# Design of a low voltage, high current extraction system for the ITER Ion Source

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**Abstract.** A Test Facility is planned to be built in Padova to assemble and test the Neutral Beam Injector for ITER. In the same Test Facility the Ion Source will be tested in a dedicated facility planned to operate in parallel to the main 1 MV facility. Purpose of the full size Ion Source is to optimize the Ion Source performance by maximizing the extracted negative ion current density and its spatial uniformity and by minimizing the ratio of co-extracted electrons. In this contribution the design of the extractor and accelerator grids for a 100 kV, 60 A system is presented. The trajectories of the negative ions, calculated with the SLACCAD code [1], have been benchmarked by a new 2D code (BYPO [2]) which solves in a self consistent way the electric fields in presence of electric charge and magnetic fields. The energy flux intercepted by the grids is estimated by using the Montecarlo code EAMCC [3] and the grids designed according to the constraints set by the permanent magnets and by the cooling channels. The interaction of backstreaming ions due to the ionization process with the grids and the Ion Source backplate is investigated and its impact on the project and performance discussed.

**Keywords:** ITER, ion, source, extraction
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## INTRODUCTION

The ITER Neutral Beam Test Facility (NBTF) is planned to be built at Consorzio RFX (Padova, Italy) in the framework of an international collaboration, and has the purpose to test and operate the ITER Neutral Beam Injectors (NBIs) [4, 5, 6, 7]. A full size ion source is the first experimental device to be built and operated, aiming at testing the extraction of a negative ion beam (made of $H^-$ and in a later stage $D^-$ ions) from an ITER size ion source. The main requirements of this experiment are a current of 60 A $H^-$ (and later 40 A $D^-$) and an energy of 100 keV. A good beam uniformity and optics are required to match the operating scenarios foreseen for the ITER NBIs.

## DESIGN OVERVIEW

The extraction and accelerator system for the full size ion source, sketched in Fig. 1 is composed of three grids: the Plasma Grid (PG), the Extraction Grid (EG) and the

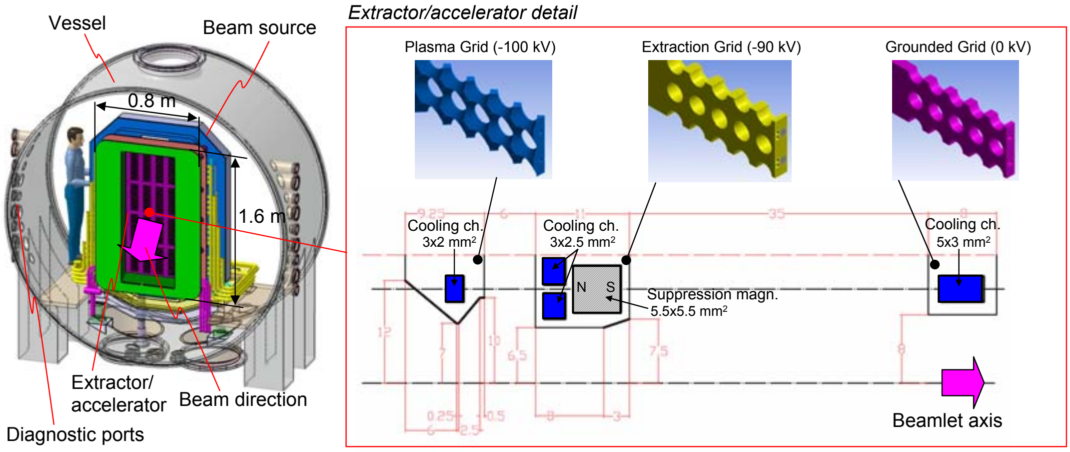


**FIGURE 1.** Design overview of the extractor/accelerator system

Grounded Grid (GG). Each grid features 1280 apertures, where the ion beamlets are extracted from the ion source and accelerated up to 100 kV.

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.

The plasma grid is heated by the plasma inside the RF ion source, with a surface power density that is estimated to be about 20 kW $m^{-2}$ (IPP experimental results [8]). 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. For the same reason, it 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 [9]. 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.

The extraction grid has an electric potential that is about 10 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 and concentrated, hence this grid is the most critical by the structural point of view, and is designed with a high performance cooling system.

The grounded grid has the function to accelerate the ion beamlets up to a potential of about 100 kV, and is also loaded by co-extracted and stripping electrons.

