# RADIATION FROM LASER-MODULATED AND LASER-SLICED ELECTRON BUNCHES IN UVSOR-II*

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*Abstract*

It was successfully demonstrated at UVSOR-II that, by using an external laser source, various micro-density structures such as a femtosecond dip or periodic modulation could be created on an electron bunch circulating in a storage ring. The bunch with femtosecond dip emitted broadband coherent synchrotron radiation. That with periodic density modulation emitted coherent and monochromatic terahertz radiation in a uniform magnetic field of a bending magnet. The results indicate that the laser modulation technique makes it possible to control the wavelength, bandwidth, amplitude, phase or number of cycles of radiation field emitted by relativistic electron bunches.

## INTRODUCTION

Coherent synchrotron radiation (CSR) was theoretically investigated in 40's and 50's, in connection with the energy loss problem in high energy accelerators [1, 2, 3]. When the electrons form a bunch shorter than radiation wavelength, radiation fields emitted by electrons are linearly summed and an intense coherent radiation field is produced. Since the radiation power is proportional to the square of the field strength, it is proportional to the square of the number of electrons.

Experimentally, CSR was observed for the first time in late 80's by using short electron bunches from a linear accelerator [4]. They observed a quadratic dependence of the radiation intensity on the electron beam intensity, which was a clear evidence of CSR. Since then, CSR in the terahertz (THz) range was observed in many linear accelerators.

On the other hand, it had been believed that CSR could not be produced in electron storage rings, because typical bunch length is a few centimetres and such long wavelength radiation is suppressed by the shielding effect of the metal vacuum pipes [5]. However, in 2000's, THz CSR was successfully produced by operating a storage ring with a small momentum compaction factor, making the bunch length as short as radiation wavelength [6].

Synchrotron radiation intensity emitted by an electron bunch can be expressed as follows [7]:

$$P(\lambda) = P_0(\lambda)\{N_e + N_e(1+N_e)f(\lambda)\} \quad , \qquad (1)$$

where $\lambda$ is the radiation wavelength, $P_0(\lambda)$ the radiation power emitted by a single electron, and $N_e$ the number of electrons in the bunch. The $f(\lambda)$ is the form factor given by:

$$f(\lambda) = \left(\int \cos(2\pi z/\lambda) S(z) dz\right)^2 , \qquad (2)$$

here, $z$ is the longitudinal coordinate in the bunch and $S(z)$ the longitudinal density distribution.

The first term on the right hand side of Eq.(1) corresponds to the normal (incoherent) synchrotron radiation which is proportional to the number of electrons. The second term corresponds to CSR which is proportional to the square of the number of electrons. The second term is also proportional to the form factor $f(\lambda)$, the square of Fourier transform of the longitudinal density distribution of the electron bunch.

When the bunch is shorter than the radiation wavelength, the form factor becomes unity and the second term dominates since the number of electrons in a bunch is usually huge, typically, $10^{10}$. Eq. (1) also indicates that, even when the electron bunch is longer than the radiation wavelength, the second term can be dominant. This happens when the bunch shape has some micro-density structure and its Fourier transform has finite (non-zero) value at the wavelength (see Eq. (2)).

Indeed, in many storage rings, intense bursts of THz synchrotron radiation were observed [8, 9, 10, 11, 12], although the electron bunches were much longer than the observed radiation wavelength. Because the bursts are more intense by many orders of magnitudes than the normal synchrotron radiation, it is widely believed that they are CSR whose origin is micro-density structure created on the bunch by some instability [13].

The bursts of THz CSR is attractive because of its high intensity, however, they are unstable in nature (see Fig.1). If one can create micro-density structure on electron bunches artificially, one can produce CSR in control. Such a technique was proposed in 90's, which was named "laser slicing" [14]. As the result of the interaction between an electron bunch and a ultra-short laser pulse, a dip and fragments are formed on the bunch. Although this technique was originally proposed to produce ultra-short X-ray pulses from the fragment, it was also noticed that THz CSR would be emitted from the micro-density structure [15].

