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BEAM PHASE SPACE RECONSTRUCTION FOR MONITORING THE LUMINOSITY IN THE VEPP-2000 COLLIDER*

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Abstract

16 synchrotron light imaging monitors available in VEPP-2000 can be used for evaluation of dynamic betas and emittances at collision. Tomographic techniques are useful for reconstruction of non-gaussian beam phase space at the IPs at high intensities of colliding bunches. The output is applied for prompt luminosity monitoring.

INTRODUCTION

VEPP-2000 is used for hadron cross section measurements in the energy range of 0.4 ÷ 2 GeV [1]. It accumulate statistics at several dozens of energies every season, thus emphasizing the tuning tools' importance. The collider has a two-fold symmetry lattice with 16 CCD cameras that take beam images using synchrotron light (Fig. 1). 8 CCDs are aimed at electrons and 8 at positrons.

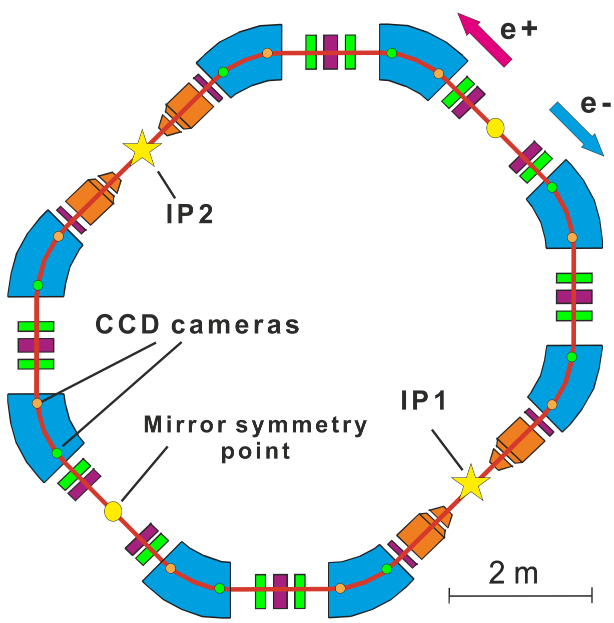

Figure 1: VEPP-2000 layout.

There are a number of theoretical and empirical considerations regarding lattice configuration depending on the energy [2], but the last step of the final tuning is almost always unique and done manually. Fine-tuning requires fast and reliable luminosity estimation tools. Unfortunately, the speed and precision of luminosity measurements from the detectors are not sufficient, especially at low energies.

Two fast estimation methods were developed at VEPP-2000 [3]. Both methods assume that an accurate optics model of the real accelerator ring is available. Assuming that there are no focusing perturbations in the lattice other than those caused by the collisions, and thus located at the Interaction Points (IPs), one can use known transport matrices to evaluate beam sizes at the IPs from the beam sizes measured by CCDs. The assumption of Gaussian transverse distribution of particles in the bunches limits the precision of both methods. To overcome this limitation the beam phase space tomography is proposed.

PHASE SPACE TOMOGRAPHY

A relatively small number of CCDs – 8 for electrons and 8 for positrons – led to a pessimistic estimation of the classical approach to the beam phase space tomography methods which use several tens of projections [4]. Therefore, a feasibility study regarding this task was started after the shutdown of VEPP-2000.

Inverse Problem Solver

The success in solving inverse problems using Singular Value Decomposition (SVD) of linearized model, inspired its use in the beam phase space tomography method. Given a set of experimental data $V_{exp,j}$ is available the goal is to find the parameters P_i of the model $\mathfrak{M}_j(P_i)$ that best describes the measurements:

$$V_{mod,j} = \mathfrak{M}_j(P_i). \tag{1}$$

In the case of a liner model, the task simplifies to:

$$\Delta V_{mod,j} = \mathfrak{M}_{ji} k_i \frac{\Delta P_i}{k_i}, \tag{2}$$

where k_i are the normalization coefficients.

The difference between the experimental data and the model is:

$$D_j = V_{exp,j} - V_{mod,j}. \tag{3}$$

The goal is to find a variation of the parameters ΔP_i that cancels the difference between model and experimental data:

$$\Delta V_{mod,j} = -\Delta D_j = D_j. \tag{4}$$

The model parameters variation can be obtained from here by applying pseudo inversion to $\mathfrak{M}_{ji}$. Singular Values Decomposition is a powerful method for such calculation. One remarkable feature of this technique is easy control over the influence of statistical errors in the experimental data on the output result. Application of SVD gives the parameters variation as:

$$\Delta P_i = k_i \left(\mathfrak{M}_{ji} k_i\right)^{-1}_{SVD} D_j. \tag{5}$$

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The idea of the proposed method is to use the density of particles in the phase space at some point, as a fitting parameters P_i. The experimental data $V_{exp,i}$ is composed of all points from all projections measured by the selected CCDs. For the known optics model, the transportation of the particles distribution to the locations of CCDs and calculation of the projections $V_{mod,i}$ is straightforward.

