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Optics and Thermo-Mechanical Analysis of the Accelerator for the DEMO Neutral Beam Injector

Piero Agostinetti and Piergiorgio Sonato

***Abstract*—The injection of high energy neutral beams is one of the main tools to heat the DEMO plasma up to fusion conditions. A conceptual design of the Neutral Beam Injector (NBI) for the DEMO fusion reactor is currently being developed by Consorzio RFX in collaboration with other European research institutes. High injector efficiency and RAMI, which are fundamental requirements for the success of DEMO, have been taken into special consideration for the DEMO NBI. A novel design of the beam source for the DEMO NBI is being developed featuring multiple sub-sources, following a modular design concept, capable of increasing the reliability and availability of the DEMO NBI. A full comprehensive model of the extraction/acceleration system has been developed, able to estimate all the main physics and engineering aspects (beam optics, co-extracted and stripped electrons, heating power deposited on the grids, working temperature of the grids and related stress and deformations) in a self-consistent way. The paper describes the results obtained applying the full comprehensive model to the present design of the extraction/acceleration system.**

***Index Terms*—DEMO, NBI, accelerator, grids.**

I. Introduction

THE objectives of the nuclear fusion power plant DEMO, to be built after the ITER experimental reactor, are to prove the industrial feasibility of fusion by showing the electricity production from the fusion reaction, the safety aspects and the Tritium self sufficiency. As a consequence, in DEMO the issues related to efficiency and RAMI are among to most important drivers for the design. In fact, the cost of the electricity produced by this power plant will strongly depend on these issues. In the framework of the EUROfusion Work Package Heating and Current Drive (WPHCD) work programme within the Power Plant Physics and Technology (PPPT) activities, a conceptual design of the Neutral Beam Injector (NBI) for the DEMO fusion reactor is currently being developed by Consorzio RFX in collaboration with other European research institutes and integrated into the DEMO1 reference design [1], [2], as shown in Fig. 1a. The presented NBI conceptual design is proposed as a possible option for the usage in DEMO. Nevertheless, some of the design solutions here mentioned are still in the early R&D phase and their effective viability is to be demonstrated. This is particularly true for the photo-neutralization, for the Non-Evaporable Getter (NEG) pumps and for the accelerator with increasing size and decreasing number of apertures. Hence, it should be considered as a wished "Advanced DEMO NBI". High efficiency and RAMI, which are fundamental requirements for the success of DEMO, have been taken into great consideration for the conceptual design of the DEMO NBI. In the state-of-the-art negative ion based neutral beam injector (NNBI) under construction for ITER working at high energy (in the range of 1 MV), the beam source, the neutralizer and the beam duct were identified for efficiency improvements to gain for the needs of a high efficient NBI for a future DEMOnstration power plant. This paper focuses on the conceptual design of the extraction/acceleration system and on the related analyses, where, by using a newly developed full comprehensive model, all the most critical aspects have been taken into account in a self-consistent way, both on the physical side (beam optics, co-extracted electrons, secondary electrons generated by stripping reactions) and on the engineering side (heating power deposited on the grids, cooling systems, working temperature of the grids and related stress and deformations).

II. Design Description

In the current conceptual design, the DEMO neutral beam injector features the following main components, shown in Fig. 1b:

- A negative ion beam source, composed of 20 sub-sources (two adjacent columns of 10 sub-sources each).
- A photo-neutralizer based on the "closed recirculating cavity with nonlinear gating" (RING) concept [3]. By means of a second harmonic generator, the second harmonic remains trapped in the mirror system.
- A Residual Ion Dump (RID) with a water cooled CuCrZr plate.
- A duct connecting the beam line vessel to the tokamak chamber. The duct features a dedicated pumping system pump (to reduce gas density and re-ionization losses) and two heat dumps (to dump the heat loads by re-ionization). The duct heat dump ♯2 can act also as a calorimeter by rotating of a suitable angle.

A detailed description of the current conceptual design of the DEMO NBI and its main operating requirements and parameters can be found in [4]. A detail view of the extraction/acceleration system corresponding to a sub-source is shown in Fig 1c. The dimension of each sub-source is approximately 0.4 x 0.4 x 0.4 m^3. The total width and height of the sub-sources cluster is around 1 m and 4 m, respectively.

