NON-INTERCEPTIVE TOMOGRAPHIC RECONSTRUCTION OF THE TRANSVERSE SPATIAL DISTRIBUTION OF SILHI ION SOURCE BEAM

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Abstract

Particle accelerators with high intensity beams require non-interceptive diagnostics because any interceptive tools can be damaged or can perturb the beam during measurements. At CEA Saclay, tomography is incorporated with non-destructive and non-interceptive beam-induced fluorescence profiler, to produce a 2D reconstruction of the transverse spatial distribution of the beam from the Source d'Ions Légers de Haute Intensité (SILHI). Six cameras, positioned at six different directions around the beam, were aligned with respect to the beam axis and were installed to obtain the image of the emitted light due to the beam-residual gas interaction. At present, due to software limitations, profile measurements from each camera cannot be done simultaneously. Instead, there is a one-second interval on measurements from one camera to another. This makes a total of about ten seconds to obtain the profiles and to reconstruct the 2D spatial beam distribution.

INTRODUCTION

Increased average beam currents in present accelerators and storage rings, is a subject of great interests to the accelerator community because of its applications in industry, medicine, and fundamental research. However, intense charged particle beams, require non-interceptive diagnostics.

One of these is the Beam-induced Fluorescence (BIF) profile monitor [1]. Since the first attempt to use this method to measure beam size in CERN in the ISR rings, it has evolved to varied forms and is continuously being studied because of its versatility and effectiveness. In such profilers, the fluorescence which is naturally induced inside the vacuum chamber is exploited. This fluorescence is due to the excitation and de-excitation of the residual gas molecules by the beam.

When the beam passes through the gas molecules in a vacuum, collisions with gas molecules occur. The transfer of energy from accelerated particles to the gas molecules can either ionize the gas molecules or excite its electrons. Photons are generated when these excited electrons fall back to their lower energy levels. BIF monitors strive to optically observe these photons from which a profile can be obtained. In several installations, external gases are introduced inside the chamber in order to increase light production. In contrast to other techniques like measurements based on residual gas ionization and multiwires, optical diagnostics allow for multiple simultaneous measurements of several beam projections at the same cross section but at different angles around the beam.

A potential method that can be incorporated with optical diagnostics is the tomography technique. [2] 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 paper, tomography is being implemented with optical measurements at CEA Saclay in order to study the profile of a proton beam produced by the source of the IPHI project. It is being demonstrated that the profile can be measured non-destructively by utilizing tomography.

TOMOGRAPHY

Tomography is a method used to reconstruct the cross sectional image of an object given multiple projections taken from multiple angles around this object. It has been used for many years in medical applications. The problem is defined in the 3D Cartesian coordinate system (x,y,z). In this case, the beam direction is along the z-axis. The object in question is represented by f(x,y), which represents the spatial distribution of the object in the z=0 plane. The measured projections taken from the 2D multiple images around an object can be defined mathematically by the Radon transform. [2] The projections or 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 as depicted in Fig. 1.

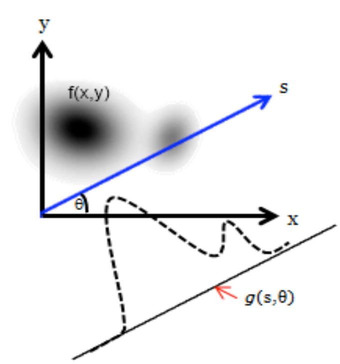

Figure 1: The geometry of the tomographic projections.

In tomographic reconstruction, the desired computation is an inverse problem. Given the projections, $g(s,\theta)$, the object, f(x,y), must be computed. There are several ways of solving this. One example is the 2D Fourier Transform which is commonly used in x-ray tomography. In this

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technique, a large number of projections is required to be able to reconstruct the image. However, for accelerator diagnostics, with speed of acquisition constraints and the limitation of space for camera and viewport installation, it is imperative to be able to reconstruct the image in few projections. One way to do reconstruction with few projections is by an algebraic reconstruction technique (ART) [3].

