

## Optimisation of the magnetic field configuration for the negative ion source of ITER neutral beam injectors

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The negative ion source of the neutral beam injectors for ITER requires that the co-extracted electron current is not larger than the negative ion current. To this purpose a suitable magnetic field configuration was adopted, generated by a current flowing in the plasma grid and by two permanent magnets on either side of the source. In the present design of the system however the magnetic field lacks uniformity across the beam.

This paper focuses on strategies aimed at optimising the magnetic field distribution and improving the beam optics, based on two-dimensional magnetic simulations, including permanent magnets, ferromagnetic materials and electrical currents.

A careful distribution of the filter field current can provide a more efficient extraction of negative ions with respect to electrons. The use of ferromagnetic material can reduce the magnetic field downstream from the accelerator, resulting in lower beam deflection. The interference with the permanent magnets of ITER reference design is also discussed.

It is proposed that the path of the plasma grid current is divided between several conductors to minimise the stray field. Moreover, ferromagnetic material should be inserted in the grounded grid. It is shown that the proposed modifications reduce the magnetic field in the region downstream from the grounded grid, with the advantage of a smaller deflection of the beam.

The effect on electrons is discussed. However, a three-dimensional simulation will be necessary to address the issue of electrons as well as the vertical uniformity of the beam, taking into account the effects of finite extension of the permanent magnets, and optimising the return current path.

Keywords: ITER, heating and current drive, negative ion source, beam magnetic deflection, magnetic field computation, numerical computation

### 1. Introduction

The negative ion source of the neutral beam injectors for ITER requires that the co-extracted electron current is not larger than the negative ion current [1]. To reduce the number of extracted electrons, the reference design [2] is characterised by a magnetic field configuration generated by a current flowing in the plasma grid and by two permanent magnets on either side of the source [3]. In this configuration however the magnetic field is not uniform across the beam.

The present contribution focuses on strategies aimed at optimising the magnetic field distribution and improving the beam optics, based on two-dimensional magnetic field simulations. Specifically the following objectives will be pursued:

- uniformity of magnetic field in the beam source
- reduction of the axial component of the magnetic

field in the ion source

- reduction of the horizontal magnetic field inside the accelerator
- reduction of the horizontal magnetic field downstream from the grounded grid.

Several magnetic field configurations have been considered, including the role of ferromagnetic material, suitable current distributions and permanent magnets; the overall aim is to obtain a more efficient and uniform extraction of negative ions with respect to electrons and to reduce the deflection of ions. The path of the filter field current is also carefully analysed to minimise the stray field.

In the following, the sources of the horizontal magnetic field will be introduced along with the numerical model developed in the ANSYS environment; then the results of the best cases will be presented; finally a comparison of the proposed solutions, in terms of  $\int Bdl$

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and particle trajectories, will be given.

**2. Magnetic field sources**

In the ITER beam source the magnetic configuration results from two different contributions, which can be considered separately in a first analysis. The so-called filter field principally lies on the horizontal plane and should be as parallel as possible to the grids in the region immediately upstream from the plasma grid (PG); it has the aim to reduce the electron current extracted through the plasma grid apertures by forcing the electrons to hit the PG or the source walls, due to their lower Larmour radius than the ions. A vertical magnetic field is generated around the extraction grid (EG) by permanent magnets embedded in the EG, with the purpose of deflecting the co-extracted electrons onto the EG.

The present paper is devoted to a two-dimensional investigation of the horizontal magnetic field; according to the ITER reference design, such field is generated by the current in the PG and by the permanent magnets,.

