EU development of the ITER Neutral beam injector and test facilities

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Abstract. The activities towards the establishment of the NB Test Facility (NBTF) in Padua-Italy and those related to the procurement of the heating neutral beams for ITER have recently reached a good level of progress thanks to the finalization of the agreements on the NBTF between F4E (the EU Domestic Agency for ITER), Consorzio RFX (the host of the NB test facility) and the ITER organization. This paper presents the status of the design of the various components within the EU scope of procurement, with a focus on the modifications implemented in the last years as a result of intense R&D activity undertaken in EU.

1. Introduction

The ITER NB test facility, given the acronym PRIMA-MITICA-SPIDER, is intended to capture the benefits of the experiments on full scale prototypes for ITER primary heating and current drive beams (HNB) and diagnostic neutral beam (DNB).

PRIMA (Padua Research on Injectors with Megavolt Acceleration) will consist of two subsidiary test facilities at Consorzio RFX in Padua-Italy: the test bed for Megavolt ITER Injector Concept and Advancement (MITICA), which differs from the actual injector only in the diagnostic capability and the connection to the ITER torus by the “Front end components”, and an ion source test bed for the Source for Production of Ions of Deuterium Extracted from an RF plasma (SPIDER), which has to be capable of testing a full size ITER ion source at full parameters.

These facilities, along with the separate EU test stand, ELISE (Extraction from a Large Ion Source Experiment) at IPP Garching, will provide a development path along which first the ion source, then the extraction of ions to form a beam, and finally the acceleration and the balance of the beam system, can proceed in such a way that the results and experience gained from each development stage can facilitate the operation of the next. Having such a set of facilities for the development of neutral beams allows the inherent technological and physics risks of Neutral Beam injectors to be mitigated.

2. R&D activities

Among the various R&D activities carried out in EU there are the establishment of the half size ITER ion source, ELISE, in the IPP laboratories in Garching-Germany and several important demonstration activities including prototyping, which are carried out with Consorzio RFX in the framework of the NBTF agreement.
2.1. ELISE

The aim of the ELISE experiment [1] is to operate at the required ITER parameters (accelerated 30 mA/cm² H⁻ and 20 mA/cm² D⁻ at electron/ion ratios of 0.5 (H) and 1.0 (D), respectively) up to an energy of 60keV by using a multiple driver radio frequency (RF) ion source. The extraction of the beam will be pulsed with a duty cycle of 10/180s due to limitations of the HV power supply, but the plasma in the source will be run in steady state. ELISE is equipped with an ion source and extraction system of the same width, but only half the height of the ITER source (1x1 m² source area with an extraction area of 0.1 m²).

The start of the experimental phase of ELISE, initially foreseen at the end of 2011, has been delayed and presently the commissioning with first plasma and a low power beam pulse is expected to be completed by the end of 2012. The experimental program of ELISE has been defined in detail and will be monitored by an EU program committee, whose function will be reviewing the experimental results and providing feedback in support the IPP team in the effort towards the optimization of the performance. Experiments on ELISE will be extremely important for the start-up of SPIDER, identifying the solutions that will be adopted to achieve the HNB ion source target parameters.

2.2. Prototyping and testing of NBTF components

An intense activity has been carried out by the Consorzio RFX laboratories aimed at validating new technologies on mock-ups and prototypes, in particular related to the following aspects:

- Heterogeneous joint between copper and stainless steel in alternative to the friction and the e-beam welding techniques
- The creation of a relatively thick Mo coating of non-uniform copper surfaces
- The optimization of the electrical insulation of ultra high voltage in vacuum

The joint between stainless steel pipes and water cooled copper elements has been developed by manufacturing screw threads on a pipe and threading the corresponding holes on the copper plate side. The SS tubes are screwed into the plate and then copper is electro-deposited over the tube and over the plate edge on the junction region, obtaining a sealed joint. A set of samples with different dimensions have been leak tested in vacuum with helium and the result of the test was that no leaks were detected in any of them. This technique was found to be reliable, much simpler and cheaper of the e-beam welding and it is being applied for the SPIDER accelerator grids and for the prototypes of parts of the NB high heat flux components.

In order to cope with the expected amount of back streaming positive ions in the 1MV beam source, which result in sputtered copper, a technology for the deposition of a thick Mo layer for covering the back plate of the ion source has been studied. The most promising results have been obtained by using explosion bonding of 1mm Mo sheet and using special solutions for the rim of the drivers’ apertures. The manufactured prototypes have been subjected to thermal shocks and have been thermal fatigue tested under heat loads and power densities comparable with the ones under operating conditions in the MITICA and NBI sources. Neither delamination nor flaking was found on the tested specimens, confirming the very good bonding of the molybdenum to the copper substrate.

