SEEDING THE SPARC TEST FACILITY WITH HARMONIC GENERATION IN GASES: PRELIMINARY TESTS OF THE HARMONIC GENERATION IN GAS CHAMBER

O. Tcherbakoff, M. Labat, G. Lambert, D. Garzella, M. Bougeard, P. Breger,
P. Monchicourt, H. Merdji, P. Salières, B. Carré, CEA, DSM/SPAM, 91191 Gif-sur-Yvette, France
M.E. Couprie, SOLEIL, 91192 Gif-sur-Yvette, France
A. Doria, L. Giannessi , ENEA C.R. Frascati, Italy.

Abstract

A coherent short wavelength source can be realised with a Free Electron Laser by using High Gain Harmonic Generation configuration. The injection of an external light source in the first part of an undulator results in a coherent light emission in its second part. The SPARC FEL (Frascati, Italy), delivering an electron beam at 200 MeV passing through an undulator of 6 sections, can be configured to test such schemes. We propose to use High order Harmonic Generation (HOHG) in gases process as the seed. HOHG produces a coherent XUV source by focusing an intense laser pulse into a gas medium. This beam, composed of odd harmonics of the fundamental laser, is then shaped using a telescope of two spherical mirrors, allowing the focusing at a given position, in the SPARC undulator. Appropriate tuning of the undulator gaps will amplify the 3rd and 5th harmonics seeded, and non-linear harmonics of those wavelengths, allowing the perspective of producing VUV coherent radiation. The chambers for harmonic generation and shaping have been realised and tested at the CEA (Saclay, France). We present these tests.

INTRODUCTION

Along the last few years, other Free Electron (FEL) schemes than the common Self Amplified S neous Emission (SASE) [1] have been proposed to ge intense and short pulse duration in XUV domain. In Gain Harmonic Generation (HGHG) configuration an external seed, a laser source, induces energy modu of the relativistic electrons in the modulator, leadir coherent emission of the microbunched electron be the radiator at the n^{th} harmonics of the laser funda wavelength. The harmonic radiated is selected tuni undulator gap. The properties of the output radiati determined by the seed laser and can thus inherit degree of temporal coherence. Seeded FEL amplif eration in combination with harmonic generation ha demonstred experimentally in midinfrared and VUV domain [4, 5].

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 (HOHG), is based on the interaction between the laser beam and a gas target [6, 7]. Microjoule energies can be obtained at wavelengths down to 50 nm [8, 9]. It has been proposed to use HOHG as seed to inject an undulator, either in the amplifier or in the HGHG configuration [10]. HOHG seem 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 [11].

EXPERIMENTAL SETUP FOR THE HARMONIC CHAMBERS

SPARC undulator is composed of 6 sections of 75 periods each. The e-beam energy may be varied up to 150-200 MeV. A Coherent femtosecond laser which delivers 120 fs, 2.5 mJ pulse with a central wavelength at 800 nm and a modified repetition rate of 10 Hz, generates HOHG in a gas jet. The VUV radiation is then injected into the undulator by means of a magnetic chicane. Electron and photon ... the undula- ... llow to test

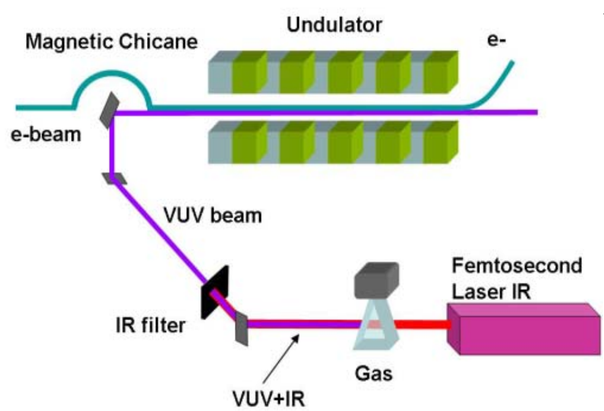

Figure 1: Experimental layout to seed harmonics generated in gas into FEL.

