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FAR-INFRARED POLARIMETRY IN FUSION PLASMAS: INSTRUMENTS AND DATA ANALYSIS IN RFX-MOD AND JET

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“You will begin to touch heaven, Jonathan, in the moment that you touch perfect speed. And that isn’t flying a thousand miles an hour, or a million, or flying at the speed of light. Because any number is a limit, and perfection doesn’t have limits. Perfect speed, my son, is being there.”

Jonathan Livingston Seagull by Richard Bach

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Abstract

This thesis reports the work performed during the three years of my PH.D. course at the Electrical Engineering Department of the University of Padova. Most of my research activity has been carried out at Consorzio RFX¹ (Padova) where the RFX-mod experiment is located. RFX-mod (Reversed Field eXperiment-MODified) is the largest toroidal device built to study magnetically confined plasmas of thermonuclear interest in the so-called *Reversed Field Pinch* (RFP) configuration.

The RFP, together with the Tokamak and the Stellarator, is one of the main configurations used to confine plasmas in toroidal devices with the purpose of studying controlled thermonuclear fusion as an energy source. The energy production by fusion in magnetically confined plasmas is an ambitious and important goal, which could contribute to solve the problem of a sustainable energy source for mankind. To be an efficient energy source, a sufficiently dense and hot plasma must be confined for a time long enough. In order to fulfill this goal, energy and particle losses, heating properties, transport and energy confinement must be understood and eventually controlled. One of the most interesting characteristics of RFP plasmas, discovered in the last years in RFX-mod, concerned particular self-organized regimes (SHAx) where transport barriers are observed and the confinement is improved with respect to the traditional RFP configurations. These plasma configurations are characterized by a spectrum of the MHD modes leaded by few but well defined components and by the presence of high temperature and high X emissivity plasma regions. The most recent works suggest that the structure of the modes is strongly related to the profiles of the magnetic field. The measurement of the magnetic fields in the inner regions of the plasma is very important for understanding these plasma configurations. My research activity aimed to experimentally investigate the profiles of the magnetic fields by Far Infrared (FIR) polarimetry in order to characterize such particular plasma regimes and to compare them with the traditional ones.

The measurement of the profiles of the magnetic fields in RFX-mod is performed by a Far Infrared polarimeter. This diagnostic is based on the measurement of Faraday rotation angle. In fact a radiation propagating through a magnetically

¹<http://www.igi.cnr.it>

confined plasma suffers a rotation of its polarization plane that is proportional to the line integrated product of the electron density multiplied by the component of the magnetic field parallel to the propagation direction.

My research activity concentrated in the measurements and analyses of the polarimetric effects of the plasma column on a radiation probing it, in order to obtain detailed information about the distribution of the magnetic fields inside the plasma. In particular I have been involved into laboratory activities and also in the installation, operation and optimization of the FIR polarimeter in RFX-mod machine. The analysis of the data obtained by this diagnostic allowed me to characterize the plasma column and to get information about the evolution of the magnetic fields inside the plasma during the discharge. In fact, the polarimetric measurements together with the electron density measurements, allow the reconstruction of the profile of the poloidal magnetic field and thus the reconstruction of the position of the magnetic inner surfaces, in particular of the magnetic axis. Given these information it is possible to estimate the plasma current and therefore the safety factor q .

My research activity carried out at Consorzio RFX, concerned the installation of the polarimeter in the RFX-mod machine. After several tests in laboratory, the diagnostic has been fully mounted and the entire optical line has been aligned by a visible laser previously put on the FIR beam. The additional activities done to make the polarimeter operative are reported in detail. Innovative acquisition modules have been adopted allowing to acquire many samples with a sampling frequency up to 25kHz. Moreover I contributed to the development and implementation of a software which processes the raw data coming from the detectors and it gives out the Faraday rotation angle in real time. All these activities allowed me to obtain the first polarimetric measurements along five channels.

The international context of fusion science and the cooperation with other European Associations involved in the European fusion program, i.e. CEA (F) and CCFE (UK), allowed me to be in contact with many fusion experts and to personally contribute to some advanced aspects of the European and international scientific research, recently reached. In particular, I spent four months at the Culham Research Centre (UK), where the JET machine is sited. During that period I studied in depth the interferometer/polarimeter operating at JET, analyzing its optical characteristics and testing some models useful to obtain measurements of the electron density from polarimetric data. I contributed to the implementation of a code for the raw data processing and I tested some procedures which starting from raw data evaluate all the polarimetric effects of the plasmas accounting of the properties of the optical beam path.

This thesis focuses on the main results obtained at RFX-mod and JET machines. The first measurements performed with the polarimeter installed in RFX-mod during my PhD, are reported. Regarding the activity at JET, this thesis describes the results that confirm the polarimeter can provide reliable information of the electron density, very useful for the real time control.

The thesis is organized as it follows:

- In *Chapter 1* the polarization of light is introduced, describing some important historical stages which led to the discovery of this fundamental property of the light. In this chapter the light is represented as an electromagnetic wave and its components are mathematically expressed as sinusoids. At the end the concept of polarimetry, as technique to measure the polarization state of a radiation, is introduced.
- The *Chapter 2* introduces the issues of energy production, highlighting the main characteristics that a new energy source needs; the thermonuclear magnetic fusion is presented as an effective actor in the future energetic outline. A description of the physics of magnetic confinement equilibria and, with more detail of the RFP and Tokamak, is given.
- In *Chapter 3* the basic theory of polarimetry and interferometry is introduced. The Stokes and Mueller formalisms for the description of the polarization state of a radiation are described. Some polarimetric and interferometric techniques are discussed.
- The *Chapter 4* is focused in the activities carried out at the RFX-mod machine. In this chapter RFX-mod is briefly described with details on the set of diagnostics. The entire setup of the polarimeter is accurately described and the first results are presented and compared with the theoretical values evaluated according to models.
- The *Chapter 5* is focused in the activities carried out at JET. In this chapter the JET experiment is briefly introduced and an overview of diagnostics is given. The entire polarimeter/interferometer system is described and the measurements of the electron density obtained by Cotton Mouton values are presented and discussed. The preliminary results of an investigation performed to understand the source of an anomaly behaviour of the calibration data are reported. Finally the polarimetric results evaluated by a new raw data processing code are shown.

Prefazione

In questa tesi vengono riassunte le attività scientifiche svolte nei tre anni della Scuola di Dottorato in Ingegneria Industriale, indirizzo Energetica. La mia attività si è svolta principalmente presso il Consorzio RFX² a Padova, dove ha sede il più grande esperimento toroidale per lo studio dei plasmi confinati magneticamente nella cosiddetta configurazione *reversed field pinch* (RFP).

La configurazione RFP, insieme con i tokamak e gli stellarator, risulta una delle maggiori configurazioni per confinare i plasmi in esperimenti toroidali, con lo scopo di studiare la fusione termonucleare come sorgente di energia. La produzione di energia attraverso la fusione in plasmi confinati magneticamente è un ambizioso e importante obiettivo, che potrebbe contribuire a risolvere il problema di una sorgente sostenibile di energia per tutta l'umanità. Per essere una sorgente di energia efficiente, un plasma sufficientemente denso e caldo deve essere confinato per un tempo sufficientemente lungo. A questo scopo, in relazione alle proprietà di riscaldamento, del trasporto e del confinamento dell'energia del plasma, il mio progetto di ricerca ha riguardato lo studio sperimentale delle configurazioni magnetiche nei plasmi di tipo Reversed Field Pinch, mediante tecniche di polarimetria nel lontano infrarosso. Una delle caratteristiche più interessanti dei plasmi RFP emerse negli ultimi anni sia nell'esperimento RFX-mod di Padova che in altre macchine RFP, è stata la scoperta di configurazioni magnetiche che si caratterizzano sperimentalmente per proprietà di riscaldamento, trasporto e confinamento dell'energia superiori a quelle delle configurazioni RFP tradizionali. Queste configurazioni di plasma sono caratterizzate da uno spettro dei modi MHD dominato da poche e ben definite componenti e dalla presenza di regioni di plasma ad alta temperatura e emissività X. Gli studi più recenti suggeriscono che la struttura dei modi sia fortemente correlata ai profili di campo magnetico, la cui misura sperimentale nelle regioni interne del plasma riveste una importanza decisiva per lo studio di queste configurazioni. Il progetto di ricerca proposto prevede appunto lo studio sperimentale del campo magnetico di queste configurazioni e il confronto con quelle tradizionali.

Dal punto di vista sperimentale, per la misura dei profili di campo magnetico

²<http://www.igi.cnr.it>

nell'esperimento RFX-mod si utilizza una diagnostica polarimetrica. Questa tecnica si basa sulla misura della rotazione del piano di polarizzazione (rotazione di Faraday) di un fascio laser nel lontano infrarosso (FIR), dovuta alla propagazione nel plasma magnetizzato. Tale rotazione è proporzionale all'integrale di linea del prodotto tra la densità elettronica locale e la componente del campo magnetico parallela alla direzione di propagazione della radiazione.

Al fine di ottenere informazioni sulla distribuzione dei campi magnetici all'interno della colonna di plasma, la mia attività di ricerca è stata focalizzata sulla misura e sull'analisi degli effetti polarimetrici del plasma stesso su una radiazione che lo attraversa. In particolare, sono stato coinvolto in esperimenti e attività di laboratorio, nell'allestimento, nell'operazione e ottimizzazione del polarimetro FIR presso la macchina RFX-mod. L'analisi dei dati raccolti con questa diagnostica mi ha consentito di caratterizzare la colonna di plasma e di fornire informazioni sull'evoluzione dei campi magnetici al suo interno. Come detto sopra, le misure polarimetriche associate a misure della densità elettronica, permettono la ricostruzione del profilo di campo poloidale e il monitoraggio della posizione delle superfici magnetiche interne, in particolare dell'asse magnetico. Da queste informazioni è possibile risalire alla misura della corrente di plasma e quindi alla misura del fattore di sicurezza q .

La mia attività di ricerca svolta sull'esperimento RFX-mod ha riguardato la messa in funzione del nuovo polarimetro come diagnostica di RFX-mod. Dopo aver completato tutti i test di funzionamento in laboratorio la diagnostica è stata installata sulla macchina e ivi ultimati gli allineamenti con la sorgente laser FIR. Le attività accessorie svolte per la messa in funzione della diagnostica sono descritte nel dettaglio in questa tesi. Sono stati installati dei moduli di acquisizione che permettono di acquisire più segnali con una frequenza di campionamento fino a 25kHz. Ho contribuito allo sviluppo di un software che elabora i segnali grezzi provenienti dai rivelatori e fornisce in uscita la misura dell'angolo di Faraday in tempo reale. Tutte queste attività mi hanno permesso di ottenere le prime misure di effetto Faraday su cinque canali, grazie a cui, come detto prima, è possibile caratterizzare il plasma.

Il contesto internazionale delle ricerche e la collaborazione con altre Associazioni Europee coinvolte nel programma fusione Europeo, CEA (F) e CCFE (UK), hanno favorito numerosi contatti con esperti internazionali e la possibilità di contribuire in prima persona agli aspetti più avanzati della ricerca scientifica in sede Europea e internazionale maturata negli anni più recenti. In questo ambito ho trascorso un periodo di tempo presso l'esperimento JET (Joint European Torus) del Culham Science Centre (UK). Durante queste visite ho approfondito lo studio della diagnostica Interferometro/Polarimetro operante presso la macchina JET, analizzandone le caratteristiche ottiche e mettendo a punto dei modelli per ricavare la misura di densità dalle informazioni polarimetriche. Ho contribuito in maniera significativa alla scrittura del codice per l'elaborazione dei dati forniti dalla diagnostica mettendo a punto procedimenti di calcolo che a partire dai dati grezzi, calcolano tutti i parametri polarimetrici del plasma tenendo conto delle caratteristiche del percorso ottico compiuto dal fascio laser di misura.

Questa tesi descrive i risultati ottenuti presso i due esperimenti RFX-mod e JET. Nel caso di RFX-mod si riportano i primi risultati ottenuti con il polarimetro installato durante il periodo del dottorato. Nel caso di JET si riportano dei risultati che confermano la possibilità della diagnostica di fornire misure polarimetriche tali da poter ricavare informazioni sulla densità elettronica utili per il controllo in tempo reale della scarica.

La tesi è strutturata come segue:

- Nel *Capitolo 1* viene introdotto il concetto di polarizzazione della luce, attraverso la descrizione di alcune tappe di interesse storico scientifico che hanno condotto alla scoperta di questa importante caratteristica della luce. In questo capitolo la luce è rappresentata in termini di onda elettromagnetica e le sue componenti sono espresse matematicamente come sinusoidi. Infine viene introdotto il concetto di polarimetria come strumento per la misura e la determinazione dello stato di polarizzazione di una radiazione.
- Il *Capitolo 2* introduce il problema della produzione di energia, evidenziando le principali caratteristiche che una nuova fonte di energia deve avere: la fusione termionucleare a confinamento magnetico è presentata come un attore importante nel futuro panorama energetico. Viene fornita la descrizione della fisica degli equilibri magnetici per il confinamento nel caso di macchina di tipo Reversed Field Pinch e Tokamak.
- Nel *Capitolo 3* vengono presentati i concetti base della polarimetria e dell'interferometria. Vengono descritti i formalismi di Stokes e Mueller per la descrizione dello stato di polarizzazione di un'onda. Inoltre vengono discusse alcune tecniche interferometriche.
- Il *Capitolo 4* è dedicato all'attività svolta presso la macchina RFX-mod. In questo capitolo viene descritto brevemente l'esperimento RFX-mod con un dettaglio sulle diagnostiche installate. Si passa poi alla descrizione puntuale del set-up del polarimetro per arrivare ai primi risultati ottenuti. I risultati vengono confrontati con i valori attesi secondo alcuni modelli teorici.
- Il *Capitolo 5* è dedicato all'attività svolta presso la macchina JET. In questo capitolo viene descritto brevemente l'esperimento JET con un dettaglio sulle diagnostiche installate. Si passa poi alla descrizione puntuale del set-up del polarimetro-interferometro per arrivare ai risultati ottenuti nella ricostruzione del profilo di densità elettronica dalle misure di effetto Cotton Mouton. Si presentano i risultati di un lavoro svolto a capire un comportamento anomalo delle misure del polarimetro in fase di calibrazione. Infine si mostrano i primi risultati ottenuti con un nuovo codice di rielaborazione dei dati grezzi.

CHAPTER 1

Polarization of light

During the centuries up to the present day, many philosophers and scientists contributed to understand the nature of light. As well as for other theories, the discovery of the polarized light seems to have many fathers, some belonging to the legend some to the history of science. Some scholars award the discovery of the polarization to the Vikings, who might have used the polarization of the sky for navigation. In the Icelandic sagas, which probably are a mixture of true history and fiction, the story of how the Viking discovered the dichroic properties of crystals like Sunstone¹ is reported. By means of these crystals they observed the polarization of the blue sky and they could navigate in the absence of sun. The stone, a mineral called Icelandic spar², changes color as it is turned in the light. A certain color indicates the position of the sun through the fog or clouds but can only be used when there is at least a sliver of blue sky. These dissertations belong to a mythological context but they have a romantic appeal as it stands out reading the following brief tale:

A Viking ship is late in its return home from the newly discovered lands far west. Winter is around the corner and the weather will soon turn ugly. It's imperative that the helmsman maintains the course due East. But where exactly is Home? The sky is becoming more cloudy every passing day. Most nights the stars are not visible and even during the day the sun has difficulty breaking through. Daylight is short and during good part the sun illuminates the sky from below the horizon...somewhere. Hanging from the top of the knorrship mast a sailor squints his eyes looking for clues in the brightness of the clouds...to no avail. Then Leif the Lucky spots an opening in the clouds. He reaches for the pouch hanging from his waist and takes out his Sunstone. Through the crystal he looks at the small patch of blue sky. He turns the rock until it becomes yellow. Next he shouts to the helmsman with his stretched arm pointing starboard...towards Home [1, 2].

No direct evidence of these facts has been found. However some scholars [3] have tried to use the sky compass and they demystified many aspects of Viking navi-

¹Sunstone is a plagioclase feldspar, which when viewed from certain directions exhibits a brilliant spangles appearance; this has led to its use as a gemstone.

²<http://www.mindat.org/min-4900.html>

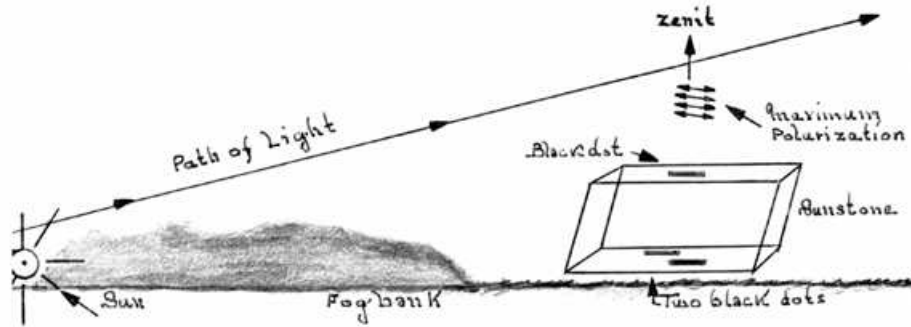


Figure 1.1: Drawing of the Sunstone principle to determine the position of the sun. The sky compass is particular reliable at the sunrise or at sunset, when the light from zenith is completely polarized [3]

gation explaining for example the principle of the sky compass. Looking at figure 1.1, the unpolarized sunlight at horizon is scattered by the earth's atmosphere and becomes plane polarized. The crystal behaves as an analyzer for light arising from the zenith, and it is turned until the darkest or strongest reaction is determined. The position of the crystal related to these events allows to determine the position of the sun with respect to the direction of navigation.

Even if many people don't trust this theory, it cannot be contradicted that the Iceland Spar has been involved in the official discovery of polarization.

1.1 The discovery of the polarized light

The discoverer of the polarization of the light may be considered a Danish mathematician at the University of Copenhagen, **Erasmus Bartholinus** (1625 - 1698), who saw the phenomenon of double refraction in calcite crystals. In fact this naturally transparent crystal (CaCO_3) separates an image into two displaced images when looked through in certain directions. This was the first scientific description of a polarization effect.

It was followed by the work of **Christian Huygens** (1629 - 1695), who was able to interpret the double refraction by assuming that in the calcspar crystal there is, in addition to a primary spherical wave, a secondary ellipsoidal wave. The "*Huygens Principle*" [4] considers each point on a wavefront the source of spherical wavefronts that add up to build the propagating wavefront. During his investigations, Huygens made the fundamental discovery of the polarization: each of two rays produced by the refraction from the crystal could be extinguished by passing through a second crystal of the same material when the latter was rotated at a particular position with respect to the former. This meant that each of the two beams were different to ordinary light, which, as further said, is not polarized. Huygens interpretation was that the crystal impressed a peculiar disposition into each beam while **Newton**, Huygens's rival and contrary to the wave theory, thought that the effect of double refraction indicate that particles of light were asymmetric [5].

It was only in 1808 when **Etienne Louis Malus** passed partially reflected light through a calcite crystal and found that it was polarized, naming it *the oriented*

light. Malus also expressed quantitatively the intensity of light emerging from a polarizing crystal when the input light is linearly polarized along a direction making a specific angle with the crystal's axis (the Malus's law).

The progress during the 19th century caused the role of mathematics to grow in importance in analyzing and interpreting physical phenomena: for instance, the principle of interference, which was used by **Thomas Young** to explain diffraction phenomena. Thomas Young performed a famous experiment in 1803 demonstrating interference from two closely spaced slits [6]. Explaining his results by interference of the waves arising from the two different slits, he deduced that light must propagate as waves. **Augustin Jean Fresnel** did more definitive studies and calculations of diffraction, presented in 1815 and 1818 [7], and thereby gave great support to the wave theory of light proposed by Huygens and supported by Young, against Newton's particle theory. Works on the polarization of light definitely confirmed the wave theory of the light. For example, it was shown that when two polarizer were crossed no light emerged from them. Furthermore, an interesting thing has been observed when light passed through double-refracting materials. Two beams of unpolarized light could be combined to form interference patterns, but combination of the ordinary and extraordinary beams emerging from double-refracting materials did not reproduce such patterns. These phenomena could be explained in terms of transverse waves. The experiments performed in 1849 by **Hippolyte Fizeau** and in 1862 by **Paul Michel Foucault**, measuring the velocity of light in different media, showed that the velocity of light was smaller in liquid than in air or in vacuum, the opposite of what the corpuscular theory predicted. In fact this last theory explains refraction in terms of the attraction of the light-corpuscles at the boundary towards the optically denser medium, and this implies a greater velocity in the denser medium. The direct measurement of the velocity of light in air and water decided unambiguously in favour of the wave theory.

In 1873 **James Clerk Maxwell** advanced the theory of light as electromagnetic wave, and experiments of **Heinrich Rudolf Hertz**, carried out in 1888, confirmed the predictions that electromagnetic wave produced by oscillating electric currents exhibited reflection, refraction, diffraction, interference, and polarization. Optical polarization phenomena could be also described in terms of Maxwell's equations. A major contribution in the understanding of optical polarization was made in the 19th century by numerous physicists such as **David Brewster** (polarization of light reflected by the Brewster angle), **Dominique F. Arago** who, together with Fresnel, formulated four laws governing the interference phenomenon of polarized light, **Jean B. Biot** (rotary polarization), **William Nicol** (polarizing prism), **Michael Faraday** (magnetically induced optical rotation of linear polarization, the Faraday effect described in chapter 3), and many others [8].

A significant advance to the optical research was proposed in 1852 by Sir **George Gabriel Stokes** who introduced four measurable quantities, the Stokes parameters, which allow to describe mathematically the polarization properties of light.

In the beginning of the 20th century a new view of the nature of light emerged. **Albert Einstein**, **Max Planck**, and others realized that a number of phenomena, including the energy distribution of blackbody radiation, the Compton effect, and the photoelectric effect, could not be explained in terms of light as a continuous wave of electromagnetic energy. Instead, they showed that the explanation of these

phenomena required that light be made of *photons*.

The introduction of the concept of photons produced a dilemma for the theory of light. It appeared that to interpret some experiments the wave theory of light was needed, whereas to interpret other experiments a quantum theory was needed. **Louis de Broglie** proposed the solution to this dilemma. In fact, he asserted that light exhibits both wave properties and particle properties, depending on what it interacts with. This view of the wave-particle duality of photons is the view of light most commonly held today.

In the 20th century, further developed applications of polarization of light focused attention to describe the changes in the polarization state as a result of interaction of light beam with optical elements. **Robert Clarke Jones** proposed in 1941 the Jones calculus which is based on the matrix formalism. The state of polarization is represented by a 2×1 vector and each optical element is represented by a 2×2 matrix, and the method enables to study the effect of anisotropic material on light polarization. To characterize optical devices, **Hans Mueller** proposed in 1948 the Mueller formalism, the 4×4 polarization matrix method relating the output and input Stokes 4×1 vectors [9]. This last formalism will be better treated further in chapter 3.

1.2 The wave model

Light can be represented as a transverse electromagnetic wave made up of mutually perpendicular, fluctuating electric and magnetic fields. The right side of the figure 1.2 shows the electric field in the yz plane, the magnetic field in the xz plane and the propagation of the wave in the z direction. The left side shows two lines tracing out the electric field vector and the magnetic field vector as they propagate.

The amplitude of the electric field shown in Figure 1.2 can be given by

$$E(z, t) = E_x^0 \sin[2\pi\nu t - 2\pi z/\lambda + \phi_0]. \quad (1.1)$$

This relation represents a light linearly polarized along the x direction propagating along the z direction. The frequency of the light wave is ν , λ is its wavelength, E_x^0 is the maximum amplitude, and ϕ_0 is a constant specifying its absolute phase. The frequency is often expressed as the circular frequency, $\omega = 2\pi\nu$, and the wavelength as a wave number $k = 2\pi/\lambda$, giving

$$E(z, t) = E_x^0 \sin[\omega t - kz + \phi_0]. \quad (1.2)$$

A similar expression representing the electric field of the a radiation propagating in a medium will be presented in chapter 3. The magnetic field of the light oscillates in phase with the electric field, but the magnetic field vector H is perpendicular to the electric field and it is linearly polarized along the y direction:

$$H(z, t) = H_y^0 \sin[\omega t - kz + \phi_0]. \quad (1.3)$$

For the applications discussed in this thesis, we will consider only the electric field component of the light. We will treat light as an electric field whose magnitude

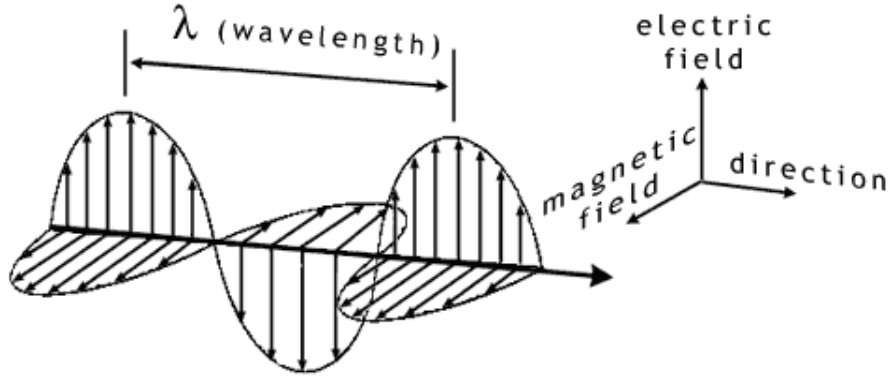


Figure 1.2: Wave picture of light showing the oscillatory nature of orthogonal electric and magnetic field vectors

oscillates in time and that, for linearly polarized light, is oriented along the polarization axis of the light, x .

The natural light is generally unpolarized, all planes of propagation being equally probable. If light is composed of two plane waves of equal amplitude differing in phase by 90° , then the light is said to be circularly polarized, which is not characterized by a vibration direction but by sense of rotation. Left handed or right handed light can be distinguished, according to the counter clockwise or clockwise motion of the wave as viewed by the observer. If two plane waves of differing amplitude are related in phase by 90° , or if the relative phase is other than 90° then the light is said to be elliptically polarized. The elliptical polarization is the most general form. For a better comprehension of the different types of polarizations see Figure 1.2.

As already said, the light is usually not completely polarized and it is called *partially polarized*. In the case of linear polarization, this means that although the vibrational plane of the wave has a preferred direction, vibration in other planes are also allowed. A partially polarized light can be considered compound by one part totally polarized and another part totally unpolarized [10]. The degree of linear polarization P is given by the intensity of light parallel to the direction of the preferential vibration plane ($I_{\parallel}$) minus the intensity of light perpendicular to it ($I_{\perp}$), divided by the total intensity. Thus:

$$P = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}. \quad (1.4)$$

Usually P is expressed in percent and varies from 0% to 100%.

1.3 Polarimetry

Polarimetry is the measurement and interpretation of the polarization of electromagnetic waves, such as radio or light waves. Typically polarimetry is performed on electromagnetic waves that have traveled through or have been reflected, refracted, or diffracted by some material in order to characterize that object.

Polarimetry can be used to measure the optical properties of a material, including

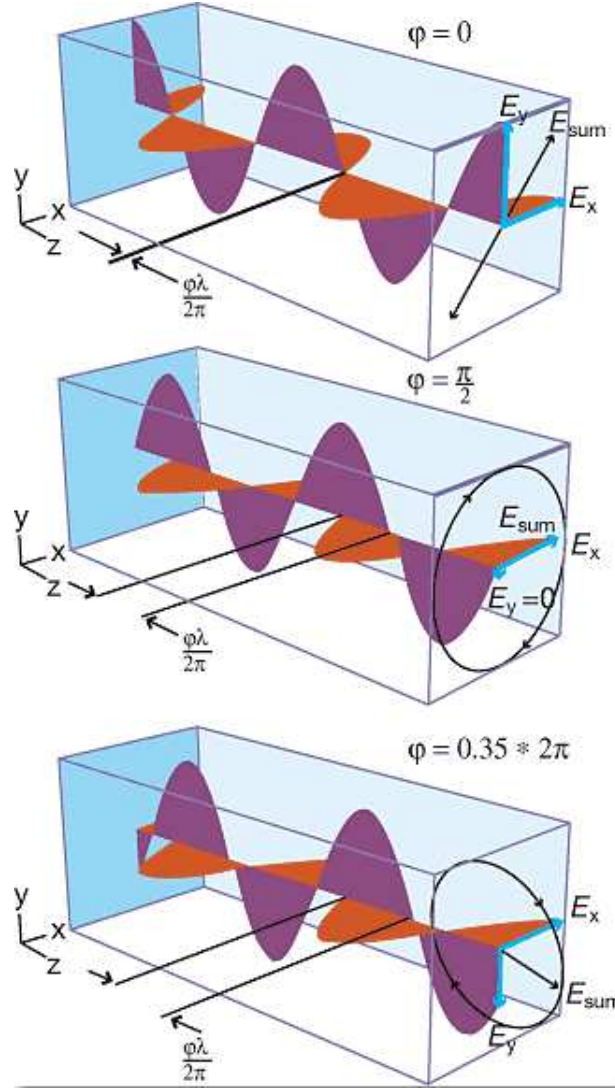


Figure 1.3: Polarized light can be represented as the sum of two orthogonal linear states. A phase delay $\varphi = 0$ between x and y components yields a resultant E_{sum} that oscillates about a line oriented at 45° (linear polarization, top graph). If $\varphi = \pi/2$, E_{sum} maintains constant magnitude but rotates about the origin (circular polarization, middle graph). An arbitrary phase delay (for example, $\varphi = 0.35 \cdot 2\pi$) yields an E_{sum} with varying magnitude and position (elliptical polarization, bottom graph).

birefringence, dichroism and scattering. There are many designs of polarimeters to measure the various properties of media (see chapter 3). Conventional polarimeters are based on arrangements of polarizing filters, wave plates or other devices, as in the case of the polarimeter operating at the RFX-mod machine and widely described in chapter 4. Polarimetry can also be used in the radar detection, considering the wave polarization to improve the characterization of the targets. In this case, polarimetry can be used to estimate the fine texture of a material and to resolve the orientation of small structures in the target.

