Tomographic reconstruction of beam's spatial distribution

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Introduction

High ion beam requirements for accelerator researches such as IFMIF demands the use of non-destructive diagnostic techniques. One of such non-interceptive diagnostics is the optical method of measuring profile of the beam by utilizing the interaction of the beam neutrals and ions with the residual gas particles inside the vacuum chamber. This optical diagnostics must obtain spatial profiles and relative amounts of different beam species. In contrast to other techniques like measurements based on residual gas ionization and multiwires, which only permit measurements in only one direction, optical diagnostics allows multiple measurements of several beam projections at the same cross section, at the same instant, but at different angles around the beam.

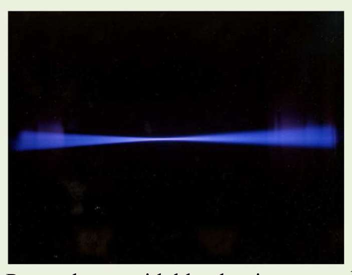
A potential method that can be incorporated with optical diagnostics is the tomography technique. When combined with tomography, the aforementioned optical technique will be used to provide a reconstructed cross-sectional spatial distribution of the beam. This is of advantage when dealing with beam shapes that are more intricate.

In this contribution, a tomography algorithm is developed and tested computationally and experimentally. This algorithm is based on the formulation of iterative Algebraic Reconstruction Technique (ART) problem and the Maximum-Likelihood Expectation Maximization (MLEM) for the iteration step. The algorithm is optimized within the limit of using 6 projections only. Several beam shapes are generated and reconstructed computationally. Actual measurements were also done to verify the tomographic reconstruction process.

Principles of the Technique

Beam-induced luminescence

Interaction of the ion beam with the molecules of the residual gas excites electrons onto the outer shell and produces luminescence when they fall back to their stable lower shells.



Proton beam with blue luminescence [1]

- A profile at one slice of the image can be obtained
- At first approximation, the intensity of the luminescence is given by

$$I_{luminescence} = I_{beam} \cdot \sigma \cdot P_0$$

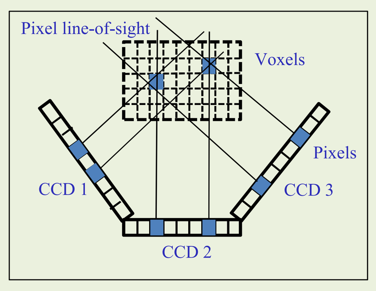
beam current (I_beam), cross section (σ), gas pressure (P_0)

[1] Pottin, B, (2001) Etude d'un profileur optique de faisceaux intenses de protons par absorption laser, Doctor of Science thesis. Institut de Physique Nucléaire

Tomography

Computed tomography, is a technology for slice image reconstruction from multiple 1-D scans taken from multiple angles around the object.

For diagnostics of particle beams, tomography can be applied if we consider the beam in the residual gas as the object of reconstruction. The figure below shows the schematic of multi-camera tomography reconstruction.

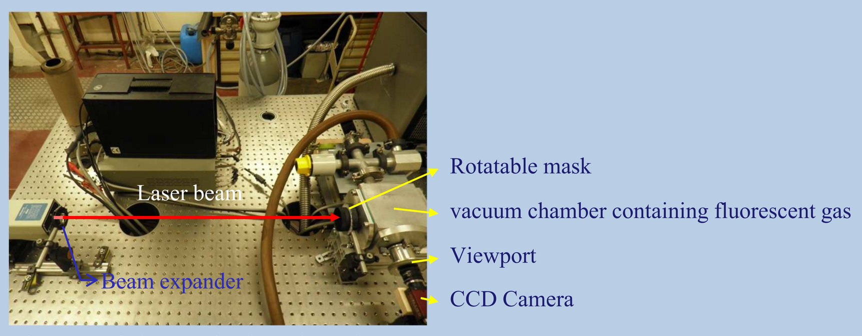


Filled voxels represent particle locations required to satisfy the filled pixels in each CCD recorded projection.