HIGH ORDER HARMONIC GENERATION

HOHG is obtained by focusing an intense laser pulse into a rare gas medium. The atoms of the gas medium are irradiated and ionized by the strong laser field, releasing free electrons with no kinetic energy. Those electrons are then accelerated by the laser electric field. When the electric field sign changes, the electrons can be driven back in the vicinity of the parent ions, and if a collision occurs, the extra-energy of the ion-electron recombination is released by emitting a photon. New frequencies are created and, after the gas medium, one can observe odd high order harmonics of the fundamental frequency co-propagating with the fundamental laser beam. This VUV radiation also exhibits an excellent spatial and temporal coherence [14, 15, 16]. The coherence properties of the harmonics are similar to those of the fundamental laser beam which make them suitable for seeding experiment.

The setup for the production of the harmonics in gas is mainly composed of two chambers. The laser is focussed by a plano-convex lens (f=2 m) and delivered through an antireflecting coated 790 nm window in the first chamber where HOHG occurs. Then, 1.5 meters downwards, the second chamber is used to adapt the waist, i.e. the harmonic beam mode in the middle of the first undulator for a correct overlap with the e-beam. This shaping is performed using two spherical mirrors reflecting nearly at normal incidence, both equipped with motorized mounts, and an additional translation stage under the second mirror, for the adaptation of the focusing point in the undulator. The distance between the gas jet and the middle of the first undulator is about 8 m. A scheme of the experimental setup is given in Figure 2.

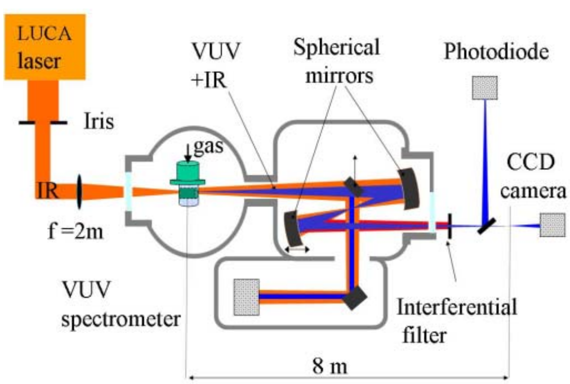

Figure 2: Experimental setup

CHARACTERISATION OF THE HHG PRODUCED IN CEA-SACLAY

In order to prepare the seeding experiment on SPARC facility, the chambers for harmonic generation have been tested during two months at the CEA-Saclay (see Figure 3). The radiation generated in the chambers passes through an interferometric filter centred at 266 nm (H3) eliminating

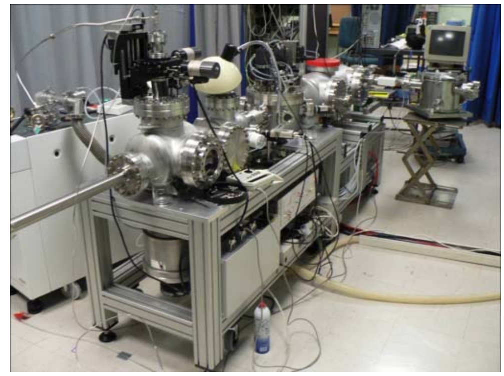

Figure 3: Picture of the chambers being tested at CEA-Saclay.

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 femtosecond laser system (LUCA) of the Saclay Laser-matter Interaction Center (SLIC) has been used as fundamental source for the tests. The characteristics of this laser based on 2 TW, 20 Hz CPA Titanium:Sapphire System [17] are given in Table . Both duration and energy of the laser pulse were tunable: several tests were performed using a 2.5 mJ - 120 fs laser pulse in order to work in similar conditions as the one expected on SPARC facility.

Table 1: Characteristics of the laser system LUCA used for the tests. The pulse duration was measured using autocorrelator, assuming a gaussian profile.