At UVSOR-II, a laser injection system was constructed to study light source technologies based on the laser-slicing technique. Later, the technique was developed to laser modulation technique.

In this paper, some results from the experimental studies on the CSR generation by the laser modulation technique at UVSOR-II are presented.

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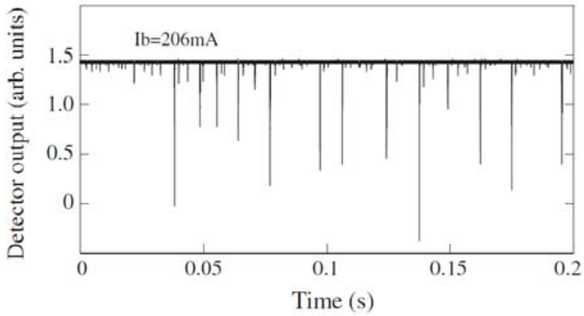


Figure 1: THz bursts observed at UVSOR-II in the single bunch operation mode. The observed wavelength is in the range of 0.2 – 3 mm. [12]

## EXPERIMENTAL SETUP

The laser modulation system at UVSOR-II was constructed by utilizing a part of the existing free electron laser system [16]. The layout of the system was shown in Fig. 2. Laser pulses provided by a Titanium Sapphire laser synchronized with the electron bunches circulating in the storage ring are injected through the optical port for the FEL optical cavity. An optical klystron type undulator is used to make interaction between the laser pulses and the electron bunches. So far, the experiments were made at the wavelength 800 nm and the electron energy 600 MeV. The laser pulses and the undulator radiation pulses are extracted to an optical bench to monitor the temporal and special overlapping between the laser and the electron beam, by using CCD cameras and a streak camera. Coherent harmonics were also extracted and analysed here to check the laser-electron interaction. CSR is extracted and analysed at the second bending magnet from the undulator, where an infrared beam-line is installed [17].

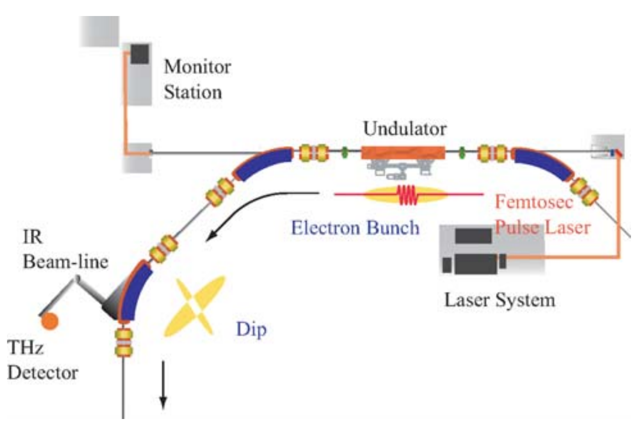


Figure 2: Layout of the laser modulation system at UVSOR-II. A part of the storage ring of 53 m circumference is shown [16].

## THZ CSR BY LASER SLICING

Laser slicing is a technology to slice out a small part of an electron bunch. An ultra-short laser pulse interacts with an electron bunch in an undulator. An energy modulation is created on the bunch. Since the laser pulse width is much shorter than the electron bunch length, only a small part of the bunch is energy-modulated. As the bunch is travelling in the ring, the energy-modulated electrons escape out from their original position and a dip and fragments of sub-picosecond width are created. So far, the laser slicing has been successfully demonstrated at several facilities [15, 16, 18].

THz CSR produced by the slicing technique at UVSOR-II is shown in Fig. 3. The laser pulses are injected at the repetition rate of 1 kHz and intense THz pulses are observed at the infrared beam-line downstream. The spectrum was broad. The intensity was proportional to the square of the peak current of the electron bunch as shown in Fig. 4, which indicates that the radiation is CSR. Recently, a direct observation of the THz field was also carried out by using the EO sampling method. The result was presented elsewhere [19].

