Compensation of beamlet deflection by mechanical offset of the grids apertures in the SPIDER ion source

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***Abstract*— The SPIDER experiment has the main goal to test the extraction of negative ions from an ITER size ion source. It is designed to extract 1280 negative ion beamlets and accelerate them up to a 100 kV potential. The negative ion beam at exit and the operating parameters will be carefully measured and optimized in order to match the ITER requirements for the NBI (Neutral Beam Injector) ion sources. Inside a negative ion accelerator, there are generally two main factors that can cause deflection of the ion beamlets: the repulsion among beamlets and the electron suppression magnetic field. These two effects are both to be considered highly detrimental for the ITER NBI, as they are expected to cause higher heat loads on the ITER NBI neutralizer and decrease the overall beam quality (in terms of aiming and divergence). Hence they should be considered and minimized also for the SPIDER device, where it will be possible to precisely investigate the beamlet footprint using an instrumented calorimeter relatively close to the accelerator exit. This paper presents a design optimization process aiming at compensating the two described effects. To make this, a mechanical offset of the grounded grid apertures is considered. The OPERA-3D code (Vector Fields Co. Ltd.) is used as the main tool for this optimization process, as it can take into account the beamlet repulsion and the interaction between beamlets and grids. This is made by solving the electrostatic Poisson's equation with a finite element approach, to calculate the particle trajectories of the negative ions under the influence of electrostatic fields, magnetic fields and space charge.**

Keywords-ITER; ions; beam; deflection; compensation

I. INTRODUCTION

In the framework of the activities for the development of the Neutral Beam Injectors for ITER, SPIDER (Source for Production of Ion of Deuterium Extracted from RF plasma) is the first experimental device to be built in Padova (Italy), aiming at testing the extraction of a negative ion beam (made of H^- and in a later stage D^- ions) from an ITER size ion source. The main requirements of this experiment are a H^- / D^- current of 60 A / 40 A and an energy of 100 keV. The main purpose of SPIDER is to optimize the ion source performance by maximizing the extracted negative ion current density and its spatial uniformity and by minimizing the amount of co-extracted electrons, in order to match the ITER requirements [1].

The Beam Source has the function of creating and accelerating the negative ions starting from hydrogen or deuterium gas, and can be considered as one of the main devices inside the NBIs. In SPIDER, the Beam Source assembly, kept at -100 kV by electrical power supplies and ceramic insulators, is made of a Radio Frequency (RF) ion source and a three grids extractor/acceleration system (see Fig. 1) featuring a Plasma Grid (PG), an Extraction Grid (EG) and a Grounded Grid (GG). Hot neutrals are converted into negative ions on low work function metallic surfaces. Cesium is evaporated in the source in order to enhance the negative ion production.

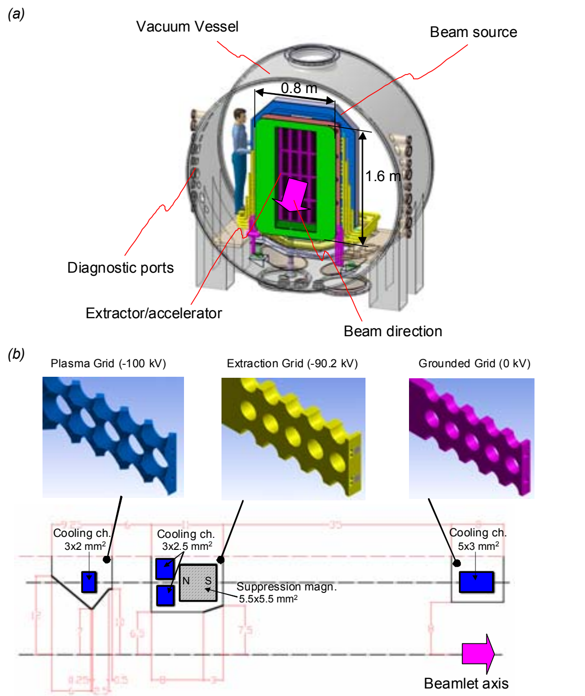

Figure 1. Scheme of the grids for the SPIDER extractor/accelerator system: (a) Design overview; (b) Detailed view of the grids.

