ELECTRON BEAM PROBE DIAGNOSTIC FOR BESSY II STORAGE RING

D. Malyutin, A. Matveenko, Helmholtz-Zentrum Berlin, Berlin, Germany

Abstract

A low energy electron beam can be used to characterize the high energy ultra-relativistic bunches. This technique allows one to obtain the bunch transverse profiles as well as the bunch length within a non-destructive single shot measurement.

In this paper the bunch length measurement technique based on the interaction of the low energy electron beam with an ultra-relativistic bunch is described. Results of numerical simulations of measurements related to BESSY II are presented. A possible setup of such diagnostic system for BESSY II and in future for BESSY VSR is proposed.

INTRODUCTION

For better understanding of the beam dynamics in particle accelerators detailed bunch characterization is required. This includes, for example, the bunch length measurements.

The bunch length can be measured, for example, using a standard method with a streak camera which analyses a synchrotron light from a dipole magnet [1, 2] or using a low energy electron beam crossing the electron bunch trajectory in the accelerator [3]. Both methods are non-destructive, i.e. does not affect the bunch, and therefore they can be used during the standard routine operation at user facilities or at others accelerators where destructive diagnostic methods cannot be used. Each method has its own advantages and disadvantages.

Streak Camera

A streak camera measures length and structure of an ultra-fast light signal by representing it as a two-dimensional image. In particle accelerators the light comes, for example, from the synchrotron radiation or optical transition radiation.

A light pulse hits the photocathode causing it to emit a bunch of photoelectrons, Fig. 1 [4]. The time structure of this bunch is identical to the structure of the light pulse.

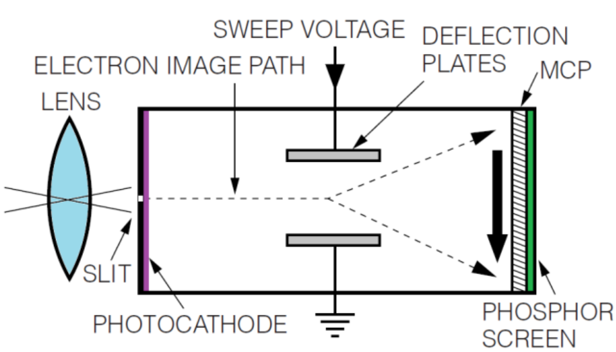

Figure 1: Streak camera basics [4].

These electrons are accelerated and then deflected by a ramped transverse electric field between the deflection plates. Afterwards the number of electrons is multiplied by the microchannel plate (MCP) and imaged on the phosphor screen. The resulted transverse profile of the screen image will represent the temporal profile of the light pulse. The minimal achieved resolution by available commercial streak cameras is in the order of 200 fs [4, 5].

Electron Beam Probe

Electron beam probe diagnostic 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 obtained [3].

A probe electron beam (3) is generated and accelerated in the electron gun (1) up to about 100 keV energy, Fig. 2.

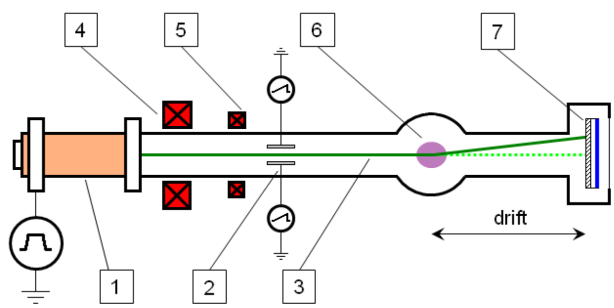

Figure 2: Electron Beam Probe layout: 1 – electron gun, 2 – horizontal deflecting plates, 3 – probe electron beam, 4 – focusing solenoid, 5 – magnetic correctors, 6 – electron bunch to be measured, 7 – detector (MCP and phosphor screen).

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). The horizontal axis on the screen will correspond to the time and the vertical axis will contain information about the bunch length. In Fig.2 the orientation of the deflecting plates is misleading: they are drown as the view from the top and all others components are drown as the side view.

The additional amplification scheme for the electron detection is required due to the low electron density of the probe beam on the observation screen. It can be realized as an electron-optical assembly of a microchannel plate (MCP) and a phosphor screen, in a similar way as it is done for the streak camera. The resulting image of the probe beam on the phosphor screen is recorded by a CCD camera. The vertical deflection angle is calculated from the image vertical size divided by the drift length, Fig. 2.

The maximal deflection angle of the probe electrons can be a parameter which can be used to characterize the bunch length. The deflection angle depends on the distance from

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the probe electrons to the electron bunch, so called impact parameter. For the case of ultra-relativistic axial symmetric bunch with Gaussian transverse distribution the vertical deflection angle θ_y can be described by the following equation [6]:

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

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.

Each electron in the probe beam will receive a different deflection after interaction with the relativistic bunch. Electrons with $x = 0$ will get a maximal vertical deflection for the case of symmetrical bunch longitudinal distribution $n(-z) = n(z)$ and maximum at $z = 0$.

