Heating Neutral Beams for ITER: Present Status

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***Abstract*— The heating neutral beam (HNB) systems at ITER are designed to inject a total of 33 MW of either 1 MeV D^0 or 870 keV H^0 beams into the ITER plasma using two injectors with a possible addition of a third injector later to increase the injected power to ∼50 MW. The injectors operate in a radioactive environment and should survive the life time of ITER, placing thereby stringent requirements on material and manufacturing choices. To ensure a smooth operational phase of neutral beams at ITER, a neutral beam test facility is under construction at Consorzio RFX, Padova, (hereinafter referred to as RFX), and consists of two test beds. The 100-kV SPIDER test bed will be used to optimize the source operation for H and D beams. The 1-MV MITICA test bed is essentially a full scale ITER prototype injector. The manufacturing and operational experiences at MITICA will not only establish the manufacturing processes of ITER HNB components but will also allow validation of the operational space of the injectors for ITER HNB. Operation of the two facilities is expected to begin in 2016 and 2019, respectively. Currently, the experiments on the ELISE facility, IPP Garching, with a half ITER sized RF beam source are underway. The ITER relevant parameters for the H beams have been achieved. Efforts are underway to optimize the same with D beams. The experimental database from ELISE will be an important input for establishing the SPIDER operation. This paper discusses the present status of the design and development of the injectors for ITER and the progress on the test facilities.**

***Index Terms*— ELISE, MITICA, neutral beam (NB), Padova Research on ITER Megavolt Accelerator (PRIMA), SPIDER.**

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I. Introduction

ITER uses a mix of auxiliary devices, such as the electron cyclotron, ion cyclotron, and neutral beam (NB) [1], for fulfilling the various requirements of heating, current drive, plasma rotation, current profile control, impurity control, and MHD control. The roles envisaged for NBs are heating, current drive, and plasma rotation. In addition, there also exists a diagnostic NB (DNB) to diagnose the He ash content using the charge exchange resonance spectroscopy technique.

Over the years, NB systems with single or multiple ion sources, with different extraction areas and a wide variety of multigrid extractor and accelerator systems, have been successfully used on various tokamaks and stellarators worldwide to achieve the above roles. However, the ITER heating NB (HNB) system is different from the existing ones in terms of its beam requirements, dimensions, and configuration. Coupled to this is the fact that at ITER these systems will operate in a hostile radiation environment which makes the systems radioactive and hands-on maintenance difficult. As a result, the requirements of the various components have not only to be conceived and implemented from their functionality point of view but also have to take into account safety aspects with low failure rates over the 20 year life time of ITER. These considerations apply to many aspects of the design, choice of materials, and manufacturing techniques. A rigorous research and development (R&D) program to ensure timely and successful delivery of NB systems to ITER with the above mentioned requirements is being pursued at various test beds under the aegis of the European and Japanese domestic agencies (EUDA and JADA). This program is not only to establish the manufacturing route of complex components meeting the ITER desired quality standards but also to establish the design in terms of its performance and beam delivery goals.

This paper describes, in brief, various aspects of R&D at the component level and for the system as a whole in order

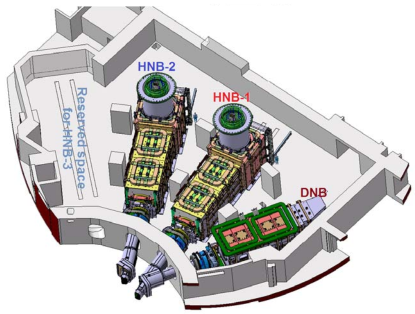

Fig. 1. Layout of the beam lines in the ITER NB cell.

TABLE I
BEAM PARAMETERS REQUIRED AT ITER

Parameter		HNB
Injected power (H-H/H-He, D-D/D-T phase)	(MW)	16.7/beamline
Beam energy / species (H-H/H-He Phase)	(MeV)	0.87/H
Beam energy / species (D-D/D-T Phase)	(MeV)	1/D
Accelerated current (H-H/H-He Phase)	(A)	46/H
Accelerated current (D-D/D-T Phase)	(A)	40/D
Beamlet divergences (H-H/H-He/D-D/D-T Phases)	(mrad)	3-7
Halo fraction (H-H/H-He/D-D/D-T Phases)		15/30
Pulse length/Duty cycle	(s)	3600/25%
Total time of beam operation	(s)	2 x 10^7
Horizontal focussing beamlet/beam group	(m)	7.2/25.5
Vertical focussing beamlet/beam group	(m)	Infinity/25.5*
NBI axis vertical inclination angle	(mrad)	-49.2
Beam axis vertical tilting angle	(mrad)	±9

*The four vertically stacked grid segments that make up each grid of the HNB extractor and accelerator have the beamlets within each segment aimed in the vertical direction at infinity, but the segments are aimed in the vertical direction so that they coincide on the beam axis at 25.5 m from the accelerator.

to make the reader aware of the present status of the progress on NBs.

II. HNB LAYOUT AND SPECIFICATIONS

Fig. 1 shows the layout of the HNB beam line in the ITER NB cell. At present, two beam lines are coupled to the two equatorial ports. An additional port is reserved port for a third HNB as a future upgrade. The HNB-1 beamline has a cross over in the duct region with the neighboring DNB beam line. NBs are intended to be used in the H-He, D-D, and D-T phases of ITER operation. The desired beam specifications for all the phases are listed in Table I. In order to ensure the delivery of 16.5-MW per beam line NB power into the ITER tokamak, a 40 MW of ion power is launched from the beam source.

The loss of power during its transport from the source to the duct opening located at a distance of 25.5 m from the grounded grid (GG) is due to 56% neutralization efficiency, finite divergence of the beamlets, presence of a beam halo (assumed to carry 15% of the accelerated ion power) with an assumed divergence of 30 mrad [2], assembly tolerances and misalignments, and reionization of the NB due to interactions with the background gas in the beam line and the duct between the injector and the tokamak. All these effects have been taken into account in the physics design of the system.

