ELECTRON BEAM PROBE FOR THE BUNCH LENGTH MEASUREMENTS AT bERLinPro

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Abstract

For the successful operation of various accelerator facilities a detailed bunch characterization is required. A complete description can be achieved using various diagnostic systems installed along an accelerator beamline. Ideally the diagnostic should be able to measure parameters of a single bunch in a non-destructive manner. For bunch length measurements this results in a complicated task especially for bunch duration below 1 ps. One of the possible solutions is a diagnostic based on the interaction of a low energy electron beam with electro-magnetic fields of the relativistic bunch. The bunch length can be readily deduced from the resulting scatter. In this paper bunch length measurement technique based on a low energy electron beam is introduced. Results of numerical simulations of measurements are presented. A possible setup of such diagnostic system for bERLinPro facility is proposed.

INTRODUCTION

There are many techniques to perform the length measurement of the relativistic bunch at the accelerator. For example:

- streak camera looking at the synchrotron light from the dipole magnet [1],
- electro-optical methods using an optical crystal near the beam path and a laser beam [2],
- transverse deflecting structure which shear the beam transversely [3],
- tomographic techniques with bunch rotation [4].

Only the first example using a streak camera is non-destructive and does not affect the beam during measurements, which means that this technique can be used parasitically during the user runs. To have sufficient synchrotron light to be detectable with the streak camera electron bunch should have adequate high energy and high current. For the low energy or low current (low intensity) accelerators this technique will not work.

bERLinPro is a future accelerator test facility to demonstrate the potential of superconducting energy recovery linacs for high current and low emittance operation [5]. The main parameters of bERLinPro are presented in Table 1:

Table 1: bERLinPro Main Parameters

Parameter	Value	Unit
Beam energy	50	MeV
Beam current @ 1.3 GHz	100	mA
Bunch charge	77	pC
Bunch length	<2	ps
Energy spread	0.5	%

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For the 50 MeV bunch energy and 77 pC charge it will be hard to detect synchrotron radiation from a single bunch with a streak camera. Also for the injector part of the bERLinPro with 6 MeV bunch energy this method is no longer applicable. In such case another technique can be used to measure the bunch length non-destructively from a single shot using a low energy electron beam as a probe.

Electron Beam Probe Basics

The low energy electron beam can be used to characterize the electron bunch properties such as transverse and longitudinal profiles [6-7]. Technique is based on interaction of the low energy electrons with the strong electric and magnetic fields of the relativistic bunch. Measuring the result of such interaction the bunch length or transverse bunch profile can be estimated.

One parameter which one can use to characterize the bunch length can be maximal deflection angle of the probe electrons. The deflection angle depends on how close the probe electrons travel near the electron bunch – so called impact parameter. For the case of ultra-relativistic bunch the vertical deflection angle θ_y can be described by the following equation [6]:

$$\theta_y(\rho,x) = \frac{2\rho r_e}{\gamma\beta}\int_{-\infty}^{+\infty}\frac{n(z)dz}{\rho^2+(x+\beta z)^2}\left(1-e^{-\frac{\rho^2+(x+\beta z)^2}{2\sigma_\perp^2}}\right). \quad (1)$$

where ρ is the impact parameter, r_e is the classical electron radius, γ und β are the probe electron relativistic parameters, $n(z)$ is the longitudinal particle distribution of the bunch, x is the relative electron coordinate in the probe beam, $\sigma_\perp$ is the transverse root mean square (RMS) size of the bunch (here it is assumed that bunch has a Gaussian transverse distribution). For the horizontal deflection angle θ_z there is the similar equation:

$$\theta_z(\rho,x) = \frac{2r_e}{\gamma}\int_{-\infty}^{+\infty}\frac{(x+\beta z)n(z)dz}{\rho^2+(x+\beta z)^2}\left(1-e^{-\frac{\rho^2+(x+\beta z)^2}{2\sigma_\perp^2}}\right). \quad (2)$$

Each electron in the probe beam will receive a different deflection after interaction with the relativistic bunch, and only electrons with the $x = 0$, for the case of symmetrical bunch longitudinal distribution that $n(-z) = n(z)$ and with maximum at $z = 0$, will have maximal vertical deflection. Example is shown in Fig. 1 for the Gaussian longitudinal distribution of the bunch with 1 ps RMS length, transverse size $\sigma_\perp$ = 100 µm, charge of 77 pC and impact parameter ρ = 0.2 mm. Probe beam energy is 100 keV.

