ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF001

TOMOGRAPHY OF A HORIZONTAL PHASE SPACE DISTRIBUTION OF A SLOW EXTRACTED PROTON BEAM IN THE MedAustron HIGH ENERGY BEAM TRANSFER LINE

A. Wastl*, Atominstitut, Vienna, Austria
M. Benedikt, CERN, Geneva, Switzerland
A. Garonna, EBG MedAustron, Wiener Neustadt, Austria

Abstract

MedAustron is a synchrotron based hadron therapy and research center in Wiener Neustadt, Austria, which currently is under commissioning for the first patient treatment. The High Energy Beam Transfer Line (HEBT) consists of multiple functional modules amongst which the phase-shifter-stepper PSS is the most important module located where the dispersion from the synchrotron is zero and upstream of the switching magnet to the first irradiation room. The PSS is used to control the beam size for the downstream modules and for this scope rotates the beam in horizontal phase space by adjusting the phase advance. This functionality is used in this study to measure beam profiles for multiple phase space angles which act as input for a tomographic reconstruction. Simulation and measurement results are presented.

INTRODUCTION

The third order resonance slow extracted beam has a bar-like, non-gaussian phase space distribution in the plane of extraction (horizontal) called 'bar of charge' while in vertical phase space it has the usual distribution [1]. This particle distribution then propagates through the HEBT up to the PSS which is composed of six quadrupole magnets powered by independent power supplies. Its 'phase shifter' functionality adapts the horizontal phase advance μ_x keeping β_x at the end of the module (Fig. 1) constant while its 'shifter' function at the same time sets the needed variation of β_y.

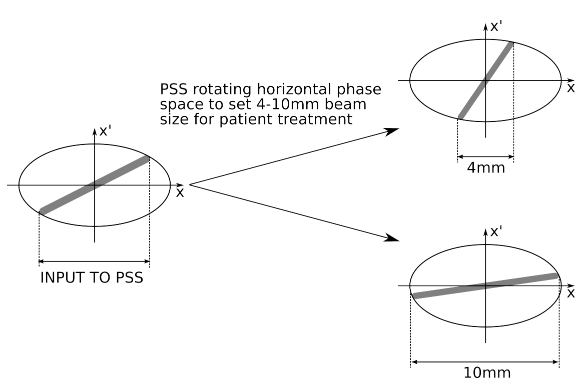

Figure 1: Adjusting the horizontal beam size [2].

Up to the entrance of the PSS the normalized strengths of optical components are independent of the required beam size at the beam line exit. Downstream the PSS 'telescope' modules project the adjusted beam size from the end of the PSS to the isocenter in the treatment room. This way the beam size is adapted to the required for patient treatment.

Using the PSS to rotate the bar in horizontal phase space and measuring the profiles downstream the module, the particle density distribution can be computed by a reconstruction techniques called tomography known from SPECT to compute the particle distribution at the monitor.

Figure 2 shows the horizontal and vertical β-functions for different horizontal phase advances and different β_y. In horizontal phase space the β-function at the PSS entrance and exit are identical. For medical purposes only four phase advance settings (representing 4mm, 6mm, 8mm and 10mm spot size at the isocenter in vacuum) are foreseen. For this study, MADX [3] was used to compute additional PSS magnet settings representing horizontal phase space rotation angles over a range of 180° (half a rotation) keeping β_y constant. Applying the different settings to the PSS, a scintillating fiber monitor SFX (64 fibers, 1mm resolution) downstream the PSS measured the different beam profiles.

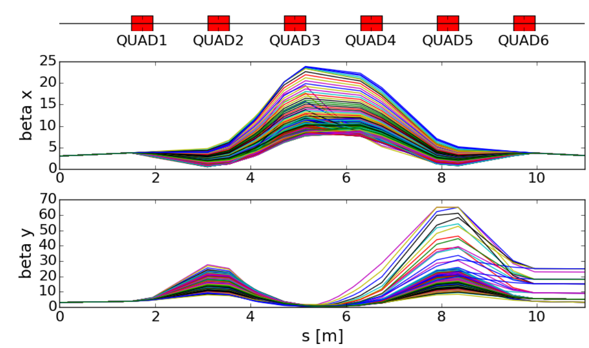

Figure 2: β_x and β_y for different beam sizes

RADON TRANSFORMATION

In modern medical diagnostics the computed tomography CT is a well-developed technique to recover information of the inner structure of the body. Density projections of a 2D 'slice' of the object of interest onto a 1D detector (the Radon transformation of the slice) performed from multiple angles around a perpendicular axis of rotation are taken as measurements and the inverse Radon transformation problem is solved to reconstruct an image of the inner structure. A medical CT performs the measurements by rotating an x-ray source and a detector around a patient who remains in place. In this study, this priciple is inverted using the PSS to rotate

