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Complete Compensation of Criss-cross Deflection in a Negative Ion Accelerator by Magnetic Technique

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Abstract. During 2016, a joint experimental campaign was carried out by QST and Consorzio RFX on the Negative Ion Test Stand (NITS) at the QST Naka Fusion Institute, Japan, with the purpose of validating some design solutions adopted in MITICA, which is the full-scale prototype of the ITER NBI, presently under construction at Consorzio RFX, Padova, Italy.

The main purpose of the campaign was to test a novel technique, for suppressing the beamlet criss-cross magnetic deflection. This new technique, involving a set of permanent magnets embedded in the Extraction Grid, named Asymmetric Deflection Compensation Magnets (ADCM), is potentially more performing and robust than the traditional electrostatic compensation methods.

The results of this first campaign confirmed the effectiveness of the new magnetic configuration in reducing the criss-cross magnetic deflection. Nonetheless, contrary to expectations, a complete deflection correction was not achieved. By analyzing in detail the results, we found indications that a physical process, taking place just upstream of the plasma grid, was giving an important contribution to the final deflection of the negative ion beam. This process appears to be related to the drift of negative ions inside the plasma source, in the presence of a magnetic field transverse to the extraction direction, and results in a non-uniform ion current density extracted at the meniscus.

Therefore, the numerical models adopted in the design were improved by including this previously disregarded effect, so as to obtain a much better matching with the experimental results. Based on the results of the first campaign, new permanent magnets were designed and installed on the Extraction Grid of NITS. A second QST-Consorzio RFX joint experimental campaign was then carried out in 2017, demonstrating the complete correction of the criss-cross deflection and confirming the validity of the novel magnetic configuration and of the hypothesis behind the new models.

This contribution presents the results of the second joint experimental campaign on NITS along with the overall data analysis of both campaigns, and the description of the improved models. A general picture is given of the relation among magnetic field, beam energy, meniscus non-uniformity and beamlet deflection, constituting a useful database for the design of future machines.

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INTRODUCTION

Consorzio RFX in Padova is hosting the construction of MITICA, the full-scale prototype of the NBI for ITER. MTICA accelerator has to reach unprecedented parameters: a D^- current of 40 A, accelerated at 1 MeV for 1 hour continuous operation [1-2]. In order to reach the required power and to sustain the thermal loads on the accelerator grids, on the neutralizer panels and on the duct below acceptable limits, the optics quality of the beam has to be very good, with low divergence and deflection angle of each one of the 1280 beamlets constituting the beam.

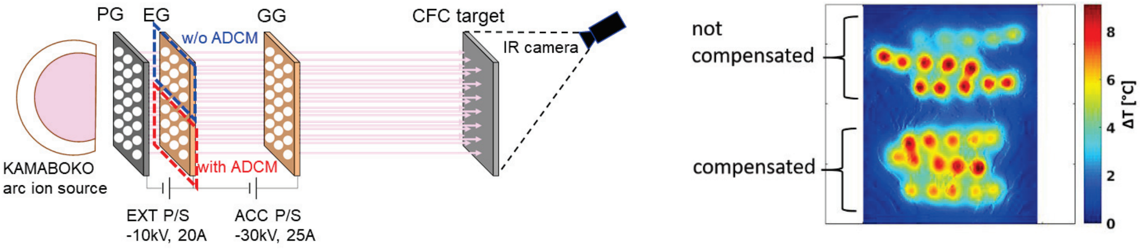
In order to confirm the validity of the design solutions chosen for MITICA accelerator and foreseen also for DEMO NBI, a collaboration was established between Consorzio RFX and QST, which led to two joint experimental campaigns on the negative ion accelerator NITS at QST Naka, Japan [3-5].

One of the main goals of the joint campaigns was to test a design solution developed at Consorzio RFX for the compensation of the criss-cross deflection, a phenomenon occurring in negative ion accelerators due to the effect of the permanent magnets embedded in the extraction grid for suppressing the co-extracted electrons. This effect produces a horizontal scatter of the beamlet rows as shown in Fig. 1(b).

The results demonstrated the complete compensation of criss-cross deflection , thus obtaining a beam with very low horizontal deflection angle, and allowed the improvement of the numerical models for simulating negative ion beams.