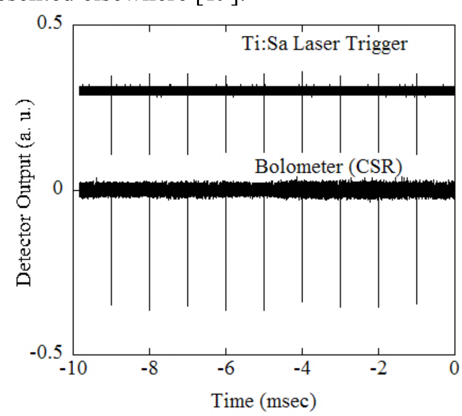


Figure 3: Laser injection timing and bolometer output. Between the intense THz emission of 1 kHz repetition, normal synchrotron radiation is continuously emitted but in the background [16].

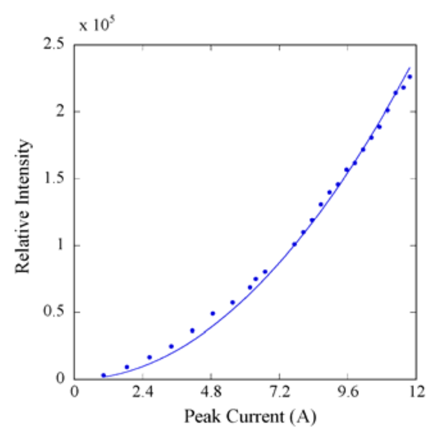


Figure 4: CSR intensity versus peak current of electron bunch [16].

## THZ CSR BY LASER MODULATION

The laser slicing technique creates a single dip on an electron bunch. By generalizing this technology, one can create various micro-density structures. The simplest example is a periodic structure. It is expected that such an electron bunch would emit coherent and monochromatic radiation at wavelength equal to the period of the micro-structure [7, 20, 21, 22].

To realize this, one may use a series of laser pulses separated by THz wavelength or an amplitude-modulated laser pulse with THz frequency. At UVSOR-II, amplitude-modulated laser pulses were successfully generated by using a technology called chirped pulse beating [23], in collaboration with a French team (see Fig.5). By injecting the laser pulses, we could produce a monochromatic THz radiation as shown in Fig. 6 [24, 25].

One remarkable point of this result is that the radiation is emitted in a uniform magnetic field of a bending magnet, not in an undulator. By changing the period of the amplitude modulation of the laser, we could change the radiation wavelength. More generally, by using this laser modulation technology, we can control the wavelength, bandwidth, amplitude, phase or number of cycles of the synchrotron radiation field.

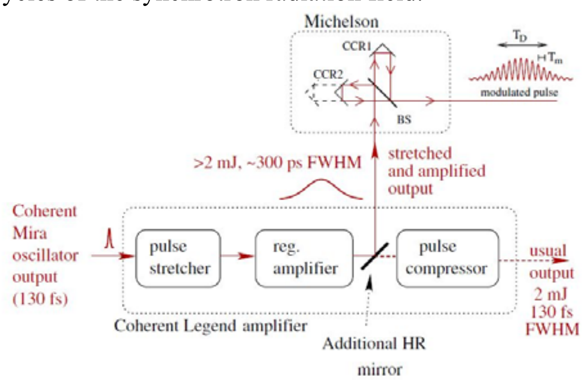


Figure 5. Laser pulse shaper to produce amplitude modulated pulses [25].

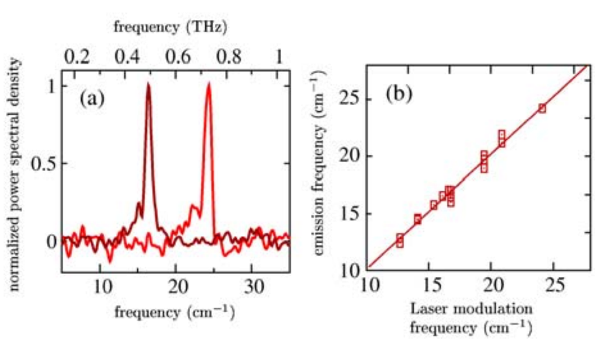


Figure 6. Monochromatic and tunable CSR produced by laser modulation technique [24]. Left: Examples of observed spectra. Right: Correlation between the laser modulation frequency and the THz emission frequency.

