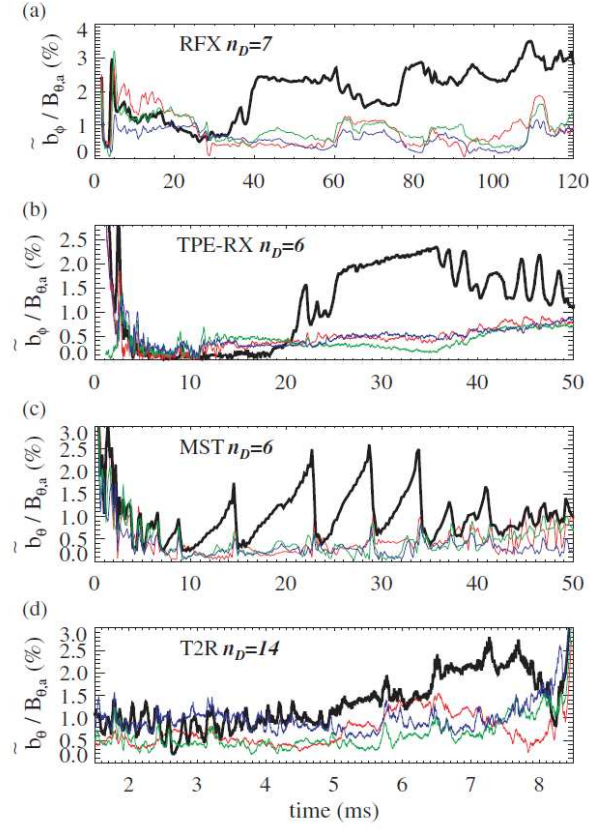


Figure 1.11: Magnetic spectra (the value of the perturbation is normalized at the value of poloidal field) for QSH states in 4 RFP experiments; the dominant mode varies with the different aspect ratio of the machines

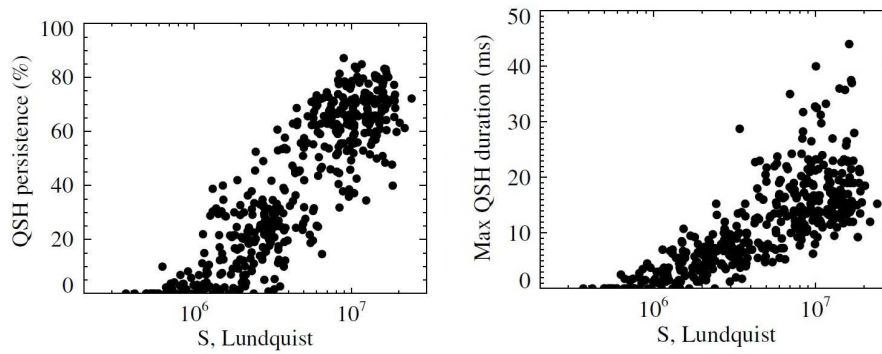


Figure 1.12: QSH fraction and duration as a function of Lundquist number

completely dominated by magnetic chaos due to the overlapping of many small islands.

Also the plasma edge is modified: in particular, the locking pattern peculiar of MH discharges is softened since radial components of the secondary modes spectrum are much lower; on the other side, the the last closed flux surface (LCFS) is interested by an uniform helical deformation, related to the finite value of the dominant mode radial componet at the plasma boundary: this configuration is clearly less hard to sustain by the first wall, from the point of view of thermal power deposition.

Depending on many factors, mainly on the normalized mode amplitude and on the slope of the safety profile in the core, the island grows while the plasma centroid is shifted toward the X-point until it is expelled: this event (separatrix expulsion) [17,18] defines a new state called SHAx (acronyms for Single Helical Axis) to stress the presence of a single, near-ideal kink mode and the disappearing of the plasma centroid and separatrix. QSH states where separatrix and centroid still exist are named Double Helical Axis or DAX.

In the past, numerical works performed with SPEcyl code predicted the existence RFP configurations characterized by an helical equilibrium and by the presence of a laminar dynamo instead of a turbulent one (where the adjectives refers to the flow velocity field $\mathbf{V}$ responsible of tht dynamo itself) [19]. Helical equilibria are characterized, in a cylindrical reference frame, by invariance along the helical coordinate $\zeta = z - k\theta$ and they are described by the helical Grad Shafranov equation ³. MHD dynamo isn' the only source of self generated electric field: in particular, it is one of the cause of the presence of electrostatic potential difference and of charge separation inside the plasma. In these conditions, a Hall dynamo effect [20,21] ($\mathbf{E} \propto \mathbf{J} \times \mathbf{B}$) can take place; its contribution is significant particularly at the plasma edge and near the dominant mode resonance radius (where indeed ∇P differs from zero). A more comprehensive form for the ohm law, accounting for all the dynamo contributions, can be written as:

$$\mathbf{E} - \eta \mathbf{J} = \langle \mathbf{J} \times \mathbf{B} \rangle + \langle \mathbf{V} \times \mathbf{B} \rangle$$

³while Grad Shafranov equation describes axysymmertic equilibria, helical GS equation describe the MHD force balance in system characterized by helical symmetry from

$$\mathbf{J} \times \mathbf{B} - \nabla p = 0, \quad 1/4\pi(\nabla \times \mathbf{B}) = 0 \quad (1.15)$$

$$\text{and } \nabla \cdot \mathbf{B} = 0 \quad (1.16)$$

$$(1.17)$$

one can write

$$\frac{1}{r} \frac{\partial}{\partial r} \left(\frac{1}{1+k^2 r^2} \frac{\partial \phi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial \zeta^2} - \frac{2kF}{(1+k^2 r^2)^2} + \frac{1}{1+k^2 r^2} F \frac{dF}{d\phi} + 4\pi \frac{dp}{d\phi}$$

with $\phi = 1/2\pi(\Phi_z - \Phi_\theta)$; $F = B_z + krB_\theta$

QSH states arise spontaneously as the current increases [22], but they can be also triggered with OFCD and, in particular for RFX, OPCD operation. Both techniques rely on the application of an oscillation: in the toroidal field for OPCD (Oscillating Poloidal Current Drive) or in both components for OFCD (oscillating Field Current Drive) [23]. OFCD is a mean to inject helicity in the plasma, if the phase difference of the oscillation of B_θ and B_ϕ is properly chosen, and it is regarded as a mean for current sustainment. OPCD offers transient improvements in the plasma features, in the half cycle in which the current drive is parallel to the dynamo field, being in the other half antiparallel⁴.

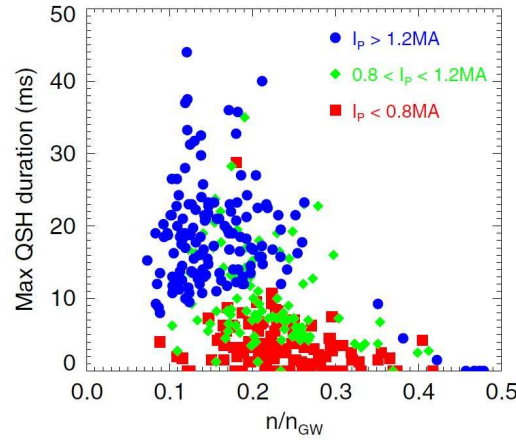


Figure 1.13: maximum duration of QSH as a function of normalized density n/n_G for different current classes

On the other hand, the occurrence of QSH states is suppressed at high values of density, in particular for density approaching the Greenwald limit (fig.1.13, [15]); it should be noted also that operations at high current, high density (being n_G a growing function of current) is hard for the difficulty to maintain the control of density (this is particularly tough from machines which mount by a graphite wall and thus characterized by high levels of recycling)

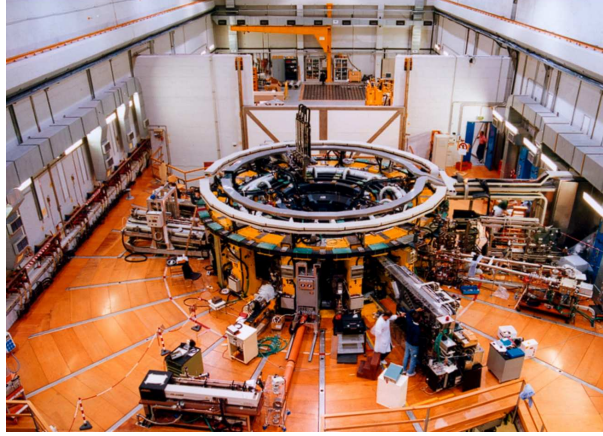


Figure 1.14: Picture of the RFX-mod Experiment

1.6 The RFX-mod experiment

Most of the work carried on in this thesis has been carried on on the RFX-mod machine. RFX mod experiment is the largest RFP machine in the world: it is based on a previously existing machine; after an accident, this device has been modified (RFX-mod, $R_0 = 2m$, $a = 0.459m$) by replacing a thick passive Al shell (65mm thickness with 450ms vertical field penetration time) with a thinner (3mm thickness and 50ms vertical field penetration time) Cu shell and by installing a set of 192 (4 poloidally $\times$ 48 toroidally) feedback controlled saddle coils with independent power supplies [24, 25]. The presence of this active feedback control on the magnetic instabilities. They allow mimicking an ideally conducting wall by locally opposing the radial field (*Virtual Shell*, VS), or to actively control individual magneto-hydro-dynamic modes.

The coils surround the thin copper shell, and, under each of them, a saddle radial field sensor of the same area is mounted on the internal part of the shell, in such a way that the flux at the sensor can be exactly balanced by a suitable current in the active coil. Each coil is individually fed with a maximum current of 400A, with a maximum radial field generated at the plasma edge of 50mT dc that decreases to 3.5mT at 100Hz. They can generate magnetic field harmonics with $m = 0$, $n = 0 \div 24$ and $m = 1$, $n = -23 \div 24$. A digital feedback system controls toroidal and poloidal circuits,

⁴From magnetic helicity K definition [11],

$$\partial K / \partial t = 2\phi_z v_z + 2 \int_V \mathbf{E} \cdot \mathbf{B} dv$$

Writing the toroidal flux and the toroidal voltage as a sum of a steady state and varying component: $\phi_z = \phi_{z0} + \tilde{\phi}_z$ and $v_z = v_{z0} + \tilde{v}_z$ it is possible to have $\dot{K} > 0$ if $\langle \tilde{\phi}_z \tilde{v}_z \rangle > 0$. In OPCD $\dot{K} = 0$

toroidal equilibrium and the saddle coils. For MHD control it performs the two-dimensional FFT of B_r and/or B_ϕ measurements, compares it with the preset waveforms and computes via inverse FFT the required references. This permits controlling the MHD modes selectively and has been used for several control schemes.

The toroidal field winding system consists of 48 coils evenly distributed around the torus. The maximum toroidal bias magnetic field it can produce is $B_\phi \sim 0.7T$ at the beginning of the discharge, and a reversed field at the wall of $B_\phi(a) = 0.5T$ during the current flat-top. The poloidal flux swing, which causes the plasma current rise, is provided in RFX-mod by the so called magnetizing winding, or transformer winding. No iron core has been adopted, even though it would have reduced the coil dimensions, power demand and costs, in order to avoid magnetic field asymmetries and to improve the accessibility. The first wall of the RFX-mod machine is composed of 2016 trapezoidal graphite tiles, which cover the entire inner surface of the toroidal vacuum vessel. Graphite was chosen because it is a low- Z material, which should keep the plasma Z_{eff} value low.

Chapter 2

Electron temperature measures with Thomson Scattering diagnostic

This chapter will briefly some of the most common diagnostics used in fusion experiments for electron temperature evaluation; the attention will then be focused on the Thomson Scattering (TS) theory and on the general features of a T_e diagnostic based on this process. As an example, the Main TS on RFX-mod will be described, since its measurements are used widely in Chapter 5.

2.1 Temperature measurements in a plasma

Electron and ion temperature T_e and T_i represent two of the most relevant plasma parameters being required to establish the performance of a fusion experiment. In fact, as described in the previous sections, T_e and T_i are essential to study:

- the value of the energy confinement time and in general the transport;
- the value of the triple product;
- the physics of instabilities;
- heat diffusivity coefficients;
- and transport coefficients.

Plasma diagnostics are based on a multitude of different physical processes and many different techniques are employed to measure the spatial profile and time evolution of various plasma parameters. The adopted methods have different performance and limitations; for this reason their combination provides sinergetic accurate profiles of T_e and T_i at many locations

with good spatial and temporal resolution. A brief description of their performance is here reported in order to explain how their combination is the only solution for a complete description of temperatures in a plasma.

2.1.1 Electron temperature

- *Incoherent Thomson scattering* (TS) is based on the Doppler shift of the photons coming from by a laser source when diffused by the plasma electrons. It can measure the T_e profile at several positions, from the core to the edge of the plasma, with high spatial resolution (down to a few mm) and with high accuracy. Unfortunately, the repetition rates of the single laser systems are not sufficient to follow the dynamic behavior of the electron temperature with a good time resolution.
- *Electron cyclotron emission* (ECE): it is based on the cyclotron radiation emitted by the electrons during their gyration around the magnetic field lines. The n -th harmonic frequency depends on the strength of the magnetic field, $\omega_n = n \cdot eB/m_e$, and hence, on the electron position in the plasma. The intensity of the radiation for optically thick plasmas is proportional to the local electron temperature, $I_n(\omega) = \omega^2 T_e / 8\pi^3 c^2$. It provides T_e profile with a time resolution in the μs range and a spatial resolution of a few cm . It cannot provide reliable measurements for the low electron densities and magnetic fields, for example in the edge region of the plasma, where reflections from the vessel become relevant. In optically thin plasma (low density) it can be more advantageous to use electron cyclotron absorption (ECA), a function of T_e and n_e , so that an independent measurement of n_e should be used to disentangle T_e . Recently, repetition rates of tens of kHz has been obtained with innovative methods, but only for a limited time interval [26]
- *Langmuir probes*: they are in direct contact with the plasma, and hence they can be inserted only at the very plasma edge. The simplest probe consists of an isolated metallic pin exposed to the plasma. By applying a voltage to the tip, a current is drawn from the plasma, and from the exponential part of the $I - V$ characteristic, the T_e at the edge can be deduced, with a time resolution of MHz .
- *Bremsstrahlung emission*: the bremsstrahlung radiation, emitted on a wide continuous spectrum from the plasma frequency ω_p to the x-ray region, is caused by unbound electron acceleration; its T_e spectrum dependence is measured by two main techniques.
In a first method, the double foil technique, an ensemble of at least two silicon diodes collects the X-ray emission in the low energy branch (less affected by recombination radiation) along the same line-of-sight

crossing the plasma spatially, integrating the emitted spectrum. The detection bands are individually limited by Beryllium high-pass filters of various cut-off energies, E_c ; since the local emissivity for a given detection band is proportional to the product $n_e^2 Z_{eff} e^{E_c/T_e}$, T_e can be determined from the ratio between the detected power in two different channels.

2.2 Incoherent Thoson scattering and T_e measure

Thomson scattering is a process of photon-electron interaction; it is a peculiar case of the more general Compton scattering in the sense that the Thomson process refers to the limit of negligible photon momentum with respect to the electron one; this is generally a good approximation for photon generated with an optical or NIR laser and for a typical laboratory plasma, where $E_\nu \approx 1\text{eV} \ll E_e \approx 100\text{eV}$. Thomson scattering process is modelled considering an electron which emits radiation once accelerated by an incoming electromagnetic wave; after discussing the single interaction between one photon and one electron, the collective phenomena related to the presence of many particles will be shortly discussed. In the following treatment (fig 2.1) the suffix i will be referred to the incoming wave, while s to the scattered wave; ω_i and $\mathbf{k}_i$ are the incoming frequency and wavevector, ω_s and $\mathbf{k}_s$ the scattered ones and $\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$; $\hat{\mathbf{i}}$ and $\hat{\mathbf{s}}$ are referred to the versors, while $\mathbf{v}$ is the electron velocity and m_0 its rest mass. With this approach [27], one can write the motion equation for an electron in an electromagnetic field as:

$$\frac{\partial}{\partial t} \frac{m_0 \mathbf{v}}{\sqrt{1 - \beta^2}} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (2.1)$$

where $\mathbf{v} = c\boldsymbol{\beta}$ and $\gamma = \sqrt{1 - \beta^2}$; the term on the left hand side can be calculated and the expression becomes:

$$m_0 \gamma \dot{\boldsymbol{\beta}} + \gamma^3 m_0 \boldsymbol{\beta} (\boldsymbol{\beta} \cdot \dot{\boldsymbol{\beta}}) = -e \left(\frac{1}{c} \mathbf{E} + \boldsymbol{\beta} \times \mathbf{B} \right).$$

Solving for $\dot{\boldsymbol{\beta}} = \partial \boldsymbol{\beta} / \partial t$ one gets

$$\dot{\boldsymbol{\beta}} = \frac{-e}{m_0 \gamma} \left[\frac{\mathbf{E}}{c} - \left(\frac{\boldsymbol{\beta} \cdot \mathbf{E}}{c} \right) \boldsymbol{\beta} + \boldsymbol{\beta} \times \mathbf{B} \right]$$

considering the electric and magnetic field as related to a flat incoming wave with *hati* direction, that is $\mathbf{B}_i = \frac{1}{c} \hat{\mathbf{i}} \times \mathbf{E}_i$, one gets for the electron acceleration:

$$\dot{\boldsymbol{\beta}} = \frac{-e}{m_0 c \gamma} [\mathbf{E}_i (\boldsymbol{\beta} \cdot \mathbf{E}_i) \boldsymbol{\beta} + (\boldsymbol{\beta} \cdot \mathbf{E}_i) \hat{\mathbf{i}} (\boldsymbol{\beta} \cdot \hat{\mathbf{i}}) \mathbf{E}_i]$$

A moving charge generates an electric field in the form:

$$\mathbf{E}_s = \frac{e}{4\pi\epsilon_0} \left[\frac{1}{\kappa^3 R c} \left\{ \hat{\mathbf{s}} \times \left[\dot{\boldsymbol{\beta}} \times (\hat{\mathbf{s}} - \boldsymbol{\beta}) \right] \right\} \right]$$

where $\kappa = 1 - \hat{\mathbf{s}} \cdot \boldsymbol{\beta}$. Substituting $\dot{\boldsymbol{\beta}}$ in the former, for E_s holds:

$$\begin{aligned} \mathbf{E}_s = \frac{e^2}{4\pi\epsilon_0 m_0 c^2} & \left[\frac{E_i \sqrt{1-\beta^2}}{R(1-\beta_s)^3} \left(-(1-\beta_i)(1-\beta_s)\hat{\mathbf{e}} - \beta_e(1-\beta_s)\hat{\mathbf{i}} \right. \right. \\ & + ((1-\beta_i)\hat{\mathbf{s}} \cdot \hat{\mathbf{e}} + (\hat{\mathbf{s}} \cdot \hat{\mathbf{i}} - \beta_s)\beta_e)\hat{\mathbf{s}} \\ & \left. \left. - ((1-\beta_i)\hat{\mathbf{s}} \cdot \hat{\mathbf{e}} - (1-\hat{\mathbf{s}} \cdot \hat{\mathbf{i}})\beta_e)\boldsymbol{\beta} \right) \right] \end{aligned}$$

where $\hat{\mathbf{e}} = \frac{\mathbf{E}_i}{E_i}$, $\beta_\alpha = \boldsymbol{\beta} \cdot \hat{\boldsymbol{\alpha}}$ and the factor r_e is the classical value for the electron radius:

$$r_e = \frac{e^2}{4\pi\epsilon_0 m_0 c^2} = 2.82 \cdot 10^{-15} m \quad (2.2)$$

The previous expression can be simplified considering the case in which the incoming wave polarization is perpendicular to the scattering plane ($\hat{\mathbf{e}} \cdot \hat{\mathbf{s}} = 0$), which is what typically occurs in a TS diagnostic layout:

$$\hat{\mathbf{e}} \cdot \mathbf{E}_s = r_e \left[\frac{e_i \sqrt{1-\beta^2}}{R(1-\beta_s)^3} ((1-\hat{\mathbf{s}} \cdot \hat{\mathbf{i}})\beta_e^2 - (1-\beta_i)(1-\beta_s)) \right]$$

In the case $\beta \ll 1$ (*dipole approximation*) the previous formula is simplified and the motion equation becomes:

$$\dot{\boldsymbol{\beta}} = \frac{-e}{m_0 c} \mathbf{E}_i$$

while for the radiated field holds:

$$\mathbf{E}_s = \frac{-e}{m_0 c} \left[\frac{1}{R c} (\hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \dot{\boldsymbol{\beta}})) \right] = \left[\frac{r_e}{R} (\hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \mathbf{E}_i)) \right]$$

that corresponds to a dipole emission.

From the dipole approximation follows that the scattered field can be written:

$$\mathbf{E}_s(\mathbf{x}, t) = \left[\frac{r_e}{R} (\hat{\mathbf{s}}\hat{\mathbf{s}} - 1) \cdot \mathbf{E}_i \right] \quad (2.3)$$

where $\hat{\mathbf{s}}\hat{\mathbf{s}} - 1$ is an operator in the form $\hat{\mathbf{s}} \times \hat{\mathbf{s}} \times$.

To evaluate the spectrum of the scattered radiation in finite time interval T it is necessary to perform the Fourier transform of the electric field in eq. 2.3:

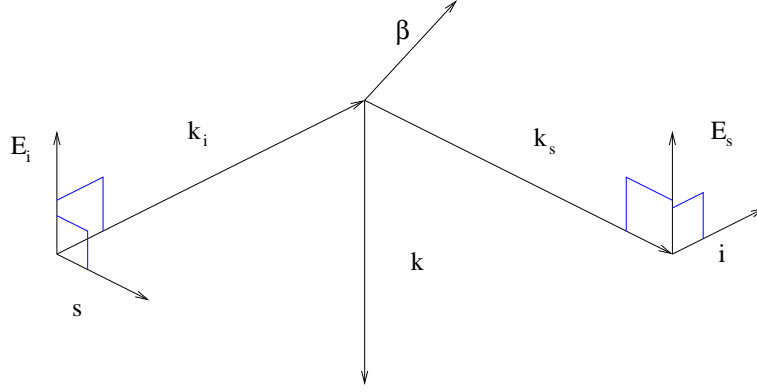


Figure 2.1: geometry of scattering process

$$\mathbf{E}_s(\nu_s) = \int_T E_s(t) e^{i\omega_s t} dt = \int_T \left[\frac{r_e}{R} (\hat{\mathbf{s}}\hat{\mathbf{s}} - 1) \cdot \mathbf{E}_i \right] e^{i\omega_s t} dt$$

Under these assumptions it is possible to demonstrate [27] that the integral can be solved in the form:

$$\mathbf{E}_s(\nu_s) = \frac{r_e e^{i\mathbf{k}_s \cdot \mathbf{x}}}{x} 2\pi\kappa (\hat{\mathbf{s}}\hat{\mathbf{s}} - 1) \mathbf{E}_i \delta(\mathbf{k} \cdot \mathbf{v} - \omega).$$

Finally the frequency of the scattered radiation is obtained, corresponding to a doppler shift whose contributions are the components of the electron velocity with respect to the source and to the observer:

$$\omega_s = \omega_i + \mathbf{k} \cdot \mathbf{v} = \omega_i + (\mathbf{k}_s - \mathbf{k}_i) \cdot \mathbf{v} = \omega_i \frac{1 - \hat{\mathbf{i}} \cdot \boldsymbol{\beta}}{1 - \hat{\mathbf{s}} \cdot \boldsymbol{\beta}}$$

The latter expression contains all the information on a single electron-photon scattering process. From a practical point of view, the instruments detect radiated powers; hence it is necessary to obtain information on the scattered Poynting vector. By inverse Fourier transforming of $\mathbf{E}_s(\nu_s)$, one has:

$$E_s(t) = \int_{-\infty}^{+\infty} E_s(\nu_s) e^{-i\omega_s t} d\nu_s = \frac{r_e e^{i(\mathbf{k}_s \cdot \mathbf{x} - \omega_s t)}}{x} (\hat{\mathbf{s}}\hat{\mathbf{s}} - 1) \mathbf{E}_i$$

and, from the square modulus of electric field, the Poynting vector value for a single electron is:

$$\langle S_s \rangle = \langle c\epsilon_0 [\Re(E_s(t))]^2 \rangle = \frac{1}{2} c\epsilon_0 \left| \frac{r_e}{x} (\hat{\mathbf{s}}\hat{\mathbf{s}} - 1) \mathbf{E}_i \right|^2$$

2.2.1 Incoherent Scattering

The collected scattered radiation is the sum of the contributions coming from all the electrons in a scattering volume; in terms of electric fields contributions, for the scattered power holds:

$$\frac{dP}{d\Omega} = \rho^2 \epsilon_0 c \cdot \left(\sum_i \mathbf{E}_i \cdot \sum_j \mathbf{E}_j \right) = \rho^2 \epsilon_0 c \cdot \left(\sum_i \mathbf{E}_i^2 + \sum_{j \neq i} \mathbf{E}_j \cdot \mathbf{E}_i \right)$$

where the first additive term represents the incoherent part and the second the interferential or coherent part. The condition of incoherence is related to absence of collective phenomena and hence to the possibility of neglecting interferential term in the scattered power evaluation.

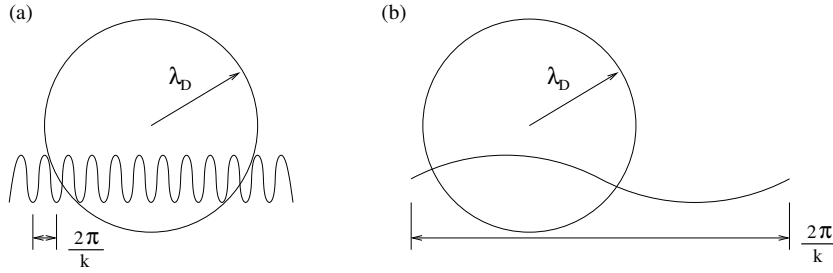


Figure 2.2: Condition for incoherent scattering ($k\lambda_D \gg 1$, left) and for coherent scattering (right, $k\lambda_D \ll 1$)

Electrons in a plasma are mutually influenced if they are close enough to interact electrically; since in a plasma the distance of shielding for the electric field is defined by the Debye length:

$$\lambda_D = \sqrt{\frac{\epsilon_0 T_e}{ne^2}}$$

The condition for incoherent scattering can be written $k\lambda_D \gg 1$. This corresponds to have large phase differences in the scattered radiation coming from particles in within a Debye sphere and, so, interference phenomena average to zero.

For a typical laboratory plasma ($T_e \approx 1 \text{ KeV}$, $n_e \approx 10^{20} \text{ m}^{-3}$) and for laser wavelengths around $1 \mu\text{m}$ this condition is well satisfied, being :

$$k\lambda_D = k \sqrt{\frac{\epsilon_0 T_e}{ne^2}} \approx 10^4$$

allowing the treatment of diffused radiation in term of incoherently scattered power from many electrons.

The Poynting vector can be written in differential form considering its dependence on the frequency ν_s and the solid angle Ω_s and, in the second passage, introducing a distribution function f on the velocity space:

$$\frac{d^2 P}{d\Omega_s d\nu_s} = r_e^2 |(\hat{\mathbf{s}}\hat{\mathbf{s}} - 1)\hat{\mathbf{e}}|^2 \langle S_i \rangle \delta(\nu_s - \nu_d) = r_e^2 \int_V \langle S_i \rangle \int |(\hat{\mathbf{s}}\hat{\mathbf{s}} - 1)\hat{\mathbf{e}}|^2 \delta(\mathbf{k} \cdot \mathbf{v} - \omega) \kappa^2 2\pi f d^3 v d^3 r$$

The general expression for the term $(\hat{\mathbf{s}}\hat{\mathbf{s}} - 1)\hat{\mathbf{e}} = \hat{\mathbf{s}} \times \hat{\mathbf{s}} \times \hat{\mathbf{e}}$ is demonstrated to be [27]:

$$(\hat{\mathbf{s}}\hat{\mathbf{s}} - 1)\hat{\mathbf{e}} = \frac{\sqrt{1 - \beta^2}}{\kappa^3} \cdot \hat{\mathbf{s}} \times ([\hat{\mathbf{s}} - \boldsymbol{\beta}] \times [\hat{\mathbf{e}} - (\boldsymbol{\beta} \cdot \hat{\mathbf{e}})\boldsymbol{\beta} + (\boldsymbol{\beta} \cdot \hat{\mathbf{e}})\hat{\mathbf{i}} - (\boldsymbol{\beta} \cdot \hat{\mathbf{i}})\hat{\mathbf{e}}])$$

Which in the following will be simplified, by comparing the two following expressions:

$$\begin{aligned} \hat{\mathbf{e}} \cdot \mathbf{E}_s &= r_e \left[\frac{e_i \sqrt{1 - \beta^2}}{R(1 - \beta_s)^3} ((1 - \hat{\mathbf{s}} \cdot \hat{\mathbf{i}})\beta_e^2 - (1 - \beta_i)(1 - \beta_s)) \right] \\ \mathbf{E}_s &= \left[\frac{r_e}{R} (\hat{\mathbf{s}}\hat{\mathbf{s}} - 1) \mathbf{E}_i \right] \end{aligned}$$

With the condition of polarization perpendicular to the scattering plane only the component $\hat{\mathbf{e}} \cdot \mathbf{E}_s$ has to be considered, so it's possible to operate a substitution in 2.4 to write:

$$\begin{aligned} \frac{d^2 P}{d\Omega_s d\nu_s} &= 2\pi r_e^2 \int_V \langle S_i \rangle d^3 r \int |\hat{\mathbf{e}} \cdot (\hat{\mathbf{s}}\hat{\mathbf{s}} - 1)\hat{\mathbf{e}}|^2 \kappa^2 f \delta(\mathbf{k} \cdot \mathbf{v} - \omega) d^3 v \\ &= 2\pi r_e^2 \int_V \langle S_i \rangle d^3 r \frac{\omega_s^2}{\omega_i^2} \int \left| 1 - \frac{1 - \hat{\mathbf{s}} \cdot \hat{\mathbf{i}}}{(1 - \beta_i)(1 - \beta_s)} \beta_e^2 \right|^2 (1 - \beta^2) \frac{1}{k} f(\mathbf{v}_\perp, v_k) d^2 v_\perp \end{aligned}$$

There are two terms in the integral which multiplies the distribution function. First, the $(1 - \beta^2)$ term accounts for the blue-shift and asymmetry of the spectrum (*head-light effect*). In the electron frame, the scattered power must still have a symmetrical doughnut shape (dipole emission), while in the observer frame it is changed by the introduction of the factor $(1 - \hat{\mathbf{e}}_s \cdot \boldsymbol{\beta})$. The dipole emission of a relativistic electron is more stretched forward than backward. This causes approaching electrons to scatter more light in the direction of the observer (blue shifted) than those which are receding. Thus, the effect of using the non-relativistic approximation is an overestimation of

T_e , that at 100eV for $\theta = 90^\circ$ can be even 5%. A λ -first order approximated expression of the blue shift is

$$\Delta\lambda_m = -[7(a/c)^2 \sin^2(\theta/2)]\lambda_i$$

where a is the mean thermal speed, $a \equiv (2K_B T_e/m_e)^{1/2}$ [28]. The second term

$$q(\beta) = |1 - \frac{1 - \hat{\mathbf{s}} \cdot \hat{\mathbf{i}}}{(1 - \beta_i)(1 - \beta_s)} \beta_e^2|^2 \quad (2.4)$$

is called the polarization term; it causes the spatial distribution of the emitted electric field being polarized in a direction orthogonal to the incident polarization in a fraction $\sim \beta^2$ of scattered light. At 20keV this term accounts for a correction of 13% on n_e .

For temperatures below 10 KeV, the term of the second order in β can be neglected, finally getting:

$$\frac{d^2 P}{d\Omega_s d\nu_s} = 2\pi r_e^2 \int_V \langle S_i \rangle d^3 r \frac{1}{k_i [2(1 - \hat{\mathbf{i}} \cdot \hat{\mathbf{s}})]} \left(1 + \frac{3\omega}{2\omega_i}\right) f_k\left(\frac{\omega}{k}\right)$$

The difference with the non relativistic case is in the factor $f_k(\frac{\omega}{k}) = f(v)$ which multiplies the distribution function. $f_k = f_k(T_e)$ is the quantity related to the plasma temperature: it can be written as a non relativistic maxwellian:

$$f(v) = n_e \left(\frac{m_e}{2\pi T_e}\right)^{1/2} \exp\left(-\frac{m_e v^2}{2T_e}\right)$$

as well as a relativistic distribution:

$$f(\beta) = n_e \frac{\alpha}{2\pi K_2(2\alpha)} \frac{\exp[-2\alpha(1 - \beta^2)^{-1/2}]}{(1 - \beta^2)^{5/2}}$$

with $\alpha = m_e c^2 / 2\kappa T_e$ and K_2 , the second-order, second-type Bessel function.

The choice of one distribution with respect to the other has to be consistent with the limit in β ; it depends basically on the plasma temperature and, definitely, on the ratio between the electron thermal energy and their rest energy. For instance, in the case of RFX-mod $T_e \approx 1keV \Rightarrow \langle E_e \rangle \approx 1.5 \cdot 10^{-3} m_e c^2$. Neither the approximation of the distribution with an equilibrium maxwellian is always justified: in particular conditions (e.g. with ECR heating) fusion experiments display the presence of non-thermal electron populations with their own distributions, added to the thermal one of the bulk plasma electrons. However, this is not the case of RFX-mod, since the heating of the machine is purely ohmic and the plasma is sufficiently collisional to thermalize the electrons population.

Actually, for the analysis routines implementation, it has been used an analytical expression (derived by Selden [28]) for the spectrum reconstruction at a given T_e , wavelength $\lambda_s = \lambda_i(\epsilon + 1)$ and scattering angle θ :

$$S(\epsilon, \theta, \alpha) = c[\alpha(T_e)] \frac{e^{-2\alpha B(\epsilon, \theta)}}{A}$$

where

$$\begin{aligned} A(\epsilon, \theta) &= (1 + \epsilon)^3 [2(1 - \cos\theta)(1 + \epsilon) + \epsilon^2]^{1/2} \\ B(\epsilon, \theta) &= \left[1 + \frac{\epsilon^2}{2(1 - \cos\theta)(1 + \epsilon)} \right]^{1/2} \\ c(\alpha) &= \left(\frac{\alpha}{\pi}\right)^{1/2} \left(1 - \frac{15}{16}\alpha^{-1} + \frac{345}{512}\alpha^{-2} + \dots \right) \\ &\text{and } 2\alpha(T_e) = m_e c^2 / \kappa T_e \end{aligned}$$

Selden spectra agree with the fully relativistic, numerically obtained ones within 0.1 % at 20 keV and 1% at 100 keV, being completely justified for the temperature range in RFX-mod (0-1.5 keV) [29]. Summarizing, at first approximation the scattered spectrum is a gaussian whose integral is proportional to the plasma density (which enters the formula when accounting for the distribution function) and whose FWHM is a growing function of temperature [30]:

$$FWHM \approx 4\lambda_i \sin\left(\frac{\theta}{2}\right) \sqrt{\frac{2kT_e}{m_0 c^2} \ln 2} \quad (2.5)$$

The aim of a Thomson scattering measure thus become the spectrum reconstruction in terms of its height and shape to obtain respectively T_e and n_e ; this is done using various type of dispersion systems that samples the spectrum itself, as will be described in the following sections.

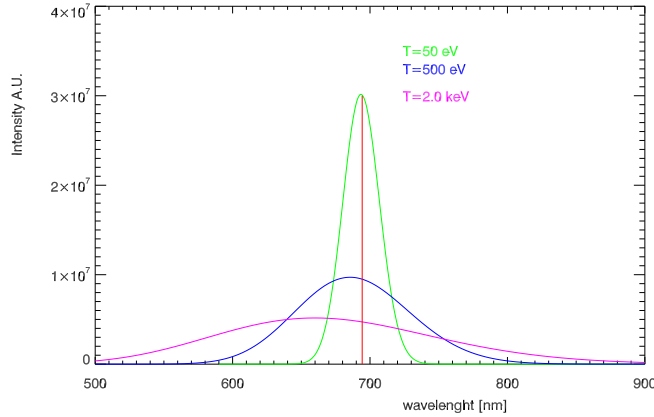


Figure 2.3: Selden spectra for three different temperatures, $\theta = 150^\circ$

2.3 General Layout of a TS Diagnostic

In the previous treatment the case of a single incoming photon of wavevector $\mathbf{k}_i$ has been generalised to a source of arbitrary power P_i ; to realize a TS diagnostic, the requirements of monochromaticity and high power practically limit the choice of the radiation source to solid state, pulsed lasers.

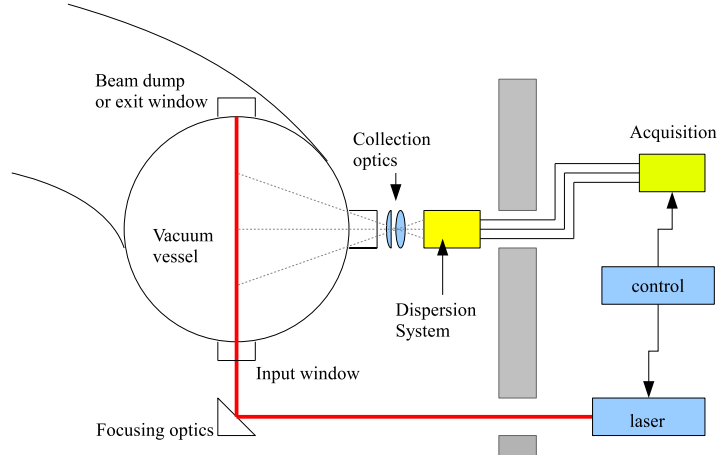


Figure 2.4: general layout of a TS diagnostic, showing the principal components: laser, collection optics, spectrometers and acquiring electronics

It should be noted here that the requirements on the laser power are quite demanding, since the TS cross section is of the order of $8\pi r_e^2/3 \approx 6 \cdot 10^{-29} \text{m}^2$, the density $\approx 10^{19} \text{m}^{-3}$, the length of the scattering volume and the solid angle for the collection optics of the order of 10^{-2}m and 10^{-2}sr . The resulting ratio between the scattered and the incoming power is thus $\approx 10^{-12}$.