SUMMARY OF FIRST JOINT EXPERIMENTS

The first Joint Experiments (JT1) took place in 2016; their purpose was the validation of the criss-cross deflection compensation by the use of an innovative technique involving a set of magnets called Asymmetric Deflection Compensation Magnets (ADCM) in addition to the standard Co-extracted Electron Suppression Magnets (CESM). At that time, a MITICA-like extraction grid was designed and realized by Consorzio RFX, and then installed on NITS accelerator at Naka [3]. For the joint experiments, NITS accelerator is configured to extract two beamlet groups of 3x5 apertures each. ADCM were installed in only a half of the grid, corresponding to the bottom beamlet group, so as to directly compare their effect with the top beamlet group, where the beam is left not compensated. Criss-cross deflection is evaluated by analyzing the IR images formed by the beam on a CFC target, as shown in Fig.1.



(a) (b)

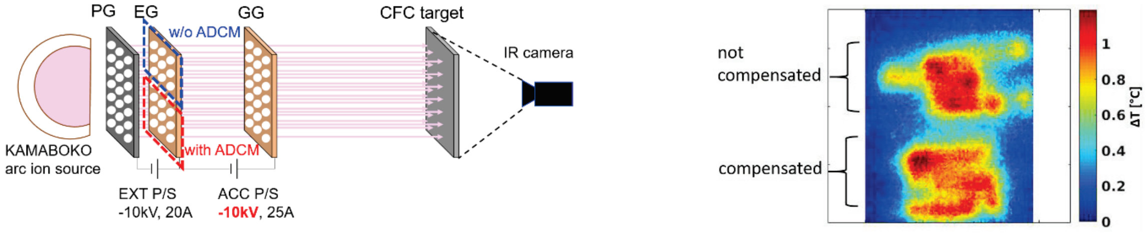
FIGURE 1. (a) Experimental setup of first joint experiments (b) example of IR image formed on CFC target.

JT1 demonstrated the effectiveness of the ADCM in compensating the criss-cross magnetic deflection [4]; anyway, a complete compensation of the deflection was not achieved, due to a non-perfect design of the CESM and ADCM magnets, caused by an under-estimation of the residual deflection by the numerical models. By a detailed analysis of the results, it was supposed that the origin of the increased criss-cross deflection might be a non-uniformity of the negative ion current extracted at meniscus (the interface between the plasma and the beam), possibility already highlighted by Veltri in [6] and [7]. This non-uniformity can be due to an **E x B** plasma drift inside the source. This hypothesis seems to be confirmed by the work of Fubiani [8] and Taccogna [9]. Details are given in the next sections.

SUMMARY OF SECOND JOINT EXPERIMENTS

The Second QST-Consorzio RFX Joint Experiments (JT2) took place in December 2017, although a series of troubles with the NITS acceleration power supply retarded the operation and limited the acceleration voltage to 10 kV. The permanent magnets for JT2 were designed on the base of the results of the first campaign. The IR camera was moved in coaxial position with respect to the beam (Fig. 2 a).

Though the IR images obtained during JT2 have much lower beamlet resolution, due to the limit on the acceleration voltage, with consequent worse beam optics and lower signal on the calorimeter, it can be noticed how this time the criss-cross deflection has been almost completely compensated (Fig. 2 b).



(a) (b)

FIGURE 2. (a) Experimental setup of second joint experiments (b) example of IR image formed on CFC target.

After JT2, the numerical models were further improved, exploiting the assumption that the current non-uniformity at meniscus is proportional to the transverse magnetic field. In this way, all the experimental results were reproduced by simulations, with a good approximation. In the next section, the analysis of the results of both the campaigns is presented.

