COHERENT HARMONIC GENERATION USING THE ELETTRA STORAGE-RING OPTICAL KLYSTRON

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Abstract

Coherent harmonic generation using single-pass devices or oscillators is based on the frequency up-conversion of a high-power laser focused into the first undulator of an optical klystron. The seeding signal, which is necessary to produce the modulation of the electron density and hence to induce the coherent emission, may be provided by an external laser or, in the case of storage-ring oscillators, by the FEL itself. The latter possibility has been recently explored at Elettra allowing to generate radiation at 220 nm, i.e. the third harmonic of an intra-cavity signal at 660 nm. As for seeding using an external laser, a detailed campaign of simulations shows that the Elettra storage-ring optical klystron is also well suited for the realization of this configuration. These results make the Elettra FEL an attractive test-facility in view of coherent harmonic generation experiments planned on dedicated next-generation devices.

INTRODUCTION

The standard process leading to the generation of coherent harmonics (CHG) using single-pass devices or storage rings is based on the up-frequency conversion of a high-power seeding signal focused into an undulator, which can be the first one of an optical klystron, and synchronized with an upcoming electron bunch [1, 3]. In the optical klystron configuration (see Fig. 1), the seed-electron beam interaction leads to a modulation of the electrons energy inside the first undulator (Modulator). When the beam crosses the dispersive section, such a modulation is converted into a spatial partition of the electrons in micro-bunches separated by the seed wavelength. Therefore, a Fourier analysis of the bunch density shows, at the end of the dispersive section, a series of lines at the laser frequency and its harmonics. Finally, in the second undulator (Radiator), the light emission at the harmonics of the seed wavelength is enhanced by this coherent bunching and becomes proportional to the square of the number of electrons.

When installed on storage rings, an optical klystron generally serves as interaction region for oscillator free-electron lasers (FELs). In this case, electrons amplify the light stored in the optical cavity during successive interactions, till the achievement of the laser effect. The obtained intra-cavity signal, which is naturally synchronized at each pass with the electron bunch(es) at each pass, may provide the seeding power necessary to initiate CHG [4]. As an alternative, CHG can be obtained by removing the cavity mirrors and by coupling the electron bunch(es) with an external laser [5, 6]. It is worth stressing that in both cases a major difference with respect to the single-pass configuration is due to the fact the electrons are re-circulated and, therefore, they can keep track of previous interactions.

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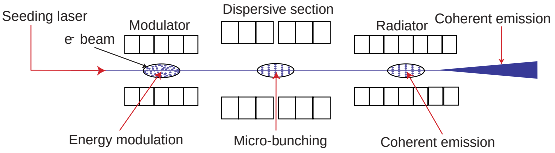

Figure 1: Schematic layout of CHG using an optical klystron.

FEL-induced CHG has been recently realized at Elettra, allowing to generate the third harmonic of an intra-cavity signal at 660 nm. In the first part of this paper, we report about the set of measurements that have been performed with the aim of characterizing the energy as well as the spectral and temporal features of the harmonic radiation. As for seeding using an external laser, a detailed campaign of simulations, partially reported in the second part of the paper, shows that the Elettra optical klystron is also well suited for the realization of this configuration.

THEORETICAL FRAMEWORK

The light-electron beam interaction inside each undulator can be studied by solving the coupled pendulum-maxwell equations (see, e.g., [7]):

$$\begin{cases} \dfrac{\mathrm{d}\zeta_j}{\mathrm{d}\tau} = \nu_j \\[2ex] \dfrac{\mathrm{d}\nu_j}{\mathrm{d}\tau} = |a_n| \cos\left(\zeta_j + \phi_n\right) \\[2ex] \dfrac{\mathrm{d}a_n}{\mathrm{d}\tau} = -2\pi g_{0,n} \left\langle \exp\left(-in\zeta\right)\right\rangle . \end{cases} \tag{1}$$

