NON-DESTRUCTIVE MEASUREMENT OF ELECTRON MICROBUNCH SEPARATION

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Abstract

With the development of femtosecond lasers, the generation of micro-bunched beams directly from a photocathode becomes routine; however, the monitoring of the separation is still a challenge. We present the results of proof-of-principle experiments measuring the distance between two bunches via the amplitude modulation analysis of a monochromatic radiation signal. Good agreement with theoretical prediction is shown.

INTRODUCTION

Potential applications of "pre-bunched" or "micro-bunched" charged particle beams include the development of next generation of light sources [1–3] and particle accelerators [4, 5]. In these examples the ability to measure the distance between the micro-bunches would improve the efficiency and reliability of these studies. At present, popular techniques used to measure micro-bunch separations include measurements of the autocorrelation functions [1,6] and the use of a transverse deflection cavity. The first requires multi-shot measurements while the latter - although single-shot - is a destructive method. The development of diagnostic that would provide single-shot measurements of the distances between micro-bunches using coherent Smith-Purcell radiation (cSPr) is the goal of this project. Here we discuss the theoretical basis for such a diagnostic and show preliminary experimental results of the measurement of the distance between two micro-bunches carried out at the Laser Undulator Compact X-ray source facility (LUCX) at KEK, Japan.

THEORY

The coherent radiation frequency spectrum from a single femtosecond bunch is broadband (up to tens of THz) [7], and for a single bunch consisting of N_e electrons, the energy generated at frequency ω into a solid angle $d\Omega$ is given by equation (1) where I is the energy emitted by the bunch, I_e is the energy emitted by a single electron and $F(\omega)$ is the normalized "form factor" (the Fourier transform of the bunch temporal profile).

$$\frac{d^2 I}{d\omega d\Omega} \propto \frac{dI_e}{d\omega d\Omega} {N_e}^2 |F(\omega)|^2 \qquad (1)$$

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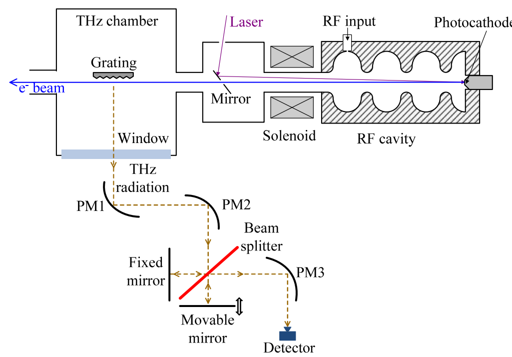

Figure 1: Schematic experimental set-up showing: photocathode gun, 3.6-cell RF cavity, grating, sapphire window and the Michaelson interferometer.

For a pre-bunched beam consisting of M micro-bunches separated by interval Δt, then $|F(\omega)|^2 = |F_1(\omega)|^2 G_M(\omega, \Delta t)$, where $F_1(\omega)$ is the form factor of a single micro-bunch. The form factor $|F(\omega)|$ is measured during the experiments. It is modulated by an oscillating function $G_M(\omega, \Delta t) = 1/M^2 \sin^2(M\omega\Delta t/2)/\sin^2(\omega\Delta t/2)$, which depends on the number of micro-bunches, observation frequency and micro-bunch spacing. If the measurements are made at a single, fixed frequency of interest ω, any changes in the interval Δt between micro-bunches will lead to amplitude variation of G_M, and this will be referred throughout the paper as multi-bunch signal modulation (MBSM). cSPr has been proposed for use in this diagnostic due to its dispersion relation, which leads to the detection of cSPr of a specific frequency at a particular angle, removing the need of a spectrometer. As two bunches were used in experiment at LUCX, the oscillating function $G_2(\omega, \Delta t) = [1 + \cos(\omega\Delta t)]/2$. In this letter we demonstrate that the MBSM function can be measured via measurement of the coherent Smith-Purcell radiation intensity modulation to monitor the distance between the two bunches.

EXPERIMENT

In the experiment, two electron micro-bunches were generated directly from a Cs_2Te photocathode embedded in 3.6-cell RF cavity (fig.1) by illuminating it with a series of femtosecond laser pulses [3].

The micro-bunches are emitted from the photocathode sequentially and the initial distance between micro-bunches was determined by the femtosecond laser pulse separation.

The parameters of the LUCX accelerator relevant to this experiment are given in Table 1. There were no beam dispersive or compressive elements between the gun and the interaction point (located around 1.5 m from the exit of the RF cavity), where the measurements were made.

Table 1: LUCX parameters

Parameter	Expected values
Beam energy, typ	8 MeV
Micro-bunch charge	30 pC
RF frequency	2.856 GHz
Accelerating field (amplitude)	80 MV/m
Cavity length	0.18 m

The experiments were carried out using a 1mm period grating. The cSPr emerged from the vacuum chamber through the sapphire window. The signal was collected by pair of off-axis parabolic mirrors, which were positioned to collect the radiation at 90 degrees (normal to the grating). The frequency measurements were done with a Michelson interferometer. A Zero Bias Diode with a detection range from 325 GHz to 500 GHz and a cut-off frequency of 268 GHz [8], was located at the focus of the third of-axis parabolic mirror. cSPr was detected at a frequency of 300 GHz, which is in agreement with the dispersion relation for an observations angle of $\theta = 90°$.