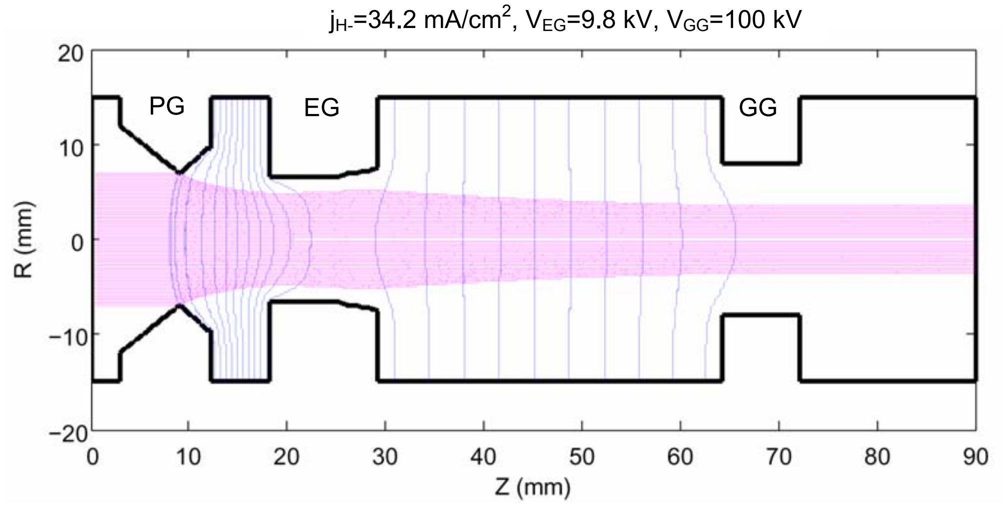


**FIGURE 2.** SLACCAD simulation of the beam optics: equipotential lines (blue) and particle trajectories (magenta) are estimated by integration of the Poisson's equation

## PHYSICS OPTIMIZATION

The SLACCAD code was used to estimate the electric field inside the accelerator by integration of the Poisson's equation, with cylindrical geometry conditions [10]. This is a modified version of the SLAC Electron Trajectory Program [11], adapted to include ions, a free plasma boundary and a stripping loss module [12]. The geometry shown in Fig. 1, obtained after several optimizations, permits to obtain at the same time good optics and low stripping losses. Fig. 2 shows the equipotential lines and the corresponding beam trajectories obtained with SLACCAD using the geometry of Fig. 1. Ref. [1] gives a detailed description of these analyses.

Alternative approaches, ranging from fluid models [13] to ray tracing [14] and interpolation, to simulate a richer physical description of the plasma sheath-beam interface (traditionally called meniscus in source physics) were summarized elsewhere [15]. Several length scales coexist, from the Debye length $\lambda_D$ to the size of the electrodes, for example the extraction diameter $2r_h$; this suggests to study the sheath formation in 2D models before generalizing to 3D models. Moreover, magnetic field effects on the space charge and on the selfconsistent electric field can be easily simulated in a planar geometry used in BYPO [15, 16]; here $z$ is the beam axis and $x$ is parallel to the long axes of the permanent magnet bars embedded into the EG: the model planar geometry is the $y = 0$ section of the extraction system. Magnetic field is assumed to be in the $\hat{y}$ direction at $y = 0$. Electron space charge is enhanced, since electron trajectories are lengthened, as apparent from the code BYPO, and computation time accordingly increases. Magnetic field is specified by suitable analytical approximations as

$$B_y + iB_z = \frac{i k_7 B_R}{\pi} \left[ \arctan \frac{\sinh(a_z \pi / L_y)}{\cosh((z - z_m + i(y-a))\pi / L_y)} \right]_{a=-a_y}^{a=a_y} \tag{1}$$

