INVESTIGATION OF COHERENT DIFFRACTION RADIATION IN RESONANT CONDITIONS FOR DEVELOPING OF AN INTENSE MONOCHROMATIC RADIATION SOURCE

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Abstract

The motivation for intensive THz source development at KEK LUCX is coming from the growing interest to THz radiation from various scientific communities worldwide. High gradient photo-cathode RF gun and few tens of femtosecond laser system are used to generate a pre-bunched electron beam of a few hundred femtoseconds. Here we report the production of the intense quasi-monochromatic Coherent Diffraction Radiation (CDR) in the range of 0.3 – 0.5 THz generated by micro-bunched 8 MeV electron beam. Usually CDR is generated in a broad spectral range when a charged particle moves in the vicinity of a conductive target edge or through a slit. When radiation wavelength is comparable to or longer than the bunch length it becomes coherent and even more, it enters a "super-radiant" regime if micro-bunch spacing became comparable with radiation wavelength. In case of pre-bunched electron beam, it is possible to obtain quasi-monochromatic CDR spectrum. In this reports the status of the experiment, electron beam characterization, and the evidence of quasi-monochromatic CDR detection will be presented.

INTRODUCTION

Intense THz radiation sources are widely used for different applications [1]. However, the problem of designing of a non-expensive, compact, wide-range tunable short pulse duration THz sources is not yet solved. A few approaches to design such a source on the basis of laser technologies and electron beam accelerators are now extensively discussed [2]. Also there is a demand from a users community to achieve monochromaticity of generated THz radiation. Undoubtedly, the usage of any sort of diffractometers and bandpass radiation filters can reduce output power and introduce undesirable spectra distortions. In this respect the THz source based on Coherent Diffraction radiation (CDR) mechanism when generated by a THz sequence of a short electron bunches is promising due to quasi-monochromatic emission which can be understood through analysis of the longitudinal form-factor. Longitudinal form-factor or bunching factor $F(\omega)$ is the Fourier transform of the longitudinal particles distribution and was first introduced in [3] when the total emitted power of coherent radiation P was considered.

$$P(\omega) \propto \frac{dW}{d\omega d\Omega} F(\omega) N^2, \tag{1}$$

where $dW/d\omega d\Omega$, $F(\omega)$, ω, and N are the power emitted by a single electron into a unit solid angle in unit frequency range, bunch form-factor, radiation frequency, and number of electrons per bunch respectively. Single Gaussian bunch longitudinal form-factor can be written as:

$$F(\omega) = \left(\left| \exp\left(\frac{-\omega^2 \sigma_z^2}{\beta^2 c^2} \right) \right| \right)^2, \tag{2}$$

where σ_z is the rms bunch length, β - reduced electron velocity and c is the speed of light. It can be generalized to account for N_b arbitrary spaced (λ_j - j-th bunch spacing) micro-bunches with different bunch lengths σ_z^j as [4]:

$$F(\omega) = \left(\left| \frac{\sum\limits_{j=0}^{N_b-1} A_j \exp\left(\frac{-\omega}{c\beta} \left(\frac{\sigma_z^{j\,2}}{4} \frac{\omega}{c\beta} + ij\lambda_j \right) \right)}{\sum\limits_{j=0}^{N_b-1} A_j} \right| \right)^2. \tag{3}$$

where A_j are normalization factors linearly proportional to bunch charges and i is imaginary unit.

The proposal to use CDR generated by a train of short electron bunches as the basis of THz radiation source was made by authors of the work [5]. Certainly, the important characteristic of such source is its monochromaticity. The radiation monochromaticity generated by infinite number of microbunches is $\Delta\lambda/\lambda \propto \frac{1}{kN_b}$, where k is the spectral order. In reality, however the usage of the infinite amount of bunches is not practically possible. Also, individual bunch parameters if accelerated on a single RF cycle are different what leads to radiation spectrum broadening as can be seen at Fig. 1. Calculations of $F(\omega)$ were performed using

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ASTRA-simulated micro-bunched beam parameters in experimental chamber. Hence the main objective of this paper is to show a possibility to produce CDR with a certain degree of monochromaticity by using a THz sequence of relativistic electron micro-bunches.