Moreover, since it is mandatory to maximize the ratio of scattered power with respect to background radiation (which limits the S/N ratio), short pulse operation is desired, typically in the order of few ns. Due to the very low fraction of scattered radiation, a particular care is taken in avoiding the direct collection of laser light diffracted or diffused inside the chamber (stray light). The critical elements are the input optics and windows, and any mechanical elements encountered by the beam (baffles or dumps); it is worth noting here that the fraction of directly collected laser light with respect to the beam energy has to be less than the previously discussed estimate of 10^{-12}sr/m .

The equations obtained at the end of the previous section apply if the dipole approximation is verified, hence the laser polarization is oriented perpendicularly to the scattering plane.

The scattered radiation is collected for each scattering volume by a col-

lection optic group and focused into a dispersion system which analyses the TS spectrum; given the high level of EM noise related with the experiment operation, one prefers to use optical fiber bundle to couple the collection optics and the spectrometers to protect its front-end electronics (though this solution is not always adopted). With this arrangement it is possible to place the dispersion systems (and so the detectors and the front-end electronics) in a shielded location.

The scattered volumes in the chamber are defined by the intersection of the laser beam (more or less cylindrical) with the projections on the focal plane of the images, typically, of the collection fibers. The problem of spurious signals will be discussed in details in Chapter 3, however it is clear that each scattering volume has to be maintained as little as possible, to minimize the amount of intrinsic plasma radiation which is collected. To minimize the alignment issues of the scattering volumes on the laser beam, there are two basic possibilities; the first is working near the laser focus with the volumes slightly larger than the beam; the second is maintaining the beam unfocused and the scattering volumes smaller than the beam section. Obviously the first solution (which is the one adopted on RFX-mod) exploits the beam available energy in a better way.

Dispersion system can be of different types, principally gratings or multifilters polycromators; as far as regards the detectors, the two most common choices are the use of a single CCD camera or a certain number of detectors (typically avalanche photodiodes, APDs). CCD generally are cheaper and easier to operate, but they have a lower sensitivity (in terms of quantum efficiency) and a higher readout time, which limits the time resolution they achieve. Moreover, the high integration time can be a limit a situation where the background radiation is variable in time, making its treatment difficult (this is a limit in RFX-mod, but not in machines with lower plasma-wall interactions, such as in most tokamaks where the interaction is localized in the divertor region). Finally, the type of detector has to be chosen on the basis of the laser wavelength: the most common lasers such is Nd:YAG, which operates in the NIR range (>1000 nm), where the APD efficiency is low, but the CCD one is approaching 0.

2.3.1 Temperature evaluation

The following treatment concerns the signal treatment necessary to get temperature (and density) measures; the signals are intended to be generated by APD detectors coupled to interferential filters polycromators, since all the diagnostics this thesis deal with are based on such a setup. The spectrometers sample the scattered radiation on a certain number of spectral channels to reconstruct its shape: the signal on each channel is the convolution of the channel transmission function with the scattered spectrum. The choice of proper values for the spectral channels bandwidth, as well as the

number of channels, are related to the temperature range one is interested in: lower temperatures mean channels closer to the laser line (see 2.2). Since we work in a 2 parameters space (density and temperature) it is necessary to rely on at least 2 measured quantities, while 3 permit to define an uncertainty. The choice for RFX-mod TS systems is the use of four spectral channels, so that it is possible to cover different temperature range with at least two of them; for an indication on the channel bandwidth for a given temperature range one should refer to fig. 2.5.

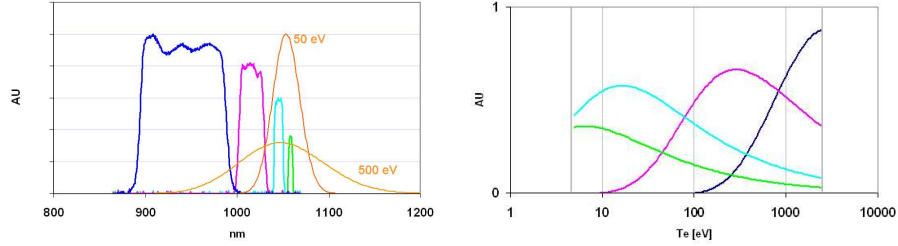


Figure 2.5: transimssion windows and gamma functions for the four spectral channels of the main TS diagnostic

From a general point of view, the signal collected in terms of scattered power can be written as:

$$P_s^T = P_i^T \cdot \frac{d\sigma_T}{d\Omega} \cdot n_e \Delta\Omega \cdot T \cdot L \cdot G \cdot \eta \int_{\lambda} Z(\lambda, T_e) \Phi(\lambda) d\lambda$$

where P_i^T is the incident laser power, n_e the electron density, $\Delta\Omega$ the solid angle, T the transmission G and η respectively the gain and quantun efficiency of the detectors. $\Phi(\lambda)$ accounts for the dependence of the system sensitivity respect to the wavelenght and will be identified with the transmission function of the i spectral channel. Z is related to S and is necessary to deconvolve the dependency on the scattering angle, which will be useful in the discussion of density evaluation. For Z holds:

$$\frac{d\sigma_T}{d\Omega} \int_{\lambda} Z(\lambda, T_e) \Phi(\lambda) d\lambda = K \int_{\lambda} S(\lambda, \theta, T_e) \Phi(\lambda) d\lambda$$

with $S(\lambda, \theta, T_e) = S(\epsilon, \theta, \alpha)$ defined in sect.2.2 and K a normalization constant accounting for the condition $\int_{-\infty}^{+\infty} Z(\lambda, T_e) d\lambda = 1$. To measure the plasma temperature, the first step is calculating tables containing, for a large interval of T_e , the values of the signals expected for all channels: these values will be the convolution of selden spectra related to T_e with the transmission function $\Phi_i(\lambda)$ of each spectral channels (fig 2.5):

$$\Gamma_i(T - e) = \int_{\lambda} S(\lambda, T_e, \theta) \Phi_i(\lambda) d\lambda$$

These functions(*gamma functions*) has to be generated separately for each scattering volume, being different the related angle of scattering.

Named S_i the signal measured by the polichromator in the i channel and σ_i its error, the temperature can be calculated minimizing the function $\chi^2(T_e, n_e)$:

$$\chi^2(T, n_e) = \chi^2(T, A) = \sum_i \frac{1}{\sigma_i^2} (S_i - A\gamma_i(T))^2$$

which is the χ^2 distribution of the deviation between the measured signals and the expected ones (proportional to γ_i); the constant A is a normalization function and together with T_e is one of the two degrees of freedom of the distribution; in particular the A constant is proportional to plasma density, $A \propto n_e$; this point will be discussed in details in the next section. The function has a single minimum in the parameters space, hence the conditions of minimization can be written in the form:

$$\begin{aligned} \frac{\partial \chi^2(T, A)}{\partial T} &= \frac{\partial \chi^2(T, A)}{\partial A} = 0 \\ \frac{\partial^2 \chi^2(T, A)}{\partial^2 T} &> 0; \quad \frac{\partial^2 \chi^2(T, A)}{\partial^2 A} > 0 \end{aligned}$$

The errors on T_e are related to the inverse of the Hessian matrix $H(f)$ (whose i, j element is defined by $H_{i,j}(f) = \partial^2 f(i, j) / \partial i \partial j$) and thus to second derivatives of the function χ^2 with respect to T and A; naively, lower curvatures around the minimum of χ^2 corresponds to higher uncertainties. For a detailed treatment of the method, refer to R.Pasqualotto dissertation [31]; In a more quantitative way, limiting our treatment to the temperature:

$$\begin{aligned} \frac{\partial \chi^2(T, A)}{\partial T} &= \frac{1}{\sigma_i} \sum_i 2A(S_i - A\Gamma_i) \frac{\partial \Gamma_i}{\partial T} \\ \frac{\partial^2 \chi^2(T, A)}{\partial^2 T} &= \frac{1}{\sigma_i} \sum_i \left[2A(S_i - A\Gamma_i) \frac{\partial^2 \Gamma_i}{\partial^2 T} + 2A^2 \left(\frac{\partial \Gamma_i}{\partial T} \right)^2 \right] \end{aligned}$$

Here comes the importance, to reduce the errors on T_e , of choosing the transmission functions of the filters in order to get high values in the slope of the $\Gamma_i(T)$ (at least for some of them) for all the operating temperatures.

As anticipated, the constant A in the fit is related to the density: $A = kn_e$; the exact evaluation of the constant k is done via an absolute calibration of the system, which will be discussed in the following section.

2.3.2 Rotational Raman Scattering and density evaluation

While temperature measure requires only the knowledge of the spectral distribution of the scattered radiation, to calculate density it is necessary to

evaluate the exact amount of scattered power the scattered power; this operation requires an absolute calibration of the system, since it is impossible to know precisely a priori the solid angle, the optical transmission of the system and the detector response. Let us recall from 2.3.1 the expression for the signal on the detector generated by a TS process [32, 33]:

$$P_s^T = P_i^T \cdot \frac{d\sigma_T}{d\Omega} \cdot n_e \Delta\Omega \cdot T \cdot L \cdot G \cdot \eta \int_{\lambda} Z(\lambda, T_e) \Phi(\lambda) d\lambda$$

The factor $\Delta\Omega \cdot T \cdot L \cdot G \cdot \eta$ needs to be known to evaluate the density; for such purpose, the system is calibrated via Rotational Raman Scattering (RRS) in a low temperature, controlled density biatomic gas (in our case Nitrogen) ¹

The signal generated from a RRS process can be calculated from the theory [35]; in an analogue form with the previous, holds:

$$P_s^R = P_i^R \cdot \sum_j n(j) \left(\frac{d\sigma_j^R}{d\Omega} \Phi(\lambda_j) \right) \cdot n_r \Delta\Omega \cdot T \cdot L \cdot G \cdot \eta$$

Again, P_i^R is the incident laser power and $d\sigma_j^R/d\Omega$ the differential cross section for the j Raman scattering line and $\Phi(\lambda_j)$ the responsivity, i.e. the value of the transmission function for the wavelength λ_j . The main difference respect to Thomson scattering case is that RRS spectrum is discrete, consisting of a certain number of j lines: each line corresponds to a molecular transition from a rotational state of momentum J to one of momentum J' ; the selection rule $J' = J \pm 2$ holds. The term $\Delta\Omega \cdot T \cdot L \cdot G \cdot \eta$ (optical transmission and electronic sensitivity) is easy to measure once known $d\sigma_j^R/d\Omega$:

$$\begin{aligned} d\sigma_j &= a\sigma_{J \rightarrow J'} = \frac{64\pi^4}{45} \frac{3J(J-1)}{2(2J+1)(2J-1)} \frac{\gamma^2}{\lambda_j} \\ &\text{if } J' = J-2 \text{ (Anti-stokes branch)} \\ d\sigma_j &= a\sigma_{J \rightarrow J'} = \frac{64\pi^4}{45} \frac{3(J+1)(J+2)}{2(2J+1)(2J+3)} \frac{\gamma^2}{\lambda_j} \\ &\text{if } J' = J+2 \text{ (Stokes branch)} \end{aligned}$$

The occupation of the J state is defined by $N(J) = n(J)/n_{N_2}$ with

$$n(J)/n_{N_2} = \frac{1}{Q} g_j (2J+1) e^{-E_J/\kappa T} \text{ and } Q = \sum_j \frac{n(J)}{n_{N_2}} = 1;$$

¹The most common method is Rotation Raman scattering, while Rayleigh scattering [34] is seldom used; in the latter case the scattered radiation is of the same wavelength of the incoming one, so it is necessary to provide a dedicated channel at the laser line λ , with additional complication and costs; as discussed, for temperature measuring purpose the laser line should be excluded from the channels bandwidth to avoid stray light collection

Here g_j is a nuclear-spin dependent statistical weight ($g=6$ for J even, $g=3$ for J odd) and $E_J \approx J(J+1)hcB_0$ is the rotational energy in the state J with the constant $B_0 = 1.99 \cdot 10^2 m^{-1}$ for Nitrogen; E_J defines also the scattered line wavelength $\lambda_j = hc/(E_J + E_i)$.

Finally, one has

$$\Delta\Omega \cdot T \cdot L \cdot G \cdot \eta = \frac{dP_s^R}{dN_{N_2}} \left(\sum_j n(j) \frac{d\sigma_j^R}{d\Omega} \Phi(\lambda_j) \right)^{-1}$$

The only unknown term is $\frac{dP_s^R}{dN_{N_2}}$, which has to be experimentally evaluated; its measure constitutes the aim of the absolute calibration process. From a practical point of view, this requires a number of mesures of the scattered radiation, taken performing a density scan; since the density cannot be directly controlled, one act on the pressure and monitor the gas temperature.

The value $\Delta\Omega \cdot T \cdot L \cdot G \cdot \eta$ represents the k constant used in the χ^2 minimization procedure described in the previous paragraph, for $A = kn_e$.

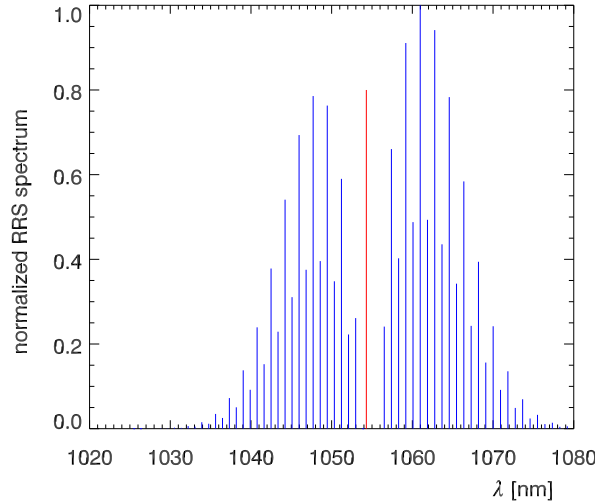


Figure 2.6: Raman spectrum for molecular nitrogen, $\lambda_i = 1054nm$

2.4 A Ts diagnostic example: the main TS in RFX-mod

The main TS [36–38] system on RFX-mod contains some of the most common features of present TS diagnostic in plasma fusion devices, and it can

be therefore considered as a typical example. In addition, T_e and n_e profiles from the Main TS will be extensively used in the analysis presented in Chapter 6, and it is necessary introducing the diagnostic to the reader.

The system measures plasma electron temperature and density profiles along an equatorial diameter, measuring in 84 positions with 7 mm spatial resolution. It is based on a custom built Nd:YLF laser (1053nm), optimized for producing a fast burst of high energy pulses, suitable for measuring the profile evolution in the relatively short plasma discharge of RFX. It delivers a burst of ten pulses with pulse energy of normally 3 J, but potentially up to 7 J, and pulse duration 20 ns FWHM.

The burst is produced discharging ten capacitor banks in sequence and the switch off time of the flashlamps imposes a maximum rate of 50 Hz. The beam is focused 15 m far from its output in the center of the vacuum vessel using a Galilean telescope ($f_1=+2000$ mm, $f_2=-2000$ mm). After passing through a 2.5 m input tube closed by a vacuum window at Brewster angle and containing a set of three stops, aiming at reducing the stray light, it shines across the plasma chamber along a diameter in the equatorial plane, with a beam diameter of 2 mm at the waist and less than 3 mm inside the plasma along the scattering volume. The beam finally hits the inner wall and it is absorbed by a recessed graphite dump.

Alignment of the laser beam is obtained firstly with a collinear He-Ne laser and then minimizing the stray light level, which ensures that the beam is completely falling inside the light trap. The energy of each laser pulse is measured by a detector mounted behind a mirror and a fast digitizer channel is used to acquire the pulse waveform, which is also used as a time mark to find the occurrence time of the TS pulses.

Scattered light is collected at $\approx 90^\circ$ from the incident beam through 3 windows at the end of short vertical ports. Three objective lenses ($f=180$ mm, magnification=0.33, F/7 collected solid angle on the plasma axis) image the laser beam on a row of 84 pairs of optical fibers (diameter 1 mm, 0.37 NA quartz fibers), sampling the scattering volumes from 0.96 to 0.84 r/a in 84 positions with a spatial resolution of 7 mm (along the beam) $\times$ 3 mm (across) -fig. 2.7. All fibers are mounted on a motorized mechanical support, which allows to remotely align the collection optics onto the laser beam with sub-mm accuracy.

In the diagnostic area, fibers are arranged into bundles, one per spectrometer. Each bundle is made of three different length pairs of fibers plus an additional shorter fiber carrying a signal from a source used during calibration operations (calibration fiber). Such arranged bundle serves as a multiplexing system which allocates 3 scattering volumes per polychromator by means of optical delay lines: the different length of the fibers (14 m difference) produces three separated pulses [39]. The same setup is used for edge TS and will be described in details in the next chapter

The dispersion system is based on interference filters and APDs. The

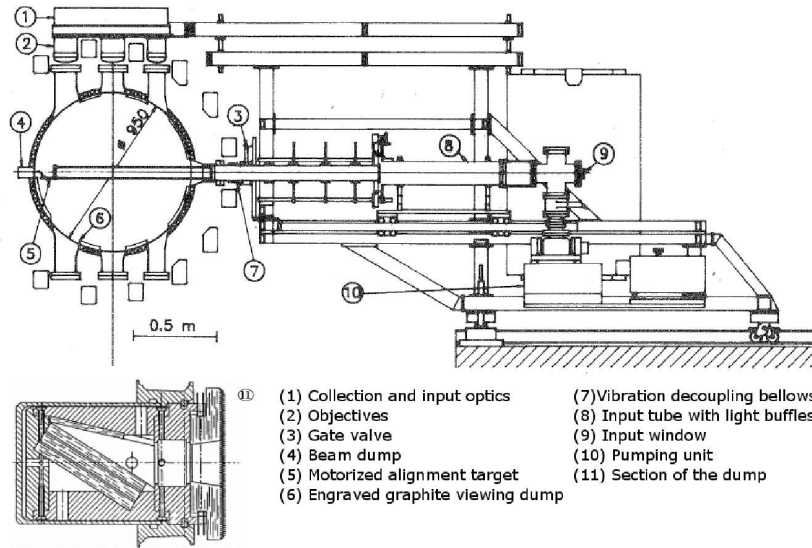


Figure 2.7: layout of the main TS diagnostic in RFX-mod, with a detailed view of the beam dump on the left

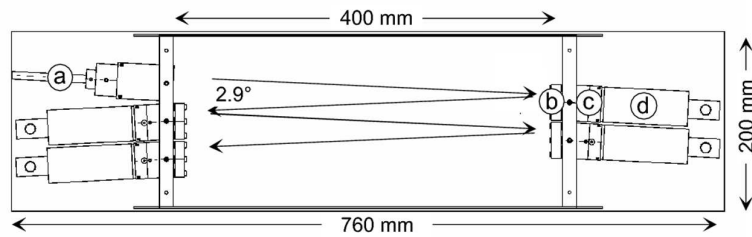


Figure 2.8: Layout of the polychromator: a) fiber input bundle, b) interference filter, c) APD detector, d) amplifier. The path of the light fed by the fiber bundle is indicated by arrows.

radiation fed into each polychromator by the fiber optic bundle is cascaded through four spectral channels in a zigzag path (fig. 2.8), a scheme already used for other TS systems like those of Frascati Tokamak Upgrade [40] and DIII-D [41, 42]. The measured transmission curves of the spectral channels are shown in fig 2.9 This scheme has proven to be simple, compact easy to align and, with the chosen set of filters, suitable to measure T_e in the range 20-2000 eV.

The radiation for each of the four spectral channels is acquired By an APD detector placed in the polycromator after each filter. Detectors are APDs optimized for the IR, with 3mm diameter active area. A three stages amplifier has been specially designed and constructed, providing a transimpedance of 7.9 k Ω . The signal is then split in two 50 Ω outputs: an AC output with an additional voltage gain of 10 provides the scattering signal filtered of the background plasma light and a DC output without additional gain to record the plasma light background.

TS signals are acquired by waveform digitizers. The general advantage of measuring the time trace is that the known pulse shape can be fitted to the measured waveform at a fixed time, well recovering even weak signals from noise. In addition, only a waveform recording approach allows to use the optical delay technique to measure with one acquisition channel the TS pulses from different scattering positions, separated by few tens ns.

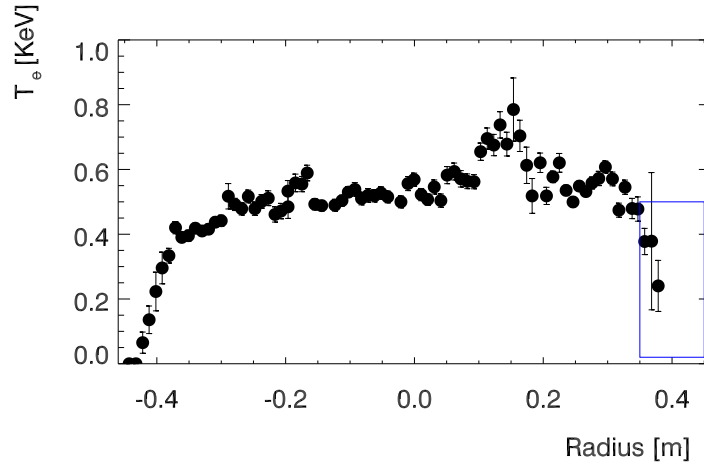


Figure 2.9: Example of temperature profile obtained with the main TS; the blue area on the right indicates the region covered by the Edge TS, which is required for a better definition of the external temperature gradient

In RFX-mod the TS signal from the ac output of the detector amplifiers is recorded by fast waveform digitizers, now shared with the Edge TS system. A modular, four channels, cPCI digitizer board DC265 from Acqiris is dedicated to each spectrometer. It has 150 Mhz analog bandwidth and

500 MS/s sampling rate, full-scale range selectable between $50mV \div 5V$, 8 bits resolution and 128k samples acquisition memory per channel. All 28 modules are housed in 4 cPCI crates controlled by a PC in star configuration.

Dc output signals are acquired with a slow recording system based on two National Instruments 6071-E boards, with 64 input channels. Each board samples all dc signals from 14 spectrometers at 10 kHz sampling rate and with 12 bits resolution. Two air-conditioned cabinets house 14 polychromators each, together with their power supply and acquisition system. Connection to the power line through a transformer and to other electrical signals through electro-optical transducers provides galvanic insulation and electromagnetic shielding inside each cabinet, reducing noise otherwise produced by electromagnetic field mainly coming from the laser power supply system.

Figure 2.9 shows a temperature profile obtained with the main TS system of RFX-mod: the radial coverage of the system goes from $r/a=0.96$ on the internal side of the torus to $r/a=0.84$ on the external side. The limitations in the external side are due to the viewing pipe shape and the results is that the external 8 cm are not covered: the detailed characterization of this region is one of the reasons which lead to the development of a second TS diagnostic, exploiting the availability of the single pulse ruby laser used for the main TS during the 90's [43].

Chapter 3

The Edge TS diagnostic in RFX-mod

In both MH and QSH states, measurements of T_e and n_e are essential to study plasma thermal properties and energy confinement time, and to compare different operational scenarios. In RFX-mod, T_e is measured by the Main Thomson scattering (Main TS) diagnostic, which covers almost the entire plasma diameter ($-0.96 < r/a < 0.84$) with a resolution of 84 points at 50Hz repetition rate. The poor temporal resolution is compensated by the double filter SXR camera [44] and the CO_2 interferometer [45], providing line integrated T_e and n_e measurements respectively with a resolution of several kHz. The outermost 3-4 cm of the plasma equatorial region are covered by dedicated viewing chord of the interferometer and by the gas puffing imaging (GPI) and the Thermal Helium Beam [46, 47] systems, which measure T_e and n_e simultaneously with few mm spatial resolution and at frequencies of the order of kHz. This set of combined diagnostics can provide a detailed description of energy and particle transport; however, in the region $0.7 < r/a < 1$, this combination is subjected to a high uncertainty, since the presence of edge T_e and n_e gradients, typically stronger than in the core, makes uncertainties in flux mapping more relevant. The edge TS [48] was built to cover also this region of the plasma and, after a commissioning period and some upgrades aiming at extending its operational range, it is now able to return reliably density and temperature measures.

3.1 Diagnostic description

3.1.1 Laser and Mechanical layout

The laser is a Q-switched, flash-lamp pumped ruby device ($\lambda=694.3\text{nm}$) built by Innolas; it has a three stage amplifier design (being manufactured with two stages plus the oscillator, a third amplifying stage was added later

to raise the output). It can deliver a 15 J maximal beam energy, with a pulse lenght of 30 ns at FWHM and it can produce up to four pulses in within a lamp discharge (which is less than 0.5 ms), 3.5 J each. However, being the multipulse operation based on subsequent openings of the pokels cell ¹, in practice it is safe and reliable only for a burst of two pulses: the risk is to have an optical damage related to an unbalanced energy partition among the pulses, due to oscillations in the lamps discharge or in the pokel cell operation.

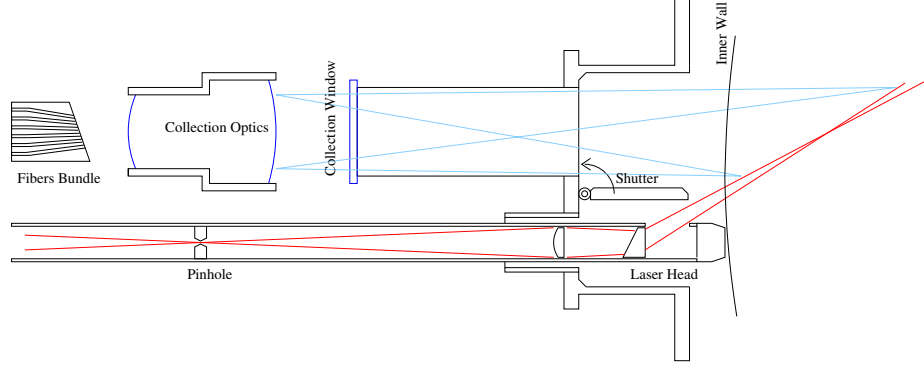


Figure 3.1: Layoyt of the TS edge launching system and colleption optics

The laser is located at the same level of the experiment, in a a separate room, together with the main TS laser; in this room there are also the lasers power supply modules and the acquisition electronics of both systems. At the laser output it is placed a telescopic system (convergent+divergent lens) to control the beam aperture in the far field; after that the beam enters the torus hall and passes through a 50% beamsplitter whose function is to intercept part of the beam for the Laser Blow off system(see chapter 5).

The beam reaches the input optics, contained in a stainless stell vacuum pipe, with vertical polarization, by means of a $\lambda/4$ waveplate; the air-vacuum sealing of the pipe is assured by a quartz window tilted by a Brewster angle on the horizontal plane. The waveplate is placed just before a $f=1200$ mm convergent lens, which focuses the beam on a 4mm pinhole placed in the pipe: the latter can be remotely inserted in the vacuum vessel when the diagnostic is requested to operate. The pipe axis, the scatterd volumes and the collection optics lie on the equatorial level of the the torus.

At pipe head, the beam is focused and left tilted of 30 degrees; the pinhole is imaged at a distance of 100 mm after the pipe exiting to work with the scattering volumes near the beam focal point. The insertion mechanism of the pipe is motorized and remotely controlled; this allows the extraction of

¹Pokels cells are fast eletro-optical devices, based on Pokel effect, which are able to dump or open the oscillating cavity of a laser in times of the order of ns; the variation in the cavity gain obtained with such device is called Q-switching.

the launching head during wall treatment processes, in order to avoid carbon and impurity deposition on the sapphire prism. The collection pipe, placed aside the launching pipe, can be shielded in the vacuum side by a shutter, mounted to avoid carbon and impurities deposition on the window (which is a problem for the core TS and for other diagnostics [49]).

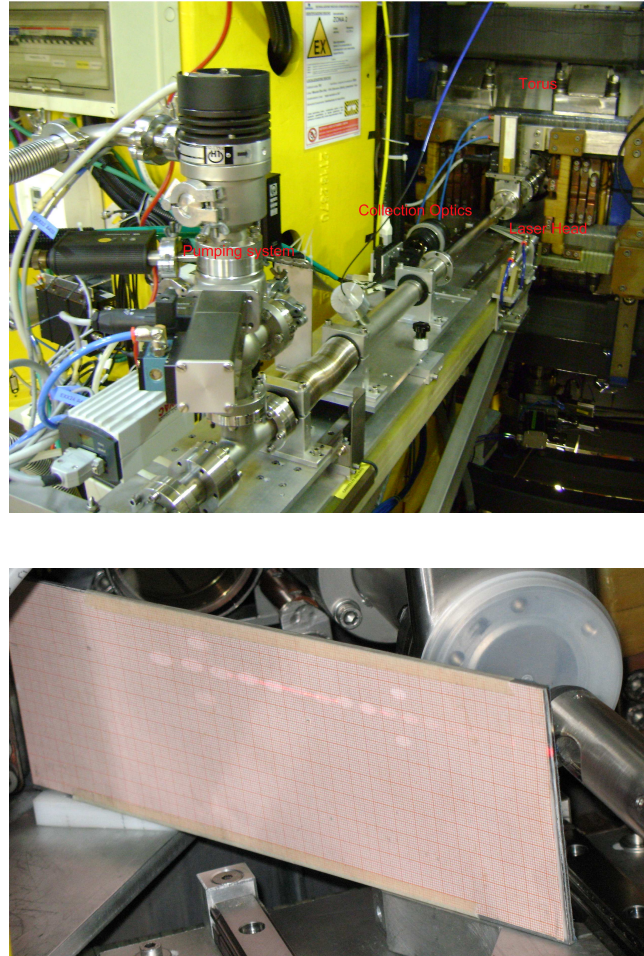


Figure 3.2: Top, picture of the machine-side part of the edge TS diagnostic; the head is extracted. Bottom, detail of the extracted head with a screen placed on the beam path to identify the positions of the scattering volumes (fibers are back-illuminated)

3.1.2 Collection optics and acquisition system

The scattered radiation passes through a 83 mm diameter, F#1.2 camera lens and it is collected by a linear bundle of 12 optical fibers (core silica, hard clad, 1 mm diameter). The magnification of the system changes from fiber to fiber ($M \approx 4.5 \div 5.5$): the scattering volumes lie on a tilted focal plane (and so the fibers end) since the beam direction isn't perpendicular to the collection optics axis (see fig. 3.1). Then average scattering angle is 150° ($\pm 7^\circ$ for off-axis scattering volumes)

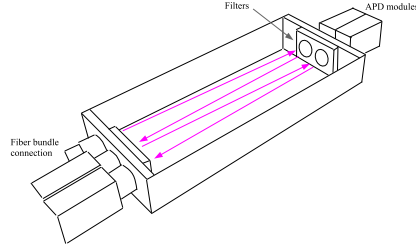
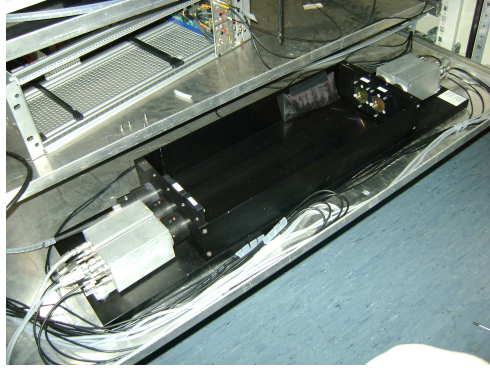


Figure 3.3: picture and of one of the two polichromators

The fibers bundle goes in the laser room and here it is connected with two APD interference filters spectrometers, of the same type of those monted on the main TS (fig 3.5): they consist of an alluminium case which holds the APD modules (detector, supply and pulse shaping circuitry) and the housing for the fiber bundle (6 fibers arranged in an hexagonal frame + 1 calibration fiber in the middle). The bundle is repetetively imaged on the APD detectors, placed beside the interferential bandpass filters.

APD (Avalanche PhotoDiodes) differ from standard photodiodes since the biasing voltages is enough to cause avalanche multiplications: the electrons produced in the depleted area of the photodiode acquire during their mean free path a sufficent energy to extract other electrons (impact ion-

ization). The wavelength limit for the use of silicon in the photodiodes is defined by $\lambda_{lim} = \frac{hc}{E_{gap}} \approx 1120nm$, being E_{gap} the energy difference between the conduction and valence band, which in silicon is 1.11 eV. In this setup each APDs is fed by an individual voltage supply, whose tension is tuned in order to get a factor 75 in the current gain; the latter depends on the bias voltage and so this has to be maintained as stable as possible (fig 3.4). The bias is supplied with passive circuitry, without any active feedback; when exposed to relevant flux of power, the APD impedance drops, changing the load on the power supply and reducing the APD bias voltage.

The polycromators, and hence the APD detectors, are closed in air conditioned cabinets, to maintain a stable temperature and to limit the humidity, in order to preserve the filters which are hygroscopic.

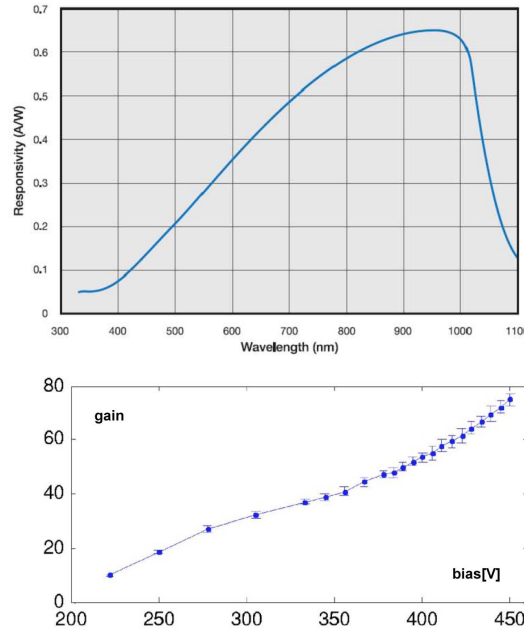


Figure 3.4: top, typical gain curve for an APD silicon detector: the peak of response is around 800 nm while most the spectrum lies around 700 nm; bottom dependence of the detector gain on the bias voltage

Interferential filters spectrometers (also called polycromators in the following) works on successive imaging of the fiber bundle end on the different detectors corresponding to different spectral channels: in front of each detector is placed a bandpass filter which transmits part of the radiations and reflects the other part to successive stages. To maintain the image focused on successive reflections, convergent optical elements have to be inserted; in particular, in the case of the spectrometers used for the main and for the edge TS, the first focusing element is a lens assembly placed in front of the

fiber bundle, the other are lenses mounted in front of the filters, on the same holders; a third set of condensing lenses is placed in front of the detectors, behind the filters (fig. 3.5).

A slightly different geometry is also employed [50, 51], in which the convergent mirrors are placed in one side of the polycromator, while the other is occupied only by the filters placed on the detector; this configurations, though characterized by higher losses (it doubles the reflections for the same number of channels) ensure the same illumination pattern in all channels. In this case the fiber bundle can be imaged directly on the detector for every stage, while in the previous only in odd stages (while in the even ones it is the input lens field to be re-focused).

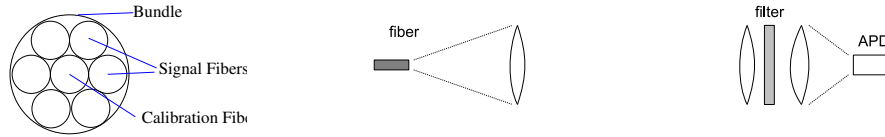


Figure 3.5: Optical layout of the one module of the polycromators; left, detail of the fiber bundle arrangement

The present 6 scattering volumes (two fibers each) can be analyzed with only two spectrometers thanks to the presence of optical delay lines: a difference of 25 meters in fibers length separates the signal coming from different scattering volumes of about 120 ns (5ns per meter of fiber length); the same solution has been employed for the main TS system. The delays has to be chosen in order to be ≈ 2 times the FWHM of the laser pulse, in order to obtain in the signal waveforms peaks clearly separated and to mantain their overlap as low as possible.

As for the Main TS, detectors are connected via a two-stage transimpedance amplifier to two different acquiring system, a fast one used for the scattering signal and a slow one for the control of background radiation [36]. The acquisition electronics is shared with the main TS (see also chapter 2): the fast outputs of the APD are AC coupled to two CompactPCI DC265 acquiring modules manufactured by Acquiris; each one can handle 4 channels, with 8 bits dynamic range and a sampling rate of 500 kHz. The slow ones are DC connected with a 6071E board of National Instrument, capable of 10 kHz bandpass with a 12 bit dynamic range; a device of the same type is used to monitor the biasing voltage of the detectors.

3.2 Commissioning: from CCD to fast digitizer

The diagnostic was first developed to work with a CCD coupled with an image intensifier instead of APD detectors [48]. The spectrometer in use worked on the same principle (cascade interferential filters) but its design was quite different; in order to exploit the CCD camera, the fiber bundle was a 4x4 square array, whose images on the four spectral channels were focused on four regions (quadrants) of the camera field. In this sense its layout is similar to the second solution previously discussed for zig-zag polychromators: the bundle is imaged on all the spectral channels, no image of the input field is used.

