Edge Radiation Based System for Beam Diagnostics on Siberia-1 Electron Storage Ring

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Abstract

Edge Radiation based system for measurement of horizontal and vertical angular divergences and transversal sizes, position and energy of electron beam on Siberia-1 storage ring is described. The parameters are numerically determined from registered intensity distribution of visible range radiation emitted at bending magnet edges and at elements of electron beam optics. The method takes advantage of high sensitivity of this radiation to the above-mentioned beam parameters. Being very simple experimentally, it may be applied to practically every electron storage ring. Measured Siberia-1 beam parameters are given.

1. INTRODUCTION

The radiation emitted by relativistic charged particles in a region of a sharp change of magnetic field at a bending magnet edge has been studied in proton and in electron synchrotrons [1]÷[3]. In both cases the Edge Radiation (ER) was found to differ essentially from the standard synchrotron light generated in homogeneous vertical magnetic field within a bending magnet.

Though the proton and electron ER reveals similar properties, there are significant distinctions between these two cases. The ER studied in proton synchrotrons was a short-wavelength one with respect to the spectrum of the standard synchrotron light, while the ER in high-energy electron synchrotrons (storage rings) is emitted at long waves for the most part ($\lambda>\lambda_c$, where λ_c is the critical wavelength of standard synchrotron radiation from correspondent bending magnet). Noteworthy is that the visible range, where most of the experiments were done, refers to short-wavelength region for protons and to long-wavelength one for electrons.

Just after the first experimental studies, the proton ER was successfully applied for beam profile measurements [2]. The application took advantage of much higher intensity of the proton beam ER in visible range than that of the standard synchrotron radiation.

In this paper we describe a practical application of the ER for advanced electron beam diagnostics in a storage ring. Our application differs from the one mentioned above. It uses special features of intrinsic intensity distribution of the ER emitted by electrons.

2. BASIC IDEA OF THE METHOD

The intensity map of the monochromatic ER generated by an electron (as well as by an infinitely thin electron beam) represents series of peaks resulting from intrinsic distribution of a single bending magnet edge radiation and from the interference of radiation emitted at two adjacent magnet edges [4]. If the distance L between adjacent bending magnet edges is long enough, i.e. $L \gg \lambda_c\gamma^2$ (where γ is the reduced energy of electrons, $\gamma \gg 1$), then in the wavelength region of $\lambda_c \ll \lambda < 2L\gamma^{-2}$ the characteristic angular dimensions of peaks in the ER intensity distribution are γ^{-1} and widths of the interference circles $(\lambda/(2Lk))^{1/2}$, supposing $k \gg 1$ for the circle number. The ER peaks' locations depend on γ.

For real electron beam, when either angular divergences or transversal sizes divided by observation distance are comparable with or exceed the values indicated, the ER peaks are "smoothed off", i.e. the distribution becomes sensitive to these beam parameters. With that, the sensitivity of the distribution to beam energy remains.

If one precisely calculates the ER intensity distribution with due regard for electron beam parameters and measures the distribution in reality, then one can determine the beam parameters of interest, for example, by fitting the measured distribution with the calculated data.

As may be seen from numerical estimations of values above, the ER is sensitive to beam divergences, transversal sizes and energy in large variety of electron storage rings, if the ER wavelength belongs to visible region. This makes the measurement procedure very simple.

An effective method for computation of the radiation by relativistic electron beam incorporating non-zero emittances, in a typical magnet lattice of a storage ring, was elaborated for the beam diagnostics [5]. The method starts from retarded potentials and allows to perform a large portion of calculations analytically, without any loss of precision. In addition to standard cases of the radiation, when emission conditions are the same for all the particles of the beam, the method elaborated allows to precisely compute, for example, the intensity distribution of radiation generated in quadrupole lenses. With the method, the observation point may be located near the radiation region at distances, comparable with the region length.

In actual practice, the ER intensity distributions are often influenced by portions of radiation emitted at elements of electron beam optics (quadrupole lenses, steering magnets, etc.) located in the straight section between bending magnet edges. As a rule, it does not impair the sensitivity of the resulting intensity distributions to the beam parameters (quite the reverse, in some cases the sensitivity may increase).

