NON-INTERCEPTIVE PROFILE MEASUREMENTS USING AN OPTICAL-BASED TOMOGRAPHY TECHNIQUE*

C.M. Mateo, G. Adroit, A. France, G. Ferrand, R. Gobin, S. Nyckees, Y. Sauce, F. Senée, O. Tuske,
CEA/Saclay, DSM/IRFU/SACM, 91191-Gif/Yvette, France

Abstract

Most of the charged particle beam shapes do not possess symmetry. In such cases, diagnostic measurement obtained in one direction is not enough to reconstruct the spatial distribution of the beam. The use of intense beams which demands for non-interceptive diagnostic devices posed another challenge in measuring the beam's spatial distribution. At CEA Saclay and within the DITANET framework, the use of tomography combined with optical diagnostics to develop a non-interceptive transverse profile monitor is under development. This profile monitor is presently tested on the BETSI test bench. In this contribution, a tomography algorithm suited for beam profile measurements is presented. 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 then reconstructed computationally. Actual measurements in the BETSI test bench are also done to verify the tomographic reconstruction process.

INTRODUCTION

Increased average beam currents in present accelerators and storage rings, is a subject of great interests to the accelerator community. It offers many applications in industry, medicine and in basic researches as well. For all of these researches, it is a requirement to have knowledge about the spatial distribution of particles both at the transport channel and at the experimental target site. Hence, beam diagnostics is imperative. However, for intense charged particle beams, there is an increased specific demand for non-interceptive beam diagnostic devices. Such diagnostics must not be interceptive such that it will not destruct the beam, and, at the same time, will not be destroyed by the high ion currents in the beam during operations.

One of such non-interceptive diagnostics is the optical method of measuring profile of the beam by utilizing the interaction of the beam with the residual gas inside the vacuum chamber [1]. When a beam particle hit a gas molecule present inside the chamber, electrons are excited into an outer shell and when these electrons fall back into their stable lower shells, a photon is emitted from the gas molecule. Using cameras, the emitted light can be focused onto a CCD chip that can store spatial information, and, if coupled with a spectrometer, spectral information can also be stored. In contrast to other techniques like multiwires which only permit measurements in only one direction, optical diagnostics allows multiple measurements of several beam projections at the same cross section but at different angles around the beam.

In this contribution, optical diagnostics is incorporated with the tomography technique to obtain a non-destructive reconstruction of the cross-sectional spatial distribution of the beam. It aims to verify the use of tomography for measuring the transverse profile of the beam. This is of advantage when dealing with beam shapes that are more intricate.

TOMOGRAPHY

Tomography is the method to reconstruct a 2D or 3D cross sectional image of an object given multiple flat scans taken from multiple angles around an object. Most literatures about it are in the field of medicine. In the field of accelerator physics and for the purposes of using optical diagnostics to understand the shape and the spatial extent of the beam from a 2D CCD image, it is necessary to understand and implement tomography.

The problem is defined in the coordinate system (x, y, z) with the beam direction along the *z-axis*. The object in question is represented by (x, y), which represents the spatial distribution of the object in the $z = 0$ plane. The observed data taken from the 2D multiple images around an object is given by the projection integral which can be defined mathematically by the Radon transform [2,3]. The Radon transform $g(s, \theta)$ of a function $f(x, y)$ is the line integral of the values of $f(x, y)$ along the line inclined at an angle θ from the x-axis at a distance s from the origin.

The desired computation however is an inverse problem. Given the projections, the unknown object must be computed. There are several ways of solving this. The 2D Fourier Transform is the most common way used in x-ray tomography. In this technique a large number of projections are required to be able to reconstruct the image. However, for accelerator physics, it is important to be able to reconstruct the image in few projections. One way to do this is by using the ART [4].

The idea in ART can be considered as smearing back the projection intensities back to the reconstruction area. The reconstruction area is being set up as a matrix with unknowns covering the object of interest. Then algebraic methods are used to solve for the unknowns by modifying the densities iteratively in order to make the reconstructed projections coincide with the original projections. And since the number of viewing angles in diagnostic chamber for particle accelerators is limited by space and cost of

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cameras, iterative reconstruction is more promising than the Fourier process.

In this paper, the image reconstruction algorithm is based on the formulation of the ART and combined with the MLEM in the iteration procedure.

