LUMINOSITY ESTIMATION AND BEAM PHASE SPACE ANALYSIS AT VEPP-2000*

A. Romanov, I. Koop, E. Perevedentsev, D. Shwartz
BINP SB RAS and Novosibirsk State University

Abstract

Luminosity is the main output of colliders, so it is very important to measure it with speed and accuracy. VEPP-2000 has 16 beam profile monitors (BPM) which use CCD-cameras to register synchrotron light in the visible spectrum. Two luminosity estimation methods are presented, both based on beam size analysis. Although the luminosity measurements by particle detectors CMD-3 and SND are slow and have low statistical accuracy for low beam currents, their data can be used to test new faster methods. Additionally, an attempt of the phase space tomography is presented using the simulated BPM measurements of the particle distribution in a strongly non-gaussian beam.

INTRODUCTION

VEPP-2000 is used for hadron cross section measurements in the energy range of $0.4 \div 2$ GeV [1], hence it takes luminosity 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.

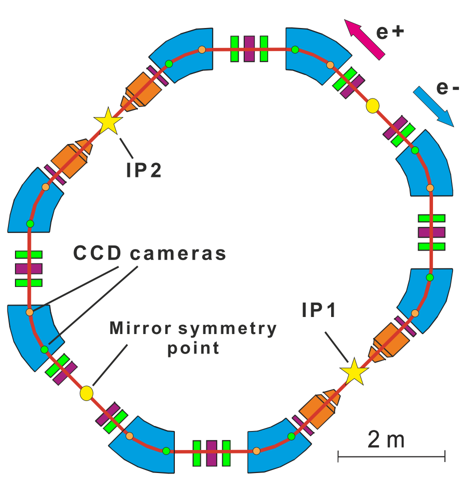

Figure 1: VEPP-2000 layout.

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. To get the best luminosity output, the operator should tune parameters such as beta-functions at the IPs, closed orbit position, betatron tunes, chromaticity, betatron coupling and others. The crude effects such as "flip-flop" can be noticed by the naked eye, however fine tuning requires the fast and reliable luminosity estimation tools. Unfortunately, the speed and precision of the luminosity measurements from the detectors are not sufficient, especially at low energies.

Both presented methods of luminosity estimation assume that accurate optics model of the real accelerator ring is available. Assuming no focusing perturbations in the lattice other than those caused by the collision, and thus located at the IP, one can use known transport matrices to evaluate the beam sizes at the IP from the beam size measurements by CCDs.

FIRST LUMINOSITY ESTIMATION METHOD

Eight measurements are available for either transverse coordinates of the two beams, while there is only a pair of strongly indeterminate parameters - beam emittance ϵ and $\beta*$ - for each mode and each beam.

For the parameters fitting procedure, it is convenient to transport all the measured beam sizes to the point of mirror symmetry where Twiss $\alpha = 0$. The center of technical straight section is chosen since this point is not perturbed by the beam-beam focusing. The beta-function for $i - th$ profile monitor is transported as:

$$\beta_i = \beta_0 \cdot t_{11,i} + \beta_0^{-1} \cdot t_{12,i}, \tag{1}$$

where t_{kl} are the elements of known transport matrix. The fitting minimizes the difference between the model and measured beam sizes:

$$F = \sum_i \frac{\left(\sqrt{\epsilon\left(\beta_0 \cdot t_{11,i} + \beta_0^{-1} \cdot t_{12,i}\right)} - \sigma_i\right)^2}{\sigma_i^2 + o_i^2}. \tag{2}$$

Here, o_i is the size measurement error with a typical value of $3 - 5\mu m$, while the beam size σ_i is a pure betatron part of measured transverse size with excluded dispersion contribution

$$\sigma_\beta = \sigma - D \cdot \frac{\sigma_E}{E} \tag{3}$$

The fitted beta-function β_0 is transported to the IP together with the emittance that gives the size needed. The luminosity can be easily calculated as:

$$L = \frac{N_1 N_2 f_0}{2\pi\sqrt{\left(\sigma_{1x}^2 + \sigma_{2x}^2\right)\left(\sigma_{1y}^2 + \sigma_{2y}^2\right)}}. \tag{4}$$

The model is extremely simple, it uses several assumptions. 1) Well-known unperturbed optics between the IPs

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without betatron coupling. Strictly speaking it is not the case for VEPP-2000 but the rotation produced by the final focusing solenoids can be ignored. 2) Both arcs and IPs are identical. 3) All particle distributions remain Gaussian. This is not true in the case of very intensive beams close to the beam-beam limit. 4) Energy spread is not perturbed and formed by synchrotron radiation. Recently the bunch lengthening in the low energy range was observed, indicating the microwave instability for the beams that are intensive enough (Fig. 3). This phenomenon would modify the dispersion contribution to the beam sizes.