The CCD does not acquire directly the signals: in between the polychromator and the camera, a gated image intensifier is mounted. In fact, the CCD shutter works on times of some ms; the TS signal, which lasts only for some tenths of ns, is more or less an order of magnitude higher than the background radiation. If the background was integrated on the whole CCD shutter opening times, the S/N ratio would approach 0. On the other side, a gated image intensifier can work with opening times in the ns order (100 ns in the specific case, a bit more than the laser pulse), acting as a second, faster shutter.

The system was originally intended to measure 12 radial points (one fiber each), while the other four fibers were positioned outside of the bundle plane and were intended to detect the plasma light level in order to subtract it from the scattering signal ². Another implemented method to subtract the plasma radiation, was the acquisition of a second frame, 13 ms far from the laser pulse. 13 ms were required because the CCD readout time is 3ms, while other 10ms has to be waited for the Image Intensifier being ready for use again: the image on its output phosphor screen decays with such a time constant.

3.2.1 Problems with CCD in stray and background light suppression

The detected signal results as the sum of three terms: the scattered radiation itself (which has to be maximized), the radiation coming from the plasma (as previously said, mainly brehmstrahlung radiation, but also line emission from impurities) and the laser light scattered from optics or solid surfaces (stray light).

The last contribution arises since the TS cross section is very small and scattered laser light can be order of magnitude higher in intensity than the TS signal; the stray light can affect the spectral channels closer to the laser line; here the filter transimssion can be finite even at the laser wavelength.

²the presence of fiber out of axis is also useful to control the laser alignment on the scattering volumes

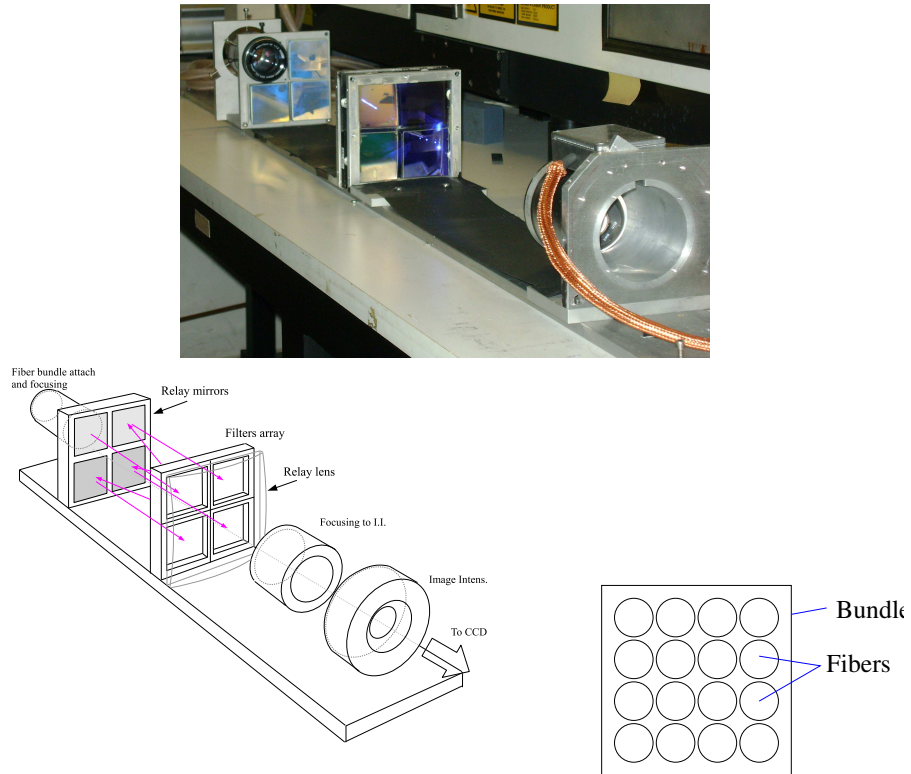


Figure 3.6: picture and sketch of the previously used spectrometer; aside, sketch of the fiber bundle arrangement containing the 12 signal fiber and the 4 fibers intended for alignment procedures

The stray light can be minimized via a careful optical design and avoiding diffraction or diffusion of the laser beam on solid objects; the stray light level is stable from shot to shot, so in principle it can be treated acquiring a frame in vacuum conditions and subtracting it, once its level is normalized to the laser energy.

The other spurious contribution, the plasma light, is subject to strong variations depending on the plasma temperature, density, on the local interaction with the wall and thus on the impurity content of the plasma. This, as will be shown, was one of the major problems which led to the substitution of the CCD with the APD detectors, since real-time subtraction was impossible. Real time background subtraction could in principle be done with the aid of the four out-of-axis fibers. If such fibers collect only background radiation, the background value on the signal fibers can be extrapolated. The scattering volumes are surrounded by a rectangle defined by the spots of the off-axis fibers (fig. 3.2), and a nearly linear spatial dependence of the plasma light inside this rectangle.

Another problem was the high level of the stray light combined to the presence of instabilities in the generator of the gate signal used by the image intensifier.

Instabilities in the generator couldn't be solved, while small benefits have been obtained shielding its case with aluminium plates, changing the connection plug and the shielding the cable going to the image intensifier. It was not even clear if measured instabilities were caused by the variation in the exit impedance due to the measure itself. The gate generator has to produce a square waveform with rise and fall slope of the order of 100 V/ns and so its operation is quite sensitive to the exit impedance; moreover, external disturbance level is high because of the proximity of the laser power supply cables. The gate width was found to be sometimes variable within 20 ns (on 100 ns of nominal value), making stray light subtraction from a reference shot not reliable; stray light is also a major problem when subtracting the background by the 4-fibers technique described above: the signal in the off-axis fiber was hard to treat because of the high level of stray light they collect.

The analysis routines used with the described setup performed 64 hyper-gaussian fits, in the form $z = f(x, y) = Ae^{[(x-x_0)^2 + (y-y_0)^2]^B}$, on the CCD image, each one centered on a defined fiber spot (x_0, y_0) : the plasma light acquisition was subtracted before fitting, while the stray light contribution was subtracted after, as a number in the signal level. This procedure was intended to manage the stray level as a degree of freedom in the χ^2 minimization routine used for determining the temperature, the quantity to be minimized being

$$\sum_i [(Ae_i(T) - c_i - Bl_i) / s_i]^2$$

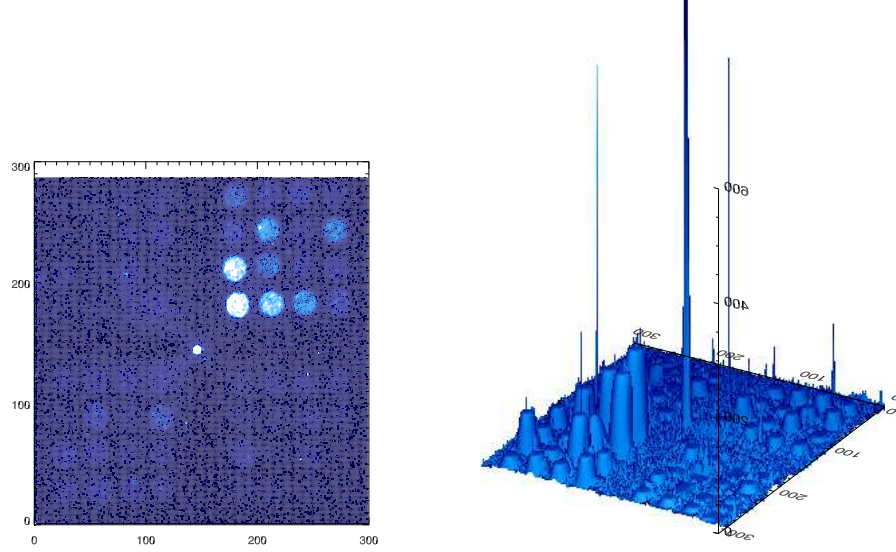


Figure 3.7: Image acquired by CCD and relative fitting with hypergaussian functions, after background subtraction, in the old Edge TS setup

instead of $\sum_i [(Ae_i(T) - c_i) / s_i]^2$ (see 2.3.1) where A account for density, c_i and s_i are respectively the signal on the i channel and its error, e_i the expected value and l_i the measured value of stray light. The value of stray light normalization B was actually unknown due to gate width variability; the system proved to work only for low levels of plasma light: again, the combination of non negligible levels of stray light and plasma light made the measures unstable and unreliable, limiting the possibility of the diagnostic to operate.

3.2.2 First attempts with digitizers and final setup

It became clear that, without being able to discriminate each term contribution in the collected radiation, the diagnostic would have been impossible to operate in most situations: hence the decision of substituting the spectrometer. This could be done rapidly, given the availability of two spare APD monochromators of the main TS system, and of some filter sets intended to be used for the ruby wavelenght (before the purchasing a multipulse ND-YLF laser for the main system).

The first attempt was made coupling a fiber directly to the bundle in the CCD spectrometer, and connecting it to one APD spectrometer; then 6 scattering volumes were measured with two APD polychromators, with one fiber per volume, relying on 15 meters delay lines. With this setup it was simple to discriminate the plasma light contribution from the scattering signal, given the availability of the fast APD detectors. Moreover, the stray

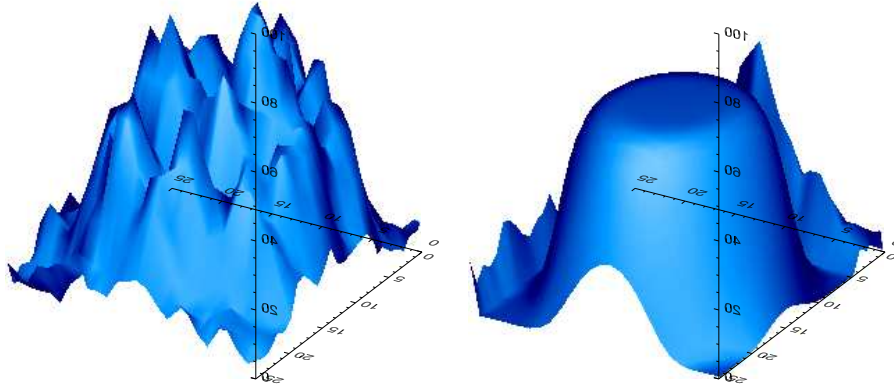


Figure 3.8: Detail of the fitting of a single peak related to a fiber spot

light could be reduced once it was found it was strongly dependent on the pipe head position - this was due to an imprecise positioning of the shutter in the opened position (see fig. 3.1), and to a consequent interference with the laser beam. In these condition, the edge TS was able to operate only for core densities above $3.5 \cdot 10^{19} m^{-3}$ which was too high, since the plasma density in RFX-mod ranges from 1 to $5 \cdot 10^{19} m^{-3}$. This lead to the decision to use two fibers per scattering volume: the final configuration consists of 6 scattering volumes, 2 fibers each, with optical delay lines of 25 and 50 meters.

The necessity of using two fibers is also due to the impossibility to raise the laser energy to gain signal level: while the laser could fire up to 15 joules, it has been found that the sapphire prism at the pipe end (the last optic encountered by the beam), has an experimentally found damage threshold of about 4 J, so that a safe operation can be performed at 3-3.5 J. The damage is localized on plasma facing surface, on a circular crown, being absent on the other side. This could be related to a deterioration of the AR coating facing the plasma; it has to be noticed, however, that in the far field the beam takes a hollow intensity profile (hence the crown shape of the damage), increasing the local energy density. The imaging of the laser trough a pinhole is a general method adopted to correct problems in the beam profile; it is possible to cut away the external part of the profile; for small pinholes, the beam is diffracted and loses the information of its energy distribution. On the other side, the pinhole mounted in the launch pipe has been enlarged from 3 to 4 mm in diameter, to achieve a compromise between the beam profile regularization, the energy losses and the reliability of the system alignment.

The increase in the pinhole size from 3 to 4 mm was decided after a serie of test performed placing a fiber on the pinhole inspection window and

coupling it with a photodiode (fig.3.2); this setup was intended to verify the passage of the beam through the pinhole without opening the diagnostic, simply minimizing the radiation diffused by the pinhole itself. Acquiring the photodiode signal with an oscilloscope, it was possible to identify an anomalous tail after the laser peak, lasting for some hundreds of ns; the latter was interpreted as black body radiation coming from an ablation process on the pinhole. This tail couldn't be suppressed improving the alignment, and this suggested that the beam diameter was however too large for the pinhole size, causing material erosion and energy loss.

3.3 Opto-mechanical modifications

3.3.1 Design problems and signal loss

Once moved to the APD spectrometers, another design defect of the diagnostic became evident: the scattering volumes laying far from the pipe axis (the most internal and most external) suffered from vignetting due to the shape of the pipe itself and to the shutter presence. This is a problem especially for the scattering points on the shutter side, which are the closer to the wall: here the loss of signal due to the vignetting is combined to the low value of the plasma density, and hence of the scattered power. As a reference, fig. 3.9 show the behavior of the objective collection angle as a function of the scattering volume position on the beam; the curve has been calculated accounting for the collection pipe geometry and the objective position.

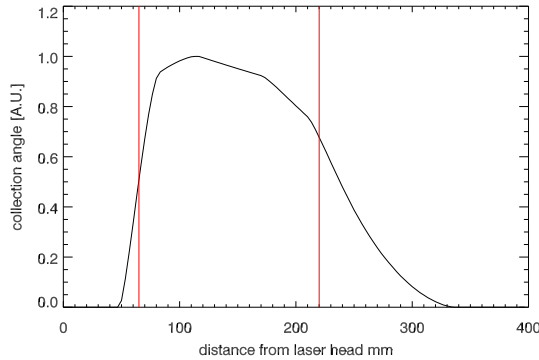


Figure 3.9: Simulated vignetting curve, on the abscissa the distance of the scattering volume from the pipe head; the main feature is the steep variation in the solid angle on the external side (closer to the pipe); hence the sensitivity of the signal on the magnification of the collection optics. Red lines represent the extreme position of the scattering volumes

The distance from the objective optical axis resulted also in a loss of transmission of some percents; this effect has been measured in a bench

test, imaging a 6mm spot of white light on the surface of a light detector and scanning the objective inclination by steps of 4 degrees on the horizontal plane. The transmission decreases by 4% at 8° , 27 % at 8° and 55 % at 12° , being the maximum angle of the fiber with respect to optical axis 8° .

Moreover, the disposition of the fibers parallel each other was related to imperfect matching of the fibers acceptance angle with the objective field: the fibers arrangement was consequently changed mounting them in a fan-like frame (fig 3.1, 3.10) .

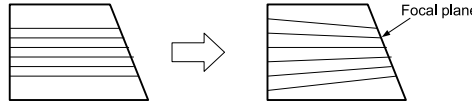


Figure 3.10: detail of the modification in the fibers arrangement, see also 3.1

3.3.2 Optics Modifications

The easiest solution to remove the vignetting of the outer scattering volumes is the reduction of the system magnification, obtained moving the objective 50 mm toward the plasma; this lead to an axial magnifying decrease from $M=5$ to $M=3.5$. The sapphire wedge at the pipe exit has been replaced with another one, manufactured without AR coating on the plasma facing side. With these changes, the system is able to measure with core densities as low as $1.5 - 2 \cdot 10^{19} m^{-3}$ (fig. 3.11).

Being the overall objective transmission limited to a 70 % , it has been planned its substitution with another lens system, designed to keep the number of surfaces as low as possible. The use of a single aspherical lens has been simulated, but would have resulted in an excessive aberration for off-axis fibers, so two lenses have been dimensioned and purchased to get a doublet with a nominal transmission of 96 % (+35%); triplets has not been considered, while the decrease in the transmission due to the use of acromatic systems is not justified, being the scattered spectrum width < 100 nm.

The system has been simulated for $\lambda = 700nm$ and $\lambda = 750nm$ displaying a negligible shift of the focal point: the main source of problem is actually astigmatism, which is reduced with the use of the doublet because of a more progressive refraction of the ray pattern.

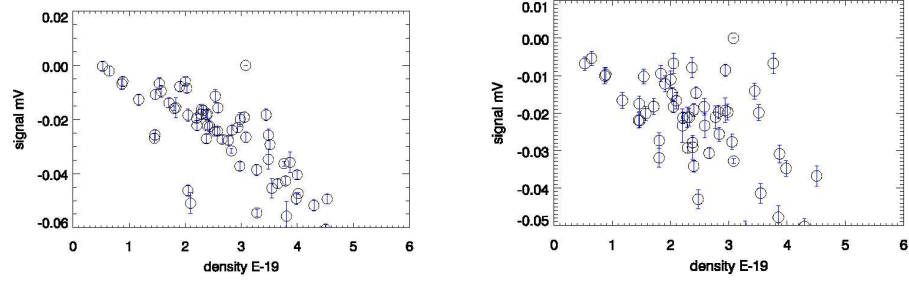


Figure 3.11: signal level in the second spectral channel (after fitting with the analysis routines) as a function of core density for a fiber on the optical axis (left) and one looking to the edge (right). For the latter, the operational limit is around $1.5 \cdot 10^{19} m^{-3}$, corresponding to 10 mV ($S/N \approx 3$); the spread of the point at the very edge depends on the local temperature and density

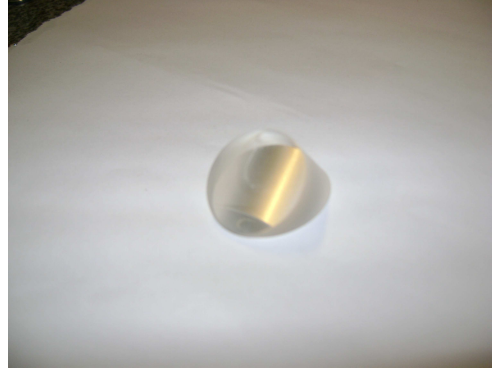


Figure 3.12: picture of the sapphire wedge showing the crown-shaped damage on the plasma faced side

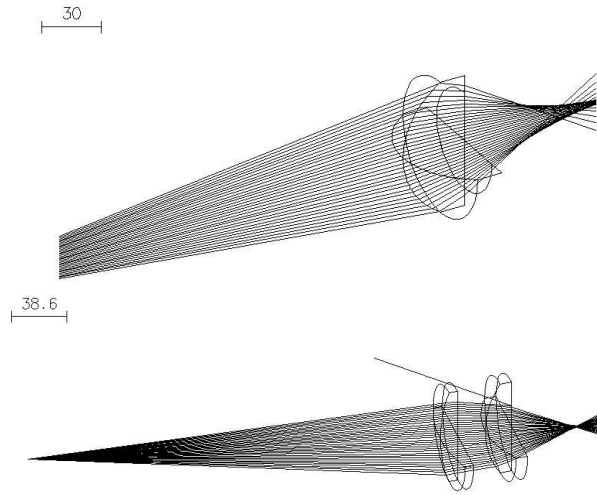


Figure 3.13: two studied solutions (up, single aspherical lens, down, doublet) for the collection optics substitution: simulations performed with OSLO raytracer show that astigmatism can cause problems in the use of a commercial aspherical singlet; both the cases refers to external, off-axis scattering volumes

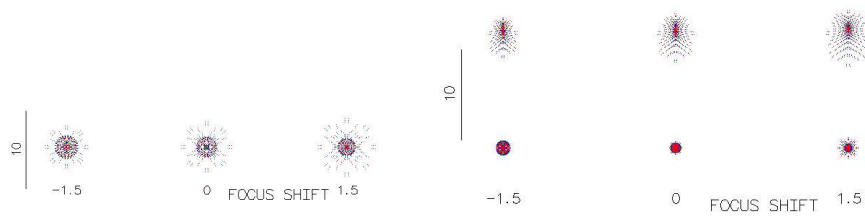


Figure 3.14: spots simulation at the focal point for the two solutions above; the aspherical spot (left) is considerably wider (scales on the left are in mm); for the doublet (right) also a spot in the extreme off-axis position is considered

The feasibility of a modification in the shutter mechanism is studied; this, changing the orientation of the shutter rotation axis, would allow the operation of the sistem with the pipe head in a rearer position, with advantages for the thermal load on the pipe and on the sapphire wedge. If, after the modification in the optics, the signal level on the density will be improved, it will be possible to double the spatial resolution working with one fiber per scattering volume.

3.4 Signal processing and data analysis

The acquired waveform for each channel of the two spectrometers consists of three peaks, each one corresponding to two fibers or one scattering volume (Fig. 3.15). The signal is fitted minimizing the χ^2 with a function in the form:

$$F = A + Bx + \sum_{i=1,3} c_i \exp - \left(\frac{x - d_i - C}{D} \right)^2$$

where the quantities d_i are the delay of each fiber line, which are known depending on the fiber lenghts. C and D parameter can vary on a small interval or be fixed. The fitting routine works leaving C and D variable within a small interval: in the case of C, this permit to account for the gitter in of ± 1 counts in the acquisition; on the other hand, a small variation in the laser pulse width of some ns (accounted by D) is common as a result of a laser maintenance or of a thermal drift in the apparatus. The acquisition is triggered by a fiber connected to the ruby laser oscillator, while the beam energy is measured with a fast photodiode coupled to another optical delay line; the latter collects the radiation passing trough a mirror placed on the laser path. The peak of the energy monitor channel is fitted and its position used as reference for the C parameter in the fit.

The errors s_i on the parameters c_i are as usual evaluated as:

$$s_i = r_{i,i}^{1/2}; R = \left(\frac{1}{2} H \right)^{-1}$$

and $H_{i,j} = \frac{\partial^2 \chi^2}{\partial c_i \partial c_j}$ is the hessian (numerically evaluated) of the χ^2 derivatives respect to the parameters; here H is a 7x7 matrix.

The c_i values and their errors s_i are the input paramters for the temperature calculation routines. According to the method discussed in 2.3.1, it is necessary to minimize the quantity:

$$\sum_i \left(\frac{Ae_i(T) - c_i}{s_i} \right)^2$$

where $e_i(T)$ are the expected value of the signal for a given temperature and A a normalization constant which, once an absolute calibration is performed, measures the plasma density

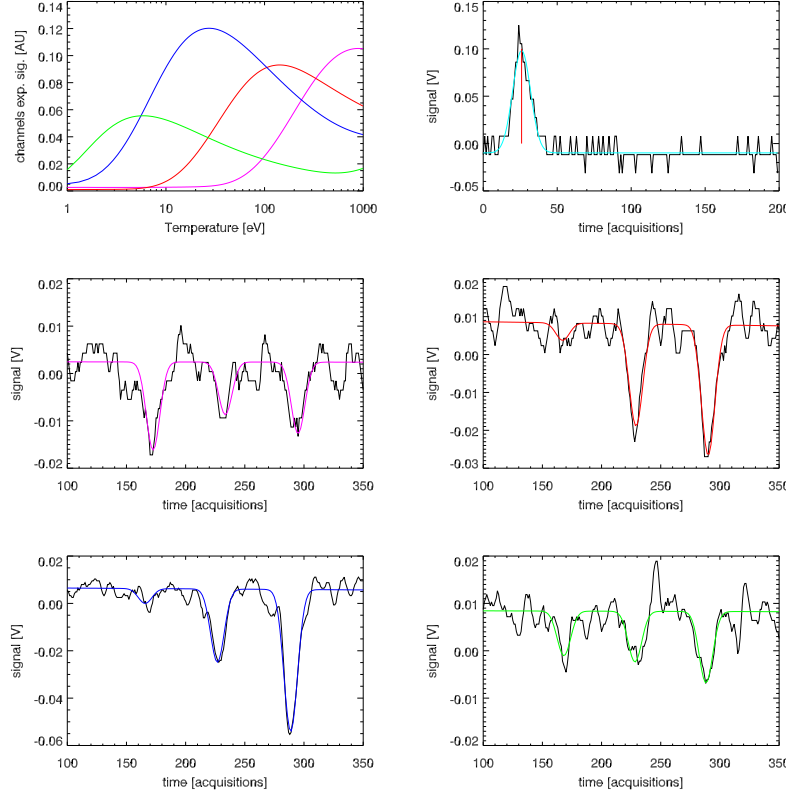


Figure 3.15: Figure showing the signal acquired by the polycromators in the four spectral channels; each peak correspond to one scattering volume. In the first row, plot of the gamma function whose colors corresponds to the shown channels, and signal coming from the energy monitor detector: it is evident a shifting of ≈ 200 ns, which is the sum of the beam time of flight to the machine and of the delay introduced by optical fibers

3.5 Alignment and Calibration procedures

The calibration procedure consists of the relative calibrations of the spectrometers for temperature evaluation and of the absolute calibration of the system made with RRS in nitrogen; the latter is used to allow the instrument to measure the plasma density. Raman scattering, as will be described, can also be used as a control procedure for testing the diagnostic alignment.

3.5.1 Spectrometers

The polichromators has to be calibrated to measure the transfer function for each channel: this operation is now done using a dedicated fiber in each spectrometer, the central one in the hexagonal fiber bundle. A stabilized light source is fed onto a grating polichromator whose spectral resolution is 0.5 nm, corresponding to slit apertures of 0.25 mm aperture. The output is imaged with a convergent lens (≈ 40 mm diameter, 100 mm focal) on the fiber end; the fiber position on the focal plane is optimized with a translating bearing to get an uniform output field at the other end. Usually, a lowpass dichroic filter is used to cut the components of upper order harmonic which aren't suppressed by the monochromator; being the transmission functions beyond 680 nm, a filter with a cutoff at 650 nm is adequate and is commonly placed on the monochromator output (fig. 3.16).

The calibration proceeds as follow:

1. After the lamp thermal stabilization (≈ 10 min.), a first scan with the monochromator has the purpose to record the intensity of the radiation at different wavelength, in order to normalize the transmission function which will be obtained. For this purpose, the head of an energy meter is placed on the monochromator exit and the power distribution of the spectrum recorded with a quite low resolution (2-5 nm).
2. The energy meter head is unmounted, while the open end of the calibration fiber is placed on the lens focal point at the monochromator exit; to achieve an uniform illumination of the fiber is better to work a little bit out of the lens focus.
3. A second wavelength scan is performed, with a 0.5 nm step, and the DC signal for each spectral channel is measured and recorded. To get its own transmission function, the signals have to be normalized to the power distribution of the spectrum, acquired in the first point.

During this last operation one should particularly care the control of the APD bias voltage, since the power to which they are exposed during the calibration is usually higher than during the measures, and this can cause a variation in the detector gain. However, this effect can be compensated: for small ΔV variations considering the gain g varying linearly as $\Delta_g \approx k\Delta_V$; from figure 3.4, the variation in gain is $\approx 1.5\%$ for each volt of bias variation.

Clearly, this method accounts for the calibrations of all the elements of the dispersion system (optical fibers, spectrometers and detectors) except the objective and the vacuum window on the collection pipe. For what regards the objective, it can be used instead of the lens at the exit of the monochromator. However, its transmission has been measured separately and

found to be stable in the range 650-800 nm and so it doesn't affect the spectral calibration. A similar behavior, though not measured, is to be expected by the vacuum sealing window.

With the CCD spectrometer previously used, this operation had to be done bringing an optical bench with the lamp, monochromator and the control PC in the experiment hall, since there wasn't any dedicated calibration fiber and all the fiber rack should be unmounted from the diagnostic structure and coupled with the monochromator itself. This, in principle, is a better procedure since one measures the exact transission of the fibers used in the signal collection, whose lenght is different from the calibration fiber.

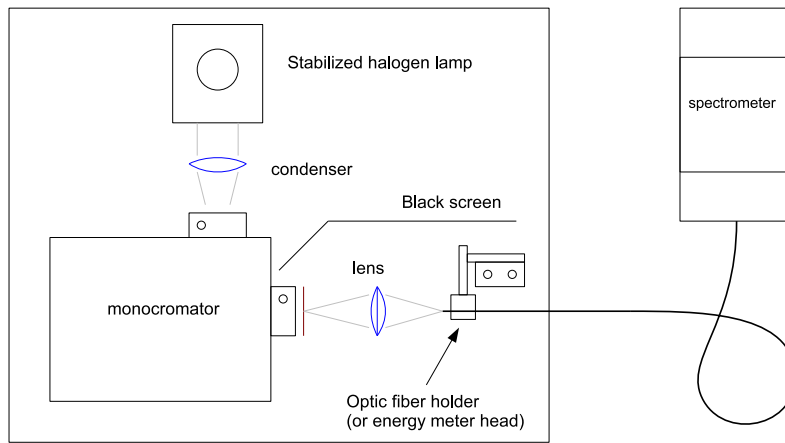


Figure 3.16: layout of the setup used for spectrometers calibrations

3.5.2 Alignement & Raman Calibration

The procedure of optical alignment of the laser and of the collection optics is performed with the diagnostic head extracted from the machine; the fore parts of the input system (beam pipe and collection optics) can be withdrawn from the vessel maintaining their reciprocal position.

1. The first step is the alignment of the beam on the pipe axis, which is done acting on the two mirror before the entrance window, and controlling the beam position at the window and on the pinhole; in this phase the orientation of the laser beam with respect to the scattering plane has to be checked. If the laser does not exit horizontally, the pipe (and so the prism) is tilted properly.

2. To align the collection fibers on the laser, they are back-illuminated, imaged through the objective on a diffusive screen placed on the laser path, and their positions adjusted (acting on the fiber holder) until the spots are correctly focused the beam path.
3. The diagnostic is closed on the vessel side and pumped; once it is inserted, it is possible to reduce the stray light performing laser shots in vacuum conditions; acting on the last mirror, the beam focal point is moved, scanning the pinhole area with a resolution of ≈ 0.2 mm, and fixed on the position corresponding to the lower stray light signal level. This is just often a check: if the beam was carefully aligned in the operations 1 and 2, the final position does not need to be tuned.
4. The last step performed with the vessel filled by N_2 : the fibers alignment is checked moving vertically their holder to find the position which maximizes the Raman signal. At this point, RRS can be used for the system calibration, varying the pressure (from 40 to 80 mbars usually) and acquiring the RRS signal (for a single channel) S_r (see 2.3.2) to get $dS_r/dP = (RT)^{-1}dS_r/dn$, where P is the pressure, T the temperature R the gas constant; the term dS_r/dP is simply evaluated with a linear interpolation, shown in fig. 3.17.

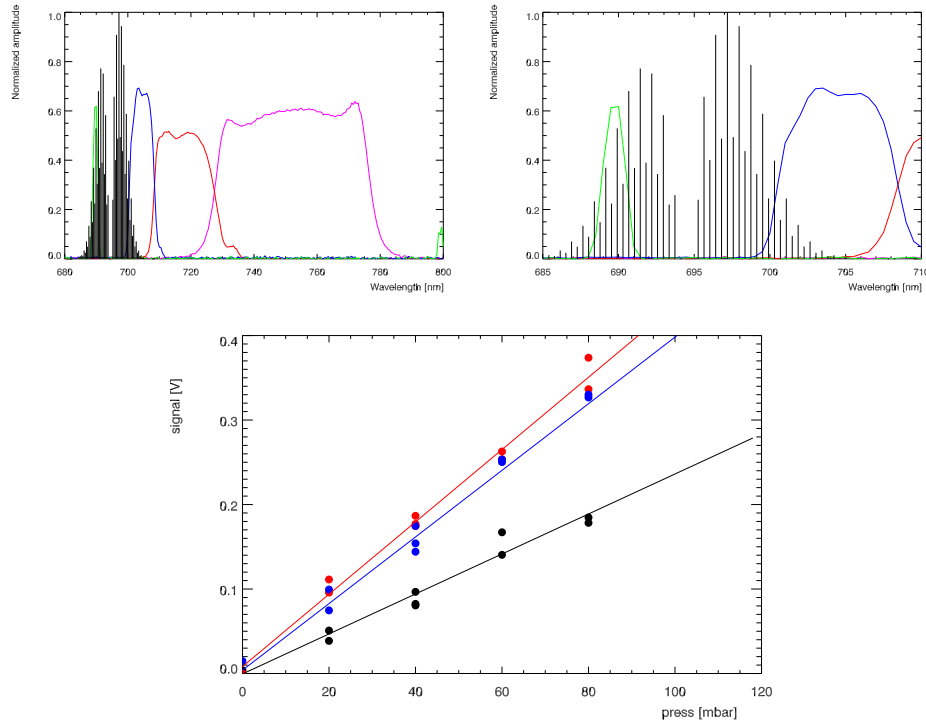


Figure 3.17: Up, nitrogen Raman spectrum plotted together with the TS transmission functions and zoom of the wavelength interval closer to the laser line. Down, measured signal as a function of pressure for the three scattering volumes of one spectrometer; the linear interpolations returns the value of the dS_r/dP term

Chapter 4

Measurements from Edge Thomson Scattering

This chapter will shortly present the first results obtained by the Edge TS diagnostic, with particular attention to some topics of the RFP physics. In most cases, profiles from the Edge TS have been combined with those of the Main TS, which, once cross calibrated with the interferometer line integrated density measurements, provides also the n_e profile. Complete p_e profiles - or edge p_e data for two close times - are thus available with the proper synchronization of the two TS systems

4.1 First analysis

The first analysis have been performed to cross and confront the data coming from the edge TS with other estimates of the edge temperature and measures, i.e. those coming from Thermal ion beam (THB [47]) diagnostic and from the main TS. THB resolves 5 radial points, 5 mm distanced starting from the wall; it gives further information on T_e and n_e at the plasma boundary, with a time resolution up to 3 kHz; the measurements are obtained with the line intensity ratio technique. Neutral helium is injected in the plasma edge and the intensity of the three emission lines ($\lambda = 667.8, 706.5, 728.1$ nm) of HeI are measured; from their ratio it is possible to evaluate the radial profiles of electron temperature and density together with their time evolution. Each points is imaged with a triplet of optic fibers, which are connected to a monochromator; the output of the latter is imaged through a photomultiplier and acquired; operational limit are $n/n_G < 0.4$, $T_e > 5\text{eV}$.

A pair of profiles is shown in fig 4.2; the matching of the data on the two diagnostics at the edge is sometimes imprecise, resulting in a qualitative difference of the temperature gradient at the very edge. On the other side, the absolute values of temperature correspond; discrepancies

in this region can be ascribed to the differences in the toroidal position ($\phi(THB) = 322^\circ$, $\phi(edgeTS) = 52^\circ$) and hence to the presence of local variations in the plasma-wall interaction. This issue will be further discussed in the following, when dealing with the detection of $m=0$ structures. It has to be reminded that for the two diagnostics is difficult to work together, since, at this development stage, the THB is limited at low densities.

As far as the Main TS profiles are concerned, they are combined with the edge TS mapping the scattering volumes on normalized flux coordinates $\rho = (\psi_p \psi_p^w)^{1/2}$, $0 < \rho < 1$, in order to account for the difference in the LCFS radial position at the two toroidal position of the diagnostic (52.5° and 82.5° respectively for the Edge and Main TS systems)¹.

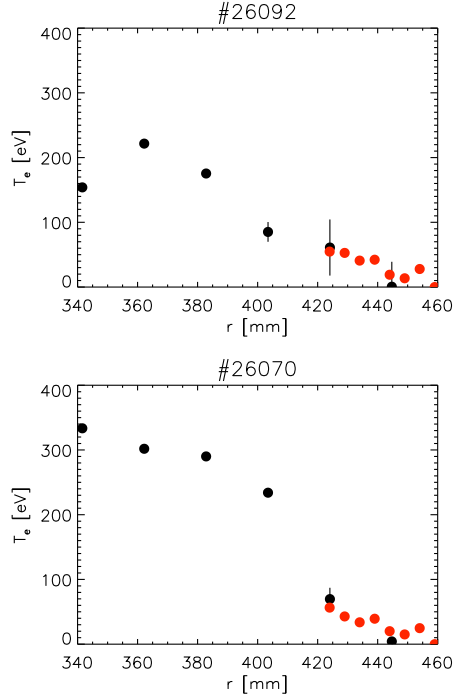


Figure 4.1: Two example of comparison of THB (red) and Edge TS (black) profiles, showing the compatibility of the temperature value at the extreme edge of plasma

Moreover, in the case the TS diagnostics are absolutely calibrated, the electron density n_e and so a complete electron pressure (P_e) profile can be obtained in the region $-1 < r/a < 1$. In Fig 4.3, an example of T_e , n_e and P_e profiles measured during a QSH-SHAX state is reported: the three rows correspond to T_e , n_e and P_e respectively, first column is the entire radial profile, while the second column shows the edge region mapped onto ρ .

¹The remapping on ρ accounts not only for the equilibrium field but also of the radial displacements of the flux surfaces near the edge, reconstructed at first order from the radial component of the $m=0,1$ perturbations at the edge

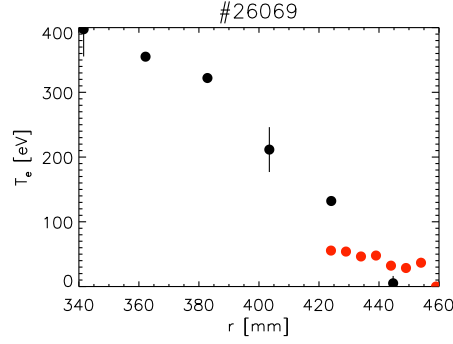


Figure 4.2: An example in which the profiles of THB (red) and Edge TS (black) are less in agreement, in particular as far as the gradient value is concerned

A further remark concerning this comparison is that in the inner edge T_e and n_e are often below the Main TS operational limits, 50eV and at $1.5 \cdot 10^{19} m^{-3}$. The Edge TS profiles represent a robust constraint for the reliability of the Main TS profile in the inner region, since up to now, localized measurements of the Main TS have been compared with T_e and n_e line integrated measurements only (from interferometer and X-ray double filters respectively) or through indirect comparison with X-ray tomography. As it is evident from fig 4.3, once mapped over flux coordinates ρ the two profiles discrepancy is below their uncertainty, which indicates the good level of the measurements.