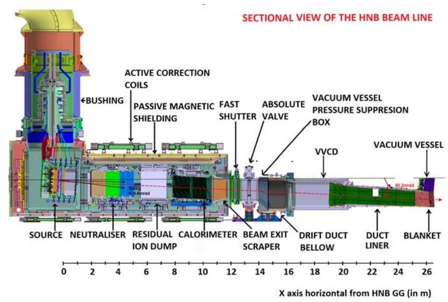

Fig. 2. Layout of the HNB beam line.

Fig. 2 shows the layout of one of the HNBs. The ion source and the beam line components (BLCs) [3], i.e., the electron dump and the neutralizer, the residual ion dump (RID), the calorimeter, the exit scraper, and the cryopumps, are installed in two connected vacuum vessels, the beam source vessel (BSV), and the beam line vessel (BLV), which in turn are connected to the front end components (FECs), i.e., the fast shutter, absolute valve, drift duct bellow, vacuum vessel suppression system box (VVPSS box), connecting duct with its liner, and the 6-m-long duct which contains several duct liner (DL) panels. The vacuum vessels are surrounded by a magnetic field reduction system consisting of a combination of a passive magnetic shield (PMS) and active compensation and corrections coils (ACCCs), which reduces the magnetic fields from the tokamak [6] to acceptable levels within the beam, typically, ∼1 Gauss in neutralizer region. The vertical center of the GG is 1.44 m above the ITER tokamak machine center line (MCL), and the beam is aimed downward at a nominal angle of 49.2 mrad. In addition, the beam can be steered upward or downward by 9 mrad with respect to the nominal angle. The beam axis at the tangency point is located vertically between −417 and +156 mm relative to MCL. Vertical tilting angle is required for off-axis current drive and to avoid beam excited toroidal Alvèn eigenmodes in the ITER plasma.

III. PRESENT STATUS

A. Status of the Physics Design Calculations

1) Design of the Front End Components and Duct Liner: In addition to the BLCs, beam power is incident on the FEC and DL of each of the two beam lines. It is necessary to calculate the incident power and the power densities on each of the component surfaces in order to establish a working mechanical design of these components. In addition to direct beam interception, additional heat loads arise from the interception of reionised beam atoms. The reionized particles see the magnetic fields from ITER which change with the changing operating scenario. The ions are deflected by the magnetic field onto surfaces within the NB duct. Power densities from the reionized ions are higher than those due to the direct interception because of focusing effects due to the variation in the magnetic fields. Calculation of the power and the power densities requires the knowledge of the operational gas profile and the magnetic fields along the beam line for the foreseen ITER operating scenarios. To calculate the

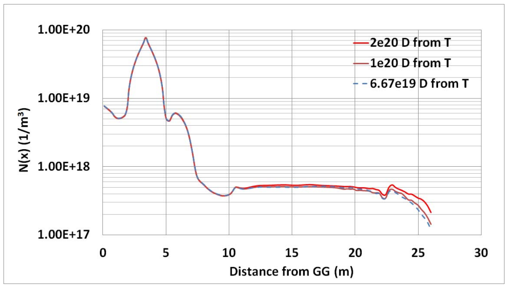

Fig. 3. HNB-1 gas profile for different gas inputs from tokamak.

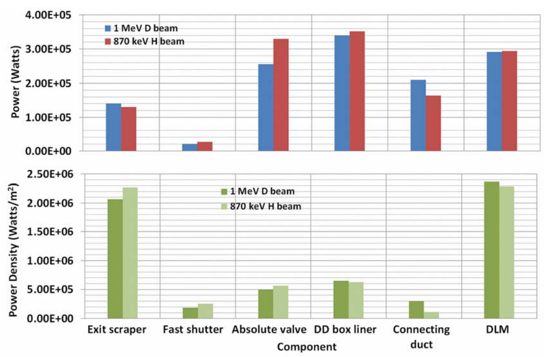

Fig. 4. Worst case power and power density on ES and FEC.

gas profiles, the MCGF code from the Russian Federation [4] has been modified to take into account all the gas sources, i.e., gas from the ion source, the neutralizer, the tokamak, the adsorbed gas molecules released from the surface of the components, and the duct when beam is incident on those surfaces, and, in the case of HNB 1, gas from the DNB. The calculated gas profiles for the HNB 1 beam line, shown in Fig. 3, give a reionzation loss of $\sim$8% for all the operational scenarios from the entry of the RID to the duct exit. The considered reionization cross sections from the ORNL red book [5] have been increased by 30% to take into account the uncertainty in the cross section values. Calculations to arrive at the worst case estimates of power and power density [6] (Fig. 4) have been carried out using the BTR code [7] from the Russian Federation for various beamlet divergences, misalignments, and beam tilting angles using the gas profiles and reionization cross sections mentioned above.