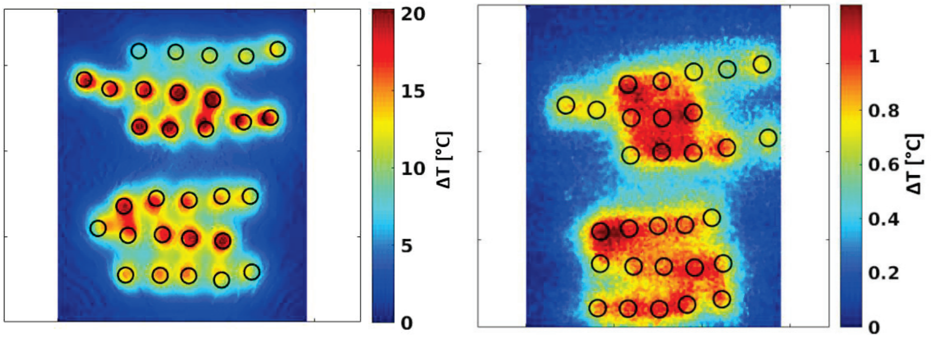
ANALYSIS OF THE RESULTS

IR images of both campaigns have been analyzed with a recently improved tool, which filters the image noise and then applies an image fitting using an approximating function defined as the sum of 30 Gaussians, one for each beamlet:

$$z(x,y)=\sum_{i=1}^{30} A_i \exp\left(-\left(\frac{x-x_i}{w_i}\right)^2-\left(\frac{y-y_i}{w_i}\right)^2\right)$$

In this equation, x and y are the spatial coordinates of the IR image (in mm), $z(x,y)$ is the approximating function, x_i and y_i are the centers of the 30 Gaussians determined by the fitting, w_i the Gaussian widths (assumed to be constant in each of the two top and bottom beamlet groups), and A_i the Gaussian amplitudes.

Figure 3 compares the IR image fitting for a pulse belonging to first JE and one belonging to second JE.



(a) (b)

FIGURE 3. Fitting of IR images. The black circles represents the position and the width of the 30 Gaussians approximating the thermal footprints of the 30 beamlets. (a) Pulse #12032, from first joint experiments, (b) pulse #36541, from second joint experiments.

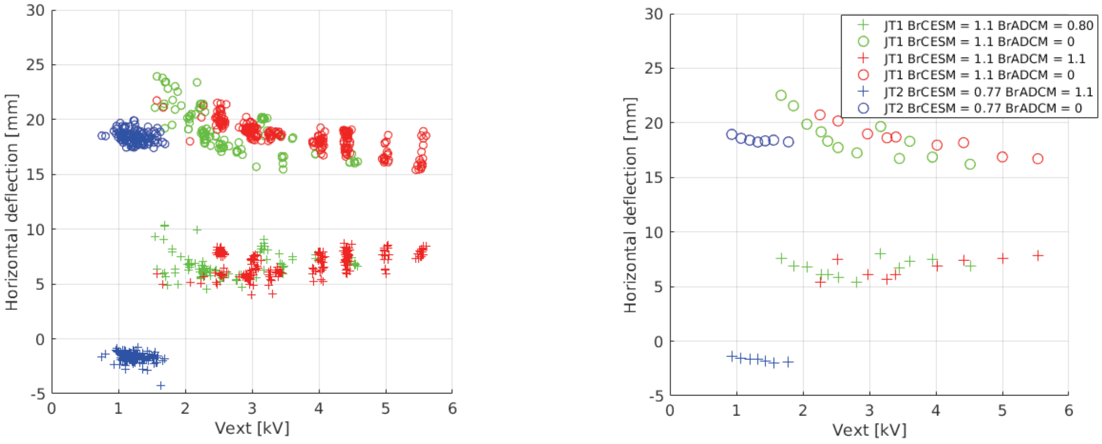
Once determined the beamlet positions by the fitting procedure, the average criss-cross deflection can be easily calculated for a given magnetic configuration. Averaging the deflection on the rows, allows also to neglect the effect of the beamlet repulsion, which may affect the absolute deflection of each single beamlet. The beamlet repulsion is anyway very little: the pitch between the beamlet footprints on target is very similar to the pitch of the apertures (19 mm horizontally and 21 mm vertically).

During the two campaigns, five different combinations of Sm_2Co_{17} CESM and ADCM with different strength have been tested, as reported in Table 1. JT1 are divided in two parts; in the first one, ADCM with Br = 0.88 T have been tested, they have been then substituted with stronger ADCM, Br = 1.1 T. Only one set of CESM was available during JT1, having Br = 1.1 T.

TABLE 1. Magnetic configurations tested during first and second joint experiments. Magnet strength is expressed through the magnetic remanence *Br*.