Each sub-source features a dedicated set of extraction/acceleration grids, shown in Fig. 1d: a plasma grid (PG), an extraction grid (EG), three acceleration grids (AG1, AG2 and A3) and a grounded grid (GG). The first three grids (PG, EG and AG1) feature 4x15 apertures (4 in the horizontal direction, 15 in the vertical direction) for the extraction and pre-acceleration of the ion beamlets. The fourth grid (AG2) features slotted apertures, while the last two grids (AG3 and

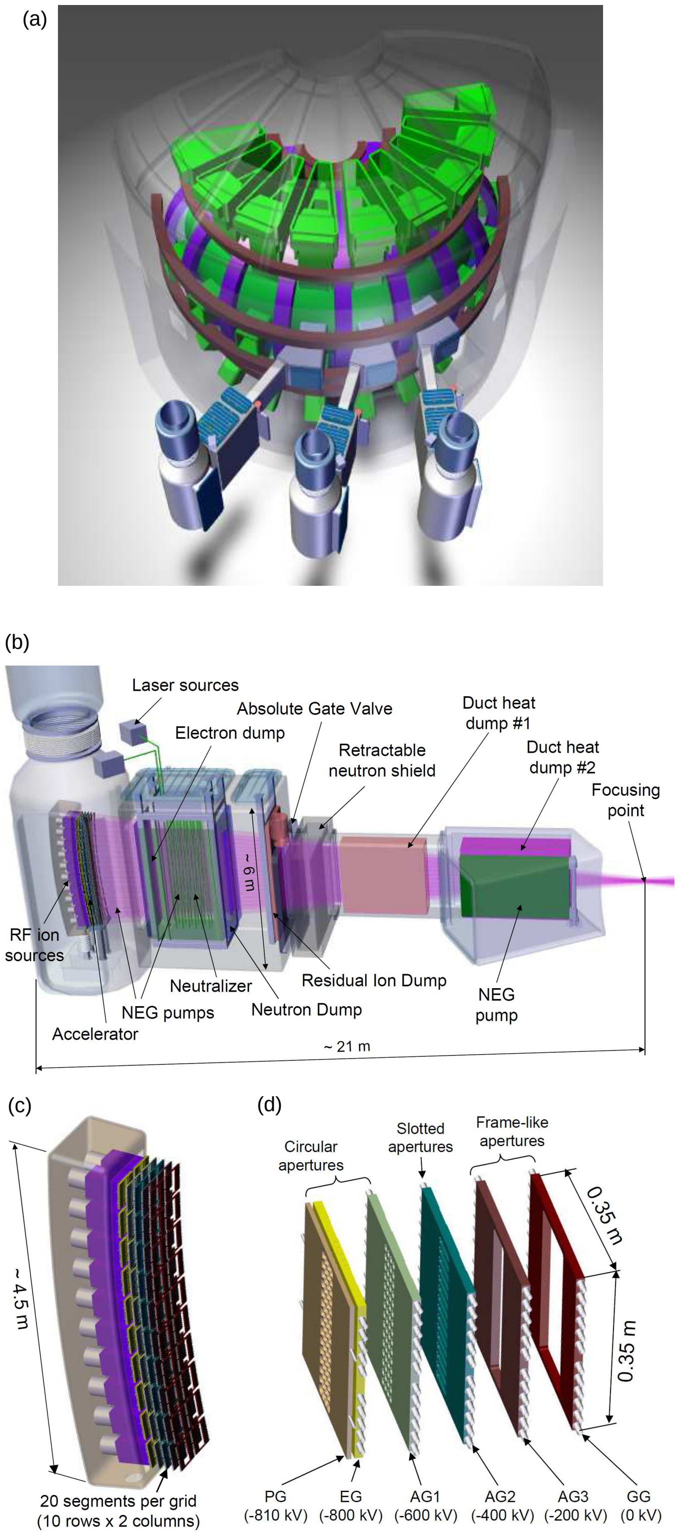

Fig. 1. Design of the accelerator for the DEMO NBI: (a) Layout of the three injectors around the DEMO main chamber; (b) overall view of the DEMO NBI; (c) overall view of the modular beam source; (d) detail view of a set of segments of the extraction/acceleration system.