In this thesis we will mainly discuss about the use of the Far InfraRed polarimetry to characterize the magnetically confined plasmas (Chapter 2). De Marco and Segre first introduced in 1972 polarimetry as a plasma diagnostic technique [11]. In fact they understood that the polarization changes of an electromagnetic wave propagating through the plasma could be measured to determine the distribution of the poloidal magnetic field. In particular they referred to the rotation of the polarization plane due to the Faraday effect, which depends from the component of the magnetic field parallel to the propagation direction as previously stated. Craig [12] proposed a numerical analysis method for deducing the current density and poloidal magnetic field from polarization changes suffered by an electromagnetic wave propagating across a series of chords. Thanks to this last contributions, Segre [13] further carried on this theory and he developed a simple numerical method which gives the output polarization as a function of plasma parameters (see Chapter 3).

On the basis of these theoretical models, in 1978 Kuntz experimentally tested the first infrared polarimeter. On one channel of the interferometer on TFR (FRench Tokamak)³, he performed Faraday rotation measurements using a ferrite modulation technique. In the same period Dodel and Kuntz tested the polari-interferometer proposed by Véron [14] which combined together a polarimeter and a Véron type interferometer, allowing the simultaneous measurement of the line integrated electron density and of the poloidal magnetic field profile along the same line of sight. In 1981, Soltwisch proved the feasibility of the technique performing preliminary measurements by Polari-interferometer under actual tokamak conditions on TFR 600 when one channel of the HCN laser interferometer was modified to allow simultaneous measurements of electron density (phase shift) and Faraday rotation [15]. Several other multichannel interferometers have also been modified to make polarimetric measurements using this technique, including TFTR (Tokamak Fusion Test Reactor)⁴ and JET, as further described in Chapter 5.

³The French TFR Tokamak led the world from 1973 to 1976 reaching temperatures of 2 keV. Crucial results on confinement and plasma heating have been achieved on this installation.

⁴The Tokamak Fusion Test Reactor (TFTR) operated at the Princeton Plasma Physics Laboratory (PPPL) from 1982 to 1997.

2.1 Introduction

Energy is one of the building blocks of modern society. Energy is needed to create goods from natural resources and to provide many services. Economic development and improved standards of life are complex processes that share a common denominator: the availability of an adequate and reliable supply of energy. The modernization of the West from a rural society to an affluent urban one was made possible through the employment of a modern technology based on a multitude of scientific advances. Political events, beginning with an oil embargo in 1973 and continuing through the Iranian revolution of 1979 and the Persian Gulf War of 1991, made many people aware of how crucial energy is to the everyday functioning of our society. Long gasoline lines and cold winters with natural gas shortages in the 1970s are still unhappy memories for some people. The energy crises of the 1970s were almost forgotten in the 1980s; however that decade brought an increased awareness of our environment. Concern about global warming, acid rain and radioactive waste are still very much with us today and each of these topics is related to our use of energy. In the next 25 years if the world continue to use the actual main energy sources, i.e. oil and carbon, it will be put in the atmosphere the same amount of carbon dioxide (CO_2), produced since the beginning of the industrial revolution [16] [17]. Moreover, it has been calculated that in the next 40 years, with the actual trends, the global use of electricity will increase by the 160%. We are thus at a crucial point in the history of energy and technology, since we need in the imminent future energy sources both clean and available in large amounts, if we want to preserve our standard of life and ensure it to the emerging countries of Asia and Africa. In the following of this Chapter, a brief overview on these items focusing in particular on the energy produced by fusion reactions which could allow to obtain large amounts of CO_2 -free energy in the future, is presented. A great effort has been spent in the last 50 years to achieve this important goal and there are good possibilities that fusion will become a reality before the half of

this century. The technology and the physics involved in this project are complex and have been representing a great challenge for physicist and engineers of past and present generations.

2.1.1 Energy sources and environmental problem

The Energy accompanies the evolution of mankind from its origin. From the solar energy to the geothermal one, from millennia the man tries to bridle them, to transform them, to render them available in order to construct his own development. Up to the XVII century energy was not a problem as we intend it today. When work was needed, to plow a field or to construct a palace, humans and animals gave the necessary energy to accomplish it; technology and science allowed also for using wind - in navigation - and the energy of falling water - in grinding wheat - but they were natural ways of making easier or eliminating muscle work. With industrial revolution, first in England and slowly almost everywhere on Earth, things changed drastically. With steam power, and then with electricity and combustion engines, it was possible to do everything was done before with chemical energy coming from muscles and even more, but with the big price of using energy from hydrocarbons. Still today, more than 90% of energy resources used in the world come from the fossil fuels - coal, oil and natural gas. Except for coal, the supply of these fuels at present rate might not last much longer than the lifetimes of the people now living. The fuel most commonly used, oil, appears to be in the shortest supply worldwide, but continues to be that commodity on which we rely most heavily. Indeed, dependence on oil, especially for transportation, leaves many countries quite vulnerable to a major economic disaster in the event of an oil shortage or interruption in supply. The consumption of fossil fuels can be measured by estimating the tons of carbon dioxide that have been released into the atmosphere in the last decades. An example of such analysis is presented in Fig. 2.1 where data take into account the different origins. The main message from this figure is that, since the industrial revolution, consumption of the hydrocarbons is increasing almost exponentially, and with the countries that now enter in the great economical competition things are not likely to get better. An obvious second conclusion from this plot is that world energy needs are increasing. Every day we use more than 80 million barrels of oil and close to 9 billion cubic meter of natural gas, which are no renewable sources. Reserves are thus limited and are diminishing.

The Association for the Study of Peak Oil and Gas (ASPO), based on current information about known oil reserves, estimates of future discovery, growing oil demand, and available technology, predicts that world oil production will peak in the next few years ¹. Even if other estimations are more optimistic, and new technology discoveries would allow in the future for easier extraction from places where now is difficult (or too expensive) to extract, the problem of finite resources remains open. Fossil fuels present also an other negative aspect, beyond their limited and non-uniform distribution over the Earth. In fact, energy is produced during their combustion; during this process, large amounts of carbon dioxide are released

¹www.peakoil.net

in the atmosphere. In the last 20 years there have been indications that the consumption of fossil fuels will have detrimental effects on our climate as a result of the accumulation of CO_2 in the atmosphere. The result of higher concentration of carbon dioxide is the strengthening of the greenhouse effect, which results mainly in the raise of temperature shown in Fig. 2.2. An evident increase, that coincides with good approximation with the beginning of our industrial revolution, is clear. The connection with increasing emissions of combustion residual shown in Fig. 2.2 is quite straightforward, and the correlation between the two data is very strong [18]. Numerical models show that without increase in annual fossil consumption between now and the year 2100, we should expect an average temperature rise of approximately 1°C by 2100. A faster rate of growth would lead to a temperature rise amounting approximately to $3\div 5^\circ\text{C}$ by the year 2100. Anyway it is only with great difficulty that the climatic effects of CO_2 can be distinguished from natural fluctuations in the yearly average temperature. In addition to the problem of CO_2 concentration in the atmosphere, many of the known reserves of coal and oil contain large amounts (several percent) of sulfur. The combustion of this sulfur-laden fuel has large scale detrimental environmental effects. In the combustion process, the sulfur combines with oxygen to form sulfur dioxide, which is vented with the stack gases in the atmosphere. The sulfur dioxide reacts with water vapor to form acids which are detrimental to fish and plant life. Acid rain tends also to acidify soil, thus retarding the growth of trees that are incapable of coping with the changed environment, such as some pines. The effects of acid rain have been the subject of international conferences and the problems of acid rain has made it necessary either to install expensive scrubbers to remove sulfur before combustion occurs, or to develop atmospheric fluidized bed combustion technology to remove sulfur during the combustion process. Anyway, up to now many factories still continue to use fossil fuels without removing the sulfur, especially in the emerging countries like China. Regardless of the role of CO_2 in the global warming and its consequences, that we don't really know and about which many opinions still coexist, we have necessary and sufficient reasons to greatly restrict and/or cease to burn fossil fuels before known reserves are exhausted.

2.1.2 Alternative to fossil fuels

Many alternative energy sources have been suggested and even implemented on a small scale. These include wind power, tidal power, geothermal power, combustion of wood and biomass, hydroelectric power and solar energy. These alternative or renewable energy sources are not too promising as long term energy options, certainly not for the energy requirements implied by projections of our level of consumption. Many of these alternate energy sources are restricted to particular geological or geographic sites (tidal, geothermal, hydroelectric) and/or tend to be least available when most needed (solar energy at night or in the winter), and/or cannot be turned on and off at will to meet the power demand curve of an electric utility. Even if they are increasing in importance due to technological breakthroughs, up to now they cover less than the 10%, the most coming from hydroelectric (7%). These alternate energy sources will be useful only to supplement a source of primary power that can be turned off and on at will and that produces

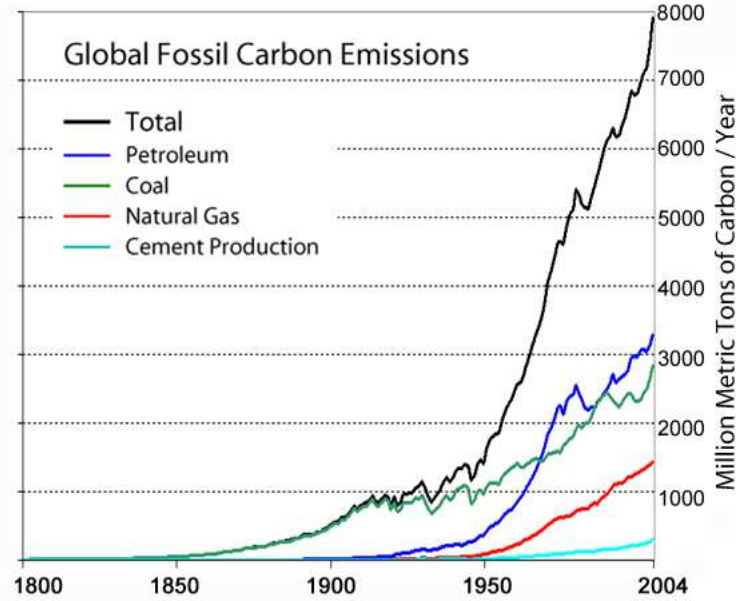


Figure 2.1: Annual carbon dioxide emission broken down into various fuel types during the years 1800÷2000 expressed in million metric tons of carbon. In the graph the increasing rate at which fossil fuels are being consumed is shown. Data taken from [19].

electrical power at an acceptable price for industry and the electric utilities. The other important source of energy used so far to fulfill world energy needs is the nuclear power. As we will see, this definition lacks of precision, since it usually refers only to one of the two nuclear reactions that can be used to generate energy, the nuclear fission. In this process the nucleus of an atom splits into two or more smaller nuclei and usually some by-product particles, emitting energy in the form of gamma and other radiation.

Up to now nuclear power provides about 20% of the world's electricity. But the use of Uranium fission to generate electricity is still controversial because of the problem of storing radioactive waste for indefinite periods, the potential for possibly severe radioactive contamination by accident or sabotage, and the possibility that its use could lead in some countries to the proliferation of nuclear weapons. In addition many detractors claim nuclear power is an uneconomic, unsound energy source, especially compared to renewable energy. Moreover, Uranium is again a non-renewable resource and, at the present rate of use, there are 50 years left of low-cost known Uranium reserves. Nuclear fission can be thus an alternate energy source in the next decades which may allow for a reduction of CO₂ from fossil fuels combustion. Anyway since the reserves of Uranium are limited, it is necessary to consider other solutions. As stated previously fission is not the only way to extract the nuclear energy from atom. The inverse process, fusion, has interesting and positive features both relative to the environment preservation and to the availability of energy.

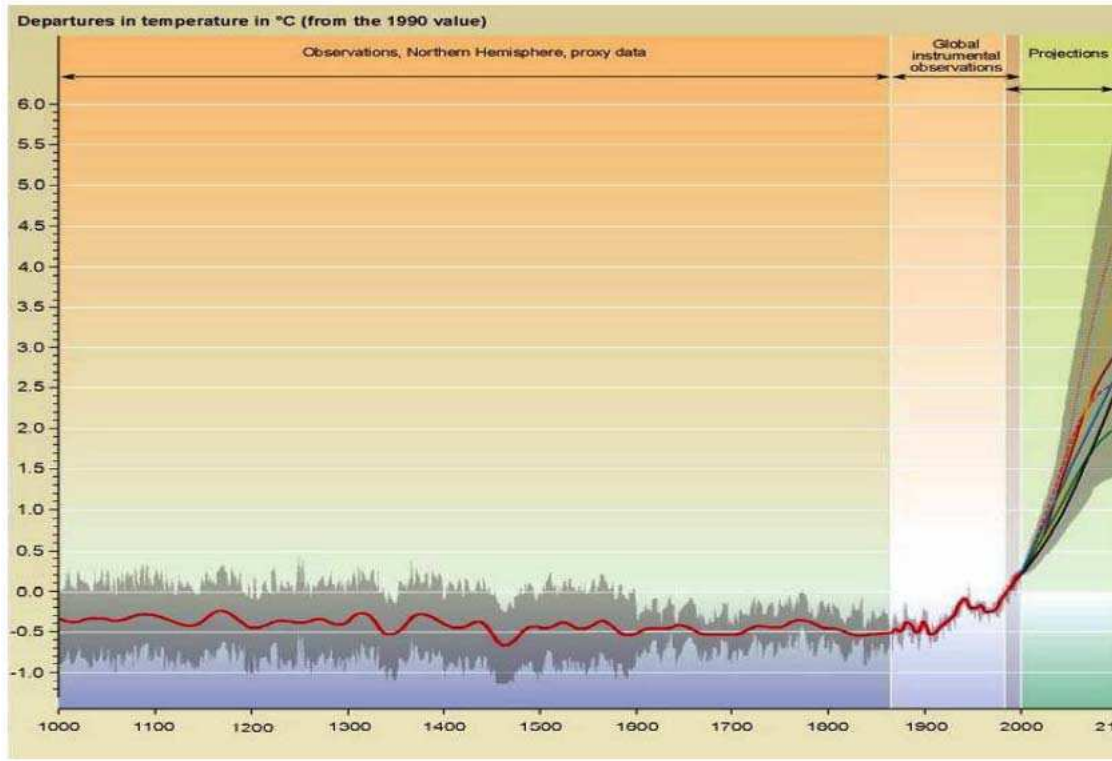
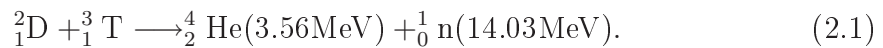


Figure 2.2: *Evolution of average Earth temperature in the northern hemisphere in the last 1000 years.*

2.2 Thermonuclear fusion

In nuclear fusion, two light nuclei fuse into a heavier one, releasing energy in the form of kinetic energy of the reaction products. This phenomenon is common in nature (for example, in the stars) and has been investigated by scientists in the second half of the 20th century in order to realize controlled fusion reactions on earth for peaceful purposes. Two light nuclei fuse only if they get close enough for the short-range attractive nuclear force to overcome by quantum tunneling the Coulomb repulsion. This is achieved if the two reactants collide with high enough kinetic energy; a significant number of fusion reactions therefore occurs if matter is brought to sufficiently high density and temperature for a sufficiently long time. In this condition, matter is in the so-called **plasma** state, which is a neutral ensemble of ions and electrons [20]. Promising methods to realize fusion conditions in laboratory are the magnetic and inertial confinement (the latter topic is not matter of interest of this thesis). In magnetic confinement experiments [21], magnetic fields allow for confining matter in plasma state: in fact, charged particles perform a Larmor motion along the field lines, and therefore motion in the direction perpendicular to magnetic field is limited to the Larmor radius $\rho = mv_{\perp}/eB$. This allows particles to be confined for a sufficient time to be heated and achieve the critical condition for the fusion reaction. Many fusion reactions can occur; the easiest to realize involves Deuterium (D) and Tritium (T) (see Fig. 2.3):



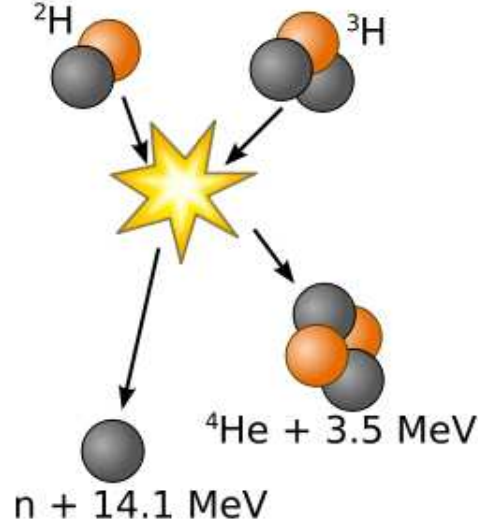


Figure 2.3: *Fusion reaction*

For this reaction the cross-section peaks at the ion temperature of $\sim 100 \text{ keV}$. Deuterium (D) resources are practically endless on earth (about 2mg of D are contained in 50 liters of sea water). Tritium (T) is radioactive, with a 12.3 year life time, but it can be produced in a fusion device by exposing a Lithium mantle to fusion neutrons. Lithium resources are practically endless too, since they can be derived from earth rocks.

In a fusion reactor, the energy produced by fusion reactions must exceed the energy required for creating and sustaining the plasma. If n is the plasma density, T its temperature and τ_E the energy confinement time, the **Lawson's criterion** [22] for the sustainment of a plasma fusion reaction leads to the following condition for the *triple product*:

$$nT\tau_E \geq 3 \cdot 10^{21} \text{ m}^{-3} \text{ s keV} \quad (2.2)$$

The density and temperature values achievable in laboratory experiments are of the order of $n \approx 10^{20} \text{ m}^{-3}$ and $T \approx 20 \text{ keV}$, requiring an energy confinement time $\tau_E \geq 1 \text{ s}$.

2.2.1 ITER: *International Thermonuclear Experiment Reactor*

The large experimental database obtained in the last thirty years magnetic confinement devices, and the improving capability of numerical simulations have provided the international community the physics basis for the design of a burning plasma experiment based on the tokamak concept, which is called International Thermonuclear Experimental Reactor (ITER). The principal physics goals of ITER are:

- to achieve extended burn in inductively-driven plasmas with $Q = Q_{fus}/Q_{aux}$ (fusion power over auxiliary power) of at least 10 for a range of operating scenarios and with a duration sufficient to achieve stationary conditions;

- to aim at demonstrating steady state operation using non-inductive current drive with a ratio of fusion power to input power for current drive of at least 5. In addition, the possibility of higher Q operation will be explored if favorable confinement conditions can be achieved.

The ITER nominal fusion power output will be about 500MW. To achieve this goal, the main frame of the project is the following: a major radius $R_0 = 6.2\text{m}$, minor radius $a = 2\text{m}$, maximum magnetic field $B = 5.3\text{T}$ and plasma current $I_p = 15\text{MA}$. The discharge duration is designed to be about 400 seconds, which can be regarded as a stationary condition on the time scales characteristic of the plasma processes. All of these parameters have been predicted for plasmas with density $n_e \approx 10^{20}\text{m}^{-3}$ and core electron and ion temperatures $T_i \approx 8.8\text{keV}$ respectively. ITER would explore many reactor relevant scientific and technological issues, which are beyond the present experimental capabilities. In particular, regimes in which the α particles contribute significantly to the plasma pressure are very interesting. In these conditions a class of plasma instabilities are predicted to be driven by the α particles, which can partially be studied in the present Tokamaks. The study of plasma instabilities and their control is only one aspect of the research in burning scenarios. A variety of technological issues could also be studied in ITER, like for example the test of advanced materials facing very large heat and particle fluxes, the test of concepts for a tritium breeding module, the superconducting technology under high neutron flux and many others. The auxiliary systems needed to achieve the conditions expected in ITER are an external heating and current drive capability of about 73MW and several advanced diagnostics for both analysis and plasma control. All of these requirements are expected to solve many of the scientific and engineering issues concerning a burning plasma, and could allow us to make a significant next step towards the demonstration of a tokamak power-plant. A schematic view of ITER is displayed in figure 2.4.

2.3 The magnetic confinement

Several magnetic field geometries have been investigated for many years in fusion research to seek the best conditions for plasma confinement. Examples are magnetic mirrors, linear and toroidal configurations, and many others. Among them the toroidal geometry has given up to now the best confinement performances. This section will be dedicated to a brief introduction to the principles of magnetic plasma confinement in toroidal devices, and in particular in the so called tokamak and reversed-field pinch (RFP) configurations. In Fig. 2.5 the toroidal coordinates (r, θ, ϕ) are defined: r is called radial coordinate, θ and ϕ are the poloidal and toroidal angles, respectively. R_0 and a indicate the major and minor radius of the torus, respectively. Magnetic field lines in toroidal experiments have both a poloidal component B_θ which is mainly generated by an externally driven toroidal plasma current j_ϕ , and a toroidal component B_ϕ , which in some configurations is only in part produced by currents flowing in external conductors. The plasma itself can produce a large fraction of current through dynamo effects. Magnetic field lines are thus helices, which wound around the torus lying over toroidal surfaces

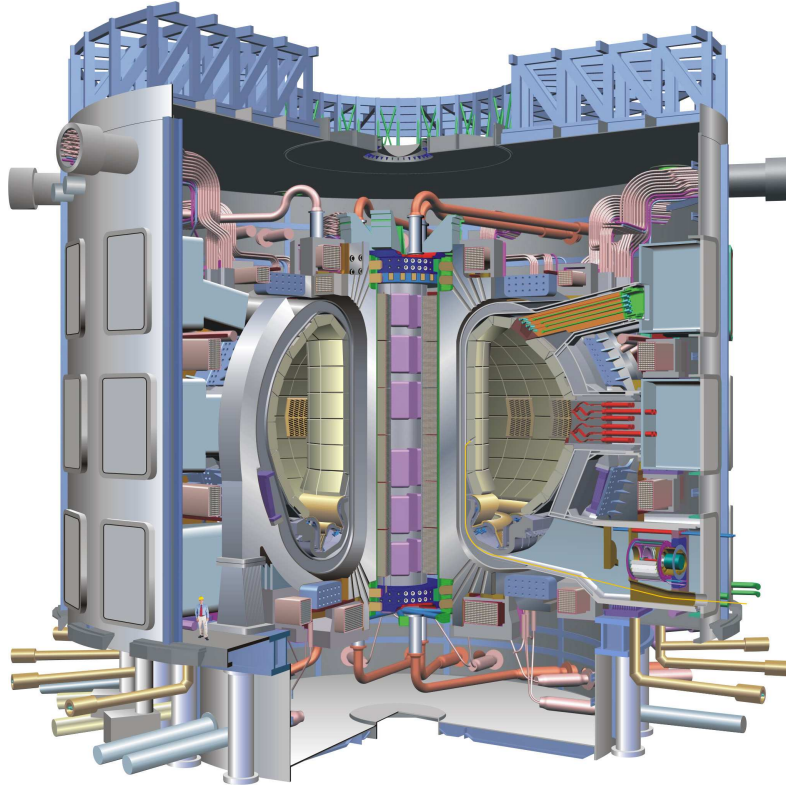


Figure 2.4: *Schematic overview of the International Thermonuclear Experiment Reactor.*

called *magnetic surfaces* (see Fig. 2.6). Helical magnetic field lines are described by the so called safety factor q , which is defined as a function of radius as follows:

$$q(r) = \frac{rB_\phi(r)}{R_0B_\theta(r)}. \quad (2.3)$$

The inverse of this quantity represents the number of poloidal turns done by a helical field line per one toroidal turn. The name safety factor comes from the fact that this quantity is crucial to determine several features of the plasma instabilities.

2.3.1 Tokamak, RFP and Stellarator

The toroidal configurations investigated in fusion research are characterized by different magnetic field and safety factor profiles, instability behaviour, and maximum attainable β^2 values at comparable input power, where β is the ratio of the plasma pressure to the magnetic pressure. We will focus here on two such configurations, i.e. the Tokamak [23] and the RFP. The tokamak and the RFP are similar under many aspects. In particular, they both belong to the class of toroidal pinch devices, in which a toroidal current is inductively driven by an external circuit, and generates a poloidal magnetic field that confines and compresses the plasma [24]. In both cases, the toroidal magnetic field is in part generated by external

$$^2\beta = \frac{nk_BT}{(B^2/2\mu_0)}$$

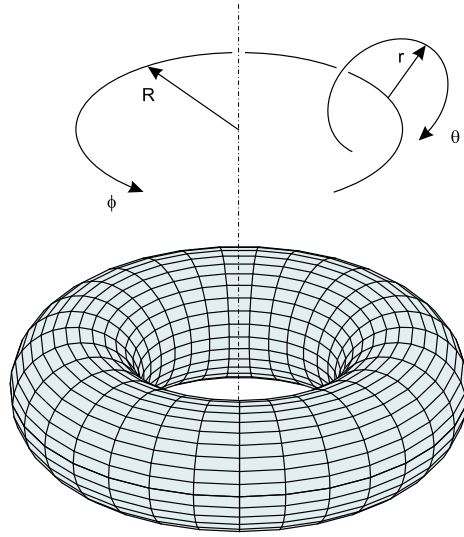


Figure 2.5: *Toroidal geometry for magnetic fusion devices. R major radius; r minor radius; θ poloidal angle; ϕ toroidal angle.*

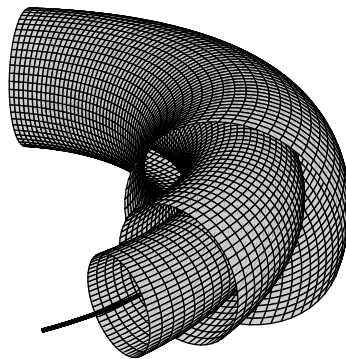


Figure 2.6: *Contours of constant pressure in a well confined toroidal equilibrium.*

coils. Differences are given in the following, both in the basic physics processes underlying their dynamics and in more technical aspects.

Tokamak. This configuration is characterized by a relatively strong toroidal magnetic field B_ϕ and a much weaker poloidal magnetic field $B_\theta \sim 10^{-1}B_\phi$ as shown in Fig. 2.7. The toroidal magnetic field can reach values up to 8T in high-field machines, like for example FTU in Rome (Italy). Given these magnetic profiles, the tokamak safety factor usually increases monotonically with the radial coordinate r , with typical values greater or close to unity in the core, as represented in Fig.2.8. For stability requirements, tokamak operation is preferable at $q > 1$, which is called Kruskal-Shafranov limit. When a rational surface $q = 1$ is present in the plasma, a strong instability can grow unstable. This is usually characterized by a strong saw toothing dynamics, which causes severe confinement losses, and in some cases it can abruptly terminate the discharge. Other kinds of safety factor profiles have been studied in advanced tokamak operation, like for examples non-monotonic dependencies, which use magnetic and flow shear to stabilize the plasma instabilities and achieve enhanced confinement conditions. The Kruskal-Shafranov limit takes to a limitation on the maximum achievable plasma current and related Ohmic heating in Tokamaks, so that additional complex heating methods, like for example neutral beam or radio frequency heating, are needed to reach thermonuclear conditions.

Reversed-field pinch. Differently from the tokamak, the toroidal and poloidal components of the magnetic field in the RFP are relatively weak and of comparable magnitude, $B_\phi \sim B_\theta$, as shown in Fig. 2.7. This implies that a simpler technology is required to generate the magnetic fields. The name RFP comes from the fact that the toroidal magnetic field reverses its sign near the plasma edge. As a consequence, the safety factor profile also changes its sign at the same radius, as shown in Fig. 2.8. Low safety factor operation in the RFP does not bring to dangerous disruptive behavior. This is due to the combined action of a high level of magnetic shear (which characterizes this configuration and has a strong stabilizing function on the magnetic modes) and of a conducting shell (which passively reacts against growing magnetic perturbations). For all the above reasons, the plasma current in the RFP is not limited by the Kruskal-Shafranov limit, as it happens in Tokamaks. As an effect, the RFP can operate at plasma currents about ten times larger than in Tokamaks with the same toroidal field, and it can reach $\beta \sim 10\%$ through Ohmic heating only.

