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Test of HHG chambers for seeding at SPARC

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ABSTRACT

We propose to use High Order Harmonic Generation (HHG) in gases to seed the SPARC FEL (Frascati, Italy) in the high gain harmonic generation configuration. HHG produces a coherent XUV source by focussing an intense laser pulse into a gas medium. This output radiation is composed of fundamental and odd harmonics of the laser. Dedicated chambers have been realized and tested at the CEA (Saclay, France). They allow generation and shaping of the harmonic beam for further focussing at variable position. A final periscope will allow the injection of the selected harmonics inside the first section of the undulator. The SPARC facility will deliver an electron beam at 200 MeV, passing through a six sections long undulator. Injection of the third and fifth harmonics (266 and 114 nm) is foreseen. Nonlinear harmonics could enable to reach 32 nm. In this paper, we present the tests performed on the seeding chambers, as well as simulations of the expected performances of the HHG seeded FEL.

1. Introduction

Free Electron laser (FEL) can be used in single pass mode to generate intense and short pulse duration in XUV domain. The common scheme is called self-amplified spontaneous emission (SASE) where the radiation amplification starts from shot noise [1–3]. In spite of a high peak power at short wavelengths, the output radiation remains very fluctuating with a poor temporal coherence. Seeding an FEL with an external high quality source is among the attractive solutions to produce XUV radiation with full temporal coherence and little energy fluctuations [4,5]. Indeed, the properties of the seed are transferred to the output FEL radiation and its higher harmonics. In the High Gain Harmonic Generation (HGHG) configuration [4], the external seeded source performs energy modulation within a first undulator section. This energy modulation is further converted into density modulation, when the electron beam passes through a dispersive section. The microbunching allows strong coherent emission inside a second undulator with harmonic content. (In the FEL amplifier case, one single long undulator is used.) The tuning of the undulators selects the amplified harmonics. Demonstration of this scheme has been given both in the midinfrared and VUV domain [6,7]. A way to reach shorter wavelengths is to use a seed laser in VUV domain. Development in femtosecond laser technology have made possible to imagine new coherent short wavelength sources. One of these sources, called High Order Harmonics Generation (HHG), is based on the interaction between the laser beam and a gas target [8,9]. The intense laser electric field free electrons of the gas medium by tunnel ionization within the continuum. Their radiative recombination leads to the delivery of an intense UVX photon, whose frequency depends on the kinetic energy acquired in the continuum. New frequencies are created and, after the gas medium, one can observe high order harmonics of the fundamental frequency co-propagating with the fundamental laser beam. The radiation presents an excellent spatial and temporal coherence [10–12], similar to those of the fundamental laser beam. The harmonics are also tunable via drive laser wavelength tuning [13], double frequency mixing [14] or laser pulse energy and/or chirp adjustment [15]. Microjoule energies can be obtained at wavelengths down to 50 nm [16,17]. Given these high qualities, it has been proposed to use HHG as seed to inject an undulator [18]. The first demonstration was recently given on the SCSS prototype accelerator [19]. HHG seems to be a very good candidate to seed FEL cascade, to extend the operating wavelength of FELs down to sub-nm. The SPARC configuration will allow the study of the problems related to the injection of an external radiation seed in a single pass FEL and the analysis of the coupling efficiency of the electron–photon beams in terms of the input parameters [20].

2. Experimental layout

The SPARC FEL is a single pass FEL which can be operated either in the amplifier or HGHG configuration. A 1.6 cell S-band rf-gun generates a high brightness electron bunch, which is then accelerated in three successive SLAC-type linac structure up to

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an energy between 150 and 200 MeV. At the output of the accelerator, the electron beam is 3.5 ps-rms long, with 2×10^{-4} energy spread, 1π mm mrad slice emittance, and 100 A peak current. SPARC undulator consists of six sections of 75 periods each. With a period of 28 mm, and a maximum deflection parameter of 2.9, this undulator enables radiation from 500 to 108 nm on the fundamental. The flexibility offered by the six independent sections will allow to test different configurations [20]. The seed will be injected by means of a magnetic chicane into the first undulator section, and overlap the electron beam. It consists of the first odd harmonics ($\approx \mu$J at 266, 160 and 114 nm) of a Ti:Sa regenerative amplifier (coherent) at 800 nm, with 2.5 mJ energy, 130 fs pulse duration and 1 kHz repetition rate.