Development of tomography algorithm

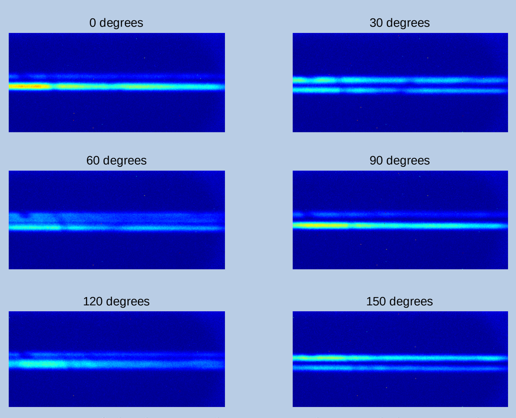
If tomography reconstruction will be incorporated with optical diagnostics based on the residual or added gas fluorescence, it is necessary that the number of projections be as few as possible without compromising the accuracy of the reconstructed image. However, few projections translate to limited information. And from theoretical point of view, a problem with limited information is considered a highly underdetermined ill-posed problem. There are various theoretical approaches for the development of algorithms for obtaining image estimates, but for this research, the algebraic reconstruction technique (ART) together with Maximum-Likelihood Expectation Maximization (MLEM) written in MATLAB is used.

Table-top measurement, with the setup shown below, is done to verify the tomography reconstruction algorithm.

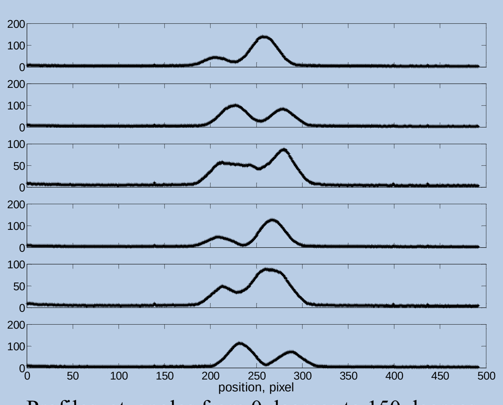


The expanded beam is then directed to a rotatable mask which defines the shape of the beam..

Six profiles were obtained by rotating the mask to a desired angle. The mask has three holes to define the shape of the beam and it is placed along the beam line before the vacuum chamber. The profiles obtained at different angles are then utilized as input data in the tomography reconstruction algorithm.

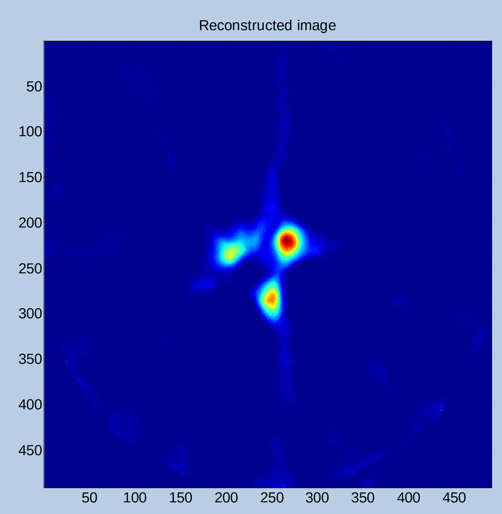


Images of the beam changes as the mask is rotated



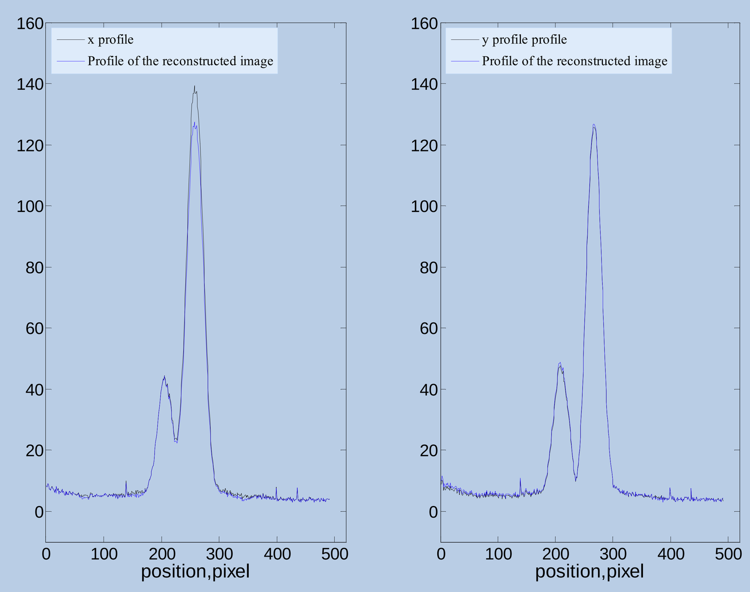
Profiles at angles from 0 degrees to 150 degrees.