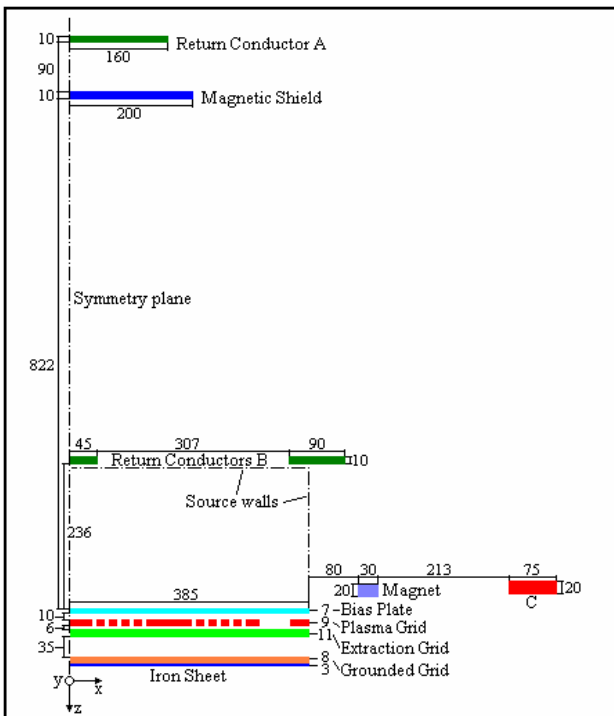


Fig.1 Geometry of the 2D ANSYS model; source walls are also indicated (RF driver not shown). The beam is along z; numbers indicate dimensions.

The possibility to improve the magnetic field profiles has been explored. A horizontal section of the ion accelerator was considered; thanks to the intrinsic symmetries, only half of the section has been modelled. The model is shown in Fig. 1: it comprises the area occupied by Bias Plate (BP), PG, EG and Grounded Grid

(GG), at the bottom left of the picture; the filter field magnet, and another conductor at the bottom right. Also the conductor for the current return was considered, and different positions and configurations were tested; in the reference design the unique conductor for the return current is located on the back side of the device (Return Conductor A), behind a ferromagnetic shield. Because of the beamlet apertures and the cooling water manifold, the current flowing in the PG is characterised by a non uniform current density; so the PG has been modelled as a plate interrupted as many times as the holes. These “equivalent 2D holes” have a width which is given by the ratio between “vacuum” volume and solid volume, multiplied by grid length and divided by aperture number.

The configurations tested are (see Fig. 1):

- a) reference case, comprising magnetic field due to the permanent magnets and to the 4 kA current flowing through the PG and the return conductors A;
- b) current return as in a; filter magnets as in a; filter field current divided between the PG, 3 kA, and two guard conductors, labelled C in fig 1 (2x1.5 kA); 3 mm soft iron sheet inside the GG;
- c) same as b, but return current divided in the three Return conductors B, located on the back side of the plasma source, between the RF drivers: central conductor carrying a 3 kA current; those in the side 1.5 kA each;
- d) same as case c, without permanent magnets.

In cases b,c, and d the PG current is within the limits of the original specifications for ITER.

In Fig. 2 the magnetic flux lines in the ion accelerator for the four different cases are compared; the line density convention is not the same in the panels: it is easy to see from cases a through d that the density of magnetic flux lines outside of the accelerator is lower than in the plasma source and such difference is strongly enhanced by the soft iron in the GG (cases b,c,d). Moreover, in cases a and b, several magnetic flux lines connect the holes of the lateral beamlet group to the plasma located upstream from the central beamlet group, thus facilitating the co-extraction of electrons; in case c only some flux lines which come from the source sides enter some apertures, whereas in case d the flux lines which reach the holes come from the region between BP and PG where the plasma has a lower density. So case d should reduce the number of electrons extracted from PG. Moreover, eliminating the permanent magnets reduces the intensity of the magnetic field at the side of the PG, and so the magnetic-mirror effect for electrons.

### 3. Particle deflection

The main objectives of the present work are the reduction and the uniformity of the effect of the magnetic field on the trajectories of negative ions. Hence the various magnetic configurations have been compared in terms of the deflection of the particle trajectories.

As the beamlet trajectories are mainly along the  $z$  direction, the  $x$  component of the magnetic field, which is given by PG current and permanent magnets, generates a vertical deflection (along  $y$ ).