2) Multigrid Multiaperture Accelerator of the Beam Source: An optimal design of the accelerator system to be coupled to the beam source is necessary to produce beams with the characteristics listed in Table I. Based on the experimental studies, a multigrid multiaperture (MAMuG) accelerator system [8] has been chosen over the alternative single gap, single aperture (SINGAP) accelerator system [2]. The MAMuG is a seven grid system consisting of a plasma grid (PG), an extraction grid (EG), four acceleration grids (AG1 to AG4), and the GG. There are five acceleration stages of $\approx$200 kV each and with 88-mm gaps. The PG–EG gap is 6 mm. Each grid is an assembly of four segments arranged vertically with each segment having four beam groups. A total of 1280 apertures are arranged in 16 beam groups, with each beam group having a 5×16 aperture matrix [8]. Besides the optimization of aperture shapes, distances, and voltages, the accelerator design has also considered the effects due to magnetic fields from the ion source, the electron suppression magnets embedded in the EG, and the permanent magnets embedded in the acceleration grids that help distribute the power to the grids from the secondary electrons. The PG filter field [9] is produced by a combination of currents flowing through the PG and return bus bars so as to have an optimal $\int$Bdl in the source while having a minimal field in the RF driver plus a long range field of $\approx$1 mT in the accelerator. In addition, they are the effects of space charge repulsion between beamlets within a beamlet group and the interaction between neighboring beamlet groups which must be taken into account. Furthermore, optimal beamlet steering is required for good transmission to the ITER plasma. The requirements include geometrical aiming of beamlet groups in the vertical and horizontal directions to the exit of the NB duct and the aiming of beamlets within each group horizontally at the horizontal center of the exit of the appropriate channel in the RID. Extensive design calculations, done in a collaboration between RFX, CEA, and ITER IO, have led to the final configuration of the accelerator [8], [17]. The beamlet deflection due to the permanent magnets in the EG is compensated by the use of a vertical array of deflection compensation permanent magnets, also embedded in the EG [9]. The effect of the space charge repulsion of the outer most beamlets and between beam groups is overcome by the effective use of kerbs on the downstream side of the EG. The horizontal aiming of beam groups is ensured by machining the segments to incline the beamgroups horizontally and the aiming of the beamlets within each beam group is achieved with kerbs mounted on the successive acceleration grids. This concept does not lead to a proper aiming of the beamlets 2 and 4 of the five horizontal beamlets but the misaiming of $\approx$1.4 mrad does not lead to any substantial transmission loss. The aiming in the vertical direction is achieved by inclining the segments with respect to the vertical direction. A very important aspect of the design is the control of electrons leaking from the accelerator such that the loads onto the cryopumps are acceptable, i.e., $\approx$10 kW to the 80 K surfaces and $<$200 W to the 6.5 K surfaces. This is done by creating magnetic fields in the extractor and accelerator that deflect the electrons onto the grid. The field is created by a combination of permanent magnets in the EG and AGs and by tuning the PG filter field to create a long range field of $\approx$1 mT throughout the extractor and the accelerator. The dumping of electrons on the grids results in high power loads on the grids. The 14-mm apertures on the AG1 and AG2 and 16-mm apertures on AG3, AG4, and GG help to limit the power of the dumped electrons to $\sim$2 MW per grid. The grid thickness, however, is increased from 10 to 17 mm to keep the consequent out of plane bending to an acceptable value of $\sim$0.6 mm.

Out of plane bending, aperture misalignments, magnetic field nonuniformities, and inaccuracy of the magnet locations can cause unwanted steering of individual beamlets. The steering due to aperture displacement has been determined to be 2 mrad/mm for the EG lens and 0.6 mrad/mm for the GG. For the intermediate acceleration grids, the apertures do not

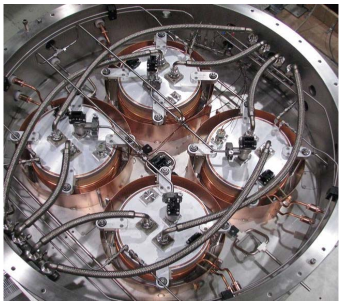

Fig. 5. Top view of the ELISE source at IPP Garching.

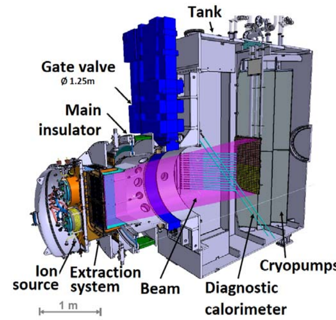

Fig. 6. Cut view of the ELISE experimental test bed.

form electrostatic lenses as the electric fields upstream and downstream the aperture are almost the same. The results of the calculations are summarized in [8]. Recent assessments on the acceptable aperture misalignment by IO have shown that misalignments of ±0.2 mm on the EG apertures and ±0.5 mm on the GG apertures with respect to the nominal beam axis are acceptable in terms of the ability to predict the beam bending angle from the beam profiles measured on the calorimeter and in obtaining the desired transmission of 16.5-MW per HNB to ITER. A measurement accuracy of the beam tilting angle of ±1 mrad is needed in order to determine the position of beam power deposition in the plasma with the desired accuracy. These calculations take into account all steering effects, both in the horizontal and vertical directions. Furthermore, a 1-mm-thick Mo layer coating on the Cu back plate helps to minimize sputtering caused by the back streaming positive ions which are the result of ionization of background gas mainly by D^- and D^0 [10].

B. Present Status on the Various Test Beds

1) ELISE, IPP Garching: The ITER specified beam current densities have been achieved with single driver-based RF negative ion sources, 1/8th the size of the ITER sources [11]. As an intermediate step before operating the eight driver-based ITER source, a half sized source with four drivers has been set up on the ELISE facility at IPP Garching [12]. The aim of the experiments at ELISE is to establish the technique of coupling RF power to two drivers fed by a single RF generator as planned for the ITER sources, and to achieve ITER relevant plasma and beam parameters for both H and D beams. ELISE incorporates the operational experiences on first generation multiple driver source, RADI [13], and includes increased diameter RF drivers for a uniform illumination of the grid areas and electromagnetic shield around each driver to avoid damage to the Faraday screen. Fig. 5 shows the top view of the ELISE source with four drivers and the shields around each driver. The schematic of the ELISE experimental set up is shown in Fig. 6.

Over the past year, the extensive experiments on this source have been performed, both in the volume and surface production modes with Caesium seeding of the ion source for both H and D beams. The magnetic filter field in the source is generated by flowing current through PG and a set of return leads, a concept similar to the one planned on ITER sources. The experiments have shown that tuning the source for H beams with the desired electron to ion ratio is a bit easier and quicker as compared with the single driver sources. However, operation with D beams still needs further investigation as the electron to ion ratio is not only higher than the desired value but also increases with time due to increasing extracted electron current. Table II summarizes the best parameters obtained so far with the ELISE source compared with the ITER requirements. The numbers in the parenthesis in the ITER column point to the parameters for the H beams during the H-H and H-He ITER phases.

