Thermo-mechanical design of the ITER Neutral Beam Injector grids for Radio Frequency Ion Source and SINGAP Accelerator

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Abstract*— This paper focuses on the thermo-mechanical design of the ITER Neutral Beam Injector plasma, extraction and acceleration grids, considering the Radio Frequency option for the negative ion source and the SINGAP option for the accelerator. The SINGle Aperture - SINgle GAP (SINGAP) accelerator for ITER NBI foresees four grids for the extraction and acceleration of negative ions, instead of the seven grids of the Multi Aperture Multi Grid (MAMuG) reference configuration. The Radio Frequency ion source is a promising alternative to the Arc Driven one, showing very good performances in recent experiments at IPP Garching (D) and having the advantage of reduced maintenance requirements. A specific plasma grid was designed for RF source considering lower heat loads and different operational requirements. In particular the thermo-hydraulic and thermo-mechanical design aims at having all over the plasma grid a precisely controlled temperature to enhance the negative ions yield inside the caesium seeded source. Analytical and numerical (FE) thermo-mechanical analyses were also carried out for the extraction and acceleration grids. Structural verifications were accomplished according to the ITER Structural Design Criteria for In-Vessel Components. Design optimizations were performed in order to limit the misalignment of the grids within the tolerance specified by beam optics requirements (0.4 mm of maximum misalignment between corresponding apertures axes). The optimum cooling parameters under different operational scenarios were identified. The paper describes the design status of the grid system for the RF ion source and discusses in detail the numerical work carried out for thermo-mechanical and fluid dynamic behaviour.

Keywords-design; neutral; beam; injector; grids; SINGAP

I. INTRODUCTION

The Radio Frequency (RF) Ion Source, shown in the sketch of Fig. 1, is made up of a main case that acts as an expansion region for the plasma generated in the drivers, which are feed by RF coils. The negative ions created next to the Plasma Grid (PG) are extracted and then accelerated by electrical fields applied by means of copper grids at different voltages.

A SINGle Aperture - SINgle GAP (SINGAP) accelerator composed of two acceleration grids with 960 kV differential voltage is presently under study as an alternative design with respect to the Multi Aperture Multi Grid (MAMuG) reference configuration that foresees five acceleration grids with 200 kV differential voltage applied at each step.

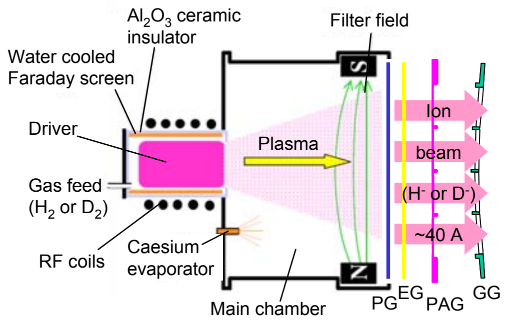

Figure 1. Beam source sketch with RF source and SINGAP accelerator

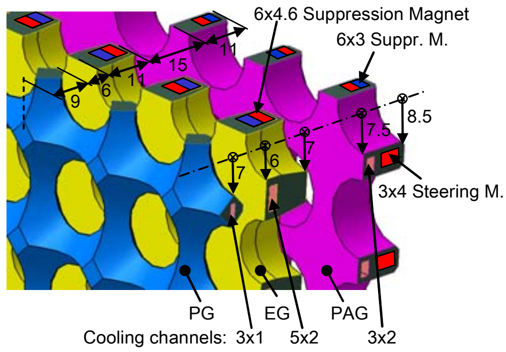

Figure 2. PG, EG and PAG detail (dimension in mm)

The grids of RF source and SINGAP accelerator are: the Plasma Grid (PG), the Extraction Grid (EG), the Pre-Acceleration Grid (PAG) and the Grounded Grid (GG) [2]. Several analyses have been carried out to assess the reliability of the design of these grids, and to optimize the design parameters in order to fulfil the ITER requirements.

