METROLOGICAL CHARACTERIZATION OF THE BUNCH LENGTH MEASUREMENT BY MEANS OF A RF DEFLECTOR AT THE ELI-NP COMPTON GAMMA SOURCE

L. Sabato[1]*, University of Sannio, Dept. of Engineering, Corso G. Garibaldi, 107, Benevento, Italy
P. Arpaia, A. Liccardo, Federico II University of Naples,
Dept. of Electrical Engineering and Information Technology, Via Claudio 21, Naples, Italy
D. Alesini, C. Vaccarezza, A. Variola, Istituto Nazionale di Fisica Nucleare -
Laboratori Nazionali di Frascati (INFN-LNF), via Enrico Fermi, 40, Frascati, Italy
A. Giribono, A. Mostacci, L. Palumbo, Sapienza University of Rome,
Dept. Scienze di Base e Applicate per l'Ingegneria (SBAI), Via Antonio Scarpa, 14, Rome, Italy
[1]also at Istituto Nazionale di Fisica Nucleare (INFN) Naples, via Cintia, Naples, Italy

Abstract

Bunch length measurement in linac can be carried out using a RF deflector, which provides a transverse kick to the beam. The transverse beam size on a screen, placed after the RF deflector, represents the bunch length. In this paper, the metrological characterization of the bunch length measurement technique is proposed. The uncertainty and the systematic errors are estimated by means of a sensitivity analysis to the measurement parameters. The proposed approach has been validated through simulation by means of ELEGANT code on the parameters interesting 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 [1]. This infrastructure is going to be built in Magurele, near Bucharest (Romania). The purposes of this machine are various: studies on frontier fundamental physics, new nuclear physics and astrophysics as well as applications in nuclear materials, radioactive waste management, material science and life sciences [2].

The GBS linac can run at maximum repetition rate of 100 Hz [3]. Therefore, at room temperature the specifications on the requested spectral density cannot be achieved with single bunch collisions. The specifications can be reached by multiple bunch collisions with trains of 32 electron bunches separated by 16 ns, distributed along a 0.5 μs RF pulse. The bunches in each train have to be spaced by the same time interval needed to recirculate the laser pulse in a properly conceived and designed laser re-circulator, in order to allow the same laser pulse to collide with all the electron bunches in the RF pulse, before being dumped [1].

The role of diagnostic is fundamental in order to achieve high brightness in high repetition rate machine. The properties of the single bunch and the whole train of bunches have to be measured [4–6]. In particular, bunch length measurement can be carried out by means of a disruptive technique based on a Radio Frequency Deflector (RFD). Applications of this measurement technique have been done in many high brightness Linacs around the world, e.g. at the SLAC free electron laser [7, 8] or at SPARC-LAB linac [9, 10].

In this paper, a bunch length virtual measurement by means of a RFD at ELI-NP-GBS electron linac is addressed showed. The simulations are carried out by means of ELEGANT code [11]. In particular, in Measurement System the basic idea and theory of this measurement technique is presented. In addition, the measurement procedure is explained in detail. In Simulation Results, the actual measurement procedure is applied to the case of GBS electron linac using ELEGANT code. Furthermore, the comparison between theoretical and simulated results are showed.

MEASUREMENT SYSTEM

Bunch length measurements can be carried out using a RFD and a screen. The RFD voltage introduces a correlation between the longitudinal coordinate of the bunch and the transverse coordinates, vertical or horizontal, at the screen position. Therefore, the information on bunch length can be derived from spot size measurements at screen [7–9]. In particular, the deflecting voltage phase is chosen in order to have a zero crossing of the transverse voltage in the center of the bunch, giving a linear transverse deflection from bunch head to tail. Consequently, the transverse displacement of each longitudinal bunch slice is proportional to its position with respect to the bunch center [12].

Theory

We can assume the RFD voltage is $V\left(z_0\right) = V_t sin(kz_0 + \varphi)$, where z_0 is the position of the particles along the beam axis with the origin in the RFD. $k = 2\pi/\lambda_{RF}$ if λ_{RF}, V_t, and φ are the deflecting voltage wavelength, amplitude, and phase, respectively. Usually the bunch length is much smaller than RF wavelength (i.e $kz_0 \ll 1$) and so we can use the following approximation [8]: $V\left(z_0\right) \approx V_t k z_0 cos(\varphi) + sin(\varphi)$. Therefore, RFD gives a

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[*] luca.sabato@unisannio.it

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vertical divergence change:

$$\Delta y_0'(z_0) = C_{rfd}\left[kz_0 cos(\varphi) + sin(\varphi)\right], \qquad (1)$$

where $C_{rfd} = qV_t/(pc)$, q is the electron charge, p is the particle momentum, and c is the speed of light [8].