$Br_{ADCM}[T]$ $Br_{CESM}[T]$	**0**	**0.88**	**1.1**
0.77	JT2	not tested	JT2
1.1	JT1	JT1-part 2	JT1-part 1

In Fig. 4(a), all the useful pulses of both campaigns are plotted in terms of horizontal beamlet deflection as a function of extraction voltage. For all these pulses, the *Vacc/Vext* ratio is about 5, which gives the best optics in these experiments. The maximum achieved extracted current density in JT1 is $Jext = 140\ A/m^2$ ($Vext = 4500\ V$), while in JT2 the typical value is $Jext = 20\ A/m^2$ ($Vext = 1500\ V$). In Fig. 4(b), an average value is plotted for points having the same Vext. In this visualization, it can be better noticed that the deflection corresponding to the uncompensated configurations ($Br_{ADCM} = 0$) seems to be more dependent on the extraction voltage than the compensated configurations ($Br_{ADCM} \neq 0$). According to the initial idea supporting the magnetic technique for criss-cross deflection compensation, in fact, in the perfectly compensated configuration, there should be no dependence on extraction voltage at all.



(a) (b)

FIGURE 4. (a) Horizontal beamlet deflection as a function of extraction voltage for all the useful pulses of both joint experiments. Different colors and markers indicate different campaigns and magnetic configurations. Green and red points were obtained in two different moments of JT1, and one magnetic configuration ($Br_{CESM} = 1.1$ T, $Br_{ADCM} = 0$) is repeated two times. (b) Same as before, but points with same *Vext* have been substituted with their average value.

In Fig. 5 the deflection is plotted against the ADCM strength. It can be noticed that in JT1 only a partial correction of the deflection was obtained, while in JT2 the deflection is almost zero (there are about 1.5 mm of over-compensation).

In the same picture, a shift in the residual deflection by about 2.5 mm between the two parts of JT1 is visible, which has not been explained yet. Anyway, the results of JT1 seem to indicate a linear dependence of deflection on ADCM strength.

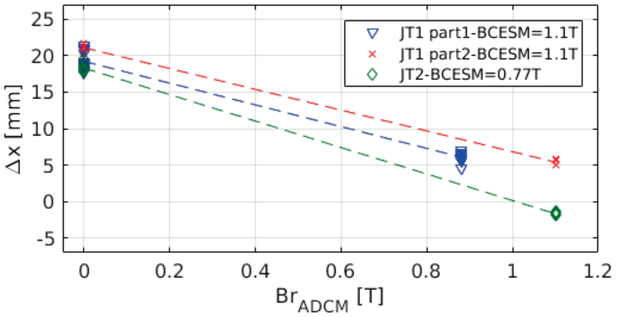
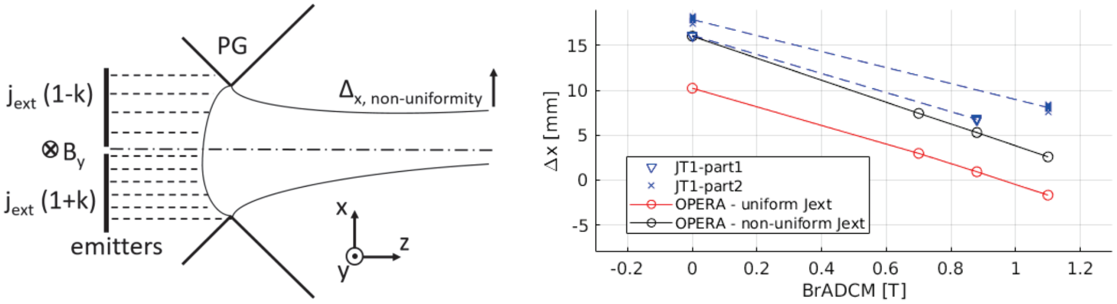


FIGURE 5. Horizontal beamlet deflection as a function of ADCM strength.

