140 ID NUMBER

Detailed design of the RF Source for the 1 MV Neutral Beam Test Facility

D.Marcuzzi, M.Dalla Palma, M.Pavei, B. Heinemann*, W. Kraus*, R. Riedl*

Consorzio RFX, Euratom-ENEA Association, Corso Stati Uniti 4, I35127 Padova, Italy

* Max-Planck-Institut für Plasmaphysik, Euratom Association, Botzmannstr. 2, D-85748 Garching, Germany

Abstract

In the framework of the EU activities for the development of the Neutral Beam Injector for ITER, the detailed design of the Radio Frequency (RF) driven negative ion source to be installed in the 1 MV ITER Neutral Beam Test Facility (NBTF) has been carried out. Results coming from ongoing R&D on IPP test beds [1] and the design of the new ELISE facility [2] brought several modifications to the solution based on the previous design.

An assessment was carried out regarding the Back-Streaming positive Ions (BSI+) that impinge on the back plates of the ion source and cause high and localized heat loads. This led to the redesign of most heated components to increase cooling, and to different choices for the plasma facing materials to reduce the effects of sputtering.

The design of the electric circuit, gas supply and the other auxiliary systems has been optimized. Integration with other components of the beam source has been revised, with regards to the interfaces with the supporting structure, the plasma grid and the flexible connections.

In the paper the design will be presented in detail, as well as the results of the analyses performed for the thermo-mechanical verification of the components.

Keywords : ITER, NBI, Ion source, Radio Frequency

1. Introduction

The ion source for the ITER NBI is requested [3] to supply a 40 A accelerated D^-/H^- beam with 20/28 mA/cm^2 current density at 1 MeV, 0.3 Pa source pressure, 3600 s pulse length, 1.5 x 0.6 m^2 cross section with a total aperture area on the plasma grid of 0.2 m^2.

In 2007 ITER has changed the baseline for the plasma source of the neutral beam injector, from the arc driven concept to the RF driven solution.

Meanwhile, the detail design of the RF source for the ITER NBI was developed in the frame of the TW6-THHN-NBD1 EFDA task, starting from the outline activity carried out within the previous contract and already reported in [4].

Several modifications were introduced, as consequence of feedbacks from IPP coming out from experimental campaigns on existing test beds and from the progress in the design of the new ELISE facility [2, 5].

Gas ionisation within the accelerator produces also positive ions that are accelerated back into the source and focused against rear vertical plates [6], with highly localized additional heat load that was taken into account for a robust design.

The RF source was integrated with the SINgle GAP (SINGAP) accelerator, in a new solution compatible with the Multi Aperture Multi Grid (MAMuG) accelerator [7], in line with the EFDA task overall aim, and all interfaces with adjacent components were defined. Moreover, the design was oriented for the injector test facility that will be hosted in Padova, prior to the ITER experimental phase in order to demonstrate target performances.

2. Design description

2.1 General description

The RF ion source is a complex chamber, featuring a main space, enclosed in a structure called source case and facing the plasma grid, on whose surface most of negative ions are generated, and eight rear smaller cylindrical chambers called drivers, where the gas is injected (hydrogen or deuterium), as shown in figure 1.

RF coils wound around the lateral wall of the drivers and connected to a 1 MHz RF generator transfer the RF power and ionize the gas: the resulting plasma flows then into the main chamber, where the additional presence of caesium enhances the number of negative ions generated on the surface of the plasma grid.

2.2 Drivers

The drivers are the components where the power is transferred and the plasma is generated.

The design of the new IPP facility (ELISE) introduced some modifications on the drivers [2]: size and inter-axis have been increased, in order to optimize source parameters, uniformity in particular, as shown in figure 2.

The drivers are powered (100 kW/driver) by pairs of RF coils (copper tube having 8 mm OD and 6 mm ID, 6½ turns) so a single tube 13.5 m long is wound around two alumina cylinders. The endpoints of each tube are electrically connected to the capacitors of the RF circuit whereas water flows from/to hollow lines that are electrically insulated with hollow ceramic breaks.