The PG, heated by the plasma inside the RF ion source, is required to operate at a temperature of about 150° C in order to enhance the cesium effect for negative ions surface generation. The apertures are designed with conical chamfers on the upstream and downstream sides of the grid. A larger surface for ion production and a more efficient extraction is obtained with this solution.

The EG has an electric potential that is 9.8 kV higher than the PG, so that the negatively charged ions (H^- or D^-) can be properly extracted from the RF expansion chamber. Suppression magnets, embedded in the grid, have the function to deviate the trajectories of the co-extracted electrons, making them collide with the EG surface. The consequent power loads are quite high and concentrated, hence this grid is the most critical by the structural point of view, and is designed with a high performance cooling system.

The GG has the function to accelerate the ion beamlets up to a potential of about 100 kV, and is also loaded by co-extracted and stripping electrons.

Each of these grids features 1280 apertures, along which the ion beamlets are extracted and accelerated. The apertures must be carefully aligned in order to obtain a good aiming of the beamlets. This is not trivial because the EG and GG are highly loaded by co-extracted and secondary electrons, and the power loads are highly influenced by the operating scenario [2].

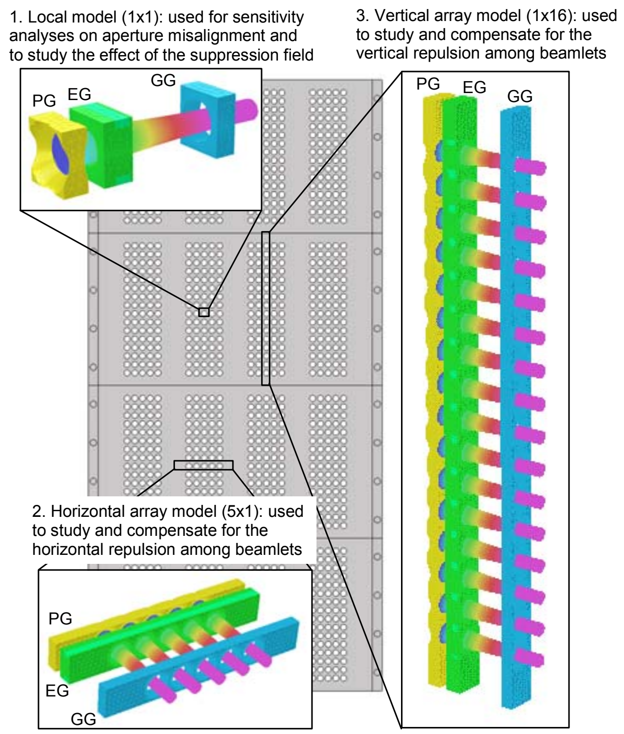

Figure 2. Models of the SPIDER extractor/accelerator system used for the investigations on beam optics and aiming.

This paper presents some analyses performed with the code OPERA-3D [3], aiming at estimating:

- The effect of possible misalignment/offset between the corresponding apertures of the grids.
- The effect of the horizontal and vertical beamlet/beamlet repulsion due to space charge, and a design proposal to compensate for it. The repulsion between ion beamlets causes a deflection effect in the outward direction, which is negligible for the beamlets located in the centre of an aperture group and maximum for the peripheral apertures, with a consequent increase in the divergence of the whole beam.
- The effect of the electron suppression magnetic field (given by the permanent magnets in the EG) on the ion beamlet trajectories, and a design proposal to compensate for it. This field is useful for the suppression of the co-extracted electrons but, as a side effect, causes a difference in deflection between adjacent rows of beamlets, with a consequent ripple effect at the vertical sides of the beam footprint.

The operating conditions considered for the analyses are the reference ones for the SPIDER device: hydrogen negative ions and 60 A total accelerated beam current. More detailed information can be found in [2]. The three considered models are summarized in Fig. 2.