GG) feature a single large aperture. This design of the grids, with increasing size and decreasing number of apertures from the entrance to the exit of the accelerator, is foreseen to maximize the vacuum pumping, permitting to achieve less stripping losses [5]. Permanent magnets are embedded in the EG to deflect the co-extracted electrons that are extracted from the ion source together with the negative ions D^-. A certain quantity of electrons is also generated in the whole accelerator by stripping and charge-exchange reactions of the D^- beam with the background gas (D_2). The amount of these electrons (here called "stripped electrons" for simplicity) is proportional to the cross section (depending on the species and on the velocity of the ions) and to the density of the background gas (depending on the vacuum pumping system and geometry of the beam source). The ion beam is made of deuterium negative ions (D^-) formed by two "blades" with large height (about 4 m) and small width (about 70 mm). Each of these blades is formed by 10 sub-beams, one per sub-source. The blades are strongly convergent in the vertical direction, with a fan shape, to focus the entire beam to the opening in the blanket, where it enters in the main chamber. More information of the beam source design are available in [5].

III. Description of the Full Comprehensive Suite of Models

To optimize the design of DEMO NBI extraction/acceleration system, a full-comprehensive suite of models of the DEMO NBI grids has been developed in the Comsol environment. This model can study all the most important operating aspects of the grids in three steps.

A. First step: self-consistent magnetic-electrical-ion particle tracking model

In a first step, the magnetic, the electrostatic and the ion particle tracking aspects are studied at the same time in a self consistent way. In this model, the D^- ions are deflected by the magnetic and electric fields at the same time, being the electric field calculated summing the field generated by the grids plus the contribution due the negative space charge of the particles themselves. Each ion beamlet is composed by 100 macro-particles, starting from a meniscus pre-calculated with the SLACCAD code [6], analogously to the SPIDER [7] and MITICA [8] cases. The output of the first step are the trajectories of the D^- ions, calculated taking into account both the effects of the electrostatic lenses and space charge, the heat loads deposited on the grids by the halo fraction and the power of the D^- ions transmitted at the exit of the extraction/acceleration system.

B. Second step: co-extracted and stripped electron particle tracking model

In a second step, the trajectories of the co-extracted and stripped electrons are evaluated. The former are extracted from the ion source together with the deuterium negative ions, the latter are generated inside the accelerator by the collisions between the D^- and the background gas (D_2). The collisions