- With only six projections, result showed that the three spots are prominent.
- Streak artefacts are present in the reconstructed image which can be removed by increasing the number of angle of projections.
- The higher intensity of one of the spots compared to the other two beams is attributed to misalignment of the laser with the viewport of the vacuum chamber.



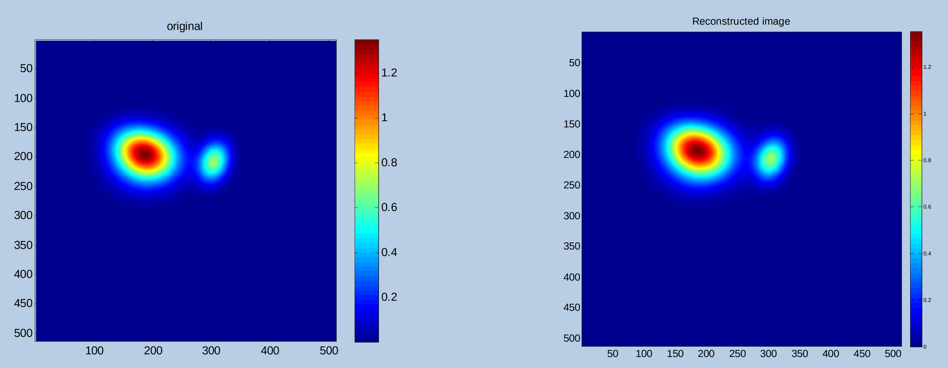
The reconstructed cross section of the beam.

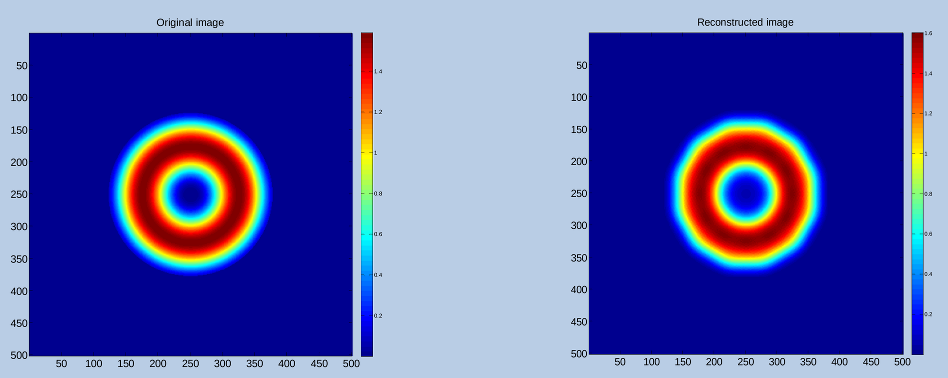
In order to illustrate the quality of the reconstructed images, the discrepancy between the experimentally measured x- and y-profiles and that of the reconstructed distributions are compared and are plotted below.



Comparison of the x- and y-profiles of the reconstructed images and the measured profiles

In parallel with the actual measurements, reconstruction of test images generated numerically is also done. A separate code that generates test images is developed. This code rotates the image to preferred angles and then records the horizontal profile of the images for each of the angles. The profiles obtained by the separate code are then used as input data on the reconstruction algorithm. The projection angles were distributed normally between 0° to 150° with an increment of 30°. Each projection is composed of 513 points corresponding to a 513 × 513 pixels in the reconstructed image. Results are shown below.



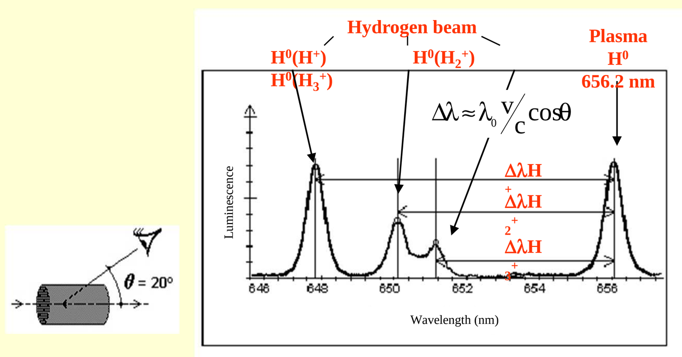


Original images generated numerically with their corresponding tomographically reconstructed image.