II. DESIGN DESCRIPTION

The overall dimensions of the grids are about 800x1600 mm^2. The first three grids (PG, EG and PAG) feature 1280 apertures, where the ion beamlets are extracted from the ion source and pre-accelerated up to 40 kV (Fig. 2). The last grid (GG) features 16 large apertures, where the beamlets are merged and accelerated up to potential of 1 MV (Fig. 3). The total ion current is 40 A, the total power of the ion beam is 40 MW [3,4].

All the grids are made by electrodeposition of pure copper onto a copper base plate. This technique permits to obtain a very complex geometric shape (with very small cooling channels that run inside the grid and embedded magnets) and to have good mechanical properties, due to the high purity and to the very small grain size. Four independent water cooling systems, shown in Figs. 3 and 4, are foreseen in order to control the temperature (and consequently stress and deformations) of the four grids.

The plasma grid is heated by the plasma inside the RF ion source, with a surface power density that is estimated to range between 3 and 20 kW/m^2 (IPP experimental results). This grid is required to operate at a temperature of about 150° C in order to enhance the caesium effect for negative ions surface generation. Hence its cooling system is designed to obtain a precise control of the temperature, with a good uniformity on the whole surface. For the same reason, this grid is Molybdenum coated on the plasma side. The apertures are designed with conical chamfers on the upstream and downstream sides of the grid. A larger surface for ion production is obtained with this solution, and its efficacy has been demonstrated by experimental results on the Batman ion source at IPP Garching [5]. A 4 kA current flows in the vertical direction, to provide a horizontal magnetic field that reduces electron temperature and the number of co-extracted electrons. Flexible electric connections are foreseen between the four horizontal segments of the PG. They feature a number of flexible lamellae in order to allow vertical and horizontal relative displacements between the segments (Fig. 5).

The number of co-extracted electrons could be very different during the various phases of the operations (conditioning, partial power, full power etc.), mainly because the electron-to-ion ratio is expected to be a function of caesium deposition on the PG, which depends on PG temperature and operating conditions [5]. Hence, the EG and PAG are designed in order to satisfy the thermal, structural and alignment requirements in different scenarios with the total power ranging from zero to the double of the nominal power (which is calculated with electron-to-ion ratio equal to the unit).

The extraction grid has an electric potential that is 9.6 kV higher than the PG, so that the negative charged ions (H- or D-) can be properly extracted from the RF expansion chamber. Suppression magnets, embedded in the grid, have the function to deviate the trajectories of the co-extracted electrons, making them collide with the grid surface. The consequent power loads are quite high (464 kW over the whole grid in the nominal operating conditions), hence this grid is the most critical by the structural point of view, and is designed with a high performance cooling system.

The pre-acceleration grid has the function to accelerate the ion beamlets up to a potential of about 40 kV. Also on this grid there are embedded magnets (suppression and steering). The total power deposition foreseen on this grid in the nominal operating condition is 89 kW.

The GG assembly (Fig. 3) is positioned about 350 mm downstream the pre-acceleration grid. This grid is relatively thick (70 mm) with sixteen (4x4) large apertures, and "V-shaped" along the vertical direction to provide vertical beam groups steering [6].

