ABSOLUTE BUNCH LENGTH MEASUREMENTS AT Fermi@ELETTRA FEL

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Abstract

Electron bunch length measurements are of crucial importance for many types of accelerators, including storage rings, energy recovery linacs, free electron lasers. Many devices and instrumentation have been developed to measure and control the electron bunch length. A very powerful class of diagnostic tools is based on the coherent radiation power emitted by the electron bunch, that allows a non-destructive shot by shot measurement, well suitable for bunch length control feedback implementation. However they usually provide measurements of the bunch length relative variation, and external instrumentation like a transverse RF deflecting cavity is usually needed to calibrate them and to obtain absolute bunch length estimations. In this paper we present a novel experimental methodology to self-calibrate a device based on diffraction radiation from a ceramic gap. We indeed demonstrate the possibility to use coherent radiation based diagnostic to provide absolute measurements of the electron bunch length. We present the theoretical basis of the proposed approach and validate it through a detailed campaign of measurements that have been carried on in the FERMI@Elettra FEL linac.

INTRODUCTION

The longitudinal electron bunch properties represent a key parameter to guarantee high performance and reliability of the most modern Free Electron Lasers, Linac and Synchrotrons. Many devices, instrumentation and techniques are used to measure and keep the electron bunch length constant. Among them streak cameras, electro-optic sampling, transverse radio frequency deflecting cavities. They can provide absolute bunch length measurements, but at the same time are complex and expensive. Moreover, they involve bunch destructive techniques, and are therefore not well suited for on-line measurements. On the other side, devices based on coherent radiation provide the possibility to measure non-destructively the longitudinal characteristics, and are routinely used to check shot by shot the variation of the bunch length, and are therefore implemented in control feedback loops.The drawback is that for an absolute estimation of the bunch length, external instrumentation like a transverse rf deflecting cavity is usually needed. Purpose of this paper is to present an experimental methodology to self-calibrate a device based on diffraction radiation from a ceramic gap. We will first introduce briefly the theoretical background needed to understand the methodology, and the equations exploited in the development of the technique used to perform the self-calibration. The device used (from now on Coherent Bunch Length Monitor, or CBLM) will then be described, with a focus on the part involving ceramic gap radiation. Then, we will describe the calibration procedure and the measurement method, the choice of the detectors and the frequency bands we selected. A validation of the method, by means of the rf deflecting cavity will then be reported.

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THEORETICAL BACKGROUND

A very short theoretical background will be introduced. For a more complete discussion, please refer to [1]. The working principle relies on the radiation emitted by an ultrarelativistic electron bunch, when this passes through a gap in a waveguide. The general solution of the Maxwell problem is provided by Palumbo [2] and relies on the seminal work of Bolotowskii [3]. We will go through the main points, here.
We start considering an electron bunch travelling along the axis of a waveguide, and having transversal dimension small compared to the transverse waveguide radius; the spectrum-angular distribution of the energy radiated by the bunch can be described as:

$$\frac{d^2W}{d\omega d\Omega} = \left.\frac{d^2W}{d\omega d\Omega}\right|_{1e^-} (N + N(N-1)|F(\omega)|^2) \qquad (1)$$

where W is the energy emitted, Ω is the solid angle, N is the number of electrons in the bunch, $\left.\frac{d^2W}{d\omega d\Omega}\right|_{1e^-}$ is the spectrum-angular distribution of the energy radiated by a single electron. In the mm-wave spectral range, the only term surviving in eq 1 is the one proportional to N^2. This term is related to the coherent radiation, in contrast to the one proportional to N, which is related to the incoherent part of the radiation. The proportionality with N^2 and the form factor $F(\omega)$ in eq. 1 applies to any source and type of coherent radiation, and what makes the difference, and has to be calculated, is the energy radiated by a single electron. A point charge moving in a discontinuous circular waveguide of radius a induces currents on the walls of the pipe. At the boundary with free space, the currents become source for an electromagnetic field radiating in the surrounding space. The problem is described in [3], and a