TABLE II
ELISE Performance and ITER Requirement

Parameter	H^- beam	D^- beam	ITER
Gas filling pressure (Pa)	0.3	0.3	≤0.3
Beam current accelerated (A)	20	15	20 (23)
Extracted current density (mA/cm^2)	26	20	29 (33)
RF power for max current density (kW)	2 x 110	2 x 110	≤2 x 200
Pulse length at 2 x 90 kW (s)	450	10	3600 (1000)
Pulse length ar 2 x 40 kW (s)	3600	10	3600 (1000)
Electron to ion ratio	0.4	1.06	<1, (0.5)
Current density scaling with power	Linear	Linear	

2) PRIMA Facility at RFX Padova Italy: The Padova Research on ITER Megavolt Accelerator (PRIMA) [14] facility (also called the NBTF) is being set up with two main aims:

1) characterizing a full sized ITER ion source to its desired performance (SPIDER test bed: 100-kV operation H and D beams) [15];
2) establishing a full scale prototype beam line similar to the ITER HNB beam line (MITICA test bed: 1-MV D beams and 870-keV H beams) [16], [17].

It is envisaged that the design of the MITICA beam line components, their layout, the materials used, and the manufacturing technologies used will be, as far as possible, identical to their HNB counterpart to mitigate any risks and to establish the route to manufacturing of the HNB components. The facility (Fig. 7) involves a total area of 17 500 m^2, of which 7400 m^2 are covered, and the maximum building height is 26.4 m at the location of the injectors installation.

Fig. 7. PRIMA site building at RFX, Padua, Italy.

Fig. 8. Vacuum vessel for SPIDER source at RFX.

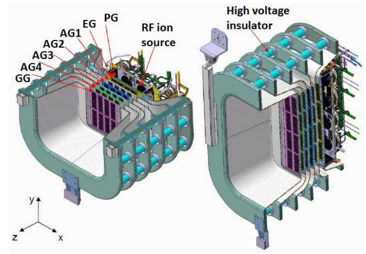

Fig. 9. CAD view of the MITICA source by RFX.

The buildings for the PRIMA facility are nearing completion. Besides housing the SPIDER and the MITICA test beds, it also has space allocated for auxiliary systems, such as the power supplies, gas, cryogenics, vacuum, and hydraulics. An agreement related to work organization on site according to Health and Safety Italian Codes was signed in June 2014 and has a joint client responsibility between Consorzio RFX and EUDA.

a) SPIDER: The SPIDER facility consists of an eight driver RF negative ion source coupled to a three stage accelerator housed in a vacuum vessel along with numerous diagnostics. The diagnostics include Langmuir probes, thermocouples, a carbon tile-based calorimeter STRIKE, various optical diagnostics, and an Indian domestic agency (INDA) supplied ion dump, which is also instrumented with thermocouples. The contract for the manufacturing of the ion source, the accelerator and the vacuum vessel for the facility are being managed by EUDA with a consortium of companies, which include THALES France, CECOM Italy, ZANON Italy, and GALVANO–T Germany and their subcontractors. The vacuum vessel (Fig. 8) has been delivered to RFX, assembled, and tested. The auxiliary systems, such as the cooling, gas, power supplies, and the control and data acquisition system, are expected to be assembled by the end of 2015. The various components of the SPIDER beam source are currently being manufactured after completion of several prototype activities. The assembly and integration activity of the source, auxiliary, and diagnostic systems in the vacuum vessel is expected to be completed by Q2 of 2017 and followed by the experimental phase. The power supplies for SPIDER are to be procured by EU and INDA. The modules, transformers, and electronic control cubicles corresponding to the INDA scope of 100-kV acceleration grid power supplies have been procured and tested in India as per test procedures mutually agreed between the INDA and the IO. Delivery of the same to the PRIMA site is expected in first half of 2016. The ion source extractor power supplies procured by EU have been delivered at RFX site.

During the course of SPIDER source manufacturing and interaction with the vendors, several experiences relevant to the manufacture of the ITER and the MITICA beam sources have been made. These include the increase in the size of the RF transmission lines under vacuum from 1 5/8 to 3 1/8 in to accommodate the expected operational temperature of 150 °C during high power, long pulse operation. Another important issue is the estimate on the best achievable alignment of the successive apertures between the three grids of the accelerator as the actual manufacturing tolerances are becoming known.

b) MITICA: The MITICA facility will house a prototype 1-MV full scale beam line which includes the eight driver RF negative ion source and the BLCs. Fig. 9 shows the cut view of the mechanical design of the MITICA beam source [11], [12], which takes into account of the results of the calculations mentioned in Section III-B for the extractor and accelerator, the experimental data from the ELISE test bed, and the manufacturing experience on the SPIDER beam source. For example, electrostatic shield has been incorporated around each driver based on the experience from RADI and ELISE and experience from the manufacturing of the SPIDER ion source led to modifications to the design of the plasma box.

The design of the BLCs has been finalized and reviewed at ITER. These include the neutralizer and electron dump, the RID, the calorimeter, and the exit scraper. Detailed thermo-mechanical design calculations using the heat loads calculated using the BTR code have helped to finalize the flow parameters of the cooling water required for these components, and to assess the mechanical stresses and out of plane or in plane bending of the various components. As the MITICA BLCs are also considered as a route to establish the ITER BLCs, the design has also been assessed for ITER relevant off normal conditions in the form of several load cases, such as the loss of coolant, loss of vacuum, loss of voltage, seismic events, and so on, either individually or in combination. Structural design criterion for ITER invessel components (SDC-IC) [18], and reliability, availability, maintainability, and inspectability (RAMI) analysis [19] verifications have been carried out on all the components of MITICA components to ensure that survival of the component under cyclic loading for the full ITER life time. The technical specifications related to the manufacture of MITICA beam source have been finalized by RFX and the call for tender launched in Q4 of 2015. By the end of 2015, all the tenders will be launched and most procurements assigned. The contract for the manufacture of the MITICA vacuum vessel has been awarded.