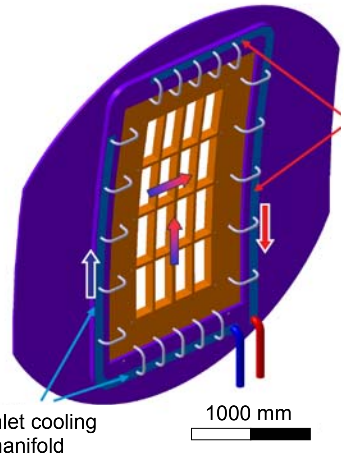

Figure 3. GG assembly view with cooling scheme

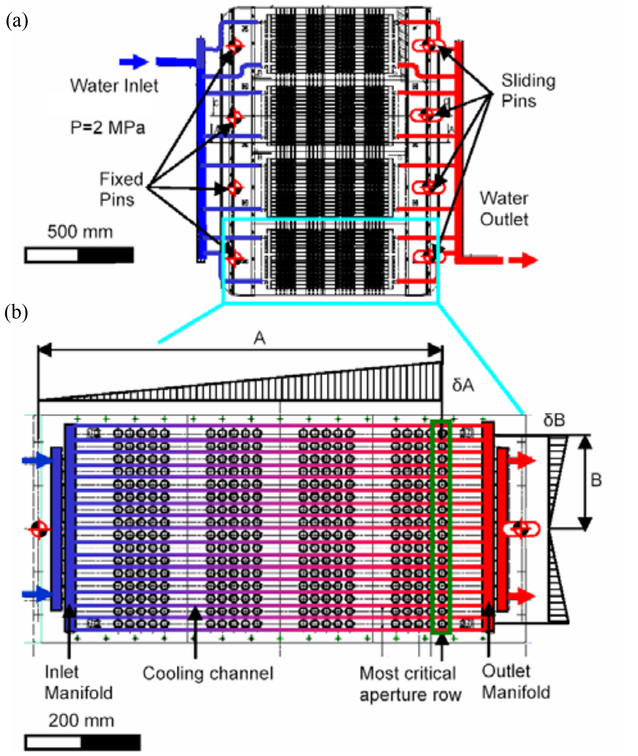

Figure 4. PG, EG and PAG cooling and positioning scheme: (a) Whole grid; (b) Segment

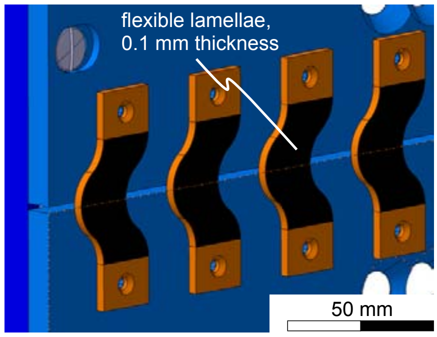

Figure 5. Typical flexible connection between PG segments

III. THERMAL OPTIMIZATION

The PG cooling system is designed with the goal to maintain the required temperature of 150°C±10°C on all the grid surface, with a power deposition density ranging from 3 to 20 kW/m^2. This requirement is fulfilled, as shown in Fig. 6, by setting the inlet water temperature at 150° and foreseeing a design with 17 cooling channels in parallel running horizontally between the apertures rows and along the whole grid width, as shown in Fig. 4.

The EG (see Fig. 6) and PAG have to withstand very high and localized peak power densities mainly due to the co-extracted electrons, that are colliding in small areas located around the apertures. A limit value of 300°C, suggested by IPP experience, is considered for the copper peak temperature. Nevertheless, experimental campaigns are foreseen aiming at investigating the mechanical properties of electrodeposited copper in function of temperature. In order to satisfy this requirement for every operating scenario (conditioning, partial power, full power etc.) the design features high water speed (up to 10 m/s) inside rectangular channels running close to the heated surface (at 1 mm distance from it).

The GG cooling system design, sketched in Fig. 3, foresees couples of channels along the frames of the apertures, both in horizontal and vertical direction. The optimum cooling parameters were identified by means of an analytical thermo-hydraulic model.

