# DEVELOPMENT OF ADVANCED THz GENERATION SCHEMES AT KEK LUCX FACILITY

Alexander Aryshev #, A), Sakai Araki A), Masafumi Fukuda A), Konstantin Lekomtsev A),
Mikhail Shevelev A), Junji Urakawa A), Alexander Potylitsyn B), Kazuyuki Sakaue C)
A) High Energy Accelerator Research Organization
1-1 Oho, Tsukuba-shi, Ibaraki, 305-0801, Japan
B) Tomsk Polytechnic University, Tomsk, 634050, Russia
C) Research Institute for Science and Engineering, Waseda University
3-4-1, Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan

*Abstract*

The motivation for developing a linac-based THz source at KEK LUCX is coming from the growing interest to THz radiation. High gradient photo-cathode RF gun and few tens of femtosecond laser system can directly generate a pre-bunched electron beam of a few hundred femtoseconds. We have proposed a new approach to produce the intense beams in the range of 0.1-5 THz based on Coherent Smith-Purcell Radiation (CSPR) in “super-radiant” regime on a 8 MeV electron beam at KEK LUCX accelerator. CSPR is generated when a charged particle moves in the vicinity of a periodical pattern or grating. The grating type and period can be chosen to make quasi-monochromatic CSPR spectrum. The radiation is coherent when its wavelength is comparable to or longer than the bunch length. It enters a “super-radiant” regime if micro-bunch spacing becomes comparable with radiation wavelength which is comparable to the grating period. To produce such a micro-bunch train of electrons a new Ti:Sa laser system for LUCX RF Gun has been developed. In this report the status of the experiment, Ti:Sa laser system, CSPR basic properties and vacuum chamber with manipulation system will be presented.

## 1. Introduction

In the last decade electromagnetic radiation in the terahertz frequency range is used in time-domain spectroscopy to understand biological processes and to create two- and three-dimensional images. 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. These properties can be applied in process and quality control as well as biomedical imaging [1] and homeland security. Terahertz radiation can also help scientists understand the complex dynamics involved in condensed-matter physics and processes such as molecular recognition and protein folding.

Nowadays there are a few ways to generate intense beams of THz radiation: optically pumped terahertz lasers [2], photomixing of near-IR lasers [3], backward-wave oscillators [4], and direct multiplied sources [5]. Other promising candidates are nonlinear optical processes occurring when an intense laser beam interacts with a material medium [6] and generation of a short and high-brightness THz-frequency coherent radiation pulses using ultra-short electron bunches in a compact accelerator.

The intensity of the coherent radiation is proportional to the number of particles per bunch squared. For a stable THz emission one should consider stable generation of an electron bunches with duration smaller than 100 fs (about 30μm). In more advance schemes it is possible to use a micro-train electron beam (THz sequence of a several tens fs-length electron bunches) what in turn requires photocathode irradiation with a femtosecond laser pulse train of ~10 pulses. When a femtosecond electron bunch train (Comb beam) is accelerated by a radio-frequency (RF) accelerating field with gradient of the order of 50MV/m it is 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 grating it generates Coherent Smith-Purcell Radiation (CSPR) in “super-radiant” regime if micro-bunch spacing became comparable with radiation wavelength which is comparable to the grating 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.

It was decided to investigate the CSPR 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, CSPR basic properties and vacuum chamber with manipulation system will be presented.

# alar@post.kek.jp

## 2. Coherent Smith-Purcell Radiation

Smith – Purcell Radiation (SPR) was predicted over half century ago by Frank and Salisbury [7, 8]. In 1953 Smith and Purcell experimentally showed that when an electron passes close to a metallic diffraction grating it induces a charge on the grating surface which gives rise to a radiation spatially distributed in a certain way. The fundamental wavelengths were defined by the following dispersion relation [9]:

$$\lambda = d(\beta^{-1} - cos\theta)$$

, where λ is the wavelength of the observed radiation, *d* is the grating period, $\theta$ is the radiation emission angle and $\beta = v/c$ is the speed of a charged particle in term of the speed of light. According to the theoretical study by Toraldo di Francia [10] the intensity of SPR, *U*, generated as a result of the charged particle passage in the vicinity of the grating depends exponentially on the impact parameter *h* (the shortest distance between the particle and the grating):

$$U \sim \exp[-4\pi h/\lambda\beta\gamma]$$

Over the last decade there was a discussion regarding the enhancement of the radiation yield from an SPR grating. It was theoretically proven that SPR generated from a blind grating consisting of tilted strips separated by vacuum gaps is considerably higher compared to a flat grating (strips are parallel to a particle momentum) or a conventional grating with continuously deformed conducting surface [11].