The Faraday Shield (FS) was modified in order to enhance the protection of the alumina case from plasma interaction. An additional inner vertical CuCrZr back plate was added to exhaust the power deposited from BSI+ with a cooling circuit independent from the lateral wall, without decreasing the internal volume, as shown in figure 3.

The updated configuration of the cooling circuit is described in sect.2.5.

The FS consists of a back plate 21 mm thick in CuCrZr alloy and electro-deposited copper. The FS cylindrical lateral wall is created around the FS plate by copper electro-deposition of a total 3.5 mm thickness. A thin Mo coating layer (by physical vapour deposition) is the reference solution chosen to be applied on all inner surfaces to reduce the sputtering effect caused by the plasma and the BSI+ [5].

An alternative solution for the FS back plate is considered, featuring a plasma facing 1mm thick Mo layer bonded to the copper bulk, in order to enhance the protection from the impinging high energy ions and to minimize the sputtering effect. Such solution requires R&D to be implemented, in fact concerns are related to the bonding stress between base plate and the thick coating as consequence of their different thermal expansion coefficient.

2.3 Source case

The source main case consists of a lateral wall and a vertical flange, also called Driver Plate (DP), that is made up of a CuCrZr plate on the inner side and a rear stainless steel plate. The former faces the plasma and is hit by BSI+ and the latter has mainly interface and structural purposes. The updated cooling circuit for the plasma driver plate is described in sect.2.5.

A thin Mo coating layer will also be applied on the inner surface of the source case to reduce the sputtering effect caused by the plasma [5]. Similarly to the FS, a thicker layer might be needed in order to enhance the protection from impinging BSI+.

2.4 Electric circuits

The power coming from the RF generator is transferred into the drivers by the RF coils to the injected gas that ionizes and generates the plasma.

Four identical electric circuits are designed: each horizontal pair of drivers is put in series with two capacitors (C_S1/2); other two capacitors (C_P1/2) are in parallel to the previous elements, as shown in figure 4.

The previous hypothesis of a single C_S variable capacitor and a single C_P fixed capacitor was modified in coherence with existing off-the-shelf components; this also helped to reduce the maximum voltage values with respect to the body of the source [8]. Moreover it was confirmed that in the NBTF (and in ITER) matching of the load impedance will be carried out by variation of the frequency of the RF generator [9]. Fixed capacitors have been chosen: a preliminary experimental phase shall be needed, featuring the substitution of at least a C_S capacitor with a variable one, in order to assess the required capacitance.

In order to limit electromagnetic interference, in particular on neighbouring diagnostic cables, the RF coaxial conductors running through the transmission line were prolonged as much as possible up to the connections with capacitors.

A dissipation of some tens of W along the conductors was estimated: the merge of the electric and hydraulic circuit was obtained having the water flowing through the RF coils and all tubular electrical connections, as described in sect.2.5.

2.5 Hydraulic circuits

All the main RF plasma source components are actively cooled owing to the high generated thermal loads. As far as the design of the hydraulic circuits is concerned, the

800 kW input RF power has been considered distributed on the source components as reported in Table 1.

Ultrapure water as coolant was selected because it gives excellent thermo-physical properties and high electrical resistivity at temperatures less than ~50 °C [10].

The main criteria adopted to develop the RF ion source cooling circuits are the limit in the water velocity (10 m/s in the cooling channels, 6.0 m/s in the manifolds) and limit in the maximum material temperature at the inner channel surface to avoid boiling conditions.

Three parallel cooling lines are designed for the source: source case, Faraday shields and electric lines. During initial conditioning, the source case and the FS initial temperature will be the inlet water temperature that is set to 40÷50 °C in order to satisfy requirements on high water resistivity and monolayer Cs distribution on inner surfaces without condensation at the walls [11].