4.1.1 Scalings

Actually, the number of available profiles does not represent a statistically significant population from which to extract robust scalings, such as those obtained from the Main TS or other edge diagnostics. Nevertheless, a good indication of the average edge electron profile change with respect to the plasma current can be obtained. In Fig 4.4, the edge T_e and p_e average values, measured in the region $\rho = 0.8 - 0.9$, are shown as a function of edge n_e : data are grouped in three different plasma current ranges between 0.2 and 1.8MA to distinguish the effect of the current I_p from that of electron density; only MH cases are taken into account. The T_e dependence is similar to that of the core T_e already reported in literature [52, 53], with an inverse dependence on the corresponding n_e ($T_e \propto I_p^{0.93 \pm 0.01} (n/n_G)^{-0.35 \pm 0.01}$); the points do not distribute over isobars since at high density a pressure higher than expected is found, especially at higher current. Similar results are found in the QSH cases. Nevertheless, in order to investigate these operational regimes, a wider statistic is needed.

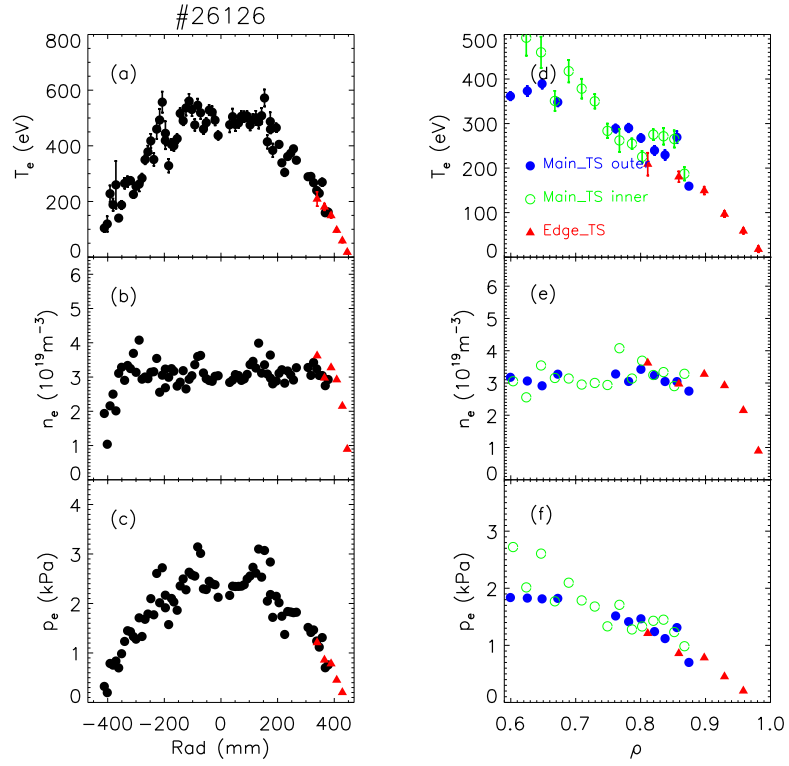


Figure 4.3: examples of T_e , n_e and P_e profiles from the Main TS (black dots) and the Edge TS (red triangles) during a QSH-SHAX state ((a)-(b)-(c)). The edge region ((d)-(e)-(f)) is plotted vs the normalized radial coordinate

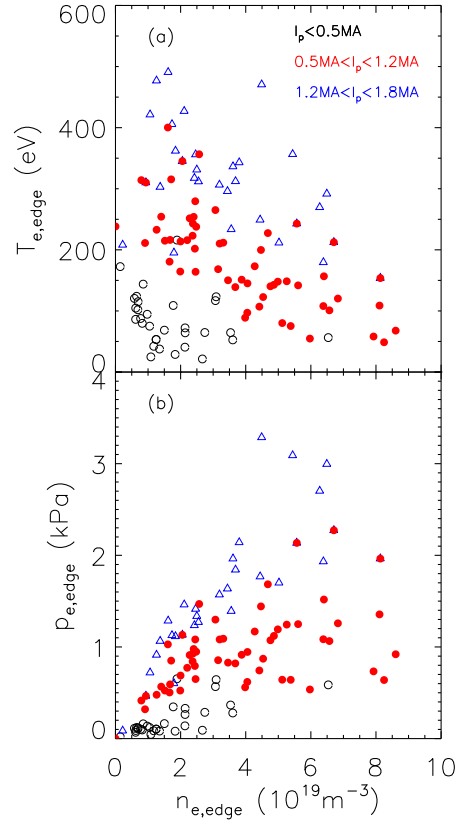


Figure 4.4: electron temperature (frame a) and pressure (frame b) as a function of density, from the Edge TS in the region $\rho = 0.8 - 0.9$. Three ranges of plasma current are considered, 0.2MA-0.5MA, 0.5MA-1.2MA, 1.2MA-1.8MA, during MH states

4.2 Density limit and topology of the $m=0$ island

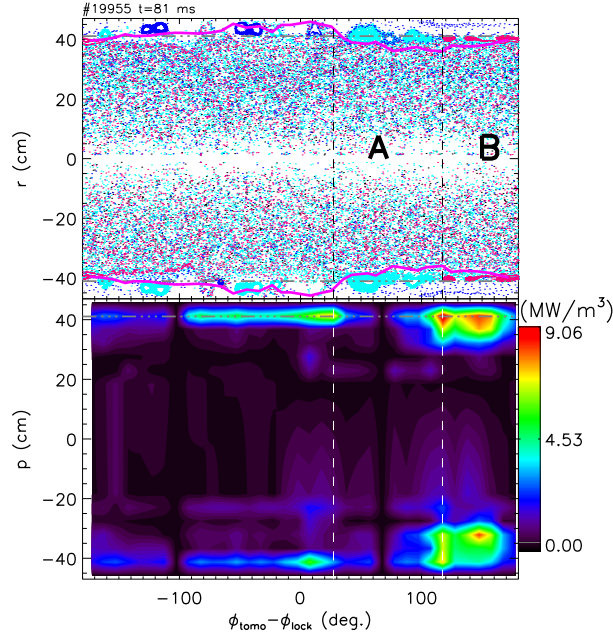


Figure 4.5: (top) ORBIT [16] toroidal Poincare' plot of magnetic field lines in a high-density RFX-mod discharge: At high density the plasma is in the MH state and much of the plasma core is chaotic, save for the edge region where conserved magnetic islands appear; the solid, magenta line marks the perturbed plasma LCFS. (bottom) Correspondent total emissivity map (equatorial cut), showing the presence of a poloidally symmetric high radiative structure ("ring")

The availability of accurate edge profiles, both from the Main and Edge TS, plays a key role in the comprehension of the role of the MHD $m=0$ modes in the occurrence of the density limit in RFX-mod [54].

All the fusion experiments cannot exceed a limit in the plasma density: in tokamaks this is the Greenwald limit, expressed as $n_G = I/\pi a^2$ (n_G in $10^{20}m^{-3}$, I in MA, a in m) and its attainment causes the discharge to disrupt [55]. Stellarators are limited -with an non disruptive behavior- as the density reaches the so called Sudo parameter [56] $n_s = (P \cdot B/a^2 R)^{0.5}$ (n_s in $10^{20}m^{-3}$, P in MW). In RFPs, as density approaches the greenwald limit, the current becomes difficult to sustain, edge plasma cools down and resistivity increases, but disruptions do not happen [57]. While it is possible to go beyond the Greenwald limit on tokamak [58], where pellet fuelling or additional heating result in peaked density profiles, the limit shift to the edge, where it originates likely as a result of a threshold in the edge density, which is definitely the critical point [54, 59].

In RFX-mod, as the density approaches n_G , radiative structures, toroidally

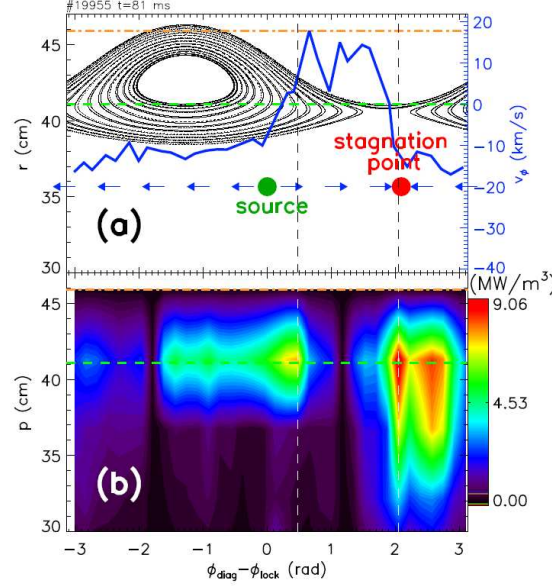


Figure 4.6: (top) topology of the only $m=0, n=1$ island and behaviour of the LCFS; the source and stagnation point of the flow is enlightened. (bottom) The emissivity map shows that the bright spots are related to the position of points where the flow reverses [60]

localized [61], develop near the plasma edge. This behavior shows analogies to MARFE phenomenon [62] in tokamaks, where such structures are poloidally localized, coherently with the different direction of the field at the plasma edge in the two types of machines [63, 64]. A breakthrough has been the observation that the radiation and density increase is correlated with the presence of $m=0$ island, that resonate at the $q=0$ surface (reversal) near the edge (fig. 4.5). The element connecting density accumulation and presence of $m=0$ islands has been shown to be the local inversion in the toroidal component of the plasma flow $v_\phi = E_r B_\theta$ (being E_r the radial electric field). In the inversion, a fundamental role is supposed to be played by E_r , which in this region is supposed to have an ambipolar nature: electrons are allowed to penetrate the plasma boundary as the changes in the magnetic topology causes the islands to touch the wall: the features of electron diffusion deeply influence the radial electric field at the edge.

As soon as the sign of v_ϕ changes, a strong toroidal flux develops in the region ($\approx 10^{23} \text{m}^{-2} \text{s}^{-1}$), much larger than the value of perpendicular diffusion in this region ($\approx 10^{22} \text{m}^{-2} \text{s}^{-1}$). The result is density accumulation, temperature decrease and consequent resistivity increase, which result in localized increase in the plasma emissivity around the flux stagnation point (Fig 4.5); actually, the plasma cooling is related to the excitation of low ionized states in the most common impurities (C, O, B). The whole process

tends to develop a radiative instability which, starting from the edge, is supposed to move to the core as a result of a positive feedback between the plasma cooling, the increase of radiation losses and the decrease of ohmic input due to current suppression. The phenomenology described so far is related to an increase of the coherence of the $m=0$ ripple, which is described by the $m=0$ dispersion parameter [65]:

$$\Delta^n = \phi^{0,n+1} - \phi^{0,n} - \phi^{0,1}$$

where $\phi^{0,n}$ is the phase of the $m=0, n$ mode. The condition of maximum constructive interference is verified when $\Delta = 0$; as density increase, experimentally $\Delta^n \rightarrow 0 \forall n$, while for low densities the phases are more dispersed, resulting in a degradation of the $m=0$ pattern. The density influences also the amplitude of the $m=0, n=1, 7$ modes, which increases for high value of n/n_G . In particular, this increase is mainly due to the first harmonic ($m=0, n=1$), resulting in single wide island toroidally localized at the plasma edge (fig 4.5). While the reasons of this trend are not fully understood, there is a clear relation between the growth of the $m=0, n=1$ mode and the phenomenon of density accumulation, which will be characterized in the following.

4.2.1 Detection of $m=0$ related structures

The $m=0$ islands are radially shifted according to the deformation of the last closed magnetic surface (LCFS): since at high density the $n=1$ is the largest mode in the $m=0$ spectrum, half of LCFS is pushed inward ($\phi - \phi_{lock} > 0$), and half outward ($\phi - \phi_{lock} < 0$), as shown in Fig. 4.7, top (the LCFS is the solid line which approximately joins the envelope of the outer portion of the islands). Here the mode locking angle ϕ_{lock} is taken as a reference for the phases of rotating MHD modes, as usually done in the RFP, with $\phi_{lock} \approx \phi_{0,1}$.

The $m=0$ pattern is related, as described in the previous section, to the development of a dense and cold edge structure, which slowly rotates toroidally in the shape of a ring. As this structure passes through the toroidal region covered by the two TS systems, a widening of the radial region at low temperature (< 50 eV) is measured at about $\rho = 0.85$. In Fig. 4.7 the edge profiles are shown for a low value of $\langle n \rangle / n_G$ (0.28) and for a high value of $\langle n \rangle / n_G$ (0.6) (with $\langle n \rangle$ the line integrated core electron density), in two different toroidal positions with respect to the cold ring. The density within the ring increases as a function of the normalized average density $\langle n \rangle / n_G$, and the edge density accumulation extends also inwards up to $\rho = 0.75$, with a corresponding lower temperature ((c)-(d)).

The small discrepancy between Edge and Main TS density profiles in frame (d) is explained by the toroidal localization of the $m=0$ structure (30-90 toroidally, namely 1 to 3 meters) of the cold ring, by its rotation, and

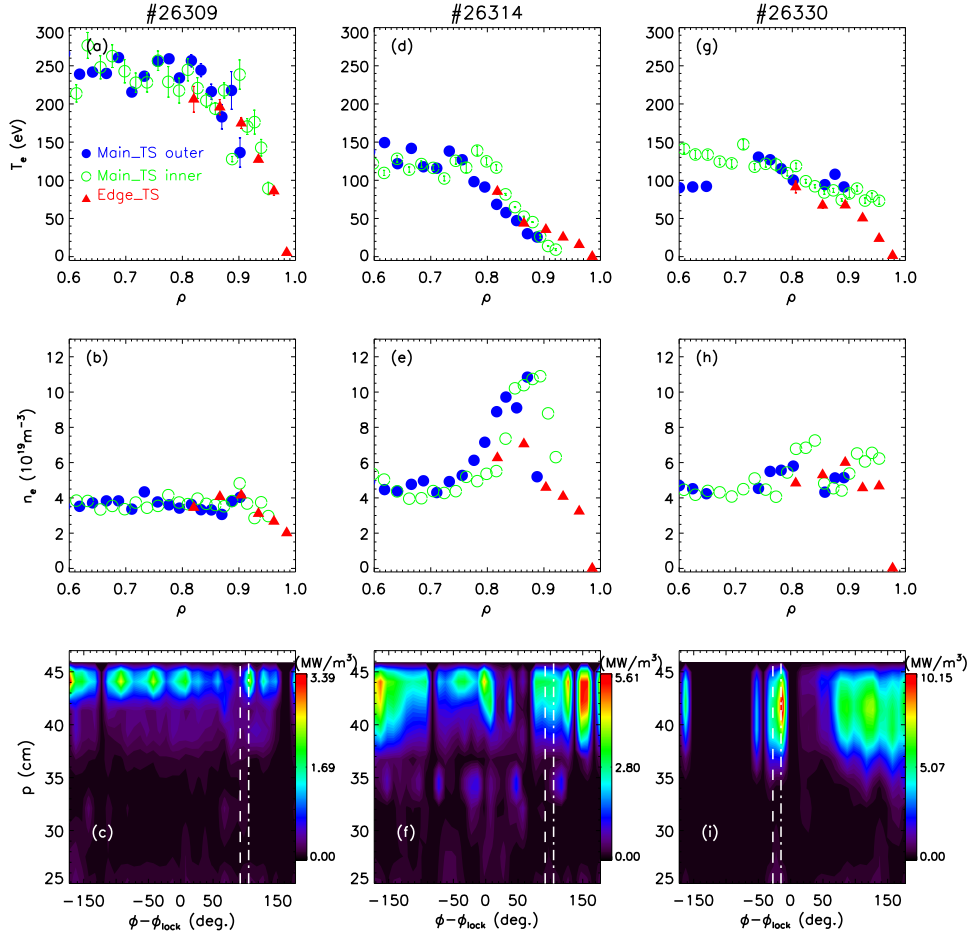


Figure 4.7: TS profiles of temperature (a)-(d)-(g) and density (b)-(e)-(h) for three discharges. The last row displays the toroidal distribution of radiated power obtained with bolometric tomography, and enlightens the positions of $m=0$ structures respect to TS lines of sight

by the different toroidal angle of the Main end Edge TS. In the case of Fig. In Fig. 4.7 the ring is closer to the Main TS, which in fact shows a higher density and a lower temperature than the Edge TS.

If the $m=0$ structure is not localized at the TS systems location, the density accumulation is not detected ((e)-(f)). A toroidally symmetric edge n_e peak with increasing $\langle n \rangle / n_G$ is always present [66], but it is less pronounced than the density accumulation due to the $m=0$: this is instead due to the presence of the mode locking structure $\phi - \phi_{lock} = 0$. This accounts also for the consistent and localized emissive region visible in frame (i): the radiative region is only in the outer radius (i.e., not poloidally symmetric) and without a relevant density accumulation; these observations are likely explained by the described radiative instability which increases the resistivity and finally terminates the plasma current [67].

The edge density accumulation with the appearance of the $m=0$ structure is also shown in Fig.4.11, where the ratio between the core average density and the maximum edge density (respectively obtained in the regions $\rho = 0 - 0.6$ and $\rho > 0.8$) are plotted as a function of n/n_G ; we considered only those cases of a three days session (30 discharges) for which the TS systems intercepted the $m=0$ structure.

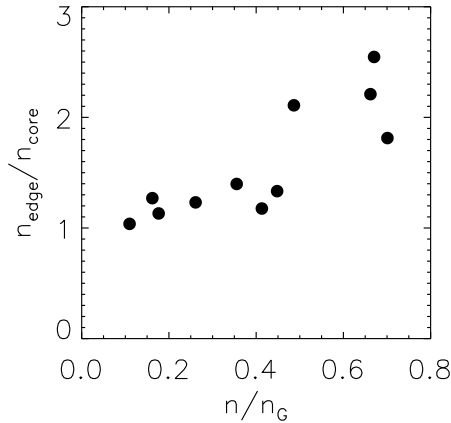


Figure 4.8: maximum edge n_e value with respect to the core n_e (obtained from the Main Thomson scattering) as a function of the n/n_G value. For these cases, the Main TS intercepts the region interested by the $m=0$ structure.

4.3 Pellets injection

As discussed in chapter 1, the presence of QSH structures inside the plasma is related to an increase in the energy content; despite this, minor or absent effects are seen in the variation of the density profile. This can be explained

if one consider the absence of any particle source inside the plasma in standard operating condition; the density in the discharge is almost completely determined by wall recycling, shifting the density source at the edge. Thus, even in presence of reduced stochasticity and conserved flux surfaces, the density profile remains almost flat [68, 69].

In the perspective of studying the behavior of density profile in presence of an internal density source, pellet injections have been performed. The multi-pellet injector of RFX-mod [70] produces pellets with a nominal mass of 1.5×10^{20} , 3×10^{20} and 5×10^{20} , with a injection velocity ranging from 450 m/s to 1200 m/s; the system comprehends a diagnostic setup for 3D trajectory tracing [71], and for the imaging of the plasmoid which forms around the pellet during its ablation.

Since pellets injection has been used mainly to study the particle transport during QSH, the injection was performed in such a way to permit the pellet to enter the island [72]: an external rotating reference was applied through the saddle coils system for the $m=1$, $n=-7$ mode [73]. With this setup, the island rotation can be controlled and reproduced, allowing the firing of the pellet at the most favourable value of the mode phase.

The overall process can be divided into two phases: the ablation, corresponding to the density increase, and a diffusion phase in which the density decreases again. In QSH discharges, a third, intermediate phase is present, whose lenght depends on the discharge type; it can last up to a few ms and is characterized by the presence of asymmetries in the density profile and temperature profile.

These asymmetries, peculiar of QSH states, are detected in the profile by the interferoter as well as by the main TS, as shown in Fig 4.9. The latter is able to detect both the cooling of the plasma regions crossed by the pellets and the local increase in density in the same regions; in particular, density measures with the edge TS rely on a cross calibration technique which will be discussed in the next chapter ([68]).

4.3.1 Effect on the edge profile of pellet injection

A way to study the pellet injection, as well as other transient events, with the two available TS diagnostics is to combine them shifting their timing by few ms and synchronizing them with such events, if those can be externally triggered. The result of such appraoch for pellet injection is shown in Fig. 4.10). In frame (g) the time marks of the Main and Edge TS with line integrated density from a core (blue full line) and edge (green dot line) chords during the injection is shown: the Main TS measures before the pellet injection (93.68ms, dash black line), while the Edge TS after 0.5 ms (dashed-dot red line). The edge temperature between $\rho=0.8$ and 0.9 drops down from 400eV to 200eV as the pellet starts being ablated, while the density passes from 2.8 to $4 \cdot 10^{19} m^{-3}$. In this case the pellet is not

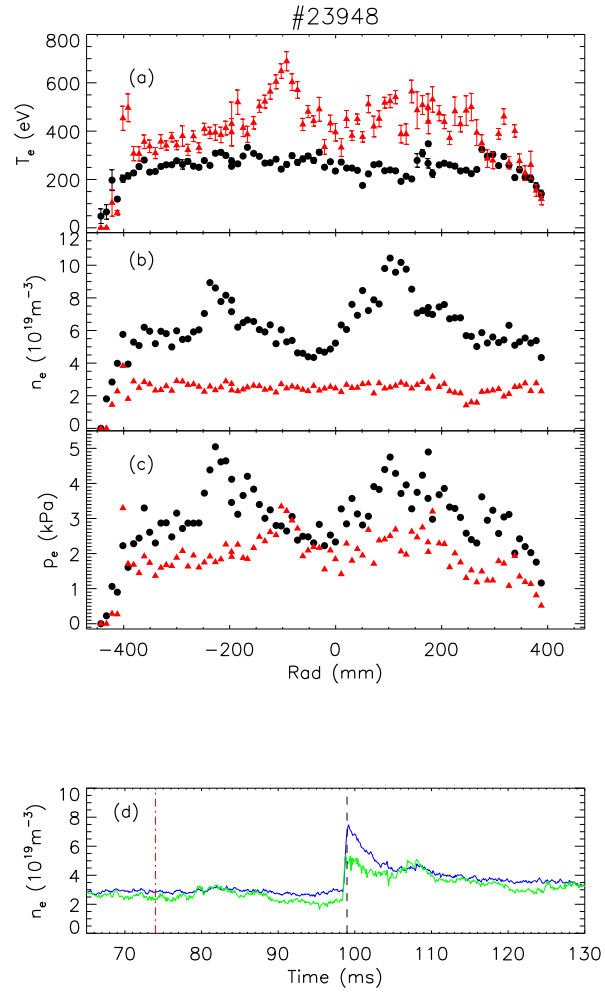


Figure 4.9: above, temperature, density and pressure from TS before (red) and after (black) the pellet injection; on the lower frame, the time evolution of density is plotted

yet completely ablated and the edge pressure profile is almost unvaried: this suggests that the confinement properties, at least in the first phases of ablation, at the edge are not degraded by the perturbing event.

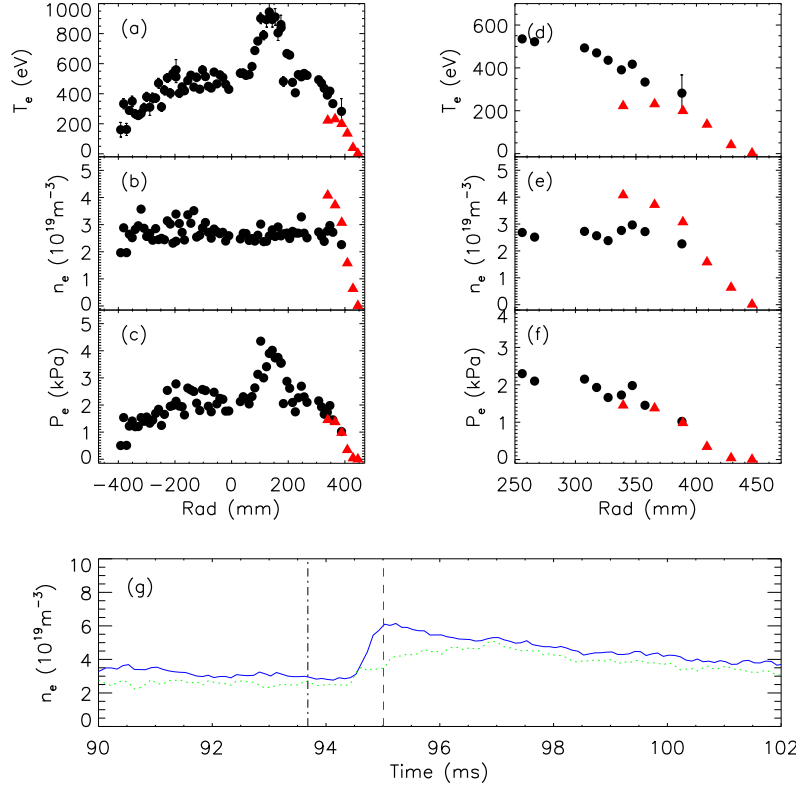


Figure 4.10: (a)-(c) T_e , n_e and P_e profiles before and after the pellet injection; (d)-(f) the core (full) and edge (dotted) line integrated density, and Main TS (dashed-dotted) and Edge TS (dashed) timings

4.4 Dynamo Relaxation Events

In chapter 1 the mechanism of poloidal current (and hence of toroidal flux) generation has been discussed as a result of a MHD dynamo mechanism. This process can proceed in a continuous way or as a result of a sequence of transient events, the so called Dynamo Relaxation Events (DRE) [74]. DRE events have been widely studied in the RFP community [75–77]; the common picture emerging from these studies is that the generation of toroidal flux through the non linear interaction of the tearing modes is a local, toroidally asymmetric phenomenon. Furthermore, if the modes are phase locked, the development of the flux perturbation and the phase locking [78] of MHD are

found to occur at the same toroidal position.

It is known that the occurrence of DREs results in cyclic loss of particles and energy confinement; the density and the radiation behavior indicates that the loss is particularly enhanced in the region affected by the wall locking of MHD modes, where the DRE deeply modifies the geometry of the plasma LCS, resulting in a strongly increased plasma-wall interaction.

DREs are clearly identified by the modes dynamics as well as by sawtooth crashes in the reversal parameter F . The $m=1$ modes are destabilized following a cascade process that starts from the innermost resonant harmonics and propagates to the outer ones; the amplitudes of outer modes peaks for a transient of the order of 1ms, while, almost simultaneously, the $m=0$ modes are involved displaying a similar behavior. Contemporarily, the F parameter crashes ($\Delta F \approx 0.1$) and recovers the initial value on the same timescales of about 1 ms.

During a DRE the electron density (measured by interferometer) generally increases, following somehow in a negative way the evolution of F parameter; however, there are cases in which a density peaking is not observed; the density growth, if observed, is not toroidally symmetric, being major around the position of mode locking: again, an influx due to the local increase in the plasma wall interaction is supposed to play a substantial role.

4.4.1 Modification in the profile during a DRE

The combination of main and edge TS can also be applied to the characterization of DREs events with the inconvenient that in this case the statistic is poorer, due to the lack of synchronization of the two TS lasers with this event. Fig. 4.11 reports an example of edge profiles modification during a DRE. The Main TS was fired few ms before the dynamo relaxation while the Edge TS occurred exactly at the beginning of a DRE. The temperature is almost unvaried in this early phase of the relaxation, while the density $\rho = 0.8 - 0.9$ is reduced from about 3.5 to $2 \cdot 10^{19} m^{-3}$ in the region. This change can be interpreted considering the toroidal position of the $m=1$ mode locking (LM) at the Edge TS location [78] and on the basis of DRE effects in terms of particle losses.

In a toroidal region of tens of degrees around the LM position, the density is unvaried or even decreases during the crash: several magnetic lines from the core are diverted towards the wall through "holes" which open at the LM position.

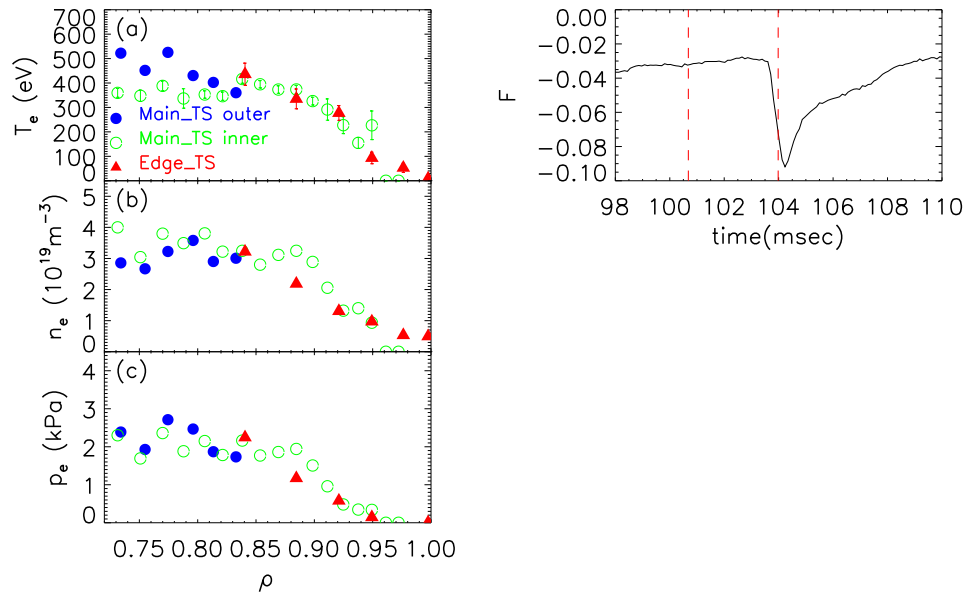


Figure 4.11: Edge T_e , n_e and P_e profiles before (Main TS) and at the beginning (Edge TS) of the DRE; aside, the correspondent plot of the reversal parameter F

Chapter 5

Laser Blow off

5.1 Laser Blow off principle

Understanding the impurity behavior is a critical issue in the determination of a reactor performance. Impurities in the plasma core enhance radiation losses and plasma dilution with deleterious consequences on fusion reactivity. These consequence worsen for high-Z impurities: in high confinement regimes of tokamak plasmas, impurities accumulate in the plasma centre with risk of disruption.

To determine the impurity transport parameters (diffusion coefficient and pinch velocity) in different plasma regimes the experimental emission pattern (line emission time evolution, SXR and radiative power profiles and time evolutions) is best reproduced with an impurity transport 1-dimensional collisional radiative model [79, 80]. Transient experiments, i.e. gas puffing [81] and laser blow off [82] are suitable to discriminate the diffusive term and the pinch velocity in the impurity flux expression and then to fully characterize impurity radial transport. In RFX-mod first LBO experiments with Ni were performed in 2008-2009; the technique will be first described and the obtained results presented.

LBO technique is intended as a weakly perturbative tool; the level of perturbation is low since the number of injected particles lies in the range $10^{17} - 10^{19}$ depending on the geometry in use; in normal conditions effects of local plasma cooling (due to enhanced radiative losses) are not important.

Impurities (typically metals, but also carbon or silicon) are deposited in films of few μm over glass or quartz slides acting as substrates; these slides are mounted away from the plasma, looking at it with their metallized faces. Material injection is performed via laser ablation: a laser beam is directed to the slide and deposits its energy on the metal film which is vaporized and whose particles travels ballistically to the plasma, with speeds of the order of a few km/s. The laser pulse should be fast enough to cause vaporization instead of melting: for this purpose, Q-switched laser are almost universally

used.

The laser energy density onto the target has to be the best compromise between an high value required to ablate all the material and a low threshold to protect the substrate and to minimize the ionization of injected particles (ions would be lost being deflected before to penetrate the plasma by the magnetic field in the injection pipe).

Once the injection is performed impurities will be traced inside the plasma following their emission: in particular VUV and XUV spectrometers record specific line brightnesses time evolutions, SXR multichord diagnostic allow to reconstruct [83] the Bremsstrahlung radiation profile emitted when ionized injected impurities interact with the surrounding plasma and bolometers measured the total radiated power time behaviour.

In particular, the spectrometers used in RFX mod are a VUV SPRED instrument and a XUV SOXMOS one. The SPRED [84] is grazing incidence spectrograph, covering the spectral range 100-1100 Å with a spectral resolutions of 2 Å and a sampling frequency up to 500 Hz. The SOXMOS [85] instrument, which is an extreme grazing incidence spectrograph, covers a (variable) spectral range of about 20-40 Å in the range 10-360 Å with a 600g/mm grating; it is capable of 0.2 Å resolution with a maximal time resolution of 3 ms.

Finally, main TS spectrometers, thanks to the position of their line of sight, are able to detect visible and NIR emission coming from the ablation process and from the first phases of the injection.

5.2 The laser blow off system on RFX-mod

5.2.1 Layout

The system installed in RFX-mod encountered a deep evolution during its commissioning; the first setup was built around a 63mm cross piece and relied on a bellow sealed manipulator, capable of axial translation of the target holder. The assembly was mounted on a ventral port of the machine at the main TS toroidal position, on one of the two off-axis pipes (being the central one, in principle more attractive, occupied by the Z_{eff} diagnostic). Actually, the pipe in use is shared with a triple Langmuir probe, which occupies part of the available section.

The laser in use the ruby laser of the Edge TS diagnostic, described in the previous chapter; its beam is intercepted and deviated with a group of 5 mirrors under the floor level of the experiment hall to reach the ventral pipe. Before the vacuum window, it is focused by a lens in order to obtain a spot of proper size (some mm) on the glass slide. The target is at a distance of ≈ 130 from the vacuum window and different lens with focal lengths varying between 100 and 250 mm were tried.

The target (dimensions 20x90 mm) can be remotely translated; to monitor the ablation the target is seen by a commercial CCD camera mounted behind the last mirror and looking at the target through the focusing lens.

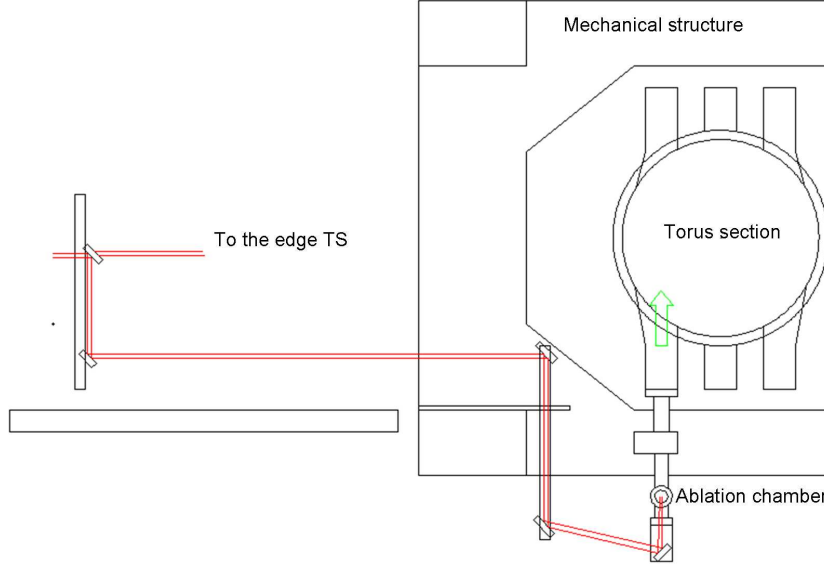


Figure 5.1: sketch of the laser beam path to LBO system

5.2.2 Commissioning

Energy modulation

As already mentioned, the optimal energy density onto the target has to be carefully determined; typical values reported are in the range 0.1 - 0.4 J/mm^2 [86–88]. Before mounting the system on the machine, atmospheric ablation tests were performed, identifying an ablation threshold of about 1.8J for 5-6mm spots. When the target chamber was placed on the machine, ablation was found to be incomplete, due to the variation in the laser pattern arising in far field and, likely, to losses on the mirrors greater than nominal values (estimated at 10 % for the 5 mirrors on the laser path). Moreover, the foil was detached but not completely vaporized: parts of foils have been found inside the chamber after operation.

During these first tests on the machine, the laser beam was splitted with a 25-75 %, 45 incidence beamsplitter, so to operate with about 6-7 J on the edge TS and 2 for the LBO. As already noted, the sapphire wedge on the head of the edge TS isn't able to tolerate more than 4 J, while 2J proved to be insufficient for ablation: both systems had to be operated in the 3 J range, leading to the substitution of the beamsplitter with a mobile mirror;

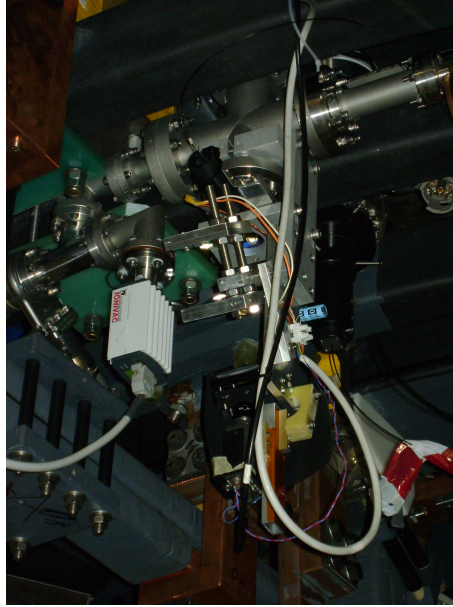


Figure 5.2: picture of the ablation chamber assembly, mounted on the machine

another 50-50 % beamsplitter has been afterwards purchased and mounted; the definitive working range for the LBO system is 2.5-3J.

Correction of the laser path

A way to correct the beam profile is the use of conical shaped lens (axicons): two of these pieces, mounted with their vertex facing each other, are able to upset the pattern of a laser beam respect to beam axis, so, in principle, to pass from a hollow radial profile to a centrally peaked one (fig.5.3). An alternative is the vacuum imaging of a mm sized pinhole, in a similar way to what happens in the edge TS. The latter solution could not be implemented, since it would have lead to excessive complication and costs, requiring a vacuum pumped pipe, placed on the beam path before the last mirror and the lens.