The comparison of this luminosity estimation technique is in good agreement with measurements from the detectors (Fig. 2).

SECOND LUMINOSITY ESTIMATION METHOD

General Outline

This method is also model dependent, but it is based on the second moments (SM) of the particles' distribution, some of which are obtained from the imaging BPMs. The idea is to transport the set of SM for both bunches over the ring and by adjusting initial values of the SM matrices and some other parameters fit the traced moments to the measured sizes. Given that the ring lattice is perfectly known, there are still interaction regions that have unknown effect on the distribution of particles in the bunches. To handle this problem the ideal ring lattice is appended with thin IP transformations.

Each IP is divided in two equal thin lenses to be able to find second moments in the center of the IP. The strength of the IP lens is calculated based on the size of the opposite bunch. First tests of this approach reveal discrepancies of the fitted and experimental second moments at large currents, when bunches became strongly non-Gaussian. The calculated luminosity also became unrealistic. To fix this effect, an additional set of fitting coefficients was introduced to adjust the counter beam focusing kick.

The final focus solenoids in the present VEPP-2000 lattice configuration cancel the rotation of the betatron oscillation planes after passage through the interaction straight. Since all the CCDs are located outside the IP's straight sections, the solenoids could be treated as axially symmetrical lenses without rotation. Due to the two-fold symmetry of the VEPP-2000 and by omitting the rotation from the solenoids, the SM in the center of each IP should be diagonal. Second moments of the electron and positron bunches in the first IP form the main part of the fitting parameters.

$$M_{IP1} = Diag[m_{1,00}, m_{1,11}, m_{1,22}, m_{1,33}, m_{1,44}, 0] \quad (5)$$

The longitudinal distribution has been set to zero because it has no effect on transverse beam size in VEPP-2000.

The total number of fitting parameters p_j is 18: 10 second moments and 8 from beam-beam force fitting parameters (2 IPs, 2 bunches, 2 dimensions). Experimental data from 16 working CCD cameras gives 32 points, which provides enough information to keep the task well overdetermined.

The target function is:

$$F = \sum_i \left(\frac{M_{exp,i} - M_{fit,i}}{M_{exp,i}} \right)^2 = \sum_i V_i^2. \quad (6)$$

The beam sizes vary strongly from CCD to CCD and this form gives equal weight to all data points.

Minimization Algorithm

To minimize F, the set of variations of parameters Δp_j must be found that leads to the cancellation of the V_i. Linearizing the $\Delta V_i(\Delta p_j)$ this goal can be written as:

$$\Delta V_i(\Delta p_j) \simeq \sum_j \frac{1}{k_j} \frac{\partial V_i}{\partial p_j} k_j \Delta p_j = -V_i, \quad (7)$$

here, k_j are normalization coefficients that can be used to adjust impacts of different model parameters. To find the desired set of parameters, the rectangular matrix $\frac{\partial V_i}{\partial p_j}$ should be inverted. The flexible way to find a pseudo-inverse matrix is provided by the singular value decomposition (SVD):

$$\Delta p_j = \sum_i \left(\frac{\partial V_i}{k_j \partial p_j} \right) \Bigg|_{SVD}^{-1} \frac{-V_i}{k_j}. \quad (8)$$

Implementation of the found corrections finishes the iteration that should be repeated several times, since the model depends nonlinearly on the parameters. After convergence of the fitting, luminosity is calculated with Eq. (4). The comparison of the second luminosity estimation method with others is shown in Fig. 2.

One of the differences between two algorithms is that latter has the energy spread in the beam as the fitting parameter. First runs supported the presence of microwave instability, first observed with phi-dissector – optical tool for bunch length measurements (see Fig. 3) [3, 4].