BENCHMARK OF NUMERICAL MODELS

In JT1, only partial compensation of the magnetic deflection was achieved. This is because the starting deflection estimated by the numerical models, particularly by the software OPERA, was underestimated. Before JT1, in the OPERA models, it was always assumed that the current density extracted through the meniscus is uniform. After JT1, this hypothesis was abandoned, also based on the numerical results obtained by Veltri [6-7], Fubiani [8] and Taccogna [9]. Using PIC codes, Fubiani and Taccogna showed that in a negative ion source, due to the effect of magnetic filter field, a plasma drift is established, with the consequent effect that the negative ion density at meniscus exhibits a top-bottom non-uniformity. Although not directly simulated by Fubiani and Taccogna, a similar drift, on the local scale, can be assumed to be produced by the vertical magnetic field of the CESM. Its effect would be a left-right non-uniformity of extracted current at meniscus. A new OPERA model was built including a left-right asymmetry of 17% and the match with the experimental results was much better, as shown in Fig.6.



(a) (b)

FIGURE 6. (a) Scheme of OPERA model with left-right non-uniformity and consequent additional horizontal deflection (b) Experimental results compared with OPERA results with uniform Jext at meniscus, and with left-right non-uniformity. Simulation parameters: $Vext = 4500\ V$, $Vacc = 22500\ V$, $Jext = 127.7\ A/m^2$, $k = 0.17$.

A further step in the refinement of the numerical models was done after JT2 and consists in the assumption that the left-right non-uniformity is proportional to the vertical magnetic field in the extraction region, consistently with the models of Fubiani and Taccogna, so:

$$k = p * B_{y,meniscus}$$

In this way, also the slope of the line in the $(\Delta x,\ \ Br)$ plane can be adjusted, and a null deflection is obtained when there are no magnetic fields.

Based on the experimental point at $Vext = 2500\ V$, an optimal value of $p\ =\ 0.5\%\ /\ mT$ has been determined, and then a series of simulations has been carried out trying to match the experimental results in all the other cases. In order to have a third term for comparison, the same simulations have been carried out using the software COMSOL. In OPERA, the meniscus shape is determined by the code, depending on the other inputs, while in COMSOL it is imposed by the user (and constant in these simulations). The results of both codes exhibit a quite good agreement with the experimental results, as shown in Fig. 7.

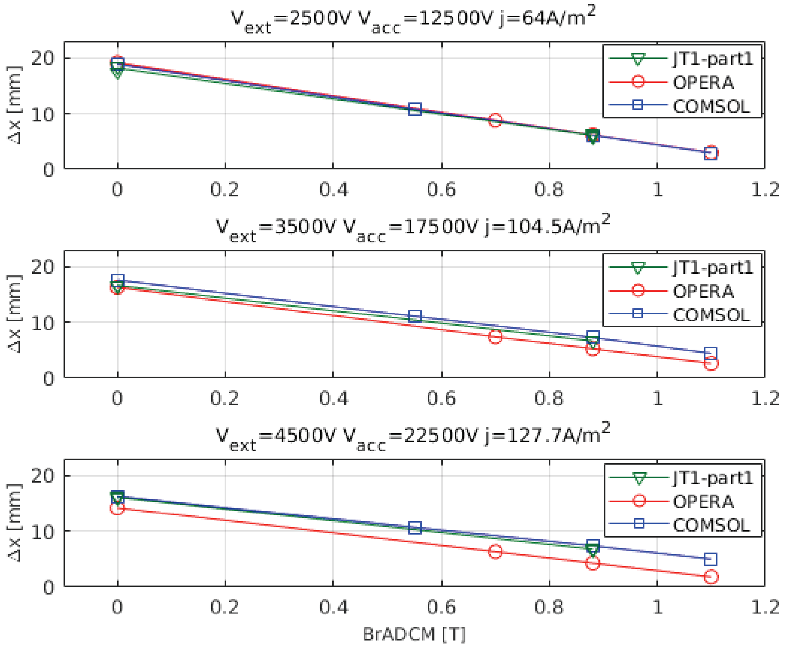


FIGURE 7. Comparison of experimental results with OPERA and COMSOL simulations (Br_{CESM} = 1.1 T).

Finally, using the refined OPERA models, another series of simulation has been carried out with the purpose of exploring and characterizing the whole operative space $\Delta x = f(B_{r,ADCM}, B_{r,CESM}, V)$ of which just a little portion was explored experimentally.

For a constant beam energy (constant *Vext* and *Vacc*), the dependence of the deflection on magnet strength, even considering the meniscus non-uniformity, appears to be perfectly linear, as shown in Fig. 8.

