Several hundred femto-second soft X-ray source in compact several meter facility

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Abstract. A compact MW peak power THz source is of high interest and possible to construct in a small accelerator facility (~2 m) by using pre-bunched FEL scheme. High gradient photocathode RF gun and few tens of femto-second laser system can directly generate a pre-bunched electron beam of a few hundred femto-seconds. Furthermore, small undulator can coherently generate MW THz photons in a few hundred femto-seconds. We are considering the reflection of the THz photons to make a collision with the pre-bunched electron beam and to generate a few hundred femto-second soft X-ray. A multi-bunch photo-cathode RF gun to generate ~10 MeV electron beam is under development. The design for the soft X-ray source is presented.

1. Introduction

The short pulse high-brightness coherent THz light source of ~0.3 to 10 THz in the intermediate zone between radio and light waves has caused a breakthrough in the rapidly expanding field of THz photon science. A photocathode is irradiated with a fs (femto-second) laser pulse train of ~10 pulses, and an fs electron bunch train (Comb beam) is accelerated by a radio-frequency (RF) accelerating field of more than ~50 MV/m. In this way, the Comb beam is carried on a single RF accelerating field, enabling it to be accelerated to 5 MeV in a 7.5 cm RF gun. When the Comb beam is passed through a small wiggler (30cm), super-radiance in the THz region arises. The objective is to develop and apply an ultra compact high-brightness coherent THz light source, with short pulses of ~10 MW which can vary between 0.3 and 10 THz with a radiation of ~10 μJ/pulse.

The peak power of ~10 MW is about 100 times that of earlier THz light sources, and comparable to the intensity of THz light generated by the 10m facilities using advanced accelerator technologies that are being developed around the world. With this light source, it is possible to substantially reduce THz time-domain spectroscopy (THz-TDS) measurement time, and greatly improve the accuracy of measurement. In addition, it enables the fs timescale and multi-photon absorption nonlinear science phenomena to be captured with high precision. Applied experiments using the developed device will be carried out from 2014.

The THz-FEL is a good candidate due to its characteristics of high peak brightness, short duration, and tunable wavelength. However, the need for a facility in excess of ~10 m and for substantial funds has limited THz-FEL development. Two important goals of the proposed facility are to make the THz-FEL facility compact and to increase its output radiation power. Furthermore, the compact accelerator facility for the THz photon source may have additional possibilities as a novel and interesting photon source, making this compact facility very attractive. For this reason a several hundred fs soft X-ray source facility that can be installed into a ~5m area is proposed. Figure 1 shows the proposed compact THz source using pre-bunched beam train and edge-focusing wiggler [1], which can be installed on a...
2 m long table. Later a short accelerator to generate a relatively high bright and fs soft X-ray will be added to the table-top THz light source.

Figure 1. Table-Top Short Pulse and Coherent THz Light Source.

2. Research Methods
In order to maintain the time structure of the photoelectrons generated in the RF gun, it is necessary to engage them with an RF phase that overcomes the Coulomb repulsion and in which bunch compression arises dynamically. The cathode end plate of the RF gun is fixed in the position where the high electric field of the cavity arises. If the accelerating field is an increasing phase (20 degrees) and the cathode is irradiated with 100 fs micro-pulses, the S-band (2856 MHz) RF accelerating field (130 MV/m) is changed from 44.46 to 44.68 MV/m. The subsequent photoelectrons gain a slightly larger acceleration or a dynamic bunch compression while at the same time receiving rapid acceleration. By coming close to relativistic energy, the Coulomb repulsion and Lorentz force reach equilibrium. The time difference between the beginning and end of the Comb beam is about 8 ps. The accelerating field increases to 61.03 MV/m, therefore the 8ps bunch receives about 30 % bunch compression at the RF gun exit. The electron micro-bunch structure predicted in the simulation is confirmed by CDR (Coherent Diffraction Radiation) measurement.

3. Basic Technologies
3.1. High Gradient S-band RF Gun
A laser-driven RF gun with a Cs$_2$Te photocathode has been in development at KEK since 2002. This gun has been operated as an electron source for the ATF (Accelerator Test Facility) and generates a beam with an operational intensity of up to $2 \times 10^{10}$ electrons per bunch. In 2008, a new gun incorporating all of the earlier modifications was produced for the ATF. Tests have confirmed a significant improvement of the Q value of the latest model. A typical transverse emittance of $1.3 \pi \text{mm}\cdot\text{mrad}$ at 80 MeV has been obtained under the following conditions: solenoid field of 0.18 T, beam intensity of $1 \times 10^{10}$ electrons per bunch, and RF power of 9 MW. The usual maximum accelerating gradient is 120 MeV/m for the multi-bunch beam generation [2].