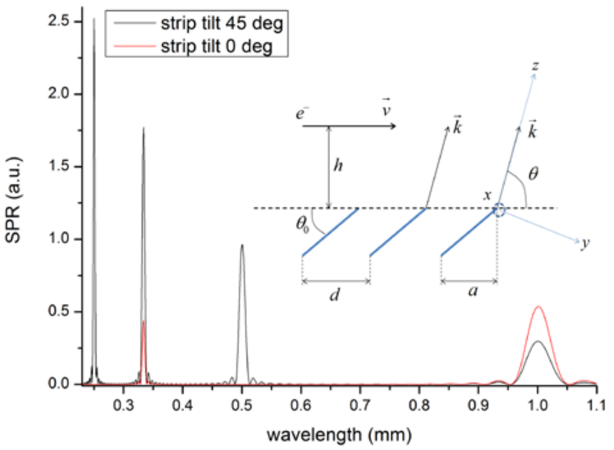


Figure 1: CSPR spectrum of a blind and a flat grating: $h = 0.15\ mm; a = \frac{d}{2} = 0.5\ mm;\ \gamma = 20;\ \theta = 90\ deg.; N_{strips} = 20;$

In order to achieve optimal performance of the radiation generation from a grating the following parameters have to be analyzed: power propagation, grating type and period, interference factor and grating structural factor. Optimizing these parameters one can modulate CSPR radiation and obtain quasi-monochromatic CSPR spectrum, Figure1.

## 2. LUCX accelerator

The experimental setup for the observation and investigation of the CSPR is under construction at LUCX facility in KEK [12]. The electron beam parameters are summarized in Table 1.

Table 1: LUCX, RF Gun section beam parameters

| Parameter | Expected Values |
|---|---|
| Beam energy, typ. | 8 MeV |
| Intensity/bunch, max | 1nC |
| Number of micro-bunches, max | 10 |
| Bunch length, max | 10 ps |
| Bunch length, min | 50 fs |
| Repetition rate, max | 12.5 train/s |
| Normalized emittance, $\varepsilon_x$ x $\varepsilon_y$ | 4.7x6.5 $\pi$mm mrad |

In order to develop an advanced THz generation schemes the modification of the RF Gun laser system and modification of the LUCX beamline are required. Also a THz spectral-spatial measurement system is considered.

### 2.1 LUCX RF Gun Laser system

Currently the standard 12.5 Hz, Q-switch Nd:YAG RF Gun laser system is used. It produces train with up to a few thousand 266nm, 10 uJ/pulse, 7ps laser pulses [13]. This laser system is capable to generate a multibunch electron beam and is used for the Compton experiment [14]. To generate high-intensity THz coherent radiation one need to illuminate an RF-Gun cathode with a femtosecond laser pulses and therefore another laser system was needed.

We choose well-established commercially-available Titanium-Sapphire laser technology to construct a femtosecond laser system for the RF Gun. This system is based on the so-called "Chirped Pulse Amplification" (CPA) technique [15], Figure 2.

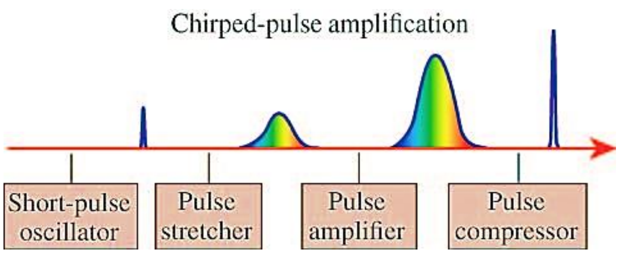


Figure 2: CPA technique: the pulse from the oscillator is stretched, amplified and recompressed to its original duration.