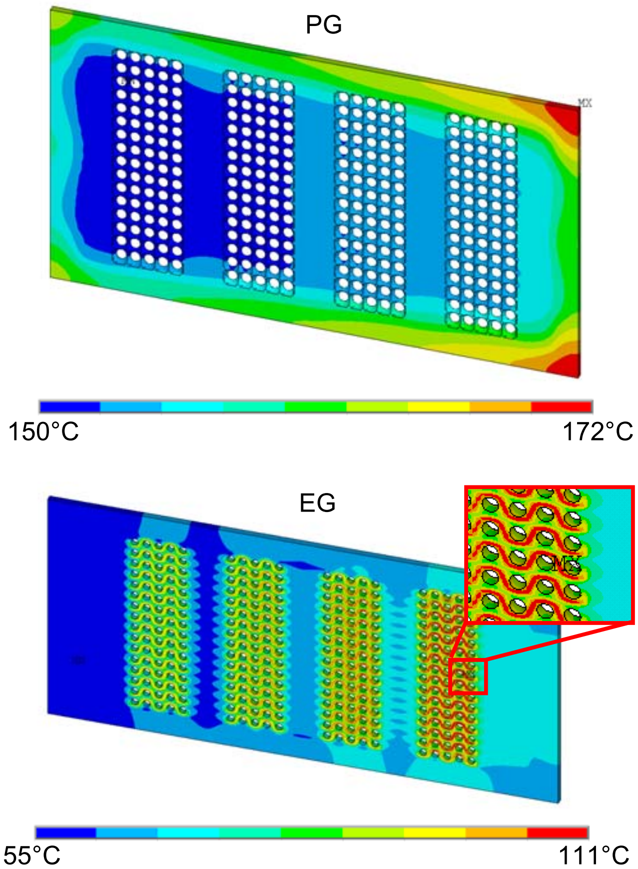

Figure 6. PG and EG temperature contour plots, under nominal power

IV. STRUCTURAL OPTIMIZATION

The grids have to withstand two categories of stresses (Fig. 7):

- Cyclic thermal stress due to the temperature gradients between hotter and colder zones. The grids must have the capability to withstand the required number of thermal cycles ($4{\cdot}10^4$ beam on/off cycles plus $4.5{\cdot}10^5$ breakdown cycles).
- Static stress due to the water pressure. The design of cooling channels and manifolds must be optimized in order to obtain the local values of equivalent stress lower than the allowable values for electrodeposited copper (fixed at 100 MPa).

All the grids were designed in order to satisfy the structural, ratcheting and fatigue verifications according to the ITER SDC-IC criteria, considering all the foreseen scenarios.

V. ALIGNMENT OPTIMIZATION

The first three grids must be designed in such a way that the corresponding apertures are well aligned, in order to obtain good beam optics. For this reason and for manufacturing requirements they are vertically split in four segments, independently supported with a fixed pin at the left side and with a sliding pin at the right side, as shown in Fig. 4.

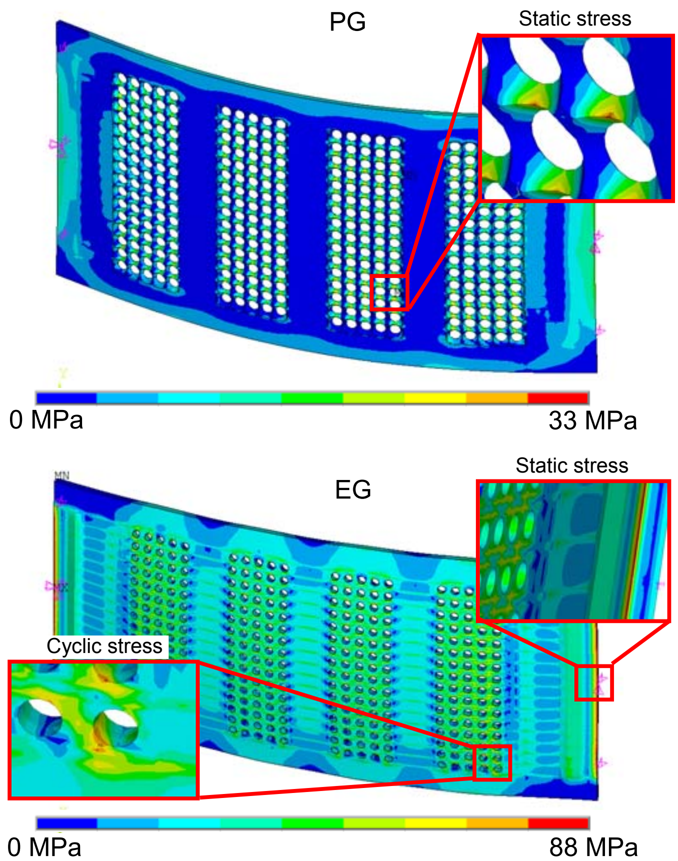

Figure 7. PG and EG equivalent (Von Mises) stress contour plots, under nominal power

The maximum allowable misalignment between the corresponding apertures of the three grids is fixed to 0.4 mm, for optic reasons. Since 0.2 mm can be considered as a reasonable manufacturing tolerance, the remaining 0.2 mm is set as a maximum value for the misalignment due to thermal expansion. Imposing this requirement under power loads ranging from zero to the double of nominal power (see Fig 8 for nominal power), the horizontal pre-offset of the PG apertures is identified ($\delta A'_{PG}$=1 mm), as well as the minimum water velocities along the channels (10 m/s for EG and 4 m/s for PAG) and corresponding pressure drops (see Fig. 9).