Here ζ_j is the phase of the jth electron in the combined "ponderomotive" (radiation + undulator) field; ν_j, the relative energy of the jth with respect to the resonance condition, is the variable conjugated to ζ_j; τ is the distance along the undulator (normalized to the undulator length); a_n and ϕ_n are, respectively, the nth harmonic component and the phase of the complex optical field; $g_{0,n}$ is the small signal gain and $\langle \exp(-in\zeta)\rangle$ stands for the bunching coefficient relative to the nth harmonic. The extracted power at a given harmonic is maximized optimizing its bunching coefficient. This can be done by means of a proper adjustment of both the electron beam energy and dispersive section strength. When the case of CHG on a storage ring is considered, the system (1) has to be “closed” by two further equations. The first accounts for the laser evolution inside the optical cavity [8]:

$$(a_n)_{new} = (a_n)_{old}\sqrt{1-T_n} + (a_n)_0 \qquad (2)$$

where $(a_n)_{old}$ is optical field at the exit of the Radiator and $(a_n)_{new}$ its value at the beginning of the Modulator after a double reflection on the optical cavity mirrors. In practice, $(a_n)_{new}$ provides, turn after turn, the initial seeding value for Eqs. (1); T_n is the mirrors transmission (depending on the harmonic number) and $(a_n)_0$ stands for the spontaneous emission of the optical klystron.

The second equation, which is necessary for closing the loop, takes into account the damping of the electron-beam energy spread, σ_ν, when, along the ring, electrons do not interact with the seed [8]:

$$(\sigma_\nu)^2_{new} = (\sigma_\nu)^2_{old} - \frac{2T}{\tau_s}\left[(\sigma_\nu)^2_{old} - (\sigma_\nu)^2_0\right]. \qquad (3)$$

Here $(\sigma_\nu)_{old}$ is energy spread at the exit of the Radiator and $(\sigma_\nu)_{new}$ its value after one turn of the ring; $(\sigma_\nu)_{new}$ provides, turn by turn, the initial r.m.s. value of the v_j distribution (assumed, in first approximation, to be a Gaussian) in Eqs. (1). T and τ_s stand, respectively, for the bounching period of the laser in the optical cavity and the synchrotron damping time; $(\sigma_\nu)_0$ is the initial (laser-off) value of the energy spread. Note that Eq. (2) is no longer necessary when the optical cavity is removed and use is made of an external seed.

CHG INDUCED BY THE FEL INTRA-CAVITY SIGNAL

Let’s start considering the case of CHG self-induced by the FEL light stored in the optical cavity.

Harmonic macro-pulse characterization

As demonstrated theoretically by Dattoli et al. [9] and experimentally on the Duke storage-ring FEL [4], the only way to generate enough intra-cavity power so to get a detectable harmonic signal is to run the FEL in giant-pulse regime. This can be done by means of different techniques. The one employed at Elettra [10] for Q-switching is based on a periodic variation of the radio-frequency so to induce a modulation of the temporal overlapping between the electron beam and the light stored in the optical cavity. When the system is completely detuned, the laser is switched off. If such a condition is kept for a time long enough (order of few synchrotron damping times), the electron beam cools down and the gain recovers its initial (laser-off) maximum value. The minimum duration of such a period of time fixes the maximum repetition rate at which the system can be operated. When the gain has recovered its maximum value, the perfect light-electron beam synchronism is re-established and maintained for the time (order of few hundreds of microseconds) necessary for a single giant pulse to be generated. Then, the system is detuned again and the entire cycle repeated. The obtained signal, which is found to be relatively stable and reproducible, is characterized by an increase of the peak intensity of about a factor 50 with respect to standard “cw” operation mode. In Table 1 are listed the experimental conditions for which results reported in the following have been obtained.

Table 1: Experimental conditions for CHG using the Elettra FEL as seed. The Elettra storage-ring optical klystron is made up of two identical undulators having 18 periods, 10 cm long. The mirrors of the optical cavity have total losses of about 0.2% at the fundamental wavelength.

Beam energy	900 MeV
Beam current (4 bunches)	25 mA (max)
Fundamental wavelength	660 nm
Intra-cavity peak power (fund)	$\simeq$ 100 MW
Third harmonic wavelength	220 nm
Repetition rate	2-10 Hz

The correlated temporal evolution of the fundamental and harmonic macro-pulses is shown in Fig. 2.

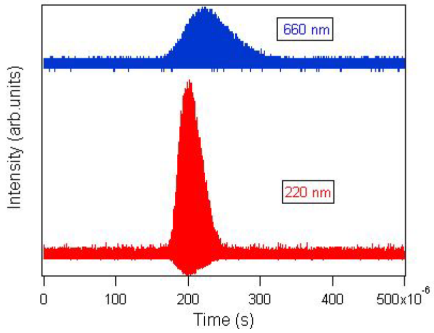

Figure 2: Correlated evolution of the fundamental (upper trace) and harmonic (lower trace) macro-pulses.