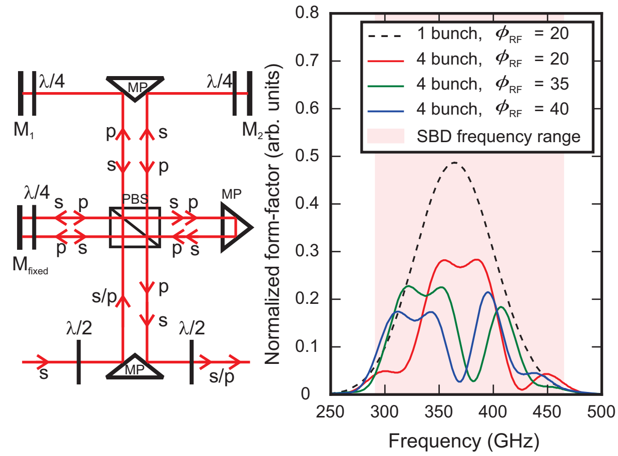

Figure 1: *Left*: Schematics of the laser twofold Michelson interferometer. *Right*: $F(\omega)$ normalized by SBD frequency response, calculated for different RF gun injection phases and number of micro-bunches.

EXPERIMENTAL RESULTS

The measurements were done at the Laser Undulator Compact X-ray facility (LUCX) at High Energy Accelerator Research Organization (KEK), Fig. 2. LUCX is a multipurpose

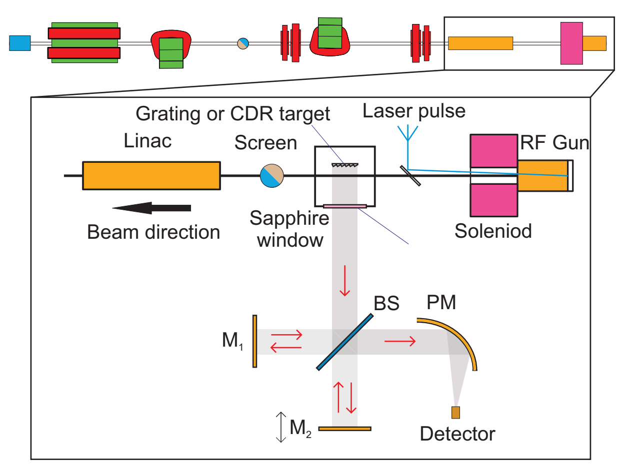

Figure 2: LUCX beamline and experimental schematics. Abbreviations: M_1 - fixed interferometer mirror, M_2 - movable interferometer mirror, *BS* - 300μm-thick silicon beam splitter, *PM* - off-axis parabolic mirror.

linear electron accelerator facility initially constructed as a RF gun test bench and later extended to facilitate Compton scattering [6] and coherent radiation generation [7] experiments. It consists of RF gun [8], which was designed to produce a multi-bunch (2.8ns separation) high quality electron beam with up to 1000 bunches, a 0.5 nC charge per bunch, and ~ 10 MeV beam energy. This beam can be then accelerated to 30 MeV by the normal conductivity compact linear accelerator [9]. Two klystrons are used for the RF gun and accelerating structure. Also, two laser systems: picosecond Nd:YAG and femtosecond Titanium-Sapphire were employed for different LUCX operation modes.

Table 1 summarizes electron beam parameters in femtosecond operation mode. Short electron bunches were generated in the RF gun via photocathode illumination by the femtosecond laser pulses with wavelength of about 266 nm. These laser micro-pulses were produce by twofold Michelson interferometer, Fig. 1, installed in the laser system [10, 11]. Generated electron bunches were accelerated to the energy of approximately 8 MeV in the 3.6 cell RF gun. The experiment was performed with the beam parameters given in Table 1. The number of micro-bunches was varied from 1 to 4 by blocking laser interferometers arms. The longitudinal electron bunch separations were changed by varying the RF gun injection phase and were confirmed by the method described in [9]. Schottky barrier diode detector with spectral sensitivity 320 – 460 GHz was used in the experiment. Detailed parameters list is shown in Table 1.

Table 1: LUCX Beam Parameters in fs Operation Mode and SBD Detectors Characteristics

Beam energy, typ.	7 MeV
Micro-bunch charge Q and stability	25 pC, 6 %
Number of micro-bunches,	1,2,4
Bunch length, for given Q	250 fs
Normalized emittance, $\epsilon_x \times \epsilon_y$	1.5×1 πmm mrad
SBD parameters	
Frequency range	320 – 460 GHz
Wavelength range	0.94 – 0.65 mm
Response time	~ 250 ps
Antenna gain	25 dB
Input aperture	4×4 mm
Video sensitivity	1250 V/W

The vacuum chamber was equipped with the sapphire vacuum window which provided aperture of 145 mm. 5-axis manipulator was used for fine adjustment of the target's position in 3 orthogonal directions and in two rotation angles with respect to electron beam propagation direction. In the case of CDR geometry, the distance between target and the electron beam was set to 0.6 mm. The radiation spectral characteristics were measured by the Michelson interferometer (described in [12]) installed directly in front of the chamber vacuum window (see Fig. 2). To generate coherent Diffraction radiation the 60×30 mm flat target was placed in the vacuum chamber.