The installation phase of the first MITICA components, i.e., transmission line and high voltage power supplies components, will start in December 2015 and will continue until spring 2017. This will be followed by the integrated commissioning of all plant and interlocks with data acquisition and control system and by the PS integrated tests. The MITICA beam source will be installed in 2019, followed by the first experimental phase. For the MITICA test bed, the power supply procurement is shared between the EUDA and the JADA. All JADA supplies [20] are currently under manufacturing by Japanese firms in line with the original planning. In particular, the −1.3-MV 10-mA dc generator to be used to test the voltage holding of the high voltage transmission lines and the high voltage deck has been manufactured and fully tested.

C. Prototype Development

Successful development of several prototypes has been carried out to verify the design and establish the manufacturing of different components. The experience gained is being utilized in defining the technical specification documents for each of the components. The prototype developments performed by RFX include high voltage post insulators for the accelerator and the source, dis-similar metal jointing techniques, deep drilling over 2-m lengths, and swirl tape insertion and fixation in the tubes for the calorimeter panels. An ITER relevant CODAC system has also been prototyped using the similar platforms as those envisaged for ITER [21]**.** The manufacturing of the 1.6-m diameter ceramic rings for the HV bushing and prototype developments related to the HV shields to be used in the bushing are some of the successful prototype activities carried out by JADA.

D. Front End Components and Duct Liner

Detailed design for the FECs along with the BLV, BSV, PMS, and ACCC has been developed and the preliminary design review completed. It incorporates the results of calculations mentioned in Section III-A, SDC-IC validation for ITER envisaged load cases and RAMI analysis. The final design review for the DL has been completed and the complete CAD model and the 2-D drawings are expected by the end of 2015. The components will be procured by EUDA and the procurement arrangements are expected to be signed in early 2016. The built to print design for the exit scraper and the VVPSS box has been developed, which will be procured by the INDA. The study of the absolute valve, to be procured by EUDA, is on-going at VAT with the final design review expected in late 2016.

E. Nuclear Safety Requirements

Detailed calculations related to the nuclear analysis of the NB cell have been carried out to map the dose rates in the different regions of the cell. In order to achieve the acceptable level of the shutdown dose rate of <100 μSv/h in all areas where the human access is foreseen, the design of the PMSs has been modified by filling the interspace between the shields with 10-cm-thick polyethylene and by shielding external faces with 1–2.5-cm-thick lead.

IV. Conclusion

The present status of the physics and design activities related to the development of the HNB for ITER has been described in brief and includes the progress of the experiments at the ELISE test facility and the design, construction, procurement, setting up, and testing activities for the SPIDER and MITICA test beds at the PRIMA facility. The experimental experience from the test beds is expected to shorten significantly the commissioning time of the injectors on ITER. The extensive diagnostic capability at these test beds is also expected to establish the operational limits for ITER injectors. That should allow operation at higher performance than would otherwise be the case. The present planning allows for the procurement activities of the HNB ITER components to finish by Q2 of 2026. The manufacturing and the installation phase are expected to be over by Q4 of 2026 and will be followed by the commissioning and experimental phase to deliver beams to ITER in time with the H-He phase of ITER.

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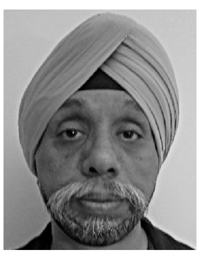
Ronald Stephen Hemsworth received the B.Sc. degree from London University, London, U.K., in 1966, and the D.Phil. degree from York University, York, U.K., in 1970, followed by a three-year post doctorate at York University, Toronto, ON, Canada.

He joined the United Kingdom Atomic Energy Authority Culham Laboratory, Oxon, U.K., in 1973, where he was responsible for the design and construction of the neutral beam injection system for the DITE tokamak. He moved to the Neutral Beam Group of the joint European torus (JET) in 1979 to be responsible for the physics design of the injectors for JET, becoming the Leader of the JET Neutral Beam Test Bed Group in 1983. In 1991, he moved to the Département de Recherche sur la Fusion Contrôlée (DRFC), Cadarache, France, to take up the development of negative ion sources for neutral beam injection. In 1994, he moved to the International Thermonuclear Experimental Reactor (ITER), Naka, Japan, to be the Leader of the group responsible for the design of the neutral beam injectors for ITER. In 1997, he returned to the DRFC to be responsible for the development of the long pulse negative ion source for ITER, and he was also made Task Area Leader for the neutral beam development in Europe under the European Fusion Development Agreement. In 1998, he was made Group Leader for the DRFC Neutral Beam Group with the additional responsibilities of the development of the SINGAP 1 MeV D^- accelerator and the positive ion based diagnostic injector for Tore Supra. In 2007, he joined the ITER Organization and soon became the Neutral Beam Section Leader with responsibilities for the design of the ITER heating and diagnostic injectors and the related development for the neutral beam systems with the Domestic Agencies of ITER. In 2010, he retired from ITER and set up RSH Research Consultants Ltd., under which he has since worked as a Consultant on neutral beams for ITER.



M. J. Singh received the Ph.D. degree in accelerator-based physics studies on ion-atom collisions from Benaras Hindu University, Varanasi, India, in 1997, followed by a two year post-doctoral fellowship with the J. R. Mac Donald Accelerator Based Laboratory, Kansas State University, USA. He joined the Institute for Plasma Research (IPR), Gandhinagar, India, in 1999, to work on positive ion based neutral beam injector for the SST-1 program and designed the ion deflection and ion dump system in particular. He played a key role in the set up of the single RF driven ion source, ROBIN, and facility for the negative ion beam development program at IPR. His contribution toward the design for the large negative ion sources for the ITER neutral beam lines includes the physics design of the ion extractor and accelerator system for the ITER diagnostic neutral beam, DNB, and injector. In 2012, he joined the Neutral Beam Team, ITER IO, France, and has worked on physics design aspects of the various components for the HNB beam lines and source for ITER.

