ELECTRON BEAM DIAGNOSTICS
WITH VISIBLE SYNCHROTRON LIGHT ON SIBERIA-1 RING

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Abstract

Three methods for beam diagnostics using visible synchrotron light were applied to determine electron beam parameters on the Siberia-1 storage ring: an edge radiation based scheme for measuring effective angular divergences of the electron beam, a “Lloyd’s Mirror” interference scheme for transverse beam size measurements, and a standard scheme of beam profile measurements with focusing lens. In each of the three methods, practically identical experimental equipment was applied, yet absolutely independent experimental data were obtained, since different wave-optics phenomena of synchrotron light were used. The combined approach lets us make the resulting data on beam parameters more solid with no additional expenses for the experimental equipment. In the paper to be presented, the methods’ comparison is given and the experimental results are discussed.

1 BRIEF DESCRIPTION OF THE METHODS USED

1.1 Introductory Notes

This paper summarises application results of two recently developed electron beam diagnostics methods: the Edge Radiation (ER) based method [1], [2] and the one on the basis of the Lloyd’s Mirror (LM) scheme of synchrotron radiation interference [3]. The methods are compared with a more widely used one incorporating a focusing lens for beam profile imaging [4]. The methods were applied on the Siberia-1 450 MeV electron storage ring, a small ring of the Kurchatov Synchrotron Radiation Source (Moscow), in addition to the “initial” Siberia-1 beam diagnostics equipment including dissectors [5].

Experimentally, the newly-developed methods are very simple. On the Siberia-1 ring, they were realised in visible wavelength region (though potentially, the methods can work with a shorter wavelength radiation). The main common peculiarity of the methods is that both take advantage of high-precision wave optics based computation of synchrotron radiation.

1.2 Edge Radiation Based Method

The ER, i.e. the radiation generated at bending magnet edges, and the radiation emitted within elements of electron beam optics in storage rings was found to be very sensitive to angular divergence and transverse size of the emitting electron beam [1]. Therefore, if one can measure the ER intensity distributions and one can perform precise calculation of the corresponding distributions for particular magnet lattice and measurement system, at different values of the beam parameters, then the real beam parameters can be determined as a result of fitting the measured and computed ER intensity distributions.

1.3 “Lloyd’s Mirror” SR Interference Scheme

It is well-known that visibility of fringes in an interference pattern essentially depends on characteristics of a light source [5]. For a finite-size source, the smaller is the source size, the better is the visibility of fringes in the interference pattern. Just this simple feature, with electron beam as a source emitting the synchrotron radiation (SR), is used in the method concerned.

In actual practice, precise calculation of interference patterns in view of the emitting beam and interference scheme parameters is needed to determine actual values of the beam parameters. Advantageously, SR intensity distributions in the patterns produced with simple interference schemes can be calculated to a very high accuracy. With that, the procedure of determining the beam transverse sizes consists of measuring the intensity distributions concerned and fitting the measured and calculated distributions by varying "guess values" of the actual beam transverse sizes.

Fig. 1 shows two modifications of the Lloyd’s Mirror interference scheme dedicated to determine horizontal (a) and vertical (b) size of the electron beam.

1.4 Experimental Schemes

Experimental schemes illustrating the practical implementation of the Edge Radiation and Lloyd’s Mirror methods on the Siberia-1 storage ring are shown in Fig. 2.

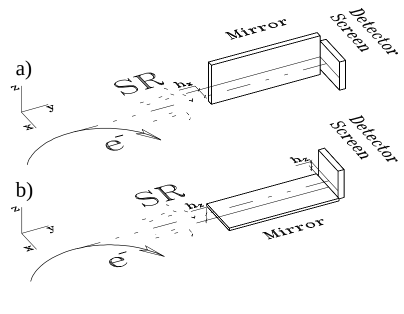

Figure 1: Lloyd's Mirror schemes of SR interference:
a) vertical mirror, to determine horizontal beam size;
b) horizontal mirror, to determine vertical beam size.

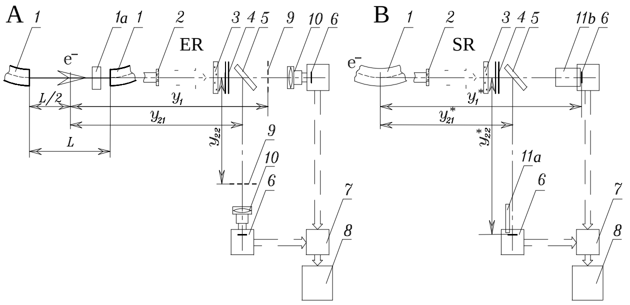

Figure 2: Realisation of the ER (A) and “Lloyd’s Mirror” (B) based methods on the Siberia-1 storage ring.
1- bending magnets; 2- extraction window; 3- neutral filters;
4- interference filter; 5- semitransparent mirror; 6- CCD-matrix cameras; 7- interface; 8- computer; 9- object plane; 10- lens; 11- vertical (a) and horizontal (b) flat Lloyd’s Mirror plates.

