LONGITUDINAL PHASE SPACE MEASUREMENT AT THE ELI-NP COMPTON GAMMA SOURCE

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Abstract

Virtual bunch length measurement can be carried out by means of ELEGANT code for tracking the bunch particles from RF deflector to the screen. The technique relies on the correlation between the bunch longitudinal coordinate and transverse coordinates induced through a RF deflector. Therefore, the bunch length measurement can be carried out measuring the vertical spot size at the screen, placed after the RF deflector. The deflecting voltage amplitude affects the resolution. Adding a dispersive element, e.g. a magnetic dipole between RF deflector and the screen, the full longitudinal phase space can be measured. In this paper, we discuss some issues relevant for the electron linac of the Compton source at the Extreme Light Infrastructure - Nuclear Physics (ELI-NP).

INTRODUCTION

The Gamma Beam Source (GBS) at ELI-NP is going to be an advanced Source of up to 20 MeV Gamma Rays based on Compton back-scattering, i.e. collision of an intense high power laser beam and a high brightness electron beam with maximum kinetic energy of about 720 MeV. This infrastructure is going to be built in Magurele, near Bucharest (Romania) [1, 2]. The GBS electron linac can run at maximum repetition rate of 100 Hz. Therefore, at room temperature the specifications on the requested spectral density can be reached only by multiple bunch collisions. The final optimization foresees trains of 32 electron bunches separated by 16 ns, time needed to recirculate the laser pulse in order to allow the same laser pulse to collide with all the electron bunches in the RF pulse, distributed along a 0.5 μs RF pulse [1].

The properties of the single bunch and the whole train of bunches have to be measured in order to achieve high brightness in high repetition rate machine [3, 4]. In particular, bunch length measurement can be done using a Radio Frequency Deflector (RFD) and a screen in an electron linac. This disruptive measurement technique is well-known and widespread used in high brightness Linacs around the world, e.g. at the SLAC free electron laser [5, 6] or at SPARC-LAB linac [7].

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In this paper, the effect of a non-negligible energy chirp on bunch length virtual measurements is treated. Moreover, the energy chirp affects energy spread measurements. The simulations are carried by means of ELEctron Generation ANd Tracking (ELEGANT) code [8]. In section **MEASUREMENT TECHNIQUE**, the basic idea, the working principle and the procedure of the bunch length measurement technique using a RFD are explained. In section **SIMULATION RESULTS**, the RFD and bunch parameters of GBS linac case are reported and the bunch length virtual measurements are discussed.

MEASUREMENT TECHNIQUE

Basic Idea

Different types of measurements can be done with a RFD. Bunch length measurements can be done using only a RFD and a screen. Adding a dispersive element, e.g. a magnetic dipole between RF deflector and the screen, the full longitudinal phase space can be measured. The basic idea of these measurements is based on the property of the RFD transverse voltage to introduce a correlation between the longitudinal and vertical coordinates of the bunch at the screen position. Therefore, the bunch length measurement can be carried out measuring the vertical spot size at the screen, placed after the RF deflector [7, 9].

Working Principle

When the particles pass through the RFD, they feel a deflecting voltage when they pass through the RFD. The effect on every particle is a change in vertical divergence [10]. Considering the bunch length much smaller than RF wavelength (i.e. $kz_0 \ll 1$), we can assume the RFD voltage is [6, 11]:

$$V(z_0) \approx V_t \left[kz_0 cos(\varphi) + sin(\varphi)\right]. \tag{1}$$

where z_0 is the position of the particles along the beam axis with the origin in the RFD, $k = 2\pi/\lambda_{RF}$, λ_{RF}, V_t, and φ are the deflecting voltage wavelength, amplitude, and phase, respectively.

Therefore, RFD gives a vertical divergence change [6]:

$$\Delta y'_0(z_0) = C_{rfd} \left[kz_0 cos(\varphi) + sin(\varphi)\right], \tag{2}$$