For the case of the flat bunch like in storage ring, where the vertical bunch size is much smaller than the horizontal one due to synchrotron radiation damping, the deflecting angle can be calculated as a sum of the deflection from axial symmetric Gaussian bunches. A non-symmetric Gaussian transverse distribution can be represented as a sum of the 2*N*+1 symmetric Gaussian distributions with $\sigma_x = \sigma_y$ and different amplitudes with a horizontal step of two sigma:

$$n(x, y) = A \cdot e^{-\frac{y^2}{2\sigma_1^2}} \sum_{i=-N}^{N} e^{-\frac{(x-2\cdot\sigma_1\cdot i)^2}{2\sigma_1^2}} \cdot e^{-\frac{(2\cdot\sigma_1\cdot i)^2}{2\sigma_2^2}}, \quad (2)$$

where A is the normalization coefficient, σ_1 is the RMS size of the axially symmetric bunch and σ_2 is the desired horizontal RMS size of the flat bunch ($\sigma_2 \gg \sigma_1$). Comparison with the Gaussian distribution having RMS size of σ_2 is shown in Fig. 3 for $N = 15$ and $\sigma_2 = 10 \cdot \sigma_1$.

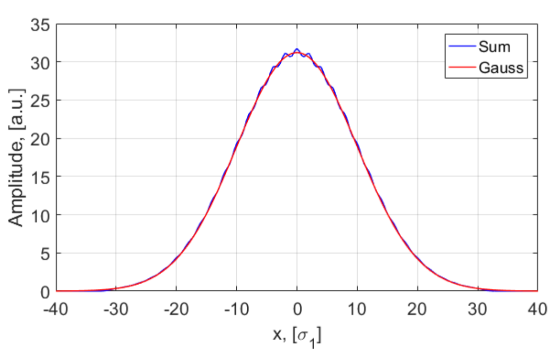

Figure 3: Representation of the long Gauss as a sum of the short ones – the blue curve, see Eq. (2), and Gaussian distribution – the red curve.

The difference with the original Gauss distribution is negligible and is in order of 1%. Making the step in Eq. 1 of one sigma will remove this difference, but it will require two times more elements in the sum and in result will double the calculation time.

Dependence of the maximal deflection angle of the probe electrons versus the bunch length is shown in Fig. 4 for horizontal and vertical bunch orientations. The vertical bunch orientation here means that the probe beam sees the relativistic bunch whose vertical size is bigger than horizontal one. For the horizontal bunch orientation all the way around: the probe beam sees that the vertical size is smaller. For the experiment these two orientations mean that the diagnostic can be installed not only horizontally but also vertically relative to the storage ring plane.

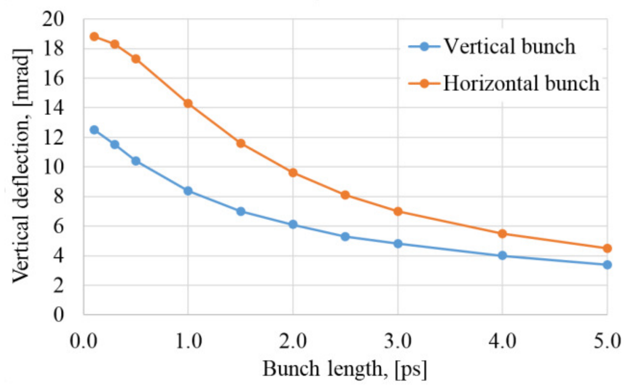

Figure 4: Maximal vertical deflection angle θ_y of the probe electrons as a function of the bunch length for vertical and horizontal bunch orientations.

This example was calculated for bunch charge of 144 pC and RMS sizes of 17 and 170 µm respectively. Horizontal bunch orientation is preferable as it produces higher deflecting angles to the probe electrons, which in turn is increasing the method resolution.

NUMERICAL SIMULATIONS

Particle tracking simulations were performed in analytical fields for an axially symmetric ultra-relativistic bunch. Space charge forces of the probe beam were not taken into account. The bunch has Gaussian charge distributions: 17 µm vertical RMS size and 170 µm horizontal 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 the bunch are crossing – the probe beam electrons have impact parameter in the range from –0.3 mm to +0.3 mm.

Figure 5 shows simulated images of the probe electron beam on the observation screen after interaction with two consequent bunches of 15 (left) and 1.7 ps (right) long with 1.4 and 0.6 nC charge respectively and with 2 ns delay between them. The drift length after interaction is 10 cm and image grid size is 2x2 mm. Bunch parameters were taken from the standard operation mode of BESSY VSR [7].

