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Active steering system for the Neutral Beam Injector for ITER

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ITER requires an additional power injection of 33 MW from neutral beams, which can be provided by two injectors, delivering 16.5 MW each, having an ion current of 40 A and an accelerating voltage of 1 MV.

The requirement of on-axis and off-axis injection into ITER is presently accomplished by mechanical tilting of the injector source. To preserve the integrity of the beam line components, on the horizontal plane, very tight misalignment is tolerable (±3 mrad); such accuracy requires precise installation of the components. Breaking the vacuum and executing a long series of operations is required to provide proper beam alignment. It would be helpful if such alignments could be performed remotely.

A study has been conducted on the possibility of steering the negative ions by suitable magnetic fields, generated by dedicated coils located at the exit of the accelerator. It results that the magnetic system can meet the requirements in terms of beam alignment. The steering system will heavily affect the trajectory of the electrons extracted from the accelerator and can be used to deflect the electrons onto suitable dump plates.

The system can steer the ions and dump the electrons in a controlled way, even in case of modulation of the acceleration voltage; a flexible beam aiming system can be used to adapt the power deposition profile in ITER to the plasma characteristics; active steering can provide a suitable way to control the power deposition with respect to the possibility of exciting Alfvén eigenmodes, which can reduce the performances of ITER plasmas.

The present contribution reviews the preliminary design of the active steering system and provides an analysis of advantages and disadvantages.

Keywords: ITER, heating and current drive, plasma instabilities, beam steering, heat loads

1. Introduction

Depending on the operating scenario, ITER requires an additional power up to 33 MW from neutral beam injection; such power can be provided by two injectors, each one delivering 16.5 MW; the ion current should be 40 A and the accelerating voltage 1 MV [1]; this high particle energy implies the use of negative ions based on consideration of neutralisation efficiency [2].

It is required that the design allows both on-axis and off-axis injection into ITER; presently this is accomplished by mechanical tilting of the injector source. At the same time, on the horizontal plane, very tight misalignment is tolerable (±3 mrad), to preserve the integrity of the beam line components; such accuracy must be obtained by precise installation of the components.

Modifications of the alignment using these systems require breaking the vacuum and executing a long series of operations. Consequently it would be helpful if such alignments could be performed remotely.

Active aiming would allow to modify the power deposition profile in ITER according to the characteristics of the plasma; active steering can provide a suitable way to control the power deposition with respect to the possibility of exciting Alfvén eigenmodes, which can reduce the performances of ITER plasmas [3].

A study has been conducted on the possibility of steering the negative ions by magnetic fields, generated by suitable coils located at the exit of the accelerator.

As a by-product, the steering system would heavily affect the electron trajectories outside of the accelerator and deflect the electrons onto suitable dump plates.

Advantages of this system are the possibility of steering the ions and dumping the electrons in a controlled way, even in case of modulation of the acceleration voltage; aiming of the ions is provided without the need of moveable parts in vacuum and of flexible connections.

The present paper reviews the preliminary design of an active steering system for ITER and describes the numerical tools developed to give the main specifications; finally advantages and disadvantages are analysed.

2. Operating principle

The principle of operation of an active steerer is illustrated in Fig. 1: the negative ions emitted from the accelerator are deflected by the magnetic field produced by suitable coils. Two sets of coils are required to provide

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vertical and horizontal steering. Since the effect of magnetic fields on electrons is larger than on ions, the system can be used to deflect the co-accelerated electrons and a suitable dump plate must be provided.

Two schemes are proposed for the system: a single steerer can be used to deflect the ions; the electrons leaving the accelerator are also deflected and are intercepted by the electron dump. The advantages of such a system are: little space required for magnetic field coils and simplicity of use; moreover, monopolar power supplies are required. The drawback is that the electron deflection is related to the deflection of negative ions; therefore the position of the panels intercepting the electrons requires a careful study, to comply with the requirements of beam steering in two directions. In this case the beam source is tilted and the steerer must recover the ion deflection at any time.

