Development of microwave and soft X-ray sources based on coherent radiation and Thomson scattering

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Abstract. Compact, high-brightness and reliable sources in the VUV and the soft X-ray region may be used for numerous applications in medicine and biochemistry. We propose a new approach to produce the intense beams of X-rays in the range of $\leq 500$ eV based on compact electron accelerator. We present our first experimental results obtained in the Laser Undulator Compact X-ray facility (LUCX) at KEK: High Energy Accelerator Research Organization devoted to the development of a compact microwave and soft X-ray source based on coherent diffraction radiation and Thompson scattering processes.

1. Introduction

Diffraction radiation (DR) appears when a relativistic charged particle moves in the vicinity of a medium (or target) with impact parameter comparable to or smaller than the electron field radius. The electron field polarizes the target atoms thereby inducing currents changing in time, which in turn give rise to DR. The radiation is emitted coherently (CDR) if the bunch length $\sigma_l$ is comparable to or shorter than the radiation wavelength ($\lambda \geq \pi \sigma_l$) [2]. In this case the CDR intensity is proportional to a square of the bunch population, $N_b^2$. When an electron beam passes through an opened resonator made of two mirrors with beam holes, the CDR generated in the system can be stored in it. If the beam is pre-bunched and the length of the resonator is equal to the bunch spacing, the CDR produced by a preceding bunch will stimulate the radiation generated by a subsequent bunch. The similar scheme was investigated in the experiment [3] where stimulated process of coherent transition radiation (CTR) from a resonator consisting of a two flat CTR targets was detected with more than 1 order of magnitude enhancement relative to spontaneous CTR.
In the suggested scheme, the CDR flux produced by the preceding bunch will scatter by the next bunch generating soft X-ray radiation (~1010 ÷ 1013 eV) via Thomson scattering process [4]. The yield of soft X-ray photons is proportional to a cubic power of the number of electrons in the bunch, N^3 [5].

An ultimate goal of our project is to create a compact soft X-ray source based on Thomson scattering of CDR using a small accelerator machine. In contrast to the conventional method based on the inverse Compton scattering of laser light [6, 7], the new method does not require neither any special timing control system, because the timing structures of the photon beam and the electron beam are strongly related to each other, nor the additional cumbersome laser system, which makes the X-ray generation program less challenging and relatively inexpensive.

The experimental results presented in this paper aim to demonstrate both the feasibility of our approach and the performance of our detection system, and also to investigate the coherent diffraction radiation produced by the electron beam generated by the Laser Undulator Compact X-ray facility (LUCX) at KEK: High Energy Accelerator Research Organization.

2. Experimental setup
The LUCX consists of an RF gun and a 3 meter long S-band accelerating tube (Fig. 1) [8]. It produces a multi-bunch electron beam with variable number of bunches (up to 100) with 0.5nC per bunch and 43MeV beam energy [9]. The main beam parameters are summarized in Table 1.

![Fig. 1. LUCX schematic layout.](image)

In the first stage experiment we measured the coherent diffraction radiation from a flat conducting target. The purpose was to evaluate the coherency of the radiation in mm-wavelength range, check any background contribution as a function of various electron beam parameters, and check our hardware performance.

| Parameter               | Value               |
|-------------------------|---------------------|
| Energy                  | 43 MeV              |
| Intensity               | 0.5nC/bunch         |
| Num. of Bunches         | 100 bunches         |
| Bunch spacing           | 2.8ns               |
| Bunch length            | 10ps                |
| Repetition Rate         | 12.5 train/sec      |
| Emittance               | 5 πmm · mrad        |
| (σx, σy) in vacuum chamber | 200μm, 60μm         |

Table 1: Electron beam parameters of the LUCX facility.

The W30mmxH30mmxT300um aluminum-coated flat silicon target mounted on an air-actuator was used to investigate the radiation properties. The minimal distance between CDR target and the electron beam was 10 millimeters which is greater than the transverse electron beam size and much smaller than the relativistic electron field radius. As a detector we used an ultrafast Schottky Barrier Diode (Fig. 2b) detector along with 30x22mm conical horn antenna. The detector parameters are:
response time ~ 250 ps, detection frequency range 60-90 GHz, typical sensitivity 1250 mV/mW (Fig. 2c), typical flatness ±2 dB. The basic principles of these detectors are described in [10, 11]. This detector provides an output voltage which is directly proportional to the input power level (Fig. 2c).

This is a room temperature zero-biased detector. That makes the detector very attractive for accelerator physics and many other applications. The SBD detector has a flat frequency response. To collect the radiation energy and to feed it to the metal–semiconductor contact, an impedance matched pyramidal horn antenna was used [12]. This antenna responds to a single mode of the radiation field only. Therefore the detector is polarization sensitive. The horn antenna has a beamwidth of 25° and a typical midband gain of 24 dBi.

![Fig. 2](image.png)

**Fig. 2.** (a) Schematic layout of the experiment side view with dimensions, (b) photograph of two SBD detectors, (c) SBD detector power calibration curve.

The radiation pulses were extracted out of the vacuum chamber through a 30 millimeter diameter fused silica window located 143 millimeter from the beam line center and reflected into the SBD detector by remotely controlled 50 millimeter diameter rotatable aluminum mirror. The mirror was used to measure CDR angular distributions. Fig. 2a shows a general geometry of the experiment. The Inductive Current Transformer (ICT2, Fig. 1) installed after a bending magnet in front of the beam dump was used to measure the electron beam charge. In order to acquire both signals simultaneously, the output of SBD detector as well as the ICT output was connected to the 1 GHz, 5 GS/s Tektronix 684C Oscilloscope.