Stellarator. A further toroidal configuration which could give interesting results in the development of a fusion reactor in the future is the Stellarator. Only its main features are mentioned since the work described in the Thesis will not deal with this configuration. In a stellarator, the screw-like twisting of field lines around the torus center is generated by external coils and it does not need a direct-axis flow component in the plasma, like in the Tokamak or in the RFP. The stellarator can therefore operate in steady state. For a fusion power plant, the stellarators could provide a technically simpler

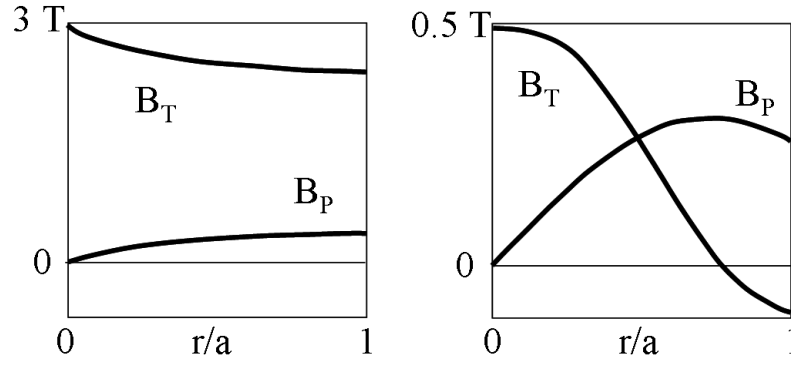


Figure 2.7: Typical radial profiles of the toroidal B_ϕ and poloidal B_θ components of the equilibrium magnetic field in a tokamak (left) and a RFP (right). The profiles are for typical values of magnetic fields in JET and RFX-mod machines.

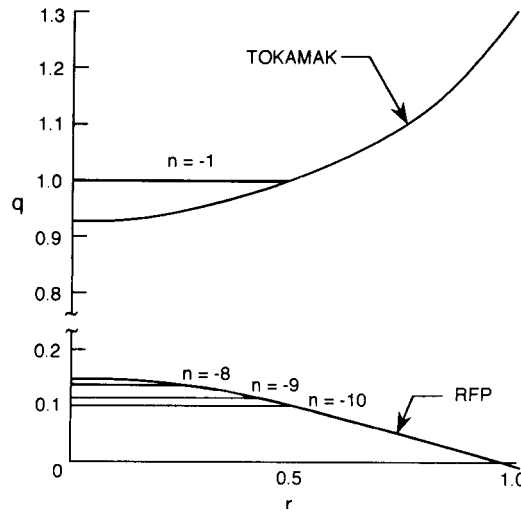


Figure 2.8: Safety factor profiles for a tokamak and a RFP. Horizontal lines indicate the $(m = 1; n)$ rational radii.

solution than Tokamaks but this asserts an experimental verification. A picture of a stellarator configuration is shown in Fig. 2.9 which shows the W7-X experiment [25] [26] of the Max Planck Institute for Plasma Physics.

2.4 Relevance of the measurements on plasmas

Progress in magnetic confinement fusion depends on improvement of the quality of the plasma confinement. Since this quality has to be monitored during the discharge, measurements of the main plasma parameters with sufficient accuracy and resolution, spatial and temporal, are important. One of the parameters governing the confinement is the distribution of the poloidal magnetic field over a cross-section, since this field is responsible for a significant reduction of drift effects. Contrary to the situation in a stellarator, the poloidal magnetic field in a

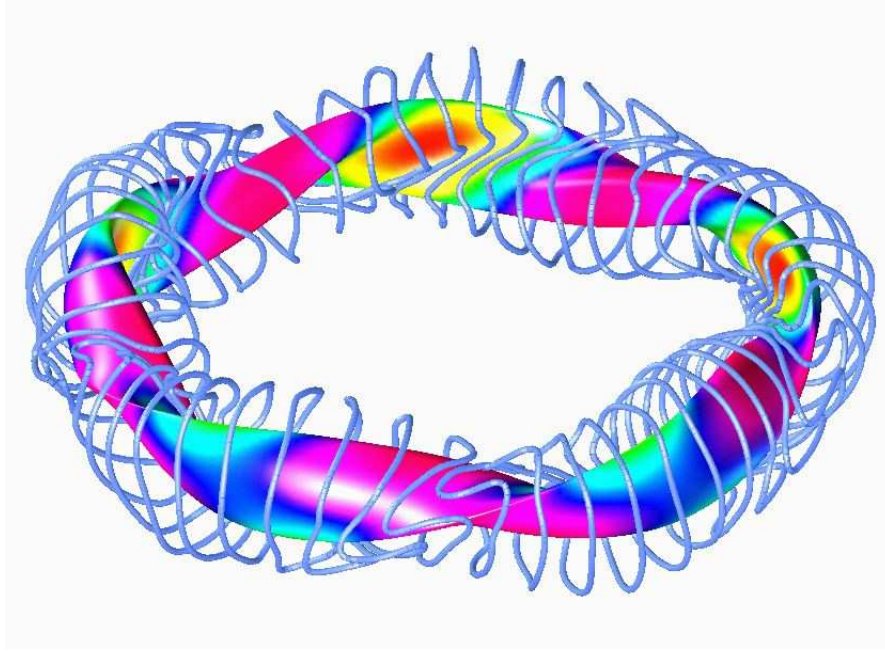


Figure 2.9: *Stellarator configuration of the experiment W7-X. The colors correspond to different values of the magnetic field strength. Note the helically deformed plasma produced by the complex 3-D shaped coils.*

tokamak or in a RFP is determined by the poloidal distribution of the current density. The quality of confinement can also be evaluated through measurements of the electron temperature and electron density profiles, from which information on heat and particle transport in the plasma can be deduced. Measurements of the poloidal field shape at the plasma edge is quite easy, and is done by means of a set of magnetic coils (i.e. Mirnov)³. Measurement of the distribution of the poloidal magnetic field in the plasma interior is much more complicated. In this field, polarimetry plays an important role, since it allows accurate measurements. Polarimetry is inherently line-integrated, because the amount of the rotation of the emerging beam is determined by all local magnetic field values that the wave has experienced along the beam trajectory. Polarimetry can yield current density profiles with sufficient accuracy under many experimental circumstances, especially when a large number of viewing lines is available.

³A small cross-section, multiple-turn coil of wire, used to measure the component of the local magnetic field perpendicular to the plane of the coil. These coils are generally referred to as "pickup" coils, when the output voltage is integrated. Fluctuations in the field are best measured by using the unintegrated signal - the coils are then referred to as "Mirnov" coils [www.fusion.org.uk/glossary/glossmain.htm MIRNOV_COIL]

Basic aspects of polarimetry and interferometry

3.1 Polarimetry in fusion plasmas

The plasma exhibits birefringence, and two orthogonal polarization eigenstates with slightly different refractive indices are present in the plasma. In case of an incident linear wave, it causes a rotation of the direction of polarization of this wave. As already stated in section 1.2, the electric field components of a fully polarized electromagnetic radiation, with frequency ω , propagating in the z direction in an isotropic and homogeneous medium (refraction index n) can be written as:

$$E_x = E_{0x} \cos(\omega t - kz + \delta_x) \quad (3.1)$$

$$E_y = E_{0y} \cos(\omega t - kz + \delta_y) \quad (3.2)$$

$$E_z = 0 \quad (3.3)$$

where $k = \frac{n\omega}{c}$. For $z = 0$, the previous relations become:

$$E_x = E_{0x} \cos(\omega t + \delta_x) \quad (3.4)$$

$$E_y = E_{0y} \cos(\omega t + \delta_y). \quad (3.5)$$

In general the tip of the electric field vector describes an ellipse (see Figure 3.1). The shape of the ellipse and the sense of rotation are fully described by α and δ , where

$$\tan \alpha = \frac{E_{0y}}{E_{0x}} \quad \text{and} \quad \delta = \delta_y - \delta_x. \quad (3.6)$$

These two parameters vary in the ranges: $-\pi \leq \delta \leq \pi$ and $0 \leq 2\alpha \leq \pi$. Looking at the Figure 3.1 the state of polarization can also be described by the angle ψ ($0 \leq \psi \leq \pi$) between the major semi-axis and the x direction and by the angle χ defined by $\tan \chi = \pm \frac{b}{a}$ ($-\frac{\pi}{4} \leq \chi \leq \frac{\pi}{4}$) with positive or negative sign for clockwise or counter clockwise rotation (looking towards the radiation source).

It is also very useful to introduce the Stokes vector in its reduced form $\mathbf{s}$ with three components, $s_1 = \cos 2\chi \cos 2\psi$, $s_2 = \cos 2\chi \sin 2\psi$, $s_3 = \sin 2\chi$, so that:

$$|\mathbf{s}|^2 = s_1^2 + s_2^2 + s_3^2 = 1. \quad (3.7)$$

These three components s_1 , s_2 and s_3 are related to the angles χ and ψ by the following relations

$$\psi = \frac{1}{2} \arctan \left(\frac{s_2}{s_1} \right) \quad (3.8)$$

$$\chi = \frac{1}{2} \arcsin(s_3). \quad (3.9)$$

To evaluate the ellipticity the following relation can be used:

$$\epsilon = \frac{|s_3|}{1 + \sqrt{1 - s_3^2}}. \quad (3.10)$$

The three components of the Stokes vector can be also written as function of α and δ :

$$s_1 = \cos 2\chi \cos 2\psi = \cos 2\alpha \quad (3.11)$$

$$s_2 = \cos 2\chi \sin 2\psi = \sin 2\alpha \cos \delta \quad (3.12)$$

$$s_3 = \sin 2\chi = \sin 2\alpha \sin \delta \quad (3.13)$$

Then the relations between the parameter (ϕ, ψ) and (α, δ) are the following

$$\cos 2\alpha = \cos 2\chi \cos 2\psi \quad (3.14)$$

$$\tan \delta = \tan 2\chi / \sin 2\psi \quad (3.15)$$

$$\tan 2\psi = \tan 2\alpha \cos \delta \quad (3.16)$$

$$\sin 2\chi = \sin 2\alpha \sin \delta \quad (3.17)$$

and

$$\alpha = \frac{1}{2} \arccos(s_1) \quad (3.18)$$

$$\delta = \arctan \left(\frac{s_3}{s_2} \right). \quad (3.19)$$

It is clear that $\mathbf{s} = (1, 0, 0)$ represents linearly polarized radiation aligned with the x axis; $\mathbf{s} = (0, \pm 1, 0)$ represents linearly polarized radiation oriented at $\pm 45^\circ$ respect to the x axis; $\mathbf{s} = (0, 0, \pm 1)$ represents circular polarized radiation with either of the two senses of rotation.

It is convenient to refer to the Poincaré sphere of unit radius in (s_1, s_2, s_3) space, see Figure 3.2, where each possible state of polarization is uniquely represented by a point P on the sphere, having latitude 2χ and longitude 2ψ . Two orthogonal polarizations¹ are represented by two diametrically opposite points on the sphere.

¹Two polarization states (ψ_1, χ_1) and (ψ_2, χ_2) are orthogonal when $\psi_2 = \psi_1 + \pi/2$ and $\chi_2 = -\chi_1$.

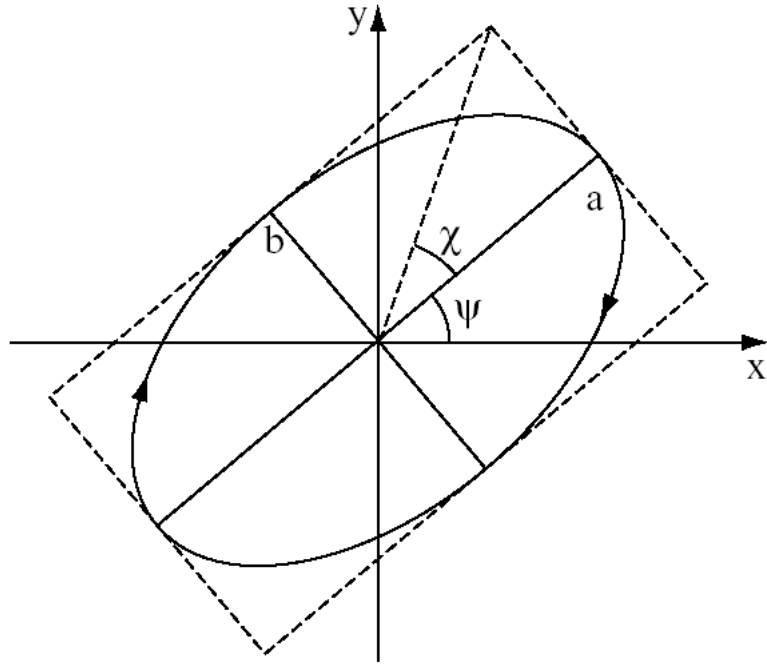


Figure 3.1: The polarization ellipse for propagation in the z direction (the sense of rotation for $\chi > 0$ is shown).

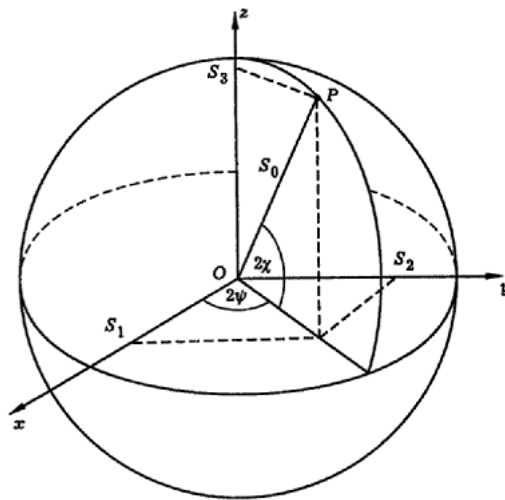


Figure 3.2: The Poincaré sphere.

3.1.1 Change of the polarization due to the propagation in plasma

It can be shown [27] that the evolution of the polarization during propagation in an anisotropic medium, having (slow and fast) characteristic refractive indexes n_1 and n_2 (with $n_1 > n_2$), is represented on the Poincaré sphere by a rotation about an axis passing through the points representing the characteristic polarizations (which are orthogonal) and the angle of rotation is $\Delta\varphi = L(n_1 - n_2)\omega/c$ where L is the path length. Therefore, the evolution of the polarization can be represented by the vector equation, *the evolution equation*:

$$\frac{d\mathbf{s}(z)}{dz} = \mathbf{\Omega} \times \mathbf{s}(z) \quad (3.20)$$

where $|\mathbf{\Omega}| = d\Delta\varphi/dz = (n_1 - n_2)\omega/c$. For a uniform medium n_1 and n_2 do not depend on z , so that also $\mathbf{\Omega}$ is a constant and equation (3.20) can be easily integrated. The evolution equation can be extended to describe propagation in a non-uniform medium simply by considering n_1 , n_2 and hence also $\mathbf{\Omega}$ in equation (3.20), as functions of z . This corresponds to considering the medium as approximately uniform over each infinitesimal slab of thickness dz .

In the case of cold plasma and $\omega_p^2 \ll \omega^2$, $\omega_c \ll \omega$, (ω_p , ω_c and ω being the plasma, electron cyclotron and probing wave frequency respectively), the components of $\mathbf{\Omega}$ depend on plasma density and magnetic field $\mathbf{B}$ [28]

$$\begin{pmatrix} \Omega_1 \\ \Omega_2 \\ \Omega_3 \end{pmatrix} = \frac{\omega_p^2}{2c\omega^3} \times \begin{pmatrix} \frac{e^2}{m_e^2}(B_x^2 - B_y^2) \\ 2\frac{e^2}{m_e^2}B_xB_y \\ 2\frac{e}{m_e}\omega B_z \end{pmatrix} \quad (3.21)$$

where $\omega_p^2 = n_e e^2 / m_e \epsilon_0$ and B_x , B_y and B_z are the perpendicular, radial and the parallel components of the magnetic field with respect to the wave's propagation direction, as shown in Figure 3.3. The magnetic field has two effects on the state of output polarization: the changes in the ψ angle, or rotation of the major axis of the polarization ellipse, and the changes in the χ angle, or in the ellipticity. The rotation of the plane of polarization is mainly related to the Faraday effect. The change in the ellipticity is mainly related to the Cotton-Mouton effect, that arises from the magnetic field perpendicular to the direction of propagation. It is useful to define the quantities:

$$W_i \equiv \int_{z_1}^{z_2} \Omega_i(z) dz \quad \text{where } i = 1, 2, 3 \quad (3.22)$$

where z_1 and z_2 are the extremes of the path of the polarization beam inside the vessel.

Then from equation (3.21) it is possible to evaluate :

$$W_1 \propto \int_{z_1}^{z_2} n_e(z)(B_x^2 - B_y^2) dz \quad (3.23)$$

$$W_2 \propto \int_{z_1}^{z_2} n_e(z)B_x(z)B_y(z) dz \quad (3.24)$$

$$W_3 \propto \int_{z_1}^{z_2} n_e(z)B_z(z) dz \quad (3.25)$$

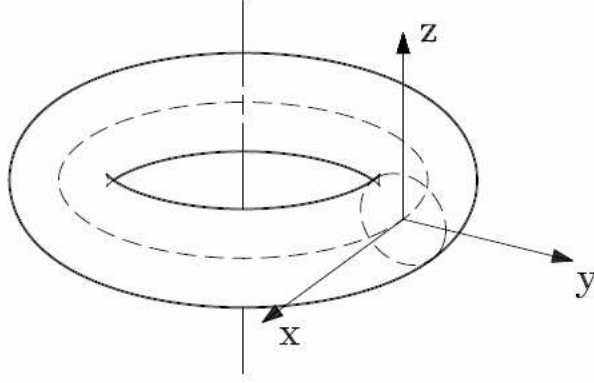


Figure 3.3: Reference system for a torus. The radiation is assumed to propagate along the z axis.

where the proportional factors depend on the employed wavelength. In a tokamak with $B_x^2 \gg B_y^2$ and for vertical chords (toroidal magnetic field $B_t = B_x = \text{const.}$) W_1 can be approximated as:

$$W_1 = C_1 \lambda^3 B_t^2 \int_{z_1}^{z_2} n_e(z) dz, \quad (3.26)$$

with $C_1 = e^4 / (16\pi^3 c^4 m_e^3 \epsilon_0) = 2.44 \times 10^{-11} \left[\frac{\text{rad}}{\text{m T}^2} \right]$. If W_1 is known, the line integral of the electron density is given by:

$$\int_{z_1}^{z_2} n_e(z) dz = \frac{W_1}{C_1 \lambda^3 B_t^2} \quad (3.27)$$

This possibility represents an interesting alternative method to traditional interferometry and it is one of the topics presented in this thesis (Chapter 4).

3.2 Polarimeter configurations

When plasma effects are small and thus the quantities W_i defined by (3.22) are such that $W_i^2 \ll 1$ for $i = 1, 2, 3$, the measurements allow to solve easily the propagation equation (3.20). In such way the vector $\mathbf{\Omega}$ is evaluated and therefore the single quantities W_i are determined. These values are related to plasma parameters by equations (3.23)-(3.25), from which it can be seen that for typical plasma parameters ($n_e = 5 \times 10^{20} \text{m}^{-3}$, $B_T = 4T$, $B_p = 0.3T$), in order to have $W_i \simeq 0.01$ it is necessary to have $\lambda \geq 0.03 \text{mm}$. Thus the wavelength of the radiation must be in the Far Infrared range and this places strong limitations on the components which can be used in plasma polarimetry. In addition to the choice of the right wavelength there is the issue of the optimum design for the polarimeter.

A pure polarimeter can be realized using several designs. The main difference between the various configurations concerns the modulation of polarization. In fact, beside the measurements without the modulation of the state of polarization that is the technique employed in the RFX-mod polarimeter (see Chapter 4), it is very useful to modulate the state of polarization of the radiation. As already

stated, without the modulation of the polarization, the measurements of the Faraday rotation and of the Cotton Mouton angle rely on an amplitude measurement of the orthogonal polarization components. The disadvantage of amplitude measurements is that they are sensitive to power fluctuations of the laser and to refraction effects. Thus a modulation can be applied to the input radiation entering the plasma or to the output radiation leaving the plasma. The modulation consists in applying a time variation to some polarimetric parameter, say ϵ , in particular for the *progressive modulation* $\epsilon = \omega_m t$ (see Segre's U-method [28]) and for the *alternating modulation* $\epsilon = \epsilon_0 \cos \omega_m t$, where the modulation frequency ω_m is a constant. It must be underlined that just the former method can be used at Far Infrared wavelength, which are required for plasma polarimetry, because, although the alternating modulation provide very accurate measurements, the modulators needed for this technique are still in a very early stage [29].

3.3 Interferometry in fusion plasmas

A reliable measurement of the plasma density is one of the key factors in the study of the nuclear fusion. The most used technique to measure plasma density in present fusion experiments is the interferometric one which uses an electromagnetic wave as a probe. The technique is not perturbing since the energy of the radiation is negligible with respect to the plasma energy. Since the electromagnetic wave has a sufficient high frequency, the ions can be considered stationary because their inertia is too large for them to respond to a high frequency wave and the electron pressure can be neglected, as well: such approximations are cold plasma condition already presented in 3.1.1. It is equivalent to assuming $T_e = T_i = 0$. With this approximation the refractive index n is described by the theory of propagation of electromagnetic waves in a cold plasma, neglecting the particles thermal velocity, that is much lower than the phase velocity of the wave [30]. For a wave propagating perpendicularly to the magnetic field B , the expression for n depends on the polarization of the wave. For the so-called *ordinary wave*, polarized with the electric field E parallel to the plasma magnetic field B , the refractive index is:

$$n_o = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}. \quad (3.28)$$

If the wave has the E perpendicular to B (*extraordinary mode*), the expression of n_{ex} is whereas:

$$n_{ex} = \left(1 - \frac{\omega_p^2}{\omega^2} \frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_p^2 - \omega_{ce}^2}\right)^{1/2}. \quad (3.29)$$

where $\omega_p = \left(\frac{n_e e^2}{\epsilon_0 m_e}\right)^{1/2}$ is the *plasma frequency* and $\omega_{ce} = \frac{eB}{m_e}$ is the *cyclotronic frequency*. The expression (3.28) set the first boundary to the frequency of the electromagnetic radiation used: $\omega > \omega_p$ so that the wave can propagate in the plasma, the so called *transparency condition*. For typical plasma parameters $\omega_p \gg \omega_{ce}$, which allow to approximate equation (3.29) with equation (3.28) in all the fusion relevant cases.

3.3.1 Phase difference measurements

Figure 3.4 shows the general scheme for plasma density measurement: a laser beam is divided by a beam splitter into two beams, one that passes through the plasma, named *scene beam*, and the other, the *reference beam*, that covers an equivalent optical path outside the plasma. The change in the phase of the scene beam is proportional to the electron density integrated through the plasma:

$$\phi_p = \frac{2\pi}{\lambda} \int_l (n_V - n_o) dl \simeq \frac{\lambda e^2}{4\pi c^2 \epsilon_0 m_e} \int_l n_e(l) dl \simeq 2.85 \times 10^{-15} \lambda \int_l n_e(l) dl \quad (3.30)$$

where n_V is the vacuum refractive index, λ is the wavelength of the beam and $n_e(l)$ is the local density along the line l . The so-called *heterodyne measurement* requires that a laser or microwave radiation probing the plasma is divided into two components: the scene and the reference beams where the reference one is shifted in frequency of a quantity $\Delta\omega$. Recombination of the reference and the scene beam produces a beat signal at the difference frequency $\Delta\omega$. One can obtain the phase shift due to the plasma ϕ_p comparing the signal from a couple of beams probing the plasma to the interference signal of a couple of beams passing outside the plasma. The analytic value of the phase difference ϕ_p is given by equation (3.30), from which the line integral of the density may be deduced. The beat frequency is chosen to be sufficiently high to allow a good time resolution in the phase measurement and sufficiently low to be electronically tractable (typically 10 kHz - 100 MHz for infrared systems). As already stated, the relation (3.28) requires that the wavelength probing the plasma should be short enough. On the other hand, the requirement that the interferometer should be sensitive to the electron density and insensitive to mechanical vibrations favors long wavelengths, as discussed in the following.

$$\phi_p \simeq 2.85 \times 10^{-15} \lambda \int_l n(l) dl \Rightarrow \int_l n(l) dl \simeq \frac{3.50 \times 10^{14}}{\lambda} \phi_p = \bar{n} L_p \quad (3.31)$$

where L_p is the optical path length in the plasma and $\bar{n}$ is the mean line plasma density. When mechanical vibrations change the optical paths of the reference beam relative to the scene beam of a quantity δL an error phase difference is induced:

$$\phi_{err} = \frac{2\pi\delta L}{\lambda} \quad (3.32)$$

Hence the relative error $\frac{\phi_{err}}{\phi_p} \propto \frac{1}{\lambda^2}$. For typical fusion plasma parameters: $\bar{n} = 10^{20} \text{m}^{-3}$, $L_p = 1 \text{m}$, $\delta L = 5 \mu\text{m}$ in order to have a relative error lower than 1% the wavelength should be $\lambda > 100 \mu\text{m}$. This condition counteracts the *transparency condition* that requires short wavelengths. The choice of the radiation wavelength is then determined as a compromise between these competing requirements: for typical fusion plasma parameters, wavelengths of the order of hundreds of micrometer are chosen.

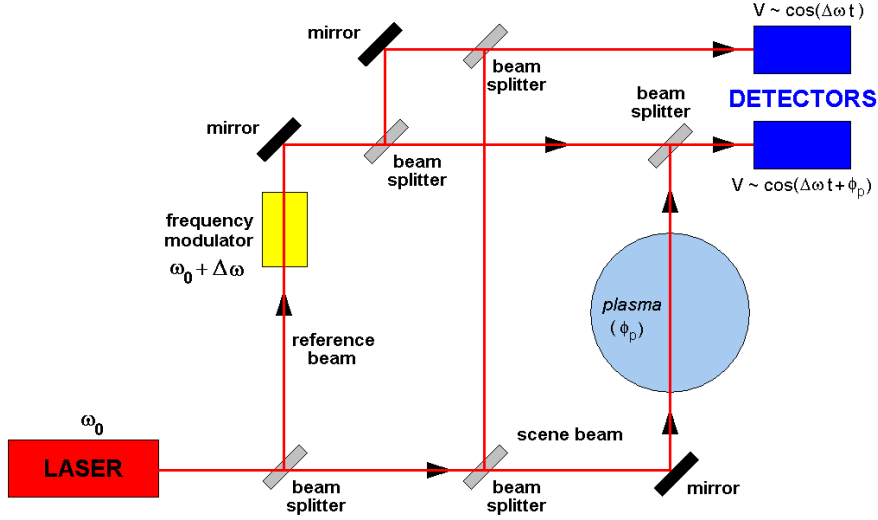


Figure 3.4: Schematic layout of the interferometer. The laser beam of frequency ω_0 is split into two beams, and recombined at the detectors. The plasma introduces a phase delay ϕ_p proportional to the plasma density. The frequency modulation $\Delta\omega$ generates a beating signal, improving the reliability of the measurement.

3.3.2 Two-color vibrations compensation technique.

The two-color vibrations compensation technique allows using shorter wavelengths, extending the measurable density range and reducing the risk of a fringe jump (that occurs when a too large variation in density induces $\phi_p > 2\pi$ between two samples). The effects of vibrations on interferometric measurements is eliminated in principle using two coaxial lasers at different wavelengths. The phase differences ϕ_{err} due to a modification of the optical path δL depends on (3.32). Using two different wavelengths λ_1 and λ_2 , the total phase differences due both to plasma and to vibrations, are respectively:

$$\Phi_1 = \phi_{1p} + \frac{2\pi\delta L}{\lambda_1} \quad (3.33)$$

$$\Phi_2 = \phi_{2p} + \frac{2\pi\delta L}{\lambda_2}. \quad (3.34)$$

By a linear combination of the two latter equation one obtains:

$$\Phi_1\lambda_1 - \Phi_2\lambda_2 = K(\lambda_1^2 - \lambda_2^2) \int_l n(l)dl \rightarrow \int_l n(l)dl = \frac{\Phi_1\lambda_1 - \Phi_2\lambda_2}{K(\lambda_1^2 - \lambda_2^2)} \quad (3.35)$$

where $k = 2.85 \times 10^{-15}$, as defined in equation (3.30). In equation (3.35) the effects of the vibrations is deleted.

