TRANSVERSE PHASE PORTRAIT TOMOGRAPHY OF PROTON BEAMS AT INR RAS LINAC

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Abstract

Measuring of the parameters of the transverse phase portraits is crucial for beam dynamics. A method of tomographic reconstruction is implemented at INR RAS linac as an alternative to already existing quadrupole variation method. In this work new feature of disturbing online measurements of phase portrait parameters and important experimental results are discussed. Comparison of tomographic method with quadrupole variation method is presented.

INTRODUCTION

Measuring of the parameters of the transverse phase space is crucial for beam dynamics. For low-energy beams these measurements can be made with slit-grid or pepper pot devices. However, for high-energy beams another method is applied – a quadrupole variation method (QVM). A typical layout of components, required for QVM measurements, is presented on Fig. 1.

Another way of measuring beam transverse phase portrait parameters, which can be attributed to QVM, is a tomographic reconstruction. It can be implemented with the same layout as QVM and differs only in processing of obtained information. Feasibility of tomographic reconstruction method is based on Radon transform and was firstly implemented in 70s [1].
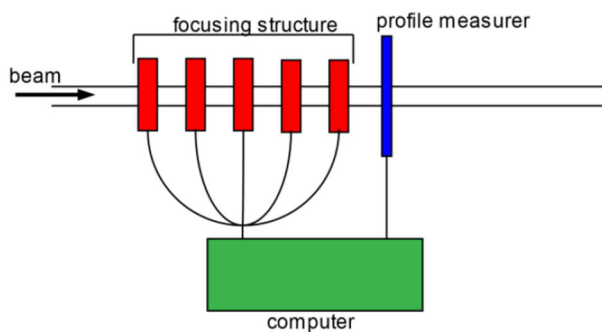

Figure 1: Typical layout of components required for quadrupole variation method measurements.

At INR RAS linac automatic procedure of emittance measurements was developed and implemented at the exit of accelerator on the base of ionization Beam Cross Section Monitor (BCSM) [2]. This procedure provides disturbing online emittance measurements during routine accelerator operation. Also a program for offline measurements was implemented.

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DESIGN FEATURES

As it was previously mentioned tomography is based on BCSM, which schematic configuration is presented on Fig. 2. Image from its phosphor screen is transferred via catadioptric system and acquired with Basler acA780-75gm camera, which is installed under concrete shielding of accelerator. Camera is connected with computer in the control room via optic fibre.
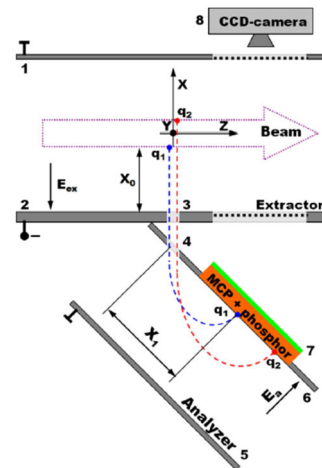

Figure 2: BCSM schematic configuration.

Phase portrait rotation is performed by eight quadrupole doublets, located before BCSM. They are powered by two independent current sources. Transfer matrix method is used for description of focusing structure of accelerator.

SOFTWARE FEATURES

Tomography software at INR is written mostly in LabVIEW [3], tomography kernel is written in Python. Image acquisition and calibration is based on luminescent diagnostics software for INR RAS Proton Irradiation Facility (PIF) and has been described in detail in [4].

Online tomography consists of several steps, which include preplanning of measurements, the measurements of beam profiles and tomographic reconstruction. Preplanning step includes input of currents, which will be set on lenses current sources. After preplanning step user starts up the measurements for tomography.

During the measurement step program changes currents in the sources according to the plan, then the program measures profiles. After making all planned measurements, the program returns initial currents in the sources

and starts tomographic reconstruction based on acquired profiles.

Reconstruction step starts with making transfer matrixes for each measured profile. Obtained profiles are transformed with use of the transfer matrixes and converted into a sinogram. The rotation angles in phase space are also obtained from transfer matrixes. The sinogram and rotation angles are then transmitted to tomography kernel.