The particle vertical positions at a screen y_s, placed after a distance L from a RFD, is given by:

$$y_s(z_0) = y_0 + L\left[y_0' + \Delta y_0'\right], \qquad (2)$$

where y_0 and y_0' are the particle vertical positions and divergences before the RFD, respectively. Assuming $\langle z_0\rangle = \langle y_0\rangle = \langle y_0'\rangle = 0$, the vertical bunch centroid at screen is:

$$C_{y_s} = LC_{rfd} sin(\varphi), \qquad (3)$$

and the rms vertical spot size at screen is [8]:

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

where $\sigma_{y_s,off}$ is the rms vertical spot size at the screen with RFD off, σ_{t_0} is the rms bunch length (in seconds), and K_{cal} is a coefficient that relates the vertical coordinate at the screen with the time coordinate of the bunch, thus

$$K_{cal} = -2\pi f_{RF} LC_{rfd} cos(\varphi), \qquad (5)$$

where f_{RF} is the deflecting voltage frequency. Comparing Eq. 3) and Eq. 5), an important characteristic of this measurement technique can be noticed:

$$K_{cal} = -2\pi f_{RF}\frac{dC_{y_s}}{d\varphi} \approx -2\pi f_{RF}\frac{C_{y_s}(\varphi_2) - C_{y_s}(\varphi_1)}{\varphi_2 - \varphi_1}. \qquad (6)$$

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 [12].

The rms vertical spot size at the screen with RFD off is given by:

$$\sigma_{y_s,off}^2 = \sigma_{y_0}^2 + L^2\sigma_{y_0'}^2 + 2L\langle y_0 y_0'\rangle, \qquad (7)$$

where $\langle y_0 y_0'\rangle$ is the correlation between vertical particle positions and divergences before RFD, σ_{y_0} and $\sigma_{y_0'}$ are the rms vertical distribution of particle positions and divergences before RFD, respectively.

Procedure

The bunch length measurement procedure is divided in different steps (Fig. 1). In the first step, the measurement of the rms vertical spot size at the screen with RFD off, $\sigma_{y_{s,off}}$, has to be done. In the second step, the measurements of vertical bunch centroid for different values of RFD phase with RFD on have to be carried out. From these measurements, by means of Eq. 6 the calibration factor, K_{cal}, can be obtained. In the third step, the measurement of the rms vertical spot size at the screen with RFD on, σ_{y_S}, has to be performed. In the last step, using the information of the previous steps, the bunch length measurement $\sigma_{t_0,m}$ can be easily obtained from Eq. 4:

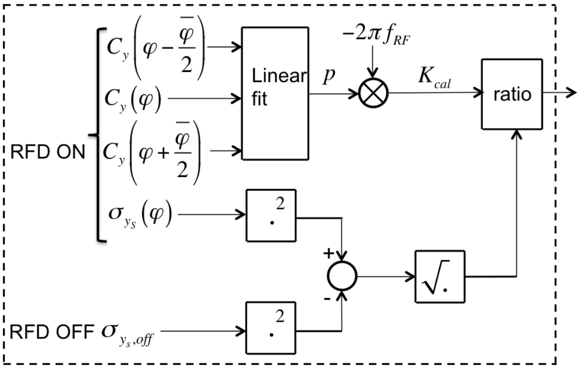

Figure 1: Measurement procedure. $\bar{\varphi}$ is the phase range where K_{cal} is calculated from vertical bunch centroid measurements.

$$\sigma_{t_0,m} = \frac{\sqrt{\sigma_{y_s}^2 - \sigma_{y_s,off}^2}}{K_{cal}}. \qquad (8)$$

SIMULATION RESULTS

In this section the result of a bunch length virtual measurement at GBS electron linac is reported for a fixed RFD phase $\varphi = 0°$, using ELEGANT code [11] and by means of the actual measurement procedure. Moreover, the comparison between simulation and theoretical results of vertical bunch centroid at screen varying RFD phase are presented. Eventually, the approximation used for K_{cal} is quantified according to Eq. 6.

Bunch Length Measurement

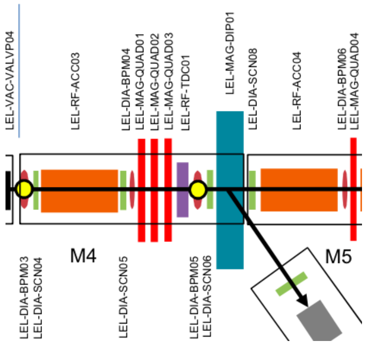

Figure 2: Zoom of GBS linac layout between the first and the second C-band accelerating section [1].

A nominal beam represented by 50000 particles has been tracked with 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 parameters used are: distance between RFD and screen L=1.1380 m, energy before RFD 119 MeV, and bunch length σ_{t_0}=0.912 ps.