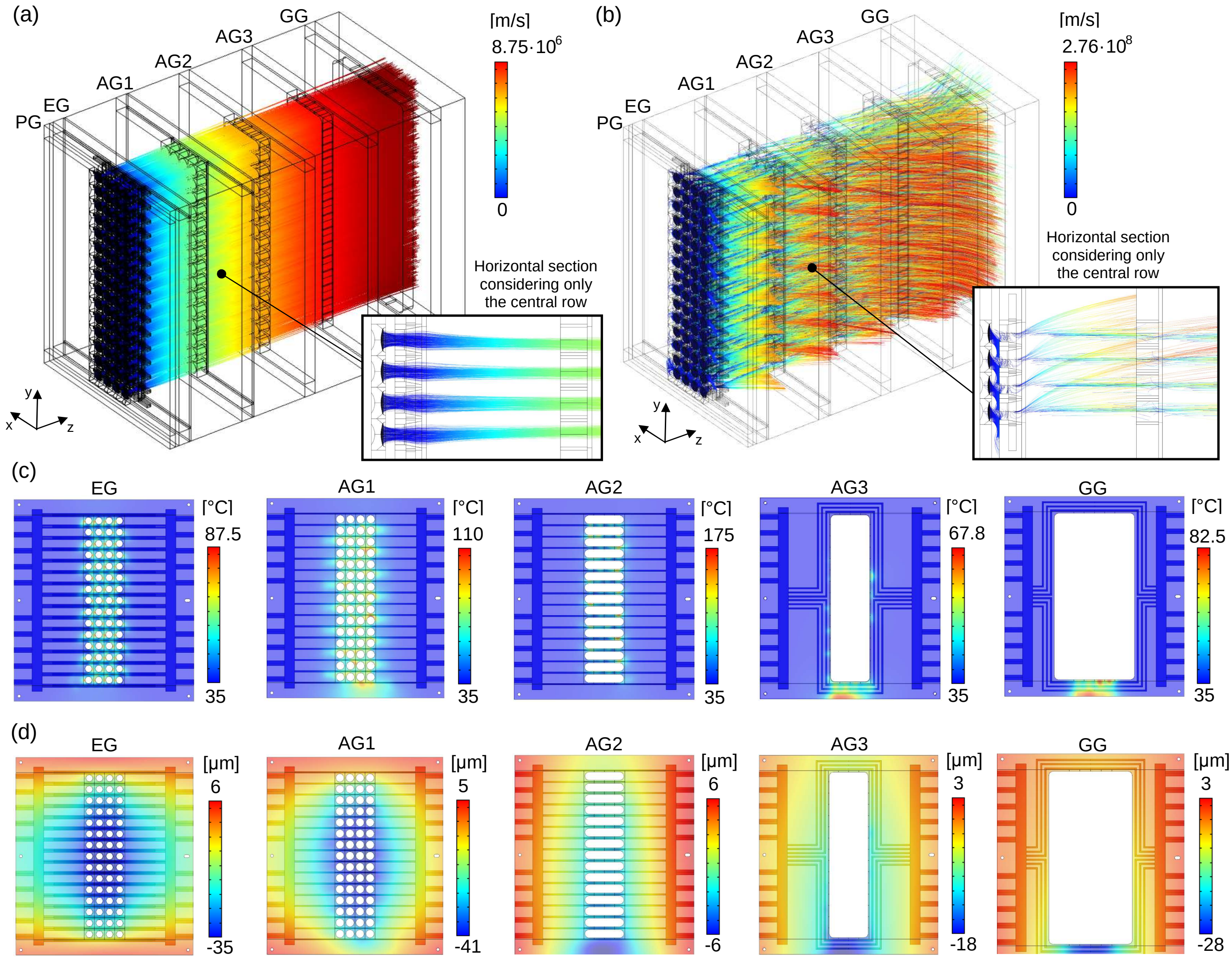

Fig. 2. Main results of the full-comprehensive model: (a) Trajectories of the D- ions; (b) trajectories of the co-extracted and stripped electrons; (c) temperature contours plot on the grid surfaces, where also the proposed cooling circuits are visible; (d) Out-of-plane deformations of the grids, or deformation along the beam axis (z) direction; negative values are along the upstream direction.

are calculated with a dedicated macro in Matlab considering the cross sections reported in [9] for hydrogen atoms and a density profile of the background gas linearly varying from $2.5\cdot10^{-19}$ m^{-3} (at the entrance of the accelerator) to $0.5\cdot10^{-19}$ m^{-3} (at the exit). This profile, estimated with analytical formulas, is to be considered as a preliminary one, while a more precise evaluation will be used in the next future. The output of the second step are the trajectories of the electrons, the heat loads deposited on the grids and the power of the electrons transmitted at the exit of the extraction/acceleration system.

C. Third step: thermo-mechanical analysis of the grids

In a third step, a thermo-mechanical analysis is carried out taking into account the heat loads calculated at the previous point and the cooling circuits and geometry of the grids. To do this, a first tentative design has been proposed for the cooling circuits of the grids, having channels with section of 3 mm x 2.5 mm, analogously to the ones foreseen in the MITICA Extraction Grid [8]. Assuming a water temperature of 35 °C and a water velocity of 10 m s^{-1} in the cooling channels (same of ITER HNB [8]), a heat transfer coefficient of 50000 W m^{-2} K^{-1} was applied at the walls of the channels, as estimated with the Sieder-Tate formula [10]. The outputs of the third step are the temperature, stress and deformations of the grids in the foreseen operating scenarios.

IV. Application of the Suite to the Current Design of the Extractio/Accelearation System

The full-comprehensive suite of models has been applied to obtain a complete analysis of the extraction/acceleration system described in [5]. In particular, the last version of the extraction/acceleration system has been considered, shown in Fig. 7e of [5]. This design option features Asymmetric Deflection Compensation Magnets (ADCM) to compensate to the Criss-Cross Deflection Effect (CCDE), kerbs on the EG and AG1 to provide a suitable focusing of the beam and an enlarged aperture on the GG to remove the de-focusing

TABLE I
MAIN RESULTS OF THE MODEL SUITE.