After the encouraging results obtained with the 300kV test stand [2], a new set up has been installed at the High Voltage Padua Test Facility [3]. The upgrade consists of a larger vacuum chamber and two 400 kV 1mA power supplies enabling to reach a voltage of 800kV between the electrodes. The new setup required also an upgrade of the control system and modification of the biological shield to cope with the new vessel and higher energy of the produced X-rays.
The facility has been commissioned by testing the sphere-plane configuration together with a single power supply. The first experimental results reveal a large emission of ionized material from the electrodes surface during the conditioning phase. Further activities will be carried out during the next campaign in order to address both the physical open issues, concerning the breakdown in the case of the large vacuum gaps, and the design issues related to the MITICA electrostatic accelerator in the presence of a magnetic field.

3. The neutral beam test facility
The NB test facility will be established in Padua-Italy on the site of Consorzio RFX, and operated in co-operation between IO, EU and the Host, with contributions from the other ITER Parties, Japan and India. The construction of the buildings, whose contract comprises all the conventional auxiliary systems, has just started and it is foreseen that they will be completed by the beginning of 2014. It will be possible to start the installation of the main infrastructures for the experiments well before the completion of the civil works.

3.1. SPIDER
The SPIDER experiment [4] will test the full size ion source of the NB up to 100keV, which is the energy rating of the Diagnostics NB in ITER. The power supplies of the acceleration grid and the calorimeter are under in the Indian Domestic Agency scope, whereas all the other SPIDER components will be procured by EU. The supply contracts of all the main components and plants have been started and the first on-site activities are now planned to begin in the second half of 2013. The specification for the I&C system, described in detail in the following section, have been also completed together with that of the diagnostics system and their supply contract will be placed very soon.

3.2. The SPIDER control system
The development of the NB control system is currently progressing with the definition and design of the SPIDER experiment control system [5, 6], which chronologically is the first one needed in order of time and address some topics that are relevant for the HNB. The control system that is developed for SPIDER will then be duplicated and extended to suit MITICA and later the HNB.

Main functions of the control system are to provide control and data acquisition function (CODAS), machine protection (Interlock) and personnel protection (Safety). Those three functions have been divided in three independent tiers as represented in fig.1. For SPIDER CODAS the analysis of the requirements has identified that they cannot be satisfied by one single tool, but a mix of tools and techniques is necessary.

The plant units (PU) to be controlled range from industrial system, continuously running with standard PLC and time constants >1s, to diagnostic systems with custom electronics and time constants <1µs. The pulse duration requires having the acquired data available for visualization and analysis during the pulse, without influencing the stream of data that need to be stored. To guarantee this, more than 10 different modes of operation have been identified (e.g. different maintenance modes and beam source conditioning modes).

SPIDER CODAS architecture is organised with the use of Plant Systems, constituting an
intermediate level where the PU are grouped and coordinated and then linked with the central CODAS, which provides higher level coordination and support services for data storage and retrieval. Different network will be used to deal with real time transmission of time and events, data acquisition, plant control and data analysis. SPIDER CODAS software architecture will integrate three open-source software frameworks (EPICS, MDSplus and MARTe) each addressing specific system requirements.

A prototype has been built including all the major software components of the central CODAS, two plant systems and a simplified PU. The short term data storage has demonstrated the feasibility of hosting all data in one short-term data storage server during data acquisition using MDSplus. The event driven data acquisition has been tested and the correct time reconstruction demonstrated in MDSplus.

The variable data exchange of EPICS with PU has been demonstrated not only with the standard PLC foreseen, but also with a Java application running on a Linux PC. This result shows how the same EPICS driver can be used for PLC-based and computer based plant unit I&C, much simplifying the interface development. Integration of MARTE to implement fast controllers is in progress.

3.3. The MITICA mechanical components

The design of the MITICA [7] components is well advanced and it is presented in detail in the following sections.

The Vacuum Vessel

The MITICA vessel (see fig.2) is an AISI 304L stainless steel vacuum vessel to host the internal components for the MITICA experiment. The complete assembly of the vessel is about 15m long, 5m tall and 6m large. It weighs approximately 120 tons and it is composed of two main parts, the Beam Source Vessel (BSV) and the Beam Line Vessel (BLV), which will be welded together on site. Both vessels have a rectangular shape and their design is the result of an optimisation of the thickness of the main plate and the height of the necessary reinforcement ribs, which have either a “U” or a “T” shape. The BSV is interfaced on the top with a dome-shaped adaptor flange and a bellow to the high voltage bushing (HVB) vessel and on the rear is closed with a large lid, which allows the installation and removal of the Beam Source (BS). Access to the other components is achieved by a top lid opened for almost all the BLV length. In addition to the large openings mentioned above, there are in total approximately 150 smaller flanges for the cooling water, gas lines and access for diagnostics. The bottom part of both the BSV and the BLV is composed of two inclined plates terminated with a sort of gutter in order to drain the water by gravity in case of a loss of coolant accident, as sketched in fig.3.