3.3.3 Interferometers

There are many different types of interferometers used for a variety of different purposes. The configurations in widest use for plasma diagnostics are as follows:

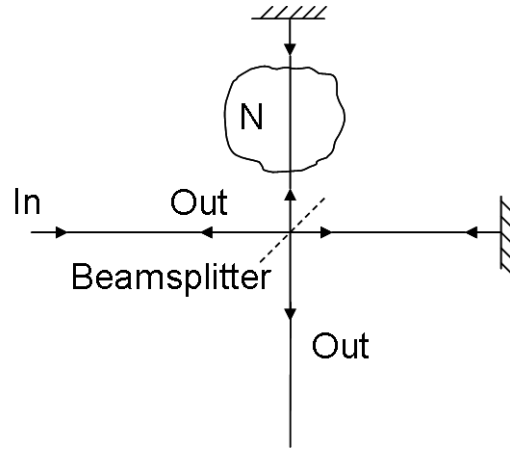


Figure 3.5: *The Michelson interferometer configuration*

1. *The Michelson interferometer* is a two-beam interferometer, as illustrated in Fig. 3.5, with one beamsplitter, two arms in which the beams travel in both directions, and two outputs, one of which is along the input. In this, as in other configurations, the arms may be free space straight optical paths or, for example, microwave guides, and the beamsplitter may be some form of partial reflector of optical character or, for example, some type of microwave coupler. The principles are the same in all cases. Phase differences between the two components of one of the output beams arise, in the case of refractive-index measurements, by changes in the refractive index in one of the arms of the interferometer.
2. *The Mach-Zehnder configuration* is also a two-beam interferometer but differs from the Michelson in having two arms in which the beams travel in only one direction. Both outputs are separate from the input (see Fig. 3.4). Phase changes are caused by variations of the refractive index in one arm.

The multichannel far-infrared polarimeter on RFX-mod

4.1 Introduction

RFX-mod is the largest toroidal fusion experiment where reversed field pinch (RFP) plasmas with current up to 2MA, are studied. Since the magnetic configuration is strongly determined by currents flowing inside the plasma, an accurate measurement of the magnetic field profile is crucial to study the RFP physics. For these reasons a multichannel far infrared (FIR) polarimeter diagnostic has been installed in RFX-mod since the last year. In this chapter this new diagnostic is described and its main sections are outlined. Emphasis is placed on the activity undertaken to optimize the design of the new system considering several indications outlined by the previous diagnostic operating in RFX and considering the stronger operative conditions due to high plasma currents up to 2MA. Examples of the first Faraday angle measurements performed on five chords are presented and compared to a theoretically calculated value, based on the $\mu&p$ model. At the end some improvements to the system are proposed.

4.2 RFX-mod: the machine

The current RFX-mod device (see Fig. 4.1) is an upgraded version of the old experiment RFX [31]. Many features have been modified in the new device but, undoubtedly, the most important are the new power supply system and the set of 192 independently driven saddle coils aimed at actively controlling and contrasting local radial perturbations at the edge, as it will be explained in the following.

The main technical components in RFX-mod are:

vacuum vessel: the toroidal chamber containing the plasma. It is an all welded, rigid structure made of INCONEL 625, with a major radius of 1995 mm and minor radius of 475 mm. It is bakeable up to 170°C, in order to eliminate the impurities of the first wall.

first wall: it's the inner side of the vacuum vessel, exposed to the plasma discharge. It is composed by 2016 graphite tiles that cover completely the inner part of the vacuum vessel (see Fig. 4.2). In RFX-mod the shape of the tiles has been redesigned to minimize the emissivity due to plasma wall-interaction. Graphite has been chosen for its low atomic number Z . In fact, the presence of other elements different from the main gas, the impurities, contribute to increase Z_{eff} and thus to enhance the radiation emission with a reduction of the energy confinement. This effect is strongly dependent on the atomic number of the impurities in the plasma.

stabilizing shell: it has the main purpose of stabilizing MHD ideal instabilities. It is made of copper and it is 3mm thick, located at 1.11a. It passively controls also the horizontal equilibrium of the plasma.

mechanical structure: the new shell is too thin to bears the weight of the vacuum vessel and of the toroidal windings, hence a new mechanical structure has been installed.

magnetizing coils: they provide the time varying poloidal magnetic flux that induces the plasma current during the discharge. It is composed by 40 coils that can carry a maximum current of 50kA and produce a 15Wb maximum flux.

toroidal coils: a set of 48 coils uniformly distributed along the toroidal direction, that surround the vessel and the shell. They are designed to generate the toroidal magnetic field needed to set-up and maintain the discharge (up to 0.7T). The coils are series-connected in 12 groups of 4: each group is connected to an independently controlled power supply unit.

field shaping coils: this set of poloidal coils is designed to generate a uniform vertical field aimed at controlling the position of the plasma column with respect to the vessel during the discharge.

active coils system: this new set of saddle coils is necessary in RFX-mod in order to control the instability arising on the shell time-scale. It is a set of 192 coils, distributed in 48 different toroidal positions and 4 poloidal positions; each coil extents 90° poloidally and 7.5° toroidally, for a full surface coverage. The power supply units are digitally controlled by a set of dedicated CPUs that can process 192 sensor inputs and generate 192 reference outputs at a rate of about 2.5kHz. The digital system allows for a great flexibility in the implementation of control system. A scheme of the saddle coils on a section of RFX-mod is displayed in figure 4.3.

In table 4.1 the main parameters of RFX-mod machine are briefly reported and in table 4.2 the best performances reached during the last plasma campaigns are displayed.

In RFX-mod a full set of diagnostics is installed in order to measure many physical quantities, in their temporal and spatial variations. A brief description of the most important ones follows:

Major radius, R	2m
Minor radius, a	0.459m
Volume	$\sim 8.3\text{m}^3$
Plasma current	2MA
Maximum toroidal magnetic field B_ϕ	0.7T

Table 4.1: *RFXparameters*

Parameter	Obtained value
Plasma Current	1.7 MA
Discharge duration	500ms
Electronic temperature	1.2keV
Electronic density	$2 \div 6 \cdot 10^{19}\text{m}^{-3}$
Electronic confinement time τ_E	2ms

Table 4.2: *Excellent performances obtained at RFX-mod*

- a complete set of magnetic diagnostics: integral probes, situated between the vacuum vessel and the shell, which measure plasma current (by means of 4 Rogowski coils) and concatenated flux variations (using 8 toroidal and 6 poloidal voltage loops) providing information on loop voltage and toroidal flux, 196 bi-axial pick-up coils, distributed along 48 toroidal directions and 4 poloidal directions, which measure toroidal and poloidal components of magnetic fields; 48×4 saddle probes, measuring the radial component of the field, coupled to the active control coils;
- a Thomson scattering diagnostic [32], which provides a 84-point radial profile of electronic temperature by analyzing the scattering properties of the plasma when a high power laser beam is injected; the repetition time is of about 25 ms, for a maximum number of 10 pulses in a discharge;
- a multichord interferometer [33] [34], which measures the electronic density averaged along 14 lines of sight. The density is evaluated measuring the phase variation induced in a CO_2 laser beam ($\lambda = 10.6\mu\text{m}$) that passes through the plasma;
- a multichord far infrared polarimeter, which measures the Faraday rotation angle acquired by the radiation probing the plasma poloidal cross section along five lines of sight. These measurements allow the reconstruction of the profiles of the internal magnetic fields and then of the currents. This diagnostic will be extensively presented in section 4.3, being the main topic of this thesis;
- spectroscopic diagnostics [35], which measure line intensities of radiation emitted by main gas and by impurities, in order to calculate their influxes at the edge, the toroidal flow of the plasma and the effective charge;
- an Integrated System of Internal Sensors (ISIS) [36], which includes poloidal and toroidal arrays of magnetic pick-up coils and electrostatic (Langmuir)

probes (used to measure and correlate fluctuations of electric and magnetic fields), and 8 calorimetric sensors. The complete set of probes are presented in table 4.3. The magnetic probes are located behind the graphite tiles, which cover the first wall of the machine, and consist of pick-up coils measuring the time derivative of the magnetic field B_T . The sampling frequency is 2 MHz, while the estimated bandwidth of the measurement is up to 400 kHz;

ISIS probes ($f_s = 2\text{MHz}$)	number
toroidal field toroidal arrays	2×24
poloidal field poloidal arrays	1×8
toroidal field poloidal arrays	$1 \times 8 + 1 \times 6$
radial field poloidal array	1×8
toroidal array of single e.s. probes	1×72
poloidal array of triple e.s. probes	1×7
toroidal array of calorimetric sensors	1×8

Table 4.3: *Set of probes of the Integrated System of Internal Sensor.*

- a Soft-X Rays multfilter diagnostic [37], used for measuring electronic temperature at the center of the plasma by means of comparing SXR emissions measured by differently filtered silicon detectors; it allows a higher time resolution with respect to the Thomson scattering, but with a lower spatial resolution; 4 chords with different filter thicknesses are used, in order to measure temperature in a wider range of emission levels;
- Soft X-Rays tomographic system [38] for the reconstruction of the poloidal emissivity map. The diagnostic is composed by 3 vertical fans each with 19 lines of sight and 1 horizontal fan with 21 lines of sight. The total 78 lines of measurements almost entirely cover the plasma cross section.

The data from all these diagnostics are collected during the discharge and are then analyzed and used as input to several numerical codes.

4.2.1 Recent results

Since its start in 2004, RFX-mod machine has made impressive progress: current regimes up to 1.7MA and discharges up to 0.5s long thanks to advanced magnetic feedback control techniques [39]. The experiments at high current, above 1MA, has displayed a new self organized regime (the Single Helical Axis - SHAx), where the confinement is improved and transport barriers are observed [40]. The existence of such state was predicted on the basis of MHD theory and, as experimentally proved, it plays a fundamental role in confinement improvement up to a factor of 4 with respect to the standard RFP [41]. This represents a satisfactory achievement which encourages to exploit plasma regimes with current up to 2MA, the top performance for RFX-mod design. These findings open new and very promising fusion perspectives for the configuration [42].

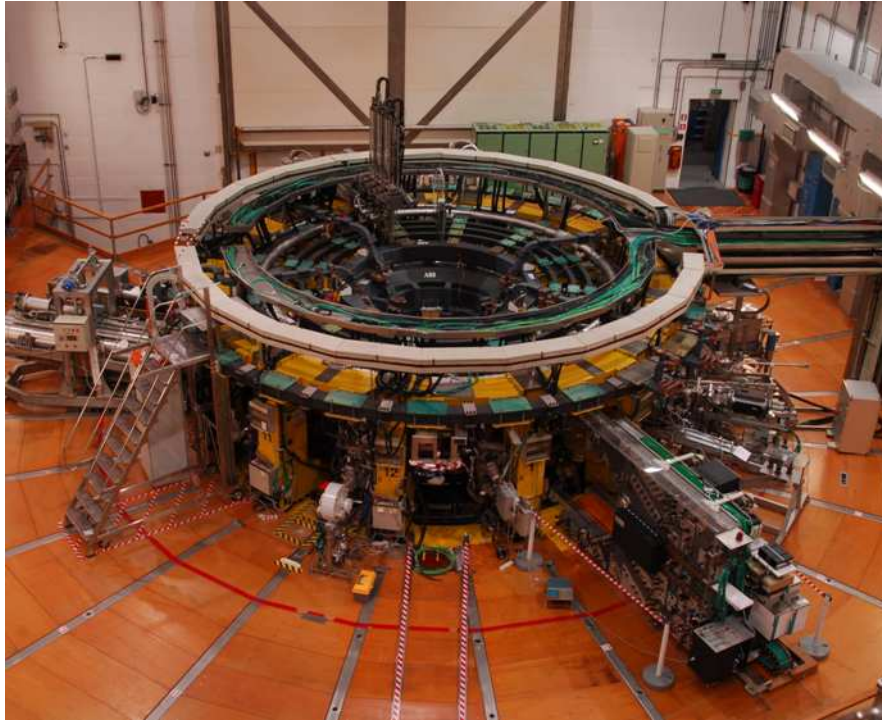


Figure 4.1: *Picture of RFX-mod experiment.*

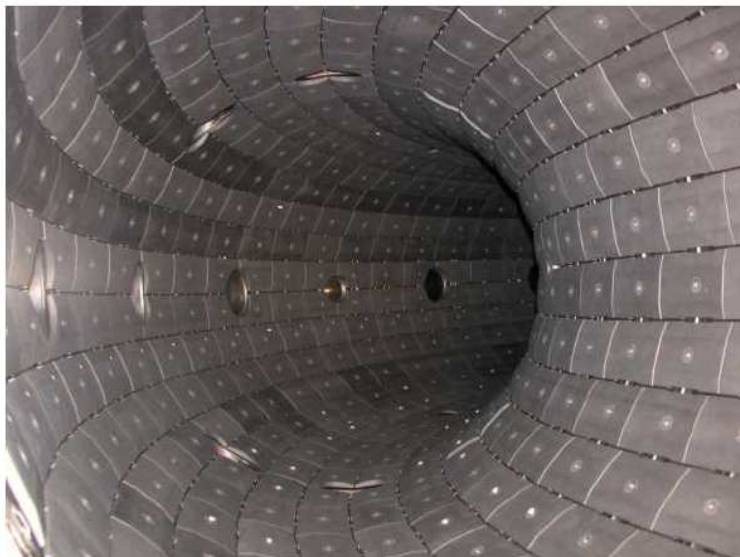


Figure 4.2: *New graphite tiles in RFX-mod.*

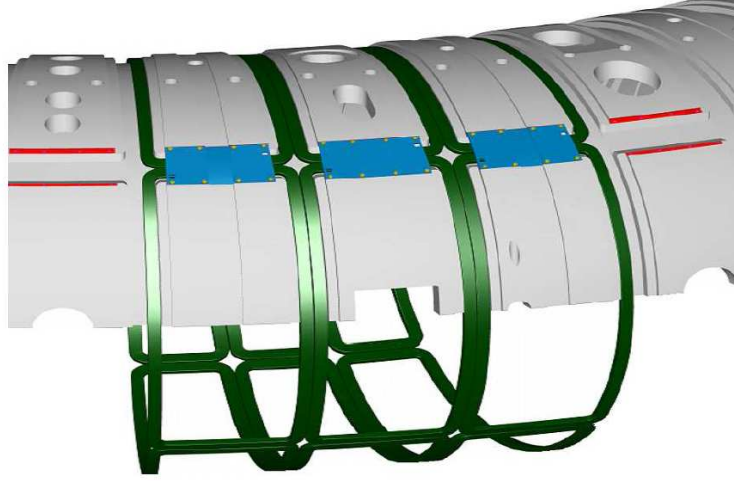


Figure 4.3: Set of 12 saddle coils (3 toroidal and 4 poloidal positions) surrounding the RFX-mod shell.

4.3 RFX-mod polarimeter

The FIR multi-channel polarimeter installed at RFX-mod machine is constituted by several parts as depicted in figure 4.4. In this section the different parts are described, highlighting their characteristics and the improvements performed with respect to the previous system. The principle of operation of the diagnostic is further described and it is well represented by the scheme in Fig. 4.6.

The laser system The laser comprises a CO₂ laser optically pumping a Far Infrared (FIR) cavity which produces a linearly polarized radiation at $118.8\mu\text{m}$. As in the past [43], the position of the laser is at a distance of 21m from the torus axis to avoid perturbations of the machine on the laser output. The laser system is mounted on a very solid optical bench, hence the laser output power is free of noise during the machine shots. The entire system has been recently covered by a box made of an aluminium frame and plastic panels, that can easily be moved, to enclose the space around the laser source. The air inside the box is controlled by an air drier which keeps the relative humidity very low ($\sim 3\%$) reducing the absorption of the power of the signal probing the plasma. In fact the FIR beam propagates through a distance of approximately 2.5m in air in the laser room. This results in attenuation of the signal amplitude due to the humidity. As displayed in table 4.4, where some typical values of attenuation are reported in percents, the radiation is attenuated up to 70% before the optical line. It is clear that the relative humidity has to be controlled to avoid strong attenuations of the signal.

The optical line The laser is guided from the laser room to the entrance of the RFX-mod's vessel by means of only one optical line in a controlled Nitrogen atmosphere. As in the previous diagnostic [43] the laser beam is diverted through an angle of 90° and lowered by the group of mirrors M_1 , M_2 , M_3 , M_4 . It then travels, inside polyethylene tubes, parallel to the wall of the machine hall for 9m and it is reflected at $\sim 120^\circ$ arriving to the

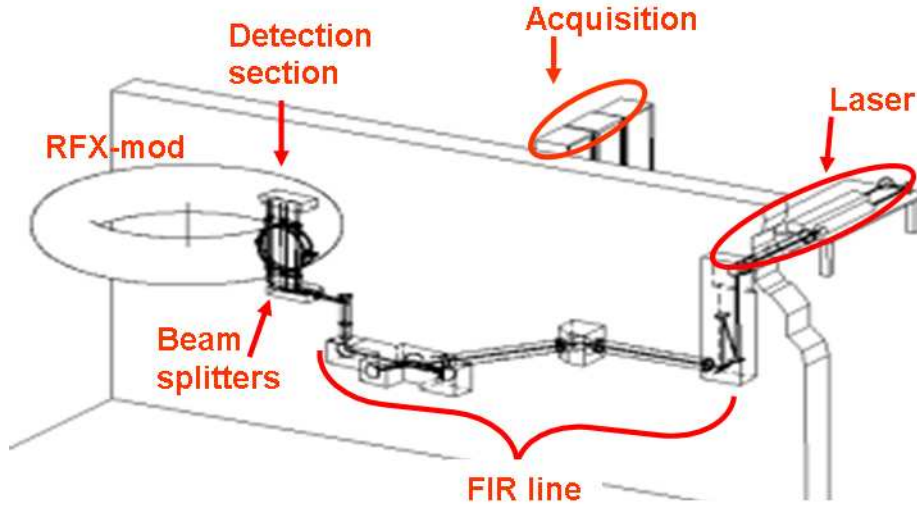


Figure 4.4: Schematic of the entire diagnostic system. Main section are highlighted: laser, optical line with beamsplitting section, detection section, acquisition and processing section

Temp. °C	Rel. Hum. %	Abs. Hum.	Trans.	Absorp. m^{-1}	Atten. dB/m
23.2	34.1	7.85	0.7	0.3567	1.549
23.6	34.2	7.92	0.6685	0.4027	1.749
23.8	35	8.16	0.6319	0.4590	1.993
25.2	51.8	13.17	0.6	0.5108	2.218
25.3	53	13.53	0.5725	0.5577	2.422
25.4	43.5	11.23	0.6867	0.3758	1.63
25.5	43.8	11.37	0.662	0.4124	1.79
25.6	44.2	11.83	0.6565	0.42	1.84

Table 4.4: Attenuation measurements for the ambient conditions. For different temperature and relative humidity the absolute humidity has been evaluated. The absorption coefficients have been calculated and the signal power attenuation is displayed.

group of mirrors M_6 , M_7 , M_8 , which are now mounted on a granite platform covered by a box made of transparent Plexiglas. The beam is elevated by M_9 and directed by M_{10} along the beamsplitting section located, below the vacuum chamber, in the space between the magnetizing coils and the field-shaping coils. It is mounted over a granite platform covered by a box made of transparent Plexiglas with five exit ports sealed by thin Mylar foils. The optical design is such that the FIR beam is split into five beams having approximately equal intensity and the minimum beam waist as close to the equatorial plane on RFX-mod machine as possible. The exiting beams are reflected through 90° before leaving the box, propagating towards the five RFX-mod polarimeter's chords.

Tungsten wire grids and quartz plates are used as beamsplitters. Z-cut crystal quartz plates have been recently mounted in the beamsplitter box after tests performed to check the reliability of these optics at $\lambda = 118.8\mu\text{m}$. Since the transmission and the reflection coefficients critically depends on the incidence angle and on the thickness as well, some simulations have been done to choose the right thickness for our purposes. The figure 4.3 on the left side shows how these coefficients vary for different thicknesses of the plate when the angle of incidence is fixed at 45° . A thickness of $\sim 2\text{mm}$ has been chosen for the plate because, as shown in the right side of figure 4.3, it makes the plate sufficiently handily and the correct splitting ratio is guaranteed with an accuracy of $\pm 1^\circ$ with respect to 45° . Looking at the plot the transmission and reflection coefficients around 45° vary in between 0.4 and 0.6, thus the power into the two arms, transmitted and reflected, is quite the same, allowing good level of the signal reaching the plasma. Moreover the quartz plates reflect both the wavelengths FIR and visible and therefore they allow a better allineament of the optical line than the wire grids which don't reflect the visible radiation. The passage of the beams into and out of the vacuum vessel is via Z-cut crystal quartz windows, tilted at 2° from the normal to avoid back reflections.

The beam detection section The FIR beam, having exited the RFX-mod ports and passed through the half wave plate, is divided into two components by a wire grid, with each component subsequently focused into its respective detector. These latter are of DLATGS-type with incorporated FET and show high responsivity ($\sim 3\text{V/W}$) and good noise ($\sim 2 \cdot 10^{-8}\text{W/Hz}^{1/2}$) characteristics at $\lambda = 118.8\mu\text{m}$ and at the chopping frequency, 3kHz.

The body of this section is made of insulating material to avoid induced eddy currents from the time varying magnetic field. The design (schematized in Fig. 4.7) and most of the optical components mounted in this section of the polarimeter are the same as the ones used in the previous diagnostic [43]. The half wave plates are now mounted on a rotating holder which is driven by a stepper motor. Their positions are remotely controlled by a software in particular during the automatic calibration procedure, which is explained below.

The signal processing section The detected signals are sent, via coaxial

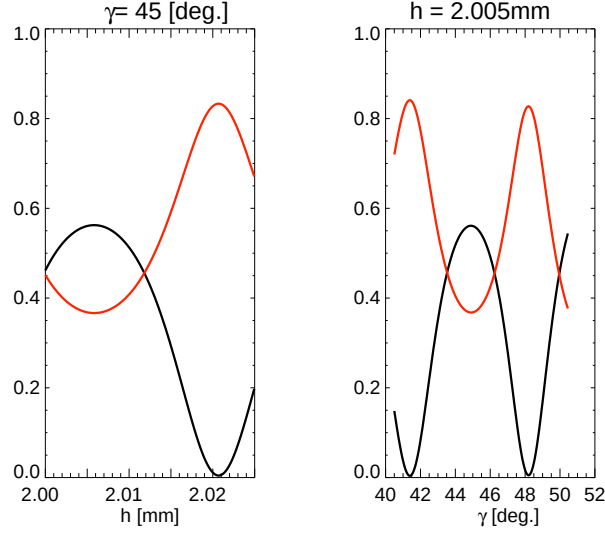


Figure 4.5: The plot on the left shows how the transmission and reflection coefficient vary for different thicknesses of the plate at 45° angle of incidence. The plot on the right shows the tolerance on the angle of incidence to have enough transmitted and reflected power in the case of a plate with thickness of $\sim 2 \text{ mm}$

cables to the diagnostic hall, where they are filtered, amplified and acquired. After each plasma pulse they are processed by a software which computes the Faraday rotation angle for each line of sight. This software amplifies the raw data with gains calculated during the calibration and it extracts from these data the amplitude of the component at the chopping frequency, about 3kHz. For each pair of detectors ($s_1 \sim \cos^2 \psi$, $s_2 \sim \sin^2 \psi$) related to the same channel, the software computes the sum $s_{sum} = s_1 + s_2$, a value related to the laser power, and the difference $s_D = s_1 - s_2 \sim \cos 2\psi$. Because ψ is initially set at 45° , when a Faraday rotation angle α is introduced by the plasma, such that $\psi = 45^\circ + \alpha$, the difference signal becomes:

$$s_D \sim \sin 2\alpha. \quad (4.1)$$

For small α angles, the ratio of the two signals depends only on α

$$\frac{s_D}{s_{sum}} \sim C \sin 2\alpha \approx C \cdot 2\alpha \quad (4.2)$$

where C is a constant determined for each chord by the calibration procedure.

The signal to noise ratio is, for small angles α , very close to that of the difference signal s_D . The noise produced by the detectors is not the only source of noise in the signals. Mechanical vibrations and laser power fluctuations are source of noise, as well; in fact rapid laser power fluctuations result in the incorrect evaluation of the Faraday angle. Furthermore electromagnetic noise can affect the raw data and thus the experimental measurements. These noises are difficult to reduce or controll because the operating environment of the diagnostic is strongly affected by varying magnetic fields.

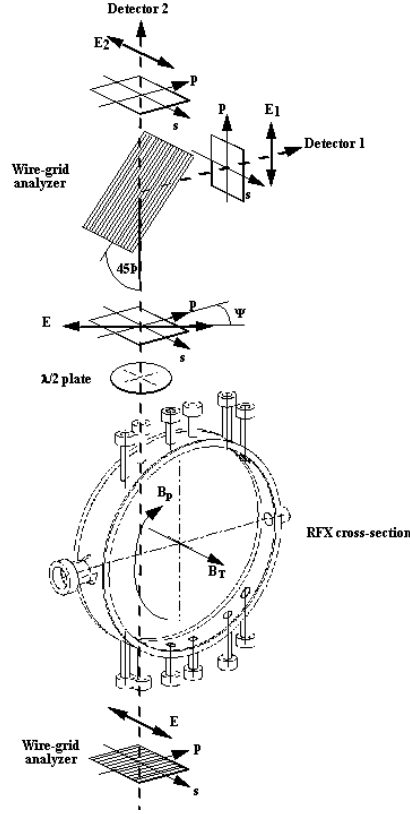


Figure 4.6: Principle of operation of the polarimeter. The linearly polarized beam crosses the plasma section and its polarization state is modified. Afterwards the components of the electric field of the radiation are selected by a polarizer and thus detected. The half wave plate is used just during the calibration procedure.

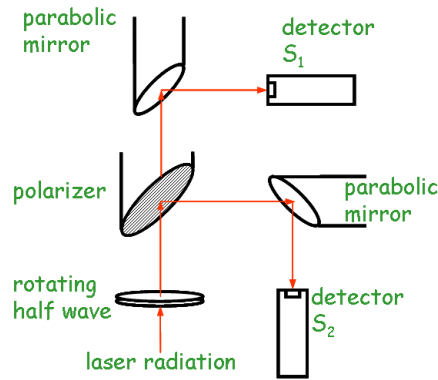


Figure 4.7: Rigid vertical assembly for the optical and detector components: the beam exiting from the vessel, passes through the rotatable half wave plate. A polarizer divides it into two orthogonal components and these are focolized into the respective detectors. The dectores are placed in different planes. The dectores named B are closer to the machine and their axes is orthogonal to the torus's surface. The dectores named A are farther from the machine and their axes are parallel to the torus's surface

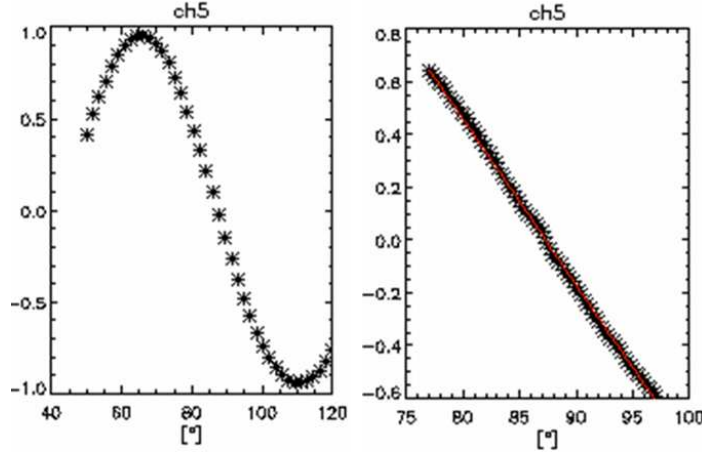


Figure 4.8: Zero-signal search performed over a wide range of angles (left plot) and calibration curve (right plot) performed by a fine angle scan close to the zero-signal position. The curves represent the evolution of the signal s_D/s_{sum} for a particular position θ of the half wave plate.

Automatic calibration procedure The calibration of the diagnostic starts equalizing the maximum power seen on both detectors for each channel. This is achieved by rotating the half wave plate until the maximum power is reached on one detector and then on the other. The gain factor for each channel is computed in order to equalize the maximum value, with respect to the other channels. The purpose of the calibration is twofold: to zero the polarimeter output signal s_D/s_{sum} in the absence of plasma and to evaluate the calibration factor prior the measurement. Rotating the half wave plate of a known angle, it is possible to simulate the effect of the plasma on the beam and to relate it to the amplitude of the polarimeter signal s_D/s_{sum} . First, the zero of the signal s_D/s_{sum} is searched, rotating the half wave plate over a wide range of angles (see left plot in Fig. 4.8). The software, implemented for the automatic calibration, stores the position θ of the plate corresponding to the zero of the signal. This sets the initial ψ usually around 45° . Afterwards, a fine tuning of the system is performed over a narrower angle range, from -10° to $+10^\circ$ with respect to the previous zero-angle position. The calibration sequence is automatically run before every shot to record a plot of polarimeter output versus the rotation angle θ of the half wave plate relative to the zero position, as previously stated. From the right diagram in Fig. 4.8, a calibration coefficient is calculated to allow the polarimetric measurements to be rescaled correctly to degrees of Faraday angle rotation.