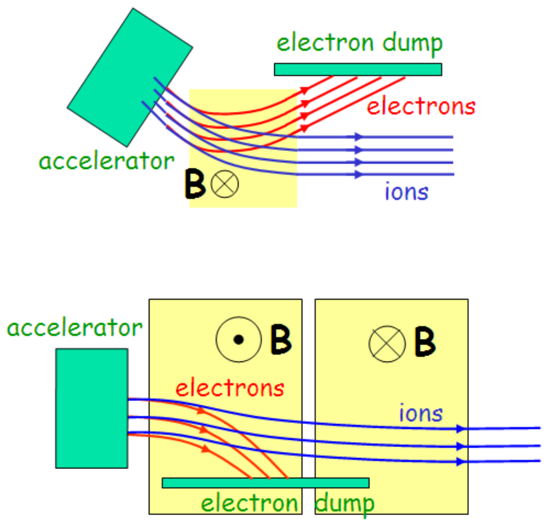

Fig.1 Operation of active steerers: in a single-stage steerer (top), electron and ion deflections are linked; ions are deflected separately from electrons in double-stage systems (bottom).

In the case of the double-stage steerer the magnetic field of the first stage filters the electrons, deflecting them towards the electron dump; the second stage compensates for the deflection undergone by the beam trajectory and gives the required deflection of negative ions. This solution allows to decouple electron dumping from beam steering, as the two sets of coils serve different purposes.

In both schemes an iron yoke is necessary, to prevent the steerer magnetic field from penetrating the acceleration region. It is worth noting that the iron yoke acts also as a protection for the cryopump panels, by intercepting the radiation emitted at the electron dump plates.

3. Numerical tools

Several numerical tools have been developed in the COMSOL Multiphysics environment [4] to investigate the performances of a steerer and to support its design.

To analyse the main features of the system, the paraxial approximation is adopted, according to which the sine of an angle can be approximated by the angle itself: $\sin\vartheta \approx \vartheta$.

So conservation of energy and Larmor radius for a particle of mass m_o and charge q_p in an accelareting voltage V read:

$$q_p V = m_o c^2(\gamma - 1) \qquad R_L = \frac{\gamma m_o v}{q_p B} \tag{1}$$

which give the particle deflection:

$$\Delta\vartheta = \frac{c\ q_p \int B_x \, \mathrm{d}z}{(q_o^2 V_p^2 + 2 m_o c^2 q_p V_p)^{1/2}} \tag{2}$$

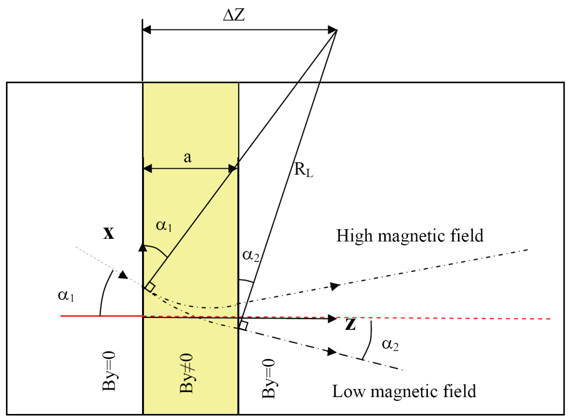

Fig.2 Ion trajectories for a single-stage steerer corresponding to minimum and maximum required deflections.

Eq. 2 shows that the deflection depends on the particle energy and on the integral of the magnetic field along the particle path. Hence uniformity of the deflection does not require uniformity of the magnetic field but uniformity of the integral of the magnetic field along the particle path: particles can have the same deflection after experiencing different magnetic fields along their paths.

The integral of the magnetic field along the particle path is intrinsically a two-dimensional quantity. This opens the possibility of increasing the spatial resolution of numerical estimates of the deflection, without resorting to huge numbers of degrees of freedom [5]. As a matter of fact the analysis of the magnetic configuration has been realised in COMSOL, using the *emqav* application module; likewise COMSOL has been used to compute the particle trajectories and to model the magnetic field coils [6].

A numerical method has been realised also to estimate the power deposited on material surfaces [6]. Specifically each beamlet is subdivided into several small areas and the corresponding contribution to the particle flux is computed. By following the particle motion, each of the beamlet subdivisions is mapped onto its final position and the numerical estimation of the Jacobian of the transformation allows the computation of the initial-to-final ratio of the beamlet surface, giving a sort of intensifying factor for the heat flux. Since the energy of the beamlet is known, this procedure provides a local estimate of the heat flux.

