Tomographic reconstruction of the visible emission of NIO1 negative ion beam

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Experimental setup.

The clean energy produced by thermonuclear fusion is one of the most attractive new renewable sources of energy, necessary to satisfy the enormous growth of world energy consumption, while restraining the global warming process. The two main requirements for achieving thermonuclear fusion are the confinement (magnetic or inertial) of the plasma for a sufficiently long time and the heating of the plasma at very high temperature, in the order of tens of keV. Neutral beam injection (NBI) is one of the most important methods for plasma heating in almost all magnetic confinement nuclear fusion experiments. Several critical aspects need to be fulfilled in the design of future NBI, such as the maximization of the spatial uniformity of the extracted beam, which is a strict requirement for ITER NBI [1]. To investigate the negative ion beam properties, the tomographic reconstruction of the extracted beam of the NIO1 negative ion source (Negative Ion Optimization phase 1) is performed. NIO1 is a small radio-frequency driven negative ion source, aiming at producing a 130 mA negative hydrogen ion beam, accelerated up to an energy of 60 kV and arranged in a 3x3 matrix [2]. The tomographic system is composed by 2 visible cameras, which look at the visible light emitted by the beam particles interacting with the background gas, in a plane perpendicular to the beam. The cameras are progressive scan CMOS, with default resolution of 1920x1200, high quantum efficiency at the H_α wavelength and high intensity signal detected by different lines of sight (LoSs). These cameras are installed on the lateral port (vertical direction) and on the bottom port (horizontal direction) of NIO1 diagnostics tube.

Beam tomography and SART algorithm.

The principal aim of beam tomography is the reconstruction of the 2D beam emission profile ϵ by measuring the brightness f of the emissive source trough many lines of sight l_j

$$f_j = \int_{l_j} \epsilon(x,y)dxdy,$$

where the integral is evaluated along each LoSs, which are considered as straight lines; $\epsilon(x,y)$ is the 2D beam emissivity calculated in the plane perpendicular to the propagation direction. By developing an appropriate algorithm, it is possible to reconstruct the beam emissivity profile from the measurements f_j. When the number of LoSs available is limited and not uniformly distributed around the beam, an algebraic reconstruction technique is to be preferred. The method is based on the modelling of the image as a discrete matrix of pixels which transforms the continuous domain function $\epsilon(x,y)$ into pixel values ϵ_i. The grid considered in this paper is composed by an array of

60x60 square pixels with 1.13 mm side. In this way the brightness I_j measured along the jth LoS is the sum of the contribution of each pixel intercepted by the LoS, $I_j = \sum_{i=1}^{npix} \epsilon_i \cdot a_{ij}$; the beam emissivity is assumed to be constant, ϵ_i, within each pixel, a_{ij} is the length of the jth LoS inside the ith pixel. Due to experimental limitations, the emissivity of each pixel cannot be reconstructed simply by inverting the matrix **a**, $\epsilon = \boldsymbol{I a}^{-1}$, but iterative techniques are developed to estimate the emissivity, knowing the integrated signals. The adopted technique is the Simultaneous Algebraic Reconstruction Technique (SART) [3], which solves the linear system of equations via an iterative error-correcting procedure. The emissivity of the ith pixel at the k+1 iteration is expressed as

$$\epsilon_i^{k+1} = \epsilon_i^k + \frac{\sum_{j=1}^{nlos}\left(a_{ij} \cdot \frac{I_j - \sum_{i=1}^{npix} \epsilon_i^k \cdot a_{ij}}{\sum_{i=1}^{npix} a_{ij}}\right)}{\sum_{j=1}^{nlos} a_{ij}}.$$

Experimental results.