With the method elaborated, there is a possibility to compute the intensity distribution of radiation emitted in a complex magnet system. To do this, one needs to know the magnetic field as a function of longitudinal coordinate in all of the magnet elements. Usually, the magnetic field mapping results obtained at the elements' production, are sufficient. In those cases when magnetic field measurements are not performed, there is a possibility to determine the field parameters together with the beam ones, by fitting the intensity distribution registered. This, however, will make the determined values of beam parameters less solid.

3. MEASUREMENT SYSTEM

The layout of the ER measurement system installed on the Siberia-1 electron storage ring (the injector of the Kurchatov Synchrotron Radiation Source, Moscow) is given in Fig.1.

To observe the ER, we adjusted a beamline from the extraction interval of the Siberia-1. The vacuum part of the beamline was finished with glass extraction window. To obtain a monochromatic radiation, interference filter was used. The average wavelength of transmitting light was $<\lambda>=$ 648 nm at $\Delta\lambda_{1/2}=$ 4 nm bandwidth. Semitransparent mirror split the system into two measurement channels, each one consisting of a lens and a CCD-matrix camera. Neutral filters were used to prevent surplus exposure of the cameras at different levels of storaged electron currents.

With the system, we measured the ER intensity distributions in "object planes" (Fig.1). Lenses were used to zoom the distributions in order to fit the sensitive window of the CCD-matrix. The distances along optical axes from the middle of the straight section to each of the object planes were different: y_1 = 199 cm, $y_2 = y_{21}+y_{22}$ = 399 cm. The aim was to set the object plane of the first camera as close to the radiation region as possible, and that of the second camera, quite the reverse, far from the radiation region.

The depth of field effect and the lens aberrations were found not to bring in any valuable distortions to the images registered. The spatial resolution was 56 μm for the first camera and 85 μm for the second one, in angular units the resolution was less than 30 μrad for both cameras. This was sufficient to measure the ER distributions with the smallest details larger than 300 μrad.

The cameras operated synchronously; the measured data were transmitted to PC for further processing. The cameras' signal-to-noise ratio was better than 70. Exposure time applied was larger than 100 ms, thus the ER intensity distributions registered and the electron beam parameters determined were integrated over many turns.

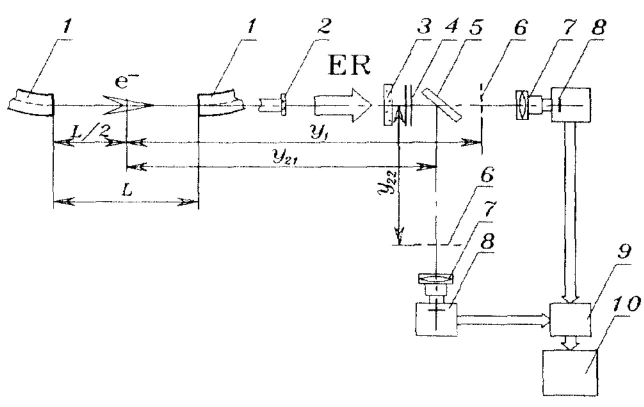

Figure 1. Scheme of the ER measurement system.
1- bending magnet; 2- extraction window; 3- neutral filters; 4- interference filter; 5- semitransparent mirror; 6- object plane; 7- lens; 8- CCD-matrix camera; 9- interface; 10- computer.

4. DETERMINING OF BEAM PARAMETERS

There were no beam focusing elements in the straight section chosen for the diagnostic measurements. The only element influenced the original ER intensity distribution was a steering magnet caused vertical deflection of the beam.

It may be shown that in this case, in terms of second moments of particle density distribution in phase space, the registered radiation intensity distribution depends on beam parameters in compositions:

$$\sigma_{x'eff} = \left(\sigma_{x'}^2 + \sigma_x^2/y^2 + 2M_{xx'}/y\right)^{1/2}; \tag{1}$$

$$\sigma_{z'eff} = \left(\sigma_{z'}^2 + \sigma_z^2/y^2 + 2M_{zz'}/y\right)^{1/2}, \tag{2}$$

where $\sigma_{x'}$, $\sigma_{z'}$ are horizontal and vertical RMS angular divergences of electron beam, σ_x, σ_z are RMS transversal sizes, $M_{xx'}$, $M_{zz'}$ are corresponding mixed second moments, y is the distance to object plane.[1] For symmetrical magnet focusing system, it takes place in azimuth symmetry plane (passing through the middle of the straight section in our case): $M_{xx'} = M_{zz'} = 0$. That is why we needed two cameras located at different y to determine $\sigma_{x'}$, σ_x, $\sigma_{z'}$, σ_z.

