TRANSVERSE PHASE SPACE TOMOGRAPHY AND COMPARISON WITH ALLISON SCANNER DATA IN THE RAON HEAVY ION ACCELERATOR*

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Abstract

Tomographic phase space reconstruction method based on the beam dynamics code Travel is applied to the RAON linear accelerator in the LEBT and in the MEBT. Due to the low beam energy and the two dipoles in the LEBT, it matters to include the space charge effect and the second-order effects of dipoles. When compared with the Allison scanner emittance data in the LEBT, the phase space tomography demonstrates a very good agreement even though the actual beam is far from Gaussian. The method of fitting rms beam sizes of wire scanners is also compared with the phase space tomography method. The method of fitting rms beam sizes produces a very good agreement when the actual beam is close to Gaussian, because the beam size fitting method uses Gaussian input beam in the simulation.

INTRODUCTION

The usual phase space tomography is based on linear mapping of several measured beam profiles onto the initial phase space to reconstruct the particle distribution at the reconstruction place. However, the emittance reconstruction methods using linear transfer matrices are reliable only when space charge force or nonlinear effects are negligible and the emittance is conserved. For instance, in the longitudinal plane, the motion is nonlinear even if the space-charge force is ignored. To overcome the limitation under space-charge force and nonlinear effects, a hybrid phase space tomography method was developed at CERN [1] which combines tomography with multi-particle tracking including space-charge effect utilizing the beam dynamics code Travel [2]. This method has been tested and validated theoretically and experimentally using the LINAC4 [3]. This method is applied to the RAON LEBT and MEBT and the results are presented in this paper, which is a summary of Ref. [4].

TRANSVERSE PHASE SPACE TOMOGRAPHY

Tomography in the MEBT

The phase space tomography method is applied to obtain the MEBT input beam transverse distribution using four wire scanners in the SCL (Superconducting Linac) which are marked by the arrows in Fig. 1 for the tomographic reconstruction. Figure 1 displays the layout of the RFQ, the MEBT and the SCL. These four wire scanners are located at periodic locations of the lattice. This is a favourable configuration because the phase advances between the two adjacent wire scanners range from 87° to 80°. The beam dynamics simulation shows that the RFQ output beam is close to Gaussian. For the beam dynamics simulation, the beam distribution obtained from the Allison emittance data is used as the initial beam distribution and is tracked to the RFQ exit.

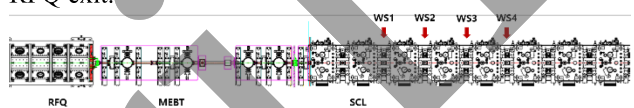

Figure 1: Layout of the RFQ, the MEBT and the SCL. Locations of the wire scanners are marked by the arrows placed between cryomodules. [Courtesy of Ref. [4]]

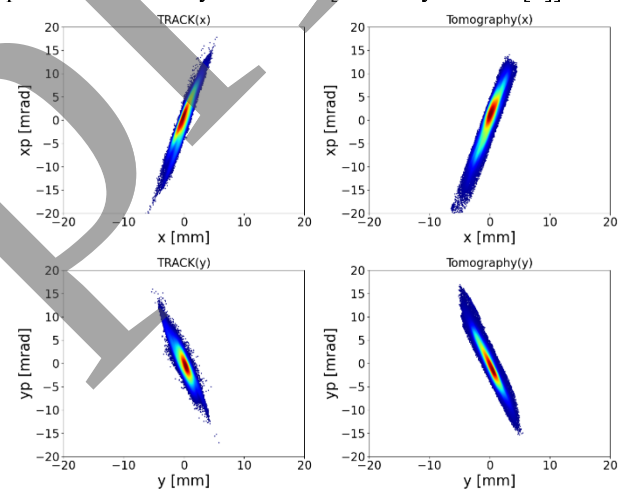

Figure 2: Plots of reconstructed beam distribution by the tomography method on the right and those from TRACK code simulation on the left. The distribution by the tomography method has more low intensity tails contributing to the rms emittances. [Courtesy of Ref. [4]]

Figure 2 shows the reconstructed beam distribution plots at the MEBT entrance by the tomography method, which reveals a Gaussian-like core and very low intensity non-Gaussian beam tails in the plots on the right. Tomography reconstruction produces very similar results to those obtained by the TRACK code. Beam parameters are then extracted from the reconstructed beam distribution which are listed in Table 1. The emittance and lattice functions are obtained from the beam distributions obtained from the TRACK simulation and from the tomography method. They are rms quantities of the beam distribution. For the TRACK code simulation, the beam distribution obtained from the Allison emittance data is used as the initial beam

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distribution and is tracked through the LEBT and the RFQ. The RFQ output beam distribution is compared with the results of the Tomography method.

Table 1: Beam Parameters at the MEBT Entrance

	Tomography	Beam size fitting
ε_x	0.0965	0.0894
ε_y	0.0780	0.0606

Tomography in the LEBT

The tomography method is applied to obtain the beam distribution using the four wire scanners in the LEBT. In the LEBT, there are also Allison emittance scanners (X and Y planes) along with the four wire scanners. This makes a direct comparison possible between the emittance data and the tomographic reconstruction data. Figure 3 displays the schematic lattice layout of the ECR ion source, the LEBT and the RFQ along with the four wire scanners (red arrows) and the Allison emittance scanners (blue arrow).