* alexander.wastl@medaustron.at

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF001

the beam in phase space while a fixed downstream monitor measures the projections of the beam onto the monitor plane. The 2D figure presenting the series of 1D projections for different measurement angles is called sinogram.

Two different techniques were used to compute the inverse Radon transformation: filtered back-projection FBP and simultaneous algebraic reconstruction technique SART [4]. FBP back-projects the measured 1D data along the initial projection axis onto a virtual, empty 2D area. Performing this from all measurement angles and summing the projected data pixel-wise reconstructs the initial phase space. To minimize blurring, the measurement data is filtered before back-projection. SART is an iterative technique that calculates the image in multiple iterations. Starting from a first guess of the 2D distribution, in each iteration it applies corrections to the distribution and verifies that the computed projections converge towards the measured projections. The additional computational effort of SART results in a noise-reduced phase space image compared to FBP.

SIMULATION RESULTS

The software WinAGILE [5] was used to track a simulated slow extracted particle distribution of 10k particles from the entrance of the HEBT to the exit of the PSS. A python script [6] then computed the sinogram (100 angles over 180 degrees, 64 histogram bars) and the corresponding reconstruction. Figure 3 shows the tracked particle distribution at the SFX and the corresponding sinogram is shown in Fig. 4. One density projection on the monitor plane represents one 'line'.The different lines illustrate the projections from the different measurement angles.

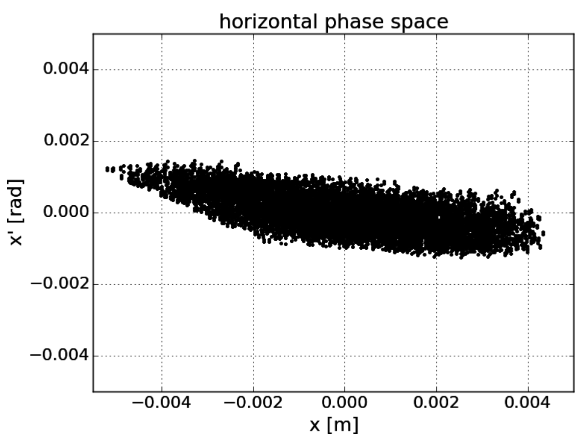

Figure 3: Simulated horizontal phase space.

SART (Fig. 5a) and FBP with a ramp filter (Fig. 5b) were used to reconstruct the phase space distribution. The reconstruction is consistent with the initial distribution and therefore indicates the correctness of the python software.

MEASUREMENT RESULTS

The commissioning of the MedAustron accelerator currently is in the final stage [7] and therefore a preliminary proton beam is available in the PSS module. One hundred

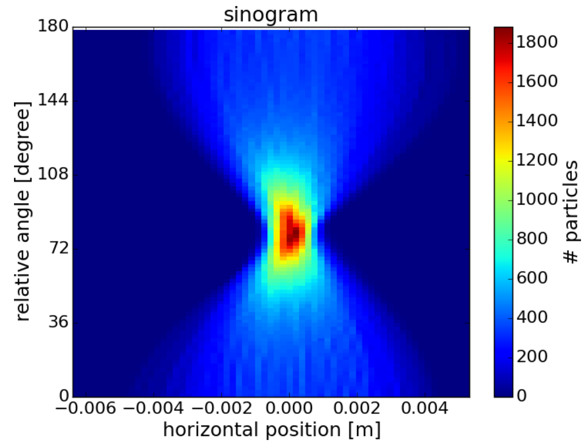

Figure 4: Sinogram of the simulated phase space distribution.