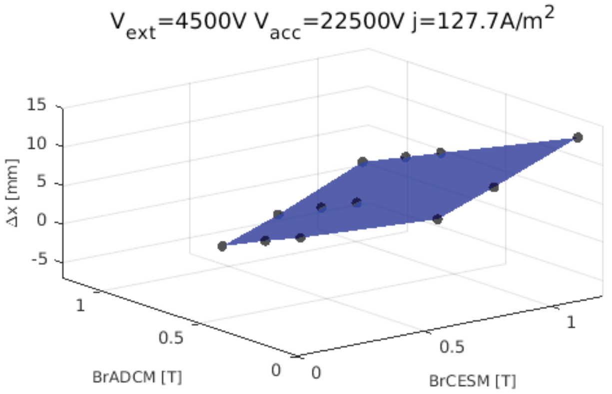


FIGURE 8. Beamlet deflection as a function of magnet strength for constant beam energy. OPERA simulation results.

When changing beam energy, the operative plane is rotated, but the points intersecting the plane $\Delta x = 0$ (perfect deflection compensation) remain fixed. This result confirms the robustness of the deflection compensation technique by the ADCM. Figure 9 shows all the OPERA results at different beam energies. This result can be assumed as the general behavior of beamlet deflection under different magnetic fields and beam energy in a negative ion accelerator.

For a given magnetic configuration (not belonging to the plane $\Delta x = 0$), it can be shown that the deflection as a function of beam energy is coherent with the theory, that is an inverse square root function of beam energy. Putting together with the linear dependence on the magnet strength, the general expression of the deflection is:

$$\Delta x = \frac{a * B_{r,CESM} + b * B_{r,ADCM}}{\sqrt{V_{ext}}}$$

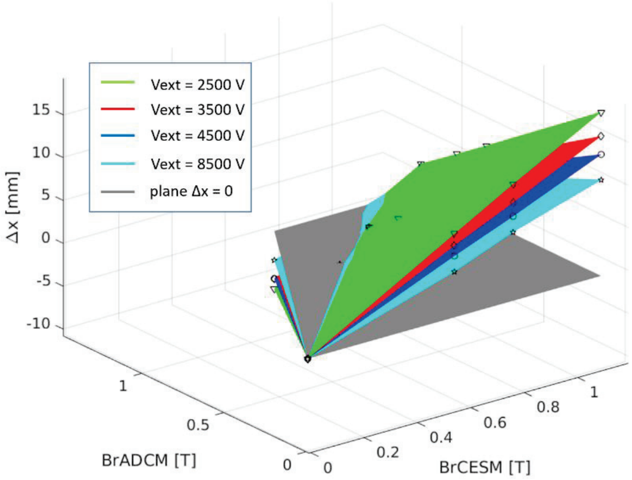


FIGURE 9. Beamlet deflection as a function of magnet strength and beam energy. OPERA simulation results.

This model can be very useful for the design of permanent magnets in MITICA, ITER, and future NBIs.

The next step is confirming its validity also on higher energy accelerators, like the Megavolt Test Facility (MTF) at QST.

POSSIBLE EXPLANATION OF BEAMLET ROW INCLINATION

If looking at Fig. 3, it can be noted that the rows of beamlets are inclined row by row in opposite directions. This effect was observed also in [6]. Here, for the first time, a possible explanation for this effect is given.

Because of its particular symmetry pattern, this deflection effect is most probably related to the magnetic field. Analyzing in detail the overall magnetic field produced by the filter magnets and the electron suppression magnets, it has been found that the z-component (i.e. along the beam axis) is the only one having a symmetry pattern similar to the vertical deflection pattern observed, i.e. alternate row by row and varying linearly from left to right. Figure 10 shows the contour plot of B_Z on a xy plane located in the proximity of the upstream side of the PG, and the vertical profile of the absolute of B_Z in front of the apertures of the first two beamlet rows.