II. Sensitivity analysis on aperture offset

The position of grid apertures in an electrostatic accelerator can influence the direction of the beamlet, as suggested by Kashiwagi et al. in [4] for the JT60 NBI accelerator.

The local model (see Fig. 2) has been used to estimate the deflection of a beamlet due to a possible misalignment between the corresponding apertures of the three grids of the SPIDER extractor/accelerator system. The beamlet was simulated by launching a high number of macro-particles (1261 in this case) from a parabolic emitter surface (generated with a macro in MATLAB®) reproducing the meniscus shape calculated by the SLACCAD code in cylindrical symmetry (see [2]). The macro-particles are then accelerated by the electrical fields applied by the grids, and at the same time they interact among each other (i.e. the repulsion due to space charge is taken into account). The electrical potential in every point is iteratively calculated by solving the Poisson's equation in a 3D domain.

Due to the curved shape of the equipotential lines, the beamlet is deflected in presence of an offset between the apertures in the three grids. In fact, there are two field curvatures inside the EG: one concave at the upstream side (close to the PG-EG gap) and a second convex at downstream side (close to the EG-GG gap), as can be seen in Fig. 3a. Due to the fact that the electrical field in the second gap is stronger than the one in the first, if the EG aperture is offset rightward the average deflection given by the second curvature prevails over the one given by the first one, so that there is a residual deflection effect rightward. As there is no field after the GG, only a concave curvature exists inside this grid at the upstream side (see Fig. 3b). Hence, when for example the GG aperture is offset rightward, the beamlet is deflected leftward.

The results of a sensitivity analysis, carried out to find a correlation between the aperture offsets and the beamlet deflection, are summarized in Fig. 3c. If there is a misalignment among the apertures on the three grids (caused for example by non-nominal thermal loads on the grids) the correlated beamlet deflection can be estimated from the interpolating formulae (reported in Fig. 3c). On the other hand, if there is some deflection effect due to other causes (like space charge or magnetic field), it can be compensated by a proper offset deliberately applied to the apertures, as described in the next paragraphs.

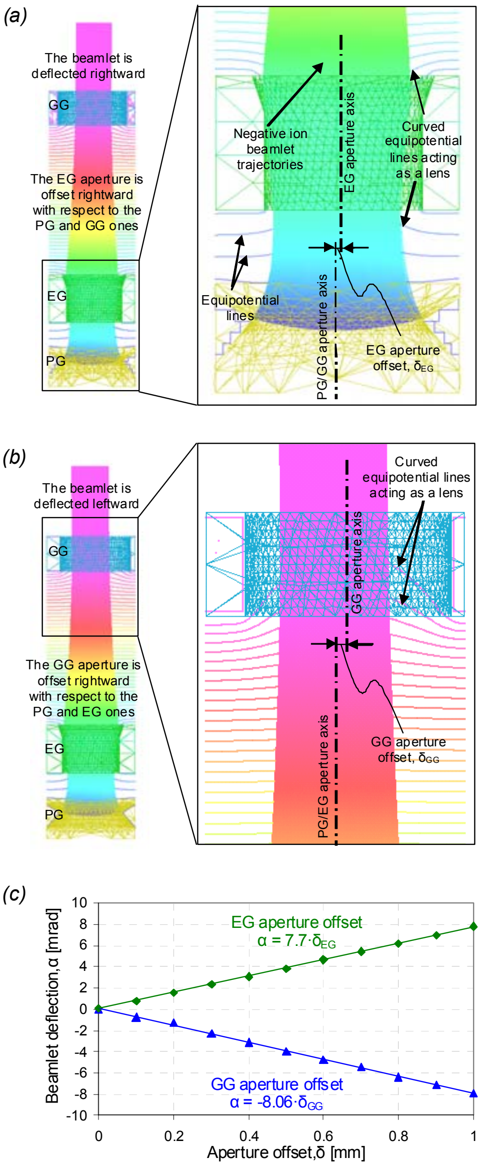

Figure 3. Analysis of the effect of misalignment or offset between corresponding apertures on the three grids: (a) Effect of an EG aperture offset; (b) Effect of a GG aperture offset; (c) Correlation between aperture offset and beamlet deflection.