The idea in ART can be considered as back projecting the projection intensities back to the reconstruction area. The reconstruction area is being set up as an array with unknowns covering the object of interest. The unknowns are solved by algebraic methods and its densities are modified iteratively in order to make the reconstructed projection coincides with the original projection.

In this study, the image reconstruction is based on the formulation of the ART and combined with the Maximum Likelihood Expectation Maximization (MLEM) in the iteration procedure [3]. The MLEM aims to find a general solution as the best estimate for the unknown distribution f(x,y). The best estimate must produce the set projections g(s,θ) with the highest likelihood.

INITIAL TESTS OF THE ALGORITHM

Measurements patterned from the results of Belyaev et al., were done to verify the developed tomography reconstruction algorithm [4]. In Belyaev's study, it was concluded that 4-8 projections are sufficient to reconstruct the intensity distribution of the beam cross section. A detailed experiment setup can be found in Mateo et al. [5].

The left side of Fig. 2 shows the reconstructed spatial distribution of the laser beam. The measured and reconstructed x-profiles also match nicely as shown in the right side of Fig. 2.

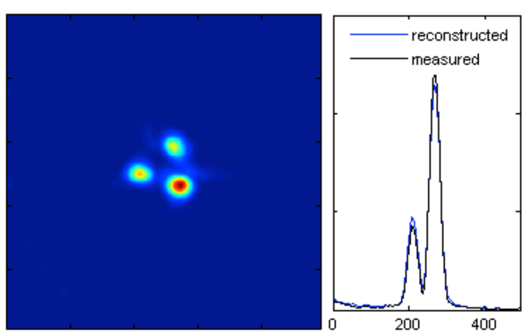

Figure 2: (Left) The three circular features of the laser beam is clearly distinguishable in the reconstructed spatial distribution. (Right) The x-profile of the reconstructed image coincides with the measured x-profile.

Numerical simulations were also done in parallel with actual measurements. This confirmed that 6 projections are sufficient to reconstruct a density distribution using iterative tomographic algorithm. Results are shown in Fig. 3.

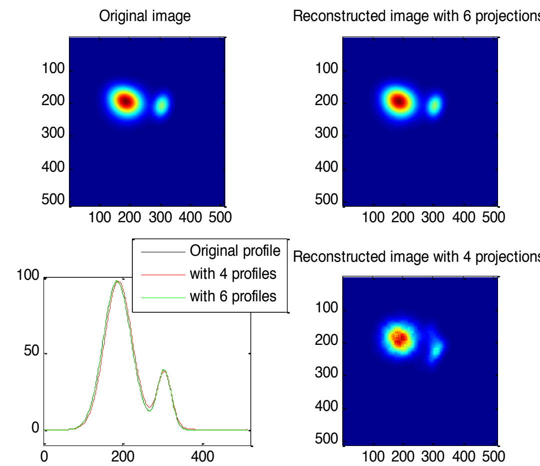

Figure 3: Six projections from 0° to 150° with 30°-increment are sufficient to reconstruct the test image.

RECONSTRUCTION OF THE SILHI BEAM

Following the table-top experiment and numerical simulations, a vacuum chamber, suitable for tomographic measurement with six projections is built. This is installed beyond the diaphragm in the High Intensity Light Ion Source (SILHI) beam line at CEA Saclay [6-7], equipped with an Electron Cyclotron Resonance (ECR) Ion Source. This beam line has been designed to inject a 100 mA proton beam into the IPHI RFQ. In the SILHI beam line, the protons from SILHI source interact with the residual gas which is mainly hydrogen, with a pressure in the order of ~10^{-5} Torr. A blue light, which can be seen by the human eye, is emitted by the de-excitation of the atoms. Previous spectrum analysis of the residual gas fluorescence in the beam line clearly shows the H_α H_β and H_γ Balmer lines [7].