We are also operating an approximately 10m long normal conducting accelerator facility [3] LUCX (Laser Undulutor Compact X-ray source) for developing the technologies on multi-bunch electron beam generation, pulse laser accumulation system and precise multi-collision. Imaging experiments for X-ray applications will be attempted and the possibilities for their applications in this facility will be confirmed in early 2012.
3.2. Multi fs Laser Pulse Train

CPA (Chirped Pulse Amplification) Titanium-Sapphire laser system will be used for this proposed experimental plan as it can generate ~10 mJ/pulse at 800 nm in the 30 to 100 fs pulse duration range. For example, the Trident laser system of Amplitude Technologies generates a 30 fs and 10mJ single pulse. By following pulse splitting and time delay methods [4], we can generate a multi-pulse laser train with pulse separation of THz wave period due to sufficient laser power. A half-wave plate rotates the S-wave by 45 degrees. PBS (Polarizing Beam Splitter) makes S-waves and P-waves by reflection and transmission. When repeated 4 times with a delay of about 500 fs, a 16 micro-bunched laser train within 7.5 psec was obtained. Figure 2 shows the generation of the multi-pulse laser train in the case of 4.

Subsequent micro-bunches create the bunching of former micro-bunches in a resonated wiggler. We need detailed research on beam loading effects due to multi micro-bunch and tuning techniques in a wiggler field created by pole-gap that makes the FEL resonate. If we accept low micro-bunch charge, say 100 pC or less, and not many micro-bunches, say 16 or less, the above research can confirm the generation of the comb beam. Also, we assume the time response of the CsI:Te cathode is same as a Cu cathode and a minimum 0.2 % QE (Quantum Efficiency). If we try to generate a total single bunch charge of 50 pC assuming 5 % conversion efficiency from 800 nm to 266 nm by nonlinear crystal, the necessary laser pulse energy is about 250 mJ.

If we assume the peak RF field gradient at the cathode surface is 100 MV/m, 200 pC total charge in a micro-bunch train and the laser injection phase 20 degrees [5], the bunching factor for 2 THz radiation is still high, 0.446 at the wiggler entrance, which is predicted by beam tracking simulation. Our simulation results indicate the necessity of a higher gradient acceleration, lower total charge and a laser injection phase of less than 20 degrees to maintain a higher bunching factor. For example, we assume the peak field gradient at the cathode surface is 120 MV/m and the laser injection phase is 20 degrees, the bunching factor is above 0.6 and the beam energy is 5.68 MeV. Also, we are considering a wiggler period length of 30 mm and 2 THz radiation (wave length 150 mm), uniform laser size on
cathode $1.0 \text{ mm} \phi$, and a total charge of 25 pC. Since a higher gradient acceleration (100 MV/m → 140 MV/m) produces a shorter bunch length and an earlier laser injection phase (20 → 10 → 1) produces a high bunching factor, the THz peak power of 100 MW will be generated by optimum tuning of the photo-cathode RF gun.

4. Soft X-ray Generation
To make the compact THz source more attractive, a booster linac and microwave cavity to generate the fs soft X-ray were added. Figure 3 shows the layout of the proposed facility. The S-band 12 cell booster linac is under manufacture and the microwave cavity is under research. Estimated soft X-ray flux is $7.5 \times 10^6$ photons/sec 10% bandwidth with 2 THz microwave.

![Figure 3. The layout of the compact accelerator for fs THz and soft X-ray generation.](image)

![Figure 4. 3.5 cell S-band RF Gun.](image)
In order to increase the photon flux of the soft X-rays, we have to increase the beam energy. So, we are manufacturing the 3.5 cell photo-cathode RF gun to get a 10MeV micro-bunch train beam. Figure 4 shows the design. After the completion of the gun, we will replace the 1.6 cell RF gun with this gun.

5. Summary
By tuning the micro-bunch spacing to the THz wavelength, it is possible to generate a narrowband coherent THz wave. Depending on whether an ideal Comb beam can be formed in the RF gun by high gradient acceleration, super-radiance peak power from the small wiggler (30 cm) reaches ~100 MW. Thus innovative THz light source applications can be developed. Also, by adding the booster linac and the microwave cavity, we can generate the fs soft X-rays for biological research applications.

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