Axicons where bench tested with photographic paper and with the metal targets; after that, they were mounted on the machine just before the last mirror, on a rotating arm in order to permit their quick exclusion or insertion.

The alignement of the axicons with the beam and between themselves is particularly critical, much more than in an optical system relying on spherical elements. To avoid the damaging of the second elements on its axis, where is concentrated all the external part of the incoming beam, it is necessary to place a carefully dimensioned diaphragm before the first elements, to cut away such external area of the beam.

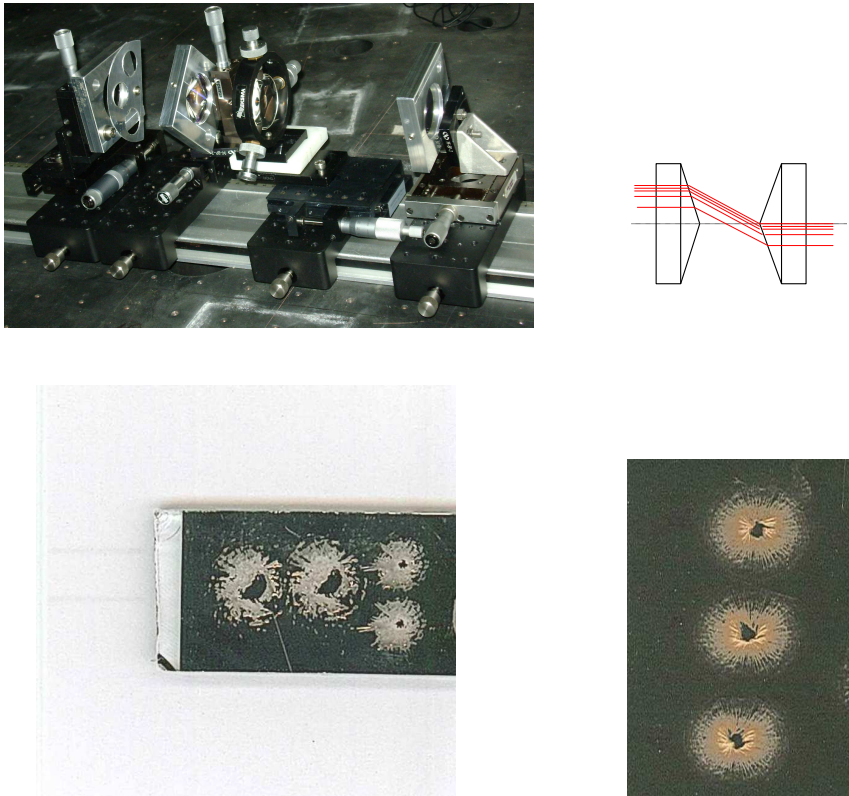


Figure 5.3: Top, picture of axicon testing setup and their working principle; down, spots obtained of photographic paper and on the target; the central dark can't be eliminated

As it is evident from figure 5.3, the use of axicons does not lead to a substantial improvement of the ablation pattern, which maintains a central dark spot, though reduced. The latter corresponds to the "shadow" of the second axicon vertex: it has to be noted that the dimensions of the dark spot increases with the length of the optical path the laser beam covers before hitting the target. Another feature of the spots obtained with the axicons is the rayed pattern, which is probably due to surface imperfections in the pieces. Axicons were seldom used: most injections were performed without their utilization, because of the risk of optical damage due to misalignments, in an environment characterized by strong mechanical vibrations. The final solution was their exclusion from the beam, maintaining a hollow energy profile; the problem of partial ablation in the center of spot was solved reducing its dimension from ≈ 8 to $5 \div 6$ mm. Smaller spots size resulted in smaller injected nickel but also in the decrease of the load on the glass slide; in case that creeps develop, they remain localised.

5.2.3 Laboratory tests

Two sessions of bench test were performed on the laser blow-off: the first one before mounting the system on the machine was intended essentially to verify the divergence of the ablated plume and its speed for standard values of energies. The plume (or better, its envelope: fig 5.4) has been imaged with a commercial camera, manually triggered and protected with a filter for the ruby laser line. The jet velocity was measured acquiring the waveforms of a photodiode looking, from a perpendicular direction, at points in front of the target through a convergent lens [89]. Different distances from the glass slide correspond to different positions of the detector in the lens focal plane. Velocities reported in the graphs (fig.5.5) refers to the positions of the peak of density, interpreted as the peak of the photodiode signal.

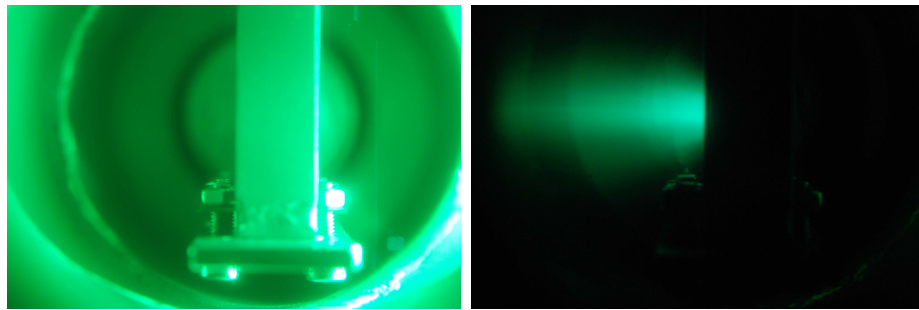


Figure 5.4: long exposure picture of the ablation plume obtained with a commercial camera; the green colour is due to the filter used to exclude the ruby laser line

Large divergences of the beam had to be expected; in fact, the ablation process can be thought as the formation of hot bubble, generated in few ns

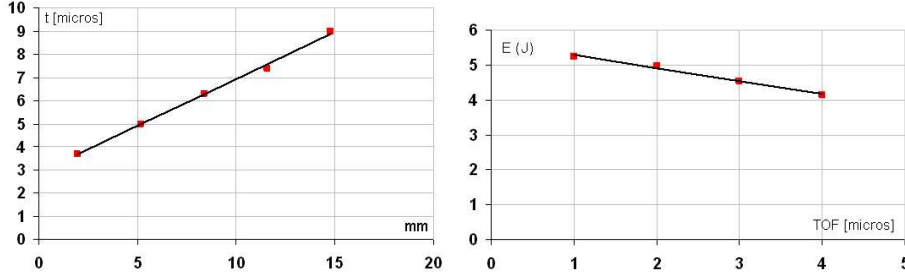


Figure 5.5: left, plot of the jet maximal brightness as a function of time; the resulting speed is; right, dependence of the jet time of flight at a given position as a function of the laser energy: the dependence on E is weak

by the laser pulse, which then expands in the vacuum: thermalization takes place in the very first moments, when the density is sufficient. The speed v_i of each particles thus can be written as:

$$v_i = v_{therm}^i + v_{group}$$

where v_{therm} and v_{group} are on the same order of magnitude and their ratio depends on the details the bubble thermalization. This ratio can be calculated also looking to the waveforms recored a given distance (i.e with the photodiode method), in particular, broader peaks in the signal correspond to higher v_{therm}/v_{group} values. Actually, the waveform -see fig. 5.7- can be interpreted as the distribution function of the particles with respect to the variable $1/v$.

Completed the commissioning and installed the system on the machine, in most cases not enough Ni entered in the plasma; this suggested to perform a second series of tests to identify possible causes of nickel depletion along the path to the vessel. The most likely explanation concerned the production of charged particles during the ablation process: actually, produced ions are lost since they are suddenly deflected by the magnetic field, whith curvature radii in the cm range.

Another possible cause of loss of Ni particles along the path can be identified in the residual gas pressure inside the pipe ($10^{-4} - 10^{-3} mbar$ during the discharge, corresponding to mean free paths of the order of $10^{-1} m$).

Presence of neutral gas was supposed to play a role also because, inside the pipe, lines of neutral nickel persisted for some ms, a time longer with respect to what could be supposed on the basis of a ballistic proagation of particles. The last measure was obtained using a spectrometer, coupled with an aptical fiber and a telescope to the vacuum window of the LBO, in such a way to look beside the target into the pipe.

The last possible cause of insufficient Ni influow could be the excessive distance from the plasma, since the solid angle under which the plasma is

seen is smaller; however, this problem could be hardly solved, since it is related to mechanical constraints of the machine.

A second test facility was built with different purposes:

1. quantify the presence of ionic species via spectroscopic analysis of the ablated material
2. verify the Ni speed values on longer distances (the first test was performed in the mm distance range)
3. check directly if the application of an external magnetic field to the first part on Ni path could modify or suppress the flux of ablated particles.
4. verify how the presence of residual gas can modify the speed or the distance covered by the ablated material

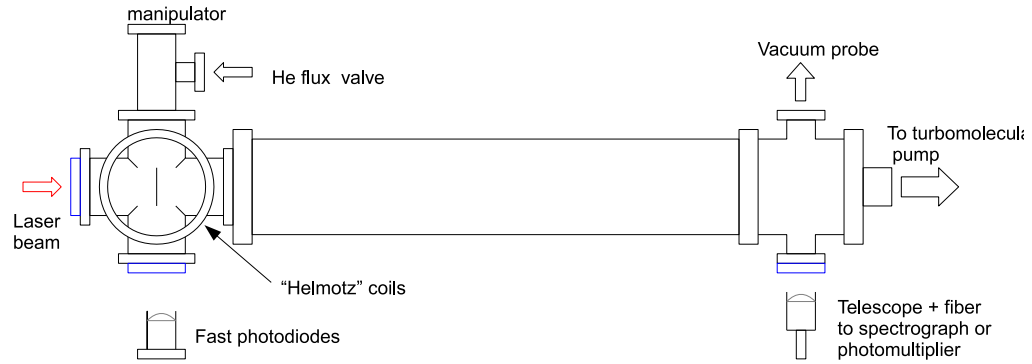


Figure 5.6: sketch of the facility used in the second session of bench test

The LBO ablation chamber has been connected to a metal pipe of 1 m length, having on the other side 2 traverse accesses and the connection to the vacuum pumps; the pipe was fluxed with helium (hydrogen was excluded for security reasons) fed in one side and pumped from the other; the gas pressure was monitored at the pumping side. Around the cross-piece, in

the area where ablation take places, were positioned two Helmotz-like coils, dimensioned to produce an axial field up to 50 mT, comparable to the field level under the machine, where LBO is mounted (fig.5.6).

The diagnostic setup consisted of a spectrograph operating in the visible range (the same used for the measures in the RFX-mod port) to discriminate lines from Ni^0 and Ni^+ . Moreover, a photomultiplier was coupled to the apertures on the dead end of the pipe with a optical fibers and a telescope; their signals were acquired by an oscilloscope. On the side of the tube containing the target, another telescope was used together with a couple of fast photodiodes, to get information on the plume propagation in the first centimeters. This arrangement, with two photodiodes in the focal plan of the telescope, is very similar to the one which was used for velocity measures during the first test session; the use of two detectors permits to measure the particles speed in within a single shot [89].

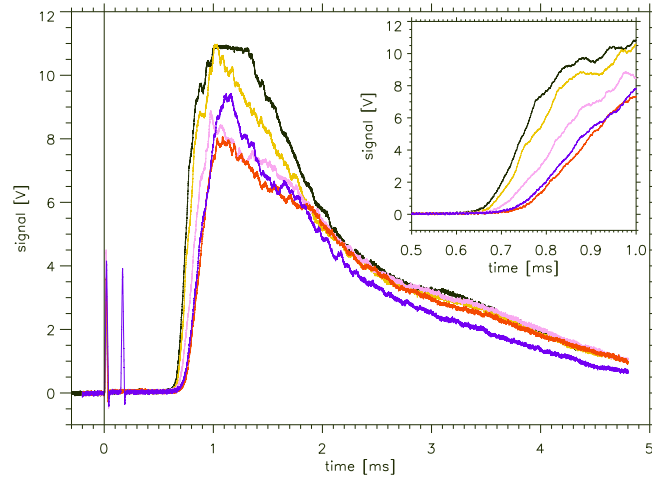


Figure 5.7: waveforms recorded by the photomultiplier with density varying from $2 \cdot 10^{-4}$ to 10^{-3} mbar; while the curve height decreases slowly with the increase of density, no influence has been found on the jet speed (see the box showing the times of details of wave rise)

The spectrometer did not trace any expected Ni line (Ni I at 5035 Å; Ni II at 4992 Å), meaning that the interaction with background gas was not able to ionise and excite the Ni. While no useful information came from the fast photodiodes, the photomultiplier signals were clearly related to the passage of a wavefront, whose emission is likely to be continuum. The jet speed, calculated from the lasertime to the start of the signal peak, was found to be related to the Ni film thickness, resulting 1.4 km/s for a 2 μm film and 2.8 km/s for a 5 μm one. Waveforms seen by the photomultipliers didn't show any variations in height or shape, when the external magnetic field was switched on.

Raising the pressure until values of 10^{-3} mbar the height of the signal was affected only by minor variations (fig.5.7), indicating that the interaction with background gas is more complicated than expected [90], either that a relevant part of the injected material could consist of droplets instead of single particles.

5.2.4 Final setup

No direct evidence of magnetic field and pressure influence was found during the test, however, to exploit an higher value of the solid angle of injection. The latter is defined as the solid angle of plasma seen by the target and depends on the distance from the plasma and on the pipe shape (especially on its section at the intersection with the torus). The decision to modify the ablation chamber relied also on other consideration, such as the possibility to work in a lower magnetic field environment (also to avoid problems with the manipulator motor) and to keep as short as possible the jet path.

The cross-piece was substituted with a custom built one, 100 mm of diameter, and moved upper the transformer coils level; a wider chamber allowed the use of drum loader for the targets, that can be changed without vacuum interruptions, simply rotating the drum (the manipulator had to be changed to permit this further degree of freedom); the use of a drum permits to gain other centimeters (the drum radius) in the distance to the plasma, respect to a target on the cross-piece axis

Since the spot size is of the order of $5 \div 6$ mm and the target width is 20mm, more spot rows can be performed on the same target; multiple rows can be obtained rotating the drum to maintain the spot centered on the pipe axis, or modifying the laser direction by acting on the last mirror. The last method has the advantage to maintain the target perpendicular to the pipe axis, so to direct in a better way the ablated plume.

In the new setup, the laser is focused before the target; this has the advantage of avoiding dangerous focusing spots in the backreflections: the target itself is built as a metallic mirror and behaves coherently; actually, a long distance between the last mirror and the focusing lens is required to avoid hot spots on the mirror itself. It has to be noticed that this arrangement doesn't improve the beam profile, since there is no diffractive elements at the focal point; on the other hand, the disadvantage is in the imaging, since the camera focus now cannot be adjusted properly on the target. In fact, if the lens used for the beam focusing has a shorter focal length and the camera still looks through the lens, the image plane lays always in front of the camera sensor.

Hence the necessity to use a different arrangement, built placing a mirror before the window to allow a direct view and leave enough space for laser passage. Unfortunately, this solution exposes the camera to damage risks due to laser reflections on the target, and thus has to be changed as will be

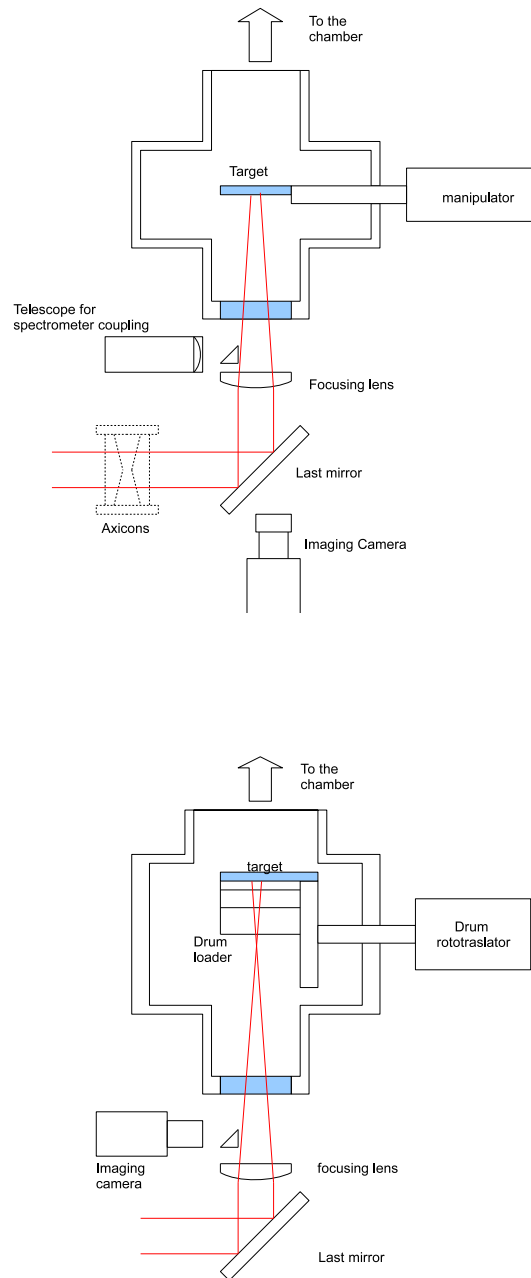


Figure 5.8: sketch of the changes done in the arrangement of the ablation chamber; up the first attempt and, down, the final setup

later discussed.

Different sets of targets, with Nickel films with thickness of 2 and 5 μm have been purchased. 5 μm targets finally proved to allow a sufficient Ni quantity to reach the plasma. Slides are made of glass (instead of quartz, which has a higher radiation damage threshold) to prevent the peeling of the Ni from the substrate. The spot size is kept in the range of 6-8 mm, which with a target thickness of 5 μm proved to inject sufficient material, smaller sizes (1-3 mm) have been tried without success; the laser energy is maintained around 3J; even with these values, glass targets are sometimes locally crepted, the powder generated falling on the vacuum window.

5.2.5 Acquired signals in case of succesful injection

The success in the tracing of Ni inside the plasma depends primarily on the density: it does not influence directly the nickel injection; however, at high n it is more difficult to detect the Ni presence, since SXR and bolometric signals worsen or saturate, making sometimes impossible to follow the enhancement of emissivity. Moreover, high density discharges are MH plasmas in most cases, and hence less attractive for the transport characterization in the plasma core. In fact, as will be discussed in chapter 5, the magnetic spectra can deeply influence the behavior of Ni in the plasma. QSH are characterized by a barrier near the edge wich opposes Ni diffusion in the inward direction; this barrier on the velocity is supposed to be still present in MH shot, while much weaker and less extended

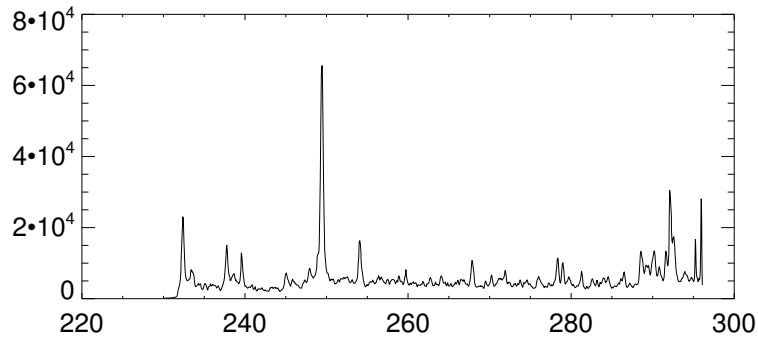


Figure 5.9: spectrum obtained by the SOXMOS spectrometer showing the two lines of Ni XVIII and XVII respectively at 249.2 and 292 Å

Evidences of Ni presence are obtained in various forms by the instruments previously described:

1. SPRED and SOXMOS spectrometers identify and follow the radiation of two Ni lines which are excited in environments of several hundreds

eV: these lines lie at 249.2 Å (Ni XVIII) and 292 Å (Ni XVII) - fig. 5.9. Moreover, at least five lines can be identified in the range 145-164 Å, belonging to lower ionization states (from Ni XI to Ni XIV)

2. Tomographic bolometry (fig.5.10, [91]) shows the presence of a thick radiation ring which localized at the edge and lasting for timescales of few ms. As a comparison, in normal discharges the radiation layer is much thinner and closer to the wall.

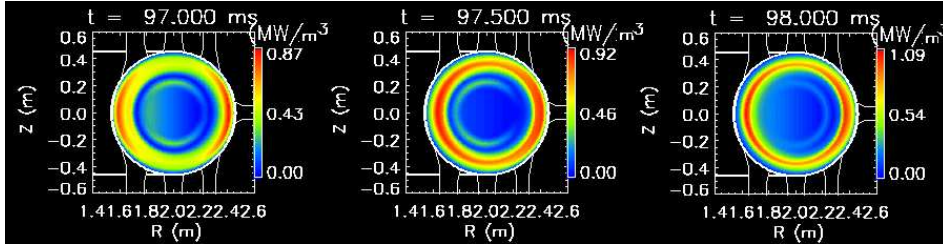


Figure 5.10: radiation ring detected by bolometric tomography after Ni injection

3. The signals of SXR detectors display step peaks in the emissivity which start from the injection and then follow the core temperature oscillations (which are closely connected to the QSH cycles); the emission lasts for tenths of ms before vanishing (fig 5.12) ¹.
4. Some spatial channels of the main TS are able to trace time behavior of Ni emission at the very edge, as it is entering the plasma. In fact, the injection pipe lies in the image field of some scattering volumes; the pipe entrance is out of the collection optics focus: the fibers collect the radiation coming from a $\approx 5 - 8$ cm wide area at the wall level. There are some differences in the signal shape among the channels looking directly inside the pipe and the ones which see only the pipe exit or the chamber wall close to the pipe intersection. Data on the influx time evolution are boundary conditions for the 1D collisional radiative model.

The radiation coming from inside the pipe shows (fig.5.11) a first narrow peak (the laser pulse) followed a first weak thermal tail; the latter comes from the ablation process and lasts for some hundreds of μs . Then a wide peak develops corresponding to Ni approaching and entrance in the chamber (low energy transition or brehmstrahlung processes are involved, since the

¹ Concerning Xray effects, it should be remember the behavior on DF temperature measures, which also last for several ms; this happens because the temperature is measured sampling the brehmstrahlung spectrum, which depends on the temperature, with two different high-pass filters. Ni lines laying in the lower part of the spectrum causes an overestimation of its integral and then an underestimation of T_e

emission lies in the NIR range). Fibers which have an indirect line of sight can detect only this second peak, which lasts for 1-2 ms, while fibers looking at the pipe neighbourhoods sees a delayed ($\approx 1\text{ms}$) spike only if the injection is successful (tracing Ni poloidal diffusion)².

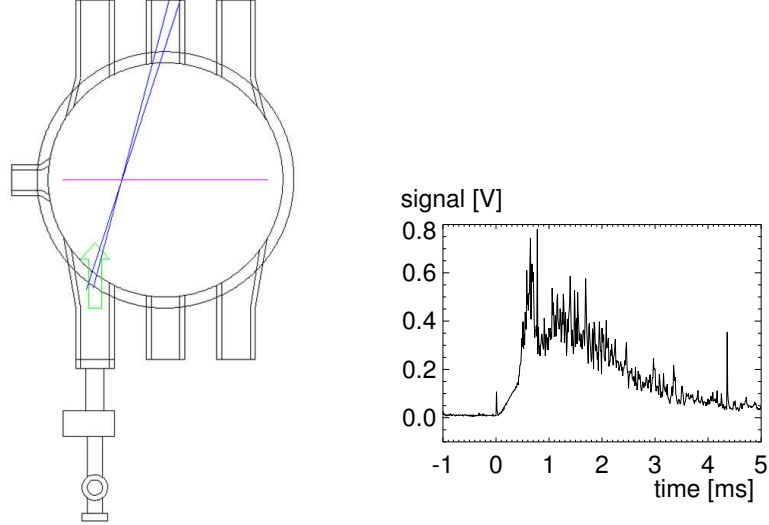


Figure 5.11: left, sketch of the Main TS lines of sight and, right, signal coming from the DC challes of a fiber looking into the injection pipe: laser peak is followed by a wide peak corresponding to Ni entrance in the chamber

5.2.6 Upgrades

The main upgrade for the systems will be, as discussed, the adoption of a new drum with dedicate holders for each target and and the change in the imaging system. The adoption of metallic holders has been chosen also to prevent breaking of the glass slides at the moment of target insertion.

The modification in the target imaging system implies the adoption of a mobile mirror placed in front of the focusing lens, which can be inserted to esclude the laser beam and to allow the camera to see the target; the described setup corresponds to a shorter optic path between the camera and the focusing lens (there aren't problems of back reflections) and the focal leght of the CCD camera can be easily corrected placing a divergent element in front of it.

Another possible upgrade, not yet planned, is the mounting of a slanting glass slide after the window, on the vacuum side, to intercept and collect

²These data rely on the low speed acquisition system of the main TS; this is normally employed to monitor the level of plasma light and it is DC coupled. to recognize all the described features, the acquisition has to be limited to few channels respect to normal operations, being limited the overlall bandwith of the electronics

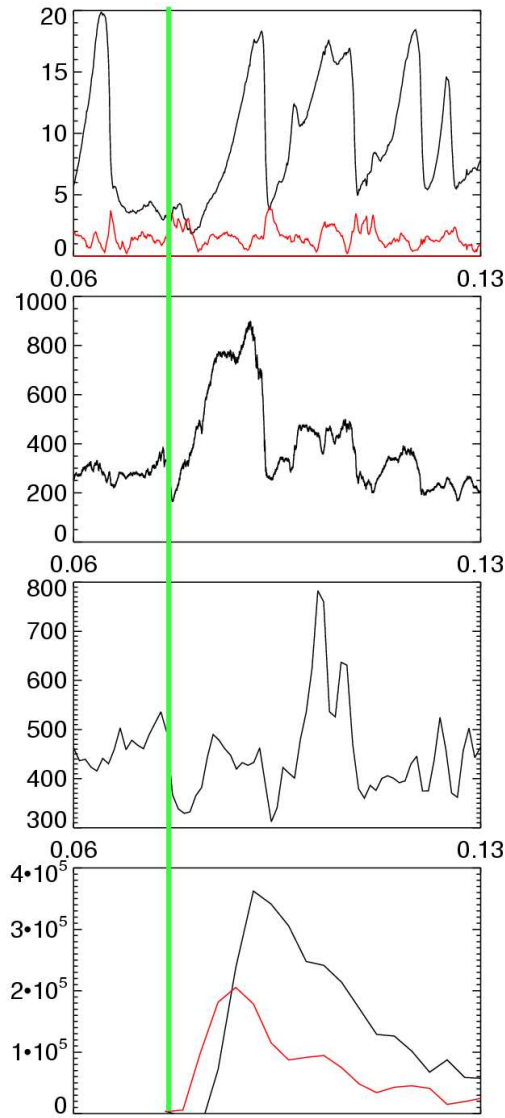


Figure 5.12: Example of data coming from an LBO injection: from the top, magnetic spectrum, SXR brightness, core temperature measured with double filter spectrometer and evolution of Ni XVII (red) and Ni XVIII lines

the dust and the glass powder which otherwise fall on the window itself; the latter has to be periodically unmounted and cleaned, since the presence of gall fragments can lead to dangerous thermal loads on the window when they are crossed by the laser beam.

Chapter 6

Transport in RFP helical states: RFX-mod

The helical states of RFPs have been introduced in the first chapter [13,92]. In this chapter these states will be analyzed and characterized with particular respect to their thermal characteristics and confinement properties. The TS systems are the two main diagnostics providing the measure of T_e profile in RFX-mod. Furthermore T_e is measured also by means of DSXC multichord spectrometer and THB. This variety of diagnostics allows a reconstruction of the T_e profile so accurate that it can be used to study the shape of the magnetic surfaces in the helical states.

6.1 Examples of electron temperature profiles in helical states

Magnetic QSH states are generally characterized by the presence of temperature structures in the core, where the profile is almost flat in MH states. The first T_e structures observed in RFX-mod have been narrow thermal structures radially localised in correspondence of magnetic islands, the so called "thermal island". With the increase of the plasma current in the machine other types of thermal structures were measured. The most recent observed are wide structures, extending all over the plasma core, structures which are still distinguishable from the edge gradients. Besides these two profile classes, there is a quite rich phenomenology of profiles showing intermediate features.

The two types of profiles are shown in fig 6.1. These two plots enlighten the typical features of the T_e profile in helical states: the edge gradients, an intermediate plateau starting at the end of the edge gradient ("knee" in the figure 6.1), an internal structure delimited by the core gradients and, in the case of SHAx, a central plateau.

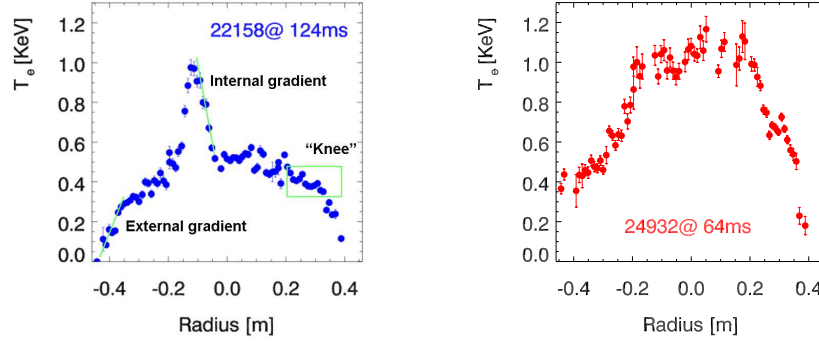


Figure 6.1: Main TS profile of a DAX (left) and of a SHAx (right) case; in the plot of the DAX case the main features of T_e profiles are enlightened

These properties of the T_e profiles are related to a variation in the magnetic field topology: both the shape of structure and its width are determined by the helical magnetic field; fig 6.2 shows a Poincare' plot obtained with the field line tracing code ORBIT [16] for a thermal island and for a wide T_e structure, together with the corresponding temperature profiles. The size of the enhanced temperature region is closely correlated to the extent of the helical magnetic structure.

The DAX T_e [92] profile is associated to a magnetic topology characterized by the presence of a magnetic island where both a helical axis (the island O-point) and the main magnetic axis are present. On the other hand, the wide thermal structures occur in magnetic topologies in which only one magnetic axis survives (Single Helical Axis - SHAx). It has been shown that in SHAx the bigger dimension of the magnetic structure is linked with the phenomenon of the expulsion of separatrix. These profiles are easily measured when the helical structure orientation on the thomson cross section is favourable, i.e. the helical axis is either around $\theta = 0$ or $\theta = \pi$, while for different angles the profile shape may vary.

The transition from a DAX state to a SHAx one is related to the increase of the dominant mode amplitude and to decrease of the secondary ones; hence a good indicator of the magnetic spectrum is the N_S parameter (see also chapter 1):

$$N_S = \sum_i (\tilde{b}_i^2 / \sum_j \tilde{b}_j^2);$$

where $\tilde{b}_i$ is the amplitude of the toroidal component of the $m=1$ mode whose toroidal number is i . This quantity can be used to run a statistical analysis on several T_e profiles measured in a wide set of discharges: they have been classified to be MH for $N_s > 3$, DAX for $1.6 < N_s < 3$ and SHAx

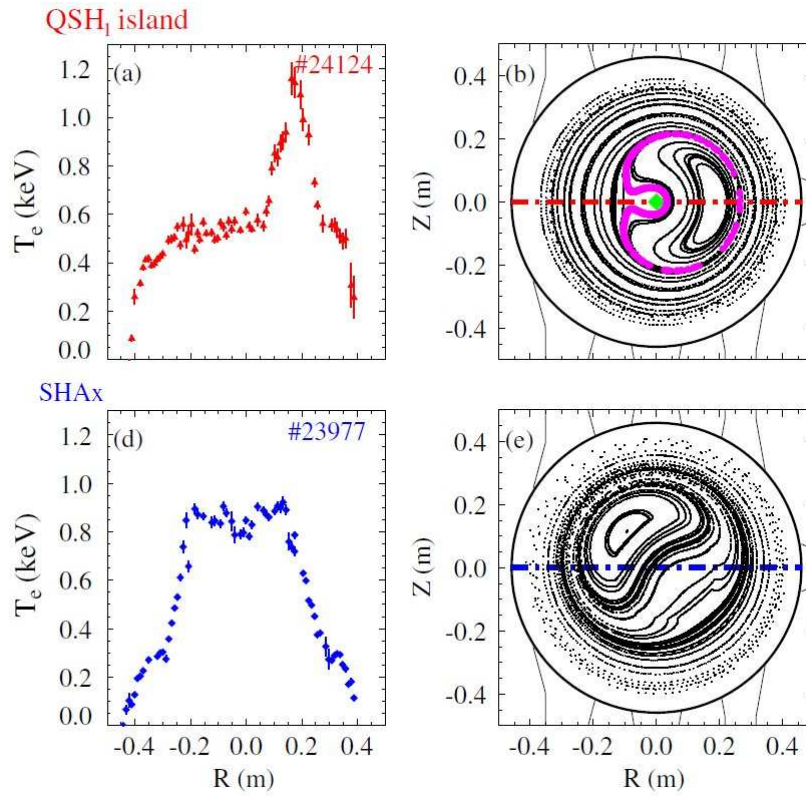


Figure 6.2: Main Ts profiles and related ORBIT Poicare' plots of a DAX and a SHAx example [68]

for $N_s < 1.6$. The results are shown in fig. 6.3. The increase in the core temperature due to the formation of a central structure can be highlighted by distinguishing the points of the data set according to their N_s - fig. 6.4- and plotting them as a function of the plasma current, for a given density interval. The same increase is observed when the data are plotted versus the I/N parameter. Therefore, even though the data are rather scattered (due to the different experimental conditions under which they were measured) an evident N_s dependence occurs and SHAx states are characterised by the highest electron temperature.

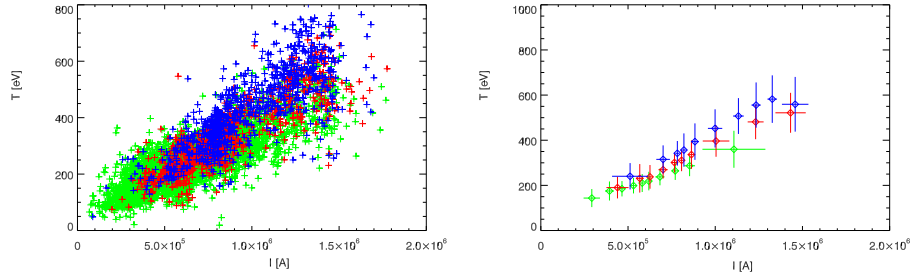


Figure 6.3: Core temperature (averaged on $r = \pm 0.1m$) as a function of the plasma current (left). The same points averaged for current intervals (right). In both plots MH are plotted in green, DAX in red and SHAx in blue. The data points relate to discharges whose I/N parameter is in the range $3e^{-14} < I/N < 5e^{-14} A/m^{-3}$.

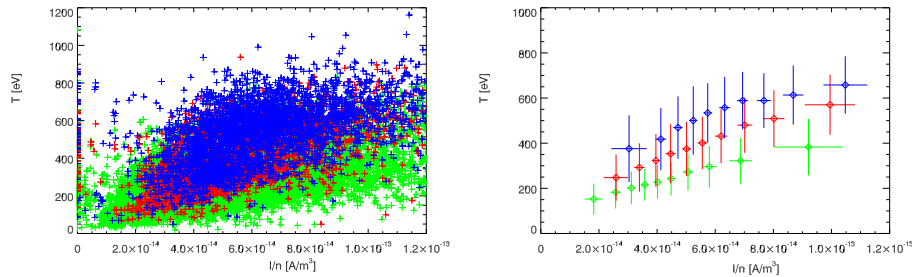


Figure 6.4: Core temperature (averaged on $r = \pm 0.1m$) as a function of the I/N parameter (left). The same points averaged for I/N intervals (right). In both plots MH are plotted in green, DAX in red and SHAx in blue. In this case the differences between the various classes is clear.

6.2 Core electron temperature and pressure

6.2.1 Statistical characterization: ensemble averaged 2D profiles

When the magnetic topology is helically shaped, measuring a profile along a diameter gives only a limited amount of informations. A complete 2D reconstruction of the plasma cross-section can only be performed by the SXR tomography [83]. Since the SXR emissivity E depends on several plasma parameters ($E \propto Z_{eff} n_e^2 T_e^{\approx 1/2}$) it is not possible to use it as a simple indication of the electron temperature.

A two dimensional characterization of the temperature has yet been performed [68], exploiting the ability of the active control system of RFX to determine the phase of the dominant mode, i.e the position of the helical axis in the poloidal section at the TS toroidal angle. In particular, 15 cases for each of the two thermal structure types have been sampled with the TS line of sight intercepting the island at different angles with respect to the O-point position. To perform the scan, an external reference for the $m=1, n=-7$ phase was applied in order to determine an uniform rotation of the island [68]; on the other side, the trigger time of the TS system was varied in order to measure T_e along diameters with different angles respect to the O-point of the island. The shots were performed in the same current conditions, controlling the density to maintain I/N constant. The points have been used to reconstruct the temperature on a plasma poloidal section; the DAX ensemble averaged profile displays a temperature island with a poloidal extent $\approx \pi$, whereas for the SHAx cases there's a wide off-axis structure which includes the plasma center (fig 6.5).

