Experimental Characterization of Nonlinear Harmonic Generation in Planar and Helical Undulators

E. Allaria,[1] F. Curbis,[1] M. Coreno,[2] M. Danailov,[1] B. Diviacco,[1] C. Spezzani,[1] M. Trovó,[1] and G. De Ninno[3,1]

[1]*Sincrotrone Trieste, S.S. 14 km 163.5, Trieste, I-34012 Italy*
[2]*CNR-IMIP (Rome branch), c/o CNR-INFM TASC National Laboratory, Trieste, I-34012 Italy*
[3]*Physics Department, Nova Gorica University, Nova Gorica, SI-5000 Slovenia*

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We present an experimental characterization of the process of coherent harmonic generation in single-pass free electron lasers. The harmonic radiation is obtained by seeding the electron beam stored in the Elettra storage ring with a Ti:sapphire laser. Different methods for generating harmonics are compared between them, and a detailed characterization of the emitted light is performed for different polarizations. Our results also contribute to the debate about the possible presence of a coherent on-axis signal in helical undulators. In this respect, we provide an experimental confirmation of recent theoretical studies that predict no coherent on-axis signal.

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During recent years significant effort has been devoted to the theoretical investigation of the process of coherent harmonic generation in free electron lasers (FELs) [1–9]. Such effort is motivated by interest in developing new light sources in the vacuum ultraviolet (VUV) and x-ray spectral regions. Theoretical studies have been also triggered by the need to estimate, and possibly control, the amount of power contained in the harmonics of the FEL fundamental wavelength. In the case of single-pass VUV/x-ray FELs, harmonic emission may have either a desirable or an undesirable effect. In some cases, it can be useful in order to extend the tunability range of FELs to shorter wavelengths that otherwise would not be accessible [4,5]. In other cases, the harmonic radiation is considered as a noise source because it contaminates the radiation used for experiments, preventing a clear discrimination of investigated effects. In the case of high average power FEL oscillators, one is interested in suppressing harmonic radiation as much as possible. The reason for this is the damage that such radiation may produce on the mirrors of the optical cavity.

In a FEL, the evolution of the electron-beam density is driven by the field at the resonant (fundamental) wavelength, which is orders of magnitudes stronger than the harmonic fields. The fundamental signal produces a significant modulation (called bunching) of the electron-beam density at the resonant wavelength, and at the harmonics of the latter. Harmonic bunching is the nonlinear source for harmonic generation, which is orders of magnitudes stronger than the spontaneous incoherent emission [1,2,4].

In the case of self-amplified spontaneous emission (SASE) or oscillator FELs, harmonic emission is usually produced in the same undulator where the radiation at the fundamental wavelength is generated. Following established nomenclature, we will refer to this process as nonlinear harmonic generation (NGH). The fact that coherent signal is produced at a harmonic of the resonant wavelength determines some of the radiation characteristics [1,6,7]. In particular, it has been demonstrated [1,10] that, in the case of planar undulators, on-axis emission occurs exclusively at odd harmonics, while even harmonics are present only off-axis, and with some peculiar polarization properties [1,7,8]. In this context, an open point that is stimulating an animated dispute in the FEL community [11] concerns the possibility for helical undulators to generate significant coherent on-axis signal. In particular, recent theoretical results [9] suggest that the NHG signal, whose characterization is also discussed in [6], should be concentrated off-axis.

An alternative approach to NHG for producing coherent harmonic emission takes advantage of the bunching created in an undulator for generating coherent emission in a subsequent undulator, where the resonant wavelength is one of the harmonics of the fundamental wavelength in the first undulator [12]. In the following, we will refer to such a technique as coherent harmonic generation (CHG). This second option usually requires the use of an external powerful laser. As shown in Fig. 1, in the first undulator, called modulator, the laser interacts with the particle beam, inducing a significant modulation of electrons' energy. Such a modulation is converted into spatial bunching when the electron beam crosses a magnetic chicane ($R56$). Finally, in a second undulator, called radiator, the bunched electrons emit coherently. If the radiator is long enough, the emitted radiation is eventually (exponentially) amplified until saturation [12,13]. The laser-electron interaction in the modulator produces bunching at all (odd and even) harmonics. As a consequence, in the radiator, coherent emission occurs at any selected harmonics, no matter the radiator polarization.