A radiation intensity distribution registered by the first camera at one of the Siberia-1's modes of operation, is shown in Fig.2(a) as a half-tone picture (vertical asymmetry of the distribution was caused by the steering magnet contribution).

To effectively "decipher" the intensity distributions, some qualitative considerations on the fitting strategy should be taken into account. In our case these were the following.

1) Each camera allows to determine $\sigma_{x'eff}$ and $\sigma_{z'eff}$, see Eqs.(1), (2).

2) There is a possibility to determine $\sigma_{x'eff}$ and $\sigma_{z'eff}$ independently, with practically no mutual influence. For example, since it takes place in most electron storage rings, $\sigma_z < \sigma_x$, $\sigma_{z'} < \sigma_{x'}$, the value of $\sigma_{x'eff}$ is better determined from the intensity distribution along horizontal line passing through the global maximum (see Figs. 2 (a), (b)), while $\sigma_{z'eff}$ is obtained from the distribution along vertical line, as far from the pattern's center as possible (Figs. 2 (a), (c)).

3) The values of $\sigma_{x'}$, σ_x, $\sigma_{z'}$, σ_z allow to estimate transversal emittances, the important characteristics of beam dynamics.

4) Whereas beam divergences and transversal sizes "smooth off" the intrinsic ER peaks, the beam energy influences the peaks' positions (beam energy spread leads to the "smoothing off" too, but for typical values of the spread in electron storage rings this effect is negligible).

[1] In former theoretical work [5] somewhat different compositions were mistakenly indicated. This, however, did not influence the main content of the work [5].