3. SPARC's HHG seed

Specific chambers for HHG have been designed at CEA Saclay for the injection of the SPARC facility. The setup for the production is given in Fig. 1. It mainly consists of three chambers kept under vacuum. The infra-red laser is focussed with plano-convex lens ($f = 2$ m) and delivered through an antireflecting coated 790 nm window into the first chamber. As interaction medium, we use a 1 cm long-windowless cell, where gas is injected by bursts of 1.3 μs through an electromagnetic valve synchronized with the incoming laser pulses. The harmonics produced in the forward direction, together with the infra-red laser, are then transported to the third chamber for beam shaping. Two concave mirrors on motorized mounts, with, respectively, a focal length of 200 and 150 mm, reflecting nearly normal incidence, are used to adapt the harmonic beam mode for a correct overlap with the e-beam in the undulator. The distance between the two mirrors is about 38 cm, and a translation stage under the second optic allows variation of the focussing point position inside the first undulator over 1.5 m. The second chamber only performs differential pumping to satisfy the vacuum level required for connecting to the SPARC accelerator.

The assembly of the chambers was completed in March 2006, and first tests performed using as fundamental source the femtosecond laser system (LUCA) of the Saclay Laser-matter Interaction Center (SLIC). LUCA is a multibeam femtosecond laser based on 2 TW, 20 Hz CPA Titanium:Sapphire System [21]. The duration of the recompressed pulse is about 60 fs and the energy can be varied up to 17 mJ at 800 nm. The energy was decreased down to 2.5 mJ during the tests to operate in SPARC's foreseen conditions. To obtain a well-defined spatial mode and to optimize the efficiency conversion we apertured the 30 mm beam up to 12 mm. For beam shaping, we used two pairs of concave mirrors (multilayers and aluminum mirrors) with high reflectivity at 266 nm. High harmonics generated in the chambers pass through an interferential filter centered at 266 nm (H3) eliminating IR beam as well as other harmonics. The 266 nm radiation is then detected with a calibrated VUV photodiode blinded for diffused IR light. The first step to optimize the harmonic yield was to control the laser aperture and the cell focus position [22,23]. Closing an iris placed before the lens means decreasing the energy laser and increasing the focal spot size, therefore decreasing the focal intensity. Fig. 2 shows, in argon, an optimum harmonic signal for an aperture size of 14 mm (resp. 18 mm) for a 60 fs laser pulse (resp. 120 fs laser pulse). These optimum correspond to a laser energy of 2.5 mJ, an intensity of 2×10^{14} W/cm^2 and a focal spot diameter of 340 μm at 60 fs (279 μm at 120 fs).

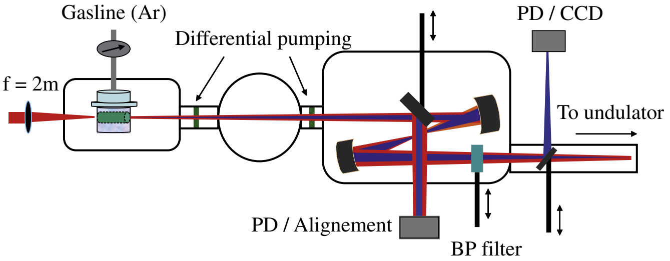

Fig. 1. Experimental setup.

In our measurements, the maximum efficiency has been reached when the focussing point of the laser beam was after the cell. Low order harmonics are optimized by maximizing the interaction volume with the help of the ionization induced defocussing. The optimal laser cell position is then obtained for a focal plane 1.5 cm after medium (see Fig. 3). At this position the spot diameter is about 370 μm corresponding to an intensity 1.8×10^{14} W/cm^2.

The influence of the pressure at optimal laser aperture has also been studied: third harmonic signal increases slowly with the backing pressure (Fig. 4). With higher backing pressure, the electromagnetic valve limits the pressure in cell. The third harmonic energy generated in the optimized conditions is 9.7 μJ. In the same conditions, when third harmonic is generated by a chirped 120 fs pulse, the energy decreases by factor 4 (2.4 μJ).

