Thermo-mechanical design of the SINGAP accelerator grids for ITER NB injectors

P. Agostinetti *, S. Dal Bello, M. Dalla Palma, P. Zaccaria

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

Received 31 July 2006; received in revised form 27 June 2007; accepted 27 June 2007
Available online 10 August 2007

Abstract

The SINGle Aperture–SINgle GAP (SINGAP) accelerator for ITER neutral beam injector 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 grids have to fulfil specific requirements coming from ion extraction, beam optics and thermo-mechanical issues.

This paper focuses on the thermo-hydraulic and thermo-mechanical design of the grids carried out by Consorzio RFX for the design of the first ITER NB injector and the ITER NB Test Facility. The cooling circuit design (position and shape of the channels) and the cooling parameters (water coolant temperatures, pressure and velocity) were optimized with sensitivity analyses in order to satisfy the grid functional requirements (temperatures, stresses, in plane and out of plane deformations). The design required a complete modelling of the grids and their support frames by means of 3D FE and CAD models.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Injector; Negative ions; Accelerator; Grids; Design

1. Introduction

The four grids of the SINGAP beam source, shown in the sketch of Fig. 1, are: the plasma grid (PG), the extraction grid (EG), the pre-acceleration grid (PAG) and the grounded grid (GG) [1,2].

The design of the grids have to be a compromise optimization in order to fulfil in the meantime conflicting requirements coming from physics and engineering issues. For this reason several thermo-hydraulic and thermo-mechanical analyses have been carried out and the main results are presented in the following sections.

2. Description of grids design

The overall dimensions of the grids are about 1.6 m × 0.9 m. The PG, EG and PAG, shown in Fig. 2, have 1280 small apertures (about 15 mm diameter) and are fixed to the ion source with suitable electrical insulators. Each of these grids is vertically subdivided in four parts (0.4 m × 0.9 m) named segments. The GG shown in Fig. 3 has 16 large apertures. It is made of...
Fig. 1. Conceptual sketch of SINGAP grids.

A single OFHC Cu piece, sustained by a support and adjusting frame connected to the beam source vessel. The grids are heated during the beam pulses by power deposition (from ions and electrons) and by radiation [3,4]. In order to control the temperatures, four separate cooling circuits for the four grids allow an independent adjustment of the water flow rates and temperatures. The coolant is demineralized water. The inlet temperature and pressure of water are presently fixed at 55 °C and 2 MPa in the ITER reference design [5].

The PG segments are made of 6 mm thick molybdenum plates that cover the opening of the ion source chamber (arc driven or radio frequency driven) and are exposed to the source plasma. Water cooling pipes are housed inside horizontal grooves machined on the surface facing the plasma. In order to keep the average temperature of the grid in the range of 250–300 °C, low conductance thermal bridges connect the pipes to the molybdenum plate.

EG and PAG segments are made of electrodeposited OFHC copper. Magnets are embedded in grooves between adjacent apertures, while the cooling channels are horizontally located between the magnets and the heated surface facing the plasma grid as shown in Fig. 2c. The critical issues for these grids are the conflicting requirements coming from beam optics (small thickness and relatively large magnets) and the need of relatively large cooling channels to exhaust the heating power.

The GG is 70 mm thick and “V-shaped” in the vertical cross section to provide vertical beam groups

Fig. 2. Plasma, extraction and pre-acceleration grids: (a) beam source overview; (b) grids detail; (c) grids vertical section; (d) grid cooling scheme; (e) segment cooling scheme, with aperture shifts.
steering. The cooling water flows both vertically and horizontally through couples of channels along the frames of the apertures. A stainless steel electrostatic shield is foreseen around the support frame in order to guarantee the voltage hold off in vacuum.

