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Application of a Low-Energy Electron Beam as a Tool for Ultrashort Bunch Length Measurement in Circular Machines

D.A. Nikiforov, A.A.Starostenko, P.V.Logatchov, K.Rusinov
Budker Institute of Nuclear Physics, Novosibirsk, Russia
D.Malyutin, A.Matveenko
Helmholtz-Zentrum Berlin, Berlin, Germany

Abstract
A new diagnostic device designed for non-destructive ultrashort bunch length measurement is described. The operating principle of the device and the measuring technique are described. The possible scheme of arrangement of the device elements is described. The results of simulations of Electron Beam Probe application for different beams under investigation are presented. The quality requirements of the low-energy testing beam are considered and the resolving detector ability is determined.

Keywords
Bunch length; electron beam probe; low energy electron beam.

1 Introduction

The experiments in particle physics and high-energy physics and the commissioning of new generation facilities for applied research and experiments with synchrotron radiation require continuous improvement of parameters of charged particle beams (particularly their intensity and luminosity). Such an improvement can be realised by means of advancement of techniques for diagnostics of charged particle beams. Ideally, these diagnostics methods should not affect the quality of the studied beam. Non-destructive methods for diagnostics are based on the measurement of electromagnetic fields that are generated by the beam under investigation. These techniques use electromagnetic interaction of the studied beam with various “probing elements” such as the vacuum chamber of accelerators, the residual gas or gas flow, a testing laser beam or the external low energy electron beam. Synchrotron radiation, which is generated in bending magnets, is also widely used for nondestructive diagnostics [1].

In this study, a low energy electron beam is considered as the possible instrument for ultra-short bunch length measurement for two accelerator facilities [2]: BESSY VSR [3] and ERL bERLinPro [4]. The main parameters of such a facilities are presented in Table 1. The device that uses low-energy electron beam is called electron beam probe (EBP) [5]. Besides length measurements this device can be used for the reconstruction of transverse and longitudinal charge distributions in a bunch under investigation.

Table 1. BESSY VSR and bERLinPro main parameters

Parameter	**Unit**	**BESSY VSR**	**bERLinPro**
Beam energy	MeV	1700	50
Max.average current	mA	300	100
Bunch charge	pC	100-8000	< 77
Bunch length	ps	0.3 – 15	0.1-2
Emittance (normalised)	π mm mrad		< 1

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In the case of BESSY VSR, it is possible to carry out a bunch length measurement by means of streak camera, but for bERLinPro with energy 50 MeV and low current, it will be hard to detect synchrotron radiation from a single bunch. Thus, EBP can be used as an alternative diagnostics method.

2 Basic operational principles of the EBP

A very thin electron beam with low current moves across the trajectory of an intense ultra-relativistic bunch with offset parameter ρ (see Fig. 1). An ultra-relativistic bunch moves in Z direction with the velocity of light c (β=1). A probe electron beam (PB) moves in X direction, perpendicularly to the Z axis, with the velocity βc. The particles of a probe electron beam suffer the deflection in the electromagnetic fields of an ultra-relativistic bunch. Each particle of a probe beam has θ_y and θ_x deflection angles after passing the interaction region. The transverse sizes of both beams are much smaller than the offset parameter ρ. The longitudinal distribution of charge density in an ultra-relativistic beam under investigation is given as a function n(z) at the time moment t=0. At the same time (t=0) each particle of a probe beam has its own value of coordinate x. As a result of scattering in the electromagnetic fields of the beam under investigation, PB describes a closed curve on detection screen (see Fig. 1). The detection screen is placed in a plane parallel to the Y-Z plane at distance L from the Z axis.

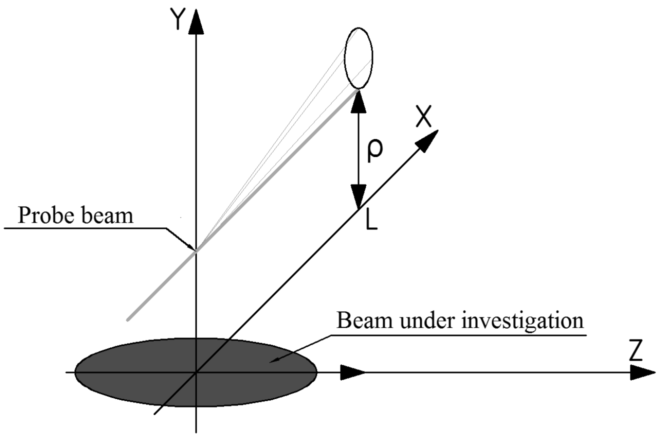

Fig. 1: Diagram illustrating the operating principle of the EBP

A small kick for the probe beam electron can be expressed as:

$$d\theta_z = \frac{dP_z}{P_x} = \frac{1}{\gamma mc\beta} \cdot \frac{e^2 2n(z)\beta}{\sqrt{\rho^2 + (x+\beta ct)^2}} \cdot \frac{x+\beta ct}{\sqrt{\rho^2 + (x+\beta ct)^2}} \cdot dt =$$
$$= \frac{2r_e}{\gamma} \cdot \frac{n(z)(x+\beta z)}{\rho^2 + (x+\beta z)^2}$$

One can use also the simple correlation between t and z for an ultra relativistic bunch (z=ct). For Z direction it is easy to find:

$$d\theta_y = \frac{dP_y}{P_x} = \frac{1}{\gamma mc\beta} \cdot \frac{e^2 2n(z)}{\sqrt{\rho^2 + (x+\beta ct)^2}} \cdot \frac{\rho}{\sqrt{\rho^2 + (x+\beta ct)^2}} \cdot dt =$$
$$= \frac{2\rho r_e}{\gamma\beta} \cdot \frac{n(z)}{\rho^2 + (x+\beta z)^2}$$

Finally the dependencies**Error! Bookmark not defined.** can be written as:

$$\theta_z(x) = \frac{2r_e}{\gamma} \int_{-\infty}^{+\infty} \frac{(x+\beta z)n(z)dz}{\rho^2 + (x+\beta z)^2} \tag{1}$$

$$\theta_y(x) = \frac{2\rho r_e}{\beta\gamma} \int_{-\infty}^{+\infty} \frac{n(z)dz}{\rho^2 + (x+\beta z)^2} \tag{2}$$

where r_e is the classical electron radius, ρ is the impact parameter, $\beta = \frac{v}{c}$ is the ratio of the probe-beam (PB) velocity to the velocity of light, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ is the relativistic factor of the PB, x is the coordinate of the PB particle at moment $t = 0$ and $n(z)$ is the dependence of the linear electron density in the relativistic bunch on longitudinal coordinate z.

2.1 Determining the length of a Gaussian relativistic bunch

In the case of an exact collision (ρ=0) of the beams, when their trajectories intersect at a right angle (see Fig. 2) and the transverse size of the PB is larger than that of the beam under investigation, quite pronounced peaks in the vertical and horizontal deflection angles of the probing particles are observed. These maxima are determined from maximum horizontal and vertical sizes of the image on the detection screen (see Fig. 3).

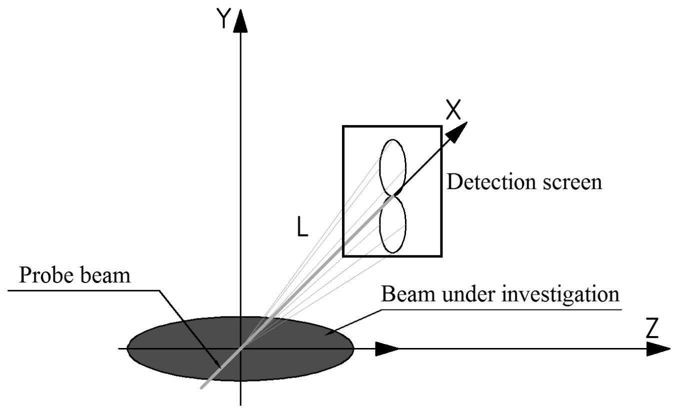

Fig. 2: Diagram illustrating of an exact collision of the beams

In this case, the total maximum deflection angles may be expressed as:

$$\theta_y(\rho, x, \sigma_l, \sigma_r) = \frac{2\rho r_e}{\beta\gamma} \int_{-\infty}^{+\infty} \frac{n(z)dz}{\rho^2 + (x+\beta z)^2} (1 - e^{-\frac{\rho^2 + (x+\beta z)^2}{2\sigma_r^2}}) \tag{3}$$

$$\theta_z(\rho,x,\sigma_l,\sigma_r)=\frac{2r_e}{\gamma}\int_{-\infty}^{+\infty}\frac{(x+\beta z)n(z)dz}{\rho^2+(x+\beta z)^2}(1-e^{-\frac{\rho^2+(x+\beta z)^2}{2\sigma_r^2}}) \tag{4}$$

where σ_r is the transverse RMS size of the studied bunch and σ_l is the longitudinal RMS size of the studied bunch and $n(z)$ is a Gaussian distribution.