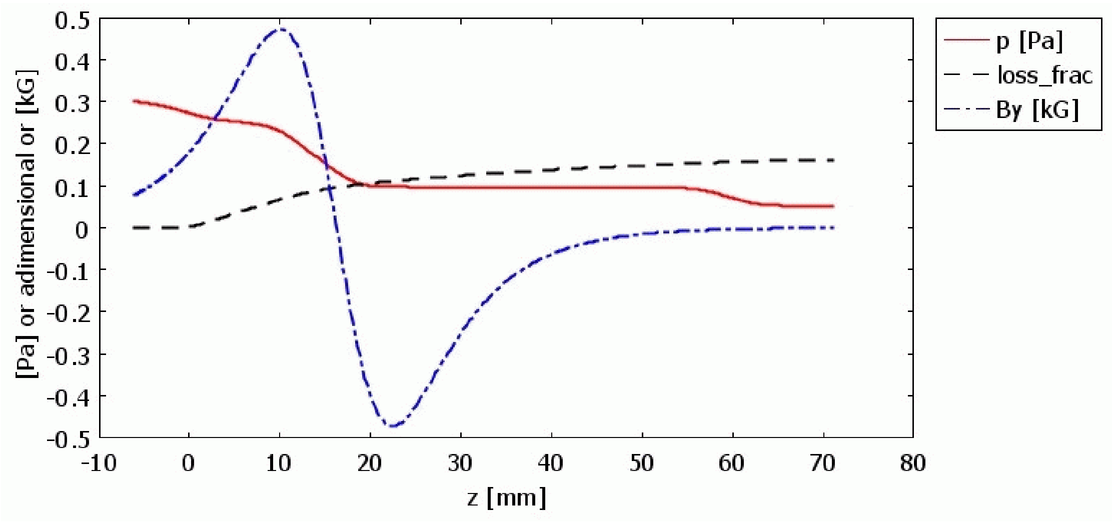


**FIGURE 3.** Profile of the gas pressure, of the stripping losses (loss_frac) and of the magnetic field vs $z$ computed with BYPO

where $B_R = 0.96$ T is the residual flux density, $z = z_m$ is the middle plane of the magnet bars, $2a_z$ and $2a_y$ are the sides of a bar $yz$ section, $L_y$ is the distance between centers of bars and $k_7 \leq 1$ is a fitting parameter. Equation 1 with $k_7 = 1$ holds exactly for the case of a infinite array of infinitely long bars, with magnetization axis alternating between $\hat{z}$ and $-\hat{z}$. Another major input to BYPO is the ratio $R_j = j_e/j_H^-$ between current densities of electrons and ions at plasma border. Without magnetic field, we expect a ratio $R_c \equiv \rho_H^-/\rho_e \cong (m_H^-/m_e)^{1/2}/R_j$ between the negative ion and the electron space charge. We set $R_j = 2$ in the examples, so $R_c \cong 21$ without magnetic field.

BYPO represents plasma temperature by using trajectories (rays) with different starting angles $\alpha_s$. It automatically refines ray spacing near the PG edges, to better resolve the ion beam envelope. It can be argued that plasma temperature is small compared to the rapid acceleration of the beam on axis, so that ion beam results approximately laminar; anyway beam acceleration is not uniform (near the extraction edges [15]), so justifying the computational effort of using several starting angles $\alpha_s$. We here assume starting angles $\alpha_s$ of -0.1, 0 and +0.1 rad for the emitted ions (with current proportional to weights 0.2 , 0.6, 0.2 respectively), which corresponds to a 'transverse' ion temperature of 0.3 eV. The effects of extraction edges (affecting the beam halo) and of the meniscus curvature (affecting the whole beam) are then modelled by BYPO, with an extreme precision in the ray tracing Runge-Kutta integration (minimum step is about 2 micron). For comparison, meniscus curvature adds an energy in the order of 2 eV to the transverse motion of ions, in typical cases as the following simulations.

Fig 3 shows the gas pressure approximately computed by an additional module recently introduced in BYPO (assuming circular openings for the gas, as in the real 3D model). Ion stripping losses are then computed as for SLACCAD. Figure 4a shows ion rays computed from BYPO, with the Fig. 1 geometry and $k_7 = 0.5$ (see the resulting $B_y$ in fig 3). Beam size is then similar to Fig. 2, even if some slightly different tuning of the voltages may be needed for an optimal beam. We also see that ion beam deviation

