# Performance Optimization of the Electrostatic Accelerator for DTT Neutral Beam Injector

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Abstract-The main purpose of the Divertor Tokamak Test (DTT) facility is to study alternative solutions to mitigate the issue of power exhaust under integrated physics and technical conditions relevant for an International Thermonuclear Experimental Reactor (ITER) and a DEMOnstration Power Plant (DEMO). DTT will be equipped with a 510-keV, 40-A neutral beam injector (NBI) based on negative deuterium ion particles, designed to yield about 10 MW of neutral power to the DTT tokamak. The strongly triangular shape of the beam and the ITER-like multifocusing strategy required a different approach than more conventional solutions in designing the electrostatic plates in order to guarantee the desired beam deflection. This article describes the performance optimization process carried out for the injector of the DTT NBI system. In particular, a new electrostatic design concept for the accelerator grids has been implemented, the hyperlens grids (HGs): additional grids with a lens-like profile, imparting to each separate beamlet the necessary exit deflection without shape deformation.

Index Terms—Beam, Divertor Tokamak Test (DTT), injector, neutral, neutral beam injector (NBI).

## I. DESCRIPTION OF DTT NBI

**D** IVERTOR Tokamak Test (DTT), whose construction is starting at ENEA C.R. Frascati, Italy, is a new experimental facility whose purpose will be to investigate high-energy scenarios and power fluxes comparable to those foreseen of an International Thermonuclear Experimental Reactor (ITER) [1], by using a significantly smaller and versatile machine; its objective is to help better understand hot plasma interactions with plasma-facing components (PFC) and aid in the development of ITER and successively a DEMOnstration Power Plant (DEMO) [2], [3]. To be able to reach reactor-relevant power densities, DTT will need a significant amount of additional external heating (around 45 MW [4]), divided between electron cyclotron resonant heating (ECRH), ion cyclotron resonant heating (ICRH), and neutral beam heating (NBH), on which this article focuses.

The DTT neutral beam injector (NBI) will be a negative deuterium ion-based injector, with the following specifications.

1) An overall acceleration voltage of about 510 kV.

Manuscript received 27 January 2022; revised 11 March 2022; accepted 7 April 2022. The review of this article was arranged by Senior Editor G. H. Neilson. (*Corresponding author: Fabio Veronese.*)

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Digital Object Identifier 10.1109/TPS.2022.3169433

Correction Coils Versel Accelerator Ion source 5.4m DTT tokamak

Fig. 1. Overall view of DTT NBI in its position near the DTT tokamak. The main dimensions are also reported.

- An expected extracted current density of 250 A·m<sup>-2</sup>; considering 1360 extraction apertures of radius 7 mm, the total extracted current is 54.4 A.
- 3) Assuming a conservative overall efficiency of 0.4, from the initial value of 27.7 MW available, about 11 MW will enter the tokamak chamber.

DTT NBI, whose current conceptual design is shown in Figs. 1 and 2, will have a single air-insulated beam source, inspired by the Japanese NBIs of JT60 [5] and large helical device (LHD) [6], but using a radio frequency source concept instead, such as the one adopted for in ITER NBI [7]. The source is placed outside of a box-like vacuum vessel containing the beamline components (BLCs), i.e., the neutralizer, the residual ion dump (RID), and the calorimeter, ITER-like in their design. For vacuum pumping, a system based on nonevaporable getter (NEG) pumps [8] and turbomolecular pumps for regeneration is foreseen. More general information about the conceptual design of DTT can be found in [9].

Its overall focal length will be of about 12 m, making it a rather short device when compared, for example, with the similarly powered JT60 NBI (22.7 m [5]) or the future ITER NBI (25.4 m [7]). Being this close to the tokamak, the NBI region faces a strong stray poloidal field, capable of affecting operating parameters if not compensated.

A key aspect to improve the beam transmission efficiency is the aiming strategy of the beam and how to effectively implement it at the accelerator level.

## A. Source Aiming Description

The proposed design divides the acceleration of the particles into five separate electrostatic grids (see Fig. 3).

 Plasma grid (PG) at about -510 kV, separating the beam source cavity from the accelerator is where the negative deuterium ions and electrons are extracted.

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Fig. 2. Top section view with a functional scheme.



Fig. 3. Horizontal section of a beam group of the accelerator assembly. The distance between grids (in millimeters) is reported.

- Extraction grid (EG) at -500 kV: this slight potential difference and grid distance is key to the beam extraction and optics and may vary to optimize the beam.
- 3) Acceleration Grid 1 (AG1) at −333 kV, providing the first great potential jump to the particles.
- 4) Acceleration Grid 2 (AG2) at -166 kV, providing the second.
- 5) Grounded grid (GG) at ground potential.