Assessments of the manufacturing processes of the vessel are being undertaken by F4E with the support of Consorzio RFX. The main challenges identified are
related to the deformation of the structure due to the large number of welds and to the relatively tight tolerances of the big flanges, in order to guarantee the necessary structural collaboration with the side walls and the lids and the vacuum tightness under high mechanical loads.

The beam source
After having completed the physics design of the beam source based on the MAMuG concept for the accelerator [8], the mechanical design has been brought to an advanced level, incorporating the design solution adopted for SPIDER and ELISE and the results of the R&D activity (see fig.4). The MITICA beam source will have to deliver a 40A H or D beam up to an energy of 1MeV. The source features overall dimensions of about 3x3x3m$^3$ with a mass of approximately 20 tons. On and off axis injection will be achieved by tilting the whole beam source on its horizontal axis by ±10 mrad. Therefore all the electrical connections and water lines have to be flexible.

The beam source for the HNB requires eventual maintenance by remote handling (RH) and this must also be incorporated in the design, making the connection design challenging.

With respect to the outline design carried out in the past years and mainly derived from that of the final design report of 2001 [9], reviewed in 2007, the main changes and introduced are the following:

- Revision of cooling circuit schemes and manifolds optimization of dimensions, routing, and calorimetric capabilities, as well as electrical bus-bars and connections routing
- New ion source and extractor support structure
- Modification of the support frames for backward displacement of the source, optimizing the electrostatic behaviour and lateral conductance
- Modification of the shapes of both frames and flanges according to the updated vessel geometry
- New design of the support on the BSV and of the horizontal adjustment and vertical tilting systems together with the actuating systems
- Complete review of shields and improvement of electrostatic and mechanical behavior
- Assessment of installation and maintenance procedures verifying the compatibility with RH equipment

The Neutraliser
The design of the Neutraliser has been optimized [10] dividing each of the five walls (forming the four channels) in three aligned panels of OFHC copper, with deep drilled cooling channels and rectangular sections inclined according to the beam aiming (see fig.5). The copper panels will be thermally controlled by means of embedded cooling circuits. Thermo-hydraulic, thermo-mechanical, structural, and gas flow analyses and verifications have been carried out considering several load combinations and satisfying the ITER design rules as for structural design criteria for in vessel components, ASME Boiler and Pressure Vessel Code, and special procedures for multiaxial creep-fatigue verifications [11] considering proper hardening parameters for modeling of CuCrZr and OFHC copper under cyclic loadings [12]. Stray
particles will be dumped on the copper Electron Dump and CuCrZr Leading Edges of the neutralizer panels. The two external dump panels are installed on a foldable stainless steel support frame to be rotated before/after lifting/lowering operations. This arrangement will guarantee a minimum clearance of 90mm between the Electron Dump and Cryopanels during lifting operation when the lateral panels are folded away. The Neutraliser and Electron Dump will be instrumented with thermocouples foreseen for component protection, thermal control, beam diagnostic, and calorimetry and with accelerometers as boiling detectors.

The ERID

The design philosophy of the Electrostatic Residual Ion Dump (ERID) is based on deflecting the residual ions emerging from the Neutraliser using electrostatic fields in four channels delimited by high heat flux elements (see fig.6). This provides specific constraints for the design of the panels in order to minimise the beam scraping and hence reducing beam transmission losses. The ERID panel design has been substantially modified with respect to the reference design and is now made up of 18 Beam Stopping Elements (BSEs) per panel, each with four deep drilled channels arranged in a double hairpin configuration to allow water feeding from one end only. The elements are held together via a clamping bar at one side of the panel, while the other side is free to expand in the vertical direction through guiding systems. The cooling layout has been revised to optimise the flow distribution through the system according to the thermal requirements of each high heat flux panel. The design was further modified to ensure adequate segregation of the pipelines at high voltage from the parts at ground potential. Particular emphasis was placed on optimising the overall design for assembly, disassembly, inspection and repair operations. A new concept for the interface to the dedicated power supply has been developed improving the compatibility with the HNB RH system.

The calorimeter

In MITICA the calorimeter (see fig.7) will be used to intercept the neutralised beam and for beam power reconstruction with a vertical resolution given by the 48 tubes forming each of the panels, whereas in the horizontal direction the information can only be obtained referring to the two halves of the Swirl Tube Elements (STEs). Although in MITICA it will always work in closed position intercepting the beam, all the features and mechanism to allow its opening will be included in order to test the component as it will have to operate in ITER. The optimization study that has been carried out defined the size and arrangement of the swirl tubes in order to cover the required height of the panels, resulting in 48 pairs of tubes on each gate with a sufficient overlap between front and back swirl tubes to minimize the chance of shine-through without either clashing or an excessive number of tubes. The current design incorporates a middle support of the swirl tubes providing more stiffness, whilst allowing
thermal expansion of heated faces. The final 20mm diameter of the CuCrZr tube with the insertion of two separate lengths of stainless steel tape has been obtained by parametric studies considering conflicting requirements for critical heat flux and pressure drops. The tubes are then welded to the SS manifold by e-beam with the interposition of nickel layer. On the end side of the gate no direct beam shine-through is possible, although a proportion of particles could be reflected by the tube surfaces and pass between them, hence a water cooled CuCrZr panel has been added to catch any reflected particles.