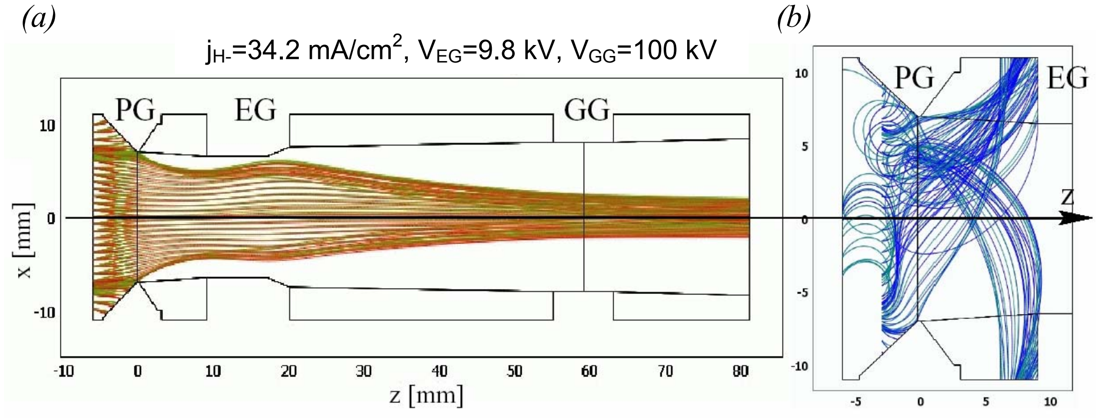


**FIGURE 4.** Beam simulations with BYPO: (a) Trajectories of $H^-$ with $\alpha_s = -0.1$ rad (red), $\alpha_s = 0$ rad (brown), $\alpha_s = 0.1$ rad (green); (b) Trajectories of coextracted electrons

is nearly critical at EG. Figure 4b shows coextracted electrons in the same simulation; note that these electrons are confined in the first gap. Periodic conditions at $x = \pm 11$ mm were used both for the selfconsistent potential $\phi$ and the electron trajectories; some electrons appear to return into the plasma. Electron load is confined (marginally) to the rear face of EG, that is good; moreover accumulation of electron space charge results tolerable in this simulation ($R_c = \rho_H^- / \rho_e \cong 10$). For the comparison with cylindrical electrode simulations, it should be taken into account that in the BYPO planar geometry the lens effects are twice as strong (for equal electrode angles).

## ESTIMATIONS OF THE HEAT LOADS ON THE GRIDS

The interactions between particles inside the accelerator, like secondary particle production processes, were analysed with the code EAMCC [3]. This is a 3-dimensional (3D) relativistic particle tracking code where macroparticle trajectories, in prescribed electrostatic and magnetostatic fields, are calculated inside the accelerator. In the code, each macroparticle represents an ensemble of rays considering the time-independent physical characteristics of the system.

This code needs as inputs the electric and magnetic fields inside the accelerator. The former was calculated with SLACCAD, as explained above. The latter was calculated by summing the field given by the SmCo permanent magnets (calculated with the semianalytical code PERMAG [17]) and the field from the plasma grid filter current (calculated by assuming an infinitely thin electron sheath).

Also a numerical approach, using the code ANSYS, was considered in order to cross-check the magnetic fields. The agreement between the two codes is quite good, provided that in ANSYS the mesh is sufficiently fine and the domain sufficiently large. So the ANSYS code can be considered as benchmarked against the PERMAG code regarding the magnetic field calculations inside the accelerator, as visible in Fig. 5. On the other hand, the PERMAG code has been benchmarked with success with many experimental measurements.