Experimental setup

An experimental chamber with six equally spaced viewports along the axial direction at 90° with respect to the beam direction is constructed. Six cameras, Stingray F146 B, with a Firewire interface and with Fujinon HF25HA-1B objective lenses were installed on each viewport as shown in Fig. 4. The objective has a constant focal length of 25 mm and has an adjustable iris in the range of F1.4 to F22.

To make sure that the cameras were all aligned with respect to the beam axis, a plastic cylinder with a diameter of 10mm was carefully installed such that, it is positioned at the center of the vacuum chamber. This cylinder, illuminated by external light, is then used as a reference for the alignment of all cameras.

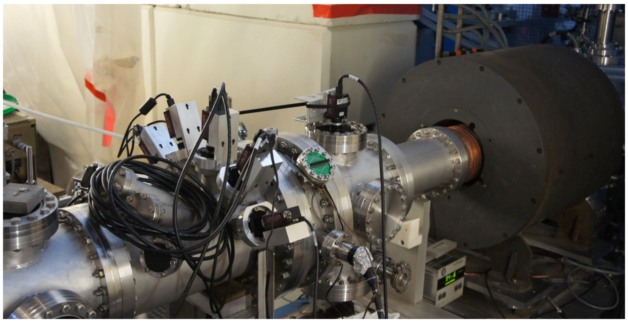

Figure 4: Six cameras were used to obtain images of the beam at six different directions. Each image corresponds to transverse beam profiles along each direction.

An acquisition program developed in LabVIEW acquires the beam profiles from the images captured by the camera. Currently, simultaneous acquisition of the six cameras is limited by the acquisition card bandwidth. Instead, a one-second interval is necessary between measurements from one camera to another. Improvement with the profile acquisition is still foreseen.

All six measured profiles are then used as input projections to the reconstruction algorithm written in MATLAB. In total, it takes 10 seconds to measure the profiles and to produce the reconstructed spatial distribution of the beam.

Spatial distribution using six cameras

The left hand side of Fig. 5 shows the reconstructed spatial distribution of the beam with a beam current of 19.6 mA. The diameter of the beam covers approximately 68 pixels, which translates to 4.5 mm of beam diameter. At this beam setting, and with the aligned position of the cameras, the reconstructed beam profile is nicely symmetric and has a Gaussian-like distribution.

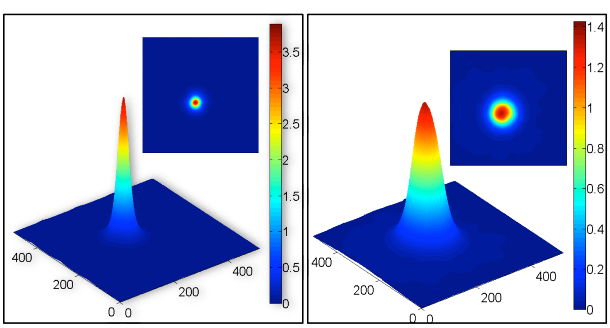

Figure 5: (Left) 3D and 2D representations of the transverse spatial distribution of the SILHI beam. (Right) 3D and 2D representations of the transverse spatial distribution of the SILHI beam at a distance of approximately 27cm from downstream.

When the tomographic chamber was moved downstream by about 27cm in distance, the diameter of the reconstructed beam spatial distribution increased to 128 pixels or 8.32mm. This is shown in the right side of Fig. 5. The increase in the beam size is expected because from the beam waist, the beam diverges at a distance. The reconstructed profile also has a Gaussian-like distribution.

CONCLUSION AND EVALUATION

Tomographic reconstruction of the spatial distribution of the beam was demonstrated in this contribution. Only six profiles, which are measured at different viewing directions around the beam; i.e., from 0° to 150° at an increment of 30°, were used for the reconstruction of the spatial distribution of the beam. Measurements with the SILHI beam shows that fast tomographic reconstruction of the beam's spatial distribution is plausible with only six profiles.

The accuracy of the reconstructed spatial distribution however strongly depends on the accuracy of the angular position of the cameras and to the accuracy of the measured profiles which are used for reconstruction.

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