To describe the particles distribution in the tested method, the mesh in phase space is set so that values P_i describe the density in the mesh points and intermediate values are calculated by linear interpolation. One of the disadvantages of this method is that negative density is allowed. The main goal is to setup the mesh evenly with respect to the phase space. To do so, one of the interaction points is selected where the Twiss parameter $\alpha = 0$ for both transverse planes. In this case, the phase trajectories represented in the normalized coordinates $(x/\sqrt{\beta}, x' \cdot \sqrt{\beta})$ form circles, and the mesh points coordinates could be selected as (r_n, ϕ_m) plus $(0, 0)$ forming a polar mesh. (Fig. 2).

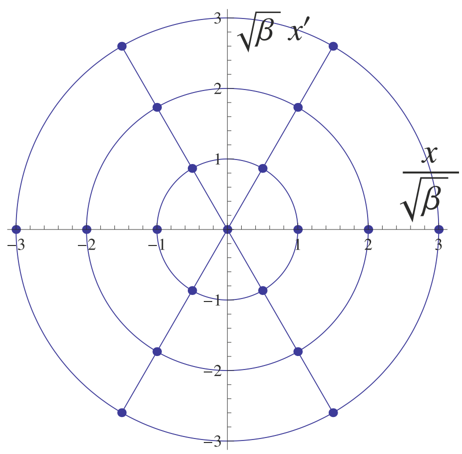

Figure 2: Example of the polar mesh.

The normalization coefficients k_j in Eq. (2) are proportional to the area related to the corresponding node.

When the mesh in the model becomes too dense, it causes an immense computing load, so compromise must be found for every configuration.

In the "linear case", the response matrix depends only on the mesh configuration and the used set of BPMs; therefore there is no need to calculate it for every experimental measurement.

Method Tests

To test this method, a simplified problem was solved for the case of no coupling and absence of the energy spread.

Figure 3 demonstrates results of the fitting for three types of distributions with 5% noise level in the "experimental" projections. For the tests, the real VEPP-2000 lattice in the horizontal plane was taken with 8 electrons' CCDs. Except for some areas with very small negative densities, it is obvious that, in general, the reconstructed distributions are in good agreement with the original. Additionally, the integral of the negative density could be used to test the plausibility of the found distributions.

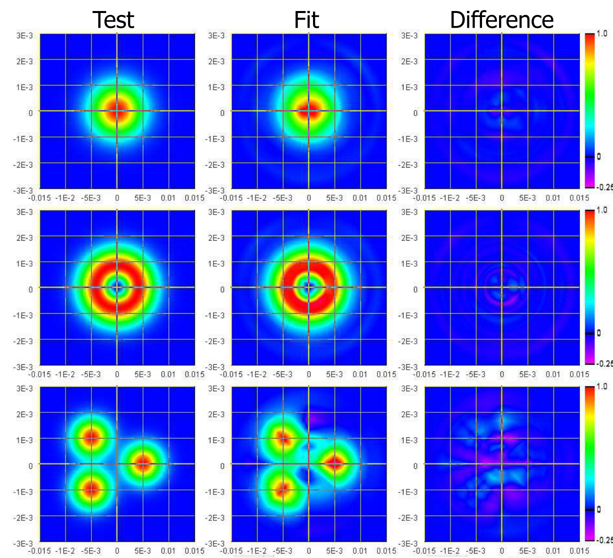

Figure 3: Test distribution, its fit and their difference for the Gaussian, ring-shaped and triple-Gauss distributions.

Analysis of Experimental Images

Collider VEPP-2000 is currently shutdown for the upgrade of the beam source and injection system [5]. Therefore, only a limited amount of specially saved raw frames are available for the tests.

Saved images were treated with the assumption that there is no coupling between transverse planes, however, the horizontal and the energy distributions cannot be separated. To deal with the momentum spread, the described polar mesh must be extended in the third dimension, creating an additional restriction on the resolution of the model. The naive approach assumes a simple form of the energy spread, allowing the use of a small amount of energy planes.