4.4 First polarimetric measurements

The improvements of the diagnostic and the low level of fluctuations in the acquired signals allowed the first polarimetric measurements to be made in RFX-mod machine. Looking at figure 4.9, it is clear that the measurements during the vacuum

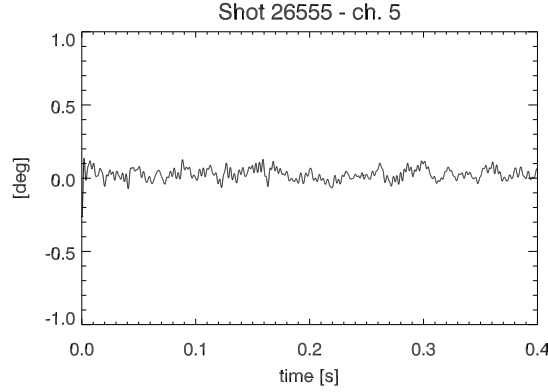


Figure 4.9: *Polarimeter signal for RFX-mod vacuum shot #26555. The accuracy of the measurement is within the $\pm 0.1^\circ$*

shot of RFX-mod are good, with zero line very well determined and an average error of about 0.1° (less than the required accuracy). The measurements of the Faraday rotation angle and the reconstructed magnetic field profiles are reported and discussed in this section. Although, as further explained, the measurements prove the reliability of the instrument for monitoring the evolution of the magnetic fields inside the plasma, the raw data collected by detectors are affected by electromagnetic noises. This aspect has been investigated and it is discussed in this section, as well.

Electromagnetic noise In the plasma discharges, a high frequency (5 kHz) noise appears on the raw signals that are closer to the machine (see Fig. 4.7). In figure 4.10 the upper diagrams show the raw signals at the two detectors s_1 and s_2 during a vacuum shot. The signals are constant during the considered time range and they don't exhibit any noise. On the contrary, in presence of plasma and hence when the coils are active, the raw data display a noise in addition to the variation of the amplitude due to the effect of the plasma. This problem clearly affects the data collected by the detector named s_2 , as it is shown in lower diagrams of the figure 4.10. These frequencies are acquired because the detector's cutoff frequency is 10kHz and the acquisition cards work at 25kHz, thus the noise at 5kHz is rightly displayed in the raw data. Fortunately this noise has a low impact in the Faraday angle measurements because just the component at chopping frequency is extracted. Therefore the high frequency noises are deleted.

Since the noise appears in presence of plasma, some investigations have been carried out to characterize the evolution of the magnetic field close to the detectors. To this purpose magnetic probes have been placed at the position of the detectors. Each probe gives the measurement of the magnetic field along two orthogonal directions, in particular for this set-up they provide information on the radial and poloidal magnetic components. The figure 4.11 on the left shows the real position of the probes used for the tests, in between the polarimetric chords 3 and 4. The different levels of noise presented in figure 4.10 (lower diagrams) for signals s_1 and s_2 have been confirmed by

this test. In fact, as shown in figure 4.11 on the right, the amplitude of the magnetic components measured at the lower level s_2 of the detection section is double with respect to the one measured at the level of s_1 . After some tests, it was pointed out that the noise appears when saddle coils, previously presented (see Fig. 4.3), are powered with a particular varying waveform. In figure 4.12 it is shown that when the current flows in the coils (250-275ms) with an amplitude bigger than 150A and frequency around 50Hz the raw data in absence of plasma exhibit a large noise. This proved again that the detectors closer to the machine and thus to the saddle coils are more affected by the electromagnetic noise and it suggested the design of electromagnetic screens for the detectors. According to these observations, the benefits of the use of a screen made of copper have been investigated. The results of this test conducted during a plasma session have been very satisfactory and level of the noise has been strongly reduced as displayed in figure 4.13, where the effect of an aluminium screen and of an additional copper screen are highlighted. The diagrams refer to different plasma discharges having the same characteristics and they represent the output voltage signals from detector s_2 of polarimetric chord 3 in absence of laser signal. The first diagram shows the high level of the noise during the entire discharge at the detector without any shell. The second diagram is referred to the signal collected by the same detector with an aluminium shell; the level of noise is about 10 times less than in the previous case and its evolution is clear over the zero line signal confirming the need of a screen. The third diagram shows the evolution of the noise collected by the detector with aluminium shell inside a copper cylinder with 5mm thickness. The level of noise is again reduced of about 85% during the entire length of the shot. Hence the use of electromagnetic copper screens is strongly recommended to reduce the influence of the noise on raw data and then new optical design for the detection section is needed.

Faraday angle measurements In figure 4.14 a typical example of measurements performed on five chords is shown. On the left side of the figures, the plasma current and electron density profile, reached in the two particular considered discharges, are displayed. These plots make easy to understand the operation regime of the polarimeter: $I_p \geq 1\text{MA}$, $n_e \geq 1 \cdot 10^{19}\text{m}^{-3}$. The polarimetric measurements confirm the reliability of the new polarimeter also during the most critical performances reached by the RFX-mod machine, i.e. $I_p > 1.5\text{MA}$. The large oscillations that affect the measurements during the plasma discharge of the RFX-mod machine [43] have been strongly reduced thanks to a careful design of the optical line, mirror holders made of insulating material and optics fixed on inertial granite platform. In some cases, residual fluctuations at about 100Hz in the polarimetric output are still visible with lower impact in the measurement than in the past. The origin of those noises is purely mechanical and they have been recently reduced by means of a better alignment by using quartz plates as beamsplitter. All these improvements have allowed first polarimetric measurements with average accuracy of $\pm 0.2^\circ$ on Faraday angle and a resolution time up to $\sim 1.5\text{ms}$. The Faraday angle measured has been compared to a theoretically calculated value based on the

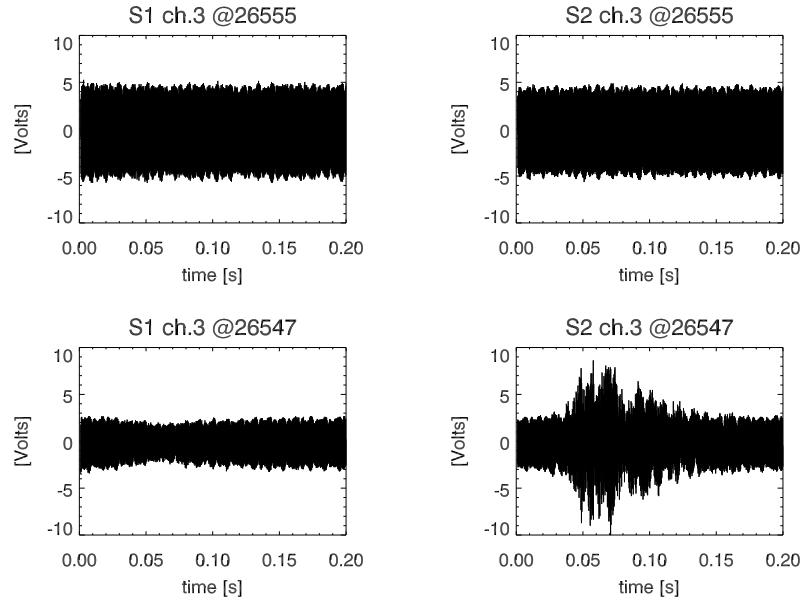


Figure 4.10: The upper diagrams show the raw signals at the two detectors s_1 and s_2 during a vacuum shot. The signals are constant during the considered time range and they don't exhibit any noise. When the coils are active, the raw data (lower diagrams) display a noise in addition to the variation of the amplitude due to the effect of the plasma.

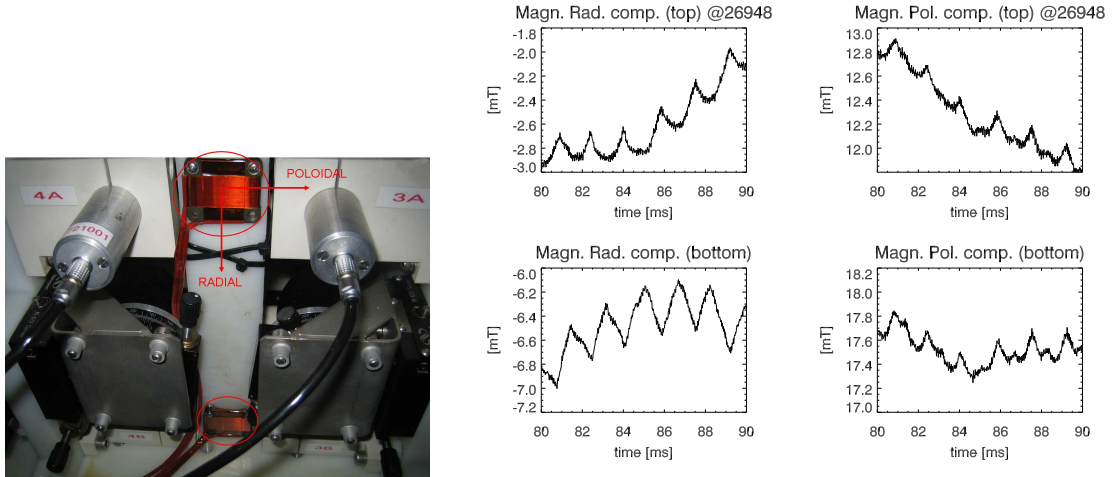


Figure 4.11: On the left the picture shows the real position of the probes in between the polarimetric chords 3 and 4. On the right diagrams, the amplitude of the magnetic components measured at the lower level s_2 of the detection section is double with respect to the ones measured at the level of s_1 , confirming the behaviour exhibited by the raw data

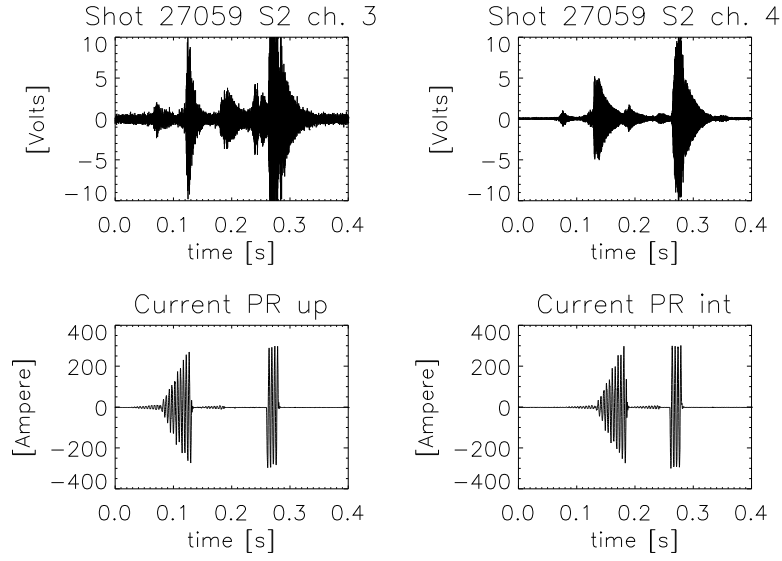


Figure 4.12: The figure shows the relation between the noise at the detectors and the waveform used to power the saddle coils. Looking at the time range 250-275ms it is clear the saddle coils affect strongly the signals at the detectors s_2 .

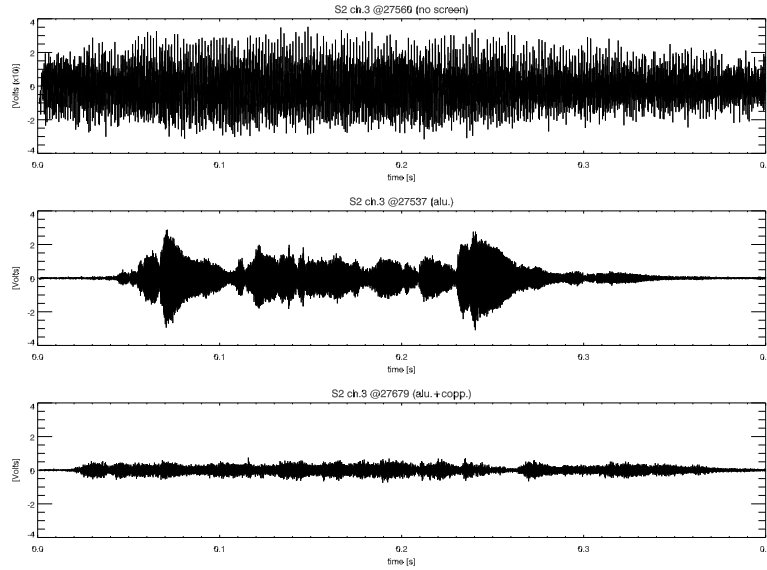


Figure 4.13: The upper diagram shows the high level of the noise during the entire discharge at the detector s_2 without any shell. The middle diagram is referred to the signal collected by the same detector with an aluminium shell; the level of noise is about 10 times less than in the previous case and its evolution is clear over the zero line signal confirming the need of a screen. The bottom diagram shows the evolution of the noise collected by the detector with aluminium shell inside a copper cylinder with 5mm thickness. The level of noise is again reduced of about 85% during the entire length of the shot

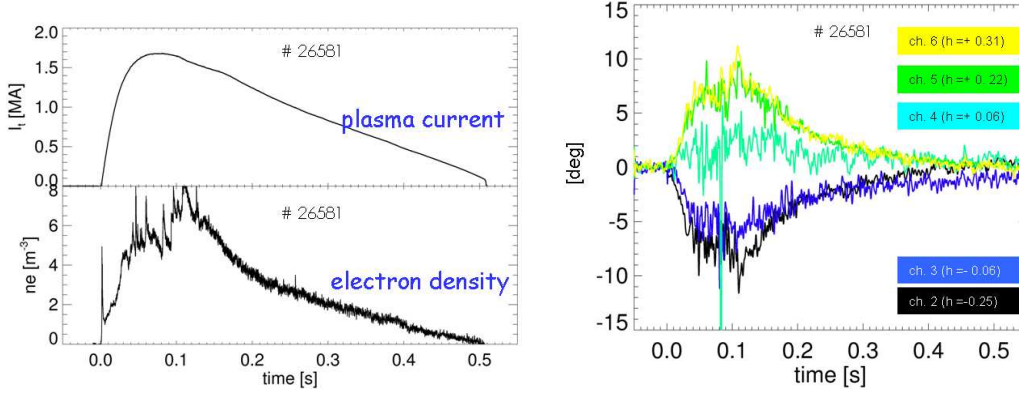


Figure 4.14: The evolution of the plasma current and of the electron density profile for the RFX-mod's pulse 26581 is plotted in the left side of the figure. On the right side the time evolution of the polarimeter output for the five channels is reported.

$\mu&p$ model [44] [45]. In fact combining together the toroidal and poloidal field profiles, reconstructed by the $\mu&p$ equilibrium model, and the electron density measurements it is possible to evaluate the expected Faraday rotation angle from the relation:

$$\psi = k\lambda^2 \int_z n_e B_{||} dz, \quad (4.3)$$

where k is a constant, λ is the wavelength, n_e is the electron density and $B_{||}$ is the component of the magnetic field parallel to the direction of propagation of the probing beam. The $\mu&p$ model provides the magnetic fields according to the following expression

$$\nabla \times \vec{B} = \mu \vec{B} + \frac{\vec{B} \times \nabla p}{B^2}. \quad (4.4)$$

The profile of parameters $\mu(r) = \mu_0 \frac{\vec{j} \cdot \vec{B}}{B^2}$ and $p(r) \sim n_e(r)T_r(r)$ are assumed as inputs for the relation such that they minimized the difference between the outputs and the external measurements of $F = B_t(a)/\langle B_t \rangle$ and $\Theta = B_p(a)/\langle B_t \rangle$ where $a = 0.475$ is the first wall radius. An example of the comparison between the measured and predicted data is given in Fig. 4.15, which is a graph of the Faraday rotation profile as a function of the distance of the chord from the centre of the vessel. The data represents the conditions of Fig. 4.14 at the time interval 134ms. The black curve is a spline fit to the predicted data calculated as above using the plasma current, the density profile and other data from shot. The measured Faraday angles are also indicated by the blue line. From the graph we can see that the measured and predicted data are in good agreement having the same order of magnitude and follow the same general profile shape. The differences increase going from the centre towards the edge highlighting how the $\mu&p$ is not able to describe the actual magnetic profiles especially in the edge of the plasma where the electron density gradient are present. Therefore a more suitable description

of the internal magnetic profile has been studied.

In fact the parameterization for $\mu(r)$ profile previously used is with 2 free parameters, but thanks to the five internal measurements provided by polarimetry it is possible to improve the parameterization by means of 4 free parameters. The result of this improvement is depicted in figure 4.16 where the profile which allow a minimum difference between internal and external measurements is represented by the red line. The new parameterization modify the profile of μ at the middle radius and leave it unchanged in the zone of gradients (edge). It is interesting to observe that using the polarimetric data the difference between the internal and external measurements is reduced up to 50%. Therefore the polarimetric measurements have been confirmed helpful for the reconstruction of the magnetic field profiles inside the plasma column allowing good measurements of the magnetic fields, as shown in figure 4.17. Looking at the figure, the equilibrium poloidal field shows a slight decrease at $r/a \sim 0.5$ (red line), resulting compatible with magnetic profile computed by the standard model.

Furthermore the graphs of figure 4.15 reveals also that the experimental values are not null at the centre of the vessel, performing an experimental determination of the position of the magnetic axis in RFX-mod, that is clearly displaced towards the outer edge of the torus. This displacement of the magnetic axis is a classic effect of the Shafranov shift [46], but depends, as well, on the new magnetic configuration assumed by RFX-mod's plasma for current higher than 1.5MA. As previously said in subsection 4.2.1, the plasma self-organizes in a helical state with a single helical axis, SHAx [47] [48].

4.5 Conclusions and further developments

RFX-mod is now equipped with a multichord FIR polarimeter for measurement of the Faraday rotation angle. Faraday rotation measurements have been obtained in high current ($I_p > 1.5$ MA) pulses obtaining values from zero up to more than 15° , with a good level of signal over noise ratio. The preliminary results highlighted the shift of the plasma magnetic axis and the measured values agree with those computed by other diagnostic. The comparison with a theoretical model for the determination of the internal magnetic radial profile shows a general good agreement. A more suitable description of the internal magnetic profile has been studied and the results are satisfactory. Still some improvement on the diagnostic are needed. In particular, increasing the S/N ratio with a new setup and design of the detection section will help to obtain a better accuracy on the measurements. A noise on the raw signals of some detectors is present and an electromagnetic screen for the detectors has been investigated suggesting to use copper screens. It can be concluded that in the present state the polarimeter is capable of giving a valid contribution to the knowledge of the RFX-mod experiments in combination with other diagnostics.

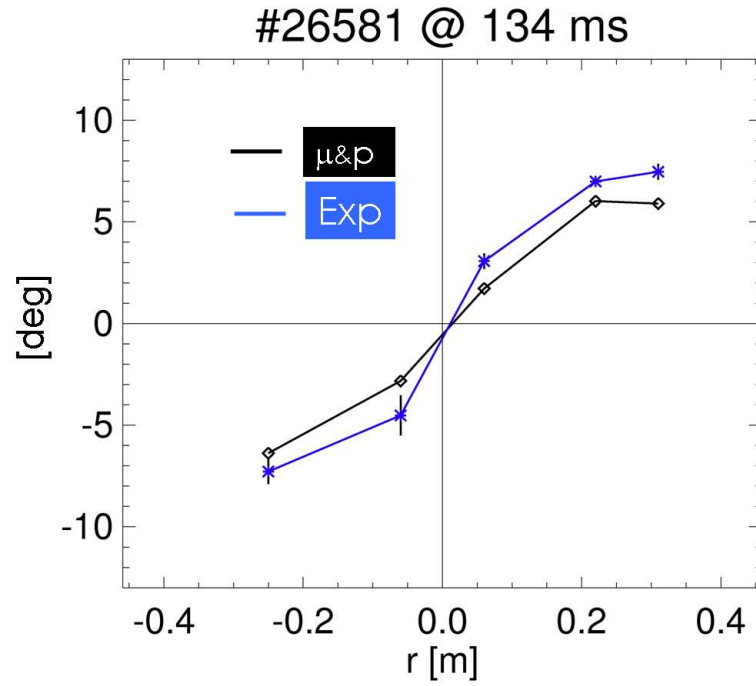


Figure 4.15: Radial profile of the Faraday rotation angle: comparison between the measured value (blue line) and the simulated values (black line)

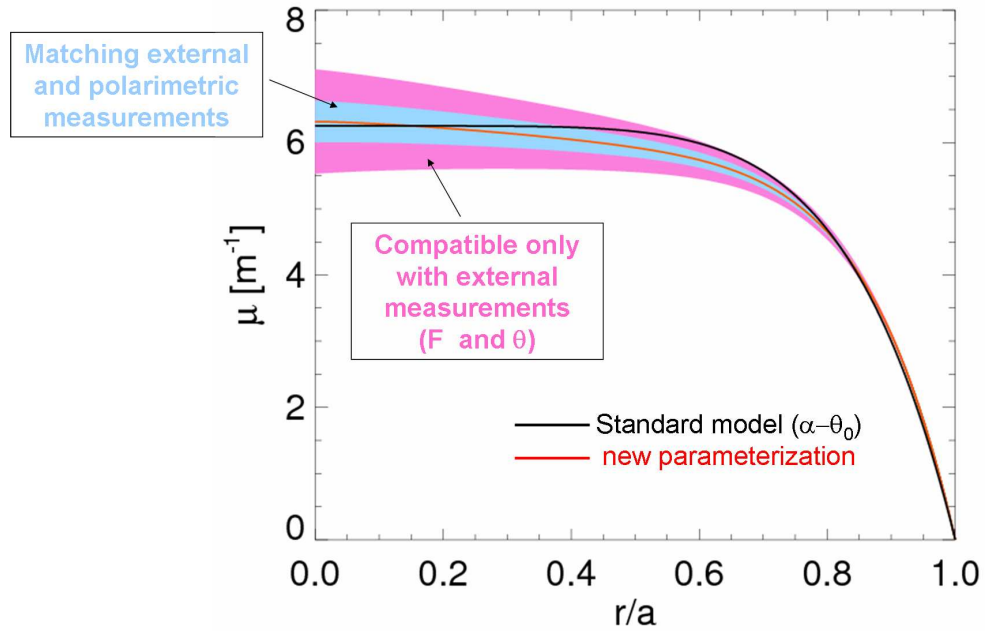


Figure 4.16: Parametric study of μ profile using 4 free parameters. The new parameterization (red line) modify the profile of μ at the middle radius and leave it unchanged in the zone of gradients (edge). The difference between the internal and external measurements is reduced up to 50%.

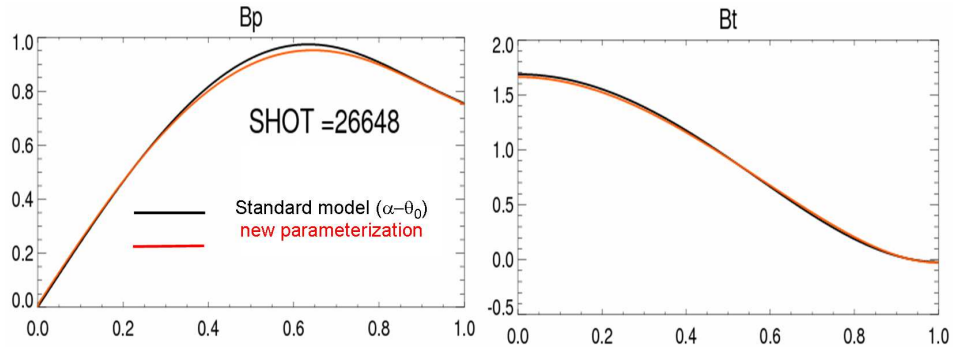


Figure 4.17: The poloidal and toroidal magnetic components of the fields reconstructed by the new parametrized μ profile. The equilibrium poloidal field shows a slight decrease at $r/a \sim 0.5$ (red line), resulting compatible with magnetic profile computed by the standard model.

Polarimetric data analysis at JET

5.1 Introduction

In this chapter the research activities carried out at the interferometer/polarimeter laboratory of the JET machine site are presented. The Joint European Torus (JET), located at Culham in Oxfordshire, is the world's largest and most powerful tokamak and the focal point of the European fusion research program. Designed to study fusion in conditions approaching those needed for a power plant, it is the only device currently operating that can use the deuterium-tritium fuel mix that will be used for commercial fusion power. All the activities here reported have been done during different periods spent at the Culham Research Centre (UK) and they can be summarized in three topics.

The first one is the reliability of measurement of the line integrated plasma electron density from polarimetric data. The purpose of this study is to have a measurement of the plasma density alternative to the one obtained from interferometer when this last diagnostic fails the measurement. In fact as a consequence of ELMs, pellet injections, fast density increases or disruptions, the interferometer is subject to fringe jumps, which produce loss of the signal preventing reliable use of the measured density in the real time feedback controller operating at JET. The right measurement can be recovered just providing to the interferometer the correct value of density. Given the results obtained at W7-AS machine [49] also at JET the possibility of obtaining the electron density from measurements of the Cotton Mouton effect has been seriously considered. As previously said in section 3.1 the Cotton Mouton effect consists of a change of the ellipticity of a beam probing the plasma due to the interaction with the magnetic fields perpendicular to the direction of the beam probing the plasma column. In section 5.4 a systematic comparison between the line integrated electron density derived from interferometry and polarimetry at JET machine is presented.

The second topic is the theoretical investigation over the sources of an anomalous behaviour affecting the polarimetric measurements at JET. During the calibration

Plasma Major Radius	2.96 m
Plasma Minor Radius	1.25 m (horizontal) 2.10 m (vertical)
Plasma Volume	$\sim 100 \text{ m}^3$
Plasma current	Circular Plasma 3.2 MA D- Shape Plasma 4.8 MA
Flat-top pulse length	20 s
NB Power	22 MW

Table 5.1: *JET parameters*

procedure of the polarimeter without plasma, the linearly polarized probing beam acquires a "spurious" ellipticity. At present the polarimetric data have to be post-processed, using a model which accounts of this spurious ellipticity, to obtain the pure polarimetric measurements. This model assumes the ellipticity is due to non ideal behaviour of unidentified optical components. The results of the analysis of some optical components which could be the source of the observed anomalous behaviour of the polarimetric measurements are reported and discussed in section 5.5.

The last topic is about a recent work carried out to write a new post-processing code for the raw polarimetric data. Since the optical components introducing the spurious effects are completely unknown, then the new procedure to evaluate the pure polarimetric measurements by processing the raw data is based on an empirical model in which a purely numerical complex fitting procedures are implemented. A new code based on the optical layout of the diagnostic has been developed. The preliminary results obtained with this new code are shown in section 5.6.

5.2 The JET machine

JET, the Joint European Torus, is based at Culham Science Centre and it was the first facility in the world to achieve a significant production of controlled fusion power (nearly 2MW) with a Deuterium-Tritium experiment in 1991. The JET program was set up to make it possible to carry out fusion test under conditions that closely resemble those of a commercial fusion power plant.

The technical design specifications of JET (see Table 5.2) have been achieved and exceeded in several cases. These results have produced a clearer picture of energy and particle transport, resulting in the development of models which describe and predict plasma behaviour. Moderate extrapolation of results of model predictions allow the size and the performance of a thermonuclear reactor to be largely defined. Knowledge gained from JET has provided valuable input into the design of "next step" devices such as ITER (see 2.2.1).