Bellows are introduced in the cooling water pipes to allow rotation of the gates. Moreover the manifolds are supported on the central part in order to allow the differential thermal expansion. On the supporting frames side, plain aluminium-bronze bearings are used to allow smooth relative movements in vacuum. The top bearings incorporate adjustability along two directions and free vertical expansion. The actuator mechanism key features comprises a motor, jack and bellows that can be removed and replaced from the outside of the vessel (with RH manipulator in the HNB); a simple method of disconnecting internal linkage for calorimeter removal; jack force feedback control via load cell to ensure that gates are loaded against stops with a suitable force.

The cryopump

The cryopump of the NB system [13, 14] consists of two 8 m long and 2.8 m high structures which are installed on the lateral walls of the beam line vessel. The pump comprises two cryogenic circuits; the first one is fed with He at 4.5 K at 0.4 MPa and cools the cryosorption panels; the second one, fed with He at 80 K and 1.8 MPa, cools the thermal radiation shields which surround the cryosorption panels and the 4 K manifolds. Different technologies for the manufacturing of the cryopanels have been explored and manufacturing processes based on laser welding or on the co-extrusion of aluminum and stainless steel are being considered.

Detailed thermal analyses of various components of the cryopump showed that the thermal conductivity of the cryopanels to which the charcoal sorbent is attached needs to be enhanced. It is currently envisioned to do this by applying an electrodeposited copper layer onto the cryopanels; other solutions which are investigated include making the fins of the cryo panels from extruded aluminum. In addition, a finite element analysis of the dynamic behavior of the pump to help with the assessment of the design margins against the very high seismic loads was performed. A subsequent static structural analysis of the pump was carried out for all operational scenarios, from pumping with 4 K / 80 K up to the high temperature regeneration at 470 K and confirmed the suitability of the present design.

3.4. The power supplies

The Ion Source and Extraction Power Supplies (ISEPS) system forms part of Europe’s contribution of the NB Power Supplies (PS). The equipment type and performance parameters of the ISEPS have evolved significantly since the 2001 baseline design because of the change to a RF driven ion source and the introduction of an air-insulated High Voltage (HV) Deck hosting the ISEPS [15]. Following the start of procurement contract in June 2010, the ISEPS final design has now been completed. A nearly identical design of ISEPS is foreseen for SPIDER, MITICA and the ITER injectors.
Europe is also procuring two non-standard HV components for the MITICA and ITER injectors: the -1MV dc air-insulated HV Deck hosting the ISEPS and associated diagnostics, so-called HVD1, and an air to gas -1MV dc bushing connecting the HVD1 with the SF6-insulated Transmission Line, accommodating internally all ISEPS power and control cables. The current design foresees a single bushing, placed underneath the HV deck, SF6 insulated for 0.6MPa at 20°C, similarly to the Transmission Lines.

Additionally, Europe is in charge of procuring the low voltage part of the AGPS system, consisting of an input stage to adapt and rectify the ac grid distribution voltage and produce a dc-link voltage, and of the inverters feeding the step-up transformers of the five dc/ac/dc conversion groups. The latest developments in the design of the AGPS system are presented in [16]. Finally, the procurement of the Ground Related Power Supply, including the ERID power supply, RIDPS (30kV, 60A one quadrant conversion system) and the Correction Coils Power Supply, CCPS, feeding the Residual Magnetic Field Coil in MITICA or the Active Control Correction Coil in ITER (3 x 200V, 880A, 3 x 100V, 880A, 6-pulses rectifiers).

4. Conclusion

Good progress has been made on the roadmap towards the achievement of the NB system of ITER, thanks to the notable effort devoted in EU on R&D and design activities. The start of the contracts for the establishment of SPIDER is an important accomplished milestone and another one is the readiness of ELISE, which will be the first experiment entering in operation in 2012 and will give important indications on the behavior of the HNB negative ion source. The experiments of ELISE will then be replicated on the full size source at SPIDER, whose commissioning is expected in early 2015. About the design of the NB full scale prototype, MITICA, many solutions have been addressed to the issues so far identified and it is expected to complete the design in 2013, whereas the starting of experiment is foreseen at the beginning of 2018.

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5. References

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