In order to improve the efficiency of the cooling circuits in correspondence of the hot spots from impinging BSI+ on rear vertical plates, rectangular channels have been designed running on both sides of each vertical line of hot spots, in order to maximize the heat load removal, as shown in figure 5 for the source case Driver Plate.

The Faraday shields (FS) cooling line feeds four parallel circuits with two drivers in series, each one featuring the parallel cooling of driver back cover, FS lateral wall and FS back plate.

The source case line feeds in parallel the drivers plates and the lateral wall. Channels of the DP running on the sides of the hot spots had to be interrupted and merged in “half moon” intermediate manifolds around holes for drivers, as shown in figure 5.

Four pairs of RF coils are cooled in parallel: water enters the inner coaxial conductor on top of the source and flows through the tubular electrical connections and the two RF coils in series. Ceramic breaks (indicated as CBx in the scheme in figure 4) have been inserted to prevent short circuits. Water temperature at inlet is 15 °C in order to limit the copper resistivity and Joule heating [10].

2.6 Beam source assembly and integration in the injector

In the TW6-THHN-NBD1 EFDA task, it was defined to develop a SINGAP accelerator solution which allows compatibility with MAMuG design, as described in [7].

Therefore MAMuG structure was adopted as a reference and the integration of the RF ion source had to be revised, as grids support frames in MAMuG have a nested configuration and limit the available space on the rear side.

The RF source is supported at two points on each vertical side of the rear stainless steel plate, with elements that are connected to the external structure of the SINGAP, MAMuG compatible, beam source. Alumina bushes insulate the ion source from the supporting structure. Figure 6 reports the updated integration in the beam source and the flexible connections towards the bushing.

The required adaptation to the NBTF brought some different design choices from ITER configuration, like bolted flanges on hydraulic and gas circuits rather than welded connections, for maintenance ease.

3. Design analyses

3.1 Criteria

The RF ions source components are subjected to very high thermal loads that lead to classify them as high heat flux components. The most restrictive verifications of the RF ion source components are related to maximum material temperatures, interlayer stresses and cyclic type of damage. Coupled thermo-hydraulic and thermo-mechanical analyses have been carried out to verify the fulfilment of the criteria. The purpose of the thermo-mechanical analyses is to identify the regions of maximum stress and maximum strain ranges that are critical for the fatigue verification. These critical regions are localized in proximity of the maximum applied power densities, maximum temperature gradients, and stress concentrations for geometrical shape changes.

3.2 FE thermo-mechanical analyses of the Drivers Plate

Many 3D FE local models have been developed to simulate the thermo-mechanical behaviour of the DP. For each of them a first reference solution with a plate made of CuCrZr and an alternative solution made of a pure copper base-plate with a 1 mm thick Mo layer facing the plasma have been analyzed. Different positions of the impinging BSI+ beamlets have also been taken into account.

The huge thermal load is due to the BSI+ beamlets impinging the DP (418 kW) and the Faraday shields back plate (462 kW), with peak power density up to 60 MW/m^2 [6]. Figure 5 shows the DP and the main FE model of a significant portion of it under the BSI+ heat load. Due to the plasma interaction a further constant distributed heat load of 20kW/m^2 has been considered all over the DP. The DP is water cooled with 9.0 kg/s mass flow rate; the total power to be exhausted is 435 kW.

The mechanical verification of the alternative solution highlighted critical shear stress at the interface between the two materials. More accurate investigations should be done on the available joining techniques.

The reference design satisfies the fatigue verification: figure 7 shows the fatigue damage of FE model nodes placed around the BSI+ beamlet axis at different depths into the material resulting from analyses. It must be noted that few nodes in a very limited surface area with diameter 1.5 mm around the beamlet axis shows fatigue damages in the order of 100% during the entire ITER life time. On the other hand it has been estimated that the same material should be eroded by sputtering phenomena in a shorter time than the one corresponding to the fatigue life limit.