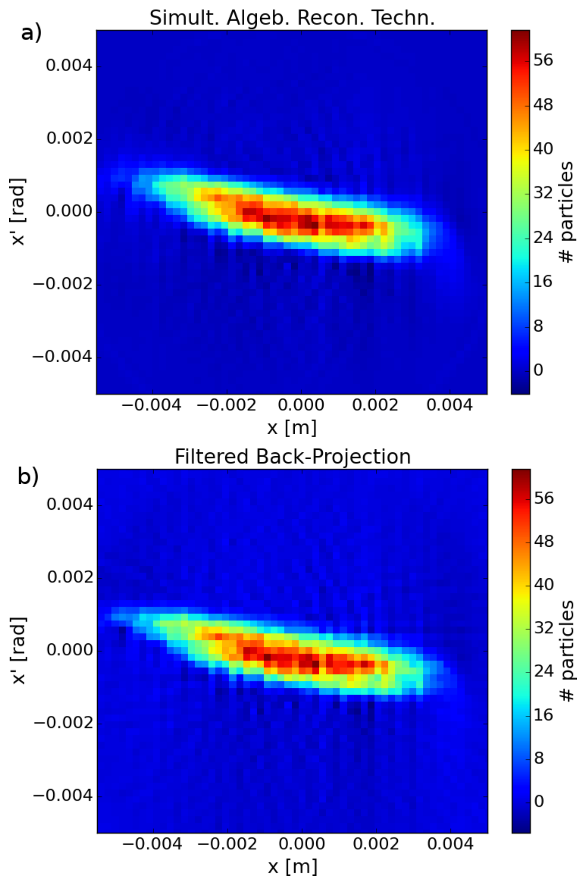

Figure 5: Reconstruction using a) FBP and b) SART

PSS module quadrupole magnets settings were computed with MADX [3] matching equally distributed horizontal phase advances in a range of 180 degrees and keeping the β-functions at the downstream beam position monitor EX-01-003-SFX constant. These settings were applied to the accelerator components consecutively by a dedicated measurement software [8]. The downstream SFX acquisition was set up to a frame rate of 20 frames per second and an exposure time of 25ms to avoid saturation effects.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF001

Figure 6 shows the sinogram of these measurements. The trajectory has not been corrected before these measurements were performed resulting in a variation of the beam position for different PSS settings. The beam positions were corrected prior the tomography by shifting the center of gravity of the profile to center position to mitigate this effect.

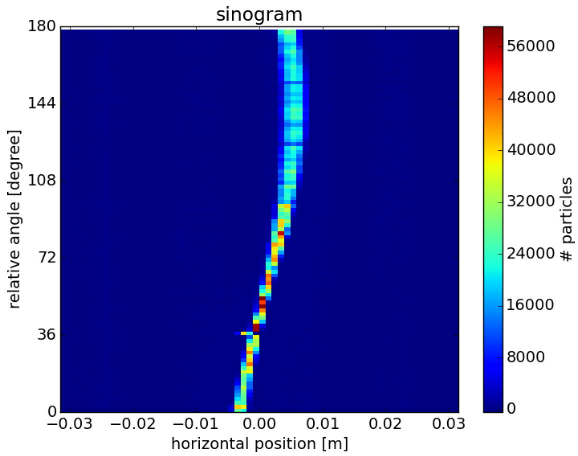

Figure 6: Sinogram of the measured projections

The most narrow beam profile can be identified at approx. an angle of 50° which indicates an upright position of the bar-of-charge in horizontal phase space while the widest beam profile at about 140° corresponds to a horizontal orientation of the bar-of-charge. Extracted beam intensity fluctuations have to be accepted as the RF channeling as a counter measure was not implemented.

Figure 7a shows the reconstruction of the measured sinogram using SART while for Fig. 7b FBP was used. The blurring effect known from FBP in Fig. 7b is very strong compared to Fig. 7a. The shape and orientation of the two reconstructed distributions are similar and correspond to the simulations. As the synchrotron RF jump was not executed and therefore the momentum spread not increased to the design, the length of the bar-of-charge does not correspond to the simulation.