In this work, we experimentally investigate the process of harmonic generation in a single-pass FEL. The used experimental setup is reported in Fig. 1, and is based on two independent APPLE II undulators separated by a dispersive section. The undulators are placed in a straight

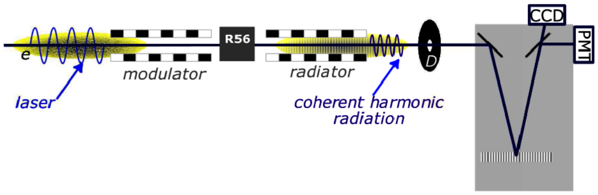

FIG. 1 (color online). Sketch of the experimental setup used for the investigation of harmonic generation in a FEL. A powerful Ti:sapphire *laser* interacts with the electron bunch (*e*) within the *modulator* and induces a modulation of the electrons' energy. After the conversion of the energy modulation into spatial bunching, which occur into the magnetic chicane ($R56$), the bunch enters the *radiator* and start emitting coherently at the resonant wavelength and, eventually, at its harmonics. The produced *coherent harmonic radiation* passes through a diaphragm (D) and is transported into a diagnostic area, where temporal (PMT) and spectral (CCD) analyses are performed. The position of the diaphragm defines the angle of emission with respect to the undulator's axis considered for the measurement.

TABLE I. Main experimental parameters.

Parameter	Value	Unit
Electron beam		
Peak current (I)	15–30	A
Energy	1.1	GeV
Bunch length (FWHM)	35	ps
Relative energy spread	$\simeq 0.1$	%
Revolution period	864	ns
Seed laser		
Power	5	GW
Wavelength	399	nm
Pulse length (FWHM)	120	fs
Polarization	Horiz., Circ.	
Repetition rate	1.0	kHz
Undulators		
Periodicity	0.10	m
Length	2×2.0	m
Polarization	Horiz., Circ.	
Dispersive section strength (R56)	$\simeq 20$	μm

section of the Elettra storage ring [14]. The system is very flexible and, depending on the undulator configuration, different harmonic generation schemes can be studied. The produced radiation is first monocromatized and then acquired on a digital oscilloscope by means of a photomultiplier tube (PMT), which is fast enough to resolve the pulsed dynamics of the electron bunches photoemission (nanoseconds scale) but does not allow to resolve the real photon pulse shape (tens of ps). A diaphragm of 1.4 mm is placed 16 m downstream the second undulator, before the detector. The diaphragm is used to select only the portion of radiation emitted within a small cone close to the undulator axis (angular acceptance of the order of 0.09 mrad). By moving the diaphragm, it is possible to characterize the transverse distribution of the produced radiation.

As explained above, the process of harmonic generation may be initialized by an external seed laser. In our case, use is made of the second harmonic (about 400 nm) of a high-power Ti:sapphire laser.

The setup is optimized in order to insure the best spatial and temporal overlap between consecutive laser pulses and electron bunches inside the modulator. The high power of the used laser ($\simeq 5$ GW) induces an electron-beam energy modulation which is typically a factor five larger than the initial electron-beam energy spread. Because of this electron-beam heating, the bunching factor (B) at the exit of the dispersive section can be estimated to be close to 0.5. Such a result is also confirmed by numerical simulations [15]. For the presented experiments, Elettra is operated in single-bunch mode, with a bunch revolution period of about 864 ns. The laser repetition rate is 1 kHz. The laser pulse and electron bunch durations are, respectively, 120 fs (FWHM) and (about) 35 ps (FWHM). A laser-electron synchronization with a jitter of few ps was achieved. This allows to guarantee an efficient and stable seeding process every laser pulse. The monocromator and the PMT are located about 40 m downstream the radiator. The main experimental parameters are reported in Table I.