Laser characteristics	Value	Unit
Wavelength	800	nm
Spectral width	20	nm
Pulse duration	56.8	fs
Energy	50	mJ
Beam diameter	35	mm

The initial configuration foreseen for harmonic generation, a simple gas jet with an aperture of 0.5 mm and no additional nozzle, allowed a very small amount of UV photons to be produced. To reach a better conversion factor, the geometry was improved through out the testing of four different configurations: Jet and vertical guide, Jet and horizontal guide, Static Cell and finally Pulsed Cell. The increasing performances are summarized in Figure 4. In the Pulsed Cell configuration, the gas is injected in a 1 cm long-windowless cell by bursts of 1.3 μs through an electromagnetic valve synchronized with the incoming laser pulses. A conversion factor of 10^{-3} was obtained as regularly acheived in recent experiments. A good stability was also reached, as well as a nearly perfectly gaussian harmonic beam.

The first step to optimize the harmonic yield was to con-

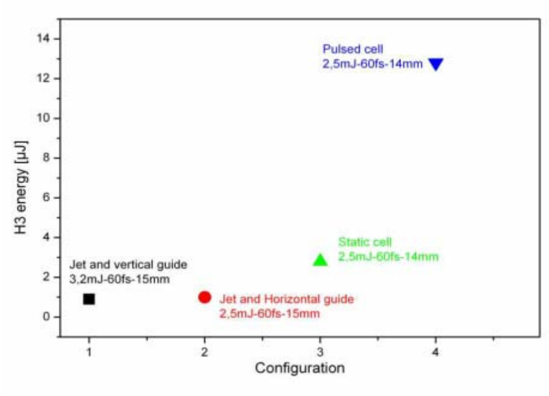

Figure 4: Energy obtained on the third harmonic using different interaction medium configurations.

trol the laser aperture and the cell focus position[18, 19]. Closing an iris placed before the lens means decreasing the energy laser and increasing the focal spot size, therefore decreasing the focal intensity. As illustrated in Figure 5 with 2.5 mJ laser energy in Argon gas, a larger aperture is needed in case of a long pulse duration: 14 mm (resp. 18 mm) for 60 fs pulse (resp. 120 fs chirped laser pulse). The energy contained in each pulse remains unchanged, and fixed to 2.5 mJ. The optimum at 60 fs corresponds to a focal spot diameter of 340 μm, and at 120 fs of 279 μm; both leading to an intensity of $2 \times 10^{14}\ W/cm^2$. The reduced spot diameter at 120 fs involves less medium in the laser-matter interaction, resulting into a lower energy emission (less photons are produced).

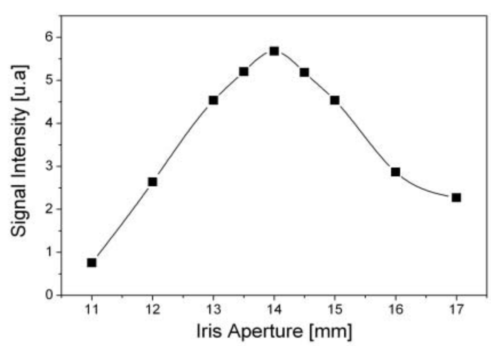

Figure 5: Aperture size dependence of H3 in Argon with 2.5 mJ laser energy for two pulse durations.

Figure 6 illustrates the third harmonic dependency in the cell position. The maximum efficiency has been reached when the focusing point of the laser beam was 1.5 cm after the cell.

Figure 7 illustrates the influence of the pressure on the 3rd harmonic signal. The amount of UV photons produced increases with the backing pressure. No optimum could be reached, since the electromagnetic valve was limiting the available pressure in the cell.

