PROGRESS TOWARDS TABLETOP PRE-BUNCHED THZ FEL

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Abstract

The motivation for developing a linac-based THz source at KEK LUCX is coming from the growing interest to THz radiation and a possibility to utilize it for soft X-ray production via inverse Compton scattering. We have proposed two approaches to produce the intense radiation beams in the range of 0.1-5 THz based on Coherent Smith-Purcell Radiation and Coherent Undulator Radiation in "super-radiant" regime on a 8 MeV and 30 MeV electron beam at KEK LUCX facility respectively. First radiation type is generated when a charged particle moves in the vicinity of a periodical pattern or grating. When radiation wavelength is comparable to or longer than the bunch length it becomes coherent. Similar radiation enhancement is happening when micro-bunch period coincided with undulator period. To produce such a micro-bunch train of electrons a new Ti:Sa laser system for LUCX RF gun has been developed and electron micro-train has been confirmed. In this report the status of the experiment, Ti:Sa laser system modification, CSPR and CUR basic properties and electron beam characterization will be presented. The maximum achievable THz power from both approaches will also be discussed.

1. Introduction

In the last decade electromagnetic radiation in the terahertz frequency range is widely used in time-domain spectroscopy to understand biological processes, for THz imaging and chemical reactions [1]. Much of the recent interest in high-brightness coherent THz light source (0.1 – 5 THz) radiation associated with its ability to penetrate deep into many organic materials without the damage produced by ionizing radiation such as X-rays and gives a breakthrough in the rapidly expanding field of THz photon science. Usual expectation from THz users community is a high brightness (high photon flux, density and short duration), wide spectrum tunability and compactness as well as low cost of the system. There are a few effective ways to construct such a THz source using particle accelerators. Most common way is to utilize high charge bunched relativistic electron beam after compression to produce various types of coherent polarization radiations (Transition, Diffraction and so on). In this case one needs to maintain large accelerator complex and carefully control initial beam parameters as well as bunch compression. As a result it is possible to obtain high intensity radiation pulses of a wide spectrum in exchange of the overall system complexity.

Another approach is to generate short electron bunches directly illuminating an RF gun photocathode with femtosecond laser pulses. In this case space-charge dominated beam properties should be taken into account and to obtain similar THz pulse intensity it is necessary to consider several measures to enhance radiation power.

One of the most effective ways is to make radiation emission "super-radiant". This term was introduced a while ago [2, and references therein] and attribute to the case when coherent radiation emission is made by a sequence of electron bunches, so-called comb beam. Indeed, the intensity of the coherent radiation is proportional to the number of particles per bunch squared, but for a comb electron beam (THz sequence of a several tens fs-length electron bunches) it also multiplies by the number of micro-bunches. This would not give much of a gain if there was no spectral modulation in this case. In the reality it is expected that coherent spectrum will become discrete and peak power will scale exponentially as a number of electrons.

The second most effective way is to accumulate radiation from many comb bunches or even machine cycles in some kind of enhancement cavity. It will give further spectral shaping and the total radiation power gain will depend on the cavity quality factor. The proof-of-principle experiment on radiation accumulation was already performed [3] at LUCX "FEM experiment" section, Figure 2.

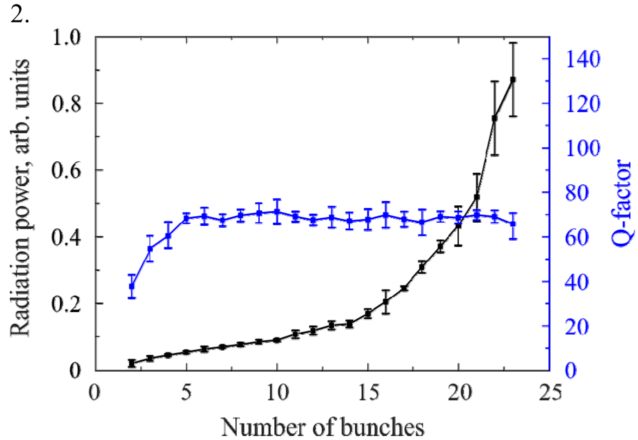

Figure 1: Dependence of radiation intensity (black dots) and quality factor (blue dots) of the cavity for every acquisition on the number of bunches.

At that time the first observation and investigation of the Stimulated Coherent Diffraction Radiation (SCDR) in an

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open resonator as a possible mechanism for the generation of intense THz radiation beams for numerous applications were presented, Figure 2. The detailed investigation of the radiation stored in the resonator cavity as well as the cavity intrinsic properties was measured. We clearly observed the stimulation process as an exponential growth of radiation power stored in the resonator as a function of the number of bunches in the train. Nowadays we are planning to resume THz enhancement cavity study both at LUCX and cERL [4].