Each grid is divided into four symmetric segments around a common main axis, connecting the center of the grid with the main focal point. In turn, each of these four main segments is then subdivided again into four "aiming planes" hosting a  $5 \times 17$  beamlet array. These 16 planes are slightly inclined so that their surface is tangent at the center to the spherical surface centered at the focal point and with a focal distance equal to the radius (see Fig. 4). In this way, each plane is already directed toward the desired focal point, thus requiring less effort for aiming the beam; also, from a beam trajectory standpoint, they are equal, meaning that all successive finer aiming corrections can be developed on a single plane and then extended to all without problems, which will simplify the work considerably.

## B. Full-NBI Aiming Strategy

"Aiming strategy" refers to the set of angular directions imposed on each beamlet to guide them along the beamline, allowing them to reach the plasma target with the highest power possible. For DTT NBI, the choice fell upon a



Fig. 4. Scheme detailing how the grids are segmented and each plane aligned in the direction of the focal point. Due to symmetry, analysis can be restricted to the area enclosed by the blue rectangle.



Fig. 5. Scheme detailing a horizontal section of the multifocus aiming strategy adopted for DTT NBI.

"multifocus" approach, inspired by the ITER NBI beamline (see Fig. 5).

- 1) Horizontally, each aiming plane has its main axis aligned to the main focal point, while each beamlet of the respective group is aimed at 6 m along the main axis.
- 2) Vertically, all aiming planes and beamlets are aimed at the main focal point.

This approach is very effective in reducing the horizontal beam cross section near-critical BLCs that would otherwise be more exposed to direct beam interception. This is especially true for the neutralizer: to guarantee an ideal neutralization rate, a fixed gas target thickness must be maintained within its walls with the lowest gas input possible, to avoid excessive particle fluxes for the vacuum system to remove; this is done by having very narrow and tall beam channels to reduce the gas conductance and hence the needed gas throughput to maintain the ideal gas density. However, this in turn means that there is very little space for the beam to pass without impinging, and reducing the beam cross section in this region increases transmission efficiency.

#### **II. HYPERLENS CONCEPT**

The aiming system described previously can guarantee a significant improvement of the overall transmission efficiency but needs a proper device, acting at the electrostatic level, able to enforce the desired aiming at the accelerator. Other



Fig. 6. Diagram detailing the concept at the base of the HG: the grid shape locally deforms the electric field imposing a specific direction to the beamlet.

machines make use of electrostatic aiming devices such as steering grids and kerbs, but these were found to be either not effective enough in aiming (when trying to preserve the beam shape) or deforming excessively the beam shape (when trying to meet the desired beam directions) in the DTT NBI case, mostly due to its relatively short focus distance and adopted multifocus aiming strategy. This led to the proposal of a new type of aiming device, the hyperlens grids (HGs).

The idea consists of adding companion grids placed in contact with the main ones, whose rear side profile is composed of different inclined exit planes, one for each beam aperture; in this way, each beamlet will be steered by the electrostatic field in the direction normal to its own plane (see Fig. 6). By accurately designing the inclination of these planes to have them steer each beamlet toward an intended focal point, a lenslike profile naturally emerges, hence named hyperlens.

This aiming effect can be adjusted independently in the horizontal and vertical directions, meaning that two separate focal points are not an issue; it can also be split between successive grids, to increase the steering effect while minimizing the overall length of the accelerator assembly and avoiding undesired beam loads. Indeed, inside the apertures, beams feel little electrostatic pull and start to diverge due to self-charge, and if the channel is too long due to excessive additional grid thickness, it may start to impinge inside the aperture itself.

#### A. Application to the DTT Accelerator Assembly

The HG concept has then been applied to the DTT accelerator.

- The first step is to determine the control quantities; it is easy to see a direct correlation between beamlet direction and plane slope, in either horizontal or vertical direction. Achieving the ideal aiming is therefore a matter of finding the correct set of slopes.
- 2) The second step is to check the symmetries of the problem: due to how the aiming strategy in DTT is set up, all the  $5 \times 17$  beam group arrays are formally equal and also symmetric around their center. This means that only two columns (plus the center column) by eight rows (plus the center row) need to be simulated.



Fig. 7. Scheme illustrating the principle of the complete hyperlens profile. Its modular nature is evidenced in dashed lines: these hexagonal shapes allow a continuous junction even if the aiming planes have not the same inclination.