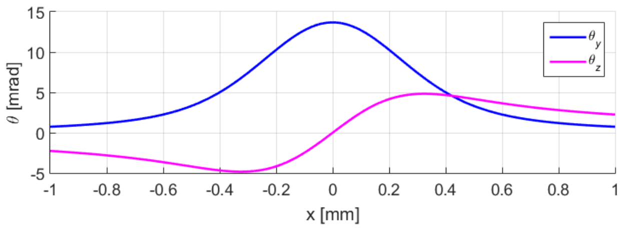

Figure 1: Deflection angles θ_y and θ_z as a function of the electron position inside the probe beam.

The vertical deflection is maximal for the probe electrons with $x = 0$ and the horizontal deflection is maximal for $x = 0.3$ mm. Despite of the both angles can be used for the bunch length measurements only the vertical one will be considered in this paper.

Example of the maximal vertical deflection angle dependence as a function of the impact parameter ρ (Eq. 1) is shown in Fig. 2 for electrons with coordinate $x = 0$.

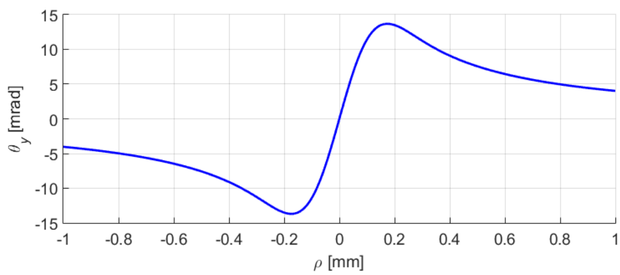

Figure 2: Deflection angle θ_y as a function of the impact parameter ρ for 1 ps bunch RMS length and 100 µm transverse RMS size.

As one can see, electrons that have the impact parameter of 0.2 mm will obtain the maximal vertical deflecting angle of approximately 14 mrad, see also Fig. 1.

Dependence of the maximal deflection angle versus the bunch length is shown in Fig. 3. This example was calculated for Gaussian transverse and longitudinal bunch charge density profiles for three transverse RMS sizes: 80, 100 and 120 µm.

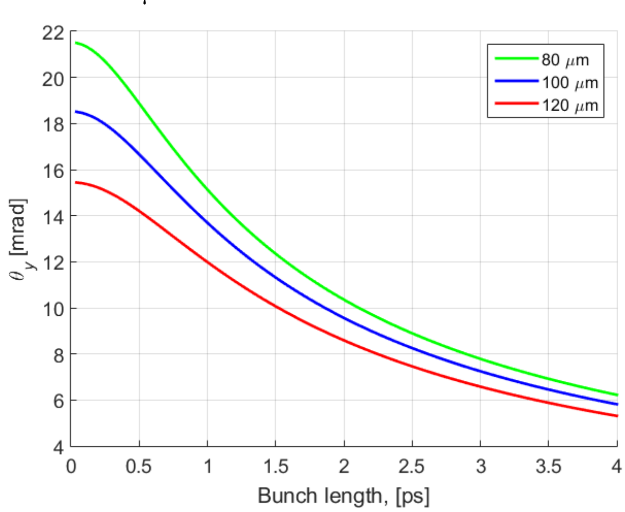

Figure 3: Maximal vertical deflection angle θ_y of the probe electrons as a function of the bunch length for three transverse bunch sizes 80, 100 and 120 µm.

Thereby, measuring the vertical deflection angle of the probe electrons the bunch length can be reconstructed.

Bunch Length Measurement Error Estimation

The resulting error of the bunch length measurement has the following parts:

- error of the bunch charge measurement,
- error of the transverse bunch size measurement,
- error of the vertical angle θ_y measurement.

For the bunch length of 2 ps and transverse size of 100 µm with error of 20%, the resulting error of the bunch length measurements will be around ±0.4 ps, see Fig. 3.

The vertical angle measurement error comes from the probe beam transverse size on the screen plus the error of this size measurement. It results in that the angle less than some value will not be measurable. Taking this value, for example, as 1 mrad and going to the bunch length around 0.3 ps (see Fig. 3) the measured deflection angle will not grow for shorter bunches (within the angle measurement resolution). The further decrease of the bunch length will not be measurable. Thereby, 0.3 ps can be considered as a resolution limit for such bunch parameters and it mainly depends on the transverse size of the bunch.

Electron Beam Probe Layout

The basic layout of the electron beam probe diagnostic is presented in Fig.4. It consists of: the electron gun (1), focusing solenoid (4), magnetic correctors (5), horizontal deflecting plates (2) and observation screen (7).

A probe electron beam is generated and accelerated in the electron gun (1) up to about 100 keV energy. The beam is focused by the lens (4) and adjusted vertically and horizontally by a two-coordinate corrector (5). Time correlation in the beam is introduced by horizontal deflecting plates (2). After interaction with the ultra-relativistic bunch (6) the beam is projected on the observation screen (7).

