OPERATION OF THE UVSOR-II CHG FEL IN HELICAL CONFIGURATION

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Abstract

In the Coherent Harmonic Generation Free Electron Laser (CHG FEL) configuration, an external laser source injected inside a first undulator modulates in energy, and consequently in phase, an electron bunch, allowing coherent radiation in a second undulator. The CHG-FEL implemented on UVSOR-II storage ring (Okazaki, Japan) consists of a 600 MeV electron beam, and of a 2.5 mJ Ti:Sa seeding laser at 800 nm wavelength, 1 kHz repetition rate, and 100 fs up to 2 ps pulse duration. Operation in planar configuration of the undulators is being characterized since 2005. Recent experiments enabled a step forward using helical configuration of the undulators. A description of the experimental setup is given, and the main results are presented: influence of seeding laser parameters (polarisation, average power, focussing) on the intensity and beam profile of the second and third coherent harmonics. Those investigations provide attractive insights for the future High Gain Harmonic Generation FEL sources, about to deliver sub-nm and sub-ps pulses.

INTRODUCTION

Free Electron Lasers (FELs) are coherent intense light sources available on a large spectral domain (IR to XUV) relying on the interaction between a relativistic electron beam and a light pulse in the periodic magnetic field of an undulator. For single–pass FELs, the interaction occurs within one pass of the electrons inside the undulator. In the Coherent Harmonic Generation (CHG) FEL configuration [1, 2, 3], the light pulse is provided by an external laser source injected in the first part of an undulator, the so–called modulator. The energy exchange between the laser and the electron bunch leads to a density modulation of the electronic distribution, further converted into a density modulation inside a dispersive section which allows coherent radiation in a second undulator, the so–called radiator. Enhancing the generation of the harmonics of the radiator resonant wavelength, such schemes are attractive candidates as short wavelength coherent light sources. In addition, the FEL pulse polarization is set by the radiator magnetic field. Indeed, with a planar (resp. helical) undulator which delivers a sinusoidal (resp. helical) magnetic field, the output polarization is linear (resp. circular). Since variable and circular polarizations are of high interest for many users experiments [10], the operation of CHG FELs in helical mode is highly motivating. Such a mode was first tested on UVSOR-II CHG FEL and gave promising results. In this paper, we present an overview of the systematic measurements performed to characterize the FEL operation in helical mode.

EXPERIMENTAL SETUP

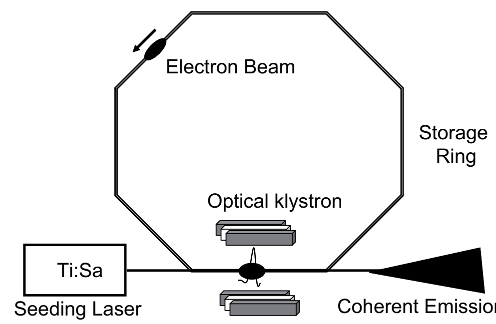

Figure 1: Coherent Harmonic Generation scheme on a storage ring.

The CHG experiment was performed on the UVSOR-II [5] storage ring (Okazaki, Japan). The scheme of the experiment is given in Figure 1, and its main parameters in Table 1. The electron beam is stored in single bunch mode at 500 MeV. Up to 40 mA of beam current (I) can be stored in the ring without any beam instability. Because life time is rather short at high current, most of the experiments were performed between 1 and 10 mA.

The seeding laser installed at UVSOR-II is mainly composed of a mode-locked titanium-sapphire (Ti:Sa) oscillator (Coherent, Mira 900-F) and of a regenerative amplifier (Coherent, Legend HE) driven by a Q switched pump laser. The system delivers fs to ps light pulses of 2.5 mJ at 1 kHz repetition rate. The laser is focussed inside the modulator with two possible focussing mode. In the strong mode, a single f=(+5 m) focussing lens is used, corresponding to a Rayleigh length of Z_R=0.15 m. In the smooth mode, a defocussing lens of f=(-1 m) together with a focussing lens of f=(+0.5 m) are used, corresponding to Z_R=1.5 m. The laser is naturally linear polarized in the horizontal direction, which matches the electron beam polarization when the undulators are operated in the planar mode. For the operation in helical mode, a quarter wavelength plate has been mounted on a rotation stage and positionned on the laser path in order to adjust the laser polarization from linear to circular. The angle of the plate (angle between the incident polarization and ordinary axis of the plate) is referred as θ.