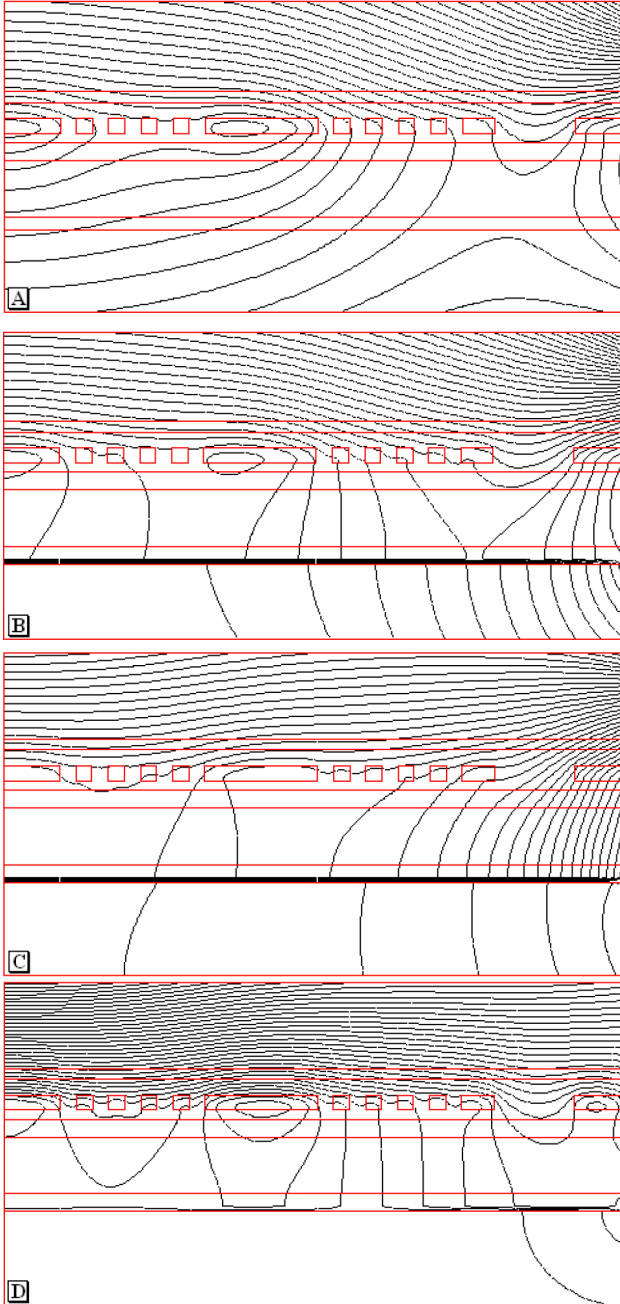


Fig.2: Magnetic flux lines for the four cases investigated. A discontinuity is produced by a 3 mm soft iron plate in the GG (cases b,c,d).

The vertical deflection angle,  $\vartheta$ , can be defined, in the vertical plane, as the angle between the beamlet direction and the geometrical axis of the apertures. The vertical offset, defined as the vertical distance between beamlet centre and geometrical axis, is approximately proportional to the deflection angle for a given accelerator and position.

The code EAMCC (Version 3.1) [4] was used to calculate the beamlet trajectories inside the accelerator. Table 1 shows that the difference between the deflection angles calculated at the ‘‘Central’’ and ‘‘Lateral’’ positions, 18 mm downstream from the GG, is about 2 mrad with magnetic configuration a, about 1 mrad with configuration b, about 0.5 mrad with configuration c and about 0.2 mrad with configuration d.

	Deflection angle ‘‘Central’’ beamlet [mrad]	Deflection angle ‘‘Lateral’’ beamlet [mrad]	Differential deflection between beamlets [mrad]
Case a	-3	-1	2
Case b	+0.5	+1.5	1
Case c	+1.5	+2	0.5
Case d	+1	+0.8	0.2

Table 1: Deflection of ‘‘Central’’ and ‘‘Lateral’’ beamlets for the four cases investigated.

Hence, it is confirmed that the magnetic configuration d gives the best results in terms of deflection uniformity.

The evaluation of the vertical deflection of the beamlets by the EAMCC code is a time-consuming task when the computation must be carried out for a long distance downstream from the GG.

In the paraxial approximation, using conservation of energy along the particle path and neglecting the contribution of focusing gaps of the accelerator give the following approximation for the deflection:

$$\vartheta = \frac{q \int B_x(z) dz}{\sqrt{m^2 v_0^2 + 2qm(U_0 - U(z))}} \quad (1)$$

where  $U$  is the electric potential on the  $z$  axis,  $U_0$  its value at the extraction and  $v_0$  the speed at the extraction. This integration has been numerically carried out along  $z$  in the paraxial approximation.

The results of the integrals are shown in Fig. 3 for all cases under investigation and 1 m downstream from the PG. It is clear that the vertical deflection of all beamlets has been greatly reduced with the proposed magnetic configuration, from around 20 mrad to about 0.5 mrad; moreover, the maximum difference among the beamlets

decreased from 5 mrad to 0.4 mrad.

The magnetic configuration of case d has already been implemented in the mechanical design of the beam source for SPIDER, the test facility for ITER ion source (Fig. 4). The two conductors for forward PG current are copper bars having a section of  $100 \times 15 \text{ mm}^2$  each and are connected in parallel to the PG at the top and bottom of the ion source.