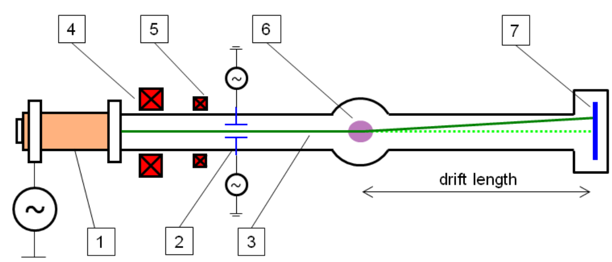

Figure 4: Diagnostic layout: 1 – electron gun, 2 – horizontal deflecting plates, 3 – probe electron beam, 4 – focusing solenoid, 5 – magnetic correctors, 6 – electron bunch, 7 – observation screen.

The low electron density of the probe beam on the observation screen yields in requirements for the additional amplification scheme for electron detection. It can be done as an electron-optical assembly of a microchannel plate and a phosphor screen [6]. The resulted image of the probe beam is recorded by a CCD camera from the phosphor screen.

The vertical deflection angle is calculated from the image vertical size divided by the drift length.

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SIMULATIONS

Particle tracking simulations were performed in analytical fields for an axial symmetric ultra-relativistic bunch without space charge forces taken into account. The bunch has 77 pC charge, Gaussian charge distributions and 100 µm transverse RMS size. Probe beam electrons have an energy of 100 keV, particles distributed uniformly inside a cylinder with transverse size of 0.6 mm and duration of 50 ps. Trajectories of the probe beam and bunch are crossing – the probe beam electrons have impact parameter in the range from –0.3 mm to +0.3 mm.

The results of numerical simulations are shown in Fig. 5: red dots are the maximal deflection angles of the probe beam electrons simulated for the different bunch lengths, blue curve is the deflection angle according Eq. 1.

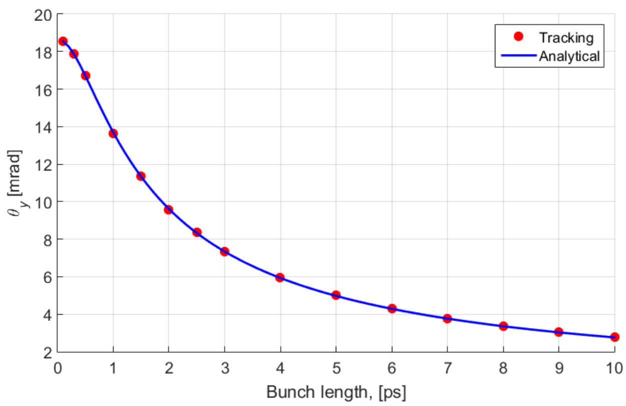

Figure 5: Maximal vertical deflection angle as a function of the bunch length according to Eq. 1 – blue curve and according to the particle tracking simulation – red dots.

The particle tracking results fully coincide with the result from an analytical equation.

Figure 6 shows two simulated images of the probe electron beam on the observation screen after interaction with bunches of 2 (left) and 1 ps (right) length respectively, the drift length after interaction is 40 cm and image grid size is 2 mm.

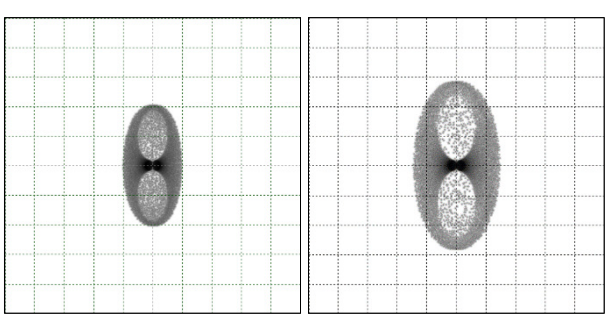

Figure 6: The probe electron beam images on the observation screen for 2 (left) and 1 ps (right) long bunch; grid size is 2 mm.

The upper half of the image shows probe electrons with a positive impact parameter (their trajectory is above the bunch trajectory) – they are deflecting up, the lower half shows probe electrons with a negative impact parameters – they are deflecting down. Bigger bunch length gives in result smaller size of the image +/- 4 mm for 2 ps long bunch and +/- 5.6 mm for 1 ps long bunch.

CONCLUSION

Low energy electron beam can be used for non-destructive single shot bunch length measurements of an ultra-relativistic bunch in particle accelerators.

Application of this technique is under study for the BESSY II and for bERLinPro accelerator facilities while it allows non-destructive single shot single bunch length measurements during the user run with subpicosecond resolution.

Such measurements can be performed with 10 Hz repetition rate with possibility to measure two or more consequent bunches in a bunch train (with 2 ns separation for BESSY II case and 0.7 ns separation for bERLinPro).

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