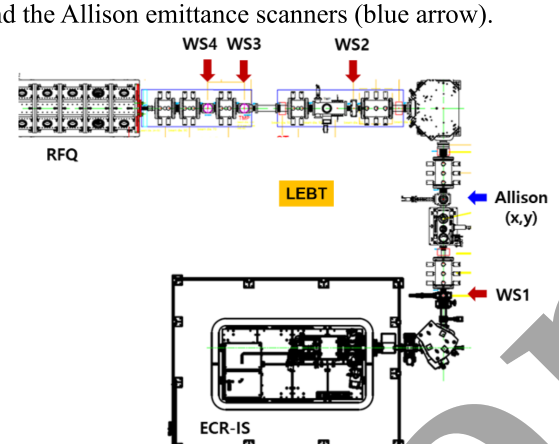

Figure 3: Layout of the ECR ion source, the LEBT and the RFQ. Locations of the four wire scanners are marked by the red arrows and that of the Allison scanners by the blue arrow. The LEBT consists of seventeen electrostatic quadrupoles, two magnetic quadrupoles and two dipoles.

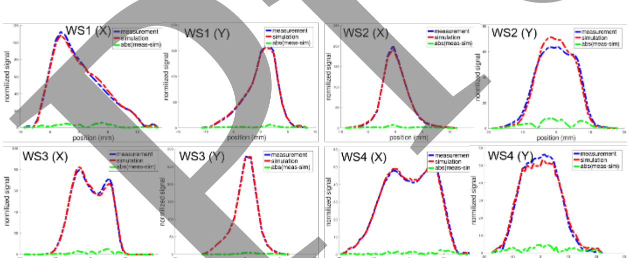

Figure 4: Plots of the wire scanner data (in blue) and the beam profiles reconstructed by the tomography method (in red). Their differences are displayed in green. Measured beam profiles indicate that the actual beam distribution is far from Gaussian. It is observed that quality of Y plane reconstruction is inferior to that of X plane. [Courtesy of Ref. [4]]

Figure 4 shows the beam profiles obtained by the tomography method (in red) and the measured beam profiles of the wire scanners (in blue). Measured beam profiles indicate that the actual beam distribution is far from Gaussian. It is observed that the agreement in Y plane is inferior to that in X plane. The overall agreement is very good, but not so good as in the MEBT case. This is attributed to the phase advances between the wire scanners: the phase advance $\phi_x = 213°$ ($\phi_y = 265°$) between the first and the second wire scanner; $\phi_x = 119°$ ($\phi_y = 140°$) between the second and the third wire scanner; $\phi_x = 10°$ ($\phi_y = 8°$) between the third and the fourth wire scanner. In Fig. 5, the tomography reconstructed beam distribution is compared with the Allison emittance data. The reconstructed data reflect a remarkable resemblance to the Allison emittance data where detailed beam structures are well reproduced: location of the peak density core, orientation of beam tails etc. Figures 4 and 5 show that the reconstruction quality in the Y plane is inferior to that in the X plane.

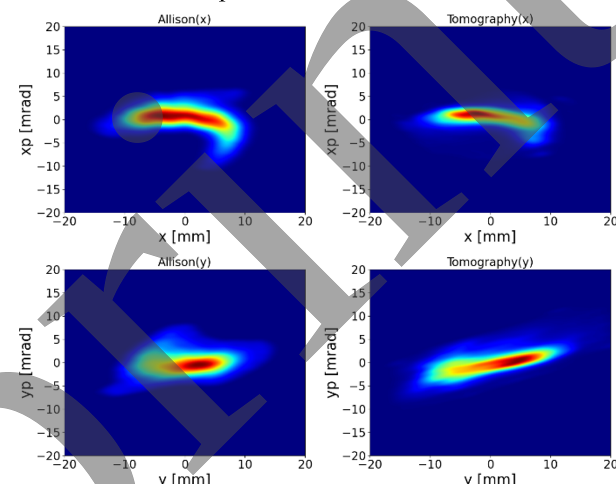

Figure 5: Plots of the Allison emittance data on the left and the corresponding tomographic reconstruction data on the right in X and Y planes. Overall good agreement is found: location of the peak density core, orientation of beam tails etc. Here the second-order geometric and magnetic field effects of dipoles and the space charge effect are included in the Travel code simulations. [Courtesy of Ref. [4]]

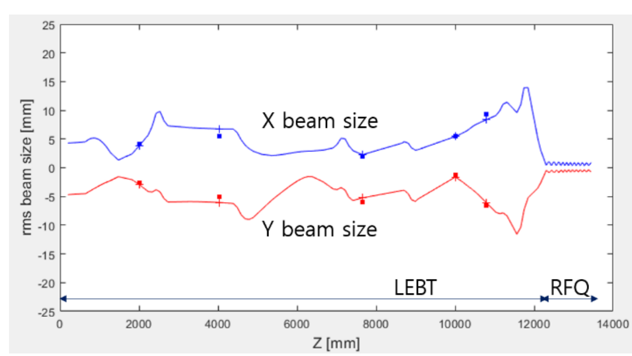

Figure 6: Plots of rms beam sizes obtained by fitting rms beam sizes of wire scanners. Solid squares represent the rms beam sizes obtained from the wire scanner profile data and from the emittance data. The second squares from the left are obtained from the emittance data. The Y beam sizes are plotted in negative values to make the plot less busy. [Courtesy of Ref. [4]]