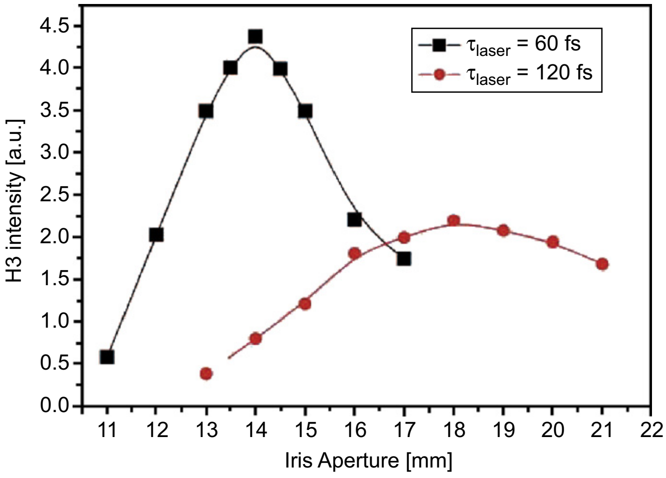

Fig. 2. Harmonic signal as a function of aperture size.

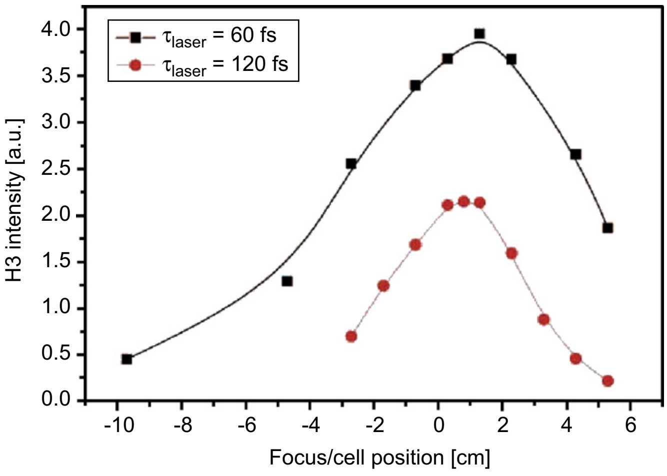

Fig. 3. Third harmonic signal generated in argon with 2.5 mJ laser energy as a function of the position of the focus relative to the cell for two pulse widths (60 and 120 fs).

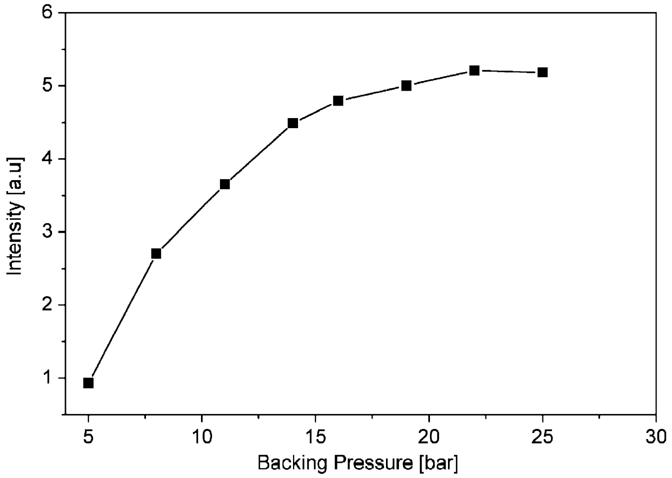

Fig. 4. Pressure dependence of H3 in argon.

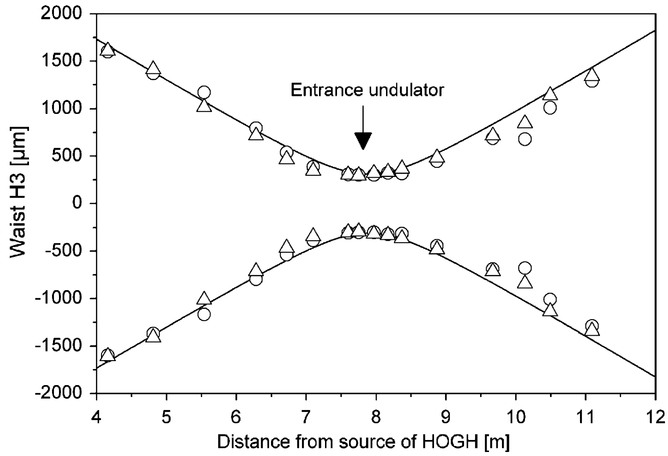

Fig. 6. Longitudinal evolution of the beam waist of the third harmonic in vertical (△) and horizontal (○) direction. Solid line indicates the quasi-Gaussian beam fit.