In this way, measuring the vertical θ_y (horizontal θ_z) deflection angle of the PB, and the charge and the transverse sizes of the studied beam it is possible to restore the bunch length. In this analytical model (Eq.3) only PB particles with coordinate $x=0$ will have the maximum vertical deflection [2]. An example of maximal vertical deflection angle on impact parameter ρ for electrons with coordinate $x=0$ and different transverse sizes of the studied beam is shown in Fig.4. Dependence of the maximal deflection angle versus the bunch length (Eq.3) is shown in Fig.5.

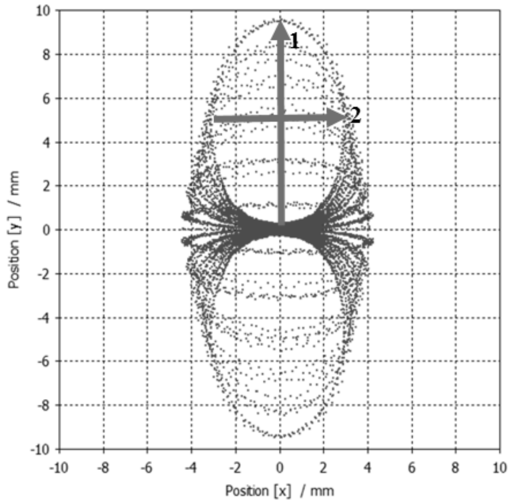

Fig. 3: Numerical simulations of the image on the EBP screen: 1 – maximum vertical deflection, 2 – maximum horizontal deflection. L = 40 cm. Simulations were performed by means of CST Particle studio.

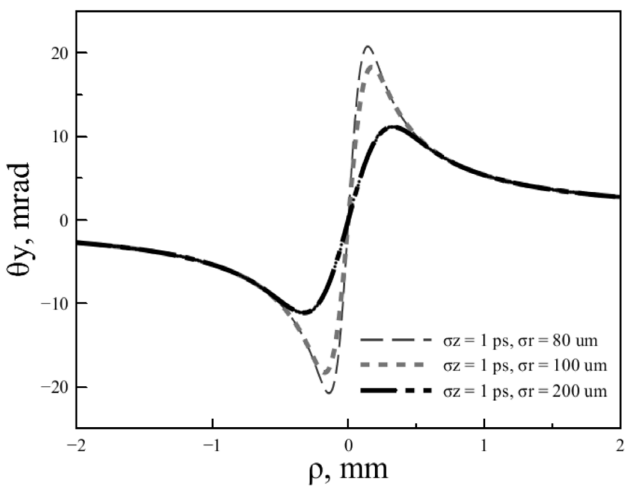

Fig. 4: Deflection angle θ_y as a function of the impact parameter ρ . RMS bunch length is equal to 1 ps

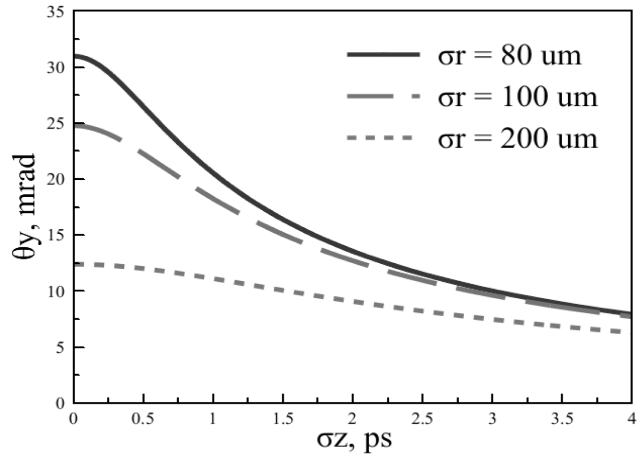

Fig. 5: Maximal vertical deflection angle θ_y as a function of the bunch length for different transverse RMS sizes (σ_r) of a studied beam. The charge of the studied beam is equal to 100 pC.

As can be seen in Fig.5, the dependence is quite significant, particularly between 0.5 ps and 3 ps. It means that it is possible to achieve a good time resolution for such a method. For example for a bunch length of 1 ps and transverse size of 80 um the time resolution will be around ± 0.4 ps, (see Fig.5) [2].