	EG	AG1	AG2	AG3	GG	Exit
Q_{ion} $[kW]$	0.005	0.37	6.5	0.05	0.41	1400
Q_{el} $[kW]$	14.8	18.1	16.8	2.4	2.75	18.6
T_{max} $[°C]$	87	110	146	68	82	/
σ_{max} $[MPa]$	118	117	127	113	112	/
δx_{max} $[mm]$	0.10	0.15	0.16	0.10	0.11	/
δy_{max} $[mm]$	0.067	0.11	0.14	0.07	0.07	/
δz_{max} $[mm]$	0.035	0.041	0.006	0.018	0.028	/

Q_{ion} is the power of the D^- beam impinging on the grids and transmitted at the exit of the accelerator; Q_{el} is the power of the co-extracted and stripped electrons impinging on the grids and transmitted at the exit of the accelerator; T_{max} is the maximum temperature reached on the grids; σ_{max} is the peak values of equivalent (Von Mises) stress; δx_{max}, δy_{max} and δz_{max} are the maximum deformations in absolute value along x,y and z axes.

effect given by the last grid. As a result, all the beamlets composing the beam are almost parallel at the accelerator exit. More details are reported in [5]. In addition to the magnetic field produced by the permanent magnets in the EG (see Fig. 5 of [5]), an uniform 5 mT magnetic field along the x direction (horizontal transverse) has been applied. This is to be considered as a "long range field" (in the sense reported in [8]) and could be applied by means of coils located on the beam source vessel. This field gives not only reduces the amount of stripped electrons reaching the exit of the accelerator, but also significantly bends the stripped electrons, so that if they can reach the accelerator exit, they will have a significant vertical angle (among 20 and 30 degrees, as can be observed in Fig. 2b) with reference to the ion beam. Hence, they will impinge not on the neutralizer but on a dedicated electron dump located on the lower part of the beam line vessel, analogously to MITICA [8]. On the other hand, this long range field produces just a slight and negligible vertical deflection to the negative ions. The co-extracted and stripped electrons generate high and concentrated heat loads on all the grids of the extraction/accelerator grids except the PG (where there are no impinging accelerated particles). These loads must be exhausted by means of high-performance cooling systems. A proposal for the cooling circuits of the grid segments is visible in Fig. 2c, where also the operating temperature on the surface of the grids can be seen. It can be observed that the co-extracted and stripped electrons generate hot spot regions on the grid surfaces, nevertheless the corresponding peak temperatures are maintained at acceptable levels thanks to the cooling circuits. The thermal gradients on the grids generate also thermal stresses and deformations of the grids, which are summarized in Tab. I. The temperature, stress and deformation of the all the grids can be considered acceptable for the operation in DEMO NBI, according to the ITER Structural Design Criteria for the In-Vessel Components [11]. In particular, it can be observed that the deformation along x and y directions are much lower than in the MITICA case [8] because the peak temperatures are similar but the dimensions of the segments are smaller thanks to the modular approach of the beam source.

V. CONCLUSION

A conceptual design of the DEMO NBI has been developed by Consorzio RFX in collaboration with other research institutes. This conceptual design features a modular approach for the ion source and for the extraction/acceleration system, and accelerator grids with increasing size and decreasing number of apertures. These modifications are aimed at increasing efficiency (or lowering the recirculating power) and better coping with the RAMI design approach.

A full comprehensive suite of models, featuring a self-consistent magnetic-electrostatic-ion particle tracking model, an electron tracking model and a thermo-mechanical model, has been set up and used as the main tool for the development of the extraction/acceleration system for the DEMO NBI. The suite of models can take into account all the main physics and engineering aspects (beam optics, co-extracted and stripped electrons, heating power deposited on the grids, working temperature of the grids and related stress and deformations) at the same time and in a self-consistent way. Hence it is a suitable tool for the optimization process that will be applied on the conceptual design of the DEMO NBI in the next future.

As a first application, the suite of models has been applied to investigate the current conceptual design of the extraction/acceleration system for the DEMO NBI, featuring grids having a decreasing number and increasing size of the apertures from the entrance to the exit of the system. The results are encouraging, as the temperature, stress and deformations of grids are acceptable. Nevertheless, many aspects of the extraction/acceleration system, like the optics of the beam and the amount of electron power on the grids, can be improved. Hence, the model suite is planned to be used in the next future to study and compare other design options and for a multi-parametric optimization stage.

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