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solution is found for the field radiated. Known the radiation from a semiinfinite waveguide, the problem can be extended to the ceramic gap. In fact, the ceramic gap can be modelled as two coaxially faced semiinfinite waveguides, at a distance from each other equal to the gap length, $2l$. At first order, the superposition principle can be applied. The spectrum-angular distribution of a single electron travelling along the axis of the waveguide, considering the structure in a spherical coordinate system (R, θ, ϕ) with the origin located in the center of the gap, can be represented as:

$$\left.\frac{d^2W(\theta)}{d\omega d\Omega}\right|_{1e^-} = \beta e^2 \frac{\sin^2\theta J_0^2(ka\sin\theta)}{4\pi^2 c(1-\beta\cos\theta)^2 I_0^2(\frac{ka}{\beta\gamma})} \cdot \left| \sqrt{\frac{1-\beta}{1-\cos\theta}} e^{jk\ell(1-\beta\cos\theta)/\beta} + j\sqrt{\frac{1+\beta}{1+\cos\theta}} e^{-jk\ell(1-\beta\cos\theta)/\beta} \right|^2 \quad (2)$$

Eq 2 is an approximation, applying in the case of frequencies high, with respect to the beam pipe radius, i.e. in the case of $ka >> 1$, with k the wave number. The general equation can be obtained evaluating the radiated field with the help of the Wiener-Hopf factorization method. For further explanation, please refer to [3] and [4].
The first term in eq 2 is related to the electron entering the waveguide, while the second term shows the emission from the electron exiting the guide. To complete the theoretical discussion, we will introduce the Energy W radiated by the bunch. This is detectable by means of rf antennas and diodes. Starting from eq 2, the radiated energy W is calculated integrating the spectrum-angular density over frequency and solid angle, i.e. detector band $(\Delta\omega)$ and angular acceptance $(\Delta\Omega_{rad})$:

$$W = N^2 \int_{\Delta\omega}\int_{\Delta\Omega_{rad}} \beta e^2 \frac{\sin^2\theta J_0^2(ka\sin\theta)}{4\pi^2 c(1-\beta\cos\theta)^2 I_0^2(\frac{ka}{\beta\gamma})} \left| \sqrt{\frac{1-\beta}{1-\cos\theta}} e^{jk\ell(1-\beta\cos\theta)/\beta} + j\sqrt{\frac{1+\beta}{1+\cos\theta}} e^{-jk\ell(1-\beta\cos\theta)/\beta} \right|^2 |F(\omega)|^2 \cdot d\omega d\Omega \quad (3)$$

BUNCH LENGTH MONITOR DESIGN

The device described in this paper is part of the Bunch Length Monitor, installed after each of the bunch compressors of FERMI@Elettra FEL [5]. The electron beam passing through the gap emits an electromagnetic field which is then collected by means of three horn antennas installed on the plane perpendicular to the beam axis. The antennas are connected through rf waveguides to three mm-wave diodes, having central frequencies around 30, 100 and 300 GHz, that rectify the signals. For the emitted power levels involved, the diodes are working in their "square root of power" region. This means that the signal from the diodes is proportional to the root of the energy radiated by the bunch. Being this radiation proportional to N^2, the output signal of the diodes depends linearly on the charge (N). This device has been used as an absolute bunch length measurement system, introducing the self calibration method described in the following section.

CALIBRATION METHOD

Before describing the method itself, and for a better understanding of the choices made, a few things need to be shown and explained.
Let's consider the spectrum-angular density of the energy radiated by rectangular bunches of different lengths as obtained in eq 2. The result obtained applying the equation is shown in Fig. 1.