JET has a wide set of diagnostics with unique capabilities in measuring the thermonuclear fusion products, i.e. the fast neutrons, gamma rays and alpha particles, confined and lost. As it can use all hydrogen isotopes, absolutely unique diagnostics are required to measure the plasma isotopic composition. Other major

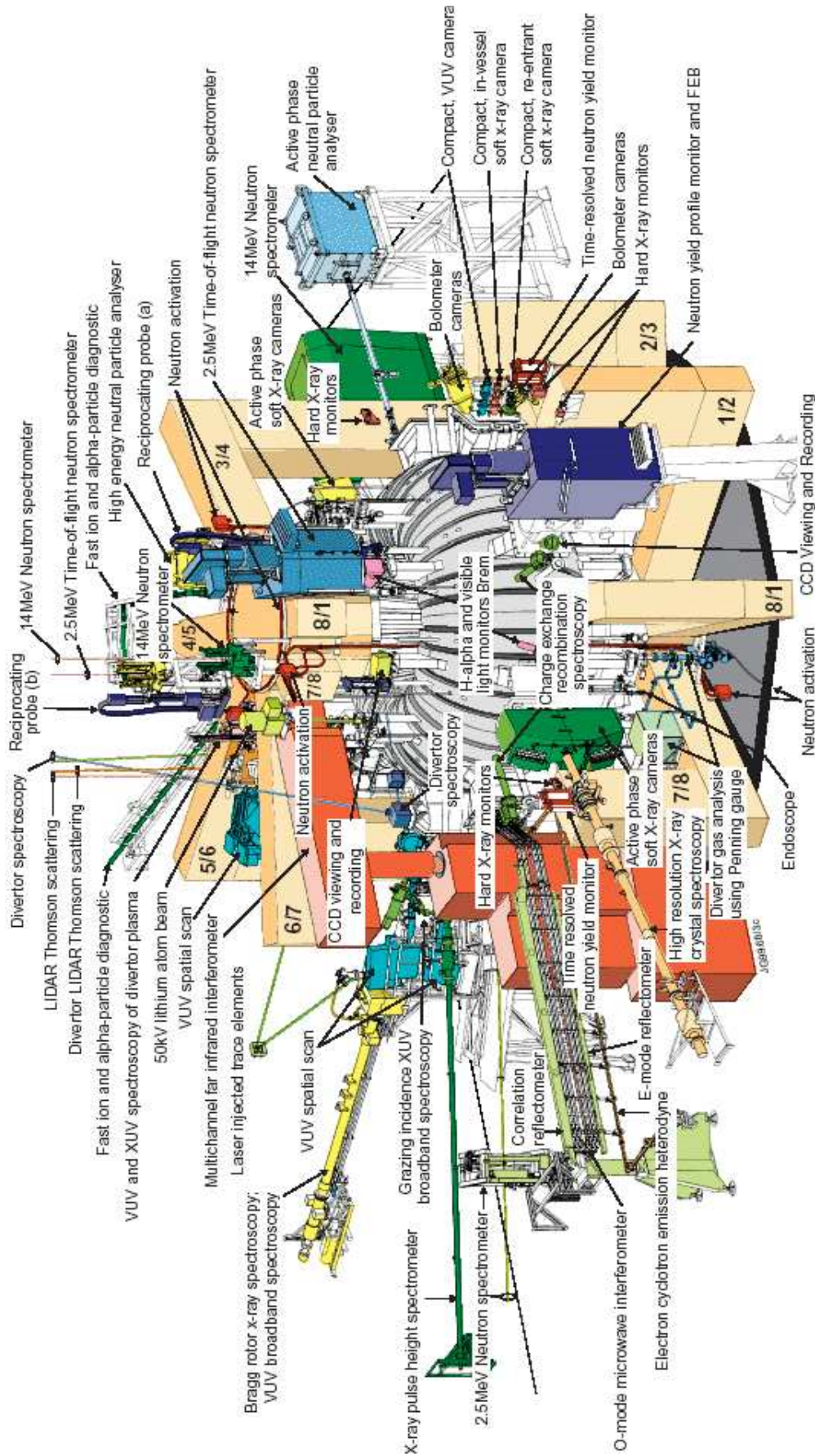


Figure 5.1: Schematic of the JET machine with all the diagnostic set

goals of the JET diagnostics are common to big fusion experiments: to determine plasma temperature and density, to measure plasma particle and radiation losses, to find out the magnetic topology and to observe plasma flows and fluctuations. The specificity of JET consists of providing conditions for these measurements that are closest to a reactor environment. The main diagnostics operating at JET (see Fig. 5.1) are:

- Charge exchange spectroscopy, which relies on importing atoms into the hottest plasma regions. A neutral beam heating system launches neutral ions into the plasma at extremely high velocity. In subsequent collision with the hot plasma they loose their electrons and then they shine light in the meantime. Observing the characteristics of this distinct light from impurity ions it is possible to know by the Doppler effect what the temperature of the plasma ions is and what direction of flow the plasma has [50].
- Motional Stark Effect Spectroscopy: the neutral beam atoms themselves emit light that can be measured separately, as the Doppler effect at the velocity of beam atoms causes a distinct phase shift in the wavelength of their light. The spectral lines of this radiated light are split and polarized due to the fact that the beam atoms cross very rapidly through a strong magnetic field. By measuring the specific feature of the light it is possible to determine the direction of the magnetic field lines even inside the hot plasma [51].
- LIDAR Thomson Scattering, which measures the plasma electron temperature and density. In the JET plasma the temperature of the electrons can range from about 200 eV near the edge to over 10 keV in the centre. One way to measure such high temperatures is to shine an intense laser pulse into the plasma and to detect the back-scattered light from the electrons. At JET two such LIDAR diagnostics operates: the "Core" system looks at the bulk of the plasma, and the "Divertor" system looks at the edge plasma. The monochromatic laser light is scattered and Doppler shifted by the fast moving plasma electrons producing a broad spectrum of scattered light. By measuring the width of this scattered spectrum the velocity distribution and hence the electron temperature (T_e) can be determined and by measuring the total intensity of the scattered light the density of the electrons (n_e) can be deduced [52].
- Neutron and gamma-ray profile monitor: tow cameras allow observations of plasma radiation fro ten horizontal and nine vertical directions. The source of the neutrons produced by fusion or of the gamma-ray produced by nuclear reactions, can be localized.
- Interferometer/Polarimeter: it measures the line integrated electron density and both the Faraday and Cotton Mouton effect. It is an essential diagnostic for JET operations for plant safety reasons and it is integrated in the real time feedback controller. The main parameters of the system are: measuring range of line integrated electron density from $\sim 5^{18} \text{ m}^{-2}$ to $4 \times 10^{22} \text{ m}^{-2}$, spatial resolution $\sim 20\text{cm}$, resolution of polarimetric measurements less than 0.2° . This last diagnostic will be better described in the section 5.3

5.3 The Interferometer/Polarimeter

At JET, the Far Infrared (FIR) diagnostic operates as a dual interferometer and polarimeter system, widely described in [53]. It was initially designed to operate as a pure multichannel Far Infrared interferometer of the Mach-Zender type [54]. The introduction of additional optics allowed measurements of the Faraday effect and then the determination of the poloidal magnetic field distribution [53]. Recently the system has been upgraded with a new set-up to allow simultaneous Faraday rotation angle and Cotton Mouton phase shift measurement [55]. The radiation source is a Deuterated Cyanide (DCN) laser at $\lambda = 195\mu\text{m}$ and the reference beam is modulated at 100 kHz by means of a rotating grating. The system probes the plasma with 4 vertical and 4 lateral (see Figure 5.2) laser beams which provide measurements of the line-integrated plasma density by means of interferometry and measurements of Faraday angles and Cotton Mouton effect by means of polarimetry [55].

When, for example, a rapid phase variation larger than 2π or, as well, a temporary deflection of the measuring beam occurs, the fringe number cannot be determined then measurement fails. Such events are usually called fringe jumps and they introduce discontinuities on the phase evaluation equal to an integer number of multiples of 2π . In the case of JET, the main phenomena which may cause fringe jumps are typically ELMs and pellets. In the case of ELMs, one or more beams passing through the plasma can be diffracted away from the detector. Actually the method to correct fringe jumps is the comparison between vertical and lateral channels (ch2-ch7, ch3-ch8 and ch4-ch5), assuming that the latter are already corrected. The detection depends on the difference between channels using an appropriate coefficient from one sample to the next. If the difference increases over an imposed limit the correction is applied.

The interferometric measurements are integrated into the real-time plasma control, and are used for machine protection against disruptions. Starting with the current experimental campaign (C-20), the measurements of the Cotton-Mouton effect were made available in the real-time system as well as the measurements of the Faraday rotation angle, that has been successfully implemented and used since 2002 for real time q-profile experiments [55].

5.3.1 Operation principle

Since the polarimetric measurements has been analyzed for this thesis, the operation principle of the JET polarimeter is presented. A simplified scheme of the general optical set-up for one vertical chord of JET polari-interferometer is shown in Fig. 5.3, where a reference frame is assumed with x-axis along the toroidal direction, the y-axis along the radial direction and the z-axis along the vertical axis of the torus. The laser beam is split into a probing beam and a reference beam (also known as "*modulated beam*"). Neglecting the beam splitter system, which divides the beam into the different chords, each of the probing beam passes through a wire grid used as an optical filter and through an half wave plate, used for calibration and diagnostic set-up prior entering the vacuum vessel. On the vertical channels, the polarization is linear at 45° with respect to the toroidal direction (x- axis) to

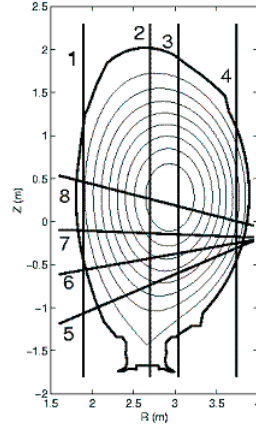


Figure 5.2: *Lines of sight for interferometry and polarimetry at JET*

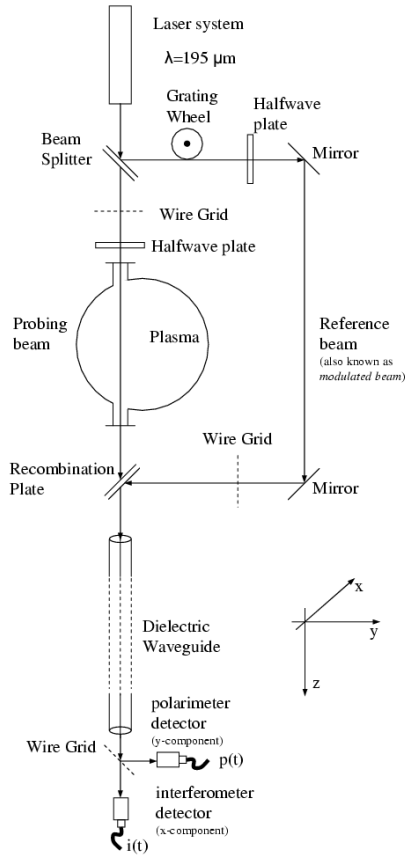


Figure 5.3: *Diagnostic layout for one vertical chord of the polarimeter-interferometer at JET.*

maximize the Cotton Mouton effect. After passing through the plasma, the polarization of the radiation experiences a rotation because of the Faraday effect and acquires ellipticity due to the Cotton Mouton effect. The input and exit windows to the vacuum chamber are made of z-cut crystal quartz.

The reference beam is modulated (frequency shifted) by a rotating grating wheel at 100kHz ($\omega_0 = 2\pi \times 10^5 s^{-1}$) and its polarization is rotated via a half wave plate of 45° ; then it is split into the different channels. Each of these beams passes through a wire grid used as an optical filter before being recombined with the probing beam by a recombination quartz plate. The recombined beam passes through an oversized dielectric waveguide (Pyrex tubes of $\sim 80mm$ inner diameter) and then it reaches a wire grid which acts as an analyzer, dividing the electric field components into two direction x and y, that are focused onto two corresponding detectors.

Supposing all the optical components behave ideally, the probing beam, when passing through the plasma can be expressed in the following complex form:

$$E_x^{(p)} = E_0 \cos \Theta \quad (5.1)$$

$$E_y^{(p)} = E_0 \sin \Theta e^{-i\Phi} \quad (5.2)$$

with time dependence $e^{-i\omega t}$, $\omega = 2\pi c/\lambda$ and

$$\Theta = \Theta_0 + \alpha \quad (5.3)$$

with $\Theta_0 = 45^\circ$.

In presence of plasma, α is due to the Faraday effect and Φ is the phase shift between the electric field components E_x and E_y due to the Cotton Mouton effect. In absence of plasma, α is produced by a rotation of the half wave plate used for the calibration. The reference beam can be expressed as:

$$E_x^{(r)} = E_{0g} \cos \Theta_g \quad (5.4)$$

$$E_y^{(r)} = E_{0g} \sin \Theta_g \quad (5.5)$$

with time dependence $e^{-i(\omega+\omega_0)t}$ and $\Theta_g = 45^\circ$.

The calculation of the average power of the radiation incident on the detectors, evaluated over times much longer than ω^{-1} but shorter than ω_0^{-1} , leads to the following expressions for the detector signals:

$$i(t) = K_x (E_x^{(p)} E_x^{(r)*} e^{i\omega_0 t} + c.c.) \quad (5.6)$$

$$p(t) = K_y (E_y^{(p)} E_y^{(r)*} e^{i\omega_0 t} + c.c.), \quad (5.7)$$

where the signals from x-component and y-component detector are indicated as $i(t)$ ("interferometric signal") and $p(t)$ ("polarimetric signal") respectively, K_x and K_y are proportional to the respective detector responsivities. Inserting relations (5.1) and (5.4) into (5.6) it possible to obtain:

$$i(t) = K_x (E_0 E_{0g}^* e^{i\omega_0 t} + E_0^* E_{0g} e^{-i\omega_0 t}) \cos \Theta \cos \Theta_g. \quad (5.8)$$

Writing

$$E_0 = |E_0|e^{-i\phi_p}, \quad E_{0g} = |E_{0g}|e^{-i\phi_g}, \quad \Delta\phi = \phi_p - \phi_g \quad (5.9)$$

the previous relation can be expressed as

$$i(t) = K_x\sqrt{2}|E_0||E_{0g}|\cos\Theta\cos(\omega_0t - \Delta\phi). \quad (5.10)$$

The phase shift $\Delta\phi$, which accounts for the different optical path between probing and reference beam and for the electron density effect on the probing signal phase, is not important for polarimetry. It can be omitted by the suitable choice of the time-line origin. A similar expression for $p(t)$ is obtained, inserting the relations (5.2) and (5.5) into (5.7). Finally the detector signals can be written in the form:

$$i(t) = A_i \cos \omega_0 t \quad (5.11)$$

$$p(t) = A_p \cos(\omega_0 t - \varphi) \quad (5.12)$$

where

$$A_i = A \cos \Theta \quad (5.13)$$

$$A_p = B \sin \Theta \quad (5.14)$$

$$A = K_x\sqrt{2}|E_0||E_{0g}| \quad (5.15)$$

$$B = K_y\sqrt{2}|E_0||E_{0g}| \quad (5.16)$$

$$\varphi = \phi_0 + \Phi, \quad (5.17)$$

where ϕ_0 is the phase shift between the two signals without plasma. It is zero just in this particular context, but generally it is not zero, as it will be further shown. The detector outputs are electronically acquired with a time resolution of 1ms up to 14 ms depending on the acquisition set-up and they are processed by analog phase sensitive electronic cards to obtain the following four signals:

$$RMS = \langle i(t) \cdot i(t) \rangle = \frac{1}{2}A_i^2 \quad (5.18)$$

$$PSD = \langle i(t) \cdot p(t) \rangle = \frac{1}{2}A_i A_p \cos \varphi \quad (5.19)$$

$$RMS' = \langle i'(t) \cdot i'(t) \rangle = \frac{1}{2}A_i'^2 \quad (5.20)$$

$$PSD' = \langle i'(t) \cdot p(t) \rangle = \frac{1}{2}A_i' A_p \sin \varphi \quad (5.21)$$

where $i'(t) \sim \sin \omega_0 t$ is generated by 90° phase shifting $i(t)$ and its amplitude A_i' is assumed different from A_i . From these four relations the following ratios can be calculated:

$$R = \frac{PSD}{RMS} = \frac{A_p}{A_i} \cos \varphi \quad (5.22)$$

$$R' = \frac{PSD'}{\sqrt{RMS \cdot RMS'}} = \frac{A_p}{A_i} \sin \varphi. \quad (5.23)$$

If the relations (5.13) and (5.14) are satisfied, the previous ratios can be rewritten as:

$$R = C^{-1} \tan \Theta \cos \varphi \quad (5.24)$$

$$R' = C^{-1} \tan \Theta \sin \varphi \quad (5.25)$$

defining

$$C = \frac{A}{B}. \quad (5.26)$$

Given the two ratios R and R' , the angles Θ and Φ can be easily obtained. In fact, their ratio gives:

$$\varphi = \arctan \left(\frac{R'}{R} \right), \quad (5.27)$$

independent from Θ , and then the Cotton Mouton phase difference

$$\Phi = \varphi - \phi_0. \quad (5.28)$$

The sum of their squares leads to:

$$\Theta = \arctan(C\sqrt{R^2 + R'^2}) \quad (5.29)$$

without any dependence on φ . The two calibration constants ϕ_0 and C are determined in absence of plasma, when $\Phi = 0$ and $\Theta = 45^\circ$. In this treatment, it is assumed that the phase shift without plasma $\varphi = \phi_0$ is independent from the Faraday rotation and therefore it remains constant during the scan of α performed to calibrate the diagnostic.

The angles Θ and Φ define the polarization state of the radiation exiting the plasma. In fact, the Stokes vector components can be evaluated as:

$$s_1 = \cos 2\Theta \quad (5.30)$$

$$s_2 = \sin 2\Theta \cos \Phi \quad (5.31)$$

$$s_3 = \sin 2\Theta \sin \Phi \quad (5.32)$$

with $0 \leq \Theta \leq 90^\circ$ and $-180^\circ \leq \Phi \leq 180^\circ$. By these expressions it is possible to calculate the main polarization parameters: ellipticity ϵ , defined as the ratio

between minor and major axes of the polarization ellipse, and ψ , the tilt angle of the polarization ellipse with respect to the x-direction

$$\epsilon = \frac{|s_3|}{1 + \sqrt{1 - s_3^2}}, \quad (5.33)$$

$$\psi = \frac{1}{2} \arctan \left(\frac{s_2}{s_1} \right) \quad (0 \leq \psi \leq 180^\circ). \quad (5.34)$$

The Faraday rotation angle is given by:

$$\Psi = \psi - \Theta_0, \quad (5.35)$$

it is equal to $\alpha = \Theta - \Theta_0$ only in absence of ellipticity ($\Phi = 0$).

5.4 Electron density measurements from Cotton Mouton effect

In the JET machine, the far infrared (FIR) interferometer ($\lambda = 195\mu m$) [53] described in section 5.3 is subject to occasional fringe jumps, as a consequence of events such as Edge Localized Modes (ELMs) [56], fast density increases, disruptions [57] and pellet injection. Due to these effects, the interferometric signal can be corrupted or even lost for significant intervals of time, resulting in an unreliable reconstruction of the measured phase angle. This phenomenon prevents the use of the measured line integrated density in a real-time feedback controller.

The measured difference in phase ϕ is in the $-\pi \leq \phi \leq \pi$ range but the true value of ϕ_p (see section 3.3) can be higher than 2π :

$$\phi_p = \phi_0 + 2\pi F, \quad (5.36)$$

where F is an integer representing the fringe number. When the number F , in case of the events above mentioned, cannot be determined then the interferometric measurement fails. There are discontinuities on the phase evolution equal to an integer number of multiples of 2π .

The idea, which inspired this work is to provide to the interferometer, affected by fringe jumps, the correct value of density. In such way, the interferometric signal can be recovered, preventing difficulties for the real time control of many experiments at the JET machine [58, 59, 60]. As previously said, an alternative method for measurements of the electron density is based on the Cotton Mouton effect (see Sec. 3.1), measured by polarimetry.

5.4.1 The method

In general the exact solution of evolution equation (3.20) shows a mutual interference between the Faraday effect and the Cotton-Mouton effect, such that it may be difficult to separate them [61]. It is convenient to consider the following approximate solution [11]:

$$\mathbf{s}(z) \cong \mathbf{s}_0 + \mathbf{s}_0 \times \int_z \boldsymbol{\Omega}(z) dz \quad (5.37)$$

where $\mathbf{s}_0$ is the initial polarization state and it is valid in the condition

$$W(z) \ll 1, \quad (5.38)$$

with

$$W(z) \equiv \int_z |\boldsymbol{\Omega}(z')| dz'. \quad (5.39)$$

The previous condition is equivalent to assuming that the effect of the plasma on the polarization state of the beam is small. The result can be put in the form:

$$\mathbf{s}_f = \mathbf{M} \cdot \mathbf{s}_0 \quad (5.40)$$

where $\mathbf{M}$, the transition matrix of the plasma [28], is given by:

$$\mathbf{M} \equiv \begin{pmatrix} 1 & -W_3 & W_2 \\ W_3 & 1 & -W_1 \\ -W_2 & W_1 & 1 \end{pmatrix} \quad (5.41)$$

For a generic input polarization $\mathbf{s}_0$, the rotation of the polarization depends not only on W_3 , but also on W_1 and W_2 , and the ellipticity depends on W_1 and also on W_2 . For input beam linearly polarized at 45° , whose Stokes vector is $\mathbf{s}_0 = (0, 1, 0)$, the final Stokes vector can be written as:

$$\mathbf{s}_f \approx (-W_3, 1, W_1), \quad (5.42)$$

which, for $|W_1| \ll 1$ and $|W_3| \ll 1$, represents a polarization rotated by an angle $\psi \approx W_3/2$ with respect to the initial 45° (Faraday effect) and with an ellipticity $\epsilon \approx W_1/2$ (Cotton-Mouton effect associated with the Ω_1 component)[28]. This result is particularly interesting because the two effects satisfy the relations for the Faraday effect and the Cotton-Mouton effect respectively, without any interference. Then it is possible to link the line integrated plasma density directly to the ellipticity of the polarization using the following equations:

$$s_{3f} = \sin 2\chi \quad (5.43)$$

$$s_{3f} \approx W_1. \quad (5.44)$$

The former is the definition for the third Stokes vector component and the latter is a consequence of the present approximation. Using equation (3.26) it is possible to write:

$$\int_{z_1}^{z_2} n_e(z) dz = \frac{\sin 2\chi}{C_1 \lambda^3 B_t^2} \quad (5.45)$$

being χ , λ and B_t the ellipticity, the wavelength and the toroidal magnetic field component respectively. Since the toroidal magnetic field is known, this effect gives the possibility of obtaining the line integrated electron density from the measurement of the ellipticity of the probing beam.

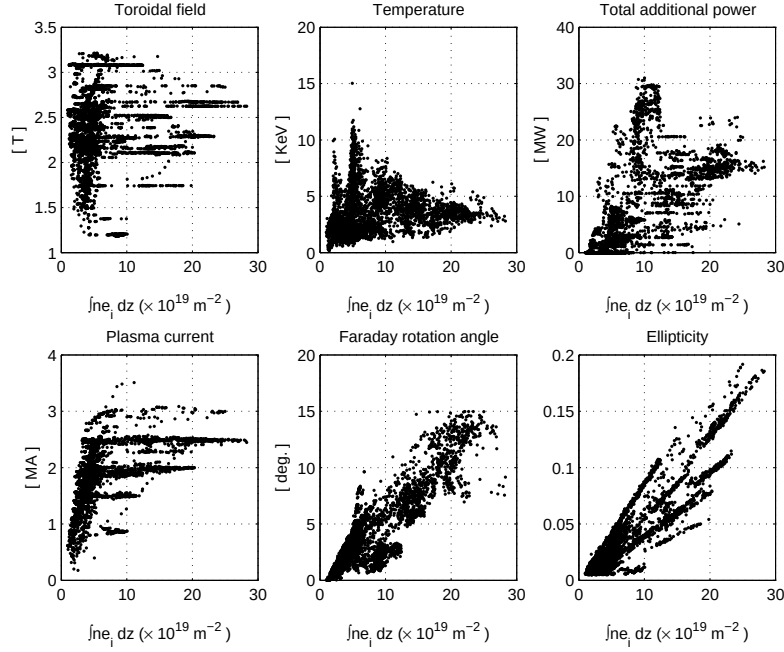


Figure 5.4: Statistical representation of the plasma parameters for all the considered shots as a function of the interferometric line integrated electron density.

5.4.2 Electron density from both polarimetry and interferometry

A large number of JET pulses covering different plasma conditions have been investigated. The selected shots belong to various campaigns (years 2006 and 2007), to produce statistics without any particular bias linked to particular experiments. The considered plasma parameters are the toroidal magnetic field, the electron temperature, the total additional power (NBI+ICRH+LHCD) and the plasma current. For each shot, the representative points of these parameters, covering a large number of plasma scenarios, are shown in Figure 5.4 as a function of the interferometric line integrated density in the range between 0 and $3 \times 10^{20} \text{ m}^{-2}$. As it can be noticed the toroidal magnetic field is up to 3.5 T, the electron temperature up to 10 KeV, the additional power up to 30 MW and the plasma current up to 3.5 MA. The values of Faraday rotation angle and ellipticity, coming from polarimetric measurements, are also plotted in the same figure. It is interesting to underline the linear dependence between these two last parameters and the density from interferometry. Faraday rotation angles greater than 15° are not shown here because of the limitations imposed by the actual set-up for calibration.

This first analysis has been performed for channels 2 and 3 on interferometer/ polarimeter system [62]. For channel 2 the available shots are less than for channel 3 because of many fringe jumps on the interferometric signal due to the beam passing through the divertor and crossing the magnetic x-point. Figure 5.5a and 5.5b show the difference between the density obtained by polarimetric data and the density

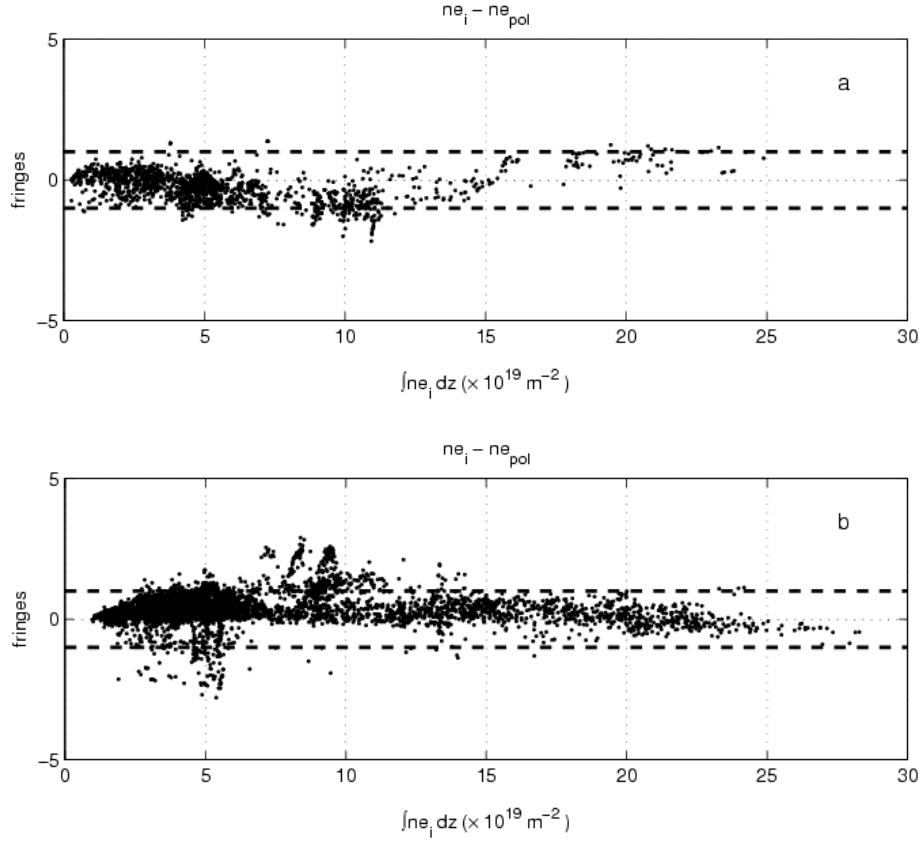


Figure 5.5: Difference between the line integrated density from polarimetric data and the interferometer line density in terms of fringes (one fringe = $1.143 \times 10^{19} \text{m}^{-2}$) for channel 2 (a) and channel 3 (b). The dotted lines are the threshold reference of one fringe.

from interferometry expressed in terms of fringes (one fringe = $1.143 \times 10^{19} \text{m}^{-2}$) as a function of the line integrated plasma density from interferometry for channels 2 and 3 respectively. The agreement is within one fringe, which represents the interferometric error, for the whole considered line integrated density range (from 10^{18} to $3 \times 10^{20} \text{m}^{-2}$). In particular for high electron density values all (99%) points plotted are within the dotted lines representing the thresholds of plus/minus one fringe. These results have confirmed that the interferometric data, after fringe jumps, can be recovered using density values provided by polarimetric measurements and thus, during the discharge, the control on the plasma density is secure.

To this purpose a preliminary study has been performed on the reliability of the real time measurements of the density by polarimetry. Figure 5.6 shows the time evolution of the line integrated electron density measured by both interferometry (solid line) and polarimetry (dotted line) for the vertical channels 2, 3 and 4, during an entire high density discharge. It can be noticed the good agreement (within one fringe) between the two curves for channels 2, 3 and 4, for almost the whole time range (40-75 s). For channel 4, the real time signal (dotted line) is not stable for low density values ($< 3 \times 10^{19} \text{m}^{-2}$) because this chord is close to LCD (last closed surface) and the magnetic field configuration is not stable, as well, during

the ramp up of the pulse. Moreover, it has to be emphasized that the interferometry density in channel 2 had more than hundred fringe jumps, which have been manually corrected off line. These results show that it will be easy to integrate a new algorithm to correct on-line the interferometric data, reading real-time values of the line integrated density from polarimetry.

It is then possible to conclude that the polarimetry could be safely used to recover the interferometry density when a fringe jump occurs, which otherwise could result in serious difficulties for the real-time control of many JET experiments. These results may have implications on the design of ITER interferometer and polarimeter systems.

5.4.3 Summary

A comparison between density from interferometry and from polarimetry has been presented for the first time considering many JET pulses. A method to measure the line integrated electron plasma density alternative to interferometry is needed to provide informations on density when the interferometric signal is affected by fringe jumps. In this case, the idea is to provide to interferometer the correct value of density, so its signal can be recovered [63].

Looking at the results reached with this work it is possible to conclude that polarimetry could be used to recover interferometric signal when a fringe jump occurs, which otherwise could result in serious difficulties for the plant safety and real-time control of many JET experiments [64]. When both the Faraday and Cotton-Mouton effects are small enough ($|W_3|, |W_1| < 0.2$), using a simple solution of the evolution equation (3.20), the density can be evaluated from polarimetric data. This type of analysis has been presented for channels 2 [59] and 3, and is going to be performed for channel 4 at JET. All these results will contribute and support the design of ITER interferometer/polarimeter.