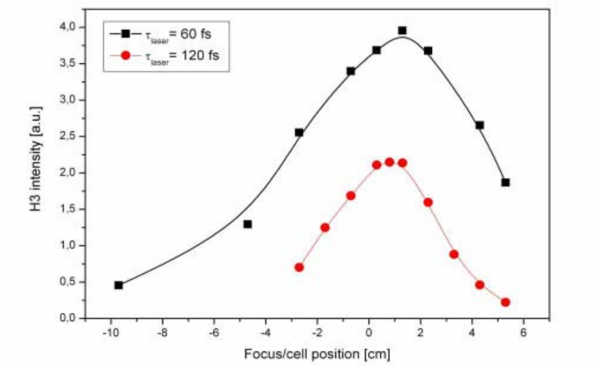

Figure 6: Cell position dependence of H3 in Argon with 2.5 mJ laser energy, for two pulse durations.

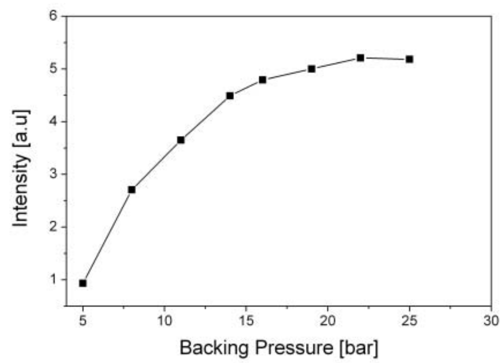

Figure 7: Pressure dependence of H3 in Argon.

The number of 3rd harmonic photons generated in the optimized conditions with 60 fs pulse is 1.3×10^{13} (9,7 μJ) and the corresponding conversion efficiency reaches 4×10^{-3}. In the same conditions, when 3rd harmonic is generated by a chirped 120 fs pulse, the number of photons decreases by factor 4.

We used a VUV spectrometer composed of a LiF prism and a photomultiplier to measure H3 and H5 with an entrance pinhole of 5 mm. Scanning on the prism angle being manual, we only measured maximum signal at one position of the prism angle for H3 and H5 allowing the coarse comparison of the relative contribution of each harmonic, as illustrated in Figure 8.

The harmonic beam propagation has also been studied. It is crucial for evaluating the overlap between the light wave and the electron bunch in the undulator. The harmonic beam is shaped using two concave mirrors optimized for 266 nm wavelength with respectively a focal length of 200 mm and 150 mm. The distance between the two mirrors is about 38 cm. The incidence angle of 2° induces small geometric aberrations. The total transmission for 3rd harmonic is 90 $\%$. The spatial profile of the 3rd harmonics has been measured using a CDD camera. Figure 9 shows the evolution of H3 from the exit of the chambers through out the undulator, and Figure10 shows the transverse pro-

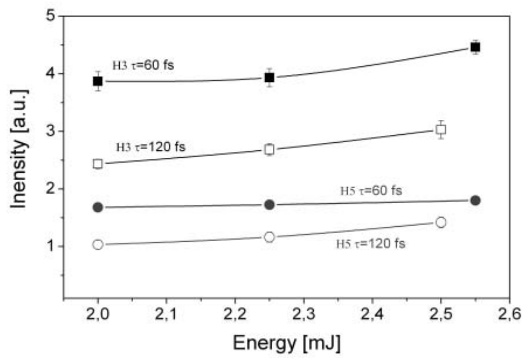

Figure 8: 3rd and 5th harmonics in argon as function of energy laser for two pulse widths.

file of the harmonic at focusing point. The focal spot size is about 940 μm. The theoretical fit with a quasi-gaussian beam [20] gives a M^2 value of 1.6 and a 3rd harmonic size of 220 μm at generation point . With these measurements, we will able to determine the filling factor which takes into account the interaction between electrons and photons.