The harmonic pulse is characterized by a shorter rise-time than the fundamental one (about a factor 3 difference); moreover, it reaches the saturation and decays faster. Measuring the ratio between the maximum intensity of the harmonic signal and its background (corresponding to the spontaneous emission of the optical klystron at 220 nm) allows one to give an estimation of the energy carried by the most intense harmonic micro-pulse, i.e. about 0.2 nJ for the case of Fig. 2. The intensity of the fundamental and harmonic signals has been studied also as a function of the dispersive section strength. The obtained result, shown in Fig. 3, is a clear signature of the nonlinearity of the process. Indeed, the dispersive section strength at which the harmonic intensity becomes maximum does not correspond to that maximizing the fundamental. The decrease of the harmonic signal above a given threshold is to be attributed to the concurrent decrease of the fundamental and not to an induced over-bunching (which never occurs in this regime).

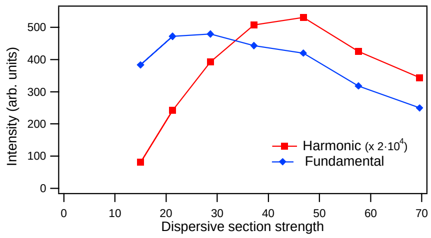

Figure 3: Evolution of the fundamental and harmonic intensities as a function of the dispersive section strength.

Temporal and spectral characterization of the harmonic micro-pulse

Measurements performed using a double-sweep streak camera (see Fig. 4) show that the duration of the harmonic micro-pulse is shorter than the fundamental one (about 6 ps r.m.s.). The measured value, i.e. 3 ps r.m.s, is at the limit of the instrument resolution [11]).

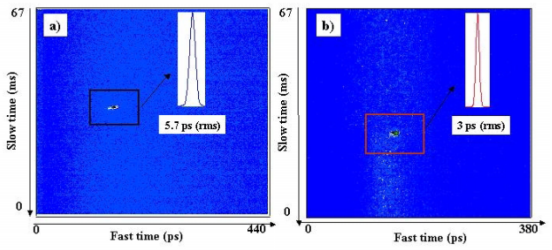

Figure 4: Streak camera images of the fundamental a) and harmonic b) macro-pulses. The insets represent the respective micro-pulse profiles.

As for the spectral domain, the pulse width has been found to be of the same order of the fundamental one (i.e. $\Delta\lambda/\lambda \simeq 10^{-3}$ and about a factor 20 narrower than the spontaneous emission of the optical klystron (see Fig. 5).

Comparison with theory

Eqs. (2) and (3) have been implemented into the numerical code PERSEO [12]. Simulations give results in good agreement with experiments. In particular, as reported in Table 2, the theoretical value of the micro-pulse peak power at the fundamental wavelength is close to the measured one. As for the harmonic, a good agreement is obtained assuming that the micro-pulse duration is 3 ps r.m.s, that is what has been measured using the streak camera (see Fig. 4).

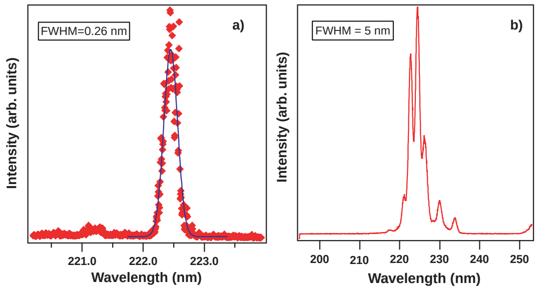

Figure 5: Specrum profiles at 220 nm of the coherent signal (Fig. a) and of the spontaneous emission of the optical klystron (Fig. b).

Table 2: Experimental and simulated micro-pulse peak power relative to the fundamental and harmonic signals.

	Fundamental (W)	**Harmonic (W)**
Experimental	$8.6 \cdot 10^5$	17.1
Simulated	$6.7 \cdot 10^5$	16.4

It is worth noting that the obtained value for the harmonic micro-pulse peak power (less than 20 W) is much weaker than the one reported by the Duke FEL group (i.e. tens of kW [4]).

CHG INDUCED BY AN EXTERNAL SEED

In the following are summarized the results of a campaign of time-dependent simulations performed, again using PERSEO, in order to investigate the possibility of CHG using the Elettra storage-ring optical klystron in combination with an external seed.