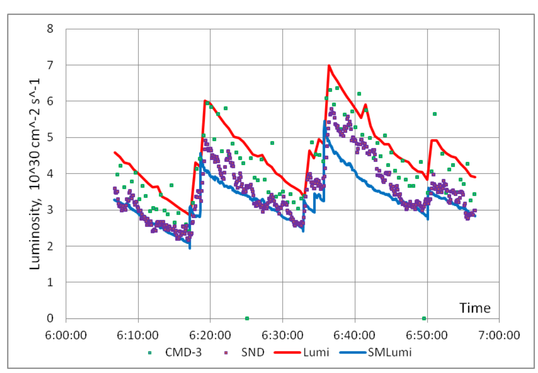

Figure 2: Comparison of the luminosity from different measurements: green dots – CMD-3, purple dots – SND, red and blue lines – estimation methods

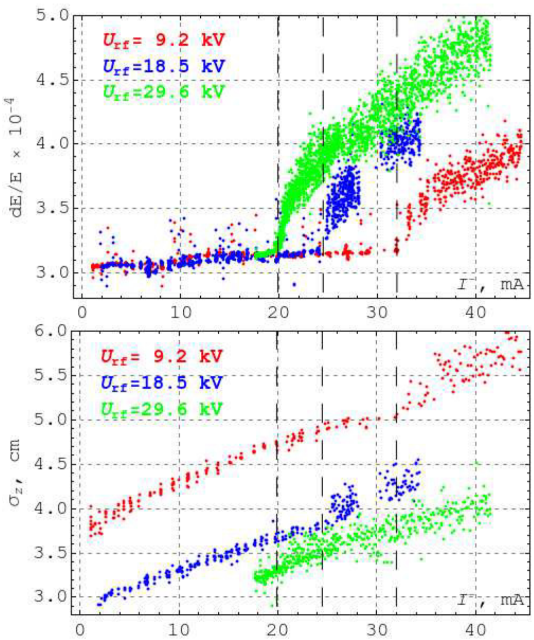

Figure 3: Correlation of the current dependence of the extracted energy spread and the measured bunch length.

PHASE SPACE TOMOGRAPHY

Relatively small number of CCDs – 8 for electrons and 8 for positrons – led to pessimistic estimations of classical approach to the beam phase space tomography methods which use several tens of projections [5]. Therefore, the feasibility study regarding this task was started after the shutdown of VEPP-2000.

The success in solving the inverse problems using the SVD inspired its use in the beam phase space tomography method. The fitting parameters p_j in this case describe the distribution of the particles in the phase space at some point. The experimental data $V_{exp,i}$ is composed of all projections' points from all the CCDs. For the known optics model, the transportation of the particles' distribution to the CCDs locations and calculation of the projections $V_{mod,i}$ is straightforward. To simplify the test problem, several assumptions were used: no transverse coupling; no energy spread; no lattice errors; no counter beam.

To describe the particles' distribution in the tested method the mesh in phase space is set so that values p_j describe the density in the mesh pointsand intermediate values are calculated by linear interpolation. One of the disadvantages of the method is that negative density is allowed. The main clue is to setup the mesh evenly with respect to the phase space. To do so, the point is selected where the Twiss parameter $\alpha = 0$. 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. The normalization coefficients k_j in Eq. (8) are proportional to the area related to the corresponding node.

Figure 4 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. The real lattice was taken for the tests. 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. Also, the integral of the negative density could be used to test the plausibility of found distributions.

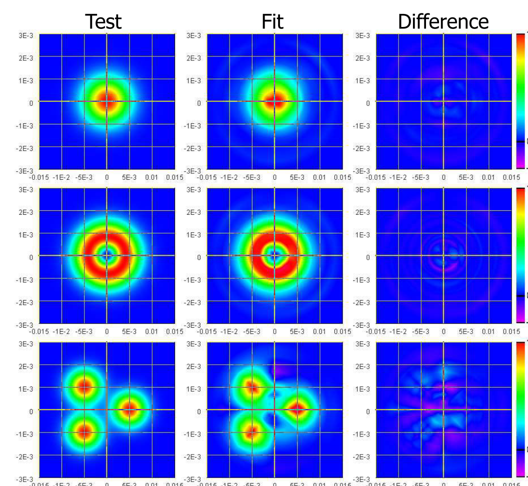

Figure 4: Test distribution, its fit and their difference for the Gaussian, ring-shaped and triple-Gauss distributions.

Further studies will include comparison of the tested method to the commonly used methods, such as inverse Radon transformation. Additionally, influences of various errors and mesh configurations should be thoroughly investigated.

The main practical goal of the beam phase space tomography at VEPP-2000 is to accurately estimate luminosity at high currents when the beam become strongly nongaussian and simpler methods may give unreliable results.

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