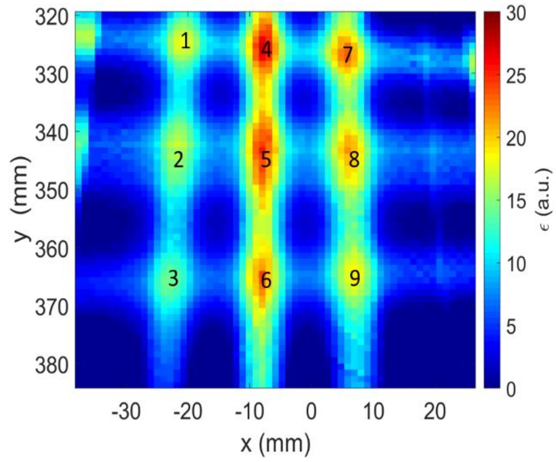

Figure 1 SART reconstruction of the experimental matrix of beamlets.

In NIO1, the beam is formed by 9 beamlets arranged in a 3x3 matrix. They are accelerated by 3 grids featuring 9 circular apertures with 7.6 mm diameter, and their centres are spaced by 14 mm along x and y directions. An example of the reconstruction of the experimental data obtained with the SART algorithm is shown in Figure 1. The reconstruction is performed using the profiles of the beam collected by the bottom and the lateral cameras, at about 200 millimetres away from the grounded grid (the last grid of the accelerator column). The data used to perform this reconstruction were taken when the machine parameters were chosen in a way to optimize the beam optics. This is the first 2D reconstruction of NIO1 experimental data and all the 9 beamlets are clearly visible. The reconstruction well reproduces the experimental data profiles, as shown in Figure 2.

By comparing the intensities of the 9 reconstructed beamlets, it is clear that the matrix of beamlets is not homogeneous: beamlets 1-2-3 are less intense with respect to the others, probably due to a non-completely optimized magnetic source configuration. The optics of a negative ions beam is described by some key parameters: the beamlet divergence, deflection and transmission, which is the ratio between the accelerated and the extracted currents. These parameters strictly depend on some quantities, such as the ratio between acceleration and extraction voltages and the magnetic field. The magnets embedded in the extraction grid determine the residual beam deflection; in NIO1 the beam particles are deflected in the vertical direction. In the reconstruction in Figure 1, the beamlet widths

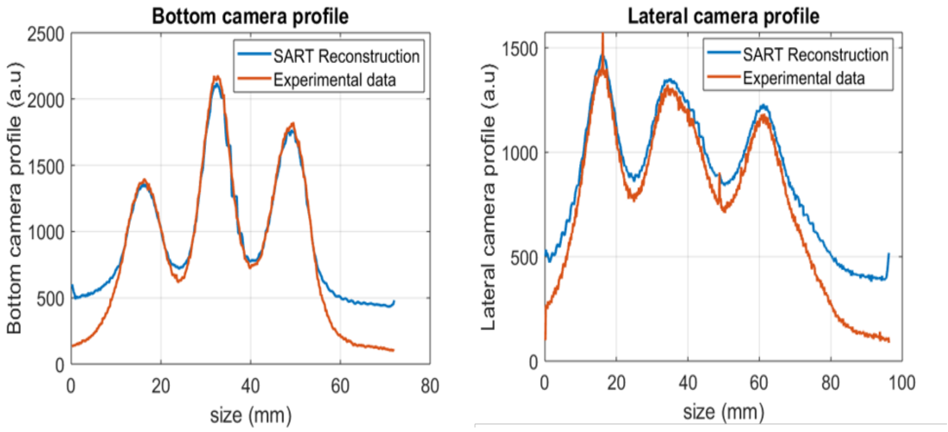

Figure 2 Bottom and lateral camera profiles and SART reconstruction.

along the vertical direction are bigger with respect to the horizontal ones. The effective vertical width of the beamlets cannot be discriminated with only two cameras from a misalignment of the beamlet positions due to a residual magnetic deflection; this could explain why the beamlets appear elongated in the vertical direction. The line-integrated signals collected by the visible cameras can give useful information on the beam divergence and therefore on the beam optics. Divergence in the horizontal direction δ_x can be measured by fitting with three gaussians the profiles of the three columns of beamlet seen by the bottom camera, at three different positions along the beam propagation direction (z axis). The positions and the profiles fitted are shown in Figure 3, the data are the same as those of the previous reconstruction.