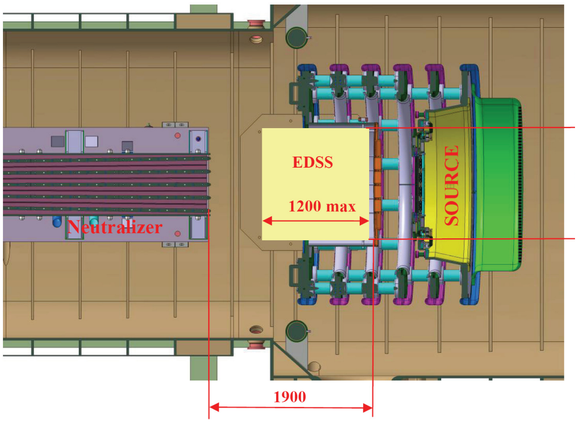

Fig.3 Proposed location of a steerer in ITER NBI.

4. Application to ITER

The feasibility of a steering system for ITER has been investigated [7]. The following requirements in terms of particle deflection have been assumed: ±3 mrad on the horizontal plane and ±14 mrad on the vertical plane.

The system has been located just downstream of the grounded grid (Fig. 3). In the vertical direction all the available space has been used; along the beam axis however, the necessity of pumping away the gas exiting the grounded grid limits the axial extension of the steerer. Due to the large difference between the vertical and the horizontal width of the beam at the exit of the accelerator, it seems better to install vertical electron dump plates. It is assumed that the plates extend 0.6 m in the axial direction.

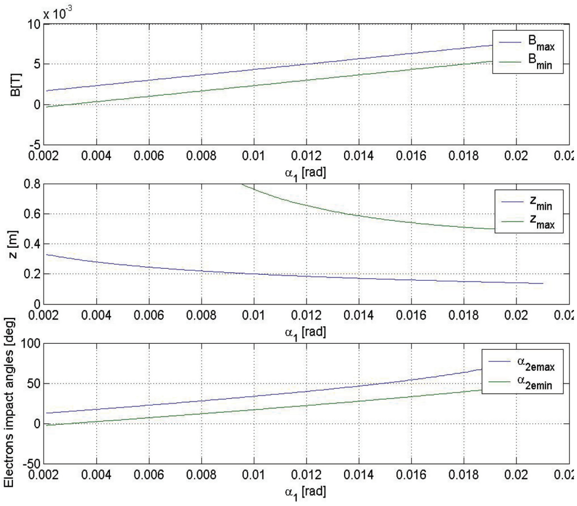

Fig.4 Single-stage steerer. Minimum and maximum magnetic fields corresponding to specified range of vertical deflection; corresponding minimum and maximum axial positions and incidence angles of impact of electrons on the electron dump.

As sketched in Fig. 2, the specified range of the ion deflection results in the specification of maximum and minimum values for the corresponding magnetic fields; in the case of a single-stage steerer, the results are shown in Fig. 4: as a function of the entrance angle of ions in the magnetic field, α_1, the required magnetic fields increase; the axial position where the electrons hit the dump plate decreases, their impact angle increases. These graphs can be used to define the minimum entrance angle of the particles, which results in the tilting angle of the beam source. A reduction of the plate length is desirable in terms of the reduction of the overall dimensions, but results in a larger impact angle and consequently in a large heat flux.

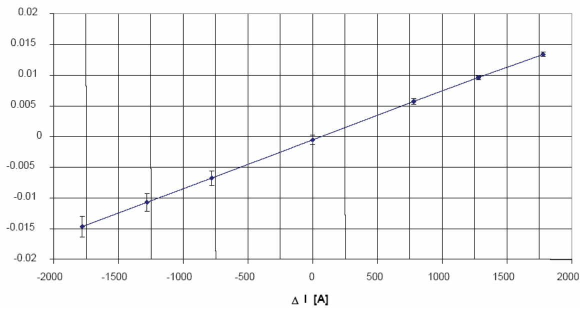

Fig.5 Negative ion deflection as a function of the current imbalance in the double-stage steerer.

