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The influence of grid positioning on the beam optics in the neutral beam injectors for ITER

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ABSTRACT

Neutral beam injectors are routinely used to increase the ion temperature in magnetically confined plasmas. Typically, the beam is produced by neutralizing a bundle of hundreds of ion beamlets, energized in a multi-grid multi-stage accelerator. Precise aiming of each beamlet is required in order to focus the full beam to the plasma, avoiding any interception with beamline surfaces and with the beam duct. This paper describes the effects of grid in-plane and out-of-plane displacements (mispositioning, thermal expansion, grid tilting, etc...) in the case of the MITICA electrostatic accelerator, which is the full scale prototype of the ITER heating neutral beam injector. Various simulations have been carried out with the OPERA 3D code, by self-consistently simulating the beam charged particles travelling in an externally applied electric and magnetic field. The accelerator grids act like a series of electrostatic lenses, and produce a net deflection of the particles when one or more grids are offset. The numerical simulations were used to evaluate the "steering constant" of each grid and also showed that the linear superposition of effects was applicable, multiple causes of mispositioning are combined and used to quantify the overall effect in terms of beam misalignment

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1. Introduction

Large scale neutral beam injectors (NBI) will be used in advanced fusion machine such as ITER. To obtain sufficient beam penetration in the dense plasma, a beam energy of around 1 MeV is required; hence the use of negative ions as precursor of neutrals is needed due to their higher neutralization rate. The current density of D^- ions in nowadays negative ion sources is around 300 A/m^2, so that a large extraction area is needed in order to obtain the current of 40 A required for the heating injectors (HNB) of ITER [1,2] and its full-scaled prototype MITICA [3,4]. In the acceleration stage of these large injectors, the beam is formed by superposition of 1280 beamlets extracted from the source by means of a set of grids biased at different potentials. A CAD view of the beam source is reported in Fig. 1. The complete accelerating system is composed by 7 electrodes, with a total voltage of around 1 MV. The first electrode, separating the high field side from the plasma source, is called plasma grid (PG) and it is biased at −1.01 MV from the ground, the second electrode, placed at a distance of 6 mm at the downstream of the PG is called extraction grid (EG) and it is biased at around −1 MV, to provide the D^- extraction from the plasma. Then the following 5 acceleration grids (AG1-AG5) are separated by a distance of 88 mm and a voltage difference of 200 kV to accelerate the beam to high energy. The last electrode AG5 is also called grounded grid (GG) since it is kept at the same potential (ground) of the NBI vessel. Permanent magnets are embedded in the EG and AGs to deflect and dump the electrons that are co-extracted or generated by beam-gas or beam surface interactions on the downstream grid surfaces. Each grid is divided into 4 segments, where beamlets are arranged in 4 beamlet groups of 5 × 16 elements. Each segment (and each beamlet group within a segment) is inclined with respect to the others, in order to focus the beamlet toward the same focal point located 25 m from the GG. A schematic of the beamline and beamlet pattern is reported in Fig. 2, together with the tilting angles $_{\alpha x}$ and $_{\alpha y}$ of each beamlet group, corresponding to 3.14 mrad and 7.7 mrad respectively. An additional focusing of the external beamlet in each beamlet group is provided by metallic frames, called kerbs, surrounding it, and placed at the downstream surface of each biased electrode [5].

After the acceleration stage, the beam passes through a neutralizer, where most of the negative ions are converted to neutrals by collisions with a gas target, and finally across a residual ion

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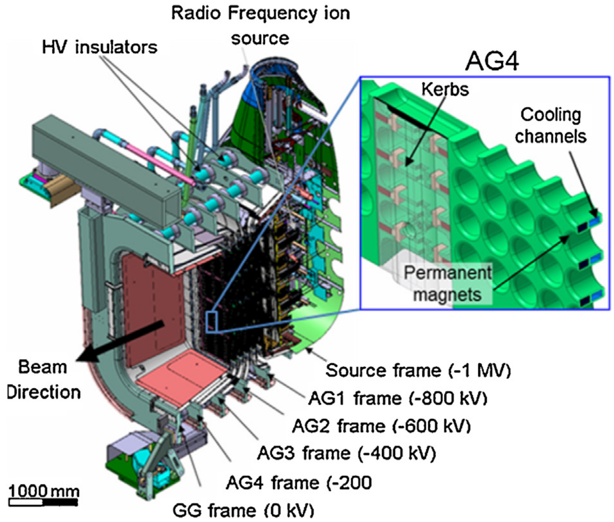

Fig.1. CAD view of the MITICA/ITER HNB beam source, and zoom on a portion of the AG4.