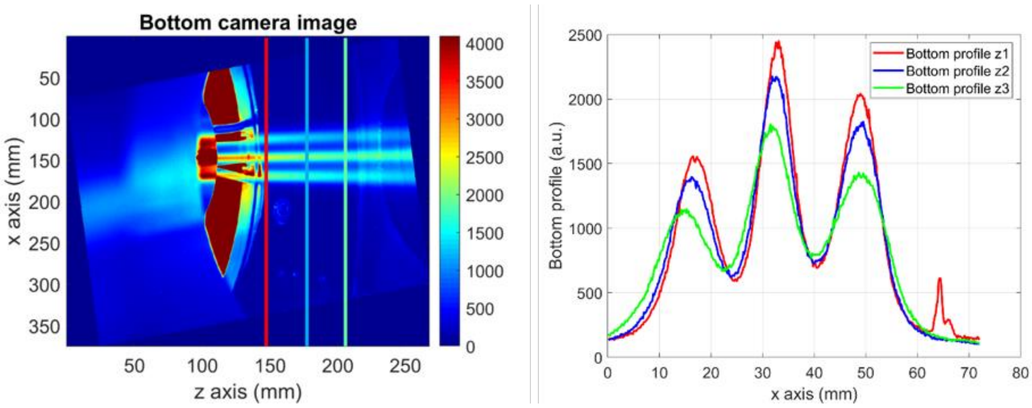

Figure 3 On the left side, bottom camera image. The data are the same used in the reconstruction. The vertical lines indicate the positions at which the 1D gaussian fit is performed, to estimate the beam divergence. On the right, the profiles corresponding to the three indicated positions.

By linearly fitting the widths of the three columns at the different positions, the divergence is evaluated as $\omega = \omega_0 + \delta_x \cdot z$, where ω is the gaussian fitted beamlets width at z_i, ω_0 is the beam width at the exit of the grounded grid and z the distance travelled by the beam. The width of each column is assumed to be equal to the width of the single beamlet, because no residual force acts on the horizontal direction. In Figure 4 the minimum of the divergence as a function of the ratio between

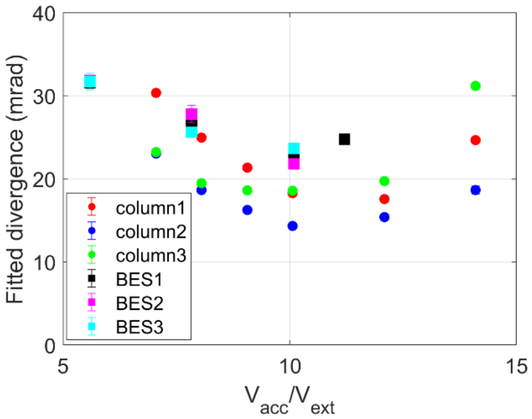

Figure 4 Comparison between the divergence estimated by the BES (squares) and the 1D gaussian fit (points).

the acceleration and the extraction voltages is shown. The best value is found to be around 10: the points are referred to the divergence of each column of beamlet while the squares are the results of the Beam Emission Spectroscopy (BES). The BES is another optical diagnostic which can estimate beam divergence, uniformity and direction of propagation, by measuring the Doppler shift of the emitted radiation of the beam particles interacting with the background gas [4]. In NIO1, three telescopes (BES1-2-3), spaced in the vertical direction, observe the beam with an angle of almost 64 degrees. Due to the residual magnetic deflection, the divergence measured by this diagnostic is a little bigger (around 5 mrad) than the one estimated by the visible camera.

Conclusions.

In this work, the first reconstruction of NIO1 experimental data using the two visible cameras is performed. The SART algorithm well reproduces the experimental data and the reconstruction shows all the 9 beamlets. A preliminary study on beam homogeneity and divergence is carried out. A 1D gaussian fit allows to estimate the beam divergence in the horizontal direction and its minimum as functions of the voltages ratio found. The optimum value is confirmed by beam emission spectroscopy. A more complete divergence estimation will be performed using the inversion, so as to simultaneously estimate the divergence in both directions and to directly compare the results of the two diagnostics.

Acknowledgments.

The work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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