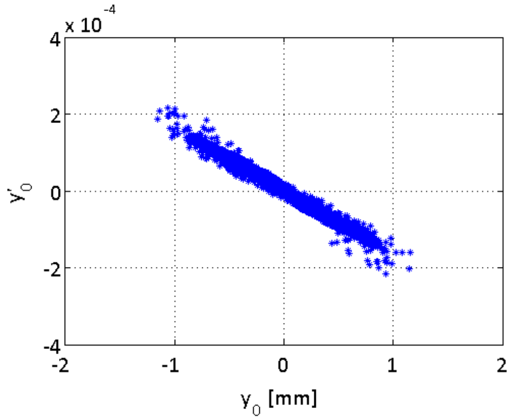

Figure 3: Vertical trace space at RFD center.

Step 1 The virtual measurement of the rms vertical spot size at screen with RFD off is 0.281 mm. In the case of GBS linac bunches, the first term of Eq. 7 is 0.120 mm^2 and so it is dominant. The second term is 0.004 29 mm^2 and therefore it is the least significant. The last term is –0.0451 mm^2 and it cannot be neglected, because GBS linac bunches are focusing between the first and the second C-band accelerating section (Fig. 3).

Step 2 The RFD parameters used are: $V_T = 1$ MV, $f_{RF} = 2.856$ GHz, and $\varphi = 0°$. C_{y_s} has been measured in three different values of RFD phase: −2.5°,0°, and 2.5°. Using Eq. 6, the calibration factor can be evaluated with a relative error about 0.04 % from the theoretical value from Eq. 5, i.e. $K_{cal} = 0.174$ mm/ps.

Step 3 The virtual measurement of the rms vertical spot size at screen with RFD on and $\varphi = 0°$ is 0.323 mm.

Step 4 The bunch length virtual measurement can be assessed by means of Eq. 8 with a relative error less than 0.01 %.

Varying RFD Phase

In next simulations RFD phase is chosen between −30° and 30° with a step of 2.5°.

Vertical Centroid at Screen In Fig. 4 the vertical centroid at screen versus RFD phase is plotted (in blue ∗ simulated data and in red line theoretical values). The Fig. 4 shows a good match between theoretical and simulated results.

Calibration Factor In Fig. 5 the comparison between theoretical Eq. 5) and approximated Eq. 6 calibration factor in function of RFD phase is showed. The maximum relative error between theoretical and approximated calibration factor is less than 0.07 %.

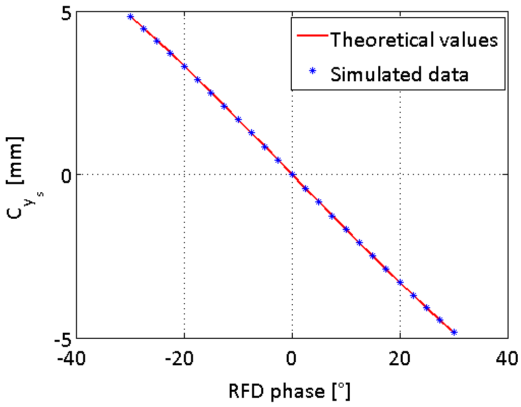

Figure 4: Vertical centroid at screen versus RFD phase. In blue ∗ simulated data and in red line theoretical values.

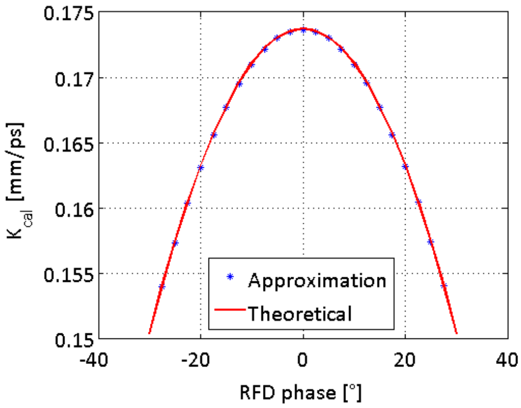

Figure 5: Comparison between theoretical Eq. 5 (red line) and approximated Eq. 6 (blue ∗), calibration factor in function of RFD phase.

CONCLUSION AND FUTURE DEVELOPMENT

In this paper, the actual bunch length measurement procedure has been applied to the case of GBS electron linac using ELEGANT code with a relative error less than 0.01 %. The comparison between simulation and theoretical results of vertical bunch centroid at screen varying RFD phase has been reported. It has showed a good match between theoretical and simulated results. Finally, the comparison between theoretical and approximated calibration factor in function of RFD phase has been reported. The maximum relative error between theoretical and approximated calibration factor is less than 0.07 %. These results are preliminary steps for a metrological characterization of this bunch length measurement technique.

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