

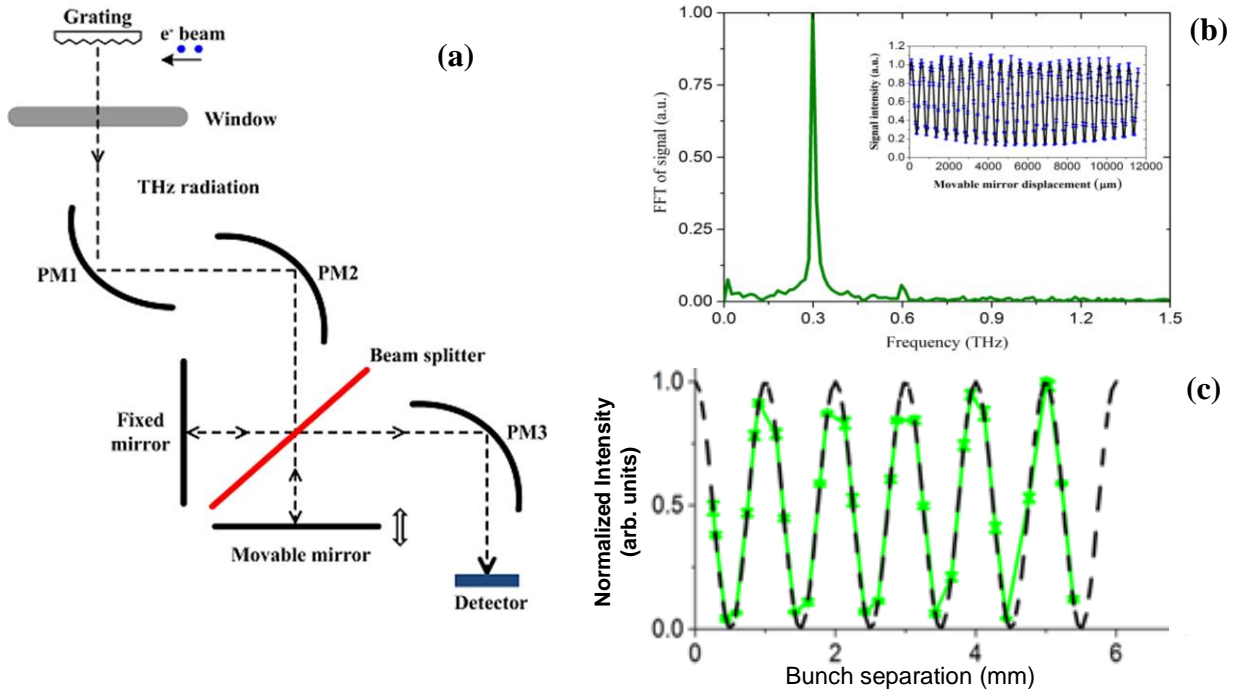
# Smith-Purcell Coherent THz Radiation Signal Modulation Measurements For Monitoring Of Separation Of Femtosecond Electron Micro-bunches.

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“Pre-bunched” or “micro-bunched” charged particle beams have attracted significant interest during the last decade. Potential applications of such beams include development of the next generation of THz light sources and particle accelerators. One notes that in conventional vacuum electronics CW beams (as compared with the period of THz oscillations) are used and micro-bunching takes place in either continuous interaction region (BWOs, TWTs, gyrotrons and etc.) or in a drift region like klystrons. Due to low energy of the beams, their modulation occurs along a relatively short distance. However if the high-energy electron beam let say above 2MeV are used beam modulation will require significantly longer distances. The solution is to generate pre-modulated beams of femtosecond periodicity before the interaction region. To enable the THz radiation source stable operation as well as its tunability, if driven by such a pre-bunched beam, an accurate knowledge and control of the distance between bunches is required. In other applications which are driven by such pre-modulated beams (including wake-field acceleration) the development of a non-invasive, a single-shot system capable of monitoring the distance between micro-bunches in non-destructive manner is important and in many cases it is still an unresolved challenge. At present, the most popular techniques used to study micro-bunch separations non-destructively is via measurements of autocorrelation functions [1], however, it requires multi-shot measurements. We demonstrate the concept of a single short, non-invasive monitor and discuss its operation. We show that the analysis of the coherent radiation signal amplitude variation can be used to evaluate the distance between the micro-bunches.