The system amplifies pulses from the Ti:Sapphire Oscillator and consists of the stretcher, regenerative amplifier and the 10 Hz multi-pass amplifier with the joint pump laser, and the compressor. Short pulses of a few tens femtoseconds from the laser oscillator are stretched in time to a few picoseconds before they are amplified in two stages up to 20 mJ of energy. After that they are re-compressed back to a few tens femtoseconds. As a result 16 mJ of pulse energy or 0.4 terawatt of optical power at Ti:Sa fundamental harmonic (FH) is available at the laser system output. This value is rather high to generate electron beam, but we deliberately made it to have a good margin for pulse stacking [16], Third Harmonic (TH) Generation [17] and possible loses along the Laser Transport Line (LTL). The laser beam parameters are summarized in Table 2.

Table 2: LUCX Ti:Sa laser beam parameters

| Parameter | Expected value |
|---|---|
| Repetition rate, max | 10 Hz |
| Pulse energy after compression FH/TH, max | 16/1.2 mJ |
| Pulse duration, FH/TH | 35/50 fs |
| Energy stability TH, RMS | <1.5% |
| Contrast @ 10 ps | $<1.10^{-4}$ |

For successful accelerator operation in femtosecond mode a well-established on-line diagnostics and control of the laser beam are needed. To monitor ultra-short FH laser pulses the method based on the registration of cross distribution of Second Harmonic (SH) energy produced in nonlinear crystal under non-collinear interaction of two beams with determined aperture [18] is used. For TH pulse duration monitoring the diagnostics based on two-photon absorption phenomena [19] is under development.

Further details concerning the choice of laser pulse stacking techniques, Ti:Sa THG and LTL design and diagnostics will be published in successive papers.

## 2.2 LUCX beam line

Vacuum chamber for THz study will be installed right after LUCX RF Gun, as can be seen in Figure 3.

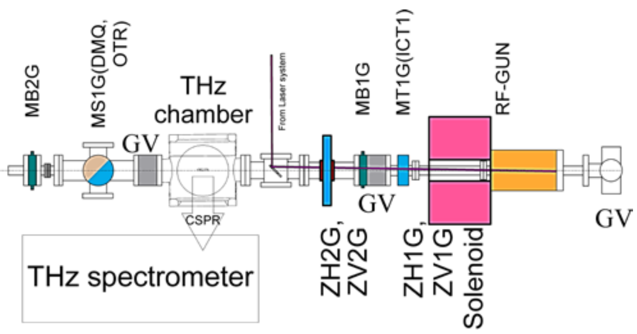


Figure 3: General design of the vacuum mirror mount

The LUCX beamline did not require significant modification. Beam position, profile and charge diagnostics was built around THz vacuum chamber. Also two Gate Valves (GV) were installed in order to isolate the RF Gun and downstream accelerator section to make THz generation targets replacement easy.

## 2.3 THz chamber and manipulator design

To position CSPR targets with respect to electron beam a high-precision motorized in-vacuum multi-axes (XYZ linear, rotation in X-Z and Y-Z planes) manipulation system [20] was designed. The system is installed into 6-way cross vacuum chamber (Figure 4) which has two side ICF203 vacuum flanges to mount THz transparent vacuum windows.

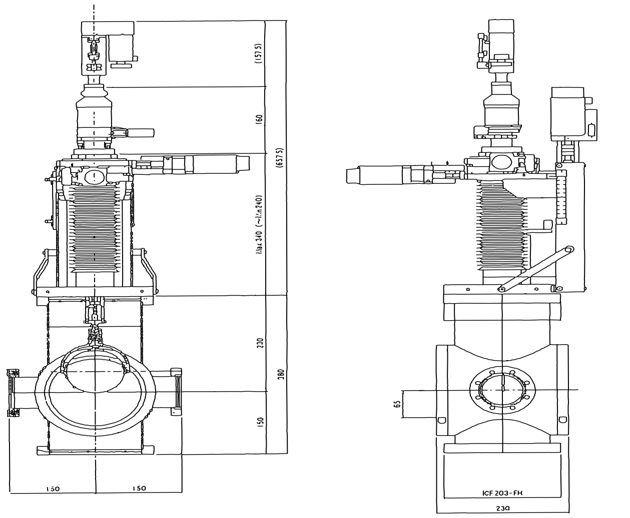

Figure 4: General view of the microwave cavity with two manipulators

The special vacuum mount was designed to accept 100 mm diameter and minimum 3 mm thickness CSPR targets. It has one manual linear (±1.5 mm in Y-Z plane) adjuster, Figure 5.