3.3 Faraday shields FE analyses

Two distinct FE models have been created to simulate the thermo-mechanical behaviour of the FS: a first 3D model for the lateral wall cooling circuit and a second 3D model of the back plate for the BSI+ dedicated cooling. The thermal load transferred to the FS (see Table 1) is applied on the inner surface as uniform power density. The power deposited by the BSI+ [6] is added onto the back plate surface. Each series of FS is water cooled with 2.6 kg/s mass flow rate.

At steady-state beam-on, the maximum lateral wall temperature (95 °C) is well below the maximum allowable value for the material (300 °C) and the maximum Von Mises stress is 65 MPa as shown in figure 6. The thermal cycles for FS lateral wall are due to source plasma-on/plasma-off that are assumed in number equal to beam-on/beam-off cycles ($5.0 \cdot 10^4$). The nodes with maximum fatigue damage are localized at the plasma exit region of the FS lateral wall where a stress concentration occurs due to the thin strips width; even so the fatigue damage results negligible and the fatigue verification is satisfied.

For the back plate similar analyses to those presented in sect.3.2 for the DP were carried out: the reference design in CuCrZr shows very limited fatigue damage, while the alternative design with a thick Mo layer presents similar high shear stresses at the interface as for the DP.

4. Conclusions

The detail design of the RF ion source has been defined.

The integration of the RF ion source and the compatibility of the SINGAP accelerator into the MAMUG accelerator have been designed together with the connections with the HV bushing.

A thorough verification of actively cooled components was carried out: fatigue life was positively assessed, in particular for vertical rear plates where impinging BSI+ cause localized high power density heat loads.

Input from IPP allowed to take into account all relevant feedback from existing experimental campaigns and to maximize the synergy between NBTF and ELISE projects.

Acknowledgements

This work, supported by the European Communities under the contracts of Association between EURATOM and ENEA, and between EURATOM and IPP, was carried out within the framework of the European Fusion Development Agreement (EFDA task TW4-THHN-IITF2). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The authors would like to highlight the work carried out by the study Design&Consulting that contributed in a fundamental way to the design.

References

[1] A. Stäbler et al., Development of a RF-driven ion source for the ITER NBI system, this conference

[2] B. Heinemann et al., Design of the half-size ITER Neutral Beam Source Test Facility ELISE, this conference

[3] ITER Neutral Beam Heating & Current Drive System, Design Description Document (DDD 5.3) N53 DDD 29 01-07-03 R 0.1

[4] D. Marcuzzi et al., Design of the RF ion source for the ITER NBI, Fusion-Engineering-and-Design, Volume 82, Issues 5-14, October 2007, Pages 798-805

[5] W. Kraus et al, Development of RF driven H-/D- sources for ITER, Proceedings of the 35th EPS Conference, June 2008

[6] G. Fubiani, H. P. L. de Esch, A. Simonin, R. S. Hemsworth, Modeling of secondary emission processes in the negative ion based electrostatic accelerator of the International Thermonuclear Experimental Reactor, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 11, 014202 (2008)

[7] L.Grando, S. Dal Bello, A. De Lorenzi, N. Pilan, A. Rizzolo, P. Zaccaria, Preliminary electrostatic and mechanical design of a SINGAP-MAMuG compatible accelerator, this conference

[8] M. Recchia, A. Zamengo, W. Kraus, M. Bigi, C. Martens, V. Toigo, Electrical and thermal analyses for the radio-frequency circuit of ITER NBI ion source, this conference

[9] Gaio et al, Fusion Engineering and Design 82 (2007) 912-919

[10] M. Dalla Palma, S. Dal Bello, F. Fellin, P. Zaccaria, Design of a cooling system for the ITER Ions Source and Neutral Beam Test Facilities, this conference

[11] E. Speth et al, Overviews of the RF source development programme at IPP Garching, Nucl. Fusion 46 (2006) S220-S238

List of figures / tables