![Fig. 3](image.png)

**Fig. 3.** Typical oscilloscope traces of (a) SBD and (b) ICT for the multi-bunch LUCX operation.

As a demonstration of the ability to monitor multi-bunch DR spikes Fig. 3 shows SBD and ICT oscilloscope traces taken simultaneously for the 16-bunch operation mode of the accelerator. It is clearly seen that we can easily resolve each CDR pulse produced by each of 16 bunches. The time...
The separation between bunches was 2.8 ns. The wide background substratum could be explained by a multiple reflections in the generation system and limited bandwidth of the Oscilloscope.

3. Results
At first we scan the RF Gun laser phase to get the maximum CDR signal (i.e. by changing the RF Gun laser phase we changed the laser arrival time on the photocathode with respect to the accelerating RF field, and, therefore, the longitudinal electron distribution in the bunch). The maximal signal on the oscilloscope at a constant charge actually corresponds to the shortest bunch length. Fig. 4a shows the dependence of the SBD signal normalized by the ICT signal versus RF Gun laser phase. As one can see the maximum of the curve corresponds to 25 degree, which is the nominal operation point of the LUCX gun and, thus, corresponds to a minimal energy spread in the bunch and a shortest bunch length.

![Fig. 4. (a) SBD output normalized by the electron beam current versus RF Gun laser phase, data taken for mirror angle 46.5 degree. (b) Dependence of the CDR intensity on the bunch charge. Data taken for 25 degree of RF Gun laser phase, 46.5 degree mirror angle.](image)

In order to show the coherent nature of registered radiation the dependence of the SBD output signal as a function of the bunch charge was measured at an optimal RF gun phase. The experimental data and the polynomial fit are shown in Fig. 4b. One may see a deviation from a quadratic dependence. One of the potential reasons is that the radiation is generated by a small fraction of the bunch (bunch core) which has some non-linear charge distribution.

![Fig. 5. SBD output normalized on electron beam current versus aluminum mirror angle, data taken for 25 degree of RF Gun laser phase.](image)
Nevertheless, taking into account detection wavelengths range and the polynomial order (1.36 in our case) the dependence presented in Fig. 4b allows us to conclude that the detected radiation is coherent. In the future we shall develop a strategy for increasing the coherency and investigate longitudinal electron distribution in a bunch.

It is worthwhile to mention that all above scans were made while the mirror angle was set to provide the maximum CDR reflection into SBD detector. To be able to set the angle correctly we measured the mirror orientation dependence (the radiation angular distribution) presented in Fig. 5. One may see that the angular distribution has a single peak. It agrees with the existing theory [3-4]. The mirror working angle was set in the maximum of the angular distribution.

4. Conclusion and future plans
We have demonstrated the status of the project on development of a novel soft X-ray source based on inverse Thomson scattering of Coherent Diffraction Radiation. We have represented the first CDR measurements at the multibunch beam of LUCX facility and demonstrated the performance of the fast millimeter wavelength range detection system based on the SBD detector. The experimental data demonstrates the feasibility of the LUCX facility for building an intense THz radiation source which can later be used for generating soft X-rays via inverse Thomson scattering process.

In the near future LUCX facility will experience a major upgrade. A new klystron producing a long RF pulse of 24 μs will be installed to create a long multi-bunch beam with 8000 bunches. The new RF gun with high mode separation and high Q value [13] is already installed to produce a high quality multi-bunch electron beam.

Nowadays two LUCX operation modes are planned. One is the low energy (5 MeV) with maximum of 8000 bunches generation. The other one is the high-energy mode (43 MeV) with a maximum of 100 bunches [14]. Both modes are very attractive for our study since the large number of produced bunches in the first mode or higher energy electrons in the second mode will result in increase of the stored radiation power in the microwave open resonator.

The resonator should have a good quality factor and one should be able to change its axis orientation in order to align the system and tune the Thomson scattering process. We are considering a step-by-step approach to achieving our goal. The first step is to have two CDR targets (concave and flat) with slits for the electron beam, forming a microwave cavity of a half length of the bunch-by-bunch spacing. In this case the radiation from preceding bunch will interact with radiation generated by the subsequent bunch because the travel distance of the radiation will be equal to the bunch spacing. However, the interaction point will be close to the upstream target in this case. The lower energy of the electron beam (γ = 84; 1/γ = 12 mrad) is, the lower energy photons (UV) are in the tail of the Thomson photon spatial distribution, which will be cleared by the downstream target. Nevertheless, it is much easier to tune the cavity and demonstrate the microwave power storage.

The second step is to add a third mirror. Two mirrors will be used to generate CDR photons (flat and concave) and the third one will be a movable concave mirror attached to the side of the vacuum chamber. The total length of this cavity will be equal to the bunch spacing and CDR photons produced by the odd bunches will be scattered by the even ones. Since the collision point is very close to the 2nd flat CDR target one can expect low losses in UV and soft X-ray due to target aperture cut and lower collision angle.

To tune the resonator the mirrors on a beam line will be mounted on multi-axes vacuum manipulation systems. The microwave radiation will be detected by Schottky Barrier Diodes capable to resolve the CDR photons produced by each bunch in a train in order to monitor power build-up.

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