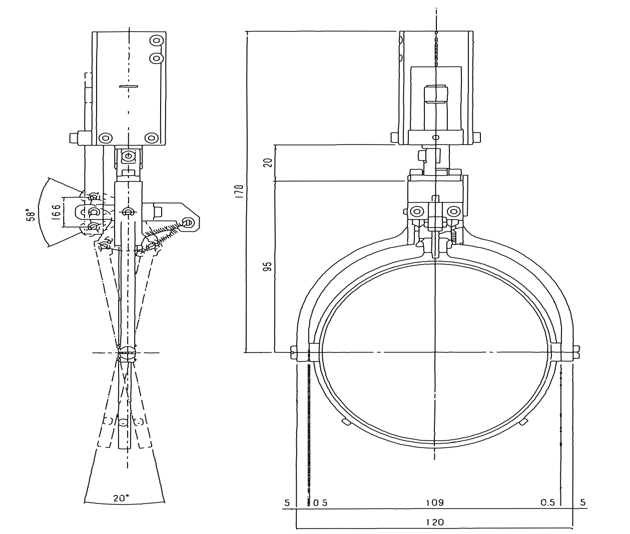

Figure 5: General design of the vacuum mirror mount

Adjuster is made in order to align the front plane of the target with respect to the rotation axis of the manipulator.

## 3. THz spectral-spatial measurement

In order to optimize THz generation mechanism it is necessary to have bunch length monitor and THz spectral measurement system. Both monitors are based on the radiation spectral measurement and consecutively can be combined. From this point of view it is critical to construct a reliable THz spectrometer.

We are considering a step-by-step approach to achieve our goals. The first step was to construct Michelson interferometer as a potential candidate for spectrometry of intense broadband radiation in THz frequency range and bunch shape reconstruction. After that the THz spatial distribution measurement system will be installed to fully characterize generated CSPR.

## 4. Conclusion and future plan

To date the progress in every direction of this project is on-going. In parallel to hardware and software work we are forming an international THz collaboration network with leading Universities from Japan and Europe.

## Acknowledgements

The work was supported by the Quantum Beam Technology Program of the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) and SASAKAWA foundation (Grant No. 3875), JSPS KAKENHI Grant No. 23226020, and program “Advancement of the scientific potential of high education” by Russian Ministry of Education and Science No. 2.1799.2011

## References

[1] D. Arnone, et al. Proc. SPIE Terahertz Spectroscopy Applications I, International Society for Optical Engineering: Bellingham, WA, 209, 1999.

[2] M.Inguscio,et al., Journal of Applied Physics , vol.60, no.12, 161, 1986.

[3] A. Andronico,et al., Optics Letters, Vol. 33, Issue 21, pp. 2416-2418, 2008

[4] G. Kantorowicz, et. al., Infrared and millimeter waves. vol 1 (A80-18951 05-33) New York, Academic Press, Inc.,185-212, 1979.

[5] E. Mueller, The Industrial Physicist, august/september 2003

[6] S. Bielawski, Nature Physics 4, 390 – 393, 2008

[7] I. Frank, Izv. Akad. Nauk. SSSR, Ser. Fiz. 6, 3, 1942.

[8] W. Salisbury, U.S. Patent No. 2, 634, 372, 26 October 1949.

[9] S. Smith and E. Purcell, Phys. Rev. 92, 1069, 1953.

[10] G. T. di Francia, Nuovo Cimento 16, 61, 1960.

[11] A.P. Potylitsyn, NIM B 145, 60, 1998.

[12] M. Fukuda, et. al., Nucl. Instrum. Methods Phys. Res., Sect. A 637, S67, 2011.

[13] K. Hirano, et al., NIMA, 560, 233-239, 2006.

[14] K. Sakaue, et.al., Rev. Sci. Instrum. 80, 123304, 2009.

[15] S. Backus et al., ”High power ultrafast lasers”, Rev. Sci. Instrum., Vol 69, No 3, March 1998.

[16] C.W. Siders, et. al., Applied Optics, vol. 37, no. 22, 1998.

[17] S. Chen, Proceedings of SPIE Vol. 4153, 2001

[18] C. Kolmeder, W. Zinth, W. Kaiser, Optics Communications, vol. 30, Issue 3, 453–457, 1979.

[19] Y. M. Li and R. Fedosejevs, Applied Optics, vol. 35, no. 15, 1996

[20] A. Aryshev, et.al., J. of Physics: Conf. Series 236, 012009, 2010.