At practical measurements, the scheme B had a modification in which instead of the Lloyd’s Mirror plates, a focusing Lens was installed in the common part of the beamline, thus realising the lens based scheme for beam profile measurements [4]. The Figure 2 clearly indicates that practically identical equipment was used in the methods. For both the ER and LM schemes, an interference filter is one of the most important elements.

As concerning differences between the schemes, we would like to point out that the ER scheme is installed on a beamline from a straight section of the storage ring, whereas the LM and Lens methods were realised on a beamline from uniform field of a bending magnet.

2 EXPERIMENTAL RESULTS

2.1 Edge Radiation

It can be shown that in the case when no beam focusing elements are located within a straight section, the ER intensity distributions depend on RMS electron beam divergences $\sigma_{x'}$, $\sigma_{z'}$ and transverse sizes σ_x, σ_z in combinations: $\sigma_{x'(z')eff}{}^2 \equiv \sigma_{x'(z')}{}^2 + \sigma_{x(z)}{}^2/y^2 + 2M_{xx'(zz')}/y$, where $M_{xx'(zz')}$ is second-order central mixed moment of particle density distribution in transverse phase space, y is distance from the middle of the straight section or some other "initial point" within straight section to detector. The values of $\sigma_{x'(z')}$, $\sigma_{x(z)}$, $M_{xx'(zz')}$, $\sigma_{x'(z')eff}$ refer to that point.

One value of $\sigma_{x'eff}$ and one of $\sigma_{z'eff}$ can be potentially determined from the ER intensity distribution measured at one distance y. Actual possibility to determine $\sigma_{x'eff}$ or $\sigma_{z'eff}$ depends on the straight section length L, bandwidth $\Delta\lambda$ of the monochromatic filter used, beam energy, detector dynamic range. Approximately, one can show that for the straight section large enough and the standard commercially available CCD detector, $\sigma_{z'eff}$ can be determined with appropriate precision if it takes place $\sigma_{z'eff} > \sqrt{\Delta\lambda/(2L)}/4$.

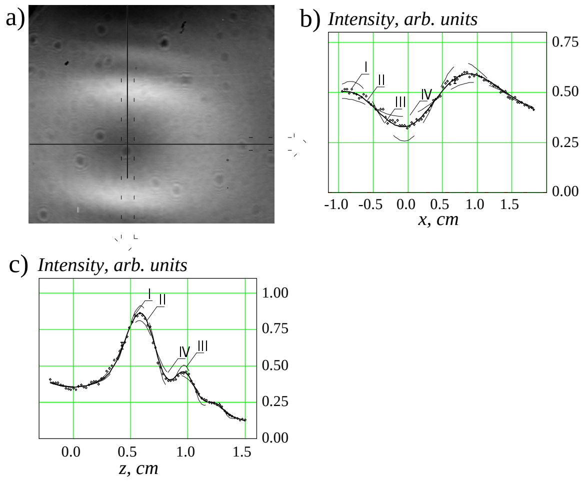

Figure 3: Fitting of measured and computed ER intensity distributions at E = 450 MeV, λ= 560 nm, y = 547 cm: a) half-tone presentation of the measured distribution; b,c) intensity distributions along horizontal and vertical lines: I- measured, II- computation best-fit giving $\sigma_{x'eff}$ = 0.70 ± 0.06 mr and $\sigma_{z'eff}$= 0.154 ± 0.014 mr, III,IV- computed distributions for the values of $\sigma_{x'eff}$ and $\sigma_{z'eff}$ 30% smaller (III) and 30% larger (IV) of the corresponding best-fit values.

Algorithms to determine beam emittances ε_x, ε_z, and energy spread σ_ε/E (as well as $\sigma_{x'}$, $\sigma_{z'}$, σ_x, σ_z, $M_{xx'}$) from the best-fit values of $\sigma_{x'eff}$ and $\sigma_{z'eff}$, applying data on beta- and dispersion- functions, were discussed in [2]. To determine the set of horizontal parameters, one needs two values of $\sigma_{x'eff}$ corresponding to different distances y (the larger the difference the better, approximate subdividing parameter is beta-function value). To determine vertical parameters, one value of $\sigma_{z'eff}$ is sufficient.

Some values of electron beam parameters derived from the ER measurements, are given in Tables 1 and 2.

2.2 Lloyd’s Mirror

A distinctive feature of the method on the basis of the Lloyd’s Mirror interference scheme is that, unlike in the previous method, the interference pattern is not sensitive to angular divergences of the electron beam: it “feels” only the transverse size. Analytical formulas for the use in fitting procedures to determine beam transverse sizes from measured intensity distributions in the SR interference patterns were presented earlier [3]. In [3], it was assumed that horizontal mirror plane is parallel to the orbit plane. However, at actual measurements, small tilt of the mirror plane can take place. This tilt can be easily determined and taken into account if vertical position of the interference pattern respective to the direct SR distribution is determined at the measurements.

