Tomographic diagnostic of MITICA neutral beam: algorithm development

M.Agostini\textsuperscript{1}, M.Brombin\textsuperscript{1}, C.Dianin\textsuperscript{1,2}, M.Mattiolo\textsuperscript{1,2}, R.Pasqualotto\textsuperscript{1}, G.Seriani\textsuperscript{1}

\textsuperscript{1}Consorzio RFX, Associazione EURATOM-ENEA, C.so Stati Uniti 4, Padova, Italy
\textsuperscript{2}Dipartimento di Ingegneria, Università degli Studi di Padova, Padova, Italy

MITICA [1] is the full-size prototype of the heating neutral beam injector (NBI) for the experimental fusion reactor ITER. It is based on a negative ion RF source and it is designed to produce a deuterium beam of 16.5MW with particle energies of 1MeV for pulse duration up to 360s. It consists of an ion source directly attached to an extractor/accelerator; then a series of seven acceleration grids extract and accelerate the ions. The grid facing the plasma (plasma grid) is at −1MV, the last one is at 0V (grounded grid). The grids have 1280 apertures (beamlets), arranged to produce 16 beamlet groups of 5×16 beamlets each, divided into four columns. The total length of MITICA is 25 m (see fig.1). Along the beam path at 1.9 m far from the plasma grid, there is the neutralizer: a simple gas cell open at each end, through which the beam passes and is neutralized. It is divided into four rectangular sections, one for each column of beamlets. At 5.4 m the residual ion dump (RID) extracts from the beam the residual charged particles. Like the neutralizer, also the RID is composed of four adjacent vertical channels. To characterize the beam along its propagation direction, various diagnostics will be installed [2]; in particular the tomographic diagnostic will be installed in three different positions [3]. Defining the z-axis along the direction of propagation of the beam with \( z=0 \) at the plasma source, tomography would be installed near the grounded grid (\( z = 1 \)m), between the neutralizer...
and the residual ion dump (RID) \((z = 5\text{m})\), and at the RID exit \((z = 10\text{m})\). In this paper the tomography at \(z = 5\) is considered. The designed tomography measures the brightness of the beam integrated along a set of line of sight (LoSs), \(l_j\), with \(j=1, n\):

\[
\int_{l_j} \epsilon(x, y) dx dy
\]

where the integral is evaluated along the \(j^{th}\) line of sight, and \(\epsilon(x, y)\) is the beam emissivity in the plane orthogonal to \(z\). Then, by a tomographic inversion, the 2D map of the beam emissivity is obtained. The aim of this diagnostic is the assessment of the uniformity of the beam and check its correct propagation. In fact the uniformity of ITER NBI is required to be at least 90% in terms of extracted current density, and in order to detect this level of uniformity, the errors in the tomographic inversion have to be substantially lower than 10%. Moreover, the application of tomography to MITICA can give a complete reconstruction of the 2D emissivity map of the beam, which can give information on useful physical quantities, in addition to uniformity.

A tomographic algorithm is an algorithm which solves the inverse problem of determining the emissivity \(\epsilon(x,y)\) from the measurements \(f_j\) [4]. In MITICA the line integrals are measured by 19 CCDs installed in the 19 portholes around the vacuum vessel, and each LoS is the integrated signal of the D\(_\alpha\) emitted by the particles of the beam, for a total of 3416 LoSs [2]. The goal of the tomography is obtaining the 2D emissivity of the beam \(\epsilon(x,y)\) from the line integrated signals \(f_j\). The geometry of the LoS and the developed algorithm are here described and tested. The beam is simulated as 1280 beamlets, which propagate along \(z\): in the \(y\) direction each beamlet group is aimed at \(z=25\text{m}\); instead in the \(x\) direction each beamlet is aimed at \(z=7.2\text{m}\). The emission profile of each single beamlet is represented by a 2D Gaussian surface:

\[
G_{\epsilon}(x, y) = A_{\epsilon} e^{-\frac{(x-x_0)^2}{2\sigma_x^2} - \frac{(y-y_0)^2}{2\sigma_y^2}}
\]

Each beamlet has a finite divergence \(\delta_x=\delta_y=3\text{mrad}\), so their widths increase along the propagation and they superimpose on each other. At \(z=5\text{m}\), the cross section of the beam emissivity is shown in the left panel of figure 2, and the appearance of 12 zones of higher emissivity due to the overlapping of vertically contiguous beamlet groups is evident. The experimental signals to be inverted are calculated by integrating this 2D emissivity along
the 3416 LoSs; then white noise is added to reproduce measurement errors. The surface of the beam cross-section to be reconstructed is divided into several pixels characterized by Gaussian shape adopted according to the beam expected structure. The number of pixels can be changed in order to obtain different spatial resolutions. It has been found that with 256 pixels it is possible to obtain a good spatial resolution and low inversion errors, and this arrangement is shown in the right panel of figure 2. Using the pixel method to the reconstruction, the unknowns are the amplitudes $\varepsilon_i$ of each pixel $i$. So the inversion problem can be written in the matrix form: $I_j = \sum_i \varepsilon_i a_{ij} = A\varepsilon$, where $I_j$ is the integral for the LoS $j$ calculated from the experimental measurements (or from the simulated phantom) and $a_{ij}$ is the fraction of area of pixel $i$ observed by line $j$. Thus the emissivity of each pixel is formally obtained by inverting the matrix $A$. The inversion is implemented using the Simultaneous Algebraic Reconstruction Technique (SART) [5]. SART is a technique for solving the linear system of equations via an iterative error-correcting procedure, which applies the following incremental scheme:

$$
\varepsilon_i^{k+1} = \varepsilon_i^k + \frac{\sum_j a_{ij} \left( I_j - a_{ij} \cdot \varepsilon_i^k \right)}{\sum_j a_{ij}}
$$

where $a_j$ denotes the $j^{th}$ column vector of matrix $A$ and $\varepsilon_i^{(k)}$ is the emissivity of pixel $i$ after $k$ iterations. The initial estimate $\varepsilon(0)$ is set to 0. The whole algorithm is completed with a regularization, which is needed when noisy signals are inverted. So at each iterations we introduce a penalty function which penalizes local gradients in those regions.

**Figure 2.** Left: cross section of the simulated beam at z=5m (phantom); right: beam cross section divided in 256 pixels.
where they are not expected, but not at the edges, where they are expected [6]. This type of regularization is called edge-preserving schemes, and it is widely used in medical tomography. The inversion algorithm has been applied to the uniform phantom (fig.2, left), and the result for a noise level of 5% in the line integrals is shown in figure 3. In the top panel the regularized tomographic reconstruction is shown, compared with the one without regularization (bottom panel). The two reconstructions (with and without regularization) correctly reproduce the simulation, and the 12 zones of higher emissivity are found in the right positions. However, using the regularization, the amelioration is evident: the strong discontinuities (introduced by the noise added in the LoS signal) between the higher emissivity zones are avoided. In particular the regularization scheme reduces drastically the noise in the inversion. Without regularization, by increasing the noise from 0 to 12% in the signal, the errors in the tomographic reconstruction of the beam cross-section increase from 7% to more than 20%. Instead with the regularization the errors in the inversion do not strongly depend on the noise level, but remain almost constant around 7% [2].

\[\text{This work was set up in collaboration and financial support of Fusion for Energy.}\]