ISBN 978-3-95450-177-9

where $C_{rfd} = qV_t/(pc)$, q is the electron charge, p is the particle momentum, and c is the speed of light. Assuming $\langle z_0 \rangle = \langle y_0 \rangle = 0\,\text{m}$ and $\langle y_0' \rangle = 0\,\text{rad}$, the vertical bunch centroid at screen is [6]:

$$C_{y_s} = LC_{rfd}sin(\varphi). \tag{3}$$

Assuming also $\langle y_0' z_0 \rangle = 0\,\text{m}$, $\langle y_0 z_0 \rangle = 0\,\text{m}^2$, and a negligible energy chirp, the rms vertical spot size at screen is [6]:

$$\sigma_{y_s}^2 = \sigma_{y_s,off}^2 + K_{cal}^2 \sigma_{t_0}^2, \tag{4}$$

where $\sigma_{y_s,off}$ is the rms vertical spot size at the screen with RFD off [12], σ_{t_0} is the rms bunch length (in seconds), and K_{cal} is a calibration factor:

$$K_{cal} = \omega_{RF} LC_{rfd} cos(\varphi), \tag{5}$$

where ω_{RF} is the deflecting voltage angular frequency. The calibration factor is a coefficient that relates the vertical coordinate at the screen with the bunch longitudinal time coordinate. Comparing (3) and (5), an important relation can be noticed:

$$K_{cal} = \omega_{RF} p, \tag{6}$$

where p is the slope of the plot vertical bunch centroid versus RFD phase. Equation (6) means that the coefficient K_{cal} can be directly calculated measuring the bunch centroid position at screen for different values of the RFD phase, i.e. it is possible to self-calibrate the measurements [13].

Measurement Procedure

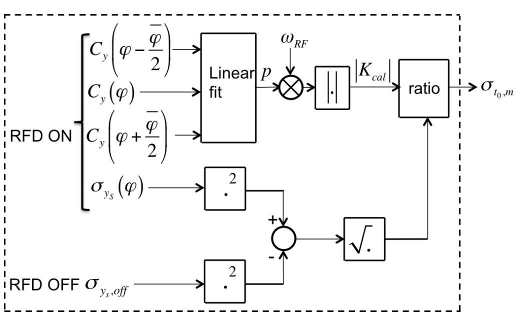

Figure 1: Bunch length measurement procedure.

The bunch length measurement procedure is divided in four steps (Fig. 1) [12, 14]:

- first step: carry out the measurement of the rms vertical spot size at the screen with RFD off;
- second step: make measurements of vertical bunch centroid for different values of RFD phase with RFD on and then calculate the calibration factor by means of a linear fit (6);
- third step: make the measurement of the rms vertical spot size at the screen with RFD on;
- fourth step: carry out the bunch length measurement from (4):

$$\sigma_{t_0,m} = \frac{\sqrt{\sigma_{y_s}^2 - \sigma_{y_s,off}^2}}{|K_{cal}|}. \tag{7}$$

SIMULATION RESULTS

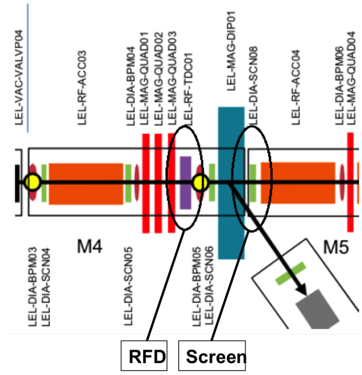

Figure 2: Zoom of GBS linac layout between the first and the second C-band accelerating section [1].

A nominal beam represented by 50000 particles has been tracked by means of ELEGANT code from LEL-RF-TDC01 RFD to LEL-DIA-SCN08 screen (Fig. 2), placed between the first and second C-band accelerating section of GBS electron linac [1]. The GBS electron linac bunch at RFD and RFD parameters are reported in Tables 1 and 2, respectively. The correlations between particle longitudinal position and vertical position $\langle y_0 z_0 \rangle$ and divergence $\langle y_0' z_0 \rangle$ at LEL-RF-TDC01 RFD are negligible, on the contrary the energy chirp is non-negligible (see Fig. 3).

Table 1: GBS Electron Linac Bunch Parameters (E Is the Bunch Energy)

σ_{y_0} [mm]	$\sigma_{y_0'}$ [μrad]	$\langle y_0 y_0' \rangle$ [m·rad]	σ_{t_0} [ps]	E [MeV]
0.3464	57.57	$-1.986 \cdot 10^{-8}$	0.9117	118

Table 2: GBS Electron Linac Bunch Parameters at Screen

V_t [MV]	f_{RF} [GHz]	L [m]
1	2.856	1.1380

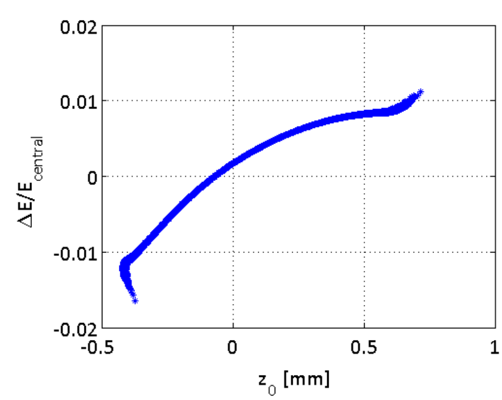

Figure 3: Longitudinal trace space of the Bunch before RFD.