In the following we present the results of our experimental study. The coherent signals obtained in CHG and NHG configurations are compared between them for different harmonic numbers and polarizations. A characterization of the spatial profile of the coherent signals is also reported. As already stated, when the resonant wavelength is provided by an external laser, CHG is the most efficient way to produce coherent radiation at one of the harmonics of the seed [12,13]. This because in the radiator electrons are not resonant (i.e. do not interact) with the strong electric field of the seed and, as a consequence, any unwanted increase of the beam energy spread is prevented. However, in the case of a short radiator that does not allow us to reach the regime of exponential amplification, like to the one we used for our experiment, the power generated in CHG and NHG configurations are similar, when NHG is feasible. This is confirmed by the results reported in Fig. 2, where the third harmonic signals detected by the PMT in

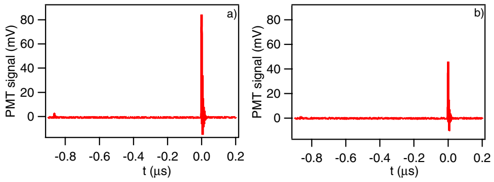

FIG. 2 (color online). Comparison between the third harmonic radiation produced in CHG (a) and NHG (b) configurations. In both cases the modulator and the seed laser are in horizontal polarization. The radiator is tuned to the third harmonic in horizontal polarization (a) and to the fundamental in horizontal polarization (b).

the case of CHG (a) and NHG (b) are reported. In both cases, the radiator is set for horizontal polarization. As it can be seen, the radiation detected from the seeded one (located at $t = 0$) is about a factor 50 larger than the synchrotron radiation detected from unseeded pulses (located at $t = -0.86\ \mu s$). Measurements have been done with a large aperture of the monocromator slits and, as a consequence, are not affected by the bandwidth of the detector, which is close to that of the spontaneous emission ($\simeq 5$ nm). Indeed, similar ratio between signals from seeded and unseeded electrons have been also observed from spectral measurements. Considering the difference in the number of photon per pulse and taking into account the difference between the pulse length of synchrotron radiation ($\simeq 35$ ps) and coherent signal ($\simeq 120$ fs), the ratio between peak powers can be estimated to be of the order of 10^4 ($P_{\mathrm{CHG}} \simeq 50 P_{\mathrm{synch}} 35\ \mathrm{ps}/120\ \mathrm{fs} = 1.5 \times 10^4$). This corresponds to what one can expect from a qualitative calculation using the parameter of our setup $P_{\mathrm{CHG}} \propto N_{\mathrm{coh}}^2$ and $P_{\mathrm{synch}} \propto N_{\mathrm{bun}}$, where $N_{\mathrm{coh}} \simeq BI\Delta T_{\mathrm{las}}/Q$ and $N_{\mathrm{bun}} \simeq I\Delta T_{\mathrm{bun}}/Q$.

As expected, the difference between the coherent signals produced with CHG and NHG is only a factor of 2. However, as already mentioned, one of the most significant advantages of the CHG scheme with respected to NHG is the possibility to freely choose the harmonic and the polarization of the produced radiation. Figure 3 shows the coherent harmonic pulses ($t = 0$) produced in CHG configuration at the second (a),(b) and third (c),(d) harmonics of the seed wavelength, for horizontal (a),(c) and circular (b),(d) polarizations. Experimental conditions are the same for all sets of measurements. Results clearly indicate the possibility to change the polarization of the coherent signal from linear to circular for both odd and even harmonics. Moreover, there is an evident improvement of the conversion efficiency in the case of circular polarization, as expected form the theory.

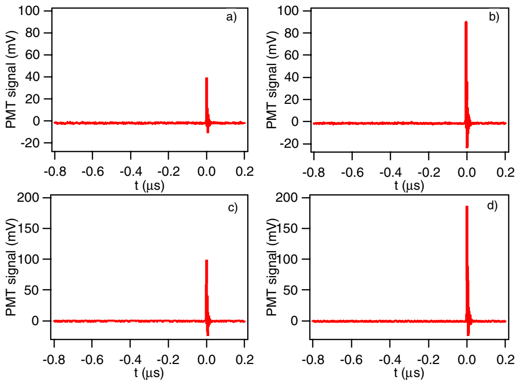

FIG. 3 (color online). Comparison of the harmonic radiation produced in CHG configuration at the second (a),(b) and third (c),(d) harmonics of the seed wavelength. The radiator is set in horizontal (a),(c) or in circular (b),(d) polarization, while the modulator and the seed are in horizontal polarization.