The seeding system that has been considered is a Ti:Sa delivering, after third harmonic generation, an optical pulse at 260 nm characterized by a duration of 100 fs and by a peak power of 2.5 GW. Figs. 6a and 6b show the seeding effect on the electron-beam phase space at the end of the modulator and of the dispersive section, respectively. The correspondent bunching coefficients for the third, fifth and seventh harmonics are reported in the Figure's caption. After the end of the dispersive section, the microbunched electron beam enters the radiator, which is tuned at the third harmonic of the seed wavelength. Fig. 7 shows the evolution of the harmonic signal along the undulator. The expected output power at 90 nm is about 1 MW. The power is reduced, respectively, by a factor 10 and a factor 100 (see Table 3) when the Radiator is tuned at the fifth ($\simeq$ 50 nm) and seventh ($\simeq$ 40 nm) harmonics of the seeding laser wavelength. Time-dependent simulations have been performed in order to get the output micro-pulse and spectrum profiles (see Fig. 8). As expected, the harmonic

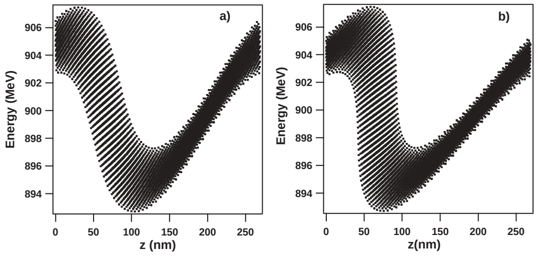

Figure 6: Effect of the seeding laser on the electron-beam phase space at the end of the Modulator, Fig. a), and at the end of the dispersive section, Fig. b). The bunching coefficients for the third, fifth and seventh harmonics (b_3, b_5, b_7) are in the two cases (0.15, 0.04, 0.01) and (0.34, 0.17, 0.07), respectively.

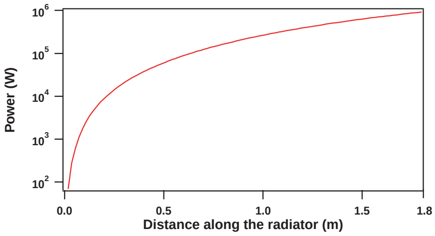

Figure 7: Evolution of the harmonic signal along the Modulator tuned at the third harmonic (about 90 nm) of the Ti:Sa seeding signal.

pulse duration is slightly shorter than the one of the seeding pulse (86 fs) and the spectrum profile is very clean ($\Delta\lambda/\lambda \simeq 1.2 \cdot 10^{-3}$).

CONCLUSIONS AND PERSPECTIVES

We have demonstrated the possibility of CHG using the Elettra storage-ring FEL as seeding signal. The temporal dynamics of the radiation at 220 nm has been studied and the harmonic micro-pulse characterized in terms of energy, duration and spectral width. Experiments are well reproduced by a simple 1D model developed exploiting the numerical code PERSEO. As a next step, we intend to extend the spectral range to the vacuum ultra-violet. As for CHG using an external Ti:Sa system, simulations performed using PERSEO in time-dependent mode (and partially benchmarked using GENESIS [13]) give the very promising results reported in Table 3.

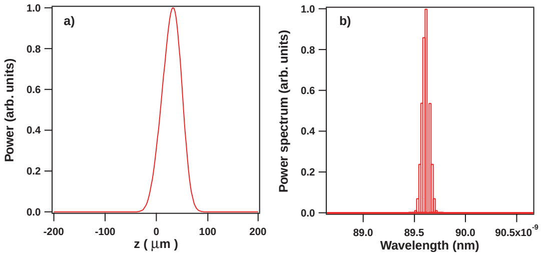

Figure 8: Simulated output micro-pulse and spectrum profiles (Figs a) and b), respectively).

Table 3: Expected performance of CHG using the Elettra storage-ring optical klystron in combination with an external Ti:Sa laser system delivering an optical pulse at 260 nm, characterized by a duration of 100 fs and a peak power of 2.5 GW.

Wavelength (nm)	90, 50, 40
Peak power (W)	10^6, 10^5, 10^4
Pulse duration (fs)	$\simeq$ 90 fs
Repetition rate (Hz)	10-100
Spectral width	Same as seed pulse

Such a results indicate the Elettra storage-ring optical klystron as an attractive, ready-to-use, test facility in view of CHG experiments planned on dedicated next-generation devices.

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