ISBN 978-3-95450-177-9

In Fig. 3, the longitudinal trace space of the bunch before RFD is reported and a correlation between the particle energy expressed in terms of $\Delta E/E_{central}$ and the particle longitudinal coordinate z_0 can be noticed. The energy chirp doesn't affect the vertical bunch centroid at screen after the RFD, and so the calibration factor (see Figs. 4 and 5). On the contrary, the energy chirp affects the vertical spot size at screen (see Fig. 6) and so the bunch length virtual measurement (see Fig. 7).

Vertical Bunch Centroid at Screen and Calibration Factor

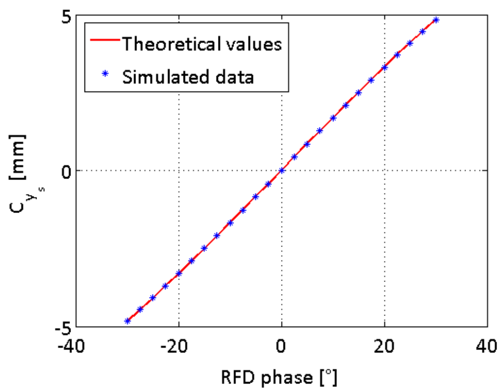

Figure 4: Theoretical predictions eq. (3) (in red line) and simulated data (in blue stars) of the vertical bunch centroid at screen versus RFD phase.

Figure 4 shows a good agreement between theoretical predictions eq. (3) and simulated data of the vertical bunch centroid at screen versus RFD phase. For every RFD phase, the calibration factor can be calculated by means of a linear fit of five different vertical bunch centroid measurements varying the RFD phase in a range of 3° eq. (6). Figure 5 shows a good agreement between theoretical eq. (5) and calculated from vertical centroid calibration factor eq. (6) versus RFD phase.

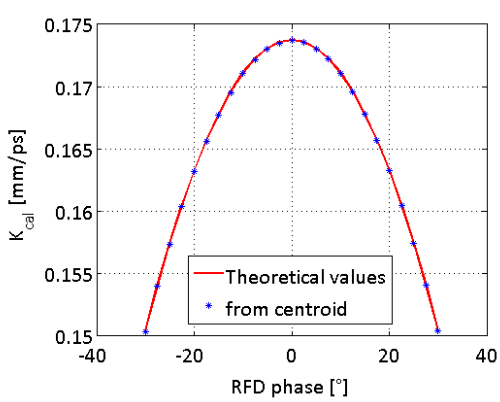

Figure 5: Theoretical eq. (5), in red line, and calculated from vertical centroid eq. (6) calibration factor versus RFD phase.

Vertical Spot Size at Screen

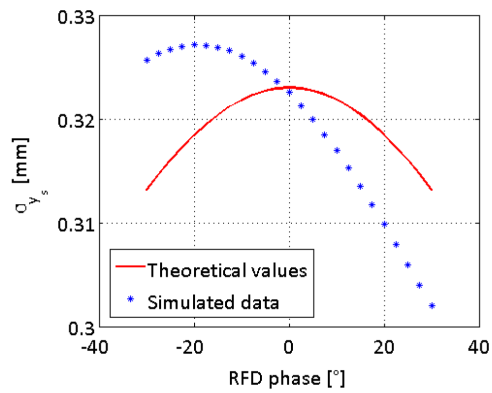

Figure 6: Theoretical predictions eq. (6) (in red line) and simulated data (in blue stars) of the vertical spot size at screen versus RFD phase.

Figure 6 shows a discrepancy between theoretical predictions eq. (6) and simulated data of the vertical spot size at screen versus RFD phase. This discrepancy is due to the energy chirp of the bunch at the entrance of RFD (see Fig. 3). For RFD phase offset of some degrees, corresponding to a vertical centroid offset of about 1 mm (see Fig. 4), the vertical spot size at screen relative error due to energy chirp can be of the order of 1% and this affects the bunch length virtual measurements.