Combining these two techniques together it is possible to construct tabletop THz FEL where a femtosecond comb beam is accelerated by a RF accelerating field with gradient of the order of 50MV/m while carried on a single RF accelerating field cycle enabling it to be accelerated to 5MeV in a 7.5cm RF gun. When such a comb beam is passed in the vicinity of a periodical structure or through short edge-focusing wiggler [5] it generates Coherent Smith-Purcell Radiation (CSPR) or Undulator radiation (UR) in "super-radiant" regime if micro-bunch spacing becames comparable with radiation wavelength which is comparable to the grating or undulator period. Our plan is to develop and apply an accelerator based ultra-compact high-brightness coherent THz light source, with short pulses of ~10MW peak power, variable frequency range from 0.3 to 5THz, and typical energy 10uJ/pulse [6]. It was decided to investigate the CSPR and UR as a potential candidate for generating intense broad-band radiation in THz frequency range as a part of a larger THz program launched at KEK: LUCX (Laser Undulator Compact X-ray project) facility. The program is aiming to investigate various mechanisms for generating EM radiation including Undulator radiation, Smith-Purcell and other special cases of Polarization Radiation. In this report the status of the experiment, LUCX RF Gun Ti:Sapphire laser system and Comb beam generation will be presented.

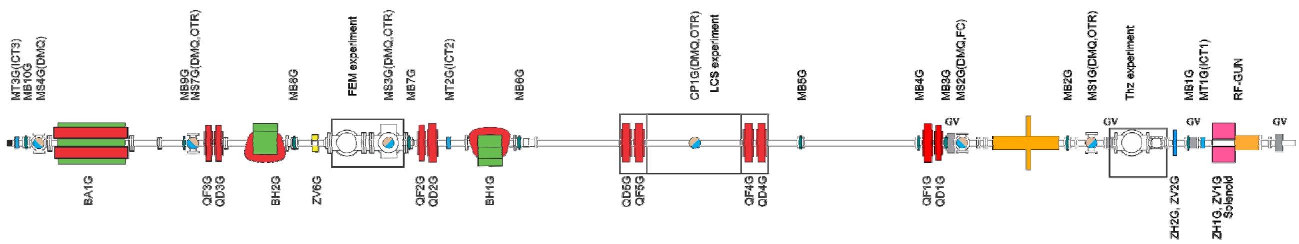

Figure 2: LUCX accelerator schematics.

To establish femtosecond comb electron beam generation the experimental setup for the observation and investigation of the different types of polarization radiations was constructed at LUCX facility in KEK [7]. LUCX is a multipurpose linear electron accelerator facility initially constructed as a RF gun test bench and later extended to facilitate Compton scattering and coherent radiation generation experiments. It consists of a high mode separation 3.6 cell RF gun, which was designed to produce a multi-bunch high quality electron beam with up to 1000 bunches, a 0.5 nC bunch charge, and 10 MeV beam energy. This beam can be then accelerated to 30 MeV by the normal conductivity 1 m 12–cell mode–separated linac booster.

Table 1: LUCX Parameters in fs Operation Mode

Parameter	Values
Beam energy, typ.	8 MeV
Intensity/4 micro-bunches	100pC
Number of micro-bunches, max	16
Bunch length, max	1 ps
Bunch length, min	50 fs
Repetition rate, max	3.13 train/s
Normalized emittance, ε_x x ε_y	4.7x6.5 πmm mrad

Two klystrons (Toshiba E 3729 and Toshiba E3712) are used to independently feed RF gun and accelerating structure. Also, two laser systems: picosecond Nd:YAG and femtosecond Titanium-Sapphire were employed to make possible different LUCX operation modes. Table 1 summarizes electron beam parameters usually obtained in femtosecond operation mode of the LUCX. Figure 1 shows LUCX beamline schematics.

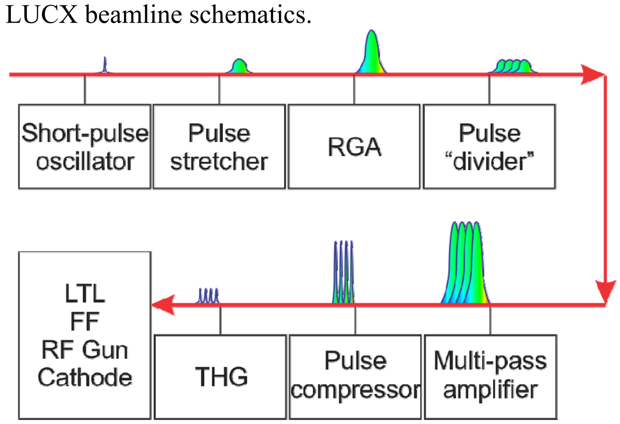

Figure 3: CPA technique: the pulse from the oscillator is stretched, amplified and recompressed to its original duration.