III. Compensation of the Repulsion Among Beamlets

The repulsion between ion beamlets can cause a deflection effect in the outward direction, which is negligible for the beamlets located near the centre of an aperture group and maximum for the ones located at the peripheral apertures, with a consequent increase in the divergence of the whole beam. This effect happens both in the horizontal and vertical directions.

The horizontal array model (see Fig. 2) has been used to estimate the beamlet deflection due to the repulsion between 5 adjacent beamlets. Parallel electrical field boundary conditions are applied to the four domain borders parallel to the beamlet axis. Half of the frame width is simulated at the left and right sides of the aperture array.

The result (see Fig. 4a) is that the external beamlets are deflected outward. In particular the first and the fifth beamlets present a deflection of 2.4 mrad, while the second and fourth ones are deflected of about 0.5 mrad. These deflections are evaluated by the calculating the average value of the horizontal deflection for every beamlet at the accelerator exit. Analyses with two beamlet groups were also performed, showing that the repulsion between beamlet groups is negligible.

In order to compensate for the deflection due to the repulsion among beamlets, a proper mechanical offset was applied to the apertures 1,2,4 and 5.

As shown in Fig. 3c, both an offset of the EG and GG apertures are able to deflect the beamlets. Nevertheless, offsetting the EG apertures seems not advisable, because of the risk to make beamlets collide with the aperture internal surfaces, as the difference between the beamlet and aperture radius is quite small at the EG (see Fig. 3a). Such an event would cause a highly concentrated heat load with a consequent power loss, spoiled beam optics and risk of localized melting.

On the other hand, at the GG aperture the beamlet is quite distant from the aperture internal surface, because the beamlet itself has a smaller diameter and the GG aperture diameter is larger than the EG one. Consequently, it appears safer to apply an offset to the GG apertures than to the EG ones. Moreover, the steering constant of the GG aperture is almost independent of the extraction voltage chosen, whereas the steering constant of the EG aperture depends strongly on it.

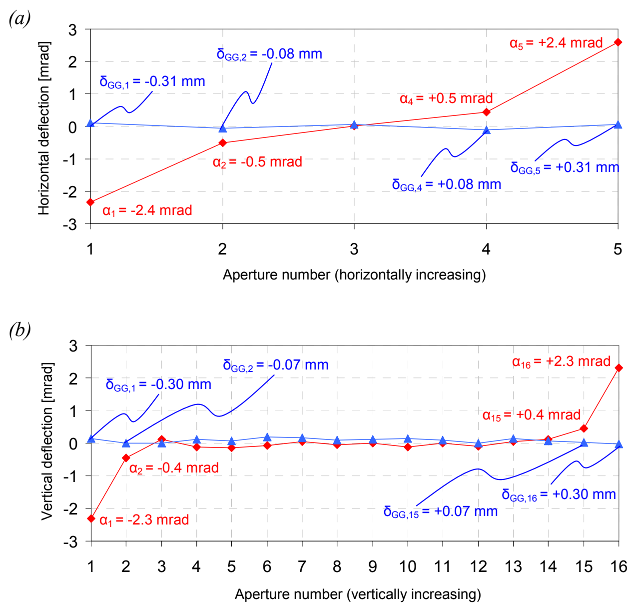

Figure 4. Beamlet repulsion compensation: (a) Horizontal deflection compensation; (b) Vertical deflection compensation. The red dots represent the beamlet deflections due to the interaction between beamlets; deflections angles for each beamlet are reported in red. The blue dots represent the beamlet deflections after introducing proper offsets to the GG apertures, that compensate for the repulsion between beamlets; the optimized values of the aperture offsets are reported in blue.