TABLE TOP EXPERIMENT

Measurements patterned from the results of Belyaev [5] are done to verify the tomography reconstruction algorithm. A He-Ne laser is expanded by a double-lens beam expander system. The expanded beam is then directed to a rotatable mask which defines the shape of the beam. After passing through the rotatable mask, the beam, which already has a defined shape, is focused to the vacuum chamber containing a fluorescent gas at 1 atmospheric pressure. To avoid unnecessary reflections inside the chamber, the inner surfaces of the vacuum are covered with black opaque material and also, the whole setup is assembled inside a dark room. A CCD camera (Stingray F146 B) connected to a computer obtains the images of the laser beam and with Labview program, the profile of the image taken by the CCD camera is obtained. Since tomography reconstruction requires several profiles obtained at different angles, other profiles were obtained by rotating the mask to a desired angle. The profiles obtained at six different angles, between 0° to 150° with an increment of 30°, are then utilized as input profiles in the tomography reconstruction algorithm.

The result of the reconstruction of the laser beam's spatial density distribution is shown in Fig. 1.

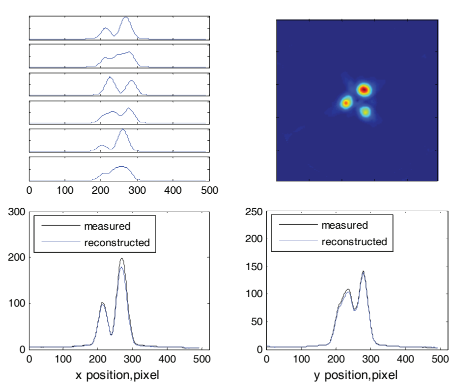

Figure 1: The six profiles at different angles (upper left) are used to reconstruct the beam's spatial distribution (upper right).

In order to describe the reconstruction qualitatively, the discrepancy between the measured and reconstructed x- and y- profiles were plotted as shown in the second row of Fig. 1.

In parallel with the actual measurements, reconstruction of test images generated numerically is also done. A separate code that generates test images is developed. An example of test image is shown in the upper left-hand corner of Fig. 2. The code rotates the image to preferred angles and then records the horizontal profile of the images for each of the angles. The profiles obtained are then used as input data on the reconstruction algorithm. The projection angles were distributed between 0° to 150° with an increment of 30° or 50°. Test images are reconstructed with 6 or 4 projections for the purpose of comparison in image quality. Initial study was made by the group of Belyaev where they concluded that 4-8 projections are sufficient to reconstruct the intensity distribution of the beam cross section [5]. For the numerical simulation, each projection is composed of 513 points corresponding to a 513 × 513 pixels in the reconstructed image.

Results of the reconstruction of the numerically generated input image are shown in Fig. 2.

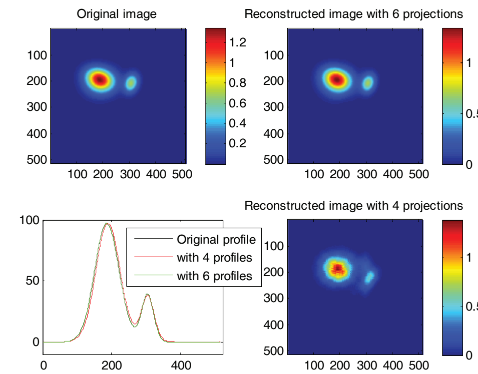

Figure 2: The reconstructed image with four and six projections.

MEASUREMENTS ON BEAM LINE

Following the table-top experiment and numerical simulations, an experiment is also done in Ion Source Test Bench (BETSI) at CEA Saclay [6], equipped with an Electron Cyclotron Resonance (ECR) Ion Source. After extraction, a solenoid is inserted to focus the beam to the focal plane of the analyzing magnet. The analyzing magnet bends the beam over 104° with a bending radius of 400 mm.

An experimental chamber with six equally spaced viewports along the axial direction at 90° with respect to the beam direction, and 6 other viewports at 30° with respect to the beam direction is constructed and is first installed in BETSI, positioned after the analyzing magnet and before the beam stop. Viewports oriented 30° with respect to the beam direction will be used for future Doppler shift spectroscopy measurements. In this contribution, only the images through the perpendicular viewports were acquired. Additional gas can also be injected inside the chamber through a gas inlet.