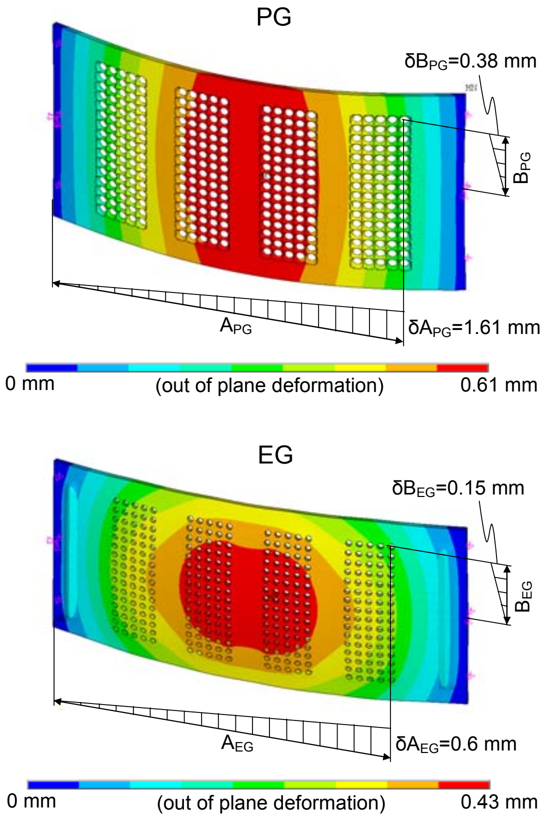

Figure 8. PG and EG deformations, under nominal power (reference temperature of 20°C is assumed)

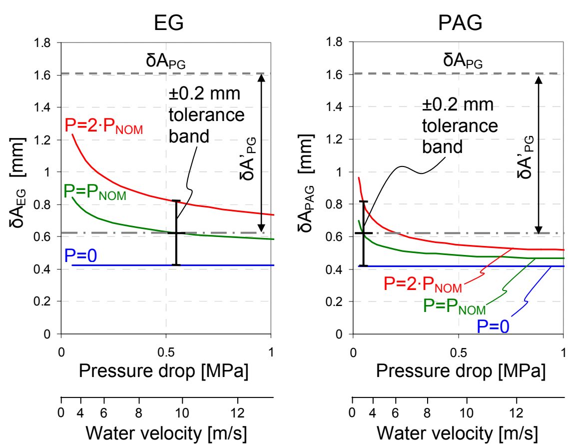

Figure 9. Identification of PG apertures pre-offset and of the minimum EG and PAG cooling parameters for alignment optimization

VI. Conclusions

The design adaptation of SINGAP grids to the RF ion source has been accomplished and optimum cooling parameters, reported in Table I, have been identified.

TABLE I. Optimum Cooling Parameters

	PG	EG	PAG	GG
Total power [kW]	4÷24	0÷928	0÷178	0÷180
Channels section [mm]	3x1	5x2	3x2	Ø=10
Inlet temperature [°C]	150	55	55	55
Inlet pressure [MPa]	2	2	2	2
Total water flow [kg/s]	0.8	8	2.8	3
Water velocity [m/s]	4.3	10	7	2
Pressure drop [MPa]	0.18	0.66	0.34	0.01

In particular, the PG design has been deeply revised to get a better temperature control and an improved efficiency in negative ions extraction. The design of the SINGAP grids for RF ion source have been assessed by the thermal, structural and alignment points of view in order to satisfy the ITER NBI requirements for all the foreseen scenarios.

Acknowledgments

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