The proper values for the offsets have been calculated with the inverse of the GG offset formula reported in Fig. 3c:

$$\delta_{GG} = -\alpha / 8.06 \quad (1)$$

where α is the deflection in mrad and δ_{GG} is the GG aperture offset in mm. By applying these mechanical offset to the GG aperture, the repulsion effect was completely compensated. This is visible from Fig. 4a, where the applied offsets are reported in blue.

An analogous method has been applied for the compensation of the repulsion among beamlets in the vertical direction. First of all, an analysis with no aperture offset was carried out using the vertical array model. The results show that the two upper and two lower beamlets are deflected respectively upward and downward (see Fig. 4b). Then, the proper offsets to be applied in order to compensate the repulsion have been calculated with formula (1), analogously to the horizontal direction. After introducing these offsets to the GG apertures of the involved beamlets (1,2,15 and 16), also the vertical repulsion was compensated.

Based on these results, the following offsets are to be applied in order to cancel the effect of the repulsion between beamlets in a 5x16 beamlet group (see also Fig. 4a and 4b):

- the GG apertures columns 1 and 5 must be offset by 0.31 outward;
- the GG apertures columns 2 and 4 must be offset by 0.08 outward;
- the GG apertures rows 1 and 16 must be offset by 0.30 outward;
- the GG apertures rows 2 and 15 must be offset by 0.07 outward.

IV. COMPENSATION OF THE SUPPRESSION MAGNETIC FIELD

The magnetic field given by the electron suppression magnets in the EG (see Fig. 1b) has the function to deflect the electrons which are extracted from the ion source together with the negative ions. As an unwanted side effect, this field deflects also the negative ions. As the polarities of the magnets are alternated from row to row, the beamlet deflections are also alternated, causing a vertical ripple effect on the beam footprint. The horizontal filter field is not considered in these simulations, as it is found to be almost uniform with the optimized magnetic configuration of SPIDER [5], and so it shouldn't be detrimental for the beam optics. Parallel electrical field boundary conditions are applied to the four domain borders parallel to the beamlet, and parallel magnetic field to all the borders.

The deflection due to the suppression magnetic field has been estimated with the local model to be in the SPIDER accelerator of about 8 mrad. In order to compensate for it, the GG apertures should be offset by 1 mm (see Fig. 5). Other possible strategies, presently under study, are to compensate for these deflections by means of magnets and ferromagnetic material inside the GG, or by means of proper kerbs near the aperture groups borders.

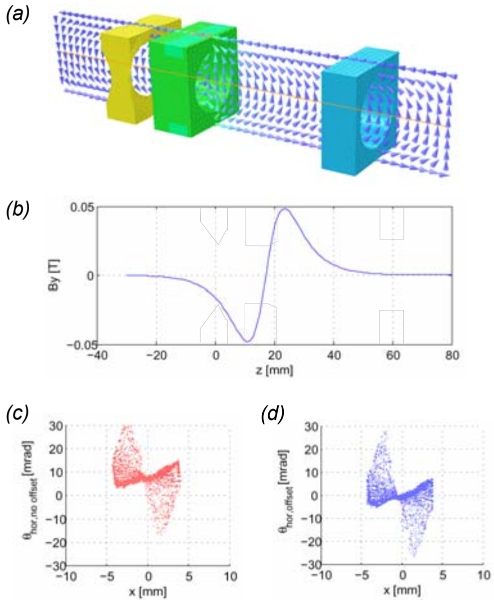

Figure 5. Magnetic field compensation: (a) Magnetic field vector plot in the analysis domain; (b) B_y field along the beamlet axis (c) Horizontal divergence, without offset. A horizontal deflection of 8 mrad rightward is observed; (d) Horizontal divergence, with offset. The beamlet deflection due to the magnetic field is compensated by a 1mm offset of the GG aperture rightward.

V. CONCLUSIONS

This paper describes a method, based on aperture offset, to compensate for beamlet deflections due to space charge (repulsion among beamlets) and to the electron suppression magnetic field in the SPIDER accelerator. Suitable offsets of the GG apertures for a proper compensation are presented.

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