A digital CCD camera with a Firewire Interface, Stingray F146 B and with Fujinon HF25HA-1B objective is used to capture images of the beam from each viewport. The objective has a constant focal length of 25mm and has an adjustable iris in the range of F1.4 to F22. At a distance of 180mm from the beam axis and an image size of 692 × 518 pixel, the field of view is 45.82 × 34.45 mm. This in turn gives 0.066 × 0.067 mm per pixel size.

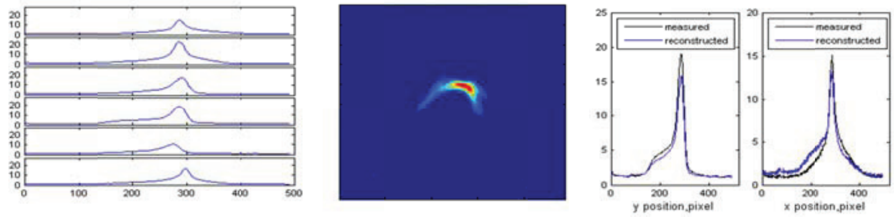

Figure 3: Six profiles measured at different angles (leftmost) are used to reconstruct the spatial distribution of the beam (middle) after the analysing magnet with a 12.22 A of current. The x- and y- profile of the reconstructed images are also plotted with the measured profiles.

A Labview program measures the beam profiles from the images captured by the camera. All 6 profiles are then fed to an ART reconstruction program written in MATLAB.

Prior to profile measurements, the current in the analyzing magnet is set at 12.22 A, in order to position the beam at the center of the chamber. The profiles obtained through the six viewports at different angles around the beam are shown in the leftmost of Fig. 3. Images of the beam at each of the view ports are captured by only one camera instead of capturing them simultaneously six cameras.

Using the six profiles, the spatial distribution of the beam is reconstructed and is shown at the middle of Fig. 3. The size of the image along the horizontal and the vertical planes spans about 154 and 100 pixels respectively. These translate to an actual beam size of about 10 mm along the horizontal plane and 7 mm along the vertical plane.

Beam shape on the other hand resembles a parabola. This parabolic envelope may be due to a second order aberration caused by the analyzing magnet, or partly because of misalignment when camera is transferred from one viewport to another.

Previous results [7] on the other hand, also reported beam profiles with parabolic envelope when measured after the analyzing magnet.

To qualitatively see the effect of the analyzing magnet on the beam, the current of the analyzing magnet is varied. Figure 4 shows the reconstructed beam profiles at different current. As expected, the beam shifts towards the positive x-axis as the current of the analyzing magnet is decreased. The beam shape on the other hand is still parabolic.

Another parameter that might induce aberration leading to a parabolic shape is the focusing of the beam through the solenoid before the analyzing magnet [8]. Therefore, a measurement wherein we did not form the waist in front of the analyzing magnet is done. As shown in Fig. 5, the spatial distribution still resembles a parabolic envelope but is more focused along the y-axis.

In order to sort out the cause of the aberration, a simulation of the extraction and transport of the beam will be done.

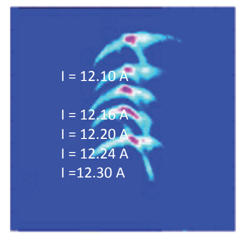

Figure 4: Beam shapes at different currents in the analyzing magnet.

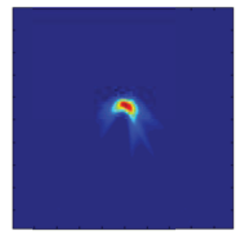

Figure 5: Beam shape when the solenoid setting is changed.

CONCLUSION

Optical-based tomographic reconstruction of the spatial distribution of the beam was demonstrated in this contribution. A reconstruction algorithm was developed, tested, and optimized for a minimum number of 6 projections. Measurements with the BETSI beam shows that the tomographic reconstruction of the beam's spatial distribution is plausible.

The next step is to transfer the chamber to the SILHI beam line. It is expected that no aberrations will be observed on the SILHI's beam spatial distribution and it will be more symmetric, in contrast to that of the BETSI beam. The Doppler shift tomography measurements will also be done with the SILHI beam.

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