## TEMPORAL EVOLUTION OF LASER SLICED/MODULATED ELECTRON BUNCHES

Micro-density structure created on the bunch disappears within a few revolution in case of UVSOR-II [26]. The synchrotron motion of electrons, which is the driving force of the micro-structure formation, destroys the structure as the bunch travelling in the ring for many revolutions. To investigate the temporal evolution of the micro-density structures seeking for the possibility to sustain CSR emission, we performed a laser slicing in the low alpha operation mode where the momentum compaction factor of the storage ring is smaller than the normal operating condition and the synchrotron motion is suppressed.

The CSR was observed by a diode detector with fine temporal resolution that enables to observe CSR, turn-by-turn. In the low-alpha condition, CSR could be observed for several revolutions, however, they showed a very peculiar behaviour as shown in Fig. 7. CSR became intense every two or three revolutions depending on the betatron frequency of the storage ring. This could be understood based on a linear dynamic theory as a result of transverse-longitudinal coupling of the electron motion [27].

Another prospect for sustained CSR emission was suggested by THz CSR emission during the free electron laser oscillation [28]. The continuous laser electron interaction in the optical cavity may have a possibility to sustain micro-density structure on the electron bunch. This will be further investigated in future at UVSOR-II.

The bunch heating is the inevitable problem for storage rings [29], which may limit the radiation intensity extracted from a bunch. Combination of the laser modulation technique and new accelerator technology such as energy recovery linac may be a promising candidate for an ultra-high power THz source [30].

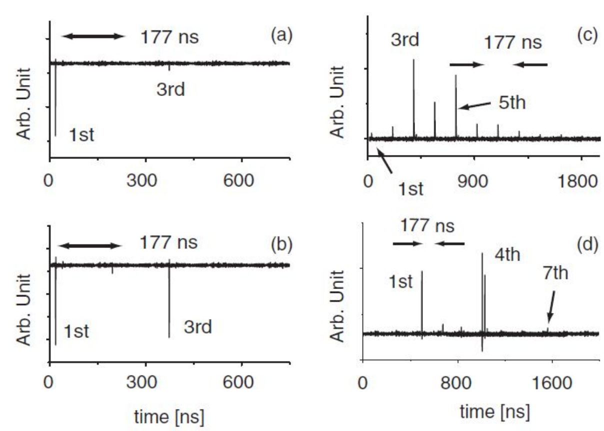


Figure 7. CSR observed turn-by-turn in the low-alpha mode [27]. Revolution time of the ring is 177 ns. (a)-(c) are for the betatron tune close to a half integer. Sensitivity ranges are (a) 11.0-16.6 $cm^{-1}$, (b) 7.3-11.0 $cm^{-1}$, and (c) 3.7-5.7 $cm^{-1}$. (d) is for the betatron tune close to one third of an integer. Sensitivity range is same as (c).

## SUMMARY AND PROSPECTS

The laser modulation technique has been developed at UVSOR-II. Intense THz radiation of broadband or narrowband was successfully produced. The results indicate that, by using the laser modulation technique, we can control the wavelength, bandwidth, amplitude, phase or number of cycles of the radiation field. We may call this “coherent control of synchrotron radiation”.

By using the same external laser source, coherent harmonic generation has been intensively investigated for these years in collaboration with a French team [31, 32, 33]. A combined use of VUV-CHG and THz-CSR would be a useful tool for material science researches [34].

At UVSOR-II, a new straight section was created by moving the beam injection point in 2010. The section will be dedicated to the light source developments including the laser-modulation THz CSR, VUV CHG, laser Compton scattering gamma-ray source and the visible-VUV free electron laser [35]. The upgrade of the laser system was completed. New optical klystron will be installed in 2011. Dedicated beam-lines for VUV-CHG and THz CSR will be constructed in 2011 and 2012.

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