Effects of Energy Chirp on Bunch Length Virtual Measurements at GBS Electron Linac

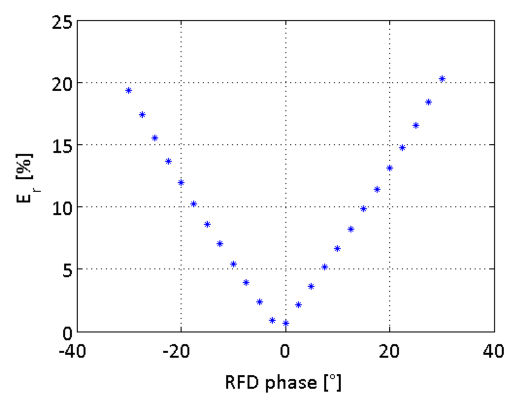

Figure 7: Bunch length virtual measurement relative error versus RFD phase.

The bunch length virtual measurement relative error can be defined:

$$E_r = \frac{|\sigma_{t_0} - \sigma_{t_0,m}|}{\sigma_{t_0}}, \quad (8)$$

where σ_{t_0} is the rms bunch length at RFD (see Table 1) and σ_{t_0} is the rms bunch length virtual measurement given by eq. (7). In Fig. 7, the bunch length virtual measurement relative error versus RFD phase is plotted. In the case of

ISBN 978-3-95450-177-9

GBS electron linac, for RFD phase offset of some degrees, the bunch length virtual measurement relative error due to energy chirp can be of the order of 5%. It can be noticed that the bunch length relative error is minimum when the RFD phase offset is null.

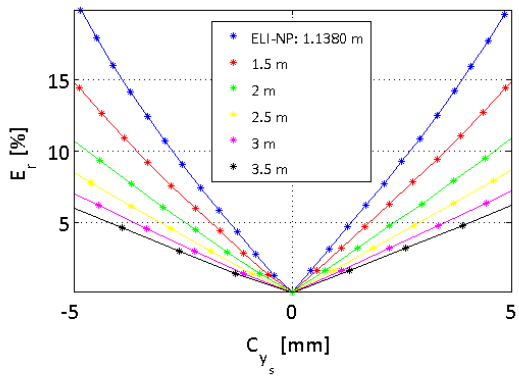

Figure 8: Bunch length virtual measurement relative error versus RFD phase varying the distance between RFD and screen (blue: ELI-NP case 1.1380 m, red: 1.5 m, green: 2.0 m, yellow: 2.5 m, magenta: 3.0 m, black: 3.5 m).

The bunch length virtual measurement relative error versus RFD phase varies with the distance between RFD and screen (see Fig. 8). In Fig. 8, L varies between almost 1.14 m (GBS linac case) and 3.5 m (SPARC-LAB linac case). For a fixed vertical centroid offset, the bunch length virtual measurement relative error due to energy chirp is greater when the distance between RFD and screen is smaller. For a vertical centroid offset of about 1 mm and L=3.5 m, the bunch length virtual measurement relative decreases to about 1%.

CONCLUSIONS

In this paper, the importance of the energy chirp for bunch length measurament is treated. The contribution of the energy chirp in bunch length measurement increases when the RFD offset increases. Therefore, in the case of a bunch with a non-negligible energy chirp, the vertical centroid offset plays a fundamental role in the bunch length measurement relative error. In particular, the bunch length virtual measurement relative errors varying RFD phase in the case of GBS electron linac are presented in this paper. The relative errors are due to the non-negligible energy chirp of the bunch at RFD. In particular, the energy chirp doesn't affect the vertical bunch centroid at screen after the RFD, and so the calibration factor. On the contrary, the energy chirp affects the vertical spot size at the screen and so the virtual bunch length measurement. When the RFD phase offset is null, the bunch length relative error is minimum.

In the case of GBS electron linac, for RFD phase offset of some degrees, the bunch length virtual measurement relative error due to energy chirp can be of the order of 5%. For a fixed vertical centroid offset, the bunch length virtual measurement relative error due to energy chirp is greater when the distance between RFD and screen is smaller. For a vertical centroid offset of about 1 mm and L=3.5 m (SPARC-LAB linac case), the bunch length virtual measurement relative decreases to about 1%.

ACKNOWLEDGEMENT

The authors would like to thank M. Borland for useful suggestions and discussion.

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ISBN 978-3-95450-177-9