5.5 Anomalous behaviour of the polarimetric raw data

Looking at the calibration curves displayed in Figure 5.7 for the vertical channel 1, the polarimetric diagnostic seems to be affected by anomalies, the source of which is still unknown makes it very difficult to analyze polarimetric data [65]. So far JET polarimetric signals have to be preprocessed using a model which includes a "*spurious ellipticity*" of the probing beam [63], assumed to be due to non ideal behaviour of unidentified optical components. It is considered very important to understand the cause of this anomaly of the polarimetric data and every effort should be done to eliminate or at least to reduce the problem possibly with a suitable intervention on the diagnostic hardware.

Assuming the recombination plate as an optical component which could introduce ellipticity in the polarization, a detailed analysis of its main optical properties and its theoretical behaviour, in accordance with the basic laws of optics, is described (subection 5.5.2). The effects of this plate on the polarimetric measurements are shown. Then, the beam transfer line from the Torus hall to the detectors, including

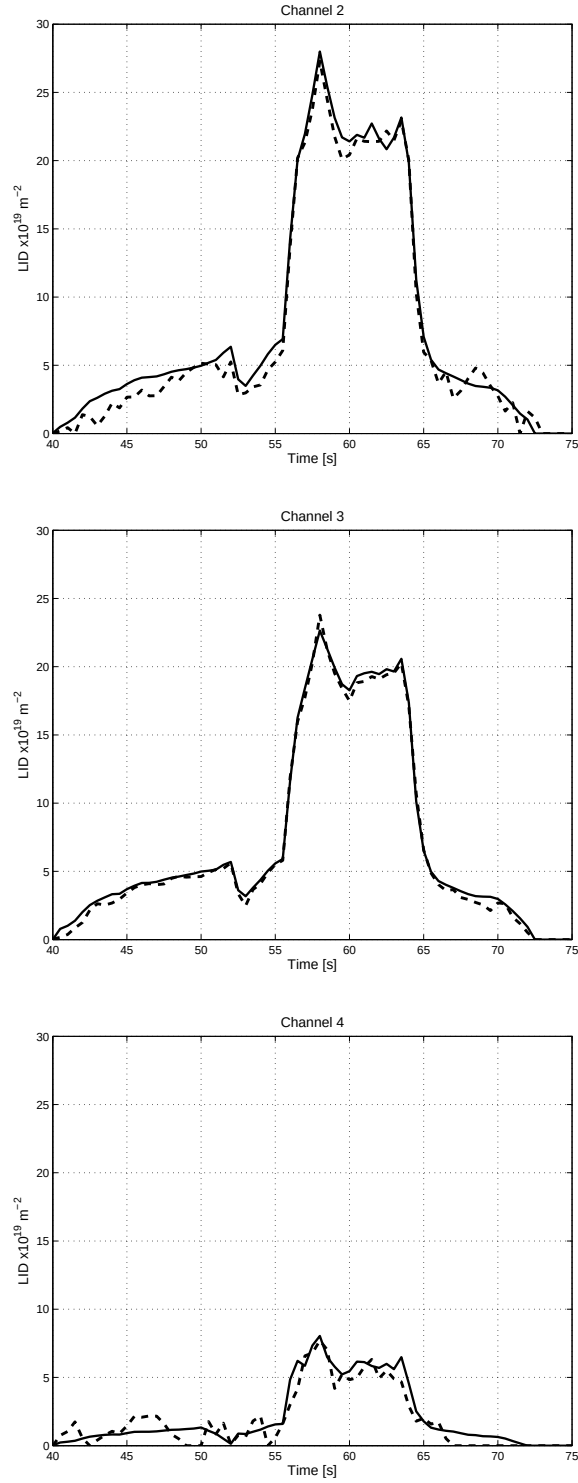


Figure 5.6: Comparison between the line integrated density evaluated by the interferometer (solid line) and the polarimetric real time measurements (dotted line) for the channels 2, 3 and 4 of polarimeter/interferometer at JET

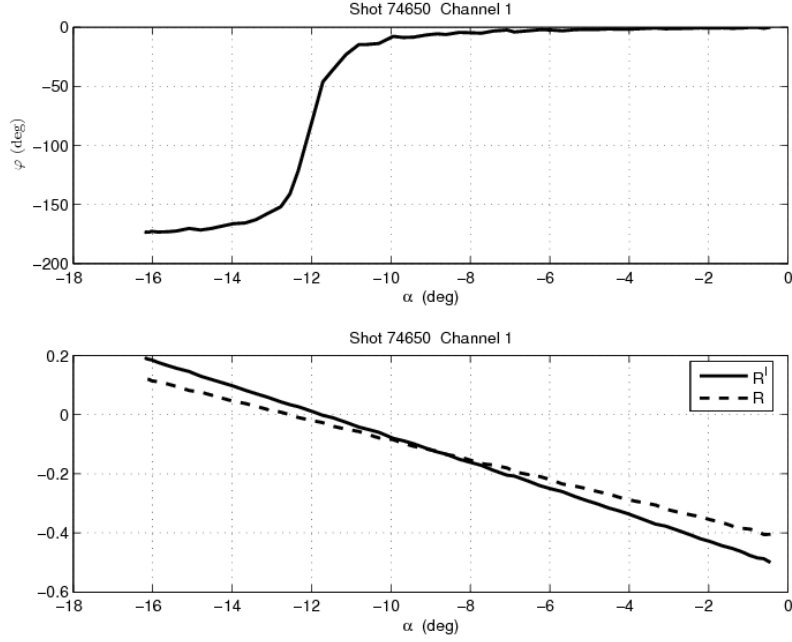


Figure 5.7: Evolution of φ , R and R' with respect to the angle α for channel 1. The evolution of these curves is the same for the other polarimeter channels

the dielectric waveguide, mirrors, wire grids and optical elbows, is considered. Given the transmission properties of the optics after the recombination plate, a general method to evaluate the signals at the detectors is described in Section 5.5.3. At last, the effect of a simple rotation of the polarization along the beam line from Torus to the detectors is calculated and the comparison with the experimental data of the calibration is reported (subsection 5.5.4).

5.5.1 Calibration and data processing

At JET an on-line calibration procedure is routinely performed before each JET pulse, rotating the polarization direction of the probing beam by a known angle α using the half wave plate. In figure 5.7 for the vertical channel 1, the R (5.22) and R' (5.23) experimental curves are plotted as functions of the angle α . The phase shift φ , calculated by (5.27), is shown as well. The angle φ (in this case it is equal to ϕ_0) is not constant for a variation of the angle α (and so of Θ). This behaviour, observed in the other channels as well, completely contravenes the assumptions of the theoretical treatment previously described (5.3.1) and it makes difficult the interpretation of the polarimetric measurements.

Because of this non ideal behaviour, at JET the polarimetric signals are processed using a model which assumes that an unspecified optical element generates an additional ellipticity ("*spurious ellipticity*") characterized by a constant phase shift $\tilde{\phi}$ referred to a rotated coordinate system of unknown orientation Ξ [63]. Optimizing four parameters by the least square method, the R and R' values, evaluated with this model in absence of plasma, fit very well the experimental calibration curves, obtained varying α . In presence of plasma, using the parameters optimized during

the calibration, the processing system evaluates on line the Θ and Φ angles and other polarization parameters.

5.5.2 The effect of the recombination plate

Assuming the recombination plate is the source of the anomaly in the polarimetric measurements it is interesting to analyze its optical properties and then the effects on the measurements.

The recombination plate is a z-cut natural crystal quartz plate with thickness $h = 1.894\text{mm} \pm 1\mu\text{m}$. The incidence angle of both the probing and the reference beams is $\theta_0 = 45^\circ$. The x and y directions are perpendicular and parallel with respect to the incidence plane. The electric field components corresponding to the probing and the reference beams, are partially transmitted and partially reflected by the plate, and they experience the following changes:

$$E'_x{}^{(p)} = P_\perp E_x^{(p)} \quad (5.46)$$

$$E'_y{}^{(p)} = P_\parallel E_y^{(p)} \quad (5.47)$$

$$E'_x{}^{(r)} = R_\perp E_x^{(r)} \quad (5.48)$$

$$E'_y{}^{(r)} = R_\parallel E_y^{(r)} \quad (5.49)$$

where the complex coefficients $P_\perp$, $P_\parallel$, $R_\perp$, $R_\parallel$, independent from Θ and Φ , are evaluated considering multiple reflections on the surfaces of the plate [66]. The birefringence of the medium is characterized by two refraction index values: ordinary and extraordinary. The former for the electric field component E_x perpendicular to the incidence plane and the latter for the electric field component E_y parallel to the incidence plane. For $\lambda = 195\mu\text{m}$, the crystal quartz has an ordinary refraction index $n_0 = 2.112$ and an extraordinary refraction index $n_s = 2.156$, for a propagation perpendicular to the optical axis [67]. Then, assuming that E_x is associated to the ordinary refraction index $n_\perp = n_0$ and E_y is associated to the extraordinary one, evaluated taking into account of the angle between the refracted beam and the optical axis

$$n_\parallel = \sqrt{n_0^2 + \left(1 - \frac{n_0^2}{n_s^2}\right) \sin^2 \theta_0}. \quad (5.50)$$

Neglecting dielectric losses, the complex coefficients in (5.46) ÷ (5.49) can be expressed as:

$$P_\perp = \frac{1 - \Re_\perp}{1 - \Re_\perp e^{i\delta_\perp}} \quad P_\parallel = \frac{1 - \Re_\parallel}{1 - \Re_\parallel e^{i\delta_\parallel}} \quad (5.51)$$

$$R_\perp = \frac{(1 - e^{i\delta_\perp}) \sqrt{\Re_\perp}}{1 - \Re_\perp e^{i\delta_\perp}} \quad R_\parallel = \frac{(1 - e^{i\delta_\parallel}) \sqrt{\Re_\parallel}}{1 - \Re_\parallel e^{i\delta_\parallel}} \quad (5.52)$$

where

$$\Re_{\perp} = \frac{\sin^2(\theta_0 - \theta_{\perp})}{\sin^2(\theta_0 + \theta_{\perp})} \quad \Re_{\parallel} = \frac{\tan^2(\theta_0 - \theta_{\perp})}{\tan^2(\theta_0 + \theta_{\perp})} \quad (5.53)$$

$$\delta_{\perp} = \frac{4\pi}{\lambda} n_{\perp} h \cos \theta_{\perp} \quad \delta_{\parallel} = \frac{4\pi}{\lambda} n_{\parallel} h \cos \theta_{\parallel} \quad (5.54)$$

$$\theta_{\perp} = \arcsin\left(\frac{\sin \theta_0}{n_{\perp}}\right) \quad \theta_{\parallel} = \arcsin\left(\frac{\sin \theta_0}{n_{\parallel}}\right). \quad (5.55)$$

It is assumed that the probing beam transmitted through the plate is still described by (5.1) and (5.2), while the reference beam is represented by

$$E_x^{(r)} = E_{0g} \cos \Theta_g \quad (5.56)$$

$$E_y^{(r)} = E_{0g} \sin \Theta_g e^{-i\phi_r} \quad (5.57)$$

to account for a possible spurious ellipticity due to reflection on metal surfaces and crossing a beamsplitter system. So, using the notations

$$P_{\perp,\parallel} = |P_{\perp,\parallel}| e^{i\psi_{\perp,\parallel}} \quad R_{\perp,\parallel} = |R_{\perp,\parallel}| e^{i\phi_{\perp,\parallel}} \quad (5.58)$$

and inserting equations (5.1), (5.2), (5.56) and (5.57) into (5.46) $\div$ (5.49), neglecting the prime sign, it is possible to write the equations for the beams out coming from the recombination plate as follows:

$$E_x^{(p)} = |P_{\perp}| e^{i\psi_{\perp}} \cdot E_0 \cos \Theta \quad (5.59)$$

$$E_y^{(p)} = |P_{\parallel}| e^{i\psi_{\parallel}} \cdot E_0 \sin \Theta e^{-i\Phi} \quad (5.60)$$

$$E_x^{(r)} = |R_{\perp}| e^{i\phi_{\perp}} \cdot E_{0g} \cos \Theta_g \quad (5.61)$$

$$E_y^{(r)} = |R_{\parallel}| e^{i\phi_{\parallel}} \cdot E_{0g} \sin \Theta_g e^{-i\phi_r}. \quad (5.62)$$

Explicit expressions for the moduli and the phases of $P_{\perp,\parallel}$ and $R_{\perp,\parallel}$ are reported in the Appendix A.1. Using these mathematical relations it is easy to calculate the ellipticity introduced on the two beams (probing and reference) by the recombination plate, supposing they are initially linearly polarized at 45° ($\Theta = 45^\circ$, $\Phi = 0$, $\phi_r = 0$). So the polarization ellipse of the reference beam has ellipticity $\epsilon_r = 0.214$ and tilt angle $\psi_r = 20.41^\circ$ with respect to the x-direction. On the other hand the polarization ellipse of the probing beam has ellipticity $\epsilon_p = 0.056$ and tilt angle $\psi_p = 144.46^\circ$. The effect of the recombination plate on the polarization of the beams is not only a modification of the ellipticity but also a rotation of the polarization ellipse such that the final angle is very far from the initial 45° .

If the recombined beam is transferred unchanged to the detection system and the x and y electric field components reach the respective detectors without any interference between them, the signals at the detectors can be evaluated as previously seen in subsection 5.3.1, putting the relations (5.59) $\div$ (5.62) into (5.6) and (5.7). The expressions (5.11) and (5.12) are again satisfied; the amplitudes A_i and A_p can be written in the form (5.13) and (5.14) with

$$A = K_x \sqrt{2} |P_{\perp}| |R_{\perp}| |E_0| |E_{0g}| \quad (5.63)$$

$$B = K_y \sqrt{2} |P_{\parallel}| |R_{\parallel}| |E_0| |E_{0g}| \quad (5.64)$$

and the relation (5.17) for φ is still true with

$$\phi_0 = \psi_{\perp} - \psi_{\parallel} - \phi_{\perp} + \phi_{\parallel} - \phi_r. \quad (5.65)$$

The two angles Θ and Φ can be evaluated using the signal processing method exposed in subsection 5.3.1. With respect to the ideal case, only the two calibration constants C and ϕ_0 are different, and the rest does not vary.

The analysis proposed in this section allows to conclude that:

1. the recombination plate modifies considerably the polarization state of both the probing and the reference beam;
2. anyway, this does not affect the polarimetric measurements of Θ and Φ , the effects of the recombination plate on the polarization state of the beams are compensated by the calibration. In particular, the phase shift φ should remain constant in absence of plasma, when α is varied;
3. if the reference beam had some ellipticity, it would be corrected by the calibration.

Note that the main reported conclusions are independent from the numerical values of the four complex coefficients $P_{\perp}, P_{\parallel}, P_{\perp}, P_{\parallel}$ which determine the transmission and reflection properties of the plate.

5.5.3 The dielectric waveguide

The dielectric waveguide used to transfer the recombined beam from the recombination plate to the detectors is not a straight single Pyrex tube but a rather complex optical system with other optics, including mirrors. Let's suppose that:

1. the x and y electric field components are still perpendicular or parallel with respect to the planes of incidence of the reflective surfaces, along the path between the recombination plate and the detection section;
2. all the other optics of the beam transfer line, included the wire grid in front of the detectors, behave ideally.

Then, without making any numeric calculation, it is possible to say that the E'_x and E'_y electric field components reaching respectively the x and y detectors are proportional to the initial E_x and E_y components by the mean of complex coefficients. This can be expressed by the use of a diagonal matrix:

$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix} = \begin{pmatrix} T_{xx} & 0 \\ 0 & T_{yy} \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \end{pmatrix} \quad (5.66)$$

where T_{xx} and T_{yy} are complex coefficients to be determined. The polarization states of the beam will be further modified with respect to the changes introduced by the recombination plate. The calculation of the signals at the detectors would lead to the same conclusions as in section 5.5.2; the procedure explained in subsection 5.3.1 should be still reliable as long as the calibration constants C and ϕ_0

are adjusted by the calibration procedure. In particular the phase shift φ between the two signals should be constant for a scan of the angle α during the calibration without plasma, which actually does not occur.

If instead, for any reason, the x and y detectors are not reached only by the E_x and E_y field components respectively, but by a combination of the two, then a non diagonal matrix should be used instead of (5.66) to calculate the signals:

$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \end{pmatrix}. \quad (5.67)$$

This formalism is more general and allows modeling other additional effects, for example a non ideal behaviour of the wire grid in front of the detectors which could have finite transmission and reflection coefficients for electric field parallel and perpendicular to the wires respectively. Writing

$$T_{jk} = |T_{jk}| e^{i\phi_{jk}} \quad (j, k) = (x, y), \quad (5.68)$$

the electric field components E_x and E_y coming out from the recombination plate (5.59) $\div$ (5.62) are inserted into (5.67); the E'_x and E'_y components so evaluated can be put into (5.6) and (5.7) to calculate the detector signals. The calculus, reported in Appendix A.2, provides relations still in the form (5.11) and (5.12), where the amplitudes A_i and A_p and the phase shift φ are given by:

$$A_i = A \sqrt{\left(\sum_{k=1}^4 a_k \cos \alpha_k \right)^2 + \left(\sum_{k=1}^4 a_k \sin \alpha_k \right)^2} \quad (5.69)$$

$$A_p = B \sqrt{\left(\sum_{k=1}^4 b_k \cos \beta_k \right)^2 + \left(\sum_{k=1}^4 b_k \sin \beta_k \right)^2} \quad (5.70)$$

$$\varphi = \arctan \frac{\sum_{k=1}^4 b_k \sin \beta_k}{\sum_{k=1}^4 b_k \cos \beta_k} - \arctan \frac{\sum_{k=1}^4 a_k \sin \alpha_k}{\sum_{k=1}^4 a_k \cos \alpha_k} \quad (5.71)$$

where A and B are given by (5.15) and (5.16) respectively, and the coefficients a_k and b_k ($k=1,2,3,4$) depend on Θ and the angles α_k and β_k depend on Φ and ϕ_r . Their explicit expressions are given by relations (A.11) $\div$ (A.26) reported in Appendix A.2.

The signals $i(t)$ and $p(t)$ at the detectors are processed to calculate the averaged out values, as in relations (5.18) $\div$ (5.21). The ratios R and R' still defined by (5.22) $\div$ (5.23), are now evaluated by the relations (5.69) $\div$ (5.71) for A_i A_p and φ . Note that their dependence on Θ and φ is very different from the one of the relations (5.24) and (5.25). In conclusion, assuming a transformation of the type (5.67), it is possible to state that:

1. the angles Θ and Φ can't be obtained from the R and R' measured values in a simple way, as it happens when the relations (5.28) and (5.29) are valid;

2. there is no direct relation between φ and Φ ; now φ depends in a complex way on Θ and Φ , as it is shown in (5.71) taking into account (A.11) $\div$ (A.26);
3. during the calibration with $\Phi = 0$ it has to be expected that the angle φ isn't constant as Θ (or α) varies, but it changes with a complex law.

As a consequence, if the waveguide system existing at JET actually operates a transformation of the type (5.67) on the field components, an algorithm to get Θ and Φ starting from given R' and R appears difficult to devise.

In addition, any possible ellipticity of the reference beam expressed by ϕ_r would not be compensated by the calibration and it would affect the accuracy of the final results. Fortunately, in the polarimeter at JET for each channel, it has been mounted a wire grid on the path of the reference beam before the recombination plate to guarantee a linear polarization, as previously said in Section 5.3.

5.5.4 A particular case

Among the optics included into the transfer beam line an important role is played by 90° elbows and focalizing mirrors, where reflections on metal surfaces occur. It is well-known that a radiation reflecting on a metal surface could experience a modification of its polarization. In fact the electric field components $E_\perp$ and $E_\parallel$, perpendicular and parallel to the plane of incidence, behaves differently, as well as in the case of dielectric plates [66]. The result can be expressed in the form:

$$E_\perp^{(r)} = \rho_\perp E_\perp^{(i)} \quad (5.72)$$

$$E_\parallel^{(r)} = \rho_\parallel E_\parallel^{(i)}, \quad (5.73)$$

with

$$\rho_\perp = -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \quad \rho_\parallel = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \quad (5.74)$$

$$\sin \theta_t = \frac{1}{\hat{n}} \sin \theta_i \quad (5.75)$$

where θ_i is the angle of incidence and θ_t plays the role of a complex refraction angle. The complex refraction index can be approximated (with $\sigma \gg \omega\epsilon_0$) as

$$\hat{n} \cong (1 + i) \sqrt{\frac{\mu_r \sigma}{2\omega\epsilon_0}}, \quad (5.76)$$

where σ and μ_r are respectively the conductivity and the relative magnetic permeability of the metal. For high conductivity metal as aluminium, copper or silver and for FIR wavelengths, the modulus of the refraction index is big, so that it results with a good approximation:

$$\rho_\perp \approx -1 \quad \rho_\parallel \approx 1. \quad (5.77)$$

As consequence, a linearly polarized radiation incident with electric field tilted at an angle θ with respect to the plane of incidence, will come out tilted at $-\theta$, so it

will suffer a rotation of an angle 2θ by the effect of the reflection. Then the metal surface behaves like an half wave plate with optical axis parallel to the plane of incidence.

Then let's analyze the case that the only effect of the optical waveguide system is a rotation of an angle γ of the radiation propagating along it. The electric field components change as:

$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix} = \begin{pmatrix} \cos \gamma & \sin \gamma \\ -\sin \gamma & \cos \gamma \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \end{pmatrix}. \quad (5.78)$$

As shown in Section 5.5.3, the calculus of the detector signals $i(t)$ and $p(t)$ leads back to the relations (5.11) and (5.12), with expressions formally equal to (5.69) $\div$ (5.71) for A_i , A_p and φ where now $a_k, b_k, \alpha_k, \beta_k$ ($k=1,2,3,4$) are given by relations (A.32) $\div$ (A.43) reported in Appendix A.3.

Attempts have been done to state if curves of φ as function of $\alpha = \Theta - \Theta_0$, with $\Phi = 0$, evaluated using (5.71) with (A.32) $\div$ (A.43), could reproduce the experimental calibration curves shown in figure 5.7, with $\Phi = 0$ and suitable choices for γ and ϕ_r .

A particularly good agreement has been found between data calculated for different γ and ϕ_r values and the experimental data for channels 1-4, as it can be seen in Fig. 5.9, where the curves of $\tan \varphi$ are compared with the experimental curve of R'/R . This agreement has been reached optimizing the values of γ and ϕ_r and the reported values are the results of the optimization. The agreement shown in Fig. 5.9 is very interesting because it demonstrates that any possible rotation of the polarization of the radiation propagating along the waveguide up to the detectors, could be a source of the anomaly affecting the polarimetric measurements at JET. As previously shown, rotations of the polarization could actually happen in reflections on metal mirrors. It is understood this cause of the anomaly was not considered for the JET polarimeter up to now.

Moreover, the fact that the agreement is optimized with a small ϕ_r angle different from zero, could be ascribed to some ellipticity of the polarization of the reference beam, perhaps due to a non perfect filtering of the wire grid.

5.5.5 Conclusions

The main results of the analysis so far developed can be summarized as follows:

1. the recombination plates don't look to be the source of the anomaly noticed in the polarimetric data at JET; they modify the polarization of the beam but these changes should be compensated by the calibration;
2. the anomaly could be ascribed to a non standard behaviour of some optical element encountered by the probing beam along its path;
3. the anomaly may be due also to changes of the polarization suffered along the optical beam line which transfers the recombined beams from the Torus hall to the detectors. The particular case of a simple rotation of the polarization proves to be very significant.

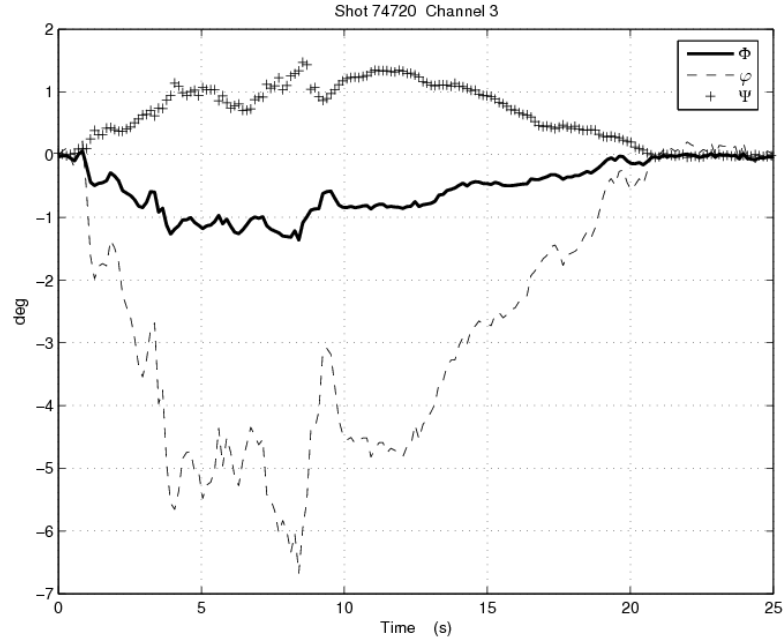


Figure 5.8: Evolution of Φ , of the Faraday rotation angle Ψ and of the phase shift φ during one shot for channel 3. The signals Φ and Ψ are processed by the software; φ comes directly from the raw data.

In order to carry on this investigation on the causes of the anomaly, it is necessary to go on two directions. One way is doing bench tests on all the optical components (or combinations of optics) crossed by the probing beam from the half wave plates to the recombination plates, i.e. quartz windows, mylar foils, TPX windows,... It is necessary to have a laser source, producing a linearly polarized beam, followed by a rotatable half wave plate and a device able to measure the polarization state of the beam out coming from the sample. It must be verified whether the beam crossing the sample suffers an ellipticity and how this ellipticity varies with the change of the orientation of the incident polarization. The other way is doing a careful inspection on the paths of the beams from the recombination plates up to the detectors. The main purpose of this inspection is to obtain a precise characterization of all the optics crossed by the beams and to draw a tridimensional map of the paths. In this way, it will be possible to properly simulate the behaviour of the beams while they travel along this section of the diagnostic. Once all these data will be available it will be possible to recognize without doubt the causes of the anomalous behaviour of the polarimeter operating at JET. It should be also possible to formulate models suitable to simulate the operation of the polarimeter. In particular, reproducing the experimental curves of φ and of the associated parameters according with α varying, as shown in figure 5.7. When this goal will be achieved, the next step will be to define the changes which have to be performed on the polarimeter to remove the anomaly.

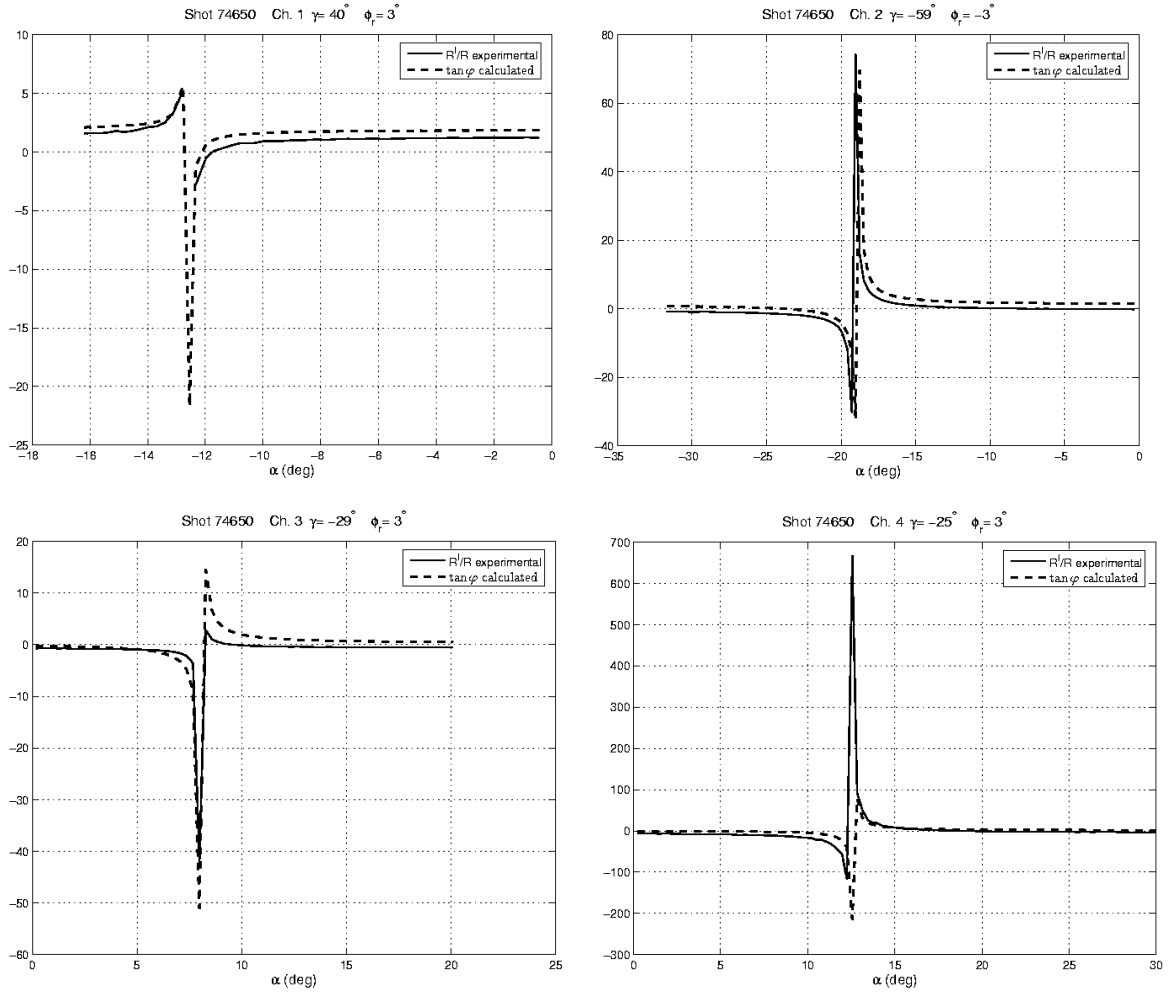


Figure 5.9: Experimental R'/R curves for channels 1-4 are compared with theoretical $\tan \varphi$, calculated with different γ and ϕ_r values.