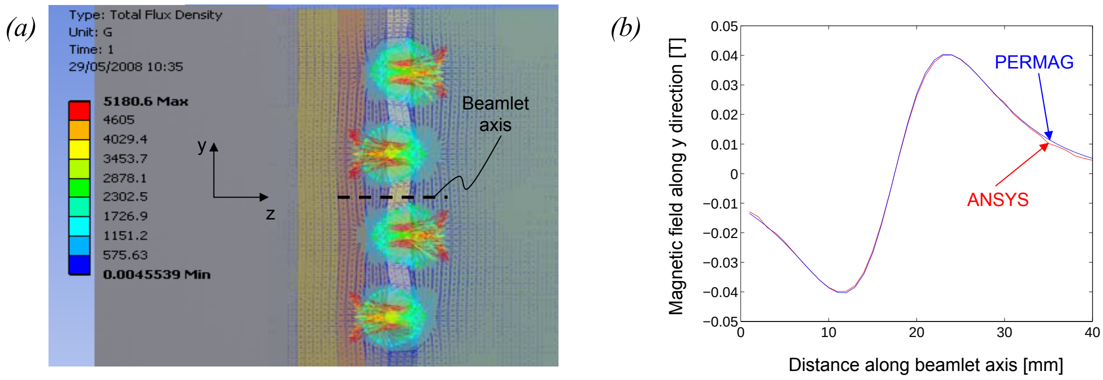


**FIGURE 5.** Estimations of the magnetic field inside the accelerator: (a) Vector plot (vertical section) of the magnetic field due to the suppression magnets inside the EG, calculated with ANSYS; the magnets are put in x direction (horizontal perpendicular to the beam axis) with polarities along z (beam axis direction) with alternated versus from row to row; (b) Comparison of the magnetic field $B_y$ along the beamlet axis, calculated with PERMAG (semi-analytical approach) and ANSYS (FEM approach).

Collisions are described using a Monte-Carlo method. The various kinds of collisions considered in the code are: (i) electron and heavy ion/neutral collisions with grids, (ii) negative ion single and double stripping reactions and (iii) ionization of background gas [3].

Fig. 6 shows the main results of the EAMCC calculations. Two different simulations are performed to simulate the $H^-$ ions (and related species generated by stripping) and the co-extracted electrons. The current density is assumed to be the same (34.2 mA $cm^{-2}$) in the two cases, considering an electron-to-ion ratio of 1. The heat loads on the grid surfaces are evaluated by summing the two contributions. While the EG is heated mostly by the co-extracted electrons, the heat on the GG is approximately half coming from the co-extracted electrons, and half from the secondary electrons due to stripping and surface reactions.

The transmitted beamlet power distribution features a ring that is hotter than the central part. These could be due to the chamfered shape of the PG apertures. In fact, this effect is reversed in case of a flat PG surface.

The backstreaming positive ions are quite concentrated in the center of the aperture area. The consequent heat power density is quite high, but covers only an area of some tens of square millimeters. These ions could give rise to sputtering phenomena on the plasma source back plate and on the driver Faraday shields, with a consequent decay of the plasma purity and problems of surface integrity. The sputtering yield due to the backstreaming deuterium ions is generally reduced by a factor of about 5 if the copper surface is coated with Molybdenum [18]. Hence, in order to minimize the detrimental effects consequent to sputtering, a layer of Molybdenum of some microns is foreseen to be applied on the plasma source back plate.