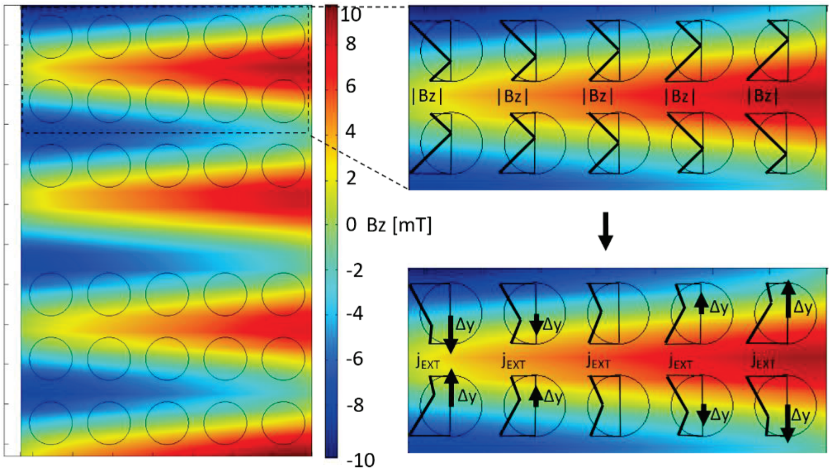


FIGURE 10. Contour plot of the axial component of magnetic field, on a vertical plane located 3 mm from the upstream side of the Plasma Grid, and correlation between the absolute value of Bz and the peculiar vertical deflection pattern observed in the experiments.

The absolute value of B_Z has been plotted because it can be put in correlation with the extracted current density at meniscus. The main hypothesis is that the presence of magnetic field lines in the beam direction in the proximity of the PG enhances the transport of newly formed negative ions, and thus the extracted current density at meniscus. If this assumption is true, then, by applying the results obtained for beamlet with non-uniform extracted current density shown in Fig. 6, the resulting vertical deflection pattern is coherent with the experimental one, as shown in Fig.10. This possible explanation, mostly based on symmetry considerations, has not been directly verified yet.

CONCLUSIONS

After three years of collaboration between QST and Consorzio RFX, and two joint experimental campaigns, some important results have been achieved.

First, the complete compensation of criss-cross magnetic deflection has been obtained, leaving good perspectives for the success of MITICA accelerator in terms of optics quality of the beam.

Second, the negative ion extraction processes have been better understood. Reasonably, a non-uniform current extraction at meniscus due to plasma drift in the source seems to play an important role in determining the final beam deflection. Now the simulation tools include this non-uniformity and are more predictive than before regarding the estimation of the beamlet deflection. Hopefully, this improvement, together with the collected experimental database, will lead to a correct initial design of the optics of MITICA, saving time and resources on ITER NBI development schedule, and being beneficial also for future negative ion multi-beamlet accelerators.

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REFERENCES

1. P. Agostinetti et al.: “Detailed design optimization of the MITICA negative ion accelerator in view of the ITER NBI”, Nucl. Fusion **56**, 016015 (2016), doi:10.1088/0029-5515/56/1/016015.
2. H.P.L. de Esch et al: “Physics design of the HNB accelerator for ITER”, Nucl. Fusion **55**, 096001 (2015), doi:10.1088/0029-5515/55/9/096001.
3. D. Aprile et al.: “Realization of a magnetically compensated extraction grid for performance improvement of next generation NBI”, Fus Eng and Design, **123**, 400-405 (2017), doi: doi.org/10.1016/j.fusengdes.2017.03.122.
4. G. Chitarin et al.: “Experimental validation of an innovative deflection compensation method in a multi-beamlet negative-ion accelerator”, AIP Conference Proceedings **1869**, 030026 (2017), doi: 10.1063/1.4995746.
5. M. Ichikawa et al.: “Determination of the meniscus shape of a negative ion beam from an experimentally obtained beam profile”, AIP Conference Proceedings **1869**, 030024 (2017), doi: 10.1063/1.4995744.
6. P. Veltri et al.: “Ion beam transport: modelling and experimental measurements on a large negative ion source in view of the ITER heating neutral beam”, Nucl. Fusion **57**, 016025 (2017).
7. P. Veltri et al.: “Effects of Negative Ion Source Characteristics on Beam Optics: The Case of SPIDER”, IEEE Transactions On Plasma Science **40**(9), 2279 - 2284 (2012).
8. G. Fubiani et al.: “Modeling of negative ion extraction from a magnetized plasma source: Derivation of scaling laws and description of the origins of aberrations in the ion beam”, Physics of Plasmas **25**, 023510 (2018).
9. F. Taccogna and P. Minelli: “PIC modeling of negative ion sources for fusion”, New J. Phys. **19**, 015012 (2017).