The idea is then to create two  $3 \times 9$  matrices (2 + 1 row)beamlets by 8 + 1 column beamlets), containing the slope values in the horizontal  $(\Delta h_{ij})$  and vertical  $(\Delta v_{ij})$  directions that can be chosen all independently of each other. The HG can be visualized as similar to an elevation map on a grid; to obtain the four corners of the desired plane for the *ij*th beamlet (represented by the *x*-coordinates in the model), the slope values must be combined such as

$$x_{i,j}^{\text{top}} = \sum_{n=1}^{i} \Delta h_{n,j} + \sum_{m=1}^{j} \Delta v_{i,m.}$$
(1)

This is the most elevated point of the aiming plane of the *ij*th beamlet. The other three points can be obtained similarly

$$x_{i,j}^{\text{left}} = \sum_{n=1}^{i-1} \Delta h_{n,j} + \sum_{m=1}^{j} \Delta v_{i,m}$$
(2)

$$x_{i,j}^{\text{right}} = \sum_{n=1}^{l} \Delta h_{n,j} + \sum_{m=1}^{J-1} \Delta v_{i,m}$$
(3)

$$c_{i,j}^{\text{bottom}} = \sum_{n=1}^{i-1} \Delta h_{n,j} + \sum_{m=1}^{j-1} \Delta v_{i,m}.$$
 (4)

This procedure, to be repeated for each of the beamlets, is shown in Fig. 7. One aspect to pay attention to is that now, there is the possibility that adjacent aiming planes are not always equally inclined, and consequently, they cannot be connected by a simple planar junction; they can be connected by triangles instead, obtaining a hexagonal modularity. Once the shape of the grid is established, other design aspects must be considered.

1) Number of HGs: An important aspect is the number of additional HGs to use in the accelerator; this is usually the result of an iterative process since not all HGs coupled with different grids give the same performance, due to the different energy of the particles in the beams between grids. In this first design iteration, the use of only two identically sloped HGs was found to be sufficient, to keep the design parameters as simple as possible.

2) Beamlet Apertures' Offsets: Another matter to consider is the placement of the beamlet apertures throughout the grids; usually, they are placed in regular arrays equally spaced across



Fig. 8. Three-dimensional render of the DTT NBI accelerator assembly in a 40-beamlet subset, where the HGs have been applied. A detail of the HG is present.

the grids, but in DTT NBI with its strongly converging beam shape, this approach can lead to intense heat loads due to beam impingement. The solution adopted in the DTT NBI accelerator was then to "follow" the quasi-parabolic beam trajectories, slightly modifying the position of each aperture on each grid such that the beamlet array at the GG level would be a predetermined one (20-mm horizontal spacing and 22-mm vertical spacing). These offsets from the regular array are once again obtained after an iterative process and have already been implemented in the first design.

3) Criss-Cross Deflection Effect (CCDE) Compensation: All negative ion beams face the issue of coextracted electrons, meaning electrons from the ion source that are coextracted with the ions and cause undesired power losses. To suppress them as early as possible, dedicated magnets are embedded in the EG to effectively deflect them onto the grid itself, but this causes an offset effect of the ion beams, alternating in the horizontal direction between rows (called CCDE). There are various methods to compensate for this effect, but in DTT NBI's case, it has been chosen to preemptively shift the apertures on the PG in the opposite direction (about 0.5 mm), such as to have ideally the beamlets centered again after the EG and not interfere with the effect of the HGs. This approach also significatively simplifies the successive simulations: by assuming that the beamlets are centered at the EG, there is no need to simulate the effect of the suppressing magnets on the ion beam.

All these aspects have been implemented together in a first design for the DTT NBI accelerator using HGs, as shown in Fig. 8.



Fig. 9. Detail of the SLACCAD simulations on beam divergence. (a) and (b) Refer to the limit cases for the HG.

## **III. PARTICLE TRACING SIMULATIONS**

To validate each iteration of the design of the accelerator, the same combination of particle tracing codes was used.

- 1) SLACCAD, a ray-tracing axial-symmetric code, capable of accurate modeling of the beamlet self-charge, responsible for the space-charge-limited emission; the formation of the so-called "meniscus," the surface where the particles start to feel the pull of the electric field and that is key to determine the initial optics of the beam; and the beamlet self-divergence. These aspects are key in determining the beam quality in terms of exit divergence and give important inputs to the successive multibeamlet simulations (see Fig. 9).
- 2) COMSOL<sup>1</sup> multiphysics, a commercial finite element method code, capable of modeling 3-D coupled electromagnetic field-particle interactions, important to evaluate beamlet-to-beamlet repulsion and the effect of the HGs. The exit directions are then postprocessed and confirmed with the reference values (see Fig. 10).

The main figures of merit that need to be evaluated in these simulations are the average deflections and the divergences of each beamlet.

