COHERENT HARMONIC GENERATION EXPERIMENT ON UVSOR-II STORAGE RING

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Abstract

In the Coherent Harmonic Generation Free Electron Laser configuration, an external seed signal, a commercial laser source, is focused inside the first undulator. The interaction between the electron beam and this seed leads to a more coherent light emission. Such devices are very promising for short wavelength operation with a rather compact facility. Experiments have been performed on the UVSOR-II Storage Ring (Okazaki, Japan) with electrons stored at 600 MeV, and using a 2.5 mJ Ti:Sa laser at 800 nm wavelength, 1 kHz repetition rate, and 150 fs up to 2 ps pulse duration, allowing emission at 266 nm. This third harmonic has been characterised versus various parameters. Optimizations have been realized on the electron beam and laser synchronisation. The dependency of the harmonic signal on the gain (undulator gap, magnetic functions) has also been studied. Theory is compared to experiment using analytical model. These encouraging results make UVSOR-II storage ring an active test facility for Coherent Harmonic Generation scheme, as well as a potential VUV source for users experiments.

INTRODUCTION

Recent Free Electron Lasers aim at reducing the radiated wavelength to the X-ray domain, the time duration to the femto-second domain, and at improving the coherence of the source. FELs based on linear accelerators are mainly experimenting SASE [1], HGHG, and seeded configurations. Coherent Harmonic Generation (CHG) is a seeded FEL configuration based on storage ring [2, 3]. The seed can be either the own spontaneous emission of the electrons as demonstrated on DUKE [4] and ELETTRA [5] storage rings, or an external source [6] such as a commercial laser. This paper presents the successful generation of the third coherent harmonic of a Ti:Sa laser in USOR-II.

In the Coherent Harmonic Generation configuration, the laser is focused in the modulator [7], and synchronized with the circulating electron bunch. The electron beam is micro bunched at fundamental and sub harmonic wavelengths of the seeded laser. The light emission of the electrons is then enhanced in the radiator at the third harmonic of the seed, i.e. 266 nm. Figure 1 presents the general scheme of the experiment.

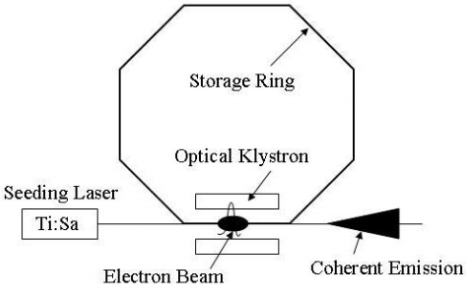

Figure 1: Coherent Harmonic Generation scheme on a storage ring

The seeding laser used for the CHG experiment was initially optimized for Slicing and Coherent Synchrotron Radiation experiments (CSR) [8], requiring high repetition rate (1 kHz) and short pulse duration (150 fs), and therefore not perfectly adapted for generation of the third harmonic. UVSOR-II facility can now provide coherent, short duration and intense light in the far infra red (using CSR) and in the VUV range (using CHG) simultaneously, using one single high power laser. Figure 2 illustrates a burst of CSR emission observed in CHG operation.

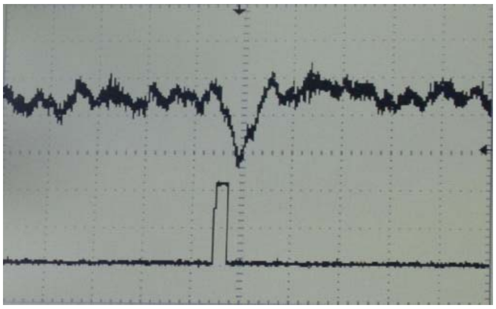

Figure 2: Oscilloscope trace of CSR signal detected by a bolometer observed in CHG operation.

Throught out this paper, an analytical model for CHG will be reminded, followed by a description of the components of the experiment. The first results and optimisation on the third harmonic are finally presented.

ANALYTICAL MODEL FOR CHG

In 1982, R. Coïsson and F. De Martini [9] proposed an analytical model to describe the Coherent Harmonic Generation process in an optical klystron. The intensity of the light emitted by a relativistic electron bunch in an optical klystron can be expressed as the sum of an incoherent and a coherent term. The coherent term equals zero for randomly distributed electronic phases. In the case of CHG process, and assuming that the energy modulation only occurs in the first undulator, the interaction between the electric field E_L and the electrons induces an additional energy spread given by:

$$\Delta\gamma = \frac{eKNE_L\lambda_0}{2\gamma^2 mc^2}(J_0(\xi) - J_1(\xi)), \tag{1}$$

where J are Bessel functions, depending of $\xi = \frac{K^2}{4(1+K^2/2)}$. K is the undulator deflexion parameter, λ_0 the spatial period, N the number of periods, c the velocity of light, e the electrons charge, m their mass, and γ their normalized energy. This energy spread results into an additional phase difference at the exit of the dispersive section, equal at its maximum to: $\Delta\alpha = 4\pi(N + N_d)\Delta\gamma$. N_d is the number of equivalent periods of the dispersive section. The intensity of the coherent emission no longer averages to zero, and is given by the following expression:

$$\frac{\delta W_{coh}}{\delta w \delta\Omega} = \frac{n^2 e^2 N_e^2 f_n^2 J_n^2(n\Delta\alpha)}{16\pi\epsilon_0 c\lambda_L^2}(\frac{KN\lambda_0}{\gamma})^2 A_n^2. \tag{2}$$

n is the harmonic number, N_e the number of electrons in the bunch, f_n the modulation rate, λ_L the seeded laser wavelength, and:

$$A_n = 1/2(J_{n+1}(n\xi) - J_{n-1}(n\xi)). \tag{3}$$

The intensity of the incoherent emission is given by:

$$\frac{\delta W_{incoh}}{\delta w \delta\Omega} = \frac{n^2 e^2 N_e}{16\pi\epsilon_0 c\lambda_L^2}(1 + f_n)(\frac{KN\lambda_0}{\gamma})^2 A_n^2. \tag{4}$$

This model, already used for ACO [2] and Super-ACO [3] storage rings configurations, allows apprehending Coherent Harmonic Generation process and its dependency to electron beam and seeded laser parameters. In addition, calculations performed before the experimental sessions provided with reasonable expectations on the generation of the third coherent harmonic with UVSOR-II storage ring, and its laser parameters.

CHARACTERISTICS OF THE EXPERIMENTAL COMPONENTS

Electron Beam

For CHG experiment, UVSOR-II [10] facility (see Figure 3) was used in single bunch mode. The characteristics of the electron beam delivered are given in Table 1. Experiments have been performed with beam current up to 40 mA, since no beam instability occurs below this value. The modulator and radiator of UVSOR-II's optical klystron [11] are identical and made up of 9 periods of 11 cm, separated by a 33 cm long dispersive section.

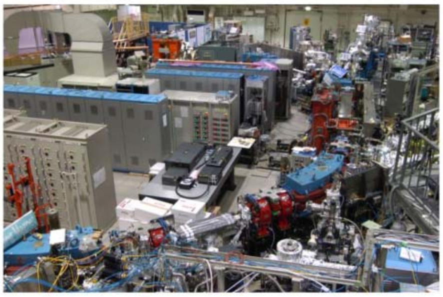

Figure 3: UVSOR-II storage ring

Table 1: Characteristics of the electron beam on UVSOR-II Storage Ring for CHG operation.

Parameter (Unit)	**Symbol**	**Value**
Energy (MeV)	E	600
Circumference of the Ring (m)	C	53.2
Cavity voltage (kV)	V_{RF}	100
RF Frequency (MHz)	f_{RF}	90.1
Harmonic number	n_H	16
Number of bunches stored	n_b	1
Period of revolution (ns)	T_0	178
Momentum compaction	α	0.028
Synchrotron frequency (kHz)	f_S	19.4
Current (mA)	I	0 - 40
Natural Energy spread	σ_γ	0.00034

Beam diagnostics

Four different diagnostics have been used to characterize the output radiation of the radiator (which includes electron beam radiations, and IR laser), and therefore the coherent emission. For spectral selection, the light is sent to an interferometric filter (CVI-F25-265), centered at 266 nm with 25 nm bandwidth. The detection of the UV light is then performed using a solar blind PhotoMultiplier (PM, Hamamatsu, R759). In order to observe the coherent emission at 1 kHz, among incoherent emission at 5.6 MHz, the PM signal is observed on an oscilloscope, triggered by the laser timing system. A streak camera (Hamamatsu, C5680) has also been used. It allows to follow the longitudinal distribution of the electron bunch, and to measure relative position in the time domain between laser pulse and electron bunch. The light was spectrally characterised using a spectrometer for spontaneous emission, and a monochromator followed by the photomultiplier for the coherent emission.

Seeding Laser

The characteristics of the seeding laser system used are given in Table 2. This system includes a mode-locked titanium-sapphire (Ti:Sa) laser oscillator (Coherent, Mira 900-F) and a regenerative amplifier (Coherent, Legend HE) driven by a Q switched pump laser, which delivers high intense femto-second pulses. Those elements are shown in Figure 4.

Table 2: Seeded Laser characteristics

Parameter	**Value**	**Unit**
Wavelength	800	nm
Spectral width	12	nm
Repetition rate	1	kHz
Pulse duration (Δt)	0.15 to 2	ps
Average Power (P_L)	1.8	W
Diameter	11.5	mm
Gaussian quality factor	1.25	
Polarization	Horizontal	

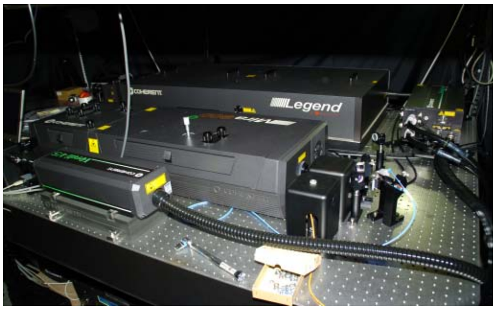

Figure 4: Photograph of the laser system used for CHG experiment.

Synchronisation

The overlap in the modulator for the micro bunching of the electronic distribution, requires a precise synchronisation of the laser pulse and the electron bunch, and therefore a specific timing system for UVSOR-II facility [12] organized as following. The mode-locked Ti:Sa laser is synchronised with the RF signal (f_{RF}) of the storage ring. In addition, the repetition frequency f_Q of the Q switched laser is based on the sub-harmonics of the revolution frequency of the bunches f_{rev}=f_{RF}/n_H=5.6 MHz, leading to f_Q=f_{rev}/5632=1kHz. To select and fix the electron bunch with the laser pulse cuts, an RF bucket selector is used for making the Q switching trigger signal. The timing of the laser pulse within the bunch spacing time is adjusted using a phase shifter modifying the phase of the RF signal. The condition of synchronisation is observed using in first stage a photodiode, receiving both laser pulses and synchrotron radiation (SR). More accurate tuning is further performed using the streak camera, which temporal resolution reaches 10 ps.

Alignment

Spatial overlap is an other key step in Coherent Harmonic Generation. An accurate alignment of the IR laser on the electrons trajectory has to be performed in the modulator. The electronic orbit of the FEL oscillator at 800 nm has been selected for this trajectory. Auto collimation was then used to mark the seeded laser path from the laser hutch through out the FEL cavity. Three periscopes made of two flat mirrors at 45^o incidence allowed the transport of the IR and a 5 m long focal lens its focusing inside the modulator. This allows to optimize the overlapping with the e-beam and to increase the local energy. Both beams have horizontal polarization. Figure 5 illustrates the experimental setup for transport and alignment of the seeding laser.

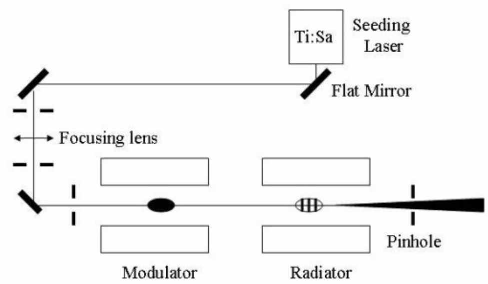

Figure 5: Setup of the laser transport to the FEL cavity.

OBSERVATION OF THE THIRD COHERENT HARMONIC

A picture of the oscilloscope screen is presented in Figure 6, illustrating the output radiation of the undulators. Central peak corresponds to the radiation of the laser heated electron bunch. The intensity at 266 nm is dramatically enhanced thanks to the coherent emission at the third harmonic of the seeding laser.

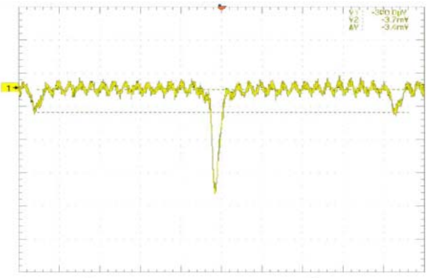

Figure 6: Oscilloscope trace of of the optical klystron out put radiation. Central peak corresponds to the laser heated bunch emission, and edged peaks to unheated bunch emission. P_L=1.78 W, Δt= 1.12 ps, I=4.29mA. Time scale: 40 ns/division.

Figure 7 shows the streak camera image of CHG signal. This diagnostic confirms the enhancement of the intensity at 266 nm radiated by the heated electron bunches (see bright blue spots). In addition, the vertical axis of the image allows to evaluate the duration of the heated bunch radiation: it is much shorter than unheated one's, and measurment of the pulse duration is limited by the streak camera resolution. The temporal coherence achieved with Coherent Harmonic Generation allows to expect pulse durations below 2 ps.

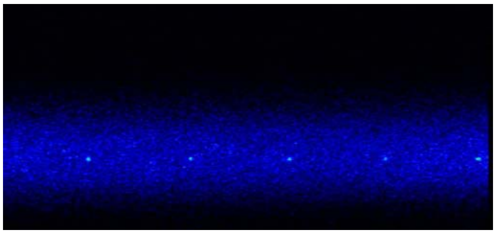

Figure 7: Photograph of the streak camera image. The bright spots correspond to laser heated bunch emission (coherent emission). Full scales are 85 ms for the horizontal and 700 ps for the vertical axis.

Once the Coherent Harmonic Generation systematic and reproducible, the harmonic radiation was studied as a function of various parameters.

According to the analytical model previously mentioned, the number of coherent photons produced is proportional to the square of the number of electrons heated by the laser, linearly related to the peak current, assuming that the electron bunch duration is much wider than the laser pulse duration (by two orders of magnitude). First results seem to confirm the expected quadratic behaviour.

The third harmonic has then been studied versus synchronisation. Using a 3 mA beam current, the laser pulse position in time was shifted back and forth by 200 ps from its initial position: where maximum UV intensity is recorded. Coherent emission could be detected over 360 ps, with total disapearing for delays longer than 200 ps, giving an rms width of 70 ps. This result is in good agreement with the rms bunch length measured at this current: 85 ps. Indeed, since the coherent emission is linked to the electronic density, maximum emission is obtained when the seeding laser heats the centre of the bunch, and a scan with the laser pulse in the time domain gives back the longitudinal distribution of the bunch.

The undulator gap has also been studied as a varying parameter. CHG process is based on the amplification by the radiator of the sub harmonics of the seeding laser wavelength. To be properly amplified, this sub harmonic wavelength must correspond to a resonant wavelength of the optical klystron, defined by the undulator parameter K, and therefore by its gap. Consequently, a detuning of this parameter might kill the radiation at 266 nm. Indeed, CHG emission is maximum for an undulator gap of 40.8 mm and the signal vanishes for gaps of 39.7 and 42.5 mm.

CONCLUSION

Using a 1 kHz Ti:Sa laser, a Coherent Harmonic Generation FEL configuration has been successfully set up at UVSOR-II facility. Short (below 2 ps), UV (266 nm), coherent laser pulses are delivered. In addition, both CHG and CSR can be operated in parallel, using the same laser system and experimental setup: an important step in the development of the fourth generation light sources.

More Coherent Harmonic Generation experiments on UVSOR-II are to be performed in order to study the influence of the seeding laser characteristics: energy, diameter, pulse duration, as well as shaping inside the modulator. Observation of the fifth harmonic is also foreseen.

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