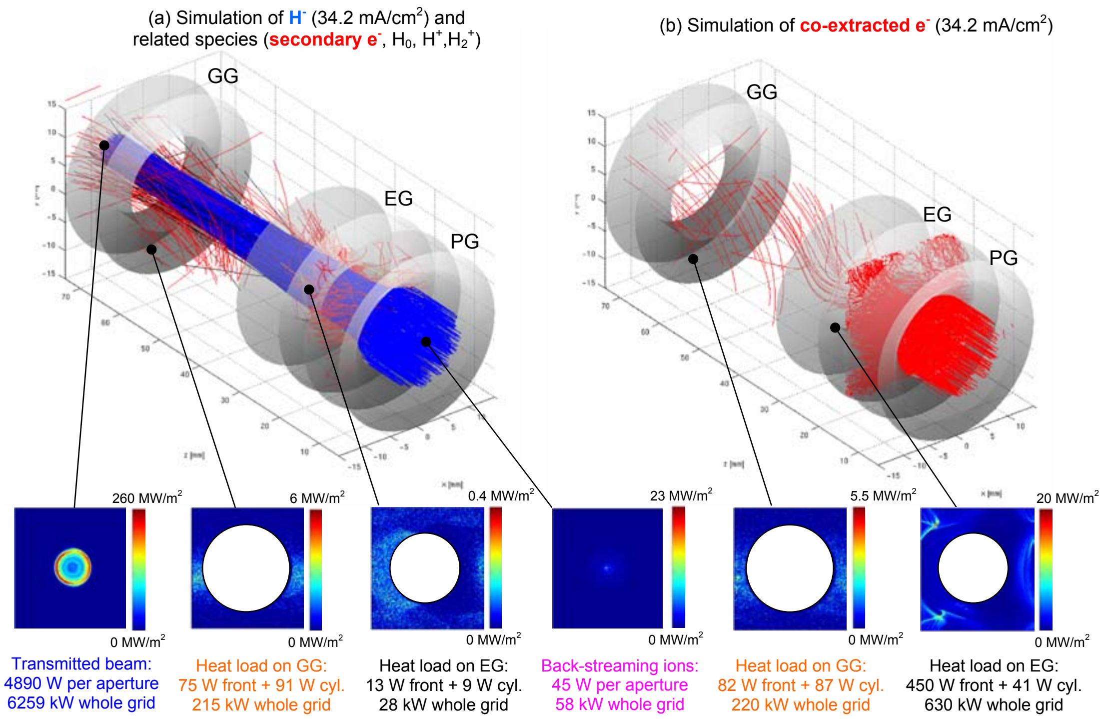


**FIGURE 6.** EAMCC simulation of the beam: the particle trajectories and stripping reaction are simulated with a Monte Carlo approach in a domain with electrical and magnetic fields. For the grids, the heat loads on the front surface (front) and on the cylindrical part (cyl.) are reported for a single aperture, as well as the load on the whole grid. For the transmitted and backstreaming beams, the power corresponding to a single aperture and the total power are reported.

## THERMO-STRUCTURAL OPTIMIZATION

The grids must be designed in such a way that the corresponding apertures are well aligned during all the operating scenarios, 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. 7a [19].

The PG cooling system is designed with the goal to maintain the required temperature of 150°C $\pm$ 10°C on all the grid surface. The EG and GG have to withstand very high and localized peak power densities due to the co-extracted, secondary and stripping electrons, that are colliding in small areas located around the apertures. The heat loads calcluated with the EAMCC code are used to simulate the thermo-mechanical behaviour with the finite element code ANSYS. A limit value of 300°C, suggested by IPP experience, is considered for the copper peak temperature.

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 [20].

Since the grids are working at different temperatures (150°C for PG and about 50°C)

(a)

(b)

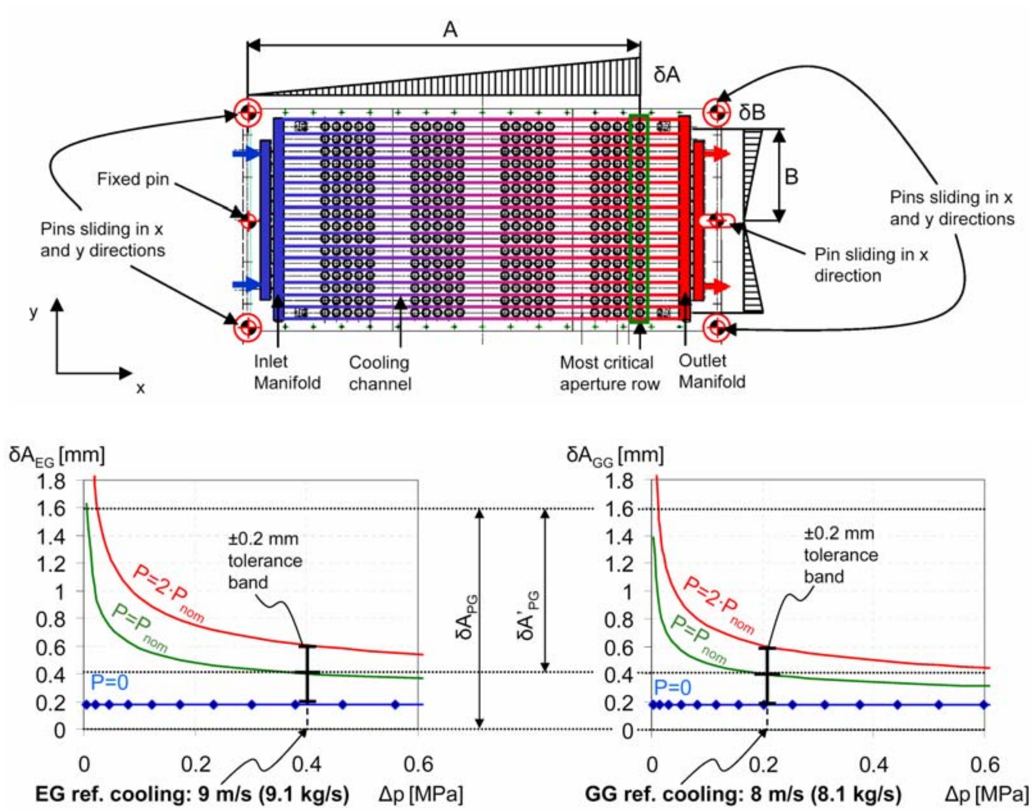


**FIGURE 7.** Alignment optimization for grids: (a) Cooling and fixing scheme; (b) In-plane deformation plots with identification of PG apertures pre-offset and of the minimum EG and GG cooling parameters. The nominal power is the sum of the power given by the secondary, stripping and co-extracted electrons, as calculated by the EAMCC code in the reference operating scenario (full power and 1:1 electrons-to-ions ratio)