CONCLUSION

The shown results provide an empirical proof of principle for the PSS concept of rotating the horizontal phase space in the HEBT. The reconstruction of a bar-of-charge like particle density distribution from the measured beam profiles indicates the proper functionality of the designed extraction mechanism, gives a good agreement between simulations and measurements as well as an estimate of further accelerator components settings and beam parameters. The results will be used for the commissioning for the accelerator and may act as input for medical physics simulations. However, the measurements for this study were only performed once and cannot make a statement on the reproducibility.

Future improvements of the analysis script could head towards intensity normalization of the input data or distribution changes over extraction time. The method could also be used to optimize the extraction to match the Hardt condition of the slow extraction or the reconstruction of the spiral step distribution. Furthermore different extraction mechanisms and settings can be investigated and compared.

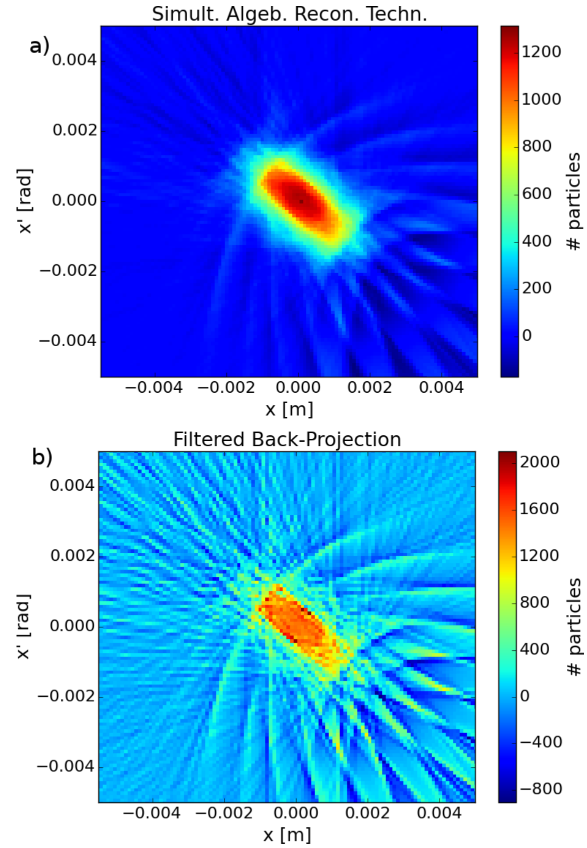

Figure 7: Reconstruction using a) FBP and b) SART.

ACKNOWLEDGMENT

This research was supported by EBG MedAustron and we want to express our gratitude to all contributing colleagues at MedAustron. Furthermore, we thank U. Dorda for initiating this study, his supervision of the first Python code and the passed on input as well as M. Pullia for accelerator physics discussions and for his WinAGILE support.

REFERENCES

[1] P.J. Bryant *et al.*, "Proton-Ion Medical Machine Study (PIMMS) Part II", CERN-PS-2000-007-DR (2000).

[2] M. Benedikt, P. Bryant, M. Pullia, "A new concept for the control of a slow-extracted beam in a line with rotational optics: Part II", Nuclear Instruments and Methods in Physics Research Section A, Vol 430, Issues 2–3 (1999) pp. 523-533.

[3] MADX website: `http://madx.web.cern.ch/madx/`

[4] A.H. Andersen and A.C Kak, "Simultaneous Algebraic Reconstruction Technique (SART): A superior implementation of the {ART} algorithm ", Ultrasonic Imaging, Vol 6 (1984) pp. 81-94.

[5] P.J. Bryant, WINdows Alternating Gradient Interactive Lattice dEsign.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF001

[6] Python website: https://www.python.org/

[7] A. Garonna *et al.*, "Status of the Proton Beam Commissioning at the MedAustron Ion Beam Therapy Centre ", presented at the 6th Int. Particle Accelerator Conf. (IPAC'15), Richmond, VA, USA, May 2015, paper MOBB1, these proceedings.

[8] A. Wastl, M. Hager, and M. Regodic, "Operational Applications - A Software Framework used for the Commissioning of the MedAustron Accelerator ", presented at the 6th Int. Particle Accelerator Conf. (IPAC'15), Richmond, VA, USA, May 2015, paper MOPHA002, these proceedings.