dump (RID) where the remaining charged particle are deflected onto actively cooled plates by electrostatic means. With the purpose of improving thickness, uniformity and compactness of the gas target and also of increasing the available surface for ion dumping, the neutralizer and RID are divided so as to constitute an horizontal array of four independent channels. Each channel is passed by a beam "column" consisting of a vertical stack of 4 beamlet groups. The aiming of each beam column in the horizontal direction is hence critical, and a wrong focusing angle of part of the beam would result in intolerable heat loads and damages of the channel enclosure [7]. On this basis, the maximum tolerable deviation from the nominal aiming angles of beamlets was fixed to 2 mrad. In such a complex system there are several possible sources of horizontal misalignments, as the asymmetries of the system or not perfectly balanced magnetic fields, but the most important contribution arises from the relative and absolute positioning of the grids. Each grid, in fact, constitutes a boundary between two regions having different values of electric field (E field), so that, on each grid aperture, electrostatic lenses are formed, that influence the beamlet trajectories according to the well-established formula of Davisson and Calbick [8]:

$$\varphi = \frac{\delta}{4V}(E_2 - E_1) \tag{1}$$

Here φ is the deflection that the beamlet receives after crossing the grid, E_1 and E_2 are the values of the electric field before and after the grid respectively, V is the beam potential when crossing the aperture and δ is the offset between the beam axis and the aperture center. The beam angle φ linearly depends on the relative position between the beam and the aperture, so that any in-plane misalignment of the grid results in deflection of the beamlets as they cross the electrostatic lens. At the same time, the grids can also suffer an out-of-plane misalignment, due to thermal deformation or non-perfect grid positioning, adding a perpendicular component to the E field between the two grids, which in turn deforms the ion trajectory. In order to evaluate the effect of both in-plane and out-of-plane positioning on the beam path a large set of numerical simulation was performed, by means of the code OPERA 3D [9]. The numerical simulations were made using a 5 beamlet model (one row of a beamlet group), and including the focusing effect induced by kerbs. A view of the OPERA model is reported in Fig. 3. In the simulation reported here, the deflection of beam at the exit of the GG in response to the misalignments imposed to any grids has been investigated. In particular, the deflection of each beamlet was compared with the deflection expected for the same beamlet when all the grids are perfectly aligned. The result of these analyses are reported in Sections 2 and 3 of this manuscript; the main outcome is the evaluation of the steering constant $S = \varphi/\delta$ (mrad/mm) that define the effect of the electrode misalignment δ of the beamlet deflection φ at GG exit. The values of S calculated with the code are also compared with some basic theoretical expectations. In the final section of the paper the steering constant are used to assess the overall effect of multiple positioning errors, in order to quantify the possible beam misalignment when all the effects responsible for the beamlet deflection are taken into account.

2. In-plane grid positioning

A particle beamlet travelling across a grid aperture can be deflected if the beamlet axis does not coincide with the aperture axis. The deflection (steering) angle can be calculated theoretically

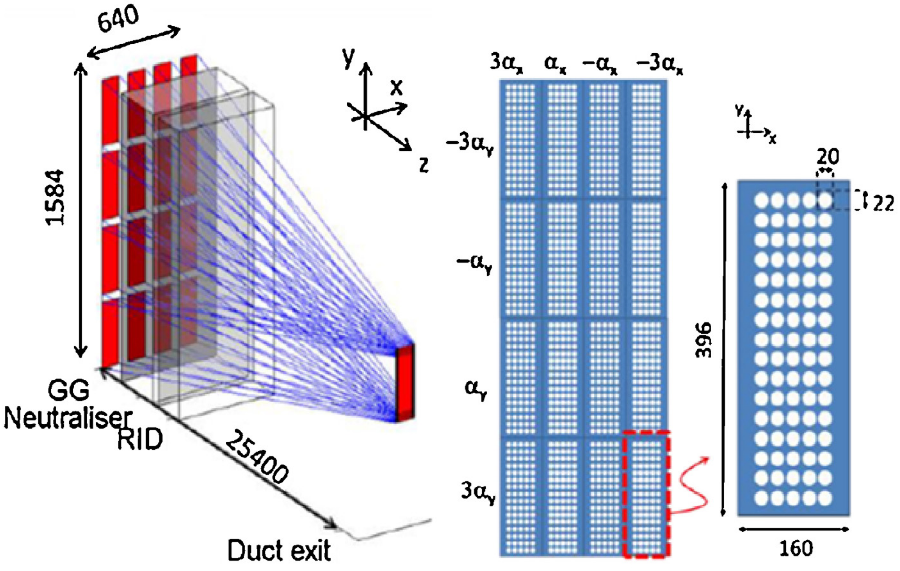

Fig. 2. Schematic of the MITICA/ITER HNB aiming system and beamlet pattern. Sizes are in mm. picture taken from [6].

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