3 Typical experimental setup of EBP

The schematic diagram of the EBP layout is shown in Fig. 6. A probe electron beam is generated and accelerated in an electron gun (1) with energy up to 100 kV. An axial magnetic focusing lens (3) forms a minimal probe beam size in interaction region (5); also, the PB can be adjusted by means of two-coordinate magnetic correctors (2). The detection system (9) consists of a micro channel plate (MCP) (6), a phosphor screen (7) and a CCD camera (8).

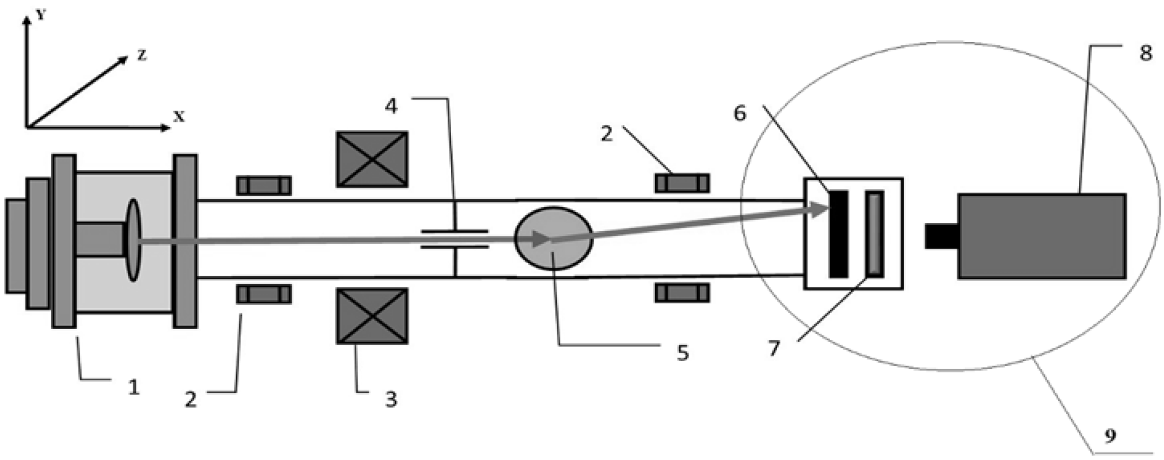

Fig. 5: The scheme of installation of EBP:1 – electron gun, 2 – magnetic corrector, 3 – axial magnetic lens, 4 – sweep plate, 5 – interaction region, 6 – MCP, 7 – phosphor screen, 8 – CCD camera, 9 – detection system.

4 Simulations

Particle tracking simulations were performed by means of CST Particle studio [6]. The studied bunch has 100 pC charge, transverse and longitudinal Gaussian distributions and a 100 um transverse RMS size. The probe beam has an energy of 100 keV, 120 um radius and a uniform longitudinal distribution. The results of the numerical simulations are presented in Fig. 6: the dashed line corresponds to Eq.3, the solid line corresponds to CST simulations for different bunch lengths.

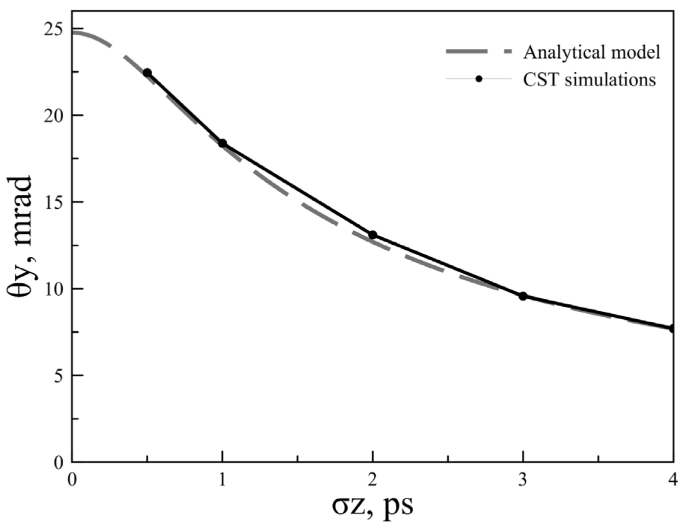

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Fig. 6: Maximum vertical deflection angle as a function of the studied bunch length: the dashed line corresponds to Eq.3, the solid line corresponds to particle-tracking simulations.

The particle tracking results are in good agreement with the analytical model.

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