Julien Chareyre received the master's degree in mechanical engineering from INSA Lyon, Lyon, France, in 2006.

He joined the company ASSYTEM France and performed mechanical analysis in the field of nuclear power plant for the customer EDF (French Electricity Company) for one year. He then joined the ITER project in 2007 and was involved two years in the design office looking after design and integration of diagnostics in the divertor component. In 2009, he started with the Neutral Beam Section in order to support the design and integration of the diagnostic neutral beam. Since 2016, he has been with the ITER Organization, Cadarache, Saint Paul-Lez-Durance, France, to finalize the design and follow the manufacturing of the DNB components.

Deirdre Boilson received the Ph.D. degree in negative ion sources for NBI from Dublin City University in 2000. She has worked on the different ion source technologies at CEA and IPP testbeds. Since 2010, she has been with the Neutral Beam Team, ITER, as the Section Leader of the NB and currently is the Division Head of Heating System at ITER.

Hans Decamps received the master's degree in electrical engineering from Arts et Metiers France, Paris, France.

He was, for ten years, an Electrical Engineer on power electronics in nuclear area (Power Station and Nuclear Submarine). In 2000, he was, for three years, an IT Project Manager in web application development. In 2007, he joined the ITER Organization and started to support the Heating and Current Drive Division. He was a Technical Responsible Officer on the ECRH, ICRH, and NB power supplies engineering design. Since 2011, he has been involved in the neutral beam power supply that will be installed in Padua, Italy, in order to prepare the installation for the ITER HNB PS in France.

Francois Geli received the Diploma degree in mechanical and material engineering from ISMANS, Le Mans Engineering School, France, in 2001.

He was a Development Engineer with the DELPHI automotive industry for five years in Gillingham, U.K. He then changed field and joined the JET Joint Undertaking, Culham, U.K., in 2007. He was with the NB Engineering Section, looking after JET and ITER NB components design. In 2010, he created his limited company and started to support the ITER heating and current drive division both on NB and ECRH engineering design. Since 2016, he joined the ITER Organization, Cadarache, Saint Paul-Lez-Durance, France, to orchestrate the design finalization and the manufacturing of the NB Ion source.

Joseph Graceffa received the Diploma degree in mechanics of structures and systems, Ecole National Superieure D'Arts et Metiers, Aix en Provence, in 2004.

He was with several sectors of industry, nuclear power, military, energy, and aeronautics. He joined ITER in 2006 in charge of design of the components and their integration and interfaces. He has been a Section Leader of the NB Section since 2016. He is a Mechanical Engineer with 16 years of working experience.

Beatrix Schunke received the Diploma degree in experimental physics and the Dr.rer.Nat. degree from the Ruhr-Universität Bochum, Bochum, Germany, in 1985 and 1990, respectively, with a focus on two-photon laser spectroscopy and laser ablation experiments.

She was with the JET Joint Undertaking, Culham, U.K., in the Electron Temperature Measurement Group for a one-year post-doctoral fellowship. In 1991, she held a staff position with JET, where she was involved in the LIDAR Thomson scattering diagnostics, and moved on to the Operations Division as an Expert Session Leader in 1995. In 1998, she was with the Département de Recherche sur la Fusion Contrôlée, Cadarache, France, where she was involved with the Visible and UV Spectroscopy Group responsible for the Zeff Diagnostics. Since 2006, she has been the Responsible Officer for the Diagnostic Neutral Beam with the ITER Organization, Paul-Lez-Durance Cedex, France.

Lennart Svensson received the M.Sc. degree in applied physics and electrical engineering from Linköping University, Linköping, Sweden, in 1987.

He was a Research Engineer and an Expert in measurement technology with the AB Volvo Technological Development Department. He then changed field and joined the JET Joint Undertaking, Culham, U.K. He was with I&C for the Neutral Beam (NB) System and was also with the operation and preparation of the tritium operation of the NB injectors. In 1998, he moved to CEA Cadarache, France, to initially work on the diagnostic NB injectors on Tore Supra and thereafter he took up the role as responsible for the SINGAP testbed, where an alternative concept was developed for the ITER 1 MV NB accelerators. In 2009, he moved to ITER with Cadarache, where he is responsible for the I&C for the NB system.

Darshan Shah received the B.E. degree in mechanical engineering from L.D. Engineering College, Ahmedabad, India, in 1997.

He was a Product Development Engineer with Bosch Rexroth, Ahmedabad, a subsidiary of Robert Bosch for seven years. He moved to Tata Consultancy Services (TCS), Ahmedabad, India, and started looking after engineering projects on industrial products, locomotive, and medical devices. In 2010, he joined the Neutral Beam Section at ITER as an External Mechanical Engineer from TCS to provide engineering support mainly for NB system's assembly at ITER, Remote handling interface for NB components and reliability studies of NBI and ECRH systems.

Anass El Ouazzani received the bachelor's degree in science of mechanical production and engineering from Conservatoire national des Arts et Metiers, Aix en Provence, France, in 2004 after having two associate degrees in mechanical, and the M.E. degree in mechanical structure and systems engineering.

He has been with the Aeronautic Sector for UTC-Aerospace-System, Figeac, Figeac, France, for three years, designing the trimmable horizontal stabilizer actuator of the A400M plane since 2004. He has been a Designer and an Engineer with the Neutral Beam Section, ITER project, since 2007, through Sogeti and has performed the engineering and analysis tasks for the design of the magnetic shield, the active correction/compensation coils, and the high voltage bushing for the ITER heating neutral beam system.