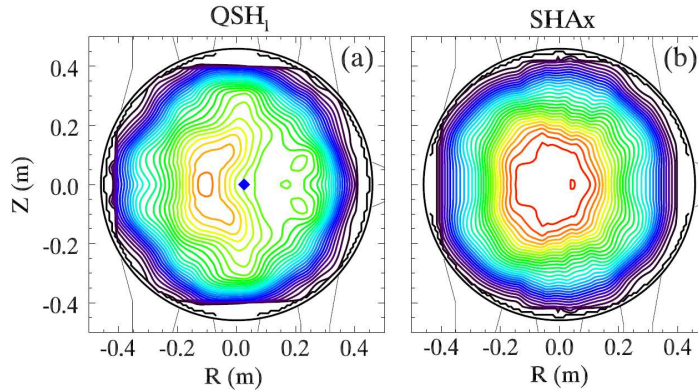


Figure 6.5: 2D maps of the temperature obtained with an ensemble average of temperature profiles [68]

6.2.2 Beyond ensemble averaging: helical remapping for single temperature and pressure profile

The results of the previous section indicate the temperature has a topology dependence on the $n=7$ mode. but do not directly allow to determine the 2D T_e profile for each discharge. It has been shown [17, 92] that T_e can be assumed constant on helical flux surfaces obtained by considering the equilibrium magnetic field and the measured $n=7$ component only. Given the magnetic topology reconstructed in this way, each TS measurement can be associated to an helical flux tube: such a procedure is defined "re-mapping".

Therefore the 2D profile can be obtained on the basis of the magnetic reconstruction rather than on multi-shot ensembles obtained with the scanning of the island poloidal position. In particular, in the following, not only temperature but also density has been remapped on helical surfaces in order to analyse pressure profiles; this remapping will also be used in sect. 6.4 for electron energy transport characterization

The re-mapping of temperature and density on helical coordinates is performed by using several diagnostics at different toroidal positions; a simple axisymmetric re-mapping cannot in fact be used for such purpose since isothermal plasma surfaces in the core region are helical during QSH. In order to succeed in the remapping a helical coordinate system need to be established. The starting point is the definition of the helical flux [92] X : $X = m\Psi + nF$ where $\Psi(r, \theta, \phi) = \Psi_0(r) + \psi^{m,n}(r)e^{i(m\theta-n\phi)}$ and $F(r, \theta, \phi) = F_0(r) + f^{m,n}(r)e^{i(m\theta-n\phi)}$. $\Psi_0(r)$ and $F_0(r)$ are respectively the poloidal and toroidal equilibrium fluxes [93], while $\psi^{m,n}(r)e^{i(m\theta-n\phi)}$ and $f^{m,n}(r)e^{i(m\theta-n\phi)}$ are respectively the poloidal and the toroidal fluxes of the m, n perturbation (in this case $m=1, n=-7$). From the helical flux function it is possible to define the effective radius

$$\rho = \sqrt{X/X_w}$$

where X_w is the value of helical flux defined at the wall radius. The usefulness of such an approach is illustrated in fig. 6.6; in particular, the internal gradients of the TS profile shown in the figure have a different radial extent, but they collapse once they are plotted versus the effective radius ρ .

T_e re-mapping: diagnostics setup

The combination of various diagnostics is a mean to overcome limits in the time/spatial resolution and in the radial coverage of each system. An accurate description of the density and temperature profile has been obtained integrating the data of the Main and Edge TS with the measurements of SXR multichord double filters spectrometer for core T_e , and with the available measurements of Thermal Helium Beam (see chapter 4) for edge temperature and density.

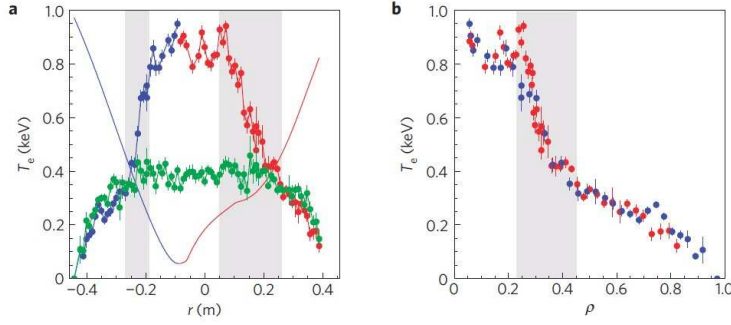


Figure 6.6: left, TS profiles plotted versus geometric coordinate r . Right, the same temperature data plotted versus the effective radius ρ . The TS profile is shown together an MH profile for comparison

Edge and Main TS have been extensively described; double filter SXR spectrometer (DSXC, [44]) provides line integrated T_e measurements in the core; it consists of four groups of five photodiodes each, measuring the SXR plasma emissivity through four pinholes; each pinhole houses a berillyum filter with different thicknesses, which acts as an energy selector. The temperature is measured with the two foils technique, sampling the brehmstrahlung spectrum with different low energy cutoffs. Even if temperature is averaged along each line of sight, the weight of higher T_e is such that, for our purpose, the measure can be treated as a punctual one, considering the chord impact parameter as the radial position to which the measure refers. This system can deliver profiles at a few kHz with a spatial resolution of $\approx 4.5cm$.

Figure 6.7 shows the different toroidal locations of the diagnostics and how they are reported at the TS poloidal section. An example of temperature and pressure profile obtained after re-mapping the measurements of the three diagnostics (THB not available) is shown in fig. 6.8. It's worth noting here that in most cases (as in the example shown) the re-mapped TS profiles do not reach the helical axis defined by ($\rho = 0$); this happens when the TS line of sight does not intercept the innermost helical flux tubes.

Density re-mapping: diagnostic setup and cross calibration

The pressure is a good indicator of the confinement quality, while a proper mapping of pressure data coming from different toroidal location can be regarded as a further confirmation of the validity of the helical equilibrium reconstruction. In order to determine pressure, it is necessary to reconstruct the electron density on helical flux surfaces.

Density data used for profile reconstruction come from Edge TS and mainly from Main TS. The absolute calibration via RRS (see 2.3.2) is stable only for the Edge TS, while the calibration constants for Main TS vary in time because of impurity depositions on the windows, due to plasma dis-

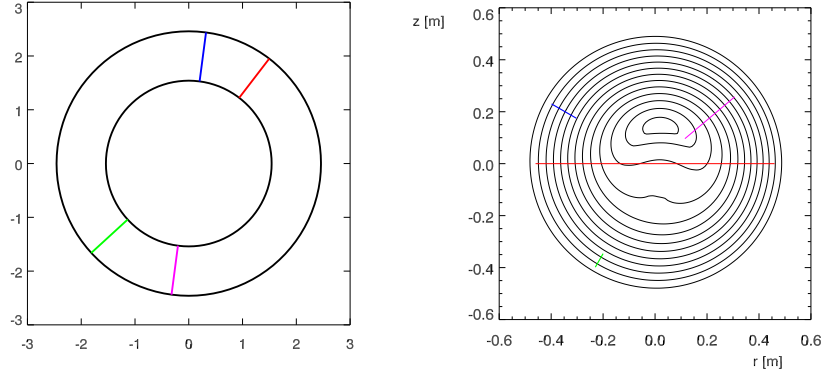


Figure 6.7: toroidal locations of the diagnostics and their position at the TS poloidal section (which holds for the $n=-7$ mode); blue corresponds to edge TS, red to the Main TS, magenta to the DSXC and green to the THB

charges and especially to the wall conditioning cycles. Nevertheless, these calibration constants can be considered stable during an experimental day and they can be directly evaluated if another, independent, density measure is available. In this case, such constants result simply as the ratio between the uncalibrated density of TS and, typically, the value of the $C0_2$ interferometer n_e profile at the corresponding radius; such a procedure is called "cross calibration", and requires a reliable density measure in at least one shot during the experimental day.

The method is based on the evidence that density profiles during MH (Multiple Helicity) states are flat and axisymmetric; actually, MH states are characterized by the absence of a dominant tearing mode and by a flat region in the core temperature profile. The plasma core is chaotic, so no internal temperature or density structures are present. The same method has been used in [68] to perform ensemble averages with QSH density profiles.

Cross calibration of main TS with the interferometer is delicate when dealing with densities near the edge, where the relative error on the measures is usually higher and the detailed behavior of the density profiles estimated by the interferometer depends on the function used in the inversion algorithm. The density profile is obtained using the line integrated measurements as constraints to determine the free parameters of the following analytical function of r :

$$n_e(r) = n_0(r/a)^\alpha + (n_1 - n_0)(r/a)^\beta - n_1;$$

where n_0 and n_1 are two parameters, the first expressing the density on the axis. In this respect, the Edge TS is the most reliable diagnostic for the density at the edge, since the absolute RRS calibration is stable and the

cross calibration method is not necessary ¹.

The cross calibration works correctly in the core region; however, the density measures of TS are subjected to errors σ_n^0 (with $\sigma_n^0/n \approx \sigma_T/T$), which are propagated to the calibration constants: being the calibrated profile obtained after multiplication by these constants, it has a higher uncertainty. In fact, for the final value of the density errors, holds $\sigma_n \approx \sqrt{2}\sigma_n^0$ and these are the main contributions to the uncertainty of the pressure profile, obtained as $p_e = T_e \cdot n_e$. Moreover, the pressure profile is characterized by a quite high dispersion in the data.

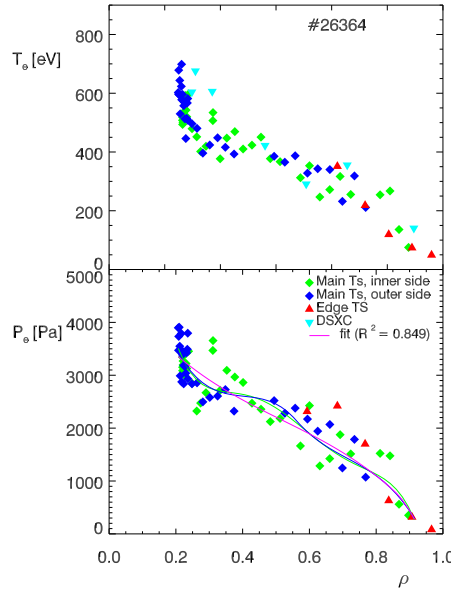


Figure 6.8: example of pressure data fitting with the three trial functions

This is reflected by the low value of the correlation coefficient R^2 , which results after an analytical fitting is performed. As far as the fitting function is concerned, it has been chosen to keep it as simple as possible, that is to use two polynomials, a 3^{rd} degree one in the core and a 2^{nd} degree one in the edge. The two functions and their first derivatives are continuous in a point which is allowed to vary inside a prescribed ρ window. The 3^{rd} degree part allows to describe a central peaking and a plateau formation, while a quadratic dependence at the edge describes the almost linear trend

¹A different technique which reduces the uncertainties on the edge n_e is based on a statistical approach, averaging the cross calibration constants over a certain number of inverted density profiles to reduce the statistical errors; the same method is automatically applied when working with the databases.

of T_e and n_e in the distance from the wall. The use of a single polynomial interpolation doesn't ever fit the profile curve, while an increase in the fit function complexity doesn't lead to an improvement in the square correlation coefficient, which remain between 0.8 and 0.9. Figure 6.8 shows the normal 2^{nd} & 3^{rd} degree polinomial fit (magenta) as well as a 3^{rd} & 3^{rd} degree fit (blue) and a 6^{th} degree, continuous fit (green): increasing the number of degrees of freedom doesn't lead to better description of the pressure profile shape.

Pressure profiles in DAX and SHAx regimes

As long as no particle sources are present inside the plasma (i.e. when pellets are not injected [72]), density profiles are not significantly affected by the presence of a central helical structure, so the behavior of core pressure essentially reflects the T_e one. Looking at DAX examples (fig 6.2.2), it can be noticed that the pressure shows a flattening at intermediate values of ρ , between two steep gradients corresponding to the core island and the edge region. In SHAx (figure 6.2.2) pressure profile remains slanting all over the plasma, while central values are higher.

To quantify such differences, the gradient scale lenght $P_{\rho=0.4}/\nabla_{\rho}P$ has been evaluated for a limited database of discharges (40 discharges at $I_p=1-1.6$ MA, $n/n_g = 0.15 - 0.35$); this dimensionless quantity typically remains below 0.5 in SHAx regime, while it takes values between 0.4 and 1.5 in DAX. In multiple helicity (MH), an axisimmetric scale lenght can be defined, whose value is significantly higher (≥ 2), i.e the temperature gradient is much smaller. Figure 6.10 displays three examples of fitted pressure profiles for the three classes of discharges: the pressure gradient lenght does not seem to depend on the plasma current, even if the DAX and SHAx data points are clearly separated (one MH point is shown for reference in the picture). On the other hand, some DAX discharges with characteristic length approaching 0.5 represent a transition condition showing intermediate thermal features; their detailed characterization is still a matter of investigation. As a final remark, this procedure confirms on a statistical basis the different width of the pressure structure in the core, and thus it is a good starting point for a better evaluation of the average pressure, which is related to the β parameter.

6.2.3 Correlation between core temperature gradients and helical magnetic shear

The previously described steep gradients located in the core region are similar to the internal transport barriers observed in tokamaks and stellarators. The physics of Internal Transport Barriers (ITB) is an outstanding item of research in magnetic fusion science; in particular, ITB triggering mechanisms such as the reversal of the magnetic shear are being intensively

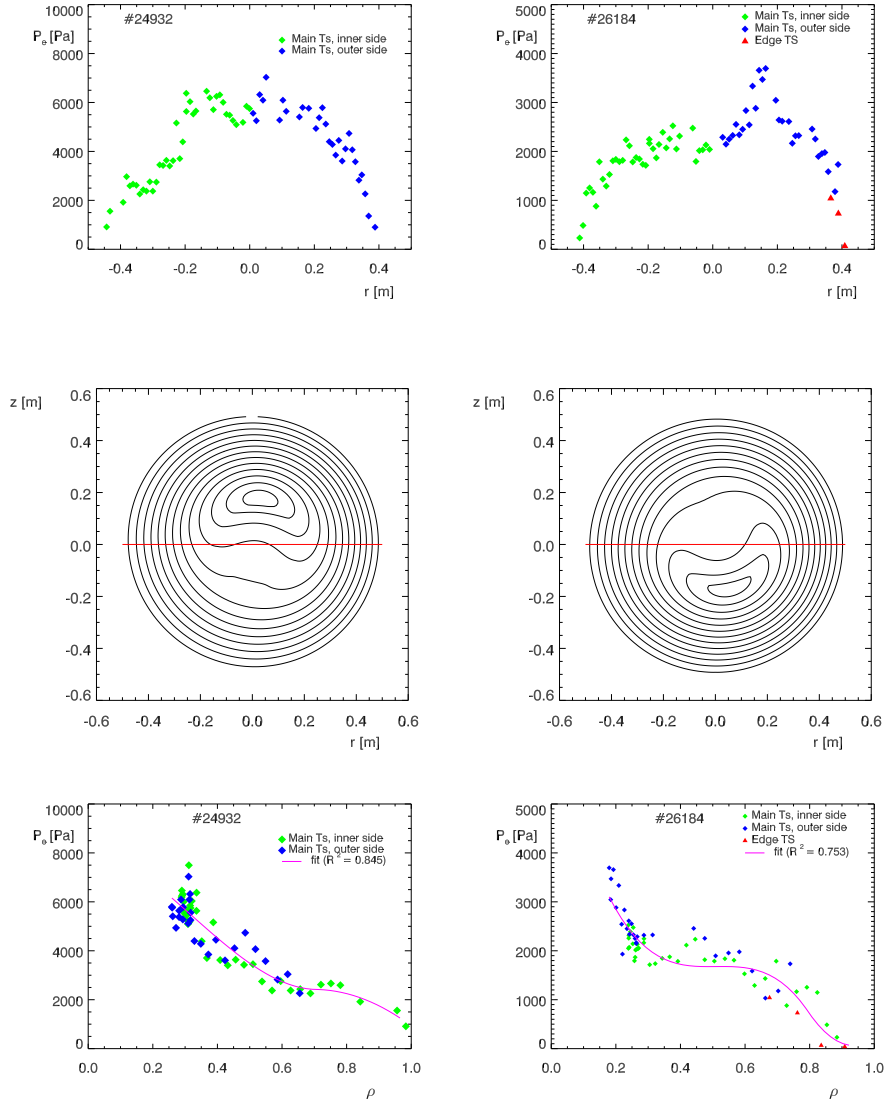


Figure 6.9: pressure profiles and ρ mapping for a DAX and a SHAx discharge

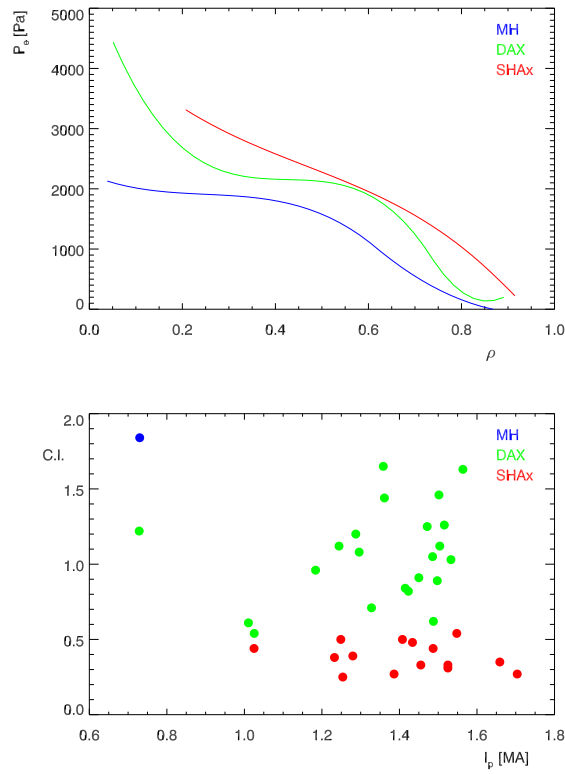


Figure 6.10: Top, pressure profiles for the three discharge types and, bottom, plot of the gradient characteristic length versus the plasma current

studied [94].

The states described in the previous paragraphs share with stellarators their helical shape, while the change in magnetic shear, described in the following, is a common element with tokamaks.

Magnetic shear for the helical configurations of RFX-mod has been computed by estimating the profile of the safety factor of the helical flux surfaces, with methods that will be described in the following section. The position where the q profile changes has been found to be closely correlated with the position of the steep gradients, both in SHAx and in DAX.

It is worth noting that in SHAx and DAX the cylindrical q does not represent anymore the pitch of the magnetic helical axis.

Definition of q, ι in helical geometry

The simplest case that can be analysed is the SHAx state; the magnetic field structure is composed, in this case, by nested helical magnetic surfaces, whose innermost one is the helical axis. For every surface the inverse of the safety factor, i.e. the rotational transform ι , has been computed as the average of the total poloidal angle around the helical axis after one toroidal transit. Each field lines parametrized in function of the toroidal angle coordinate ζ . The field line path can be written as

$$L(\zeta) = (R(\zeta), Z(\zeta), \zeta)$$

where R and Z are the cartesian coordinates on a poloidal section at the toroidal angle ζ . Let:

$$A(\zeta) = (R_A(\zeta), Z_A(\zeta), \zeta)$$

be the parametric representation of the helical magnetic axis of the considered magnetic surface, with R_A and Z_A the usual cartesian coordinates at a given toroidal angle ζ .

By definition the magnetic axis closes on itself after one toroidal turn, therefore A is a periodic function in ζ . This is not true for a generic field line since the line never closes on itself, except for lines lying on rational surfaces. At any given point of the line it is possible to define the poloidal angle respect to the helical axis, or rotational transform angle, as

$$\theta(\zeta) = \arctan \frac{Z_A(\zeta) - Z(\zeta)}{R_A(\zeta) - R(\zeta)};$$

Therefore the definition of ι is:

$$\iota = \left\langle \frac{d\theta}{d\zeta} \right\rangle$$

where the brackets $\langle \dots \rangle$ mean an average over many toroidal transit of the field line on the considered helical surface.

Note that this definition is diverging as one approaches the surfaces close to the reversal of the toroidal field, where $q \rightarrow 0$ and $\iota \rightarrow \infty$. In the present analysis this is not a significant limitation since the electron temperature steep gradients are located inside the reversal. It should be noted that, while axisymmetric q crosses the value $1/7$ at the $m=7$ resonant radius and then increases further on the machine axis, the quantity $1/\iota$ remains below $1/7$ all over the plasma.

The same algorithm used for computing ι and q in the SHAx case applies also to the DAX configuration but with some warnings. The presence of two axis, the axisymmetric one and the island O-point, do not allow to uniquely define a value of q as in the previous situation. However, it is still possible to define, for each flux tube (except for the separatrix) a rotational transform angle. The separatrix splits the plasma volume in three regions: the inner flux tubes, containing the magnetic axis, the island region, composed of flux tubes containing the O-point, and the outer flux tubes containing both axis.

The above mentioned algorithm, based on field line integration, can be applied to surfaces in each of these three regions; in the outer flux tubes the two estimates give identical results: this is due to the fact that, as stated above, these tubes contain both axes; in particular, as the surfaces approach the separatrix, q tends to the value $1/7$. The separatrix is, in fact, the remnant of the axisymmetric resonant surfaces for the $m=1$, $n=-7$ mode.

The two estimates of the q profile for the other families of flux tubes are different because they do not contain both axes. In particular, as far as the island surfaces are concerned, a slightly decreasing of q is observed when estimated around the O-point, while a flat value of $1/7$ results if the magnetic axis is used as a reference.

In order to uniquely define a q for any given surface of a DAX case, it has been chosen the estimate with respect to the axis which is contained inside the surface itself.

Statistical analysis of internal barriers

In order to identify a correlation between the temperature profile and the q one, a set of 55 discharges has been analysed: for each one the extension of the gradients has been identified with a series of 4 linear fits performed on a manually determined window, identifying the level of temperature knee, the two internal gradients and the central plateau (absent in DAX) respectively. The database covers values of density between 2 and $4 \cdot 10^{19}$, $1 < I_p < 1.6$ MA, $-0.11 < F < -0.016$.

The foot of the internal gradient has been evaluated as the intersection points of the fits (fig.6.12, upper frames); on the other side, the "knee" in the q profile is easily identified as the point in which the slope of the curves

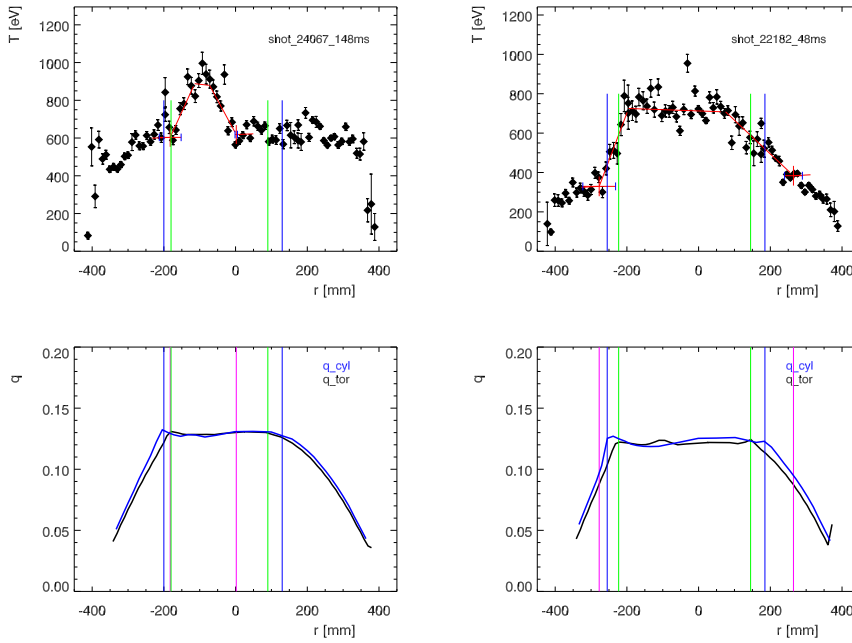


Figure 6.11: Temperature profiles and q correlation for a DAX and a SHAx discharge

changes abruptly.

It can be seen in fig. 6.12 that in both SHAx and DAX discharges the two locations are clearly correlated within a few cm, in particular for the external side (the core side of the gradients in DAX is difficult to be interpreted). For the DAX case, in particular, the internal gradient is located inside the separatrix, while this is not always true for SHAx: this may be seen as an indication that in SHAx the region where magnetic chaos is suppressed is wider compared to DAX, and this can be linked to the lower level of secondary modes.

These results indicate a general similarity in the core gradients observed in RFX-mod and the internal transport barriers identified in tokamaks and stellarators; a possible interpretation is that the magnetic shear plays a decisive role in the local enhancement of the confinement: also in tokamaks, the q shear exhibits a null point whose position is correlated with a temperature gradient and so to a transport barrier.

Besides the magnetic shear, also flow shear is supposed to play an important role in non axisymmetric configurations: in particular, it can be associated to the generation of a strong ambipolar electric field E_r . There are evidences that the latter is linked in stellarators to the formation of internal transport barriers [95].

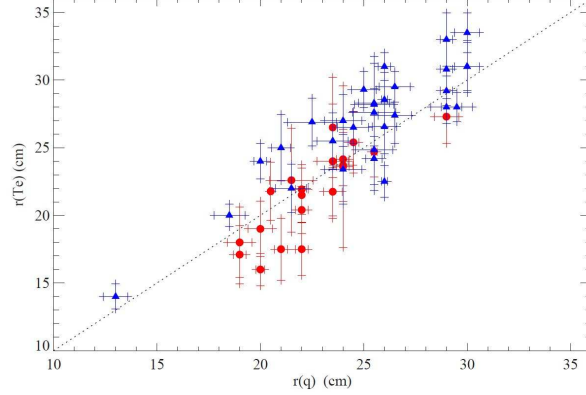


Figure 6.12: correlation between the positions of q plateau and T_e gradients: circles refers to DAX and triangles to SHAx

6.3 Edge electron temperature characterization

Edge TS aims at characterizing the T_e gradient that occur at the edge of the discharge; in particular, an investigation was performed to asses a correlation with the topology. In fact, while the core features of the profiles are deeply different in the three types of examined discharges (MH, DAX and SHAx), the edge T_e does not vary so significantly as far as the values and locations of the T_e gradients are concerned. This statement is based on a qualitative analysis performed on a relatively small sample of profiles measured by edge TS; in fact, at the time of writing this thesis, experiment are ongoing with edge TS diagnostic operations, and a more quantitative analysis will be possible on a bigger database. In this section edge gradients are estimated with the main TS.

The analysis has been performed on a database 204 discharger (40 MH, 106 DAX and 58 SHAx), which has been processed manually to overcome the approximations done by automatic routines; the results (figure 6.13) doesn't show any particular difference, nor in the electronic pressure calculated at the upper end of the edge gradient, neither in the gradient itself, as far as concerns the comparison of MH, DAX and SHAx

On the other side, a dependence of the T_e gradient with respect to the amplitude of secondary modes can be identified (fig 6.15); this fits the general trend of relative decrease in the secondary modes amplitude as the current (and the temperature) increases.

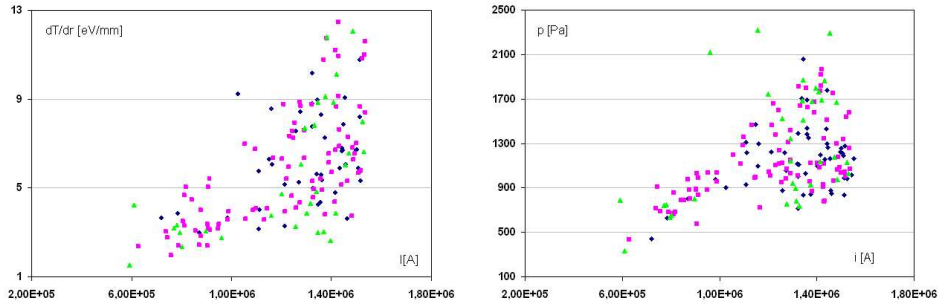


Figure 6.13: "knee" pressure and edge gradient evaluated for SHAx (magenta), DAX (blue) and MH (green) discharges, as a function of current; though the sample is dispersed, there's any defined trend for one type respect to the other

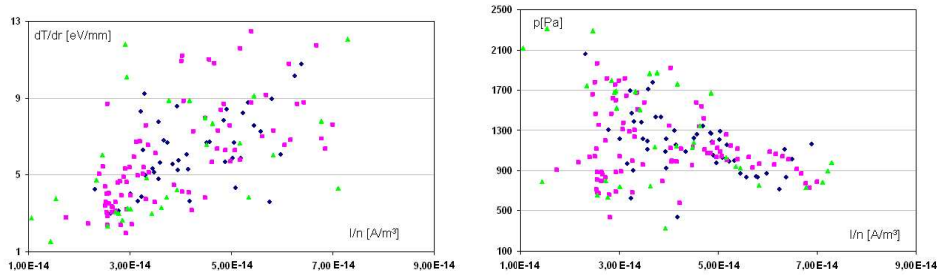


Figure 6.14: "knee" pressure and edge gradient evaluated for SHAx (magenta), DAX (blue) and MH (green) discharges, as a function of I/N

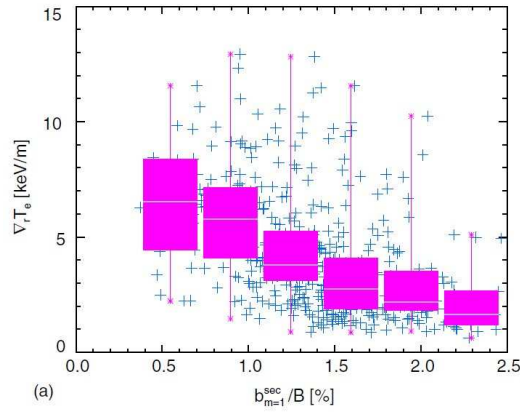


Figure 6.15: ∇T at edge evaluated as a function of relative amplitude of secondary modes spectrum

6.4 Electron energy transport characterization

6.4.1 Cylindrical approach

After the phenomenological overview of the previous sections, in the following the electron diffusivity coefficient will be evaluated quantitatively; in particular, this section describes the method which will be used in the following for transport calculations at the edge and for first order study of transport evolution during a QSH cycle.

1-D calculations have been performed in the past and are at the moment the most reliable and simple method to get informations on the electronic thermal diffusivity. By assuming that the RFP equilibrium is cylindrical, χ_e is simply calculated as a function of r from a power balance model. Adopting a single fluid approach [96], the plasma electron heat diffusivity $\chi_e(r)$ is obtained as:

$$\chi_e(r) = -\frac{q_{\perp}(r)}{n_e(r)\nabla T_e(r)} \quad (6.1)$$

In stationary conditions, if ϵ_{rad} represents the energy radiated by the plasma and Ω_r the power input, the heat flux through a surface of radius r is given by:

$$q_{\perp}(r) = \frac{1}{r} \int_0^r [\Omega(r') - \epsilon_{rad}(r')] r' dr' \quad (6.2)$$

Some hypothesis has to be formulated on the distribution inside the plasma of the power input $\Omega(r)$ and of radiation losses $\epsilon_{rad}(r)$; in the case of RFX, the $\Omega(r')$ input is evaluated as $\eta J^2(r)$ via an equilibrium BFM ($\mu&p$, see chapter 1); the $\mu&p$ assumes a flat temperature profile, hence for peaked profiles a correction in the spitzer resistivity $\eta \propto T_e^{-3/2} \ln \Lambda$ ($\ln \Lambda$ is the Coulomb logarithm) has to be accounted.

The radiated power $\epsilon_{rad}(r)$ is supposed to behave as a power law of radius $(r/a)^4$ and subtracted from the ηJ^2 term. The exponent is chosen empirically to reproduce a standard radiation pattern; however, the exact behavior of radiated power doesn't affect significantly the value of electronic diffusivity, since its total value is around 10% those of ohmic input. Both the total amount of radiated and ohmic power are directly measured; the latter in particular is used as a constraint to correct and normalize the power distribution returned by the $\mu&p$ model; in fact:

$$2\pi R \int_0^a \Omega(r') r dr \quad (6.3)$$

which is the total amount of ohmic input, has to correspond to

$$P_{\Omega} = V_{\phi} I_p - \frac{\partial U}{\partial t} = V_{\phi} I_p - \frac{\partial}{\partial t} \int_V \frac{B^2}{2\mu_0} \quad (6.4)$$

Finally, for the electron diffusivity holds ²

$$\chi_e(r) = \frac{1}{r} \frac{1}{n_e(r) dT_e(r)/dr} \int_{x=0}^r \eta J^2(x) x dx$$

Where temperature comes from the main TS and density usually from interferometer, even though a cross calibrated thomson density can be used. The gradient of temperature is a critical issue, since it is evaluated fitting the TS profile with a quadratic function in a given spatial window around r . Its value depends slightly on the window width; empirically, a width of $\pm 50\text{mm}$ is found to work give reasonable results.

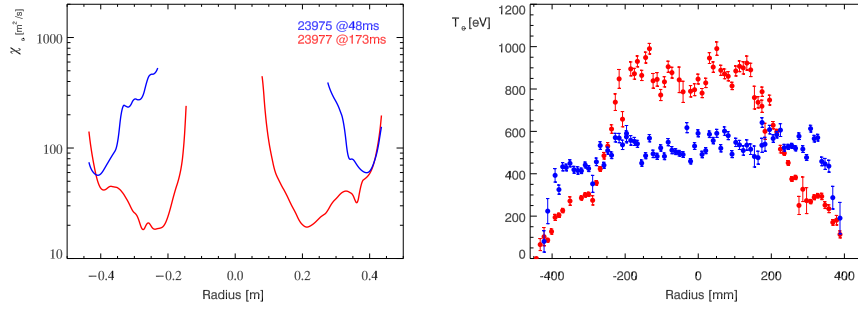


Figure 6.16: example of χ_e profile and relative TS profiles for a SHAx(red) and a MH discharge

From a practical point of view, the models calculates separately the values of electronic diffusivity on the internal and on the external radius (fig 6.16); coherently the integral of ohmic power runs on half circular crowns rather than complete crowns. The method, though not self consistent, was initially developped to better describe the temperature gradient when an island was intercepted, temperature gradient which otherwise would have been averaged on the external and internal side of the profile.

6.4.2 Diffusivity at the edge

The described method works efficiently in the edge region, which is not affected by the topological changes related to QSH. Coherently with the conclusion of 6.3, electron diffusivity at the edge scales with the secondary

²the correct formula should account, in the balance of the heat flux, also of the variations in the plasma internal energy

$$\chi_e(r) = \frac{1}{r} \frac{1}{n_e(r) dT_e(r)/dr} \int_{x=0}^r \left[\eta J^2(x) - \frac{d}{dt} \frac{3}{2} n_e(x) K T_e(x) \right] x dx$$

Usually the term $\frac{d}{dt} \frac{3}{2} n_e(x) K T_e(x)$ can be neglected; however, trying to characterize non stationary states such as in the following analysis of QSH cycles, it has been taken into account even though it has not been found to affect significantly the results

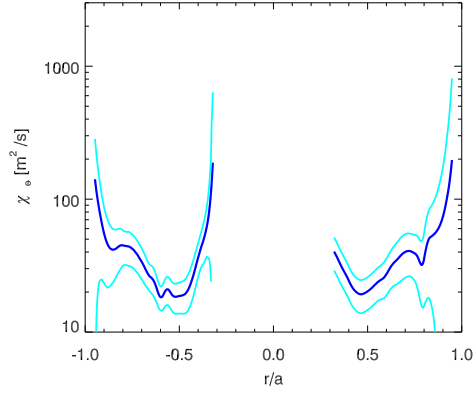


Figure 6.17: typical behavior of the uncertainty on the value of χ_e , whose main contributions are the errors on the temperature gradient (in the core) and on the density near the edge (in particular for the external side, which is not covered by the main TS)

modes normalized amplitude (fig. 6.18); here the ohmic power plays a fundamental role, since higher gradients are associated with higher core temperatures and higher plasma conductivities; the relative amount of ohmic power with respect to the temperature gradient ($P_{ohm}/\nabla T_e \propto P_{ohm}/T_e$) is supposed to decrease as one moves from MH to DAX and finally to SHAx.

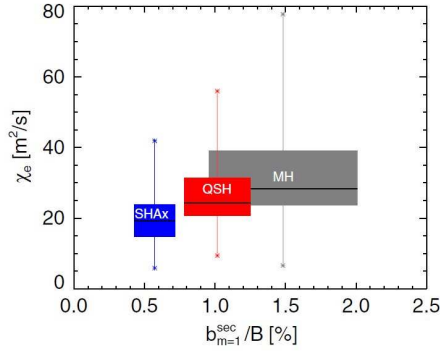


Figure 6.18: $\langle \chi_e \rangle$ at edge evaluated as a function of relative amplitude of secondary modes spectrum [97]

6.4.3 Time evolution of χ_e during a QSH cycle with the 1D model: experimental evidences and limitations

While the TS measures profiles with high spatial resolution, the time behavior of transport is difficult to estimate; i.e it would require a considerable amount of discharges and reproducible events. Nonetheless some time in-

dications can be obtained with the previously described multichord SXR diagnostic (DSXC), which can be used to "interpolate" temperature informations between TS pulses. The only difference with respect to the use of TS is the lower radial resolution of the diagnostic, which requires a larger fitting window to evaluate the temperature gradient.

Figure 6.4.3 shows three sampled temperature profiles during a whole QSH cycle one coming from TS measures and the other from DSXC data. The times of the three profiles refers to the diffusivity reconstructions in the lower frame: the values are significantly different, since where the SHAx temperature gradients develop in the core it decreases by about an order of magnitude, while exceeding $10^3 m^2/s$ during the MH phase (i.e., at the dominant mode crash). On the other hand they remain below $100 m^2/s$ at the edge, without displaying substantial variations.