We now investigate the possibility to produce on-axis harmonic radiation at even harmonics using NHG. According to theoretical predictions [1], the signal should be zero in the case of linearly polarized undulators. As already mentioned, the existence of a nonzero signal in the case of helical undulators is still an open question [6,9,16], which is lively debated in the FEL community [11].

As expected, our measurements show that the second harmonic in planar undulator configuration is virtually zero [see Fig. 4(c)], i.e., about a factor 20 smaller than the signal measured in similar experimental condition using CHG [see Fig. 4(a)]. In fact, such a small signal can be attributed to a contamination from off-axis radiation, due to nonzero dimensions of our diaphragm. Similar results have been found in the case of circularly polarized undulators, both for the second [Figs. 4(b) and 4(d)] and the third harmonics. Results presented in Fig. 4 provide an experimental validation of the theoretical results reported in Ref. [9], that predict no harmonic coherent on-axis signal generated by helical undulators. As before, the small residual signal in Fig. 4(d) can be considered as a contamination coming from off-axis radiation.

In order to better characterize the process of harmonic generation, we also performed measurements of the spatial distribution of the coherent radiation for the case of the second harmonic produced by CHG and NHG. Measurements have been performed by moving the diaphragm in order to collect off-axis radiation on the PMT.

Figure 5 shows the intensities of coherent signals measured in the case of CHG (squares) and NHG (dots), as a function of the collection angle. It is important to note that,

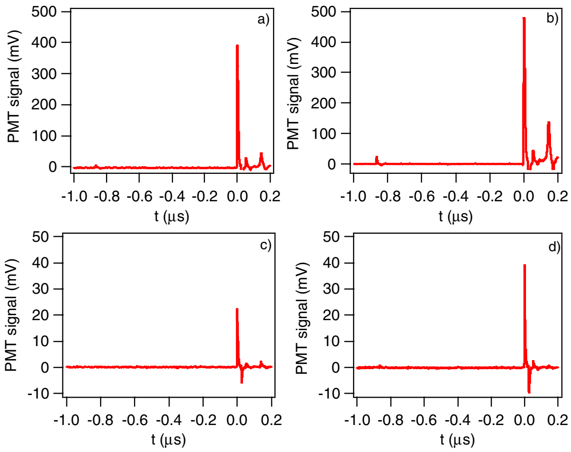

FIG. 4 (color online). Coherent harmonic signals produced at the second harmonic of the seed wavelength in CHG (a),(b) and NHG (c),(d) configurations. Figures (a),(c) refer to a condition where the seed laser, the modulator and the radiator are in planar polarization, while Figs. (b),(d) refer to a condition where both the seed and all undulators are set in circular polarization. Data reported in (a) and (c) refer to the same experimental conditions, and can be used for a relative comparison. The same holds for (b) and (d).

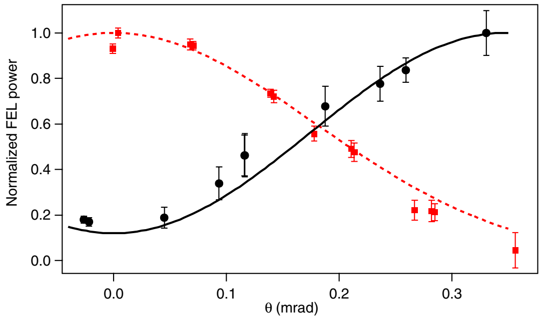

FIG. 5 (color online). Measured angular distribution of the second harmonic in the case of CHG (squares) and NHG (dots) with helical undulators. Measurements are well fitted by theoretical curves, which have been obtained by integrating the expected Gaussian profile (dashed line, CHG case) and the profile predicted in [9] (continuous line, NHG case), over an angle of 0.09 mrad.