Marc Urbani received the master's degree in mechanical and industrial automation from the University of Montpellier II, Montpellier, France, in 1999.

He was with several sectors of industry, nuclear power, military, energy, and aeronautics. He joined ITER in 2008. He is responsible for the NB front end components development supervising the procurement arrangement for the European Domestic Agency. He is a Mechanical Engineer with 15 years of experience.

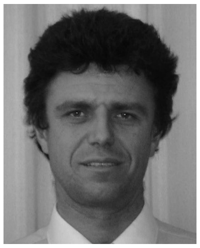
Hubert P. L. de Esch was born in 1957. He received the University degree in physics and the Ph.D. degree from the University of Utrecht, Utrecht, The Netherlands, in 1981 and 1985, respectively.

He was with FOM, The Netherlands, and CEA Fontenay-aux-Roses, France, two years, where he was involved in ECRH. He was with the Neutral Beam Heating Division, JET Tokamak, Abingdon, U.K. In 1998, he moved to CEA-Cadarache, France, to work on neutral beam physics, accelerator design, and high voltage holding in vacuum.

Etienne Delmas received the Degree in mechanical engineering from the Engineering School, Belfort, France, in 2003.

He started his career with the CEA Valduc on the development of material mechanical testing. In 2005, he joined IRFM, CEA Cadarache, where he was involved in Tore Supra Tokamak. He was in charge of the maintenance and mechanical new project for the heating systems (NB, ICRH, ECRH, and LHCD). He leads a project of upgrade of Tore Supra to integrate a new LHCD launcher on the Tokamak. He then joined the NB Section, ITER Organization, and followed-up the design of the HNB vessel, PMS, ACCC coils, and SIC feedthroughs and the nuclear analysis contract. Since 2015, he is back to CEA and follow up the manufacturing of the West project components.

Vanni Antoni, photograph and biography not available at the time of publication.



Giuseppe Chitarin received the Ph.D. degree in electrical engineering from the University of Padova, Padua, Italy, in 1982.

He joined CNR as a Researcher and participated to the design, assembly, and commissioning of the magnets for the RFX Reversed Field Pinch experiment in Padua. From 1991 to 1997, he was part to several experimental studies on RFP plasma magnetic configurations, plasma instabilities, and mode-locking phenomena and on their mitigation. He was appointed as a Research Assistant in 1990 and then an Associate Professor with the University of Padova in 1998. From 1997 to 2008, he was the Leader of the Magnet System Group with Consorzio RFX, Padua, and was responsible for the design of new local control coils for the active control of the magnetic configurations in RFX from 1998 to 2004 and of in-vessel magnetic sensors for RFX, for JET-EP from 2003 to 2007 and for ITER from 2005 to 2008. Since 2008, he has been the Deputy Programme Leader for the Physics and Engineering Developments of the Neutral Beam Test Facility for ITER with Consorzio RFX. His current research interests include design and optimization of complex electromagnetic systems for high-temperature plasma confinement and material processing, operation of magnetic-confinement fusion devices (Tokamak and RFP), design and optimization of magnetic devices and sensors for research and industrial applications, analysis of magnetic measurements data and identification of magnetic configurations, and design, development, and experimentation of high power neutral beam injector for plasma heating.

Dr. Chitarin received a fellowship on HVdc transmission lines research with CESI, Milan, Italy.

Gianluigi Serianni was born in Catanzaro, Italy, in 1968. He received the B.A. degree in physics, the M.S. degree in plasma engineering, and the Ph.D. degree in physics from the University of Padova, Padua, Italy, in 1992, 1992, and 1995, respectively.

He was involved in the field of physics and characterization of low temperature plasmas and of the edge region of nuclear fusion experiments. His current research interests include characterization and physics of negative ion sources and neutral beams for fusion applications. He has installed and operated various diagnostic systems in several experiments. From 2002 to 2009, he was responsible for the support to all the diagnostics of the RFX experiment. He is with Consorzio RFX, Padua. Since 2009, he has deputy responsible for beam physics, responsible for the NIO1 negative ion beam source, and responsible for the diagnostic calorimeter for the SPIDER negative ion beam source.

Diego Marcuzzi received the master's degree in mechanical engineering from the University of Padova, Padua, Italy, in 1994.

He has been with Consorzio RFX, Padua, since 2000, as a Professional Researcher. He has followed the modification of RFX fusion machine in the early 2000s, and then he has been involved in several international projects, e.g., the enhancement programs of the joint European torus machine. Since 2004, he contributes to the development of the ITER Neutral Beam Injector, and he is part of the team coordinating the Neutral Beam Test Facility being constructed in Padua. He is the Project Leader of the beam source of the two experiments foreseen in the facility, the core mechanical component for both injectors.

Vanni Toigo received the master's degree (Hons.) in electrical engineering from the University of Padova, Padua, Italy, in 1983.

He was Researcher with the Istituto Gas Ionizzati, National Research Council, and Consorzio RFX, Padua, from 1985 to 2001. Since 2001, he has been a Senior Researcher with Consorzio RFX. He has more than 31 years of experience in thermonuclear fusion research, resulting in wide experience in modeling, design construction, installation, commissioning and operation of electric systems for fusion plants; management of contract with industry for the procurement of the components; keep international collaborations with other laboratories in the field of the controlled thermonuclear fusion; and management of big international project. He was involved in the design and construction of RFX in 1985. In this phase, he was a member of the Electric Systems Group. From 1998 to 2008, he assumed the role of Electric Systems Group Leader. Besides coordinating all scientific and technological activities of the group members, he has been responsible for the procurement contracts of different power supply systems, proponent and main developer of an innovative system of power supply for the RFX toroidal circuit, using big converters based on new static components. From 2003 began international collaboration for the study of ITER NB Injectors managing all activities of competence of the Electric Systems Group with Consorzio RFX, including feasibility studies of critical components. In 2008, he has been nominated as the Project Leader of the Power Supply Systems of the Neutral Beam Test Facility (NBTF) for the development of the neutral beam injectors for ITER that is under construction in Padua. In 2013, he was appointed as an NBTF Project Manager and coordinates the NBTF Team in charge for the design, integration, and operation of NBTF experiments.