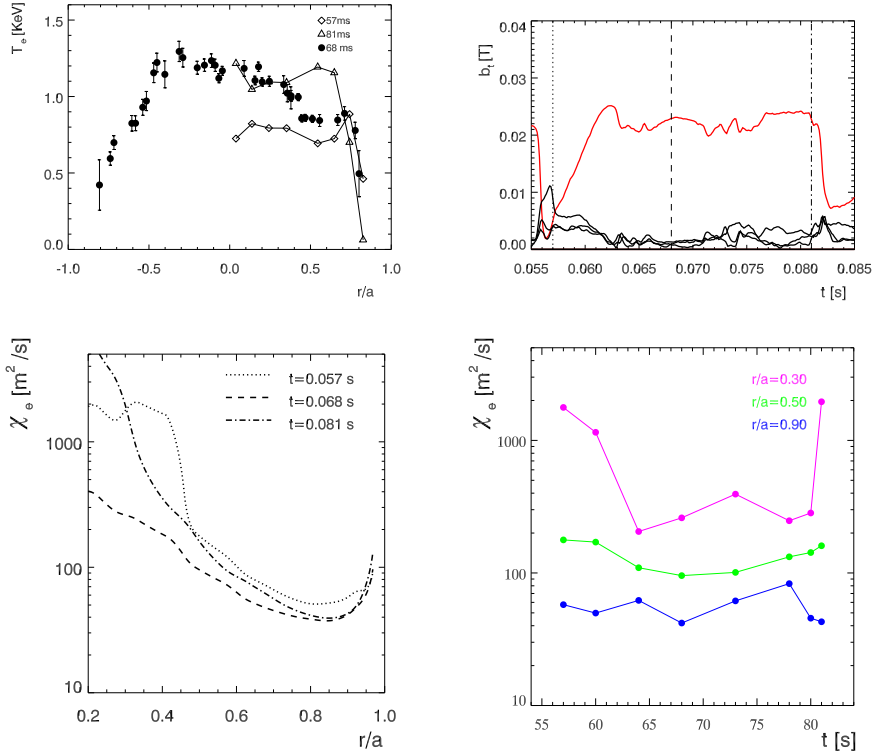


Figure 6.19: left: Thomson (filled dots) and DSXC profiles (empty dots) and, below, relative χ_e reconstructions; right, magnetic spectrum in the QSH cycle (up) and χ_e evolution at different values of the radius

Looking to a plot of χ_e time evolution at different radii (see fig. 6.4.3, last frame), it is confirmed [14,15] that the diffusivity decreases during the entire QSH phase with respect to MH frames (which correspond to crashes in

the dominant mode amplitude - fig 6.4.3). The main contribution to the χ_e variation from MH to QSH is the increase in the T_e gradient (although the latter is not correctly evaluated in cylindrical approximation); the density variations are minimal and the source term doesn't change significantly.

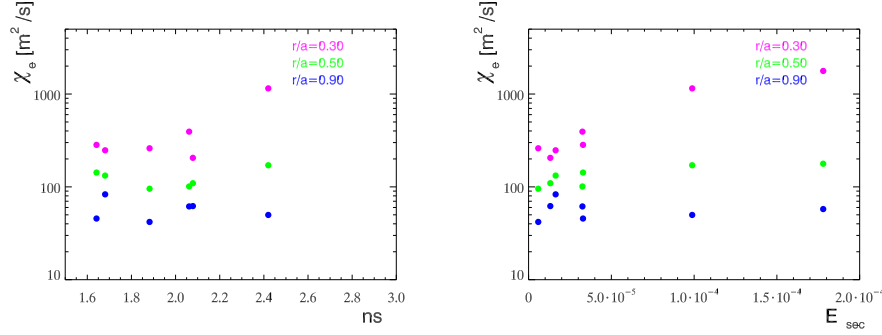


Figure 6.20: Electron diffusivity as a function of the NS parameter and of the energy of secondary modes

6.4.4 2D Approach: explanation of the technique

Even though the 1D method described in the previous section is useful to obtain the estimate of the order of magnitude of electron transport, when dealing with helical states, a 2D approach is mandatory. A 2D model is based on two dimensional discretization of the plasma cross section; each pixel (x_i) of the obtained grid is associated to particular values of temperature, pressure ohmic input and so on. For example, the temperature $T_e(x_i, y_j)$ is determined by the value of the helical coordinate ρ on the (x_i, y_j) point, through a function $T_e(\rho)$ which is defined on the TS line of sight, averaging the internal and external parts of the main TS profile and the data coming from edge TS (if available). The definition of $T_e(\rho)$ have to be carefully optimized, especially at the edge, by controlling the way the temperature profiles are smoothed and averaged; imprecise remapping can cause a broadening of the external gradient and so an underestimate of its value.

The same procedure is performed for the density $ne(x_i, y_j)$; in this case the TS density for the main system is obtained via cross-calibration. Clearly, for ρ values having no TS measure (the island core), temperature and density remain undefined, and so the heat diffusivity calculation cannot be performed.

The local value of temperature gradient is obtained as

$$\nabla T(x_i, y_j) = \left[\frac{T(x_{i+1}, y_j) - T(x_{i-1}, y_j)}{2\Delta(x)}, \frac{T(x_i, y_{j+1}) - T(x_i, y_{j-1})}{2\Delta(y)} \right] \quad (6.5)$$

while for the electron diffusivity holds:

$$\chi_e(x_i, y_j) = \frac{\langle q_{\perp}(\rho) \rangle}{|\nabla T(x_i, y_j)|}$$

The value of heat flux $\langle q_{\perp}(\rho) \rangle$ is calculated integrating the ohmic power deposition $\Omega(x_l, y_m)$ (see the following for details) within a flux surface and dividing the result by the surface area; this condition is defined on the grid by $l, m | \rho(x_l, y_m) > \rho(x_i, y_j) = \rho_0$. The area of the flux surface S_{rho} is evaluated numerically by summing contour elements; it should be noticed here that for each element a (variable) increase due to the helical inclination of the flux surfaces with respect to the plasma cross section needs to be taken into account. This effect is partially balanced by the reduction of the value of $|\nabla T|$ provided that only its projection perpendicular to the flux surfaces is considered; both effects are evaluated numerically at each point by point relying on the local geometry.

The local electron diffusivity can be finally written as:

$$\chi_e(x_0, y_0) = \frac{1}{S_{\rho}} \frac{1}{n_e(\rho_0) |\nabla x, y T(\rho_0)|} \int_{x, y(\rho < \rho_0)}^r \eta (j_{tor}^2 + j_{pol}^2) dx dy;$$

and the obtained value of $\chi_e(x, y)$ is averaged on ρ levels to be expressed as an helical flux function:

$$\chi_e \rho_0 = \frac{1}{S_{\rho}} \int_{S_{\rho_0}} \chi_e(x, y)$$

In this procedure, the current densities (j_{tor}, j_{pol}) are calculated with the same cylindrical model adopted for the 1D calculations, while the Spitzer formula is adopted to describe plasma resistivity.

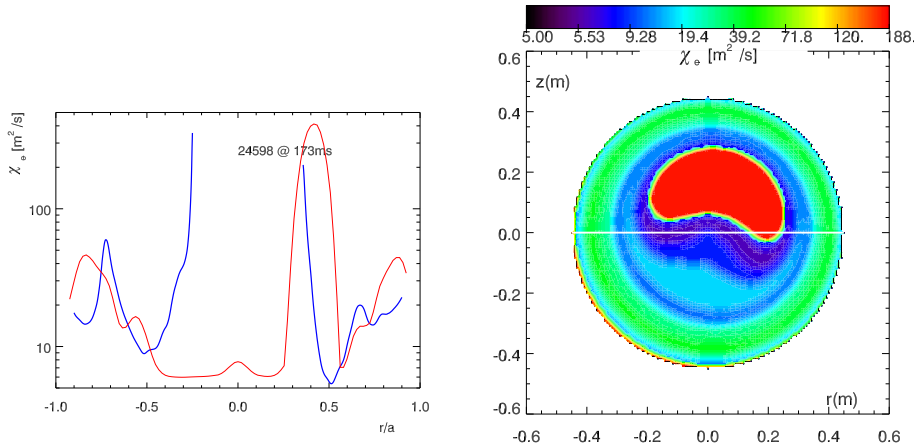


Figure 6.21: Comparison between the 1D, classical estimate of χ_e and the relative slice on the 2D map

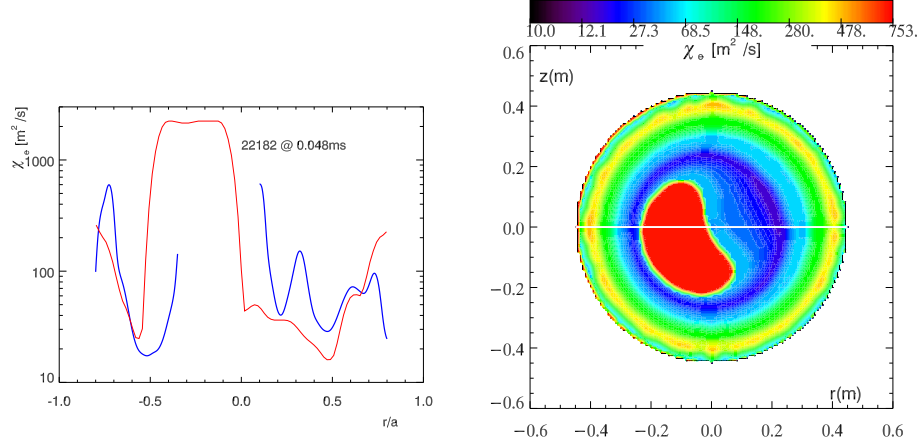


Figure 6.22: Another example with a different position of the island with respect to the TS diameter

The use of a cylindrical model for the estimate of the current density J is based on the consideration that the helical current perturbation $\tilde{J}/J$ is of the same order of magnitude of $\tilde{B}/B$, i.e. a few percents for a typical axisymmetric equilibrium approximation.

In order to get a first estimate of the magnitude, an example of perturbed current distribution has been calculated and it is shown in figure 6.23: a radial perturbation of the magnetic field is obtained from a Newcomb perturbative approach [93], in the form $\tilde{b}(r) = b_0(r)\cos(\theta - \theta_{O-point})$, the toroidal and poloidal components of the perturbation are calculated from the transverse component $\tilde{b}_{\perp r}$, which is required to maintain $\nabla \cdot \tilde{\mathbf{b}} = 0$.

These components are mapped on the same 2D grid previously described, together with the unperturbed magnetic field components B_θ, B_ϕ , in order to get a cartesian description of the overall magnetic field (which, for the z -derivatives calculation, requires three layers of grid instead of one) at this point the current is simply evaluated in a cartesian reference frame as $\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$; the derivatives are performed numerically on the grid in an similar way with 6.5

In the limits of the calculation (cylindrical geometry, perturbative approach, aliasing due to finite grid resolution), local variations in the J amplitude of the order of 10-20 % are estimated, which count even less once integrated: this justifies the use of the equilibrium current pattern in the electron diffusivity computation.

Another limit in this approach is that the perturbations are evaluated in a force-free context ($\mathbf{J} \times \mathbf{B} = \nabla P = 0$), while the presence of a density gradient suggests that the current perpendicular to magnetic field should be different from 0. However, for internal pressure gradients up to 20 kPa/m and B on the order of 1 T, the perpendicular current density is less than 1%

of the total.

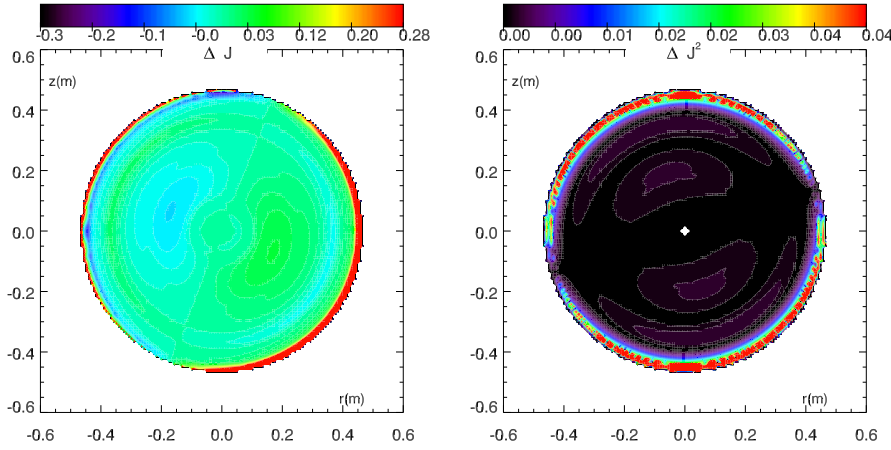


Figure 6.23: Magnitude of relative correction for the current modulus to account for the magnetic perturbations (left) and for the force-free approximation (right); the data refers to a SHAx discharge

6.4.5 Comparison with the 1D method and results

The main advantage of the 2D model approach with respect to 1D is that it is less sensitive to the poloidal position of the island O-point: as shown in Figure 6.21 in fact if the O-point is not intercepted by the Main TS line of sight, the 1D model fails to provide the correct position and value of the heat diffusivity corresponding to the island transport barrier. When the island O-point is intercepted by the Main TS laser, the heat diffusivity profiles are in a better agreement. An additional difference is at the edge, where the temperature smoothing required by the 2D model tends to soften the gradients and to increase the value of diffusivity. However, the typical uncertainty on the diffusivity at the edge is on the order of 30-40 % or more, so the values returned by the two models can be considered in the limit of their reciprocal compatibility, according to fig 6.17 and [96].

It is worth saying here that minimum values of 10 m²/s are consistent with previously published estimates [98] for a typical increase in island temperature of 300-500 eV, such as in the two examples shown in the figure 6.24. Here, the comparison between SHAx and DAX states also shows that the region of good confinement in DAX is limited to a small strip around the island, while it grows in SHAx extending to most of the plasma core. The wider extent of the hot region in SHAx states is obviously related to a consistent increase in the value of pressure (that reaches $8 \cdot 10^3$ Pa) and thus of β_e , up to 60 %. A similar trend in the electron confinement time does not clearly arise, mostly because of the varying contribution in the input

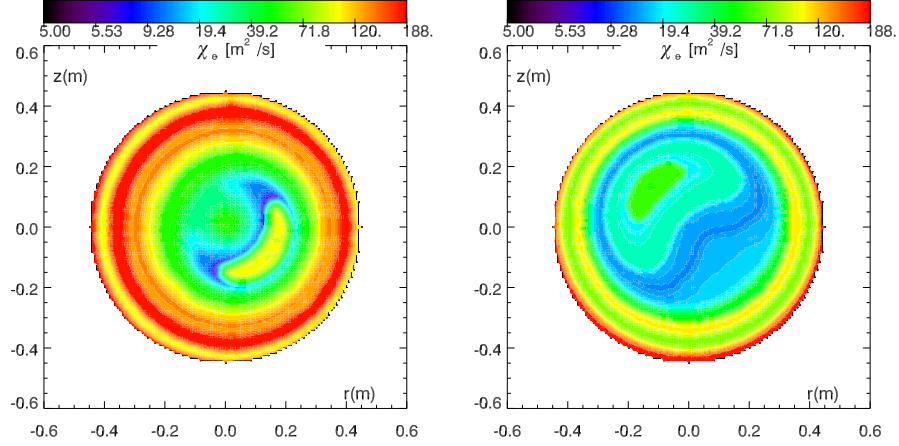


Figure 6.24: 2D diffusivity plots for a DAX and a SHAx discharge

power; however, in the best cases of SHAx, confinement time doubles its value respect to DAX states

6.5 Edge impurity transport investigations in LBO experiments

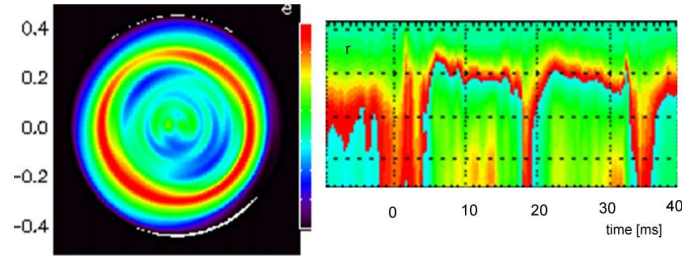


Figure 6.25: tomographic inversion performed during a Ni injection an time evolution of the radial radiation pattern

Ni injections for impurity transport test have been successfully performed in RFX-mod, thanks to the availability of the LBO system whose commissioning has been described in the previous chapter. Ni injections were performed in high current ($I_p > 1\text{ MA}$) discharges in high confinement quasi-single helicity (QSH) and multiple helicity (MH). As an example, figure 6.25, show a typical radiation pattern which characterize the first phase after Ni injection; the radiation ring quickly disappears in MH, while it can survive some QSH cycles (as shown the time evolution of a radial slice plotted in left); resilience of QSH respect to nickel diffusion is the main

phenomenological evidence with which has to deal every modelization.

The transport parameters are determined by comparing a 1-dimensional collisional radiative simulation with experimental spectroscopic data. Experimental signals from a number of spectroscopic diagnostics were monitored, including Ni XVII (249 Å) and Ni XVIII (292 Å) line emission, SXR signals and SXR radial profile reconstructions - normalised to a pre-LBO profile to remove the C and O contribution (assumed constant), the TS spectrometer signal on a chord looking to the LBO port is assumed as Ni influx from the wall.

Impurity transport is described by the diffusion coefficient D and pinch velocity v . For the injected Ni impurity we evaluated D and v by comparing the results of a 1-D impurity transport code [79] with the measured experimental signals. Experimental radial profiles and time dependencies of Te and ne are input to the code with the assumed D and v radial profiles. Ni transport in QSH and MH scenarios.

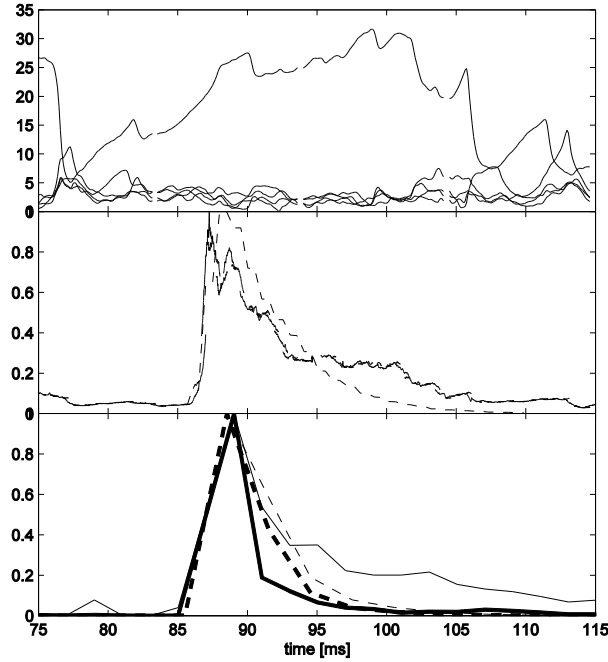


Figure 6.26: from the top: magnetic spectrum showing the develop of a qsh phase (shot 26607); signal and simulation(dashed) for SXR signal on a central chord; Experimental and simulatd (dashed lines) evolution of Ni XVII and Ni XVIII lines [99]

In fig. 6.26 the LBO injection occurred during the flat-top phase of a long-lasting QSH period allowing the whole Ni particle evolution to occur before the QSH crash. The code is able to well reproduce the time evolution of the Ni line and central chord SXR emissions. Fig. 6.27 demonstrates

that, in the simulation and experiment, immediately after LBO the SXR profiles are hollow and then become centrally peaked. The determined Ni profiles of D and v in shown in figure 6.28.

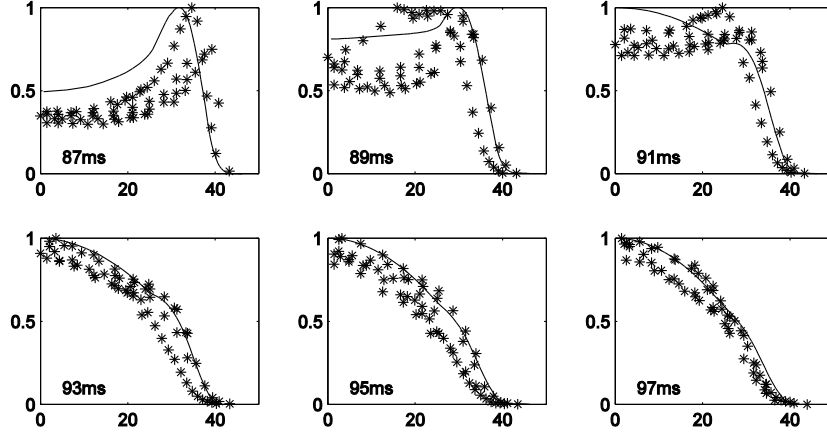


Figure 6.27: experimental SXR profiles (*) and simulated emissivity for the same time instant in a QSH shot

A significant feature is that v is directed outward over the whole plasma with an increased velocity barrier in the outer part of the plasma. This velocity opposes the penetration of Ni particles into the plasma core meaning that the Ni remains near the edge, the hollow SXR profiles immediately following LBO are indicative of this. However, observation of Ni XVII and XVIII lines indicates that the Ni does penetrate into regions of the plasma with fairly high temperatures.

D is higher in the plasma core than at the edge, although $D_{core}/D_{edge} \approx 6$, $D_{core} \approx 13 \text{ m}^2/\text{s}$. A further feature of the profile is that the low D , good confinement, region at the edge extends over nearly half of the plasma.

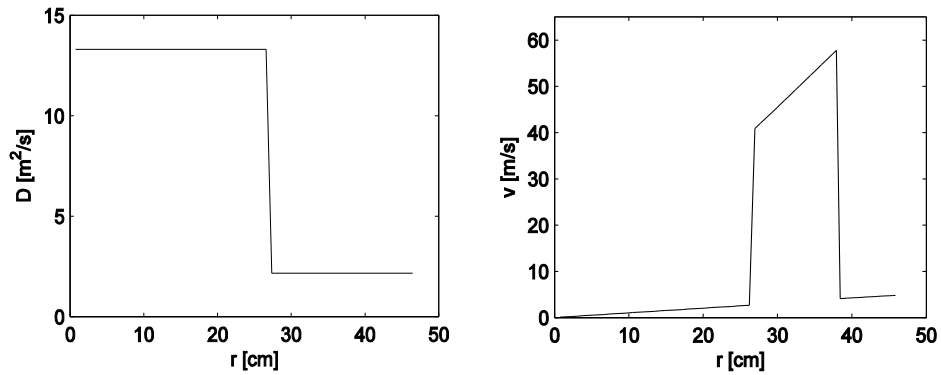


Figure 6.28: Profiles of D and v used in the simulation of Ni transport in the QSH scenario

Other discharges were obtained with LBO in MH conditions [99]. The case is illustrated in fig. 6.29 where the reconstructed SXR profiles immediately following the LBO are not hollow as in the QSH case. The central SXR and Ni line decays are slower - a 12ms time constant exponential decay compared to 8ms for the QSH case. Different impurity transport coefficients are needed (fig 6.30). The diffusion coefficients in QSH and MH case are quite similar in the central region, the principal difference in the MH parameters is that the good confinement edge region does not extend as far into the plasma; the velocity barrier is also shifted outwards. The more external D transition in MH is likely reflective of the different T_e profile which is flat to a large radius and then drops rapidly.

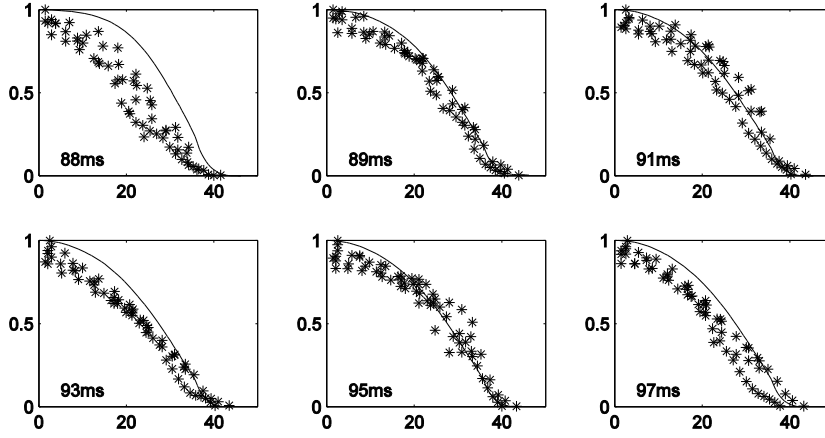


Figure 6.29: experimental SXR profiles (*) and simulated emissivity for the same time instant in a MH shot; the difference with the QSH case is evident in the first phases: here the emissivity profile is more peaked

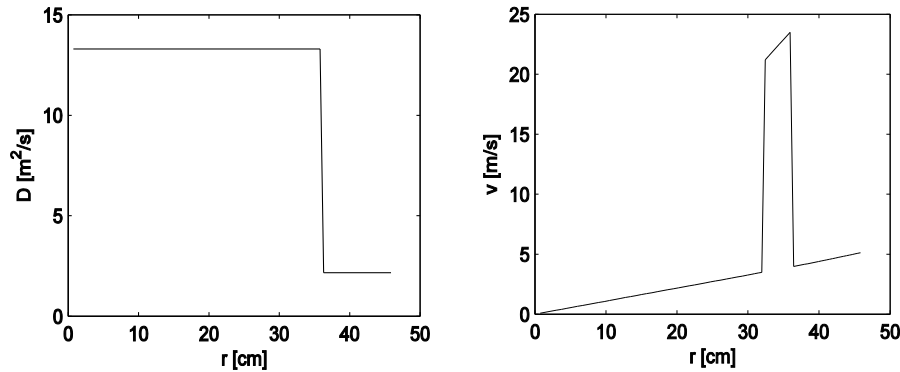


Figure 6.30: Profiles of D and v used in the simulation of Ni transport in the MH scenario

The Ni total density profiles at the steady-state have been calculated by

extrapolating the best simulations of the QSH and MH cases, assuming in both cases constant T_e and n_e (as measured at LBO in the QSH discharge) and constant Ni influx. The profiles (fig. 6.31) show that there is a very effective barrier to the Ni penetration in the QSH case whilst in MH the particle level is higher in the core and extends further out. The resulting SXR time evolutions are very alike suggesting the experimental differences may be partly due to the lower temperature and higher density of the MH plasma. It is worth to be noted that within acceptable margins, impurity transport parameters found for Ni allow to describe also Ne (puffed into RFX-mod) and Carbon transport in QSH and MH scenarios.

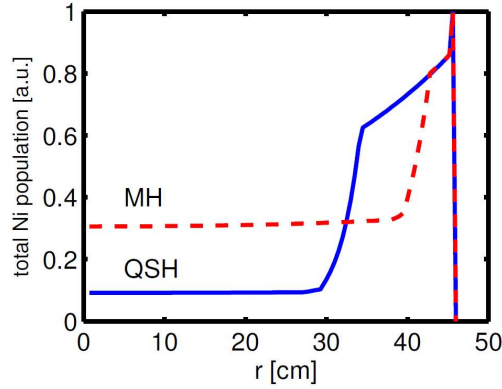


Figure 6.31: total Ni population in a stationary MH case and QSH case

All these results, which somehow confirm the dependence of Ni transport on the plasma topology, have to face a previous numerical evaluation of the diffusion coefficients for Ni, performed with the ORBIT code [100]. In this case, the diffusion coefficients for Ni impurities and main gas (H) ions have been estimated both in MH and QSH regimes, at different level of collisionality and energy of the test particles: simulations for $T_i=600$ eV and $T_i=1200$ eV have been performed to cover the possible temperature ranges in RFX-mod. Results are reported in fig. 6.32. The black curves (dots) are relative to H while the red ones (squares) to Ni ions. The MH and QSH scenarios are shown by solid and dashed lines, respectively. In the numerical simulations the interaction of the test particles with the whole plasma background is taken into account, considering both collisions with the main gas (ions and electrons) and with intrinsic impurity ions such as oxygen and carbon. In the nickel case, collisions Ni-Ni are considered too.

At $T_i=600$ eV the total hydrogen ions collisionality is in the range 0.06-0.1 collisions per toroidal transit; this interval is marked with a yellow box in fig. 6.32, a. As observed experimentally, diffusion of H ions in QSH ($\approx 1 m^2/s$) is found to be lower than in MH ($\approx 20 m^2/s$). At such low values of H collisionality, transport is strongly influenced by the magnetic field

topology which is chaotic in the MH scenario and presents helical conserved magnetic surfaces in the QSH regime. On the contrary, the typical range for nickel ion collisionality at 600 eV is 5-20 collisions for toroidal transit, as shown by the corresponding yellow box in fig. 6.32, a and the Ni diffusion coefficients are found to be about the same in MH and QSH regimes ($0.5 - 2 m^2/s$). At such a level of collisionality, random-walk diffusion processes due to classical collisions are dominant and Ni ion transport is little influenced by the magnetic field topology.

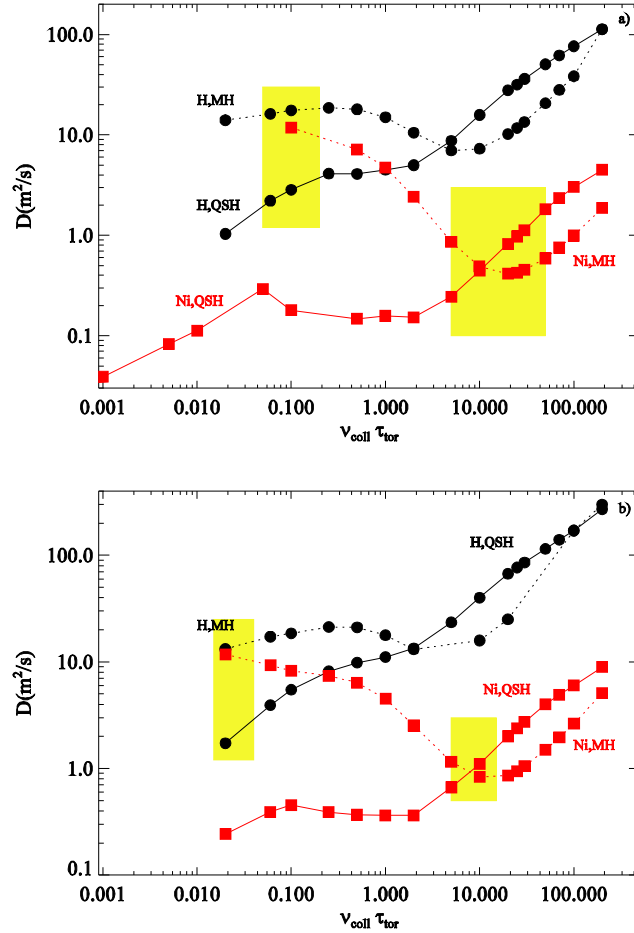


Figure 6.32: hydrogen and nickel diffusion coefficients obtained by ORBIT code as a function of collisions per toroidal transit, both in MH and QSH states, for $T_e=600$ eV (top) and 1200 eV (bottom).

The results are confirmed by ORBIT simulations also at $T_i=1200$ eV (fig. 6.32, b); also in this latter case diffusion coefficients for Ni in QSH and MH are nearly the same, about $1 m^2/s$.

Summarizing, the quantitative evaluation of the Ni diffusion coefficient

performed with ORBIT is one order of magnitude smaller than the reconstructions from the radiation patterns. This mismatch is currently being investigated and may be due to mechanism not included in Orbit which could be relevant in particle transport, such as turbulence or collective phenomena (blobs) (which are obviously beyond a single-particle approximation). Underestimation of the effective collisionality or numerical approximation (i.e. in ORBIT only monoenergetic test particle have been used and constant density profiles are assumed for the main gas and the impurities) could also play a role.

As a general consideration, it should be mentioned that the diffusion coefficient D , evaluated by reproducing the experimental emission pattern with the 1-D collisional radiative model, is a fluid quantity, i.e. the result of an ensembling of the dynamical system over long distances and times. The diffusion coefficient calculated through ORBIT is instead a local evaluation based on the actual dynamics of the particles on shorter times and local space-scales. There are theoretical indications [101] that the fluid D and the "dynamical" D are in principle different, and if plasma timescales are too fast (or, space scales too short) to completely de-correlate the motion of particles (as it is the case of a medium size experiment like RFX-mod) the fluid D could overestimate the "dynamical" D . More extensive analysis, both from the experimental and theoretical sides, is ongoing work.

Chapter 7

T_e and X-ray analysis in the MST experiment

In the following, the results obtained on data analysis on the MST machine (University of Wisconsin, Madison WI) will be presented. As will be discussed, the aim of the work was the identification of similarities and differences in the plasmas of the two machines with particular regard to QSH states.

7.1 The MST machine

MST is a large RFP experiments with 1.5 m major radius and 0.52m minor radius; it can drive plasma currents up to 600 kA. The working electron density ($0.5 < n_e < 2 \cdot 10^{19} m^{-3}$) is lower than those of the RFX-mod machine ($1 < n_e < 5 \cdot 10^{19} m^{-3}$); the I/n range for the two machines is however similar around $2 \div 5 \cdot 10^{-14} Am^3$.

There are some important differences in the way the two experiments are built: in particular, MST has not separate components for the vacuum vessel, the flux conserver, the first wall and the toroidal field winding: all these function are made by a thick aluminium vessel, interrupted toroidally and poloidally (on the torus equator). The toroidal magnetic field is obtained discharging a capacitor bank directly on the vessel, so that a current spike can flow in the poloidal direction around the chamber.

The first wall is essentially metallic, since the plasma faces the vessel inner surface except for a thin row of graphite tiles which turns toroidally and acts as limiter; this influence the density behavior: respect to RFX-mod, the recycling from the wall is lower and this is one of the reasons why the density profile appears more peaked in MST; moreover, the density control is easier, since working at low densities in RFX-mod is possible only after a wall conditioning.

Another difference lies in the poloidal winding for the inductive current

drive: while RFX-mod uses an air core transformer, in MST there's an Iron core for the couple of the winding with the plasma torus.

In MST there are not coils for the control of the magnetic instabilities neither vertical field windings for the radial equilibrium of the plasma: the radial stability is limited by the resistive diffusion time of the magnetic field across the aluminium shell. This is one of the reasons why the discharge duration is lower ($\approx 50ms$) than in RFX-mod (up to 400 ms). MST usually works with deuterium filling; this feature is important in QSH analysis since the way in which the instabilities rotate is experimentally found to depend on the gas type.

MST operates mainly in standard mode or PPCD [102]. PPCD (acronyms for Pulsed Poloidal Current Drive) [103, 104] is a transient regime developed with the aim of suppressing the magnetic chaos driving directly the poloidal current, by varying the toroidal flux and, in principle, eliminating the requirement of the dynamo to sustain the poloidal current. It is performed applying a current waveform on the toroidal magnetic system (i.e the vessel itself in MST). PPCD phase last for $\approx 10ms$ and is characterised by a great increase of the electronic temperatures; moreover, the temperature profiles look very similar to SHAx ones, featuring a central plateau and an internal transport barrier. PPCD are characterized by the decrease of all $m=1$ modes, though usually one of them remains higher than the other. This suggested the possibility to relate the internal barrier to a QSH state and to identify the internal barrier with the presence a single island in the plasma core. On the other hand, an internal barrier is associated also to cases with all the modes suppressed or with two modes which maintain a higher level than the other. Past analysis performed with PPCD discharges were able to identify rotating, bright SXR islands in the plasma core [105].

7.2 The experimental campaign

The occurrence of magnetic QSH is common in MST standard discharges and also in PPCD phases, with the difference with respect to RFX mod that, because of the larger aspect ratio ($R/a \approx 3$), the inner resonant mode is the $n=-5$ (in discharges with shallow reversal, $-0.1 < F < 0$) or the $n=-6$ (deep reversal discharges, $F \approx -0.2$). MST device is dimensionally very similar to RFX-mod and, though the current range is lower, one could expect to find some examples of hot magnetical islands, in a similar way to the cases of narrow hot structures which appear in some medium-low current discharges (≈ 600 kA) during RFX-mod operation.

In the past, bright magnetic islands, similar in topology to those observed in RFX-mod, has been identified by the SXR tomography during QSH states in PPCD phases; on the other side, the identification of the steep core gradient peculiar to the temperature profiles in RFX-mod QSH is controversial.

In fact, there are limitation in the TS geometry (it covers only half of the chamber diameter) which decrease the statistics and makes the QSH identification ambiguous. On the other side, in standard discharges the presence of temperature structures is hard to find. Statistical correlations between the poloidal position of the island O-point and the fluctuations observed in the T_e profiles lead to averages variations of some tenths of eV [106] respect to the hundreds observed in RFX. Moreover, this results holds also for MH states (computing the T_e fluctuations at the resonant surfaces of secondary modes), being not related to a QSH presence.

In a previous visit to Madison emerged that the database of discharges fitting the request for analysis (good TS and SXR data) was not sufficient, comprehending just some tens of discharges. A further experimental campaign was requested, with the constraint of obtaining plasma conditions as similar as possible to RFX-mod, in particular high current discharges. The necessity of lying in a similar range of I/n with respect to RFX-mod, required relatively high values of the density, which ranged from values of $0.7 \cdot 10^{18} m^{-3}$ (normal working conditions for MST) to $2 \cdot 10^{19} m^{-3}$.

The aim of the new campaign thus can be summarized as:

- The definitive identification of a correlation between the SXR emissivity and the modifications in the TS temperature profiles; For this point, from an operative point of view, it was necessary to rely on wide database with both good TS and SXR data.