3. Design requirements

The thermo-hydraulic and thermo-mechanical design of the grids are driven by the following main requirements:

1. The average temperature of the PG must be kept in the range 250–300 °C (with a limited temperature non-uniformity) in order to enhance the caesium effect for surface production of negative ions.
2. The grids have to resist the heat loads applied during operations with suitable safety margins also considering fatigue effects.
3. The temperature of the copper grids should be kept under 300 °C, in order to avoid an excessive decrease of copper mechanical properties.
4. In order to obtain a good beam optic the maximum misalignments between the apertures of the different grids must be less than 0.4 mm and the maximum variation of gaps between grids (due to out of plane deformations) must be less than 0.4 mm.
5. The water velocity in the cooling channels should be limited in order to reduce the erosion–corrosion effects (a maximum value of about 10 m/s has been adopted for the design).
6. The pressure drop inside the cooling channels should be limited in order to keep a reasonable safety margin against water boiling and to reduce the amount of pumping power consumed by the cooling system (a maximum value of about 0.5 MPa has been fixed for the grids design).

The grids were designed with suitable safety factors in order to allow for uncertainties on power loads (total power and non-uniformities) and different operational conditions.

4. Design criteria and assumptions for the analyses

The Sieder–Tate correlation (valid for forced convection in single-phase flow) is used to calculate the heat transfer coefficient [6].

The pressure drops along the cooling channels are calculated with the Darcy–Weisbach formula, where the friction factor is evaluated with the Colebrook–White formula, assuming a value of 0.01 mm for absolute roughness in copper channels (conservative value) [7].

The structural design criteria for in-vessel components (SDC-IC) are utilized for the structural verifications [8]. The material properties (OFHC copper, AISI 316 LN stainless steel and molybdenum) are taken from [9,10]. Since no data is available about mechanical properties of electrodeposited OFHC Cu, the properties of fully annealed OFHC Cu have been adopted. Test campaigns are advisable for material qualification, in particular for fatigue life assessment.

5. Thermo-mechanical analyses

5.1. Temperature and stress optimization

The first three grids (PG, EG and PAG) were modelled using the ANSYS FEM code. Several meshes have been developed to study the overall and local effects due to the applied power loads; as an example Fig. 4 shows the PG local mesh.

The temperature requirement on PG ($T = 250$–$300$ °C) was fulfilled using different thermal bridges along the cooling pipes (see Fig. 5a). The thermal bridges near the apertures, subjected to a lower thermal power, were designed with a smaller diameter.
Fig. 4. A detail of the PG FEM model.

(and consequently smaller thermal conductance) than the thermal bridges far from the apertures, in the frame area. The optimal temperature distribution was obtained using a 4 m/s water velocity inside the cooling pipes and a ratio of two between the higher and lower conductance of thermal bridges.

Further sensitivity analyses were performed to investigate PG behaviour under different power loads (see Fig. 5b). If the power load varies in the range ±20% around the nominal value $P_{\text{nom}}$, it is possible to keep the average temperature within 250 and 300 °C adjusting the pressure drop, and consequently the water velocity, inside the cooling pipes. If the total power is outside this range it could be also necessary to control the water inlet temperature.

The maximum temperatures and Von Mises equivalent stresses in all the grids were analyzed with analytical and FEM calculations; as an example the contour plots on the most heated zone of the EG under nominal power and a cooling water velocity of 4 m/s are presented in Fig. 6. The cooling systems were dimensioned in order to satisfy all the SDC-IC verifications (static, ratcheting and fatigue) for all the foreseen scenarios.

5.2. Alignment optimization

A maximum allowable misalignment of ±0.4 mm between corresponding apertures of PG, EG and PAG during beam on condition was identified as a com-
promise between the beam optic requirements and reasonable engineering values: ±0.2 mm misalignment was estimated for manufacturing and positioning and the remaining ±0.2 mm was then fixed as the maximum apertures misalignment due to thermal expansions of the grids. The last requirement is very demanding from an engineering point of view and was the driving issue for a second step of optimization of the first three grids PG, EG and PAG.

In order to limit the apertures vertical displacements δB, the four horizontal segments are independently fixed as shown in Fig. 2d, e and flexible electrical connections are foreseen between PG segments. Each segment is fixed at the left side of the grids and horizontally sliding at the right side. Hence the apertures located at the right-end part of the grids are the most critical with regard to horizontal misalignment.