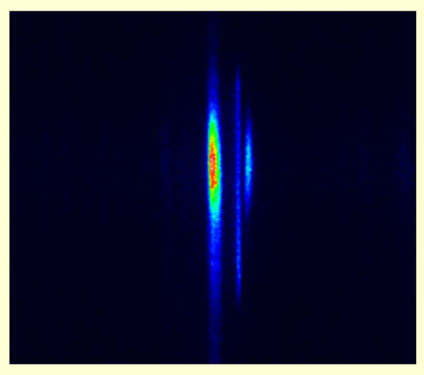
Doppler shift Spectroscopy

The tomography technique incorporated with optical diagnostics must also be able to obtain relative amounts (possibly absolute density values) of different beam species. It is therefore imperative to perform spectrally resolved measurements, exploiting the Doppler effect due to the large directed velocity of the beam. To do this, the H_α line of the Balmer emission of the hydrogen neutrals of the beam is observed along an optical axis at an angle, not equal to 90 degrees, to the neutral beam axis.

In this project, the angle is chosen to be 30 degrees. This would be enough such that, the fluorescence is sufficiently Doppler shifted and the wavelength separation between the H^+, H_2^+ and the H_3^+ peaks can be resolved.



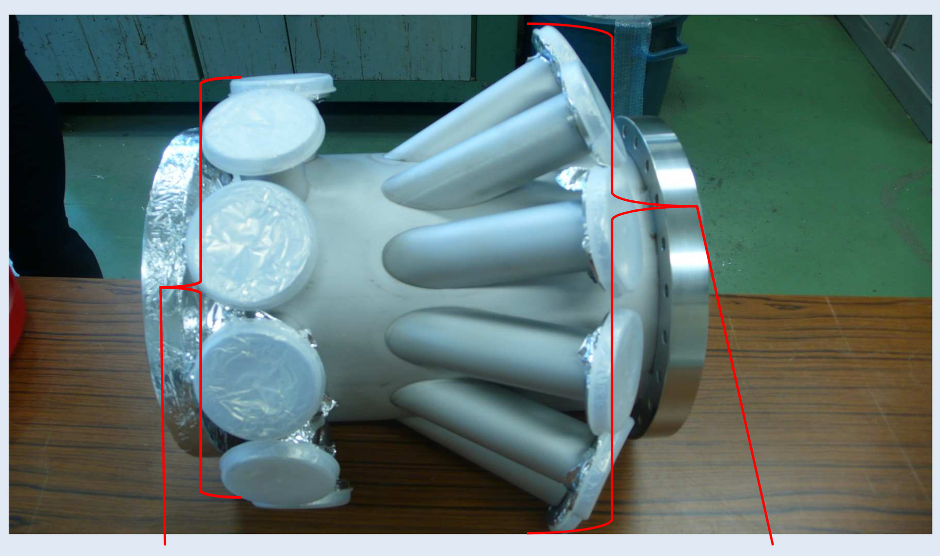
The H^+, H_2^+ and the H_3^+ peaks are blue shifted with respect to the H_α when observed at an optical axis not equal to 90 degrees.



The Doppler shift effect in the wavelength domain will discriminate the light produced by de-excitation of these atoms among the overall light[1].

With the results obtained from the experimental and numerical tests of the tomography algorithm, that 6 projections are sufficient to reconstruct the beams cross section, a vacuum chamber which is also suited for doppler shift spectroscopy was designed and was built.

A photo of the chamber is shown below. This vacuum chamber will be installed first on BETSI (Ion Source Test BEnch) at CEA Saclay



Viewports at axial angles of 30°-150° with respect to the beam axis and positioned at 90° optical axis

Viewports at axial angles of 30°-150° with respect to the beam axis and positioned at 30° optical axis

Vacuum chamber which will be installed for tomographic reconstructions of beams viewed at 90° optical axis and for incorporation of tomography with doppler shift spectroscopy.

[1] Pottin, B, (2001) Etude d'un profileur optique de faisceaux intenses de protons par absorption laser, Doctor of Science thesis. Institut de Physique Nucléaire

Conclusions

A tomography algorithm was developed and tested experimentally and numerically. Results show that 6 profiles obtained around the beam at different angular positions are sufficient to reconstruct the cross section of the beam.

After the preliminary tests, a vacuum chamber suited for tomographic measurements was designed and was built. This vacuum chamber will be first installed in BETSI and actual measurements are foreseen within the coming months.

Acknowledgements

I would like express my sincere thanks to all people who contribute to this work, particularly my supervisor Raphael Gobin and Daniel Gardes of IPN-Orsay that made the preliminary tests of the tomography algorithm possible.

This work is supported by the DITANET Marie Curie European network.

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