Table 2: Beam Parameters at the Allison Scanner

	Allison scanner	**Tomography**	**Beam size fitting**
ε_x	0.0668	0.0522	0.0412
ε_y	0.0584	0.0616	0.0384

Table 2 lists the beam parameters obtained by three different methods: the Allison emittance scanner; the tomography method, and the method fitting rms beam sizes. Figure 6 displays the result of the beam size fitting method.

It should be noted that there are two dipoles in the LEBT and that the beam energy is 10 keV/u. So, we check whether it counts to include the second-order geometric and magnetic field effects of dipoles and the space charge effect. Simulations with the Travel code show that including the second-order dipole effects and space charge is necessary for accurate reconstruction. The second-order dipole effects seem to affect primarily the vertical (Y) plane, while the space charge effect affects both planes. Figure 7 illustrates plots of the tomographic reconstruction data with and without the second-order dipole effects and the space charge effect. It is found that without nonlinear effects, the features are not well reproduced such as location of the peak density core, orientation of beam tails etc.

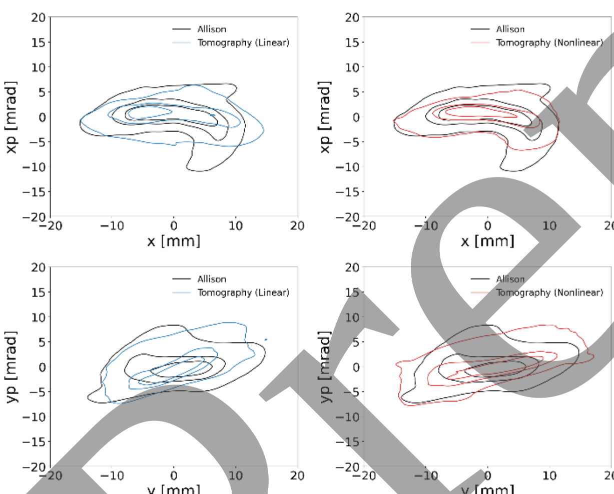

Figure 7: Contour plots comparing the Allison emittance data and the tomographic reconstruction data with and without nonlinear effects. Plots with nonlinear effects are shown on the right and those with linear effects on the left. The results with linear effects do not include the second order effects of dipoles nor the space charge effect. Tomographic reconstruction results are better with nonlinear effects. [Courtesy of Ref. [4]]

A conventional phase space tomography method relies on the back projection of the measured beam profiles onto the phase space at the reconstruction point. This approach uses linear transfer matrices for the back projection. Therefore, if the method is applied in a beamline where nonlinear forces are significant, it will not produce accurate results. In principle, the conventional tomography result can be reproduced by ignoring nonlinear effects in the beamline and using the hybrid phase space tomography described in our paper. Comparison of the cases with and without nonlinear effects is illustrated in Fig. 7 showing the overlapped plots with and without nonlinear effects. When space charge and second-order effects are switched off in the reconstruction, the quality of the tomography degrades.

CONCLUSION

With the Allison emittance scanners in the LEBT, we validated the accuracy of the phase space tomography method. Due to two dipoles in the LEBT, nonlinear effects such as the space-charge force and the second-order effects should be addressed properly. It is found that we need to include the second-order geometric and magnetic field effect of dipoles and the space charge effect. It is demonstrated that the tomography method reconstructs pretty accurate phase space beam distribution from the profile data of four wire scanners, even when the actual beam is far from Gaussian.

ACKNOWLEDGEMENT

This work is supported by the Institute for Basic Science (IBS-I001-D1).

REFERENCES

[1] V. A. Dimov, J.-B. Lallement, A. M. Lombardi, and R. Gaur, "Emittance Reconstruction Techniques in Presence of Space Charge Applied During the Linac4 Beam Commissioning", in *Proc. HB'16*, Malmö, Sweden, Jul. 2016, pp. 433-438. doi:10.18429/JACoW-HB2016-WEPM1Y01

[2] A. Perrin and J.F. Amand, Travel v4.06 user manual, CERN, 2003.

[3] S. Benedetti; G. Bellodi; D. Küchler; V. Toivanen, "The 2017 Xe run at CERN Linac3: Measurements and beam dynamics simulations", *Rev. Sci. Instrum.* Vol. 89, pp. 123301, 2018. doi:10.1063/1.5066086

[4] D. Jeon *et al.*, "Transverse phase space tomography and comparison with Allison scanner data in the RAON heavy ion accelerator", *Nucl. Instrum. Methods Phys. Res. A,* vol. 12, no. 6, pp. 127-136, 2024. doi:10.1016/j.nima.2025.171005