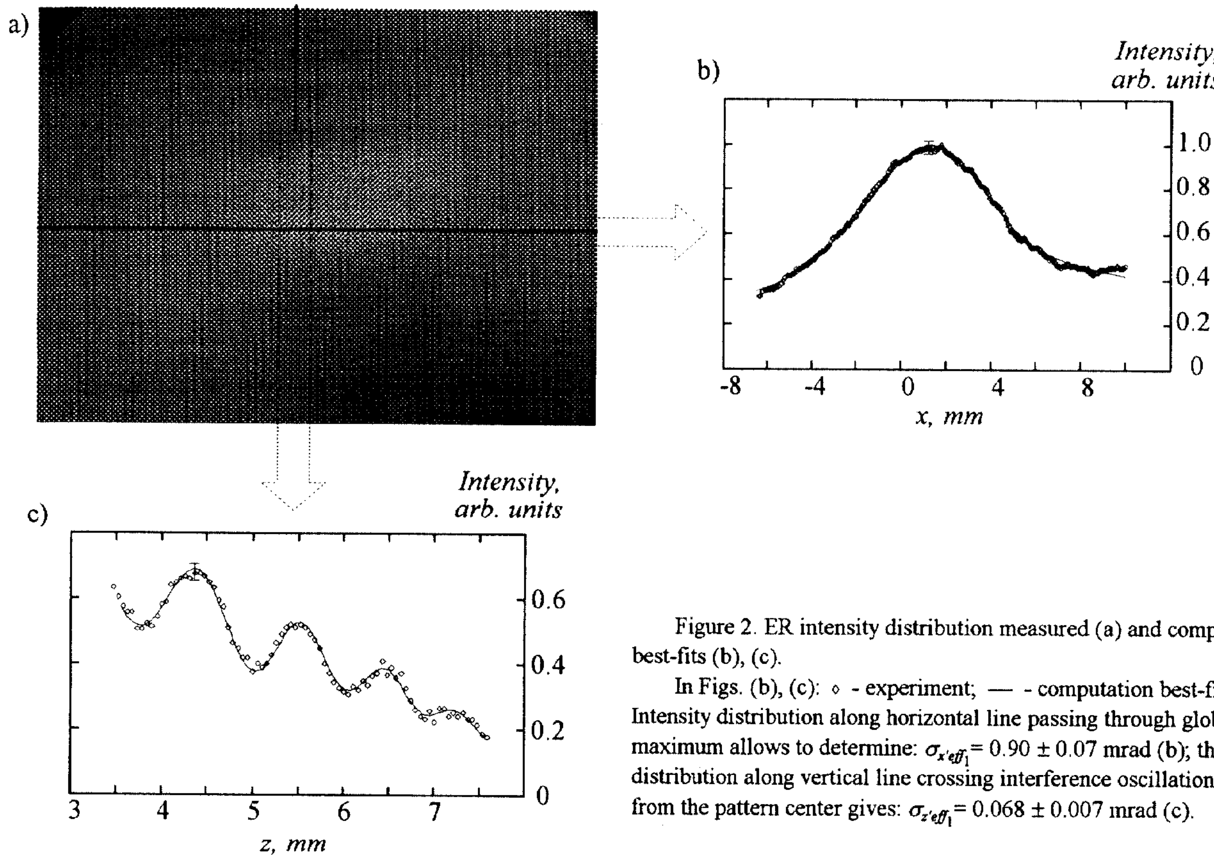

Figure 2. ER intensity distribution measured (a) and computed best-fits (b), (c).

In Figs. (b), (c): ⋄ - experiment; — - computation best-fit. Intensity distribution along horizontal line passing through global maximum allows to determine: $\sigma_{x'eff_1} = 0.90 \pm 0.07$ mrad (b); the distribution along vertical line crossing interference oscillations far from the pattern center gives: $\sigma_{z'eff_1} = 0.068 \pm 0.007$ mrad (c).

5) If absolute positions of the measurement system elements are known, there is a possibility to determine absolute "center of gravity" coordinates and averaged trajectory tilts of electron beam. The ER peaks' coordinates in the patterns from two cameras are good marks to realize that.
6) As well as the other optical methods, this one also allows to determine electron beam current, if cameras are calibrated.

The fitting algorithms based on the radiation computation method elaborated [5] and the above-listed considerations give an excellent opportunity to determine a dozen of beam parameters, using experimental data from the very simple and very chip measurement system. Some of the parameters determined at one of the Siberia-1's modes of operation, are given in Table 1. The fitting was done with IBM PC 486DX.

Table 1 Determined beam parameters and intermediate values

Energy	348 ± 11 MeV
$\sigma_{x'eff1}$ (1-st camera)	0.90 ± 0.07 mrad
$\sigma_{z'eff1}$ (1-st camera)	0.068 ± 0.007 mrad
$\sigma_{x'eff2}$ (2-nd camera)	0.47 ± 0.03 mrad
$\sigma_{z'eff2}$ (2-nd camera)	0.047 ± 0.006 mrad
$\sigma_x = y_1 y_2[(\sigma_{x'eff1}^2 - \sigma_{x'eff2}^2)/(y_2^2 - y_1^2)]^{1/2}$	1.8 ± 0.3 mm
$\sigma_{x'} = [(y_2^2\sigma_{x'eff2}^2 - y_1^2\sigma_{x'eff1}^2)/(y_2^2 - y_1^2)]^{1/2}$	0.16 ± 0.03 mrad
$\sigma_z = y_1 y_2[(\sigma_{z'eff1}^2 - \sigma_{z'eff2}^2)/(y_2^2 - y_1^2)]^{1/2}$	0.11 ± 0.02 mm
$\sigma_{z'} = [(y_2^2\sigma_{z'eff2}^2 - y_1^2\sigma_{z'eff1}^2)/(y_2^2 - y_1^2)]^{1/2}$	0.038 ± 0.009 mrad

When using interpolation formulae derived from preliminary simulations of the ER intensity distribution for different values of beam parameters, the method under discussion allows a real-time beam control.

Two factors seem to make the method suitable for application in large variety of electron storage rings. First, the radiation emitted at bending magnet edges and in elements of beam optics is very sensitive to beam parameters, even for low-emittance beams. Second, there is a possibility to precisely compute this radiation. In each particular case the application of the method may differ in some details.

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5. References

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