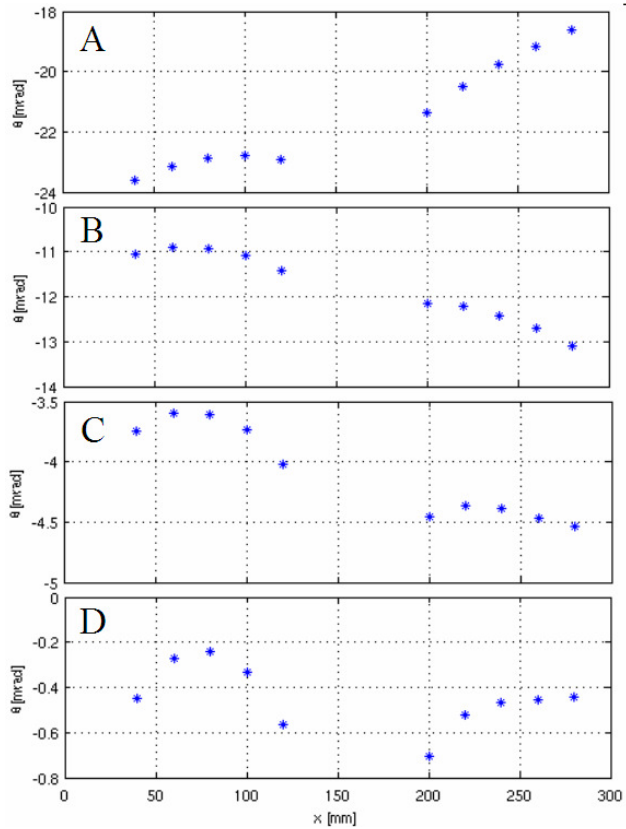


Fig. 3 Calculation of the deflection integral up 1 m downstream from the PG for each beamlet.

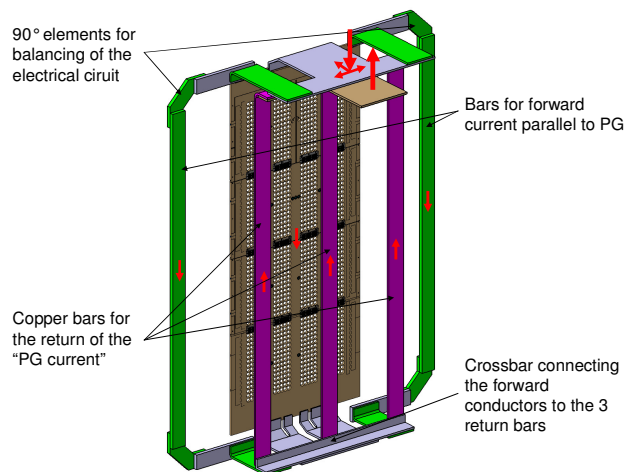


Fig. 4 Implementation of the electrical circuit in the beam source.

The sharing of the current flowing through the PG and the two parallel bars is accomplished by changing the resistance of the  $90^\circ$  elements that connect the two vertical straight bars at the top and bottom. At the bottom of the source the forward currents are connected through a crossbar to the three return bars. The return current is in fact distributed on three parallel copper bars (having a section of  $90 \times 10 \text{ mm}^2$  each) that are placed between the copper and the stainless-steel driver plates of the RF source and are insulated from them. At the top of the beam source all conductors are connected to the in-vacuum end of the power supply transmission line.

### 5 Conclusions

The configuration proposed in the present work represents a major improvement in terms of the reduction of the vertical deflection of beamlets. The final deflection is in the range of 1 mrad for all beamlet groups.

The best solution seems case d, which requires that forward and return currents are split in three conductors, and the return current paths are located within the driver plate; no permanent magnets are required, which makes the magnetic configuration more flexible and fully controlled from the outside.

3D computations are on-going, in order to assess the vertical uniformity of the configuration, including the realistic path of the current at the edges. The proposed configuration heavily affects the behaviour of electrons after the GG: since the magnetic field is greatly reduced, electrons can reach far away downstream. The 3D model will address the effect of the proposed magnetic configuration on electrons; it will also allow the analysis of the horizontal deflection of beamlets.

### Acknowledgments

This work was supported by the European Communities under the Contract of Association between EURATOM and ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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