At the beam size measurements, one should keep in mind that the finite bandwidth of the interference filter influences the interference pattern the same way as the finite beam size. More accurately, not exactly the beam

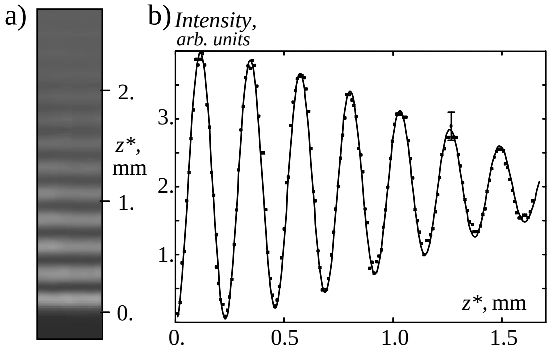

Figure 4. Intensity distribution in the interference pattern in the case of horizontal mirror: a) half-tone presentation of the distribution registered by CCD-camera; b) vertical profile of the distribution (boxes) and corresponding best-fit. The fitting gives one: $\sigma_z = 0.26 \pm 0.03$ mm.

size, but the value $(\sigma_{x(z)}^2 + h_{x(z)}^2\sigma_\lambda^2/\lambda^2)^{1/2}$ is actually determined at the fitting (σ_λ is RMS filter bandwidth, $h_{x(z)}$ is distance between radiation region and mirror plane).

Typical intensity distribution registered by the CCD-camera in the case of the horizontal mirror is shown in Fig. 4-a as a half-tone picture. The fitting of the measured and calculated distributions over σ_z and h_z is illustrated by Fig. 4-b. The best-fit vertical size value is: $\sigma_z = 0.26\pm0.03$ mm. It is realised at h_z= 5.9 mm. In this case, contribution of the filter bandwidth (σ_λ = 1.9 nm) is negligible.

In actual practice, one may require rather long mirror plate in order to measure small beam size using exactly the scheme shown on Figs. 1, 2(B). The problem can be solved by making a gap of necessary length between mirror edge and detector (instead of using the permanent long mirror). In this case diffraction of the reflected light should be taken into account at the fitting.

2.4 Summary of the Experimental Results

Table 1 shows values of “primary” parameters determined by each the tree methods (ER, LM and the one incorporating focusing Lens) in the same mode of operation of the Siberia-1 ring at E = 450 MeV, $I \approx 10$ mA. Table 2 presents the beam parameters obtained from the primary ones and data on the lattice functions (we would like to note that the values differ from those presented in the previous work [2]: the reason is that the previous results were found to be garbled, to our shame, by valuable non-linearity of the CCD detectors used). It is noteworthy that in some other modes at E = 450 MeV vertical parameters are smaller, however the combined measurements were performed only in the mode shown.

The horizontal emittance values determined at different energy are shown in Fig. 5. The figure illustrates the emittance grows due to quantum fluctuations. The beam parameters’ values determined are in agreement with theory.

Table 1: The primary beam parameters determined directly from fitting procedures by three different methods.

Method	Primary parameters determined			
	$\sigma_{x'eff}$, mr	σ_x, mm	$\sigma_{z'eff}$, mr	σ_z, mm
ER	1.01±0.11 (y=190 cm) 0.70±0.06 (y=547 cm)	–	0.154±0.014 (y=547 cm)	–
LM	–	1.43±0.13	–	0.26±0.03
Lens	–	1.36±0.14	–	0.23±0.02

Table 2: More important beam parameters determined from the primary ones using lattice functions.

Method / Combination	Parameters		
	ε_x, μm×rad	$\sigma_E/E \times 10^4$	ε_z, nm×rad
ER	0.71 ± 0.18	4.6 ± 2.7	30 ± 6
LM / LM+ER	0.75 ± 0.16	3.4 ± 1.2	37 ± 8
Lens / Lens+ER	0.72 ± 0.16	4.2 ± 1.5	47 ± 10

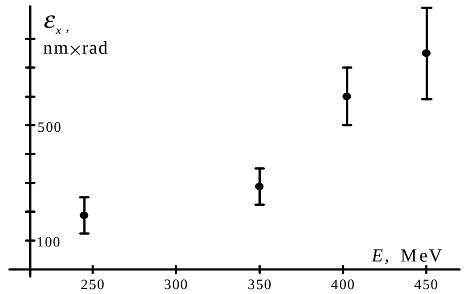

Figure 5: Horizontal emittance at different energy values.

3 CONCLUSIONS

Strong points of the ER, LM and Lens based methods used are experimental simplicity, low cost and high informational potential. Distinct physical content, different and independent primary parameters determined and, at the same time, likeness with respect to the equipment required are valuable arguments for the combined use of the methods discussed.

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