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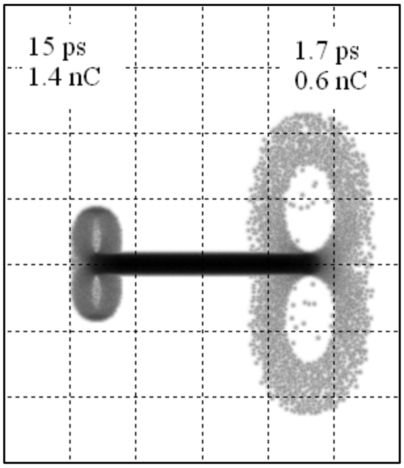

Figure 5: The probe electron beam images on the observation screen for 15 (left) and 1.7 ps (right) long bunch, bunch charges are 1.4 and 0.6 nC respectively (standard BESSY VSR mode); grid size is 2 mm.

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. The longer bunch gives as a result a smaller size of the image despite the larger bunch charge in this case: +/- 1.8 mm for 15 ps long bunch and +/- 4.4 mm for 1.7 ps long bunch.

Simulation for the case of the low alpha operation mode at BESSY VSR is shown on Fig. 6. Two consequent bunches have 3 (left) and 0.3 ps (right) length, 33 and 30 pC charge respectively, the drift length after interaction is 40 cm and the image grid size is 2 mm. The energy of the probe beam was decreased to 50 keV to have higher deflection angles. The big difference for these two bunches can be seen for the vertical deflection of the probe beam: about +/- 1.3 mm for 3 ps bunch and +/- 2.2 mm for 0.3 ps bunch.

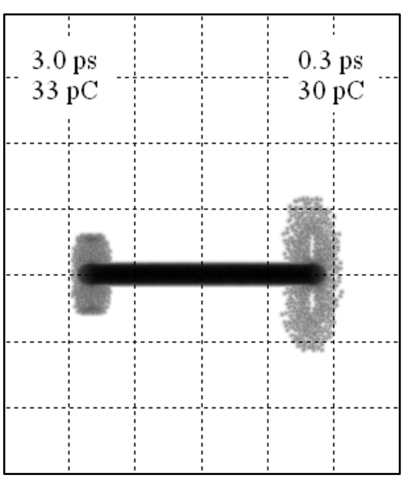

Figure 6: The probe electron beam images on the observation screen for 3.0 (left) and 0.3 ps (right) long bunch, bunch charges are 33 and 30 pC respectively (low alpha BESSY VSR mode); grid size is 2 mm.

Measurements of the bunch length bellow 0.3 ps for such small charge of 30 pC requires the deflection angle resolution better than 0.2 mrad.

In general case, the probe beam energy can be adjusted in such a way that the image of the deflected beam is occupying the full vertical size of the effective area of the MCP and the phosphor screen. This in result will give the best deflection angle resolution. Lower and higher borders come from the electron gun specification and the reasonable numbers are from 30 to 100 kV [6].

Bunch Length Measurement Errors

The measurements errors for all sets of bunches at BESSY II and for future BESSY VSR [7] are presented in Table 1.

Table 1: Bunch length measurement errors.

	Bunch type	Length, ps	Charge, nC	Err1, ps	Err2, ps
BESSYII	Bunch train (1x300)	15	0.7	±3	±1
BESSYII	Camshaft (x1)	27	4.0	±5	±1
BESSYII	Slicing (x3)	27	4.0	±1	±0.1
BESSYII	Bunch train (1x300)	3.0	0.04	±1	±1
	Booster (1x5)	60	1.0	±10	±2
BESSY VSR	Long bunch (2x75)	15	1.32	±3	±1
BESSY VSR	Long bunch (2x75)	1.1	0.144	±0.3	±0.2
BESSY VSR	Short bunch (x1)	1.7	0.64	±0.5	±0.3
BESSY VSR	Camshaft (x1)	27	8.0	±5	±1
BESSY VSR	Slicing (x3)	3.7	4.0	±1	±0.1
BESSY VSR	Long bunch (2x75)	3.0	0.036	±1	±1
BESSY VSR	Short bunch (2x75)	0.3	0.032	±0.5	±1

The Err1 is calculated assuming the bunch transverse size error of 20% and the Err2 is calculated for the case of deflection angle measurement error ±1 mrad.

Better knowledge of the transverse bunch size at the interaction point will significantly improve the resolution of this method. Also with the good optical readout system the angle resolution can reach ±0.2 mrad, which will greatly reduce the Err2.

CONCLUSION

Two non-destructive bunch length measurements have been discussed. A diagnostic based on the interaction of a low energy electrons with the fields of the ultra-relativistic bunch has been comprehensively studied. The achievable resolution is strongly dependent on how precise the transverse bunch size is known, depends on the readout optics resolution and in general can reach sub-picosecond range.

More detailed and sophisticated analysis of the electron beam image on the screen may allow this technique to get even the full longitudinal profile of the bunch like the streak camera [6]. But still there are several advantages compare to streak camera: the single shot measurement, it doesn't require synchrotron light (this is important for low energy accelerators <50 MeV or injectors, e.g. bERLinPro) and lower costs for the case of sub-picosecond bunch length ranges.

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