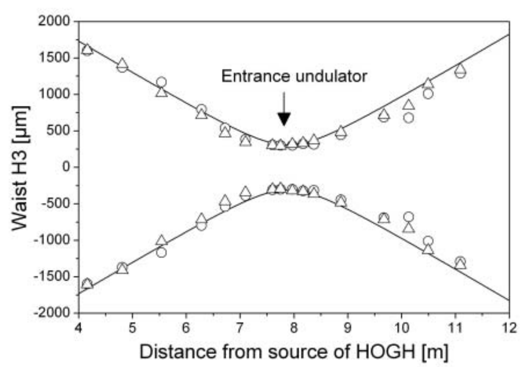

Figure 9: Longitudinal evolution of the beam waist of the 3rd harmonic in vertical (△) and horizontal (○) direction. In solid line indicate the quasi-gaussian beam fit.

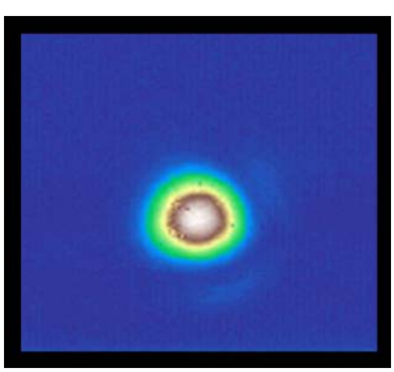

Figure 10: Transverse profile of the 3rd harmonic at focusing point

CONCLUSION

The results of the preliminary tests performed at CEA-Saclay on the chambers are encouraging. An efficient geometric configuration has been defined for the generating medium. According to those first measures, the laser system foreseen at SPARC (120 fs, 2.5 mJ) should be adapted for generation of both 3rd and 5th harmonics with HOHG. We expect more than 4μJ on the 3rd harmonic in Argon. The telescope system focuses the 3rd harmonic beam, which is slightly astigmatic, at the estimated entrance of the first undulator with a focus waist size of 300 μm.

The peak power of this coherent VUV light was estimated to be 19 MW. Calculations with PERSEO and with GENESIS 1.3 code have shown that saturation can be reached with SPARC undulator, using a 266 and 160nm wavelength seed with only a few kW power [11].

The harmonic chambers should be transported to SPARC facility by the end of January 2007. After implementation on the linear accelerator modules, in spring 2007, first seeding experiments of SPARC FEL with this scheme should start.

ACKNOWLEDGMENTS

This work was supported by the EU Commission in the Sixth Framework Program, Contract No. 011935-EUROFEL.

REFERENCES

[1] S.V. Milton *et al.*, Science **92**, 2037 (2001).

[2] L.H. Yu, P.R.A. **44**, 5178 (1991).

[3] I. Ben-Zvi *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. A **304**, 181 (1991).

[4] L.H. Yu, Science. **289**, 932 (2000).

[5] L.H. Yu *et al.*, P.R.L. **91**, 074801 (2003).

[6] M. Ferray *et al.*, J. Phys. B: At. Mol. Opt. Phys. **21**, L31 (1988).

[7] A. McPherson *et al.*, J. Opt. Soc. Am. B **4**, 595 (1987).

[8] J.F. Hergott *et al.*, Phys. Rev. A **66**, 21801 (2002).

[9] E. Takahashi, N. Y., and M. K., Opt. Lett. **27**, 1920 (2002).

[10] D. Garzella *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. A **528**, 502 (2004).

[11] L. Poletto *et al.*, FEL Conference, 63 (2005).

[12] L. Giannessi *et al.*, www.sparc.it ref:SPARC-FEL-05/004.

[13] L. Poletto *et al.*, proceedings EPAC 2006 (unpublished).

[14] T. Ditmire *et al.*, Phys. Rev. Lett. **77**, 4756 (1996).

[15] L. Le Déroff *et al.*, Phys. Rev. A **61**, 43802 (2000).

[16] L. Bellini *et al.*, Phys. Rev. Lett. **81**, 297 (1998).

[17] http://www-femtodrecam.cea.fr/slic/luca/luca1.htm.

[18] P. Balcou *et al.*, J. Phys. B **25**, 4467 (1992).

[19] T. Ditmire *et al.*, Phys. Rev. A **51**, R902 (1995).

[20] A. E. Siegmann, ”Lasers”, University Science Books.