for EG and GG) these alignment requirements can be met only by adopting a mechanical offset to the aperture positions. Imposing the alignment requirement under power loads ranging from zero to the double of nominal power (see Fig. 6 for nominal power), the horizontal pre-offset of the PG apertures is identified ($\delta A'_{PG} = 1.2\ mm$), as well as the minimum water velocities along the channels (9 m $s^{-1}$ for EG and 8 m $s^{-1}$ for GG) and corresponding pressure drops (see Fig. 7b).

The grids have to withstand two categories of stresses:

- Cyclic thermal stress due to the temperature gradients between hotter and colder zones. These stresses must be maintained low in order to satisfy the requirement on fatigue life.
- Static stress due to the water pressure. The local values of equivalent stress must be lower than the allowable values for electrodeposited copper (fixed at 100 MPa).

The position and dimensions of the cooling channels, as well as the water flow, were optimized in order to satisfy at the same time requirements on alignment as well as the

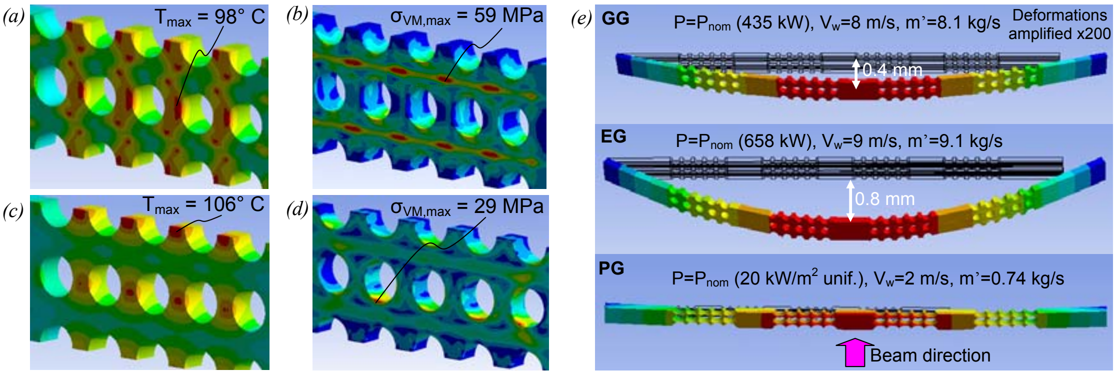


**FIGURE 8.** Main results of the thermo-structural analyses performed with the ANSYS code on the reference scenario: (a) and (b) Temperature and Von Mises equivalent stress on the EG; (c) and (d) Temperature and Von Mises equivalent stress on the GG; (e) Out of plane deformations of the three grids.

structural, ratcheting and fatigue verifications according to the ITER SDC-IC criteria and considering all the foreseen scenarios (conditioning, partial power, full power etc.). Hence, several analyses were performed to estimate the temperatures and stresses along the grids. Fig. 8 reports the main results for the the reference operating conditions. The thermo mechanical analyses are non linear elastoplastic, taking into account the kinematic hardening model for the material [21]. The copper properties are taken from the ITER Material Handbook [22].

As shown in Figure 8e the thermal stresses are causing also an out of plane deformation of the grids. These deformations give some deterioration of the beam optics, i.e. the beam divergence has an increase. For the case of the reference operating scenario, the average divergence (root mean square) increases from 3.3 to 5.1 mrad. This effect can be considered as acceptable for the full size ion source. Further analyses are advisable and foreseen on this aspect.

## CONCLUSIONS

The design of the extraction and acceleration system for the full size ion source experimental device have been accomplished by taking into account at the same time physics and engineering requirements. Several aspects will be investigated during the experimental campaigns, like the magnetic configuration and the plasma source conditioning. For this reason, possible modifications and further optimization are foreseen during the experiments.

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