**Figure 1.** (a) Schematic of experimental set up. (b) Spectrum of the coherent Smith-Purcell radiation measured using Michelson interferometer (the insert show the typical interferogram); (c) MBSM function measured with variation of the initial distance between micro-bunches and showing the distance between micro-bunches at the point of measurements

The coherent radiation frequency spectrum from a single femtosecond bunch is broadband (from 0 to tens of THz) [2,3]. For a single electron bunch consisting of  $N_e$  electrons, the energy

generated at frequency  $\omega$  into a solid angle  $d\Omega$  is given by:  $d^2I/(d\omega d\Omega) \propto (dI_e/(d\omega d\Omega)) (N_e-1)N_e |F(\omega)|^2$ , 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” [2,3]. If a pre-bunched beam is used i.e. beam consisting of  $M$  micro-bunches separated by interval  $\Delta t$  the  $F(\omega)$  is:  $|F(\omega)|^2 = |F_1(\omega)|^2 G_M(\omega, \Delta t)$ , where  $F_1(\omega)$  is the form factor of a single micro-bunch. The form factor  $|F(\omega)|$  which is measured during the experiments, is modulated by an oscillating function  $G_M(\omega_i, \Delta t)$  depending on the number of parameters including micro-bunch spacing. Indeed the behavior of the modulation function will depend on the charge distribution, individual bunch spacing and individual bunch longitudinal profile. In particular, non-uniform charge distribution or micro-bunch separation will affect, for example, the depth of modulation. The analysis of this function at a single frequency will only provide information about periodicity of the train i.e. main Fourier harmonic. However, this information can be essential and sufficient for a number of applications including high power THz radiation generation.

Let us note that in case of  $M$  identical, equally spaced micro-bunches, the oscillating function  $G_M(\omega_i, \Delta t)$  has a simple form  $G_M(\omega_i, \Delta t) = \frac{\sin^2(M\omega\Delta t/2)}{M^2 \sin^2(\omega\Delta t/2)}$ . In this work for clarity reason, we consider the most basic and fundamental case of two identical micro-bunches, equally distanced from each other i.e.  $M=2$ . If the measurements are made at a single, fixed frequency of interest  $\omega_i$ , (fig.1) any changes in the interval  $\Delta t$  between micro-bunches will lead to amplitude variation of  $G_2$ ; this will be referred as multi-bunch signal modulation (MBSM). In particular, the MBSM function can be measured via measurements of the intensity modulation of the coherent Smith-Purcell radiation (cSPr) allowing to monitor the distance between the micro-bunches non-destructively. In figure 1a the experimental set up is shown. The experiments were performed at the Laser Undulator Compact X-ray source facility (LUCX) at KEK (High Energy Accelerator Research Organization, Japan) [4]. Two identical, 8 MeV, 30pc electron micro-bunches with  $\sigma_{\perp} \sim 250\mu\text{m}$  were generated directly from a photocathode by illuminating it with a series of femtosecond laser pulses. The micro-bunches are emitted sequentially and the initial distance between them was determined by the separation of the laser pulses. The experiments were carried out using a 1mm period grating, which was positioned at 0.7mm from the beam. The coherent Smith-Purcell radiation (cSPr) emerged from the vacuum chamber through the sapphire window and was collected by pair of off-axis parabolic mirrors positioned so as to collect the radiation at 90 degrees (normal to the grating) (fig.1a). The frequency measurements were done with a Michelson interferometer and the radiation frequency was measured to be 300GHz (fig.1b). By changing the distance between laser pulses the distance between micro-bunches was changed leading to variation of MBSM function. Using the relation shown above the interval between micro-bunches  $\Delta t = G_2^{-1}(\omega_i)$  was calculated. In figure 1c the results are shown for the set of distances and the dashed line indicates theoretical prediction, while the solid line shows the experimental measurements. In conclusion, we discussed and demonstrated basic operational principles of a new monitor based on analysis of coherent signal amplitude modulation generated by the pre-bunched electron beam and a good agreement was demonstrated.

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