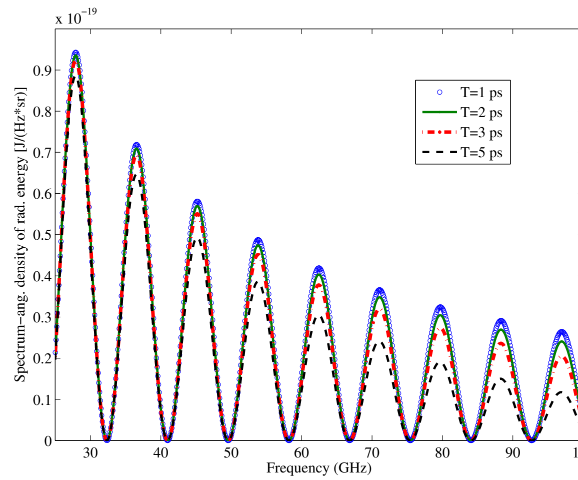

Figure 1: Spectrum-angular density of energy radiated by a 1 nC charge, 330 MeV energy rectangular electron bunch passing a gap in a waveguide, at an angle $\theta = \pi/2$.

As can be noticed, the intensity of the energy radiated drops as the frequency increases, and the relative variation of intensity at any frequency is larger for longer bunches. Eventually, the intensity variation due to the bunch shortening becomes negligible over the same frequency range. This asymptotic behaviour is the key property exploited for the method proposed to perform an absolute bunch length measurement.
The third term in equation 1 is the so-called form factor $|F(\omega)|$, which is dependent on the longitudinal beam characteristics. Fig. 2 shows the comparison between different bunch profiles: Gaussian, Rectangular, Single Horn, Double Horn, and the real profile as measured with the radio frequency deflecting cavity at FERMI@Elettra [6]. All the profiles represented have an rms length of 2.3 ps.
Fig. 2 shows how for frequencies lower than 30 GHz, the form factor is not sensitive to the details of the longitudinal distribution, and what counts is only the bunch rms length. A detector having central frequency around 30 GHz

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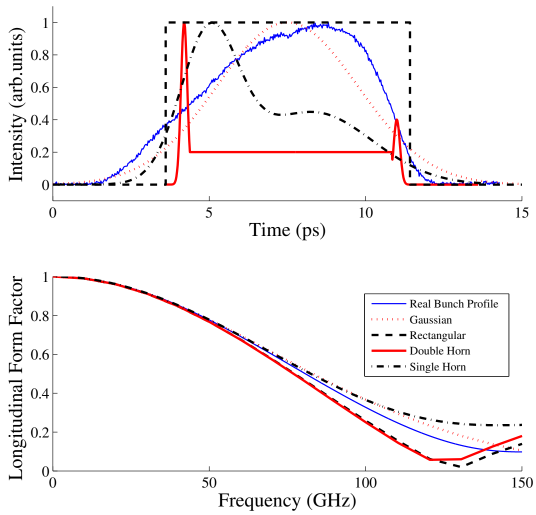

Figure 2: Form factors comparison between Rectangular, Gaussian, Single and Double Horn, and real bunch profile. All profiles have a rms length of 2.3 ps.

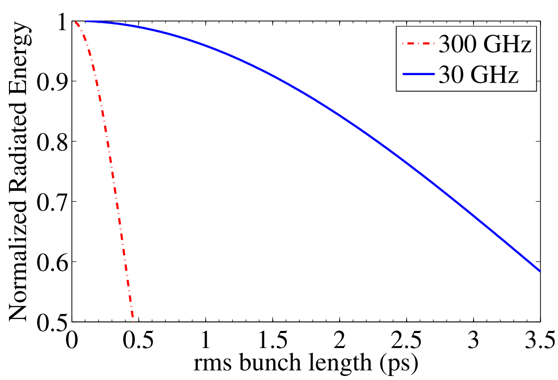

Figure 3: Energy radiated by a rectangular electron bunch at 30 and 300 GHz, normalized to the asymptotic values.

would therefore be perfect for measurement of a bunch of 2.3 ps. For shorter bunches, the first lobe of the form factor would extent to higher frequencies and a detector with higher central frequency should be chosen. In fact, also the asymptotic behaviour just described would appear for higher frequencies. Fig 3 shows the Energy radiated (eq. 3) by an electron bunch, integrated in the 30 GHz and 300 GHz detector bands.