Pierluigi Zaccaria was born in Padua, Italy, in 1955. He received the B.E. degree in civil structural engineering and the Ph.D. degree in engineering of structures from the University of Padova, Padua, in 1979 and 1984.

He has been with the National Research Council of Italy as a Researcher and Technologist with the Institute of Ionized Gas, Padua, since 1985, where he has been involved in engineering and physics studies and researches on controlled thermonuclear fusion. From 1984 to 2005, he was part of the Team for design, construction, monitoring and upgrades of RFX, the largest Reversed Field Pinch experiment in the world for nuclear fusion research. During the whole period, he covered different roles of responsibility, performing, and supervising specific activities for mechanical parts of RFX machine as vacuum vessel, support structures, main windings for magnetic fields, and sensors/monitoring systems. From 2000 to 2004, he led the upgrade of the RFX-mod machine with regards to the newly optimized first wall, toroidal support structure and thin copper shell for plasma stabilization. Since 2009, he has been the Deputy Project Leader for the Neutral Beam Test Facility and MITICA and SPIDER experiments, an international enterprise aiming to develop and optimize a prototype for ITER Heating Neutral Beam Injector, presently under construction at Consorzio RFX, Padua.

Ursel Fantz received the Dr.-Eng. degree in physics and the Ph.D. degree in electrical engineering from the University of Stuttgart, Germany, in 1995, and the Habilitation degree in experimental physics on the topic of low temperature hydrogen plasmas from the University of Augsburg in 2002.

She became a Professor with the University of Augsburg in 2008. She joined the Neutral Beam Injection Group, Max-Planck-Institut Fuer Plasma-Physik, Garching, Germany, for the development of negative hydrogen ion sources for ITER in 2004. She is currently the Division Head of the ITER Technology and Diagnostics Division with IPP and the Head of the Experimental Plasma Physics Group with the Institute for Physics, University of Augsburg.

Peter Franzen, photograph and biography not available at the time of publication.

Bernd Heinemann received the Diploma (M.S.) degree in mechanical engineering from the Technical University of Munich, Munich, Germany, in 1985.

He joined the Max-Planck-Institut Fuer Plasmaphysik (IPP), Garching, Germany, in 1986. He is currently the Group Leader of the Neutral Beam Group with IPP, which is responsible for the NBI systems of ASDEX-Upgrade and Wendelstein 7-X and involved in the development of the radio frequency ion source for ITER.

Werner Kraus studied physics with Justus-Liebig-Universität Giessen, Giessen, Germany, where he started investigating small RF driven ion sources for fusion applications in his Ph.D. thesis in 1978. Based on this work, he designed and tested with the Max-Planck-Institut für Plasmaphysik the powerful, large area RF plasma source for the second neutral beam injector of ASDEX-Upgrade. In future the NBI of W7X and the first injector of ASDEX-Upgrade will also be equipped with these sources. Since 1997, the focus of the development changed to negative hydrogen ions. The design principle of the prototype source tested at IPP became the standard of RF driven negative ion sources and is also the basis of the large source in the neutral beam injection of ITER.

Mieko Kashiwagi received the B.Eng., M.Eng., and Ph.D. degrees from Saitama University, Saitama, Japan, in 1994, 1996, and 1999, respectively, followed by a three-year post doctorate with the Japan Atomic Energy Research Institute, Naka, Japan, in 1999.

She held a position with the Neutral Beam Group, Japan Atomic Energy Agency, since 2002. She was responsible for the plasma neutralize, 1-MeV high-current density electrostatic accelerator, and a 3-D beam analysis. She is responsible for the 1-MV high voltage power supply components for ITER.

Dr. Kashiwagi is a member of the Physical Society of Japan, the Japan Society of Applied Physics, and the Japan Society of Plasma Science and Nuclear Fusion Research.

Masaya Hanada started the developments of a high-power negative ion sources and a neutral beam injector with the Japan Atomic Energy Research Institute, Naka, Japan, in 1986. Since 2016, his work has extended to the development of a large fusion reactor.

Hiroyuki Tobari, photograph and biography not available at the time of publication.

Masaki Kuriyama started research activity in the area of solid state physics with the National Institute for Inorganic Materials in 1971, and then moved to the Japan Atomic Energy Research Institute, Naka, Japan, in 1977 for charging fusion research in JT-60. In JT-60, he was involved in the development of the neutral beam heating system including 100 keV positive-ion NB and 500 keV negative-ion NB. He started to contribute to a part of the construction of the ITER NB system in 2010.

Antonio Masiello, photograph and biography not available at the time of publication.

Tullio Bonicelli received the Laurea in Ingegneria Elettrotecnica degree from the University of Padova, Padua, Italy, in 1980.

After three year with the industry as responsible for R&D on materials and components, he joined the Magnet and Power Supply Division, Joint European Torus (JET), Culham, U.K., in 1984. At JET, he was made as the Manager of the Engineering and Development Branch and then the Leader of the Power Systems Engineering and Integration Group. He was also responsible as an Engineer in Charge of the JET operation and the Session Leader for the commissioning after major shut-down periods. In 1999, he moved to the European Fusion Development Agreement–Central Support Unit, Garching, Germany, to become the Project Leader for the Heating and Systems Technology, with the responsibility for the European developments in preparation of the construction of ITER. In 2008, he moved to Fusion for Energy, Barcelona, Spain, where he holds the position of Project Manager for the Neutral Beam and Electron Cyclotron Power Supplies and Sources Team, responsible for the European procurements and related developments.