 The average deflection of the *ij*th beamlet is defined as the mathematical average of the ratio of one of the two transverse velocity components and the main axial velocity component between all of the particles of a beamlet; its value represents the direction that the beamlet is as follows. Its value is measured in millirads (mrad), and if the accelerator is oriented with the main axis along the *x*-axis, in case of a beamlet containing *N* particles, the average deflection can be calculated as

$$\theta_{y \text{ or } z} = \frac{1}{N} \sum_{k=1}^{N} \frac{v_{y,k \text{ or } z,k}}{v_{x,k}}.$$
(5)

2) The divergence of the *i j*th beamlet is defined as the rms value of the ratio of the total transverse velocity and the main axial velocity between all of the particles of a beamlet and represents the rate at which the beamlet

1Registered trademark.



Fig. 10. Main results of the particle tracing simulations. (a) Trajectory plot of a 40-beamlet subset of a beam group, where the color represents the particle deflection. (b) Graph comparing the calculated average deflection for each beamlet (blue) to the reference directions (red).

is expanding in size. Its value is also measured in mrad and written as

$$\theta_{\rm RMS} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \frac{v_{y,k}^2 + v_{z,k}^2}{v_{x,k}^2}}.$$
 (6)

The objective is to reach a design that guarantees the following:

- each beamlet not exceeding 7 mrad of exit divergence, in order to have optimally focused beamlets with limited power dispersion.
- 4) each beamlet with a deflection error not exceeding 2 mrad with respect to the ideal direction dictated by the aiming strategy.

After some iterations, a design satisfying these requirements has been found, using two HGs of thickness varying between 2.5 and 8.5 mm, with an exit divergence ranging from 2.65 to 4.66 mrad; since these grids do not have a constant thickness, beamlets do not follow the same electrostatic path, meaning also that the exit divergence is not constant but rather in a range of values. Also, the extraction voltage (the voltage gap between PG and EG, a very important parameter for the beam optics) was parametrically changed, looking for the minimum



Fig. 11. Parametric results from SLACCAD: the only value of the extraction voltage where both of the limit cases are under 7 mrad is at 7.2 kV.

range of values of the divergence; the said minimum was found with an extraction voltage of 7.5 kV. The maximum absolute error in deflection in this configuration was found to be 1.83 mrad.

## A. Application to Off-Nominal Energy Scenarios

One important and desired aspect from the plasma physics' point of view is the possibility for the NBI to operate even at different acceleration energies from the nominal one. Regarding the HGs in particular, another set of simulations has been carried out to check the performance of the accelerator in the test case of operation with half of the nominal acceleration voltage (255 kV) and the same current.

Operation in this regime requires a different strategy in distributing the voltages across the grids; it is important to maintain the same voltage jumps where the beam is still slow (i.e., near PG, EG, and AG1) rather than decreasing them uniformly. Second, the extraction voltage has to be retuned in order to obtain satisfying optics from the beamlets since the electrostatic field distribution has changed: a parametric simulation for both of the limit thickness values of the HGs changing the extraction voltage can identify a value where the exit divergence is minimized for both. The SLACCAD simulations have given interesting results in terms of divergence, identifying the new extraction voltage as 7.2 kV with divergence that ranges from 5.19 to 6.68 mrad (see Fig. 11).

Using the best case from SLACCAD, the COMSOL multibeamlet simulation has been run to obtain the exit deflections (see Fig. 12). The results show an increase in the maximum absolute error in deflection, reaching 4.11 mrad, that can be explained as follows.

- 1) The HGs losing a small part of their deflection efficacy due to the flattening of the electrostatic lenses.
- 2) The reduction in energy: in fact, HGs are affecting the transverse velocity components in the same fashion, but since the axial component is reduced by a factor of  $\sqrt{2}$ , the already present error is magnified.
- 3) The slower beamlets have more time to interact, repelling each other farther than the nominal case.

#### IV. CONCLUSION

In this article, a description of the aiming strategy to be implemented in DTT NBI has been given, intended to maxi200

180

160

140

120

100

80

60

40

20

0

0

z [mm]



200

Ideal

Calculate

y [mm] Fig. 12. Results from COMSOL, comparing ideal beam directions (red) with the calculated ones (blue) in the half-energy scenario.

100

150

50

GG exit plane

mize particle transmission along the beamline. Also, a novel aiming device able to support this strategy has been devised and applied to the DTT case: the HGs approach was found to be very effective in aiming all the beamlets with the desired directions, respecting the imposed requirements.

Moreover, this design solution has been found to be effective in aiming the beamlets not only in the reference operating conditions but also when operating the NBI with lower values of beam energy.

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