As the design resulting from the first optimization (temperature and stress) do not satisfy the requirements on alignment (see Fig. 7), two possible solutions were identified to solve this problem:

1. Working with copper grids at higher temperature (about 110 °C). This could be done keeping the same channel cross sections and reducing the cooling water velocity or increasing the water inlet temperature.

2. Introducing a mechanical offset $\delta A'_{PG}$ of the plasma grid apertures and improving the cooling efficiency. The apertures could be machined with a horizontal

| Table 1
| Optimized design parameters for the SINGAP grids |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Plasma grid | Extraction grid | Pre-Acceleration grid | Grounded grid |
| Total nominal power in beam on condition (kW) | 146 | 220 | 11 | 180 |
| Cooling channels section (mm) | $\varnothing = 1.8$ | $5 \times 2$ | $3 \times 1$ | $\varnothing = 10$ |
| Inlet temperature (°C) | 55 | 55 | 65 | 55 |
| Inlet pressure (MPa) | 2 | 2 | 2 | 2 |
| Total water flow (kg/s) | 0.7 | 3.3 | 0.4 | 3 |
| Channel water velocity (m/s) | 4 | 5 | 2 | 2 |
| Pressure drop (MPa) | 0.12 | 0.12 | 0.06 | 0.011 |
offset in such a way that the alignment is reached when the grids are operating at nominal conditions.

The first solution presents two major drawbacks:

- stresses of EG and PAG become higher. The static and fatigue verifications may be more critical;
- the out of plane deformations of the grids would become unacceptable.

The second solution allows to satisfy the maximum misalignment requirement keeping low temperatures, stresses and out of plane deformations. The main drawback is the fabrication of a PG that is only suitable for a specific range of power load and grid temperature.

The maximum displacements and misalignments of the apertures for different design solutions and operational conditions are summarized in Fig. 7. A maximum horizontal offset $\delta A'_{\text{PG}}$ of 0.4 mm was calculated for PG apertures in order to obtain a 0.2 mm maximum misalignment of EG apertures before the beam is switched on (PG at 275 °C and EG at 55 °C). When the beam is switched on the power load applied to EG will cause a further increase of apertures displacement to be limited within 0.4 mm. This becomes the driving criteria to define the cooling channel cross section and water velocity as reported in Fig. 8 and Table 1. The cooling of the EG as in the first optimized design (5 mm x 1 mm cross section and 4 m/s water velocity) should be sufficient to satisfy the alignment criteria under nominal power load $P_{\text{nom,EG}}$ (220 kW), but it has to be upgraded with an increased cross section (5 mm x 2 mm) and water velocity (5 m/s) to fulfill the criteria up to a power load of 440 kW. The nominal power load $P_{\text{nom,PAG}}$ applied to PAG is relatively low (11 kW) so adjustment of the water inlet temperature is necessary to satisfy the alignment criteria. A temperature of 65 °C has been calculated as an optimal value in order to achieve a zero misalignment under nominal power load. Active controls of water inlet temperatures and flow rates of EG and PAG are advisable, at least for Test Facility operations, to face up possible extended ranges of applied power loads.

6. Conclusions

An assessment and optimization of the grids design for SINGAP configuration have been accomplished. However for the final thermo-mechanical analyses and fatigue life assessment the mechanical properties of the electrodeposited OFHC Cu at different temperatures have to be measured with dedicated test campaigns.

The critical issue that drives the cooling channels design and the water flow rates identification is the maximum allowable misalignment between correspondent apertures. A pre-offset of PG apertures at room temperature is proposed and optimal cooling parameters are identified. A system to monitor the grids and water temperatures is necessary, at least in the Test Facility, for an active control of water inlet temperatures and water flow rates.

Acknowledgements

This work, supported by the European Communities under the contract of Association between EURATOM and ENEA, was carried out within the framework of the
European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The authors would like to acknowledge F. Degli Agostini and A. Tiso for their invaluable assistance in the development of the 3D CAD models.

References