At first, performance of the laser splitting interferometer was confirmed. It was set to produce 2 micro-pulses. The time delay between them was changed by M_2 and the 800 nm pulse energy at the output of the laser system along with the UV pulse energy near the RF gun were measured. As the laser M_2 provides $\pm 600\mu$m ($\pm$2ps or $\pm 2^\circ$ S-band RF) longitudinal delay between pulses it does not significantly changes pulse-by-pulse energy when pulses are not overlapped, Fig. 3. In case of the overlap, micro-pulses can not be longer separated and moreover, starting to produce a longitudinal interference with a period of 800nm.

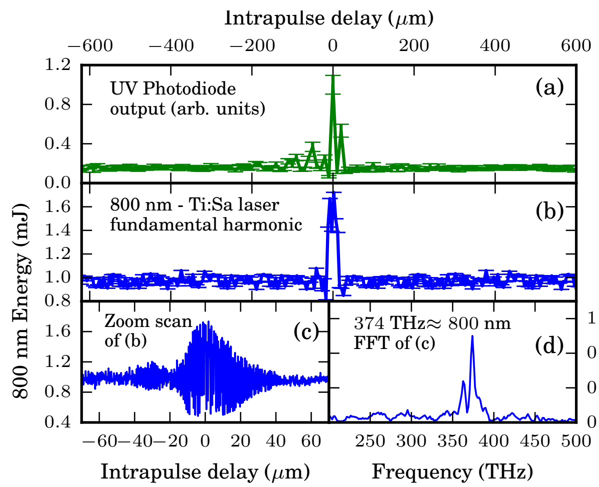

Figure 3: Laser pulse splitting characterization. Two pulse total UV pulse energy *(a)* and Ti:Sa fundamental harmonic energy *(b)* as a function of intrapulse delay. Fine delay step scan *(c)* and its Fourier spectrum *(d)*.

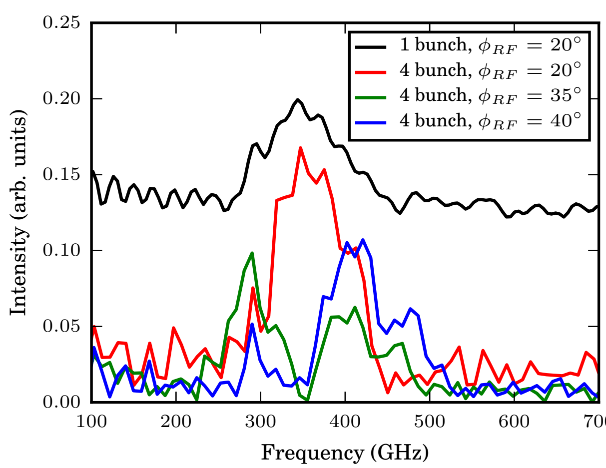

Figure 4: CDR measured spectra in the range of 320 – 460 GHz. Single bunch spectra is artificially shifted upwards for better visibility.

The CDR spectrum emitted by a single electron is assumed to be constant within detector sensitivity band. Therefore, the measured 1-bunch normalized CDR spectrum Fig. 4 was used as a spectral efficiency of entire measurement system, including spectral transmission efficiency of the vacuum window, detector wavelength efficiency, and so on. The spectral measurements by means of Michelson interferometer were done at the maximum of CDR orientation dependence. To obtain spectra from auto-correlation measurements Fourier Transform algorithm was used.

Four micro-bunch normalized CDR spectra measured in a range of 320 − 460 GHz for a different RF gun laser injection phases are also shown in Fig. 4. It is clear that for $\phi_{RF} = 35^\circ$ and 40° measured spectra have definite dip around 360 GHz what agrees well with form-factor simulation. It is important to mention that bunch separations are ramped down as 2127μm, 1919μm, and 1665μm for $\phi_{RF} = 35^\circ$ and 2181μm, 1981μm, and 1742μm for $\phi_{RF} = 40^\circ$. Also charges A_i and σ_z^i are changing with variation of ϕ_{RF} but in a much smaller ranges. As one can see, the spectral peak measured with 4 micro-bunches demonstrates spectral narrowing which can be increased by increasing a number of micro-bunches, its charge and further tailoring of ϕ_{RF}.

CONCLUSION

We have investigated micro-bunch generated coherent Diffraction Radiation spectral characteristics both theoretically and experimentally. Our experimental apparatus includes the Michelson interferometer with SBD detector. We have compared intensities and spectra of single- and multi-bunch CDR measured in identical conditions and showed that it is possible to achieve quasi-monochromatic CDR emission. Some adjustment of CDR line width can be obtained by further manipulation of bunch spacings.

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