5.6 New processing code

The last topic treated in this thesis is about the implementation of a new code to process the raw polarimetric data [68]. The actual procedure has made some mistakes in the evaluation of the Faraday rotation angle and Cotton Mouton effect because some parameters used for fitting the calibration curves are not still efficient during the last JET's plasma regimes, at high current (up to 4.5 MA) and at high magnetic fields (up to 3.6T). As well as for the previous version, the principle of the new code is the evaluation of the effects on the radiation due only to the optics. Thus the change of the polarization state of the beam reaching the detectors in absence of plasma is measured, and it is used to correct the final signals during the discharge to display just the effects of the plasma. To this purpose the entire polarimetric optical line has been represented by the cascade of a half wave plate and two retarders which rotate the polarization angle and change the ellipticity respectively. In such way it is possible to obtain the curves similar to the ones displayed by the diagnostic during the calibration phase. By a fitting procedure the parameters of the optics employed in the model are evaluated. Therefore the polarimetric effect of the optics is known and it is subtract to the polarimetric measurements to obtain the real Faraday angle and Cotton Mouton effect due to the plasma. It is clear, this is an empirical solution for the problem widely described in last section 5.5, but as it will be shown later, it allows good measurements according to the theoretical values evaluated by the solution the Stokes equation (3.20).

As described previously in this thesis, the calibration of Faraday angle is carried out rotating the half-wave plate, in absence of plasma, by a known angle (α). So, using the Mueller's formalism, this component can be represented by the following matrix [69]:

$$M_{\alpha} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (5.79)$$

that represents the matrix of an ideal rotator. It is primarily used just to change the polarization direction of the beam without modifying the ellipticity. The two retarders introducing the spurious ellipticity have been modeled with their correspondent Mueller matrices, which in the case of an ideal retarder with a phase shift (δ_1) and its fast axis along x , is:

$$M_{\delta_1} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos \delta_1 & \sin \delta_1 \\ 0 & 0 & -\sin \delta_1 & \cos \delta_1 \end{vmatrix}. \quad (5.80)$$

If the fast axis of the retarder is rotated by an angle α_1 from x , the Mueller matrix is:

$$M'_{\delta_1} = R_{\alpha_1} \cdot M_{\delta_1} \cdot R_{-\alpha_1} \quad (5.81)$$

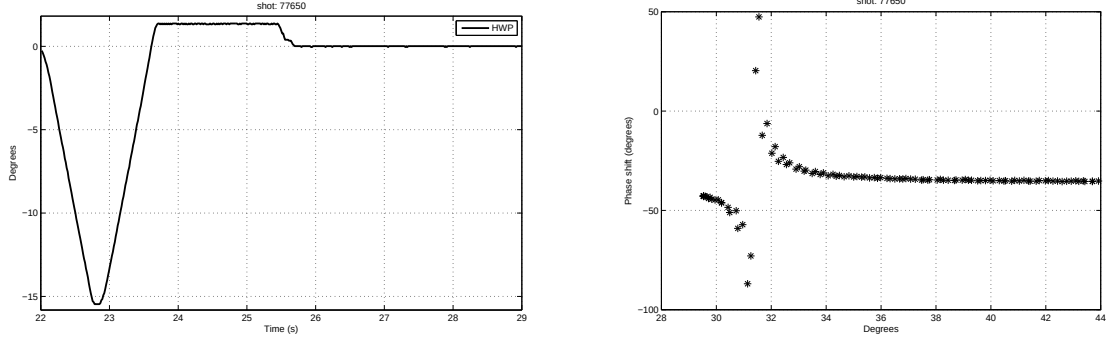


Figure 5.10: Evolution of the Faraday rotation angle imposed by the rotatable half wave plate for JET's shot 77650 (left diagram) and evolution of the phase shift φ during the calibration for the same shot

where R_{α_1} is a rotation matrix

$$R_{\alpha_1} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha_1 & \sin 2\alpha_1 & 0 \\ 0 & -\sin 2\alpha_1 & \cos 2\alpha_1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (5.82)$$

For the second retarder the Mueller matrix therefore is:

$$M'_{\delta_2} = R_{\alpha_2} \cdot M_{\delta_2} \cdot R_{-\alpha_2} \quad (5.83)$$

To estimate the phase shift values (δ_1 and δ_2) and the angles at which the retarders are located (α_1 and α_2) in the Torus coordinate system, an optimization routine has been written. The routine finds the values of these four quantities which allow to best fit the phase shift curve, shown in figure 5.10. The last optical component involved in the calibration code is the wire grid, which acts as an analyzer, dividing the electric field components into two directions x and y , which are focused onto the corresponding detectors.

Assuming an ideal behaviour of the analyzer, the Mueller matrices for transmission and reflection, M_T and M_R , can be written:

$$M_T = p_x^2 \begin{vmatrix} p_x^2 + p_y^2 & p_x^2 - p_y^2 & 0 & 0 \\ p_x^2 - p_y^2 & p_x^2 + p_y^2 & 0 & 0 \\ 0 & 0 & 2 \cdot p_x \cdot p_y & 0 \\ 0 & 0 & 0 & 2 \cdot p_x \cdot p_y \end{vmatrix} \quad (5.84)$$

$$M_R = p_y^2 \begin{vmatrix} p_x^2 + p_y^2 & p_x^2 - p_y^2 & 0 & 0 \\ p_x^2 - p_y^2 & p_x^2 + p_y^2 & 0 & 0 \\ 0 & 0 & 2 \cdot p_x \cdot p_y & 0 \\ 0 & 0 & 0 & 2 \cdot p_x \cdot p_y \end{vmatrix} \quad (5.85)$$

where p_x and p_y are, respectively, the cosine and the sine of the wire grid angle. In ideal conditions, the wire grid should be at 45° with respect to the propagation direction of the radiation, dividing the electric field into the directions x and y .

Looking at the two detector signals, it is possible to estimate the angle between the wires and the incident electric field of the radiation. As it is shown in the left diagram of figure 5.10, there is an angle of the polarization for which the phase shift diverges to $\pm\infty$. Since this correspond to a polarization for which the R signal equals zero and therefore $p(t)$ signal equals zero, it means that all the radiation is collected by the $i(t)$ detector. This condition is verified when the wires are parallel to the direction of $p(t)$ signal. Then the position of the wires with respect to the incident electric field can be estimated as $\alpha_{WG} = 90 - \alpha_0$. After this component the laser beam is divided in two parts and the corresponding Stokes vectors are given by:

$$\vec{S}_{1,T} = M_T \cdot M'_{\delta_2} \cdot M'_{\delta_1} \cdot M_\alpha \cdot \vec{S}_0 \quad (5.86)$$

$$\vec{S}_{1,R} = M_R \cdot M'_{\delta_2} \cdot M'_{\delta_1} \cdot M_\alpha \cdot \vec{S}_0 \quad (5.87)$$

The final Stokes vector ($\vec{S}_1$) is the combination of these two Stokes vectors. Therefore, it is possible to know the polarization angle and the phase shift, given by:

$$\psi = \frac{1}{2} \arctan \left(\frac{S_2}{S_1} \right) \quad (5.88)$$

$$\phi = \arctan \left(\frac{S_3}{S_2} \right) \quad (5.89)$$

where S_1 , S_2 and S_3 are components of the final Stokes vector ($\vec{S}_1$). These parameters are related to the Faraday rotation angle Ψ and to the Cotton-Mouton phase shift Φ by:

$$\Psi = \psi - \Theta_0 \quad (5.90)$$

$$\Phi = \phi - \phi_0. \quad (5.91)$$

5.6.1 Application to the plasma measurements

Once obtained the calibration curves for the Faraday rotation and the phase shift, then the experimental data have been analyzed applying the new calibration code. Starting from the raw data acquired RMS, RMP, PSP and PSD (described in subsection 5.3.1), it is possible to obtain the components of Stokes vector, which describe the polarization state of the beam through all the optical components and the plasma, using the relations:

$$RMS = \frac{1}{2} E_{H,0}^2 \quad (5.92)$$

$$RMP = \frac{1}{2} E_{H,0}'^2 \quad (5.93)$$

$$PSD = \frac{1}{2} E_{H,0} \cdot E_{V,0} \cos \varphi \quad (5.94)$$

$$PSP = \frac{1}{2} E_{H,0}' \cdot E_{V,0} \sin \varphi \quad (5.95)$$

where the $E_{H,0}$ and $E_{V,0}$ are the electric field components measured, respectively, with the H-detector and V-detector and φ is the phase shift between them. Since the position of the output wire grid could be rotated with respect to the original reference axes, a rotation of its output components has to be performed to express them in the right coordinate system. To this purpose the electric field components after the wire grid analyzer have to be expressed by means of the following transformations:

$$E_x = \alpha \cdot E_{H,0} + \delta \cdot E_{V,0} \quad (5.96)$$

$$E_y = -\delta \cdot E_{H,0} + \alpha \cdot E_{V,0} \quad (5.97)$$

where α and δ are the cosine and the sine of the wire grid angle in the Torus coordinate system. Once derived the components of the electric field at the exit of the plasma, the final Stokes vector ($\vec{S}_1$) can be calculated. Hence applying the calibration matrices to ($\vec{S}_1$), it is possible to evaluate the plasma effects on the initial polarization state of laser beam, according to:

$$\vec{S}_1 = M'_{\delta_2} \cdot M'_{\delta_1} \cdot M_\alpha \cdot M_{plasma} \cdot \vec{S}_0 \quad (5.98)$$

and thus

$$M_\alpha^{-1} \cdot M'_{\delta_1}{}^{-1} \cdot M'_{\delta_2}{}^{-1} \cdot (\vec{S}_1) = M_{plasma} \cdot (\vec{S}_0) \quad (5.99)$$

Figure 5.11 depicts the Faraday rotation calculated with the new calibration code (named *NewCal*) compared to the results of the theoretical results coming from the rigorous solution of the Stokes equation (3.20) (asterisks). Putting as inputs the density profiles from the Lidar Thomson scattering and the equilibrium magnetic fields, this theoretical calculus provides the Faraday rotation angle and the Cotton Mouton effect for the vertical chords of the JET polarimeter [58]. The agreement between the polarimetric processed data and the theoretical ones is very good for the entire length of the pulse, confirming the reliability of the new processing code and the need of it to correct the polarimeter outputs.

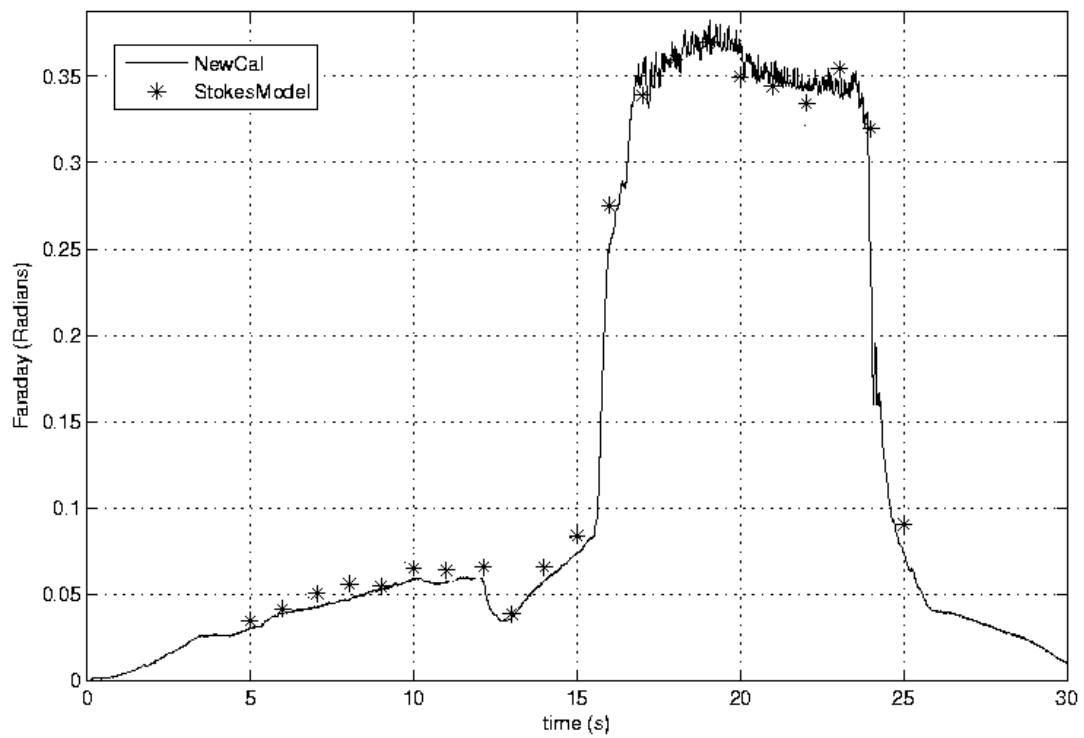


Figure 5.11: Comparison between the Faraday angle evaluated by the new processing code (solid line) and the one calculated by the theoretical model (asterisks) for JET's shot number 77650

Thesis summary

The availability of diagnostic systems in nuclear fusion research is essential for the determination of the internal properties of the plasma. An important parameter which is necessary for a complete understanding of the magnetic structure of the plasma and which is a machine control parameter to be incorporated in feedback loops in future fusion devices, is the toroidal current density profile, $J_t(r)$. By Ampere's law, $J_t(r)$ is proportional to the poloidal magnetic field profile, which traditionally is determined by means of polarimetry.

When an electromagnetic wave passes through a magnetically confined plasma, its polarization plane is rotated due to the Faraday effect. Polarimetry is the technique used to measure this Faraday rotation angle, which is proportional to the line integral of the electron density multiplied by the magnetic field parallel to the propagation direction. The electromagnetic wave experiences also a phase shift with respect to a reference wave which doesn't probe the plasma. This parameter is measured by interferometry, and it is proportional to the line integrated electron plasma density. From both of these results, the poloidal magnetic field is determined, and hence the current density profile is obtained. In tokamak devices, where the toroidal magnetic field is larger than the poloidal one, polarimetry allows the measurement of the Cotton Mouton effect. In these devices the ellipticity of an electromagnetic wave probing the plasma is modified, and the measurement of this parameter provides information on the magnetic field and on the electron plasma density. In these conditions polarimetry can measure the line integrated electron density alternatively to the interferometry, and hence polarimetry can be used in case the interferometer fails the measurement.

This thesis reported the description of the activity research on polarimetry carried out during my Ph.D. course at the RFX-mod machine and at the JET-machine. In fact my work was focused in the measurements and analyzes of the polarimetric effects on a radiation which probes the plasma column, in order to obtain detailed information about the inner magnetic field profiles and about the plasma electron density.

The activities carried out at RFX-mod machine concerned the installation of a FIR polarimeter, and in particular the thesis reported the work performed on the

diagnostic to reduce the fluctuations affecting the signals and to increase the signal to noise ratio. The entire diagnostic and its main section have been outlined and described. The optical line has been carefully designed and the mirror holders have been made in insulating material to avoid any interaction with the variable magnetic fields.

The thesis reported examples of the first Faraday angle measurements performed on five channels. These results are presented and discussed in detail showing the reliability of the instrument and confirming its usefulness in the characterization of the plasma. The measured Faraday rotation angles have been compared to theoretical values based on the $\mu&p$ model, showing a good agreement between experimental and predicted data in the central region of the plasma. Therefore the polarimetric measurements have been confirmed helpful for the reconstruction of the magnetic field profiles inside the plasma column.

Regarding the activities carried out at JET, the thesis focused into three topics: the reliability of measurements of the line integrated plasma electron density from polarimetric data, the investigation over the sources of an anomalous behaviour affecting the polarimetric calibration data and finally the implementation of a new post processing code for polarimetric raw data. For the first time the reliability of the measurements of the Cotton Mouton effect has been analyzed for a wide range of JET's plasma regimes and the possibility to evaluate the electron density directly from polarimetric data has been studied and discussed in this thesis. The purpose of this work has been to recover the interferometric data with the density derived from measured Cotton Mouton effect, when fringe jump phenomena occur. The reported results have shown that the difference between the line integrated electron density from interferometry and polarimetry is with one fringe ($1.143 \times 10^{19} \text{m}^{-2}$) for more than 90% of the cases. These results allowed to consider polarimetry as a satisfactory alternative method to interferometry to measure the electron density and it could be used to recover interferometric signal when fringe jumps occur, preventing difficulties for the real time control of many experiments at the JET machine.

The Far Infrared polarimeter at JET is affected by an anomaly which makes difficult the interpretation of both Faraday and Cotton-Mouton effect measurements. This anomaly is clearly displayed during the calibration operations in absence of plasma: as the polarization of the probing beam is rotated, the phase shift of the polarimetric signal with respect to the interferometric signal is not constant, as expected, but changes a lot. This is observed in all channels of the instrument. The thesis reported the analyzes of some optical components which could be the source of the observed anomalous behaviour of the polarimetric measurements. Assuming the recombination plate as an optical component which could introduce ellipticity in the polarization, a detailed analysis of its main optical properties and its theoretical behaviour has been presented. The effects of this plate on the polarimetric measurements have been shown. Then, the beam transfer line from the Torus hall to the detectors, including the dielectric waveguide, mirrors, wire grids and optical elbows, have been considered. Given the transmission properties of the optics after the recombination plate, a general method to evaluate the signals at the detectors has been discussed. At last, the effect of a simple rotation of the polarization along the beam line from Torus to the detectors has been calculated and the comparison

with the experimental data of the calibration have been depicted. The obtained results have made it possible to conclude that the recombination plates don't look to be the source of the anomaly noticed in the polarimetric data at JET. Although they considerably modify the polarization state of both the probing and the reference beams, the results of the polarimetric measurements of Θ and Φ should not be affected. In particular, the phase shift φ remained constant as α was varied in absence of plasma and this was very different from what really happens. Moreover it has been shown there is no evident reason why other optical components of the polarimeter, such as quartz windows, mylar foils, TPX windows, etc. could be the origin of the anomaly. Nevertheless, it has been stated necessary the execution of bench tests on optical components (or combinations of them) identical to the ones mounted in the polarimeter in order to clarify this issue. Finally, the hypothesis that the anomaly could arise from the waveguide system collecting the recombined beam away to the detectors looked very promising. Effects comparable to the ones produced by the anomaly have been found by simulating a rotation of the polarization of the propagating beam. In order to complete this investigation, some simple experimental tests have been proposed, to be done in the diagnostic hall on optical components accessible for tests.

Since, the optical components introducing the spurious effects are completely unknown, then the calibration procedure has been based on an empirical model in which purely numerical and quite complex fitting procedures have been implemented to evaluate the calibration parameters and the polarimetric measurements. Actually, this processing method works as a black box without a clear relation with the hardware setup. A statistical analysis, carried out on the polarimetric measurements acquired during the campaigns 2003-2009, has highlighted some calibration problems affecting mainly the experimental data of the most recent campaigns (2008-2009) particularly those of the high current discharges. Therefore, it has been decided to develop a new calibration code, based on the layout and hence on the physics of the diagnostic. This new calibration code is based on the description of propagation of laser beam through all optical components of the polarimetry system. To this purpose the well-known Mueller matrix formalism has been used. In the thesis the Faraday rotation calculated by the means of the new calibration code has been compared to the results coming from the rigorous solution of the Stokes equation. The agreement between the polarimetric processed data and the theoretical ones was very good for the entire length of the pulse, confirming the reliability of the new processing code and the need of it to correct the polarimeter outputs.

APPENDIX A

Additional material

A.1 Transmission and reflection coefficients of the recombination plate

The following relations have to be known to be able to express the coefficients given by (5.51) and (5.52) in the form (5.58):

$$|P_{\perp}| = \frac{|1 - \Re_{\perp}|}{\sqrt{1 + \Re_{\perp}^2 - 2\Re_{\perp} \cos \delta_{\perp}}} \quad (\text{A.1})$$

$$|P_{\parallel}| = \frac{|1 - \Re_{\parallel}|}{\sqrt{1 + \Re_{\parallel}^2 - 2\Re_{\parallel} \cos \delta_{\parallel}}} \quad (\text{A.2})$$

$$|R_{\perp}| = \frac{2\sqrt{\Re_{\perp}} \left| \sin \frac{\delta_{\perp}}{2} \right|}{\sqrt{1 + \Re_{\perp}^2 - 2\Re_{\perp} \cos \delta_{\perp}}} \quad (\text{A.3})$$

$$|R_{\parallel}| = \frac{2\sqrt{\Re_{\parallel}} \left| \sin \frac{\delta_{\parallel}}{2} \right|}{\sqrt{1 + \Re_{\parallel}^2 - 2\Re_{\parallel} \cos \delta_{\parallel}}} \quad (\text{A.4})$$

$$\psi_{\perp} = \arctan \left(\frac{\Re_{\perp} \sin \delta_{\perp}}{1 - \Re_{\perp} \cos \delta_{\perp}} \right) \quad (\text{A.5})$$

$$\psi_{\parallel} = \arctan \left(\frac{\Re_{\parallel} \sin \delta_{\parallel}}{1 - \Re_{\parallel} \cos \delta_{\parallel}} \right) \quad (\text{A.6})$$

$$\phi_{\perp} = \arctan \left(-\frac{1 - \Re_{\perp}}{1 + \Re_{\perp}} \frac{\sin \delta_{\perp}}{1 - \cos \delta_{\perp}} \right) \quad (\text{A.7})$$

$$\phi_{\parallel} = \arctan \left(-\frac{1 - \Re_{\parallel}}{1 + \Re_{\parallel}} \frac{\sin \delta_{\parallel}}{1 - \cos \delta_{\parallel}} \right) \quad (\text{A.8})$$

A.2 Evaluation of detector signals assuming the transformation law 5.67

Making the operation previously presented, the two signals $i(t)$ and $p(t)$ are represented by a four terms sum:

$$i(t) = K_x \sqrt{2} |E_0| |E_{0g}| \sum_{k=1}^4 a_k \cos(\omega_0 t - \alpha_k) \quad (\text{A.9})$$

$$p(t) = K_y \sqrt{2} |E_0| |E_{0g}| \sum_{k=1}^4 b_k \cos(\omega_0 t - \beta_k) \quad (\text{A.10})$$

where

$$a_1 = |T_{xx}|^2 |P_{\perp}| |R_{\perp}| \cos \Theta \quad (\text{A.11})$$

$$a_2 = |T_{xx}| |T_{xy}| |P_{\perp}| |R_{\parallel}| \cos \Theta \quad (\text{A.12})$$

$$a_3 = |T_{xx}| |T_{xy}| |P_{\parallel}| |R_{\perp}| \sin \Theta \quad (\text{A.13})$$

$$a_4 = |T_{xy}|^2 |P_{\parallel}| |R_{\parallel}| \sin \Theta \quad (\text{A.14})$$

$$b_1 = |T_{yx}|^2 |P_{\perp}| |R_{\perp}| \cos \Theta \quad (\text{A.15})$$

$$b_2 = |T_{yx}| |T_{yy}| |P_{\perp}| |R_{\parallel}| \cos \Theta \quad (\text{A.16})$$

$$b_3 = |T_{yy}| |T_{yx}| |P_{\parallel}| |R_{\perp}| \sin \Theta \quad (\text{A.17})$$

$$b_4 = |T_{yy}|^2 |P_{\parallel}| |R_{\parallel}| \sin \Theta \quad (\text{A.18})$$

$$\alpha_1 = -\psi_{\perp} + \phi_{\perp} \quad (\text{A.19})$$

$$\alpha_2 = -\phi_{xx} + \phi_{xy} - \psi_{\perp} + \phi_{\parallel} - \phi_r \quad (\text{A.20})$$

$$\alpha_3 = \phi_{xx} - \phi_{xy} - \psi_{\parallel} + \phi_{\perp} + \Phi \quad (\text{A.21})$$

$$\alpha_4 = -\psi_{\parallel} + \phi_{\parallel} - \phi_r + \Phi \quad (\text{A.22})$$

$$\beta_1 = -\psi_{\perp} + \phi_{\perp} \quad (\text{A.23})$$

$$\beta_2 = -\phi_{yx} + \phi_{yy} - \psi_{\perp} + \phi_{\parallel} - \phi_r \quad (\text{A.24})$$

$$\beta_3 = -\phi_{yy} + \phi_{yx} - \psi_{\parallel} + \phi_{\perp} + \Phi \quad (\text{A.25})$$

$$\beta_4 = -\psi_{\parallel} + \phi_{\parallel} - \phi_r + \Phi. \quad (\text{A.26})$$

Then, equations (A.9) and (A.10) can be expressed in the form

$$i(t) = A_i \cos(\omega_0 t - \psi_i) \quad (\text{A.27})$$

$$p(t) = A_p \cos(\omega_0 t - \psi_p) \quad (\text{A.28})$$

with

$$A_i = A \sqrt{\left(\sum_{k=1}^4 a_k \cos \alpha_k \right)^2 + \left(\sum_{k=1}^4 a_k \sin \alpha_k \right)^2} \quad (\text{5.69})$$

$$A_p = B \sqrt{\left(\sum_{k=1}^4 b_k \cos \beta_k \right)^2 + \left(\sum_{k=1}^4 b_k \sin \beta_k \right)^2} \quad (\text{5.70})$$

$$\psi_i = \arctan \frac{\sum_{k=1}^4 a_k \sin \alpha_k}{\sum_{k=1}^4 a_k \cos \alpha_k} \quad (\text{A.29})$$

$$\psi_p = \arctan \frac{\sum_{k=1}^4 b_k \sin \beta_k}{\sum_{k=1}^4 b_k \cos \beta_k}. \quad (\text{A.30})$$

A and B are given by relations (5.15) and (5.16) respectively. Finally, equations (5.69) and (5.70) can be put in the form (5.11) and (5.12) with

$$\varphi = \psi_p - \psi_i. \quad (\text{A.31})$$

Equations (A.29), (A.30) and (A.31) lead to (5.71).

A.3 Evaluation of detectors signals assuming the transformation law 5.78

With a method similar to the previous one, for the quantities A_i , A_p and φ , it is possible to obtain relations formally equal to (5.69) $\div$ (5.71), where a_k , b_k , α_k , β_k ($k = 1, 2, 3, 4$) are provided by:

$$a_1 = \cos^2 \gamma |P_\perp| |R_\perp| \cos \Theta \quad (\text{A.32})$$

$$a_2 = \cos \gamma \sin \gamma |P_\perp| |R_\parallel| \cos \Theta \quad (\text{A.33})$$

$$a_3 = \cos \gamma \sin \gamma |P_\parallel| |R_\perp| \sin \Theta \quad (\text{A.34})$$

$$a_4 = \sin^2 \gamma |P_\parallel| |R_\parallel| \sin \Theta \quad (\text{A.35})$$

$$b_1 = \sin^2 \gamma |P_\perp| |R_\perp| \cos \Theta \quad (\text{A.36})$$

$$b_2 = -\cos \gamma \sin \gamma |P_\perp| |R_\parallel| \cos \Theta \quad (\text{A.37})$$

$$b_3 = -\cos \gamma \sin \gamma |P_\parallel| |R_\perp| \sin \Theta \quad (\text{A.38})$$

$$b_4 = \cos^2 \gamma |P_\parallel| |R_\parallel| \sin \Theta \quad (\text{A.39})$$

$$\alpha_1 = \beta_1 = -\psi_\perp + \phi_\perp \quad (\text{A.40})$$

$$\alpha_2 = \beta_2 = -\psi_\perp + \phi_\parallel - \phi_r \quad (\text{A.41})$$

$$\alpha_3 = \beta_3 = -\psi_\parallel + \phi_\perp + \Phi \quad (\text{A.42})$$

$$\alpha_4 = \beta_4 = -\psi_\parallel + \phi_\parallel - \phi_r + \Phi. \quad (\text{A.43})$$

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