Calibration Procedure

The electron packets length can be progressively decreased by means of the bunch compressor, detuning the phase of the first accelerating section of the Linear Accelerator. The compression factor can be brought up to a theoretical value of 5, producing sub-ps bunches. In the meanwhile, the Energy radiated by the gap is collected. As the compression value increases, the bunch length shortens, and the signal detected increases. The highest values of the compression factor bring the diode output signal to the asymptotic value.

The self-calibration procedure consists of changing the compression factor until the rf diode signal reaches the asymptote and register this signal level as reference. At lower compression factor, the ratio between the rf diode signal and the asymptotic level is uniquely identified. The diode output signal, at any compression value, can be normalized to the saturation value, obtaining a value that can be converted in absolute rms bunch length using the curve plotted in Fig. 3.

For the method validation, a diode with central frequency around 30 GHz has been used.

Method Validation

In order to validate the method, the low energy Radio Frequency deflecting cavity has been used [6]. The bunch length measured with the CBLM has been compared with the one measured by means of the rf deflecting cavity, for different compression factors, and different values of the charge. For each compression factor, the experimental data are obtained averaging over 50 consecutive bunches acquired simultaneously with the Bunch Length Monitor and the rf deflecting cavity. Experimental results for electron bunches with a charge of 200 pC and 350 pC are reported in Fig 4 On the x-axis is reported the phase of the first accelerating section.

A value of 90 deg corresponds to a compression factor 1, while higher values of the phase correspond to higher compression factors.

The CBLM absolute bunch length measurements are in good agreement with the deflecting cavity measurements. For bunches with higher charge, the initial length is higher, and the compression factor needs to be higher in order to bring the diode signal to saturation. Anyway, in both the 200 pC and 350 pC cases, the saturation condition is met when the rf deflecting cavity measures a rms length close to 0.5 ps.

CONCLUSIONS

A novel methodology for self-calibrating a Bunch Length Monitor based on the radiation from a ceramic gap has been presented. The method relies on the asymptotic dependence of the power emitted as a function of the bunch length. The theoretical background has been shortly introduced. The bunch length monitor has then been described, with particular focus on the ceramic gap part. Then, the calibration method has been presented, justifying the frequency band chosen and showing the results of the theoretical studies. Finally, the validation method by means of an rf deflecting cavity has been explained.

The results of the comparison of bunch length measurements performed with the rf cavity and the Bunch Length Monitor show very good agreement, and demonstrate the validity of the method presented.

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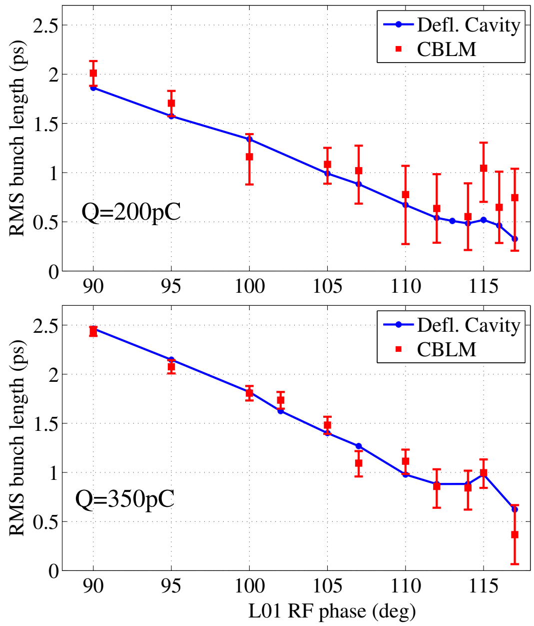

Figure 4: Comparison of bunch length measurements performed with the rf deflecting cavity and with the Bunch Length Monitor. Error bars represent the standard deviation calculated over 50 consecutive bunches at the same compression factor.

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