The tomography kernel is based on Simultaneous Algebraic Reconstruction Technique (SART) algorithm [5]. It is considered as a fast converging algorithm, which needs fewer projections for same level of RMS error in comparison with most of other algorithms. Figure 3 shows level of error depending on number of iterations for different amount of projections. SART algorithm is taken from open-source code package called "scikit-image" [6].
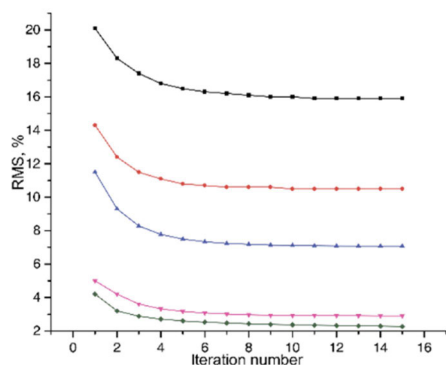

Figure 3: RMS error depending on number of iterations for different amount of projections. Black line (2 projections), red (10 projections), blue (20 projections), pink (100 projections), green (200 projections).

For most of measurement cases at INR RAS linac there are nearly ten projections taken for reconstruction. As it can be seen from Fig. 3, for 10 projections SART converges at 5th iteration, so that amount of iterations is used.

Reconstruction results, obtained by tomography kernel, are then post-processed. Each phase portrait is split into 20 sub portraits so that summarized intensity in each of them varies by 5 % of the total intensity of the original phase portrait. An envelope is calculated for every sub portrait, and this envelope is approximated by a phase ellipse (Fig. 4). Twiss parameters, emittance and center of each phase ellipse are calculated. All that data is displayed for user. One of tabs of the program with tomography settings and data is presented on Fig. 5.
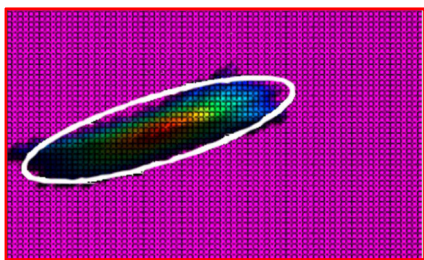

Figure 4: An approximation of phase portrait by a phase ellipse.
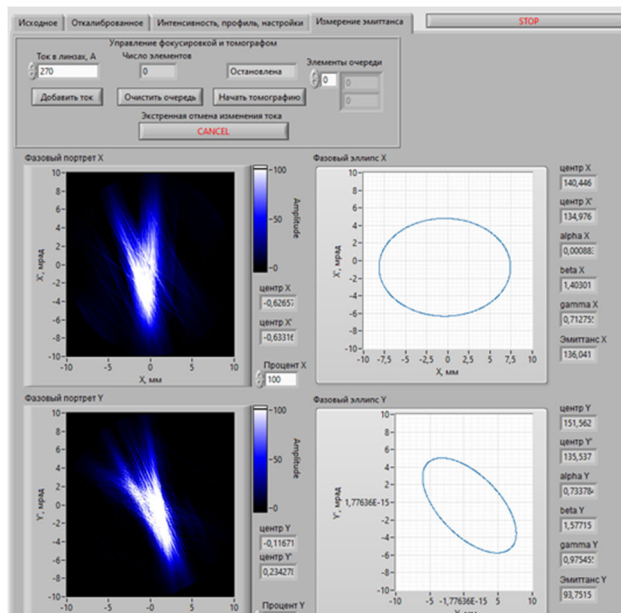
Figure 5: Main program tab with tomography data and settings.

Components and algorithms being used for tomographic reconstruction make restraints on errors of measurements. RMS errors of measurement of phase ellipse center were determined as 0.7 mm and 0.7 mrad. RMS relative errors of Twiss parameters and emittance measurement are 21%.

The program for offline tomography uses the same kernel as online version. As an input offline program needs an array of profiles, which were previously measured, and an array of transfer matrixes for every profile. This program can process data not only from BCSM but also from other profile measurers at INR linac. However, this feature has only been theoretically proved as feasible and has not been yet properly tested.

EXPERIMENTAL RESULTS

For now tomography at INR linac is going through various tests. Tests of online tomography system are mainly aimed at working out the sequence of actions during measurements. Tests of tomography itself are mainly carried out using offline tomography program with data from previous accelerator runs.

Figure 6 (a) shows results of tomography based on previously collected data from BCSM. It is seen that various "tail" artefacts exist. These artefacts are admissible inaccuracies of SART, which can be cut off. Method of splitting phased portrait to sub portraits, described in previous chapter, allows choosing sub portrait without artefacts.

A minimum of a specially constructed weight function was chosen as a selection criterion. This function uses a similarity of measured and reconstructed profiles. Figure 6 (b) shows phase portrait without artefacts. From now that phase portrait is considered as a result of tomography.
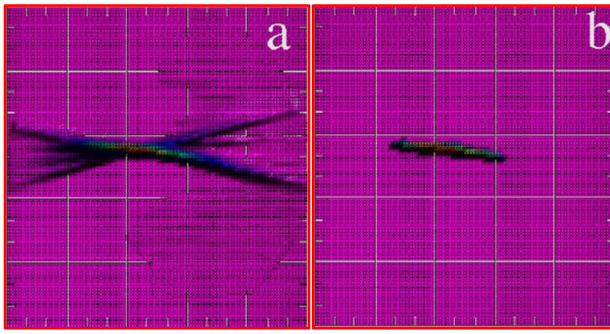
Figure 6: (a) is a raw result of reconstruction; (b) is a result without artefacts.

Tomographic reconstruction was implemented as an alternative to a method of transverse profiles [7], which is a main method for measuring transverse phase space parameters of the beam at INR linac. A comparison between two methods was made, using previously obtained data. Phase ellipses for both methods and axes are presented on Figs. 7 (a) and 7 (b). Centres of ellipses were artificially combined, because transverse profiles method calculates phase ellipse centre apart from reconstruction of the phase ellipse itself.
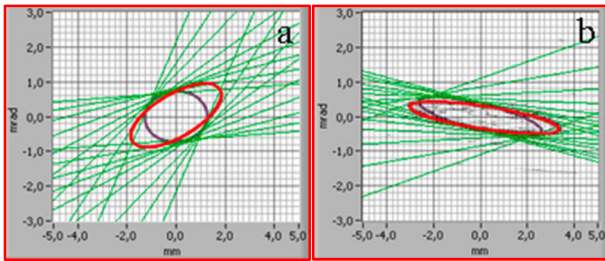

Figure 7: (a) results of tomographic reconstruction (red) and transverse profiles method (brown) for X-axis, (b) results of tomographic reconstruction (red) and transverse profiles method (brown) for Y-axis.

As it can be seen from Fig. 7, results of reconstruction are different, especially for X-axis. A simulation of beam transfer through elements, which were used for measurements, has been done for both methods. Figure 8 shows dynamics of beam position and size in the final part of the transfer line for both methods.
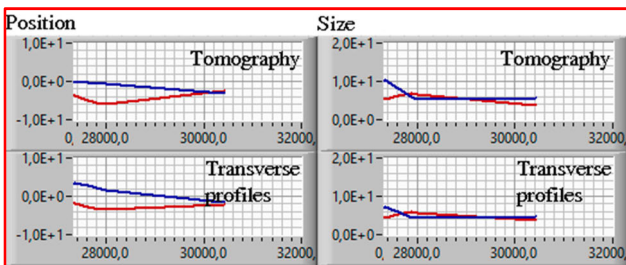

Figure 8: Dynamics of beam position and size in the final part of modelled transfer line. Blue lines are for X-axis, red are for Y-axis.

Results of simulation were compared with real measured beam position and size. Difference between real and reconstructed values, measured in standard deviations of tomographic reconstruction method, are presented in Table 1.

Table 1: Difference Between Measured and Reconstructed Beam Parameters Measured in Standard Deviations

Parameter	Tomography	Transverse profiles
x	0.9	2.8
y	0.6	1.2
σ_x	0.5	0.1
σ_y	0.5	0.1

It is seen that tomographic method is better at reconstructing beam centre than transverse profiles method, while transverse profiles method is better at reconstructing beam size, however difference between measured beam size and reconstructed from tomographic reconstruction data is less than 1 standard deviation. This proves that the tomographic method is a working alternative for transverse profiles method.

Differences in reconstruction results of two methods based on the same data can be explained by how methods treat obtained data. Tomographic reconstruction uses all information given by profile measurer and does not make any constrains on phase portrait parameters. Transverse profiles method only uses information about position and size of the beam. Moreover, transverse profiles method makes severe constrains on phase portrait parameters, based on beam size.

CONCLUSIONS

Transverse phase portrait tomography is a new method implemented at INR RAS linac. With a new method a first disturbing online emittance measurements during routine accelerator operation has been done at INR RAS. Based on previously collected data, a comparison of tomographic method and transverse profiles method has been done. This comparison showed efficiency of the implemented method.

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Transverse Profile and Emittance Monitors