due to the relatively large aperture of the diaphragm (0.09 mrad), in the case of NHG one can expect a noticeable contamination coming from off-axis radiation. For that reason it is important to take into account the aperture of the diaphragm also for the theoretical curves we want to use for fitting the data. The CHG data are well fitted by a function corresponding to the integration over a window of 0.09 mrad of a Gaussian beam profile with a divergence of 0.3 mrad (dashed line in Fig. 5). It is worth noting that a Gaussian beam with a divergence of 0.3 mrad corresponds to a beam waist of about 200 μm, which is in agreement with the dimension of our electron beam. An indication of the goodness of the fit between experimental data and the theoretical curve is provided by the statistical analysis of our measurements. In the case of CHG, the reduced χ^2 error [17] is largely smaller than 1, i.e., $\chi^2 \simeq 0.04$.

The NHG data fit with the integration over the same window of the distribution function predicted in Ref. [9] for the second NHG in helical undulator. The theoretical curve (Fig. 5 continuous line) was calculated using the parameters of our experimental setup. In this case, the goodness parameter for the fit is $\chi^2 \simeq 0.06$. It is important to note that the goodness fitting parameter χ^2 becomes larger if we consider the possibility to have together with the off-axis distribution [9] an on-axis Gaussian distribution. In particular the χ^2 becomes the double when fitting the data with a distribution that consider the presence of a Gaussian which is 10% of the off-axis distribution. The χ^2 become a factor 20 larger in the case the Gaussian is 20% of the off-axis distribution. Spatial profiles with strong off-axis contents similar to the second NHG in helical polarization presented in Fig. 5 have been seen also for the second NHG in planar polarization and for the third NHG in helical polarization (data not shown).

In conclusion, a detailed experimental characterization of the process of coherent harmonic generation in single-pass free electron lasers has been presented. The reported results for the nonlinear harmonic generation in helical undulators are in quantitative agreement with recent theoretical results [9], that predict no coherent harmonic emission on axis in helical undulators.

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[1] M. J. Schmitt and C. J. Elliott, Phys. Rev. A **34**, 4843 (1986).
[2] R. Bonifacio, L. De Salvo, and P. Pierini, Nucl. Instrum. Methods Phys. Res., Sect. A **293**, 627 (1990).
[3] Z. Huang and K. J. Kim, Phys. Rev. E **62**, 7295 (2000).
[4] S. G. Biedron *et al.*, Phys. Rev. ST Accel. Beams **5**, 030701 (2002).
[5] A. Tremaine *et al.*, Phys. Rev. Lett. **88**, 204801 (2002).
[6] H. P. Freund, P. G. O'Shea, and S. G. Biedron, Phys. Rev. Lett. **94**, 074802 (2005).
[7] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Phys. Rev. ST Accel. Beams **9**, 030702 (2006).
[8] G. Geloni, E. Saldin, E. Schneidmiller, and M. Yurkov, Opt. Commun. **271**, 207 (2007).
[9] G. Geloni, E. Saldin, E. Schneidmiller, and M. Yurkov, Nucl. Instrum. Methods Phys. Res., Sect. A **581**, 856 (2007).
[10] D. F. Alferov, Yu. A. Bashmakov, and E. G. Bessonov, Sov. Phys. Tech. Phys. **18**, 1336 (1974).
[11] Plenary discussion at the International Workshop on Frontiers in FEL Physics and Related Topics (September 8–14, 2007).
[12] R. Coisson and F. De Martini, *Physics of Quantum Electronics* (Addison-Wesley, Reading, MA, 1982), Vol. 9, p. 939; L. H. Yu, Phys. Rev. A **44**, 5178 (1991).
[13] L. H. Yu *et al.*, Science **289**, 932 (2000).
[14] For more information of the storage ring refer to http://www.elettra.trieste.it/index.php.
[15] F. Curbis, Ph.D. thesis, Univ. of Trieste, 2008.
[16] B. M. Kincaid, J. Appl. Phys. **48**, 2684 (1977).
[17] J. R. Taylor, *An Introduction to Error Analysis* (University Science Books, Herndon, VA, 1982).