- The characterization of the electron transport in the plasma core, to identify analogies and differences with respect to RFX-mod: the idea to perform such an analysis arose after a preliminary calculation of the electronic diffusion profile ($\chi_e(r)$) on some PPCD discharges, which showed a noticeable similarity in the value and shape (fig 7.1); the purpose was to investigate if the mechanism leading to such a results was the same of RFX-mod, or not. In order to obtain sufficient data, two type of discharges were requested:

- First, standard, high current, shallow F discharges, which are the easiest to replicate as well as the optimal environment to develop spontaneous magnetical QSH with a good statistics; here the dominant mode is the $n=-5$; an F scan has been also tried in order to obtain some examples of $n=-6$ spontaneous QSH, without finding significant results.

- Second, a set of PPCD discharges, in order to understand if the topology of the internal T_e barrier could be correlated to the SXR emissivity reconstructions. It was not possible to perform hydrogen discharges, which were preferred for the SXR quality of signals, since the mode rotation tends to lock at lower densities respect to deuterium discharges; nonetheless SXR data were found to be sufficiently reliable.

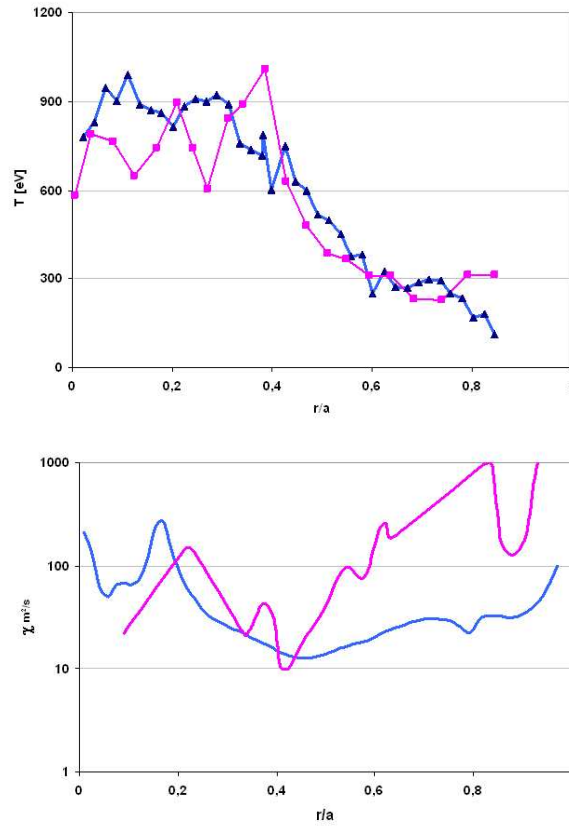


Figure 7.1: comparison between the Temperature profile and the electron diffusivity for a RFX SHAx (blue, $I_p=1.4\text{MA}$, $n_e = 3 \cdot 10^{19}\text{m}^{-3}$) and a PPCD discharge in MST (magenta $I_p=450\text{kA}$, $n_e = 8 \cdot 10^{18}\text{m}^{-3}$)

7.3 The diagnostic setup

7.3.1 Fast TS

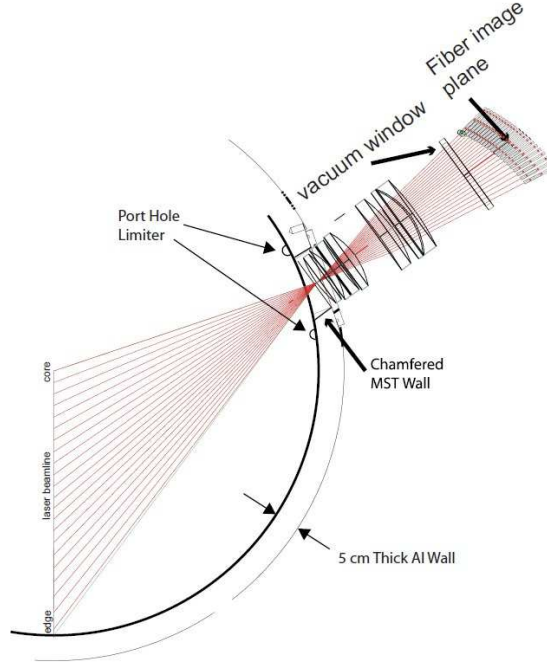


Figure 7.2: layout of the TS diagnostic in the MST experiment

The Multipoint TS system mounted on MST uses two Nd:Yag lasers, placed 15 m away from the machine in a separate room, whose beams are combined and pass through the discharge chamber in vertical direction [107].

A quite peculiar feature of the collection optics is their position, within the vacuum vessel; this solution permits to get closer to the scattering volumes and so to increase the numerical aperture of the system, without enlarging the diameter of the hole drilled on the vessel (which would result in an increase of the error field).

The scattered radiation is collected by a bundle of 21 fiber bundles, each one going to a dedicated interferential filters polychromator. They are equipped with a variable number of channels, from 4 to 8. The acquisition is done with water cooled APD modules and fast digitizers. Measurements range is 10 eV-2 keV for densities greater than $\approx 3 \cdot 10^{18} m^{-3}$.

The great capability of the diagnostic lays in the variable way the two lasers can be used and combined:

A first operating mode is the alternate firing of the two systems; in particular, each one can fire 15 times at 1 kHz rate, with variable reciprocal phasing. This kind of operation is preferred when dealing with relatively

slow events, or to sample the whole flattop of the discharge. It has been exploited mainly for standard discharges, where modes were expected to lock and QSH to develop spontaneously; the lower repetition rate is preferred to scan the discharge in an homogenous way.

The second way in which the system operates is a "burst mode", in which each laser can fire a tenth of pulses at a ≈ 10 kHz repetition rate, for an overall sampling rate of 25 kHz; also in this case, the relative phasing can be varied, and two subsequent pulses can get as close as $10 \mu s$. The latter type of operation is possible thanks to the substitution of the normal oscillators with a high-frequency Nd:YVO₄ diode pumped laser [108]; the increased thermal and electric loads on the amplifiers flashlamps required a dedicated development also on the power supplies. Burst mode operation is dedicated to analysis and characterization of fast events; in our case, it was essentially dedicated to PPCD discharges, in which the magnetic island is known to rotate with frequencies of the order of 10 kHz.

Given the relevant length of the beam path to the chamber, movement in the building structures can produce sensible misalignments of the laser beams; that is why their positions at the chamber exit are continuously monitored and corrected. This is a problem if one wants to perform not only an absolute calibration of the system, but also a cross calibration with other diagnostics (I.e: interferometer) to get density data, since the alignment varies from shot to shot.

7.3.2 SXR Tomography

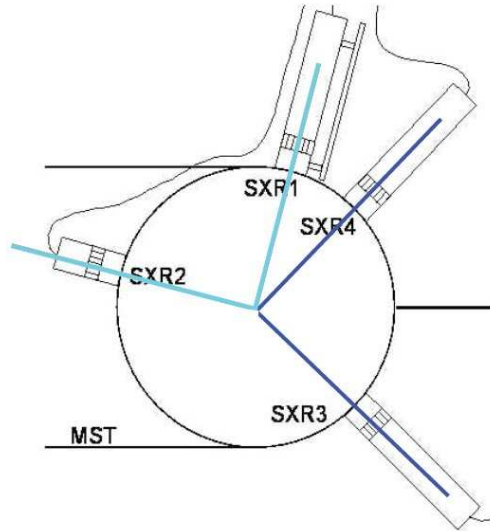


Figure 7.3: layout of the head positions in MST tomography

The SXR tomography [109, 110] consists of 4 measuring heads, 20 lines of sight each, mounted in the same toroidal position. Each head contains a silicon diode array which houses the 20 detectors on a single chip, disposed in a row; the bandwidth of the system reaches 100 kHz.

Each diode array is shielded from the plasma by a steel piece with rectangular pinhole (aligned with the photodiode itself) which defines the lines of sight. A berillium foil covers the pinhole and act as a highpass filter for the Xray radiation, the cutoff wavelength depending on its thickness. The distance between the pinhole and the detector, which is of few mm, can be set to two different values in order to vary the divergence of the lines of sight fan; this is useful if one wants to achieve a better resolution in the core (losing informations on the edge), as in our case.

The heads can be extracted from the machine to allow the filters to be unmounted and changed. The diagnostic was setted to work as a double colour temperature tomography: the four heads are divided in two couples, the two heads belonging to each couple lie at a 90° poloidal distance. Each couple can reconstruct indipendently the radiation pattern; if the two pairs are equipped with filters of different thickness, they can be used to measure the plasma temperature from the ratio of signal, as a normal double filter T_e diagnostic, but returning a 2D map.

Unfortunately, the double filter operation mode is still under commissioning; moreover, it requires the installation of very thick filters in order to cut the alluminium lines which add to the low frequency part of the brehmstrhlung spectrum (allumimin contribution to SXR spectrum is a problem since the plasma faces directly the shell). Being not only interested in the temperature, but mainly in informations on the plasma topology, it has been decided the filter substitution in order to rely on the whole set of 4 heads to obtain an SXR inversion.

It has been decided to mount 160 μm thickness filter; this value has been choosen interpolating the signal value as a function of current, filter thickness and discharge type (relying on data acquired before before the 2-color conversion). Signals of some tenths of nA where expected for the central chords in 500 kA standard discharges, and of hundreds of nA for 450 kA PPCDs, while the noise level is usually in the nA range. Again, the thickness could not be excessively reduced, to limit the effects of impurity in the emissivity reconstructions.

7.3.3 Others Tools

Besides SXR and TS correlation, another point of interest was the detailed characterization of a certain number of discharges, in particular to apply ORBIT [16] code end hence to Get information on the magnetic topology. ORBIT need the equilibrium of the plasma as an input, which is one of the outputs of MSTfit code [111]. MSTfit is a routinely used code which recon-

struct the magnetic configuration and returns also information confinement and transport.

MSTfit gets input data from the available diagnostics [112], using their measures as constraints for the equilibrium reconstruction; in particular, for the values of magnetic field it relies on FIR and MSE data.

The Far Infrared interferometer (FIR) [113] measures on a fan of 11 chords the line integrated density and the Faraday rotation of the probe beams (the latter being related to the line integral of the Poloidal magnetic field); the value of $|\mathbf{B}|$ on axis is returned by the motional Stark effect probe (MSE), working for a time window of 20 ms in the flattop, with a sampling rate of 10 kHz.

Ion temperatures are obtained by Charge Exchange Recombination Spectroscopy (CHERS) [114] for what concerns the impurities, and by Ruthford Scattering diagnostic for the main gas. Ruthford scattering measures the broadening in the energy spectrum of neutral particles injected in the plasma and scattered by ions, over a 3 ms window with a time resolution of 10 kHz.

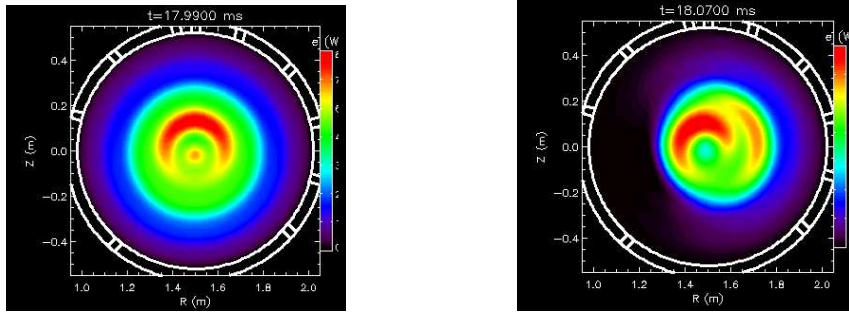


Figure 7.4: SXR inversions for a PPCD discharge, at two subsequent TS firing times, showing the rotation of the bright structure; the identification of the island phase from the SXR contour plot (fig.7.5, bottom) has been preferred to avoid aliasing effects - above, frame on the right

7.4 Experimental results

7.4.1 PPCD results

The first set of discharges was focused on 400 kA PPCD; the adopted procedure was to identify thermal structures in the TS data and then to verify the island phase at TS poloidal section relying on the soft xray and magnetic data. Actually, the phase calculation relied most on the SXR data, in order to maximize the use of direct measure: the impact parameter of the SXR maximum for each chord fan is interpolated as a function of time with a cosine function, to get information on the phase from a longer time interval.

This, known the direction and helicity of the mode rotation, identifies the "hot spot" position at TS toroidal position, which is supposed to coincide with the island O-point. The discrepancy with the magnetic measure of the mode phase are of the order of some tenths of radiant.

Not only the temperature was taken into account (see 7.5): the SXR emissivity (E) depends also on the density and the impurity content:

$$E \propto Z_{eff} n_e^2 T_e^\alpha \text{ with } \alpha \approx 1/2 \quad (7.1)$$

the role played by the density hence shall be accounted. No absolute calibration were performed on the MST Thomson Scattering neither it can be stable in time; nonetheless the interest is focused on relative variations besides absolute values. It is possible hence to look only at the variation of TS signal ($S_{TS} \propto n_e$, see chapter 2). Being the system uncalibrated, the TS signal measures essentially the product of the plasma density and the collection solid angle.

However, this value is also proportional to the beam energy, which in MST is not acquired; the method of comparing the uncalibrated profiles works if the laser energy is stable enough during the burst. All is complicated by the fact that the two lasers fire alternatively, so the comparison should be made on alternate frames; actually, only one of the laser has been found enough stable to allow a direct confront, while the data of the other could be somehow recovered normalizing the data to the profile average.

For all the considered cases, no correlations at all have been found between TS and SXR data, neither looking at temperature structures neither looking to the temperature; the samples featuring TS structures covered the complete angular distribution. On the other side, cases with favourable island position were not related to any particular variations either in density, temperature or emissivity, on a database of about 60 samples. The absence of relevant fluctuations in the density is confirmed by the interferometer data, whose line line integrated measurements remain stable within a few percents or less.

In particular, two different features should be related to a rotating hot island, that is a peaking of T_e profiles at the value of the dominant mode resonance radius, and a variations in the T_e internal gradient slope and position. The value of the n=6 resonant radius, in the examined samples, is around 80-100 mm, while it is affected by a certain uncertainty which derives from the low reliability of the reconstructed safety profile behavior in the core during PPCDs. This means that the island should be intercepted by the TS (fig. 7.2), despite the Shafranov shift on the inner flux surfaces, which is on the order of 4 cm. However, one can estimate the resonance radius on the basis of the impact parameter excursion of the maximum value for SXR chords; the latter value is approximately one half than expected. Another indication that the central peaking is not related to a rotating

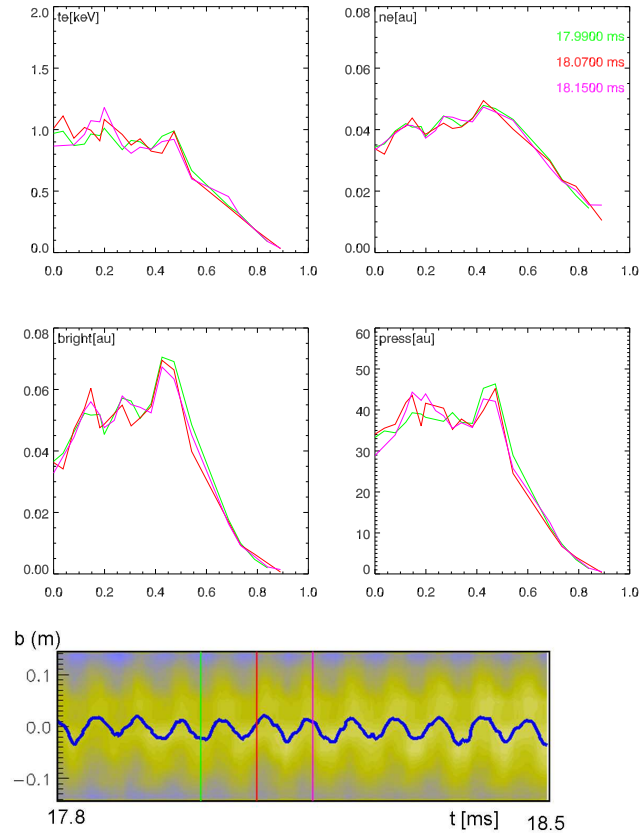


Figure 7.5: temperature, density, expected emissivity and pressure for three TS profiles acquired during a PPCD island rotation (according to the Xray contour of the impact parameter related to the maximum emissivity): no variations are found in the profiles

helical structure is the absence of shifting in the internal transport barrier radial position: if intercepted at variable values of the phase, it should show appreciable displacements, even if smaller than the value of the dominant mode resonance radius.

The entity of the variation in the local Xray emissivity can be estimated looking at tomographic inversions (fig 7.4), where $\Delta_{brightness} \approx 50\%$. Differentiating eq. 7.1, one gets $\Delta_{brightness} \approx 1/2\Delta_{T_e} + 2\Delta_{n_e}$; the conclusion is that the fluctuations in density and temperature are not sufficient to justify the emissivity variations and these could be considered an effect of selective impurity trapping in the island or the consequence of spurious contributions to the SXR signal. Actually, a source of noise is related to the geometry of the diodes array on the the SXR tomography heads: existing two different grounding points on the integrated circuit, it can behave as a pickup coil coupling to the variations of the magnetic field. An indication of the presence of this problem is the the plot of the wavelet power spectrum of the signal: the presence of a rotating island should be marked by a clear rising for the second harmonic in the central chords [105], since they intercept the island twice in its rotation. This signature is completely absent, indicating that the signal is almost completely dominated by the pickup noise (fig 7.6).

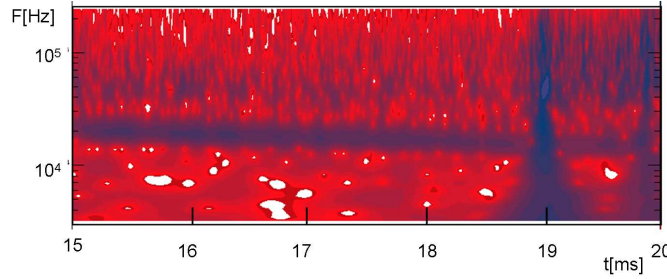


Figure 7.6: Power spectrum of the signal for a tomography chord looking to the plasma axis: while the dark horizontal strip related to the first harmonic is evident, there aren't features related to the second harmonic, which is expected to be dominant

Summarizing, SXR emissivity and temperature fluctuations are not correlated during PPCD shots. The absence of any counterpart of SXR structures in the TS data, however, can't be explained only with noise effects, since it has to face the effective detection of bright islands made with thinner filter (and so with a higher S/N ratio). A contribution from a Z_{eff} variation inside the island is definitely supposed to play a role.

7.4.2 Standard Discharges results

Data coming from standard discharges are actually easier to be interpreted: the modes are almost ever locked so SXR are not influenced by their rotation;

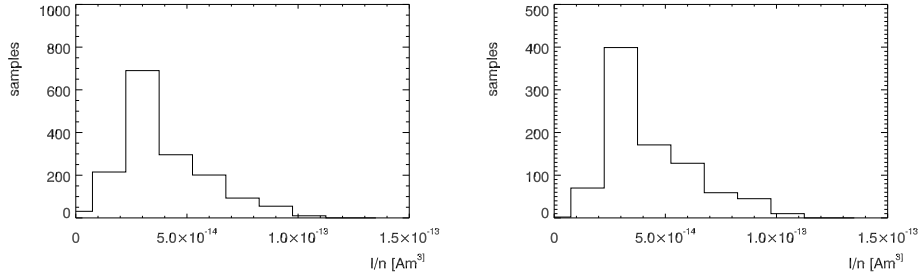


Figure 7.7: distribution of the discharge database as a function of I/N for all the sample (left) and only for the magnetic QSH (right); the distribution for the two population is very similar; here, being $I_p \approx 500 \text{ kA}$, the differences regard essentially the density, indicating that magnetic QSHs do not seem to prefer a particular density regime

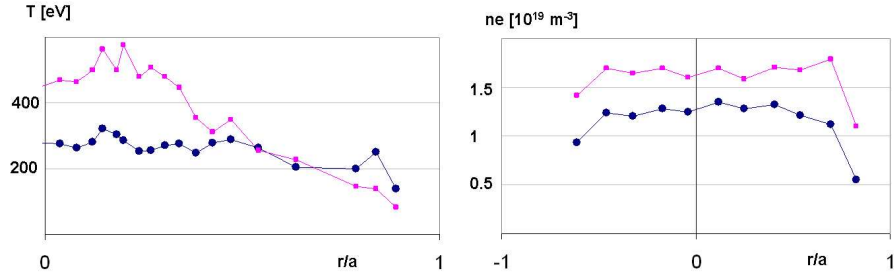


Figure 7.8: temperature and density profiles obtained in medium and high density regimes; the peaking of T_e profile is peculiar of $n_e \geq 15 \cdot 10^{19} \text{ m}^{-3}$

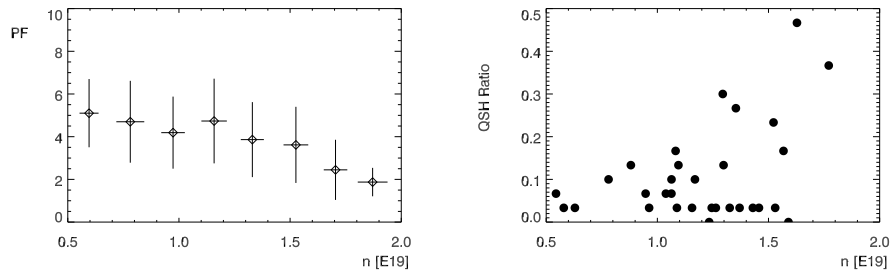


Figure 7.9: left, peaking factor of the temperature profile as density increases for magnetical QSH; right, fraction of the discharge developping a temperature peak in the core (defined as a threshold in the normalized temperature gradient); the peaking factor is defined as the exponents α in the temperature profile, once fitted with the function $T_e(r) = T_e(0)(1 - (r/a)^\alpha)$

on the other side, the temperature and hence the signal are lower. Actually, the value of $160 \mu\text{m}$ for the berillium filters was overestimated, leading, for standard discharges, to signal levels of about 10 nA ($S/N < 10$). The most important result has been the identification of a density threshold over which the magnetic QSH has a thermal counterpart, resulting in a peaking in the temperature profile in the core (fig 7.8 and 7.9); this happens as the density crosses the value of $\approx 1.5 \cdot 10^{19} \text{ m}^{-3}$, whereas the process dynamics is not clear. The temperature central peaking is not the only feature related to the density increase: the density profile itself flattens or tends to become hollow. This is similar to what happens in RFX-mod; however, in the latter the main density source is the recycling from the wall, which is supposed to be much lower for the metallic wall of MST.

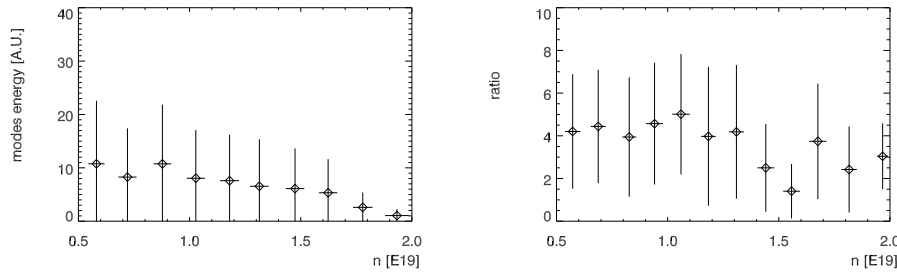


Figure 7.10: (left) the amplitude of the $m=1$ magnetic perturbations decreases as density increases but (right) there is not a defined trend regarding the ratio of the dominant energy vs the secondary one

Moreover, the overall magnetic activity decreases: there is not a defined trend in the ratio of the dominant amplitude respect to the secondaries as well as in the N_S parameter ($N_S = \sum_i (\tilde{b}_i^2 / \sum_j \tilde{b}_j^2)$)¹ For values of density approaching $2 \cdot 10^{19} \text{ m}^{-3}$ there is an increment of the relative amplitude of the $n=5$ mode, even if the statistics is too poor to get a conclusion.

To investigate the magnetic topology of such QSH states, some Poincare' plots have been reconstructed with the particle tracing code ORBIT: as expected, the effect of decrease of mode amplitude is the rising some conserved structures inside the plasma (see fig 7.11) . Actually, the aim of such reconstruction was to understand if a separatrix expulsion (DAX-SHAX transition) could be identified even in MST plasma; the problem is stricly connected to the safety profile slope in the core: in first approximation [8], the island width depend on dq/dr according to:

$$I_w \approx \sqrt{(\tilde{b}_r/B_\theta)(q/r)(dr/dq)}$$

The equilibrium has been reconstructed via the MSTfit code, which can

¹See also chapter 5

adopt different models for the equilibrium to match the experimental; among them, the $\alpha - \lambda$ model [111] has been chosen: it is a Bessel function field reconstruction which required the lower number of hypothesis (chapter 1). The use of a Bessel Function Model has been preferred also to be consistent with RFX-mod calculations, which rely on $\mu\&\pi$ model, analogous in many respects. Moreover, FIR and MSE data were not always available, in order to provide more constraints for the equilibrium reconstruction.

The secondary modes activity is still too high to define conserved surfaces at the separatrix level (fig 7.11). The decrease of the modes amplitudes as the temperature peaking suggests that the confinement (β) improvement is not simply related to the growth of a hot island: in fact the reconstructions made without accounting for the secondary modes, SHAx-like islands appear only at medium densities ($n_e < 1.2 \cdot 10^{19} m^{-3}$, where the term medium refers to sample values) whereas no temperature structure is detected in this range; coherently, the estimated island width for medium low densities returns non-physical values (half of the radius).

On the other side, a suggestion that at high density we are dealing with small, poloidally localized islands comes from SXR data. Here SXR signal is very low, but, since the island doesn't rotate, it can be integrated and averaged on fractions of ms, improving the S/N ratio. The statistic is poor and suffers from the preference of the island of remaining locked in the same poloidal position, about 90° from the TS line of sight (fig 7.12). However, the only case in which the island is intersected by the TS is also the only showing a stable bumping off from the plasma axis, while no counter examples have been found (fig 7.13).

Unlike what happens in RFX-mod [72], density variations play a relevant role in the dynamic of a locked QSH: here the TS cannot be used since we are not interested in relative fluctuations, but in absolute density values which will not change in time, given the locking of the dominant mode. However, measures from interferometer show a clear asymmetry in the density profile, which depends on the mode phase [115]. As a final remark, data on bulk ion temperature coming from Rutherford scattering did not show any particular feature during a qsh cycle, indicating that collisionality is not strong enough to permit a complete thermalization of ions with electrons. Summarizing, standard, high density discharges feature a peaking in the temperature profile closely related to the magnetic spectrum evolution. It is not yet clear if this is due only to the magnetic chaos suppression due to decreased secondary activity; there are strong indications from SXR tomography that small QSH islands are related to temperature peaking.

7.4.3 Transport and confinement in standard discharges

The same power balance model developed for RFX-mod has been used to characterize the transport and confinement features of standard QSH

in MST: here is not necessary to rely on the SXR measure to follow the time evolution of the discharge, given the high repetition rate of Thomson scattering.

The MSTfit code is actually able to reconstruct the electron diffusivity in a consistent way with other quantities. Nonetheless, we were interested in a direct comparison of the two machines, relying on the same hypothesis setup and working tools: coherently, MSTfit has been used only for the equilibrium and current reconstruction, while the electron diffusivity, β_e and τ_e were evaluated directly from temperature and density profiles.

The results (fig 7.14) is somehow interesting because, at the same values of normalized radius, the level of diffusivity and its time evolution are quite similar to RFX-mod ones. The modification in β_e along the QSH cycle is also noticeable and confirms the confinement improvement achieved at higher density (fig 7.15); β increase is directly correlated to the average temperature growth which takes place without density losses. τ_e has a less defined trend, while in single discharge a significant τ_e increase has been observed.

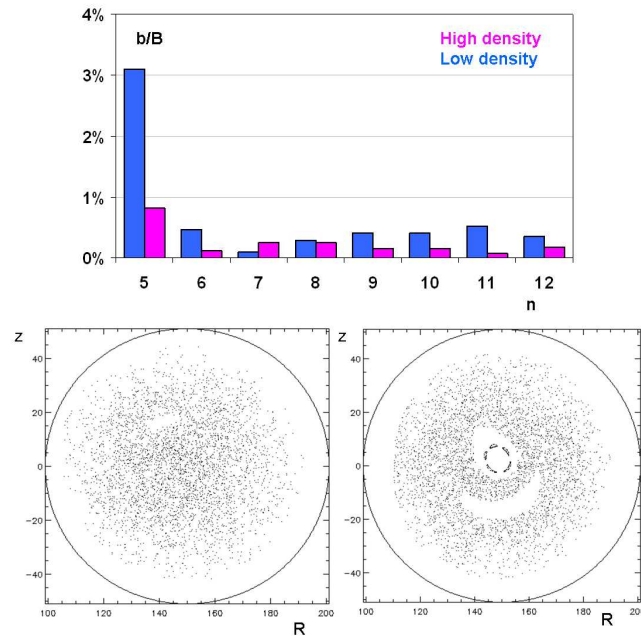


Figure 7.11: magnetic spectra for different density regimes and related ORBIT Poincaré Plots: on the right, at higher density a island-shaped structure begins to appear

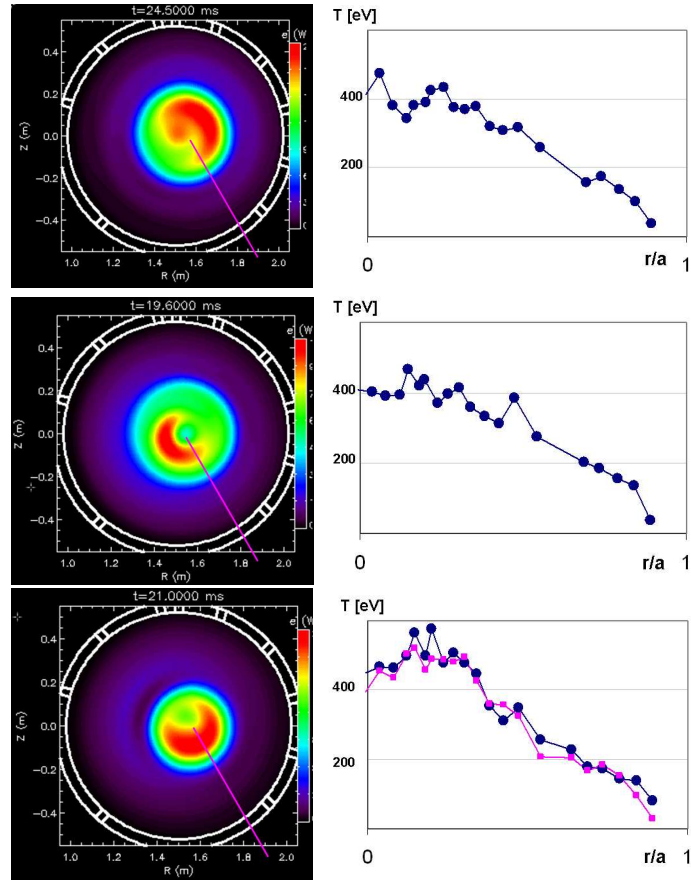


Figure 7.12: Three different positions of the island in SXR reconstructions (magenta show the equivalent position of TS once accounted for the mode helicity) and the related temperature profiles: the last case, the only in which the island is exactly intercepted, is also the only to show a stable off-axis peaking, of the order of 100 eV

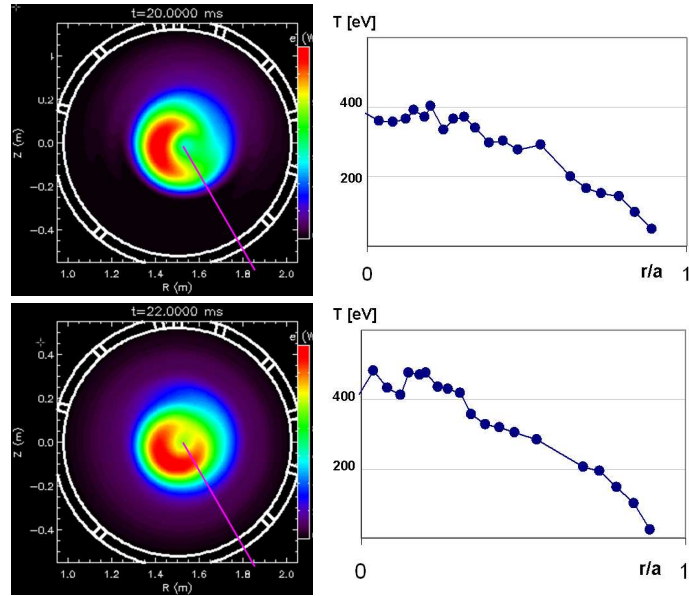


Figure 7.13: example of a moderate temperature peaking associated with the island rotation toward the TS line of sight. Even if the effect should be deconvolved from the overall temperature rising due to the magnetic QSH growth (which regards the whole profile), a small peaking in the core region is observed.

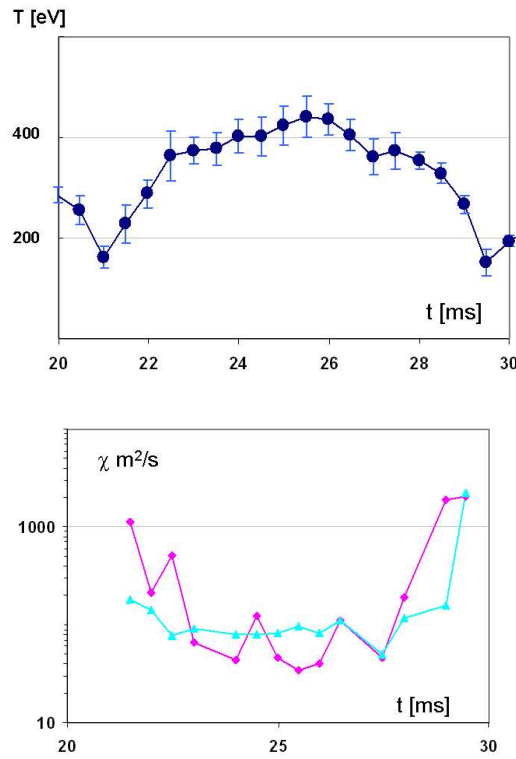


Figure 7.14: evolution of the core averaged temperature and of the electron diffusivity (magenta refers to $r/a=0.8$, cyan to $r/a=0.5$); this figure can be confronted with 6.4.3, showing a very similar behavior with respect to RFX-mod. The rising of T_e profile corresponds to the magnetic QSH phase (not shown)

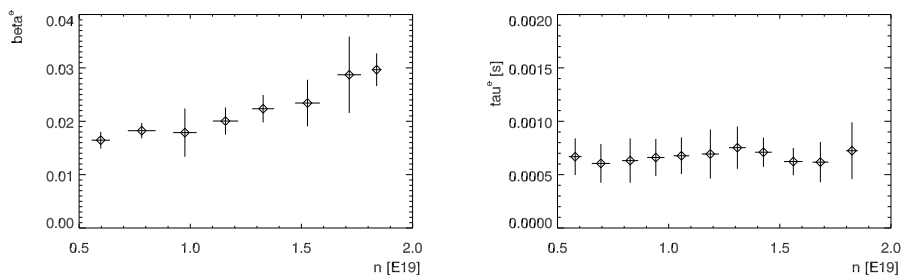


Figure 7.15: β_e and τ_e values in QSH states as a function of density

Chapter 8

Conclusions and future work

8.1 Conclusions

During my Ph.D. course, I have been involved both in experimental and analysis activity. As far as the first is concerned, the main topic has been the implementation and commissioning of the Edge Thomson scattering diagnostic to measure T_e and n_e profiles in the outer region of the RFX-mod experiment. I have the responsibility for the development of a impurity injection system based on laser blow-off, exploiting the laser of the Edge TS. Concerning the analysis, I have been strongly involved in the electron transport characterization mainly on RFX-mod, and partially also on the MST experiments. The results I have obtained in these three years can be summarized as following:

- The Edge TS diagnostic on RFX-mod started to operate in a reliable way during 2008, providing temperature and density profiles in a region covered by none diagnostic in RFX-mod. This was possible only after a change of spectrometer which increased S/N ratio allowing for reliable measurements both also at low density values (low S) and with high background (plasma) light level.
- The LBO System of RFX mod was successfully developed and commissioned, being able to inject metal (nickel predominantly) impurities in the plasma; data coming from such system proved to be useful in the characterization of RFX-mod QSH plasmas.
- Analysis and tools developed for 2D and 1D time resolved heat transport studies were able to identify specific features of QSH plasmas, both at the edge of plasma and in the core.
- The comparison work with MST experiment enlightened specific analogies and differences between the two experiments in the temperature and transport characterization during QSH states.

8.2 Developments and future work

As far as concerns future developments of this work, it is mainly related to the final commissioning of Edge TS diagnostic, in particular for multi-pulse operation and lower density operation ($1 \cdot 10^{19} m^{-3}$); practically, this latter will be possible after last planned improvement of collection optics. Further software work is required to make edge TS data available on the mainstream RFX-mod database; the possibility of adopting the same IDL routines used for Edge TS also in the main TS analysis system (now working with Fortran90) is being considered.

Laser blow off will require only minor mechanical modifications, in particular for the imaging system. On the analysis side, the development of tools for electron diffusivity study has to be implemented taking into account the exact current and ohmic power distribution.

My collaboration with MST is supposed to last at for other few months, both for QSH analysis and for some hardware test on MST fast thomson scattering. Complementary activities are the update of temperature databases, which will be carried on next experimental campaigns, and the upgrade of the Main TS diagnostic after the purchasing of a new laser at the end of 2010.

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