SEEDING HIGH GAIN HARMONIC GENERATION WITH LASER HARMONICS PRODUCED IN GASES

G. Lambert*, B. Carré, M. E. Couprie, D. Garzella, Y. Mairesse, P. Salières, CEA, DSM/SPAM, 91 191 Gif-sur-Yvette, France, A. Doria, L. Giannessi, ENEA C.R. Frascati, Italy, T. Hara, H. Kitamura, T. Shintake, SPring-8/RIKEN Harima Institute, Hyogo 679-5148, Japan

Abstract

Free electron Lasers employing High Gain Harmonic generation (HGHG) schemes are very promising coherent light sources in the soft X-ray range. They offer both transverse and longitudinal coherence, while Self Amplified Spontaneous Emission schemes have a limited longitudinal coherence. We propose here to seed a HGHG experimental setup with high harmonics produced by a Ti:Sa femtosecond laser focused on a gas jet in the 100-10 nm spectral region. The implementation of this particular laser harmonics source as a seed for HGHG is investigated. Semi analytical and numerical 1D calculations are given, for the cases of the SCSS, SPARC and ARC-EN-CIEL projects.

INTRODUCTION

In order to reach very short wavelengths in systems based on Free Electrons Laser (FEL) [1,2], and to have more compact and fully temporally coherent sources, a High Gain Harmonics Generation (HGHG) configuration [3] is studied here, in which an external laser source is seeded into a modulator, thus allowing a strong prebunching of the e-beam. The use of a long radiator section can lead to the consistent emission of radiation at high order harmonics of the seeding source while reproducing its longitudinal and transverse coherence. A very promising scheme is the one where the seeding source is already in the XUV range, provided by the harmonics of the Ti:Sa laser generated in gas. Intense, ultra-short laser harmonics can be now generated down to 10 nm [4]. We propose to use these laser High Harmonics (HH at λ wavelength) as the seed for a high gain FEL amplifier radiating at λ or $\lambda/3$ and to extract its third and fifth non linear harmonics [2,5]. This scheme is considered for different installations: first on SCSS (Spring-8 Compact Sase Source, Japan) [6] and SPARC (Sorgente Pulsata e Amplificata di Radiazione Coerente, Italy) [7] for demonstration experiments, second on ARC-EN-CIEL (Accelerator-Radiation Complex for ENhanced Coherent Intense Extended Light, France) [8] and BATES (MIT, USA) [9] for efficient X-ray generation. SCSS and SPARC are projects of linac-based FEL, providing a compact SASE source with high brightness in the X-ray range. ARC-EN-CIEL (AEC) is a proposal for an innovative HGHG in the XUV range (Phase 1 is a first step towards VUV). In this paper, we discuss the prototype experiments on SCSS, AEC and SPARC, including a brief description of the experimental setup and theoretical estimate of the performances, the latter based on analytical formulae [1, 10] and 1D simulations using PERSEO code [11].

*guillaume.lambert@lure.u-psud.fr

THEORY OF HIGH ORDER HARMONICS PRODUCED IN GASES

The high harmonic generation in rare gas (Xe, Ar, Ne, He) results from the strong non linear polarisation induced by the strong laser field E_{Laser}, at intensity 10^{14}-10^{15} W/cm^2. The process is qualitatively described in the semi-classical "three-step" model [12, 13]. Close to laser focus, for E_{Laser} comparable to the intra-atomic field, atoms ionize in the tunnelling regime [4] (step 1). The ejected electrons are then accelerated by the laser field and gain a kinetic energy (step 2). Those which are driven back close to the core may recombine to the ground state, emitting a burst of XUV photons (step 3). This three-step process reproduces every half- optical cycle.

EXPERIMENTAL SET UP

Characteristics of High Harmonics in gases

A typical harmonic spectrum generated in Ