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ENHANCEMENT OF TRANSVERSE BEAM PHASE SPACE ANALYSIS BY TOMOGRAPHY METHOD AT INR LINAC

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Abstract

The investigation of transverse beam phase space parameters behavior along the accelerator is important for proper accelerator tuning. At INR RAS linac transverse emittance and Twiss parameters are reconstructed from beam profile measurements with quadrupole scan technique at several measurement points along the accelerator. Profile treatment is performed with ordinary transverse profiles method and tomographic reconstruction method. Various experimental data is presented. The comparison of the results obtained by the two methods is done. Features of beam dynamics simulation based on the data from these methods are discussed.

INTRODUCTION

The investigation of transverse beam phase space parameters behavior along the accelerator is important for proper accelerator tuning and beam transport simulation. For low-energy beams direct measurements can be done with slit-grid or pepper pot devices. For high-energy beams direct measurements are impossible and reconstruction method is applied – a quadrupole scan technique (QST). A typical layout of components, required for QST measurements, is presented in Fig. 1.

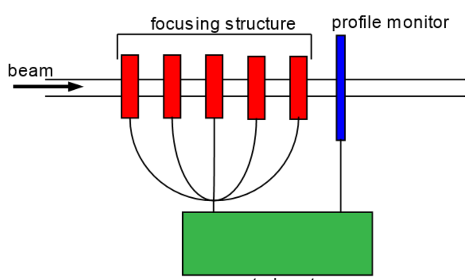

Figure 1: Typical layout of components required for quadrupole scan technique measurements.

QST is a group of methods that in general provides information only about phase ellipse parameters. That is enough for the majority of the beam transfer codes that are used for dynamics simulation. However, if accelerator is not tuned properly, particles distribution in transverse phase space can be non-elliptical. In that case inaccuracy of methods, which reconstruct phase ellipse, grows and so does inaccuracy of the simulation.

One of the methods of beam transverse phase portrait parameters measurements, which can be attributed to QST, is a tomographic reconstruction. It can reconstruct internal structure of the phase space distribution and is applicable for all possible particle distributions in phase space.

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Beam transfer simulation at INR linac is performed with TRACE 3D code and the main method for phase ellipse parameters measurements at INR linac is a typical QST realization – transverse profiles method (TPM). Also a tomographic reconstruction was implemented as an alternative and enhancement to the TPM.

TRANSVERSE PROFILES METHOD

Transverse profiles method requires rms beam size and beam centre measured for its operation. These values are represented as vertical lines in corresponding phase plane. The disposition of these lines can be transferred to arbitrary point of measuring area by transfer matrix method. Results of the measurement represent a set of lines. The phase ellipse is inscribed in these lines with the iteration algorithm (Fig. 2). Twiss parameters and rms emittance values are then obtained. In more detail TPM is described in [1].

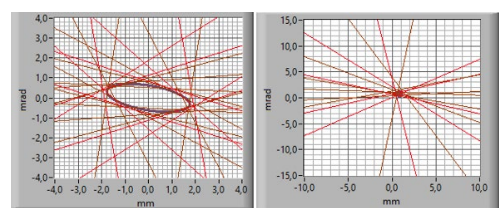

Figure 2: Results of TPM reconstruction. Phase ellipse (on the left) and phase ellipse center (on the right).

TOMOGRAPHIC RECONSTRUCTION

Tomographic reconstruction requires all information about beam profiles for its operation. Obtained profiles are transformed with use of the transfer matrices and converted into a sinogram. The rotation angles in phase space are also obtained from transfer matrices. The sinogram and rotation angles are then transmitted to tomography kernel. The kernel is based on the Simultaneous algebraic reconstruction technique (SART). Result of the tomography is post-processed so it can be used for beam dynamics simulation (Fig. 3). In more detail tomographic reconstruction kernel and post-processing of the results is described in [2].

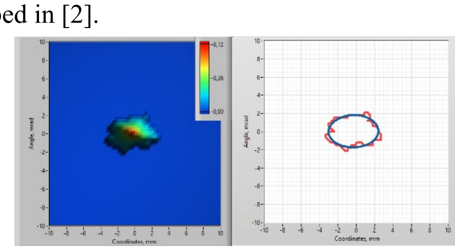

Figure 3: Results of the tomographic reconstruction. On the left – phase portrait. On the right – phase portrait envelope (red) and phase ellipse (blue).

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According to widely used emittance conventions that is also used at INR linac, emittance of the full beam, which is reconstructed by tomography, is 5-rms emittance. Due to SART features tomographic reconstruction provides almost the same level of error if phase space rotation angle is greater than 100 degrees (Fig. 4). Because of that not all measurements can be used.

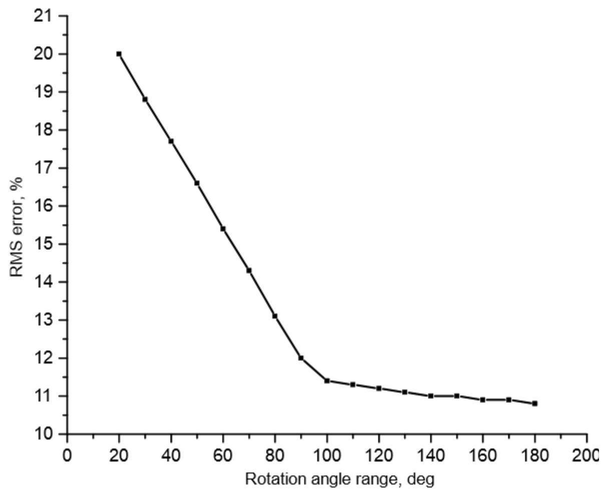

Figure 4: RMS error of the SART depending on rotation angle range.

To check tomography results we simulate the dynamics of the reconstructed phase ellipses and compare the beam position and the size of the reconstructed beams with the measured ones. A standard deviation of the reconstructed value is used as a unit of measurements. If the reconstructed beam size results of the phase ellipse transport simulation differ from the measured values by more than one standard deviation of tomographic method, then the phase portrait is not treated as elliptical and cannot be used for beam dynamics simulation in TRACE-3D codes. Difference between measured and reconstructed profiles is denoted as v_e. In these terms this criterion can be formulated as $v_e \leq 1$.

EXPERIMENTAL RESULTS

During accelerator run in April 2021 beam profiles has been measured at five different points of INR linac (Fig. 5). Measurements were made with two SEM-grids located after RFQ, SEM-grid located after first DTL tank (C1 in Fig. 5), two wire scanners (WS1 and WS2) located near the matching cavity (MC in Fig. 5), Beam Cross-section monitor (BCSM) located at the exit of the linac (C32 in Fig. 5) and SEM-grid located at the end of the Research Complex transport line. There were two measurements made with BCSM: one with 100 µs and other with 32 µs beam pulse length.

For all measurements rotation angle ranges have been checked. For SEM-grids after RFQ and SEM-grid in Research Complex transport line ranges were less than 100 degrees so these measurements were not treated.

Twiss parameters and transverse emittance values for all measurements are presented in Table 1. Data from wire scanners was treated by TPM simultaneously, so there is one column for WS measurements for TPM. Twiss parameter γ can be derived from other parameters so its values are omitted in the table. Underlined values for tomography measurements mean that v_e is greater than 1 so phase portraits cannot be treated as elliptical.

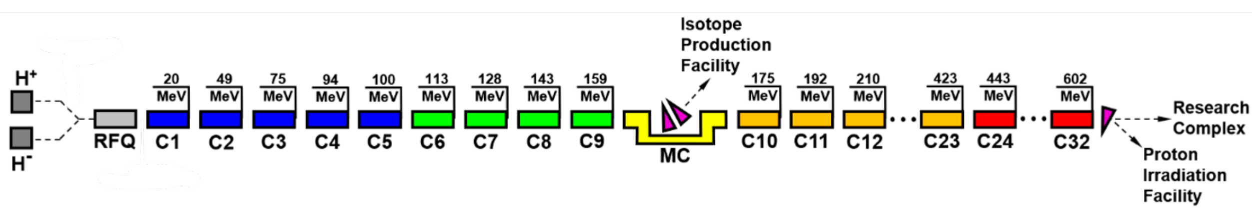

Figure 5: INR RAS linac diagram.

Table 1: Values of Twiss Parameters and Transverse Emittance for Both Methods in Different Measurement Points

Parameter	Tomography					TPM			
	SEM-grid	WS1	WS2	BCSM 32 µs	BCSM 100 µs	SEM-grid	WS	BCSM 32 µs	BCSM 100 µs
x, mm	1.18	-1.75	-0.3	-2.92	-1.98	0.36	-0.32	-3.00	-2.46
x', mrad	0.45	1.19	0.03	1.92	1.30	1.96	0.56	1.78	0.84
α_x	-0.05	0.02	-0.03	-0.46	0.03	-1.36	0.64	-0.18	0.26
β_x, mm/mrad	0.58	1.47	1.53	4.26	4.49	0.57	1.30	3.36	2.38
$\varepsilon_{x\,norm}$, mm*mrad	2.48	2.43	2.60	2.14	2.41	0.52	0.41	0.38	0.77
y, mm	0.84	2.23	0.16	-1.04	-0.60	0.60	0.08	-0.90	-1.42
y', mrad	0.95	-1.64	0.00	-0.01	0.55	0.50	-0.76	0.12	0.84
α_y	0.93	1.72	2.22	0.54	0.84	1.08	2.73	0.86	0.83
β_y, mm/mrad	0.83	4.61	5.4	5.48	5.13	0.93	5.47	5.37	3.49
$\varepsilon_{y\,norm}$, mm*mrad	3.40	2.81	3.63	3.2	4.16	0.62	0.52	0.57	0.85

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METHODS COMPARISON

Results from Table 1 show that with tomographic reconstruction not all measurements can be selected for further beam dynamics simulation because they have non-elliptical phase portraits. For elliptical measurements, results differ for these two methods. These results were used for dynamics simulation through the transport line so that reconstructed and real values could be compared.

The dynamics of the beam position and size through the transport line for both methods based on the WS1 data is shown in Fig. 6. Also, the simulated beamline structure is presented. Difference between the experimental and the reconstructed values measured in standard deviations of the tomographic reconstruction method are presented in Table 2. The tomographic method is better at reconstruction beam center than the transverse profiles method. All differences between the measured and the reconstructed beam size for both methods are less than one standard deviation.

Table 2: Difference Between Measured and Reconstructed Beam Parameters Measured in Standard Deviations

Parameter, standard deviations	Tomography	TPM
$position_x$	0.39	2.12
$position_y$	0.20	2.42
$rms\ size_x$	0.86	0.15
$rms\ size_y$	0.11	0.36

Results show a similar behaviour of the normalized emittance values for both methods: it decreases from SEM-grid to WS and then grow from WS to BCSM in case of 100 µs beam (for tomography growth starts from WS1 to WS2). For 32 µs beam there is no significant growth from WS to BCSM.

Behaviour of normalized emittance from SEM-grid to WS can be easily explained with measurements of the beam pulse current near the same points because it decreases along with the emittance values. However current continue to decrease after wire scanners while normalized emittance does not.

There is a possible explanation for this phenomenon, which can explain dynamics of the normalized emittance and the difference between BCSM measurements for different pulse length. The reason could be a problem with beam loading compensation system. This leads to energy divergence of the beam within the pulse. After first wire scanner beam position is corrected with dipole correcting magnets along the accelerator, which push apart differently accelerated parts of the beam. This leads to non-elliptical shapes of phase portrait that can be seen on BCSM. When a 32 µs beam is measured there is no emittance increase due to uniform acceleration of the pulse.

CONCLUSIONS

Transverse phase portrait tomography is implemented at the INR RAS linac as an addition to transverse profiles method. Information about internal structure of particle distribution in transverse phase space can determine if phase portrait can be treated as elliptical or not. Tomographic reconstruction will help to choose the most proper phase ellipse parameters for beam dynamics.

Results of both methods show normalized emittance growth along the accelerator. If a hypothesis connected with beam longitudinal mismatch is right then results of these two methods can be uesd as an indicator of improper accelerator tuning.

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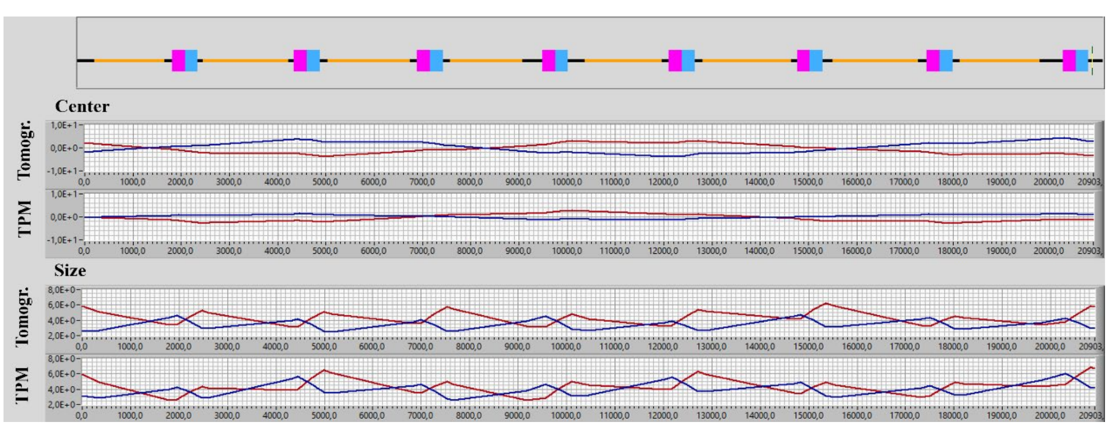

Figure 6: Scheme of the transport line around the matching cavity (on top) and beam position and size dynamics through the simulated transport line. On the scheme pink and blue rectangles are quadrupole lenses, orange lines are accelerating cavities, black lines are drift spaces. On the graphs blue lines are for the X-axis, red lines are for the Y-axis.