In the case of the double-stage steerer, the first set of coils is dedicated to the horizontal deflection of electrons onto the dump plate; the second set of coils recovers the negative ion direction and provides the horizontal steering;

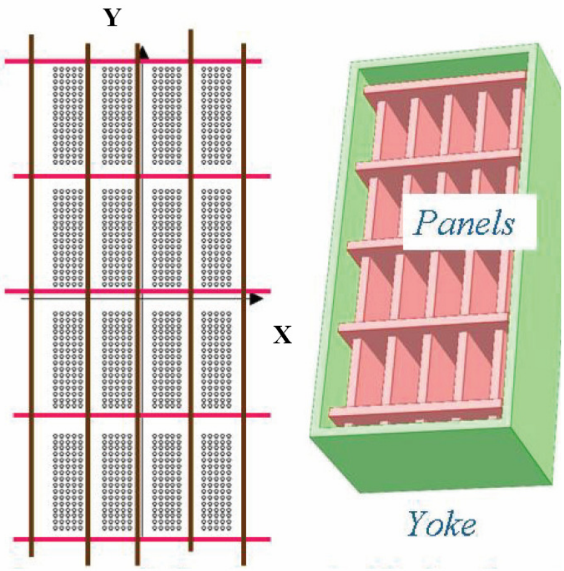

Fig.6 Conceptual design of a single-stage steerer. Electron dump plates, housing the coils, and magnetic yoke are shown.

another set of coils is interlaced to provide the vertical steering. Fig. 5 shows the ion deflection due to a current imbalance between the two sets of coils: it can be verified that the requirements are satisfied.

5. Conceptual design

A conceptual design has been developed for both steering systems; deflection of electrons is mainly performed on the horizontal plane.

Fig. 6 shows the case of the single-stage steerer. The magnetic coils are embedded in the electron dump plates. These plates are located between the beamlet groups, to shorten the distance between the plates and the apertures where electrons emerge. The magnetic yoke is also shown.

The double-stage steerer involves three sets of coils (see Fig. 7): the first stage forces the electrons onto the electron dump plates, which are vertical; a second set of coils compensates for the beam deflection induced by the previous set and provides the required horizontal steering of the beam; the last set of coils is interlaced with the second one and steers the beam in the vertical direction. The magnetic yoke surrounds the whole system.

5. Conclusions and future work

An active steerer can meet the requirements of ITER in terms of beam aiming, both horizontally and vertically. The system can be located in the space between the grounded grid and the neutraliser. The influence of the iron yoke on pumping efficiency is still to be assessed.

The advantages of active steering with respect to mechanical steering are: large flexibility, even at non-nominal acceleration voltages; control of power deposition profile and, consequently, of plasma instabilities; no need of mechanical tilting of the source; full control of beam aiming outside the vacuum vessel; controlled dumping of accelerated electrons; protection of cryopump panels from the radiation emitted at the electron dump plates.

Acknowledgments

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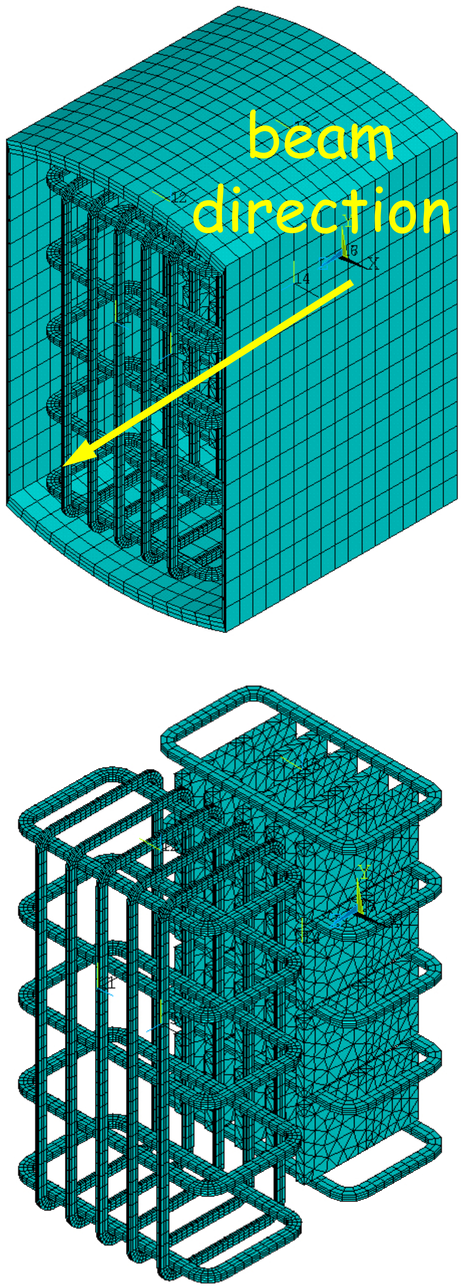

Fig.7 Conceptual design of a double-stage steerer. The three sets of coils are shown together with the electron dump plates and the magnetic yoke.