To demonstrate the proof of principle, two identical bunches were generated. By changing the laser pulse separation, the bunch separation was varied, and the modulation of radiation intensity was measured. The normalized measured intensity versus the initial bunch separation at RF phase $\phi_{RF} = 20°$ is shown in fig. 2. The dashed line is calculated by using the oscillating function for two micro-bunches $G_2(\omega, \Delta t)$ assuming the final bunch separation is the same to the initial bunch separation. The difference between dashed line and solid line indicates that the bunch separation at the point of measurement had changed during propagation.

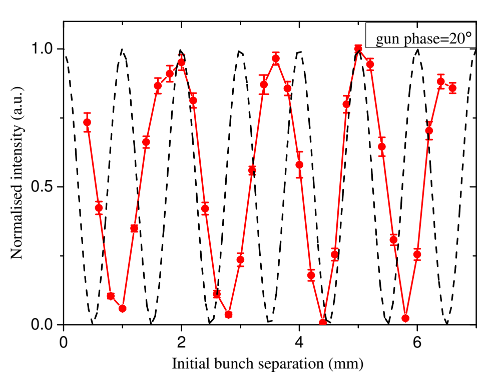

Figure 2: MBSM measured (solid lines with error bars) for the set of RF phases $\phi_{RF} = 20°$ as function of initial bunch distance.

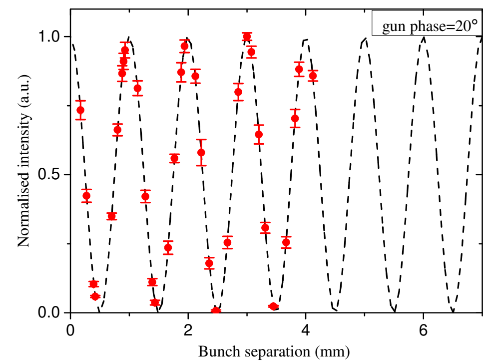

Figure 3: Calculated bunch separation. The dashed line indicates the normalised intensity from two identical bunches assuming the conservation of initial distance, defined by the laser pulses, between two bunches.

The measured intensity, solid line in fig. 2, was used to reconstruct the real bunch separation. The principle is as follows: As the variation of radiation intensity is only decided by the bunch separation in this case, for each measurement on the solid curve in fig.2, the real bunch separation Δt can be calculated by using $\Delta t = G_2^{-1}$. As shown in fig. 3, the calculated bunch separation is the real bunch separation.

In order to confirm our calculation, an analytical model [9] was used where the distance between two micro-bunches is defined as the distance between two single electrons. Using this model and taking into account the electron initial phase ϕ_0 with respect to the RF accelerating field ϕ_{RF}, the electron phase ϕ is given as:

$$\phi = \omega t - kz + \phi_0 = k\int_0^z \left(\frac{\gamma(z,\phi_0)}{\sqrt{\gamma^2(z,\phi_0)-1}} - 1\right)dz + \phi_0 \quad (2)$$

where k is the wavenumber, γ is the Lorentz factor. The distance between micro-bunches at the RF gun exit can be calculated as $\Delta t_{rf} = \Delta\phi/\omega_{rf}$ where ω_{rf} is the accelerator's operating frequency. As the accelerating phases for two bunches are different, the small energy difference of the two bunches will cause bunch separation shift when they propagate along the beamline. After adding this effect, the final bunch separation can be obtained.

As shown in fig. 4, the experimental measurements were compared with the theoretical model prediction, taking into account the initial parameters between two laser pulses (the predictions and the measurements). The graph demonstrates the dependence of the distance between micro-bunches at each measured point on the initial interval Δt_0. There is clear evidence of good agreement between the results and that the bunch spacing changes as the micro-bunches propagates through the cavity and the beamline.

It is worth noting that if a single-frequency measurement were to be used, as described here, there is a limitation associated with the non-uniqueness of the oscillating MBSM func-

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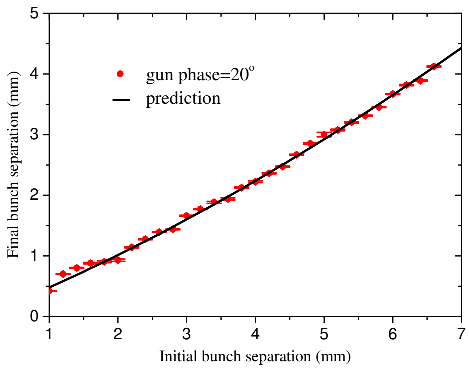

Figure 4: Graphs illustrating the dependence of final bunch-bunch separation on the initial distance between the micro-bunches for $\phi_{RF} = 20°$. Dots with the error bars: measurements. Solid black lines: calculated using the re-evaluated bunch distance Δt.

tion G_2 which arises from the fact that a single value of this function corresponds to many values of the interval between micro-bunches (fig. 3). This is a well-known problem which can be resolved by measuring G_2 at two frequencies. Such a measurement at a second frequency can be done using the same grating but with a second detector positioned at a different observation angle. The second measurement will provide a second curve allowing the determination of the absolute bunch spacing over a larger unambiguous range as achieved in multi-wavelength interferometry systems [10, 11].

CONCLUSION

In conclusion, we suggest a novel and non-destructive way of measuring of the bunch-to-bunch separation in two-bunch system by using a single-frequency measurement of cSPr. Although the results presented here were demonstrated for the case of two bunches generated directly from the photocathode, the same approach is applicable to any train of charged micro-bunches to evaluate the periodicity of the bunch train. The proposed method can be used to provide feedback to control the sub-millimeter distances between the femtosecond long micro-bunches.

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