An alternative approach accounts for the energy spread in the form of a convolution of some momentum distribution with horizontal phase space density. This will add a small amount of additional fitting parameters but will break the linear nature of the task. In the case of a nonlinear task, iterative methods must be used with recalculation of both the response matrix and its pseudo-inverse at each step for every data set. In comparison, for a single massive calculation, dependent only on the phase space mesh and lattice configuration, retaining linearity is preferable.

For the experimental data treatment, the mesh was used with 8 angle divisions and 5 radial. In addition, 3 layers for energy spread were used. The result amounts of parameters are 123 and 41 for horizontal and vertical planes. Projections from 8 CCD cameras give about 1100 and 1700 experimental points for horizontal and vertical planes.

The resulting phase space distributions for electrons and positrons at the interaction point are presented in Fig. 4.

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Figure 5 shows one of the fitted pair of projections from an electron monitor.

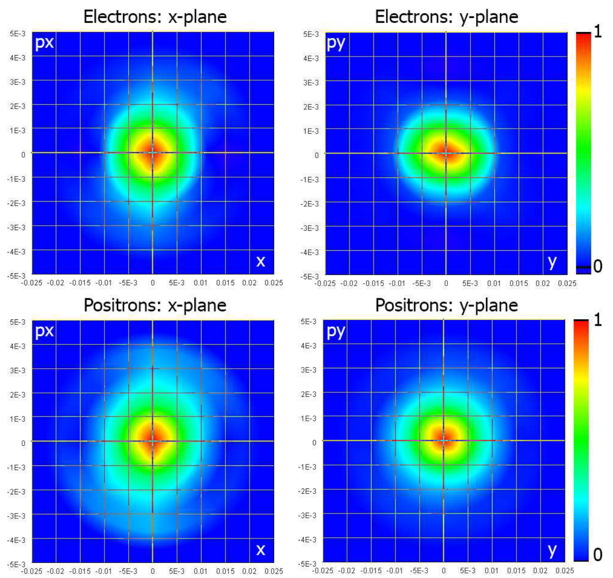

Figure 4: X and Y reconstructed phase space distributions at the IP for the electrons and positrons.

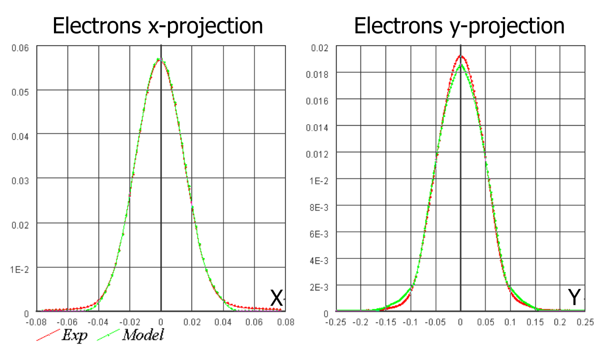

Figure 5: X and Y reconstructed and measured projections for one of the electron's monitor.

Table 1 shows significant discrepancy between the luminosity estimated from reconstructed phase space distribution and measured by detectors CMD-3 and SND, and estimated with "Lumi" software. One reason for such flow may be the bad weights for the model parameters. The other possible problem is the CCD's snapshots background, subtracting of which is very important for proper tails fitting. Figure 6 shows an enhanced frame from the CCD camera before and after a vertical smear was removed. Unfortunately, almost all stored raw frames have similar artifacts, although this effect can be reduced by proper shutter speed adjustment.

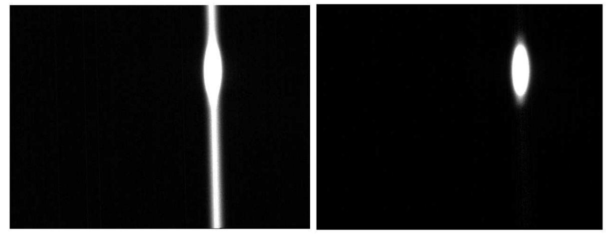

Figure 6: Enhanced frame before and after vertical smear removal.

Table 1: Comparison of the luminosity values from various sources

Source	CMD-3	SND	Lumi	Tomogr.
L, $10^{30} cm^{-2} s^{-1}$	5.3	6.3	5.0	3.0

CONCLUSION

The main practical goal of the beam phase space tomography at VEPP-2000 is to accurately estimate luminosity at high currents when the beam becomes strongly non-Gaussian since simpler methods may give unreliable results. Further studies with simulations and real beam data will be done to improve quality of the luminosity estimation with phase space tomography approach.

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