To generate a sequence of femtosecond micro-bunches the well-established Titanium-Sapphire Chirped Pulse Amplification (CPA) echnique laser system was chosen, Figure 3. Short pulses of a few tens femtoseconds from the oscillator are temporarily stretched to a picosecond level before they are amplified in Regenerative Gain Amplifier

(RGA) up to a few μJ. We have introduced "pulse divider" (PD) right after the RGA so pulses are splitted and recombined with controllable delay by the double–pass Michelson interferometer. This minor modification allows generating sequence of a spectrally chirped picosecond pulses with variable time separation. After that they are amplified up to 2 mJ per micro–pulse by the multi-pass Ti:Sa amplifier and re-compressed back to a few tens femtoseconds. This is possible due to the same micro–pulses polarizations after multi–pass amplifier. As a result 1.3 mJ of each micro-pulse energy at Ti:Sa fundamental harmonic was available at the laser system output. Also the laser system was extended to allow direct measurement of a generated micro–pulse durations and its time separations by the method based on the registration of the second harmonic energy cross distribution produced in nonlinear crystal. Resulting cross-correlations give calibrated absolute temporal measurements, which is then compared with electron beam measurements. In case of micro-pulsed input the cross-correlation dependence has an additional two peaks (for two micro-bunches) and six peaks (for four micro-bunches) symmetric around the main correlation. The time separation between main correlation and the satellite peak is equal to the real time separation between micro–pulses, Figure 4.

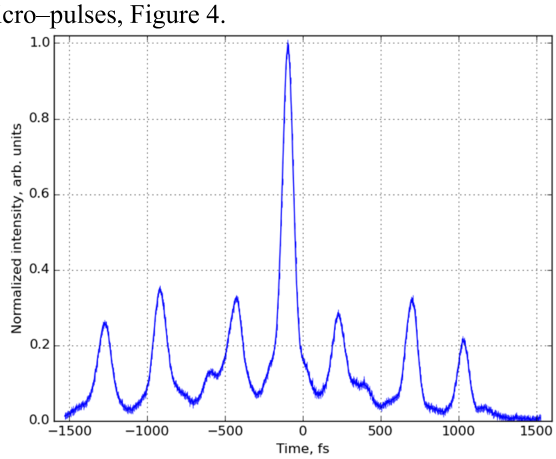

Figure 4: Four laser micro-pulse cross-correlation.

For successful accelerator operation in femtosecond mode a well-established on-line diagnostics and control of the laser beam and electron beam are needed. To confirm electron beam parameters the quasi–ballistic electron optics was designed. This optics makes 5 mm horizontal dispersion at the MS3G 300 μm–thick DMQ screen which is located beyond BH1G bending magnet after the linac booster. Calibrating transverse electron density distribution by BH1G dipole magnet current change we have measured initial electron beam center–of–mass energy is equal to $E = 8.25 \pm 0.002$ MeV and energy spread is $dE = 18.8 \pm 0.2$ keV, i.e. dE/E □ 0.2%.

The rms electron bunch length is measured by the zero-phasing technique [8]. To estimate bunch length the correlation of the RF phase with image centroid shift on MS3G screen was measured. The linear approximation of this correlation effectively gives scale of the horizontal image size in RF degrees, what in turn can be recalculated to the time scale. Our measurements show that the response time of the Cs_2Te photocathode is of the order of □ 250 fs. Detailed report already submitted for publication in peer-reviewed journal and will be published soon.

To demonstrate comb beam generation possibility we have acquired four micro–bunch electron density distribution measured at MS3G DMQ screen by RF zero-phasing technique, Figure 5. Image clearly shows four 250 fs bunches separated by approximately 500 fs what is consistent with Figure 4. Right now repetition rate of this comb is limited by Ti:Sa laser system and can not be faster than 10 Hz. In order to overcome current limitation one needs to consider new CPA laser system (presumably fiber-based) with micro-bunching capability.

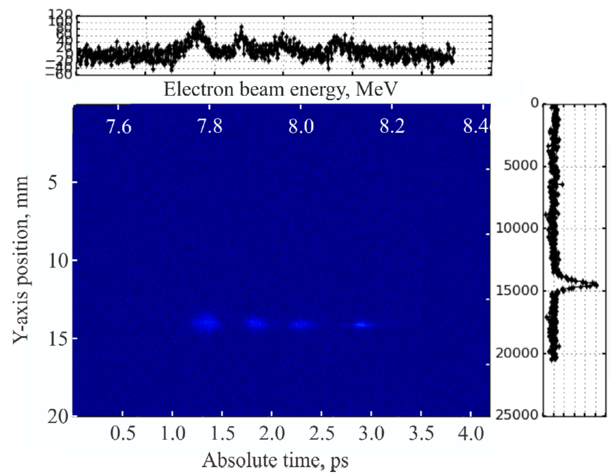

Figure 5: Four micro–bunch electron density distribution measured at MS3G DMQ screen by RF zero-phasing technique.

Nevertheless our result further widens the potential of designing a table-top tunable THz FEL based on super-radiant coherent radiation. With no doubts space-charge effects play a fundamental role in preservation of the temporal structure of the comb electron beam and limits the maximum achievable beam charge. The further work on higher charge per bunch is desired for strong THz radiation generation. It can be done by increasing of the RF gun acceleration gradient and optimization of the laser spot size at the photocathode. Also detailed comparison of zero-phasing measurements with these based on THz spectral measurement system (Michelson interferometer for spectrometry of intense broadband radiation in THz frequency range and bunch shape reconstruction [9]) is foreseen in nearest future. The work on super-radiant undulator radiation properties simulation and its comparison with CSPR is also ongoing.

Further details on the project progress will be published in successive papers.

Acknowledgements

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