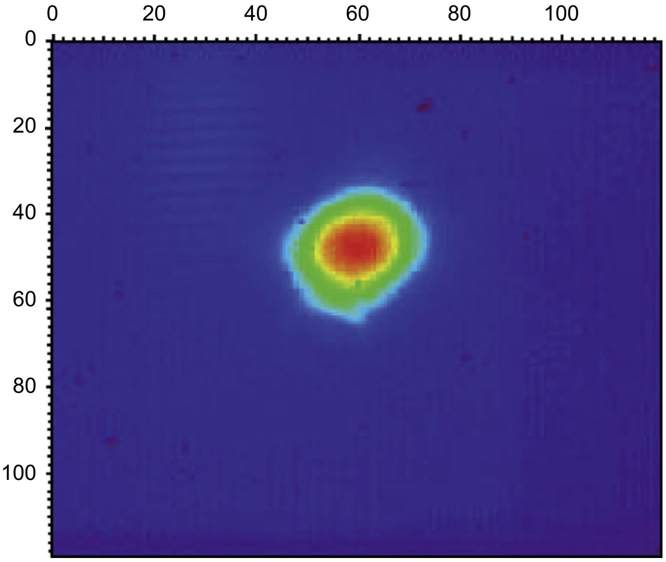

Fig. 5. CCD image of the third harmonic generated with 2.5 mJ laser energy and 120 fs pulse duration.

Table 1
HHG seeded FEL performances

λ_{seed} (nm)	P_{seed} (W)	λ_{rad} (nm)	P_{rad} (W)
266	200	266	0.24 GW
266	200	88.6	10 MW
266	200	53.2	1.5 MW
160	600	160	0.24 GW
160	600	53.3	660 kW
160	600	32	5 kW
114	8000	114	57 MW
114	8000	38	1.4 kW

λ_{seed} is the seeding wavelength, P_{seed} is the minimum input power required to reach saturation. λ_{rad} is the wavelength of the output radiation (fundamental and nonlinear harmonics) and P_{rad} the corresponding peak power.

A VUV spectrometer allowed coarse comparison of the relative contributions of H3 and H5. H5 exhibits similar dependency with the drive laser parameters than H3, thus with a lower intensity (by factor 2.4).

The harmonic beam propagation is crucial for evaluating the overlap between the light wave and the electron bunch in the undulator. For initial tests, we used concave mirrors optimized for H3, and the incidence angle of 2° was found inducing small geometric aberrations. The total transmission for third harmonic is 90%. The spatial profile of the third harmonics has been measured using a CCD camera (see Fig. 5). Fig. 6 shows the evolution of H3 from the exit of the chambers throughout the undulator. The focal spot size is about 940 μm. The theoretical fit with a quasi-Gaussian beam [24] gives an M^2 value of 1.6 and a third harmonic size of 220 μm at generation point.

4. HHG seeded FEL simulations

When operated at 200 MeV, the SPARC FEL can amplify radiation from 300 down to 108 nm. The injection of the third (266 nm) to seventh (114 nm) harmonics of the drive laser can therefore be tested. The SPARC FEL seeded with the HHG seed is simulated using PERSEO TD code [25]. Main results are summarized in Table 1. According to these preliminary calculations, the expected seed power (from tests) should allow to saturate the FEL amplifier on the fundamental at the three seeding wavelengths. In addition, nonnegligible power will also be radiated on nonlinear harmonics, i.e. at shorter wavelengths (down to 32 nm).

5. Conclusion

Specific chambers have been designed and assembled at CEA Saclay to seed SPARC FEL amplifier with HHG. The preliminary tests performed in May 2006 allowed to optimize both harmonic generation efficiency and beam shaping. The simulations using the experimental parameters obtained during these tests offer attractive perspective in terms of FEL perfromance. The quality and reliability of this HHG seed may also allow high interest investigations in the seeded FEL field. The first seeding experiments should start at the end of 2007.

Acknowledgments

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