The modulator, the dispersive section and the radiator are elements of a single structure: an optical klystron [4, 6]. The undulators are identical, consisting of 9 periods of 11 cm.

Table 1: Parameters of the CHG experiment in helical mode.

Electron beam parameters	**Value**	**Unit**
Energy	500	MeV
Energy spread	2.8×10^{-4}	
Horizontal emittance	84	nm.rad
Vertical emittance	4.2	nm.rad
Bunch length	90	ps–RMS
Revolution frequency	5.6	MHz
Laser parameters	**Value**	**Unit**
Wavelength	800	nm
Repetition rate	1	kHz
Pulse duration (ΔT)	0.15 to 2	ps
Average Power (P_L)	2	W
Optical klystron parameters	**Value**	**Unit**
Undulator period	11	cm
Number of periods	9	
Deflection parameter	1–4	
Dispersive section length	33	cm

The CHG process requires spectral, spatial and temporal overlap. The spectral matching between the undulator resonant wavelength and the seeding wavelength are ensured via the adjustment of the undulator gap. For spatial overlap, the laser is aligned on the electron beam trajectory using two flat mirrors at the optical klystron entrance and a telescope to visualize the two beams all along the modulator. Finally, for the synchronization, the laser system is triggered by the RF master clock [7] which also sets the electron revolution period, and the laser pulse is centered on the electronic distribution with an optical delay line using a streak camera to visualize the delay. The optical klystron radiation, consisting of the spontaneous emission, the IR laser and the coherent emission, can be transported to two different diagnostics. Photomultipliers (R928-Hamamatsu for the second and R729-Hamamatsu for the third harmonic) are used for intensity measurements and a fast intensified CCD camera (C4078-Hamamatsu) for imaging. Band–pass filters are used in both cases to select the harmonic to be studied (Corion-P10405A-H972 centred at 405 nm with 10 nm-FWHM bandwidth for the second and CVI-25-265 centred at 265 nm with 25 nm-FWHM bandwidth for the third harmonic). Both detectors enable the gating of the coherent signal emitted at 1 kHz among the background of the incoherent signal emitted at 5.6 MHz.

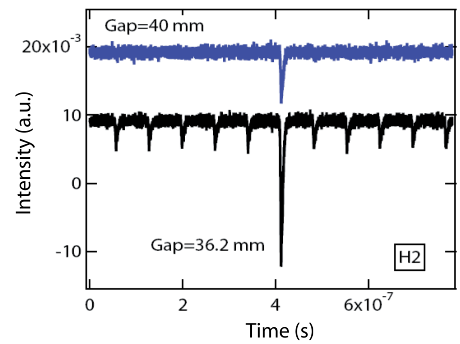

Figure 2: Second harmonic intensity vs time. Screen capture of the oscilloscope, showing the photomultiplier signal. Central peak corresponds to the sum of coherent emission and incoherent emission (spontaneous emission), and edged peaks to incoherent emission. P_L=2 W, ΔT= 1.2 ps, f=(+5) m, Linear polarization, I=2.8 mA.

SECOND AND THIRD HARMONIC GENERATION

The undulator resonant wavelength is given by:

$$\lambda_R = \frac{\lambda_0}{2\gamma^2}(1 + (K_x^2 + K_y^2)/2) \quad (1)$$

with λ_0 the undulator period, γ the normalized energy of the electrons and $K_{x,y}$ the undulator deflexion parameter in the x and y direction. The seeding laser wavelength is λ_L=800 nm. For the interaction to occur, the resonant wavelength must equal the modulation wavelength, i.e. the laser wavelength. Such condition fixes the K value for CHG operation. In the planar mode, the FEL can be operated with a 600 MeV electron beam, which corresponds to a $K_y \approx$ 6.2 and a gain (amplification power of the electron beam) of 0.15%. The second, third and fourth harmonics have been detected [9]. In the helical mode, the condition cannot be satisfied at 600 MeV because of the limited K value. The electron beam is stored at 500 MeV, which leads to a 0.09 % gain. Because of this gain reduction, only the second and third harmonics are detectable. An example of second harmonic signal is presented in Figure 2. When the laser is injected, an amplification by factor 3 is measured. Given the spectral and temporal integration of the detector, this corresponds to an effective amplification by factor 3000×3≈9000 of the second harmonic intensity.

SEEDING CONDITIONS INFLUENCE

The efficiency of the coherent harmonic generation process has been studied as a function of the seeding laser polarization (see Figure 3). The second harmonic intensity clearly depends on the seeding laser polarization. A maximum is reached for $\theta \approx 55^o$ which corresponds to a circular polarzation of the laser in the arbitrary (+) direction. The coherent signal disappears for $\theta \approx 145^o$, i.e. for a cir-

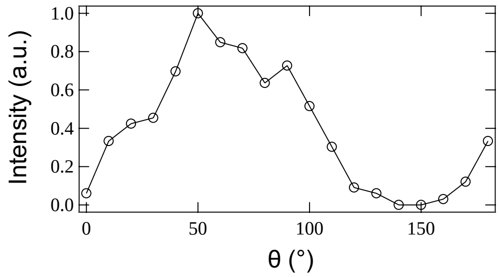

Figure 3: Second coherent harmonic intensity as a function of the quarter wavelength plate θ. The laser polarization is circular in the (+) direction for θ= 55^o, circular in the opposite (-) direction for θ= 145^o, and linear for θ= 100^o. P_L=50 mW, Δt= 1.2 ps, f=+5m, I=1 mA.

cular polarization in the inverse (-) direction. (The experimental θ is shifted by 10^o with respect to the theoretical θ (circular polarizations at 45 and 135^o) probably because of a the mounting on the rotation stage.) Finally, for linear and elliptical polarizations (intermediate θ values), the intensity is below the maximum. Therefore, the harmonic generation process strongly depends on the seeding laser polarization. Maximum efficiency is reached when the laser polarization matches the electron beam velocity vector. In the case of variable undulators, such result can be used to optimize variable polarization seeded FEL sources [11].

FEL IMAGING

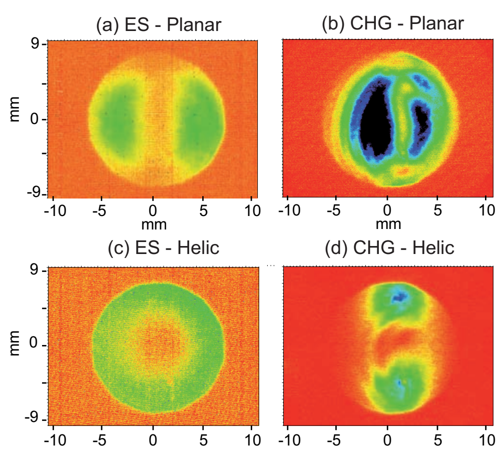

Figure 4: Second harmonic pattern recorded with the fast intensified CCD camera (C4048-Hamamatsu). In planar mode: (a) Spontaneous emission, (b) Coherent emission. In helical mode: (c) Spontaneous emission, (d) Coherent emission. In planar mode: P_L=2 W and linear polarization, undulator gap is 40.5 mm. In helical mode: P_L=0.9 W and circular polarization, undulator gap is 36 mm. Focussing mode: f=(+5m), ΔT_L= 1.2 ps, I=1 mA. Coloour scale: red for minimum and black for maximum intensity.

The second part of our experiment was dedicated to the imaging of the second coherent harmonic. Examples of snapshots are presented in Figure 4 and enable to compare the angular distribution of the coherent and incoherent radiation in the planar and in the helical mode. In both modes, the coherent angular distribution appears quite similar to the incoherent one: the emission is off–axis, with a rough annular distribution. The lack of revolution symmetry results from the azimuthal intensity modulation of the high order harmonics well known in the case of spontaneous emission [8]. In the planar mode, the intensity reaches maxima on the horizontal axis and the pattern finally consisits mainly of two lobes symetric with respect to the vertical axis. On the opposite, in the case of helical mode, the intensity reaches maxima on the vertical axis, leading to a pattern made of two lobes symmetric with respect to the horizontal axis. A reduction of the spot size (annular width) and of the divergence (annular radius) can be noticed, probably resulting from an improvment of the temporal coherence (via spectral narrowing) and of the spatial coherence.

Thanks to this imaging device, we have been able to check that the variation of the seeding laser polarization and focussing only changes the harmonic generation efficiency, not the harmonic radiation pattern.

CONCLUSION

We have succeded in operating a CHG FEL in helical mode, in optimizing the source and in imaging the coherent radiation. Those experiments provide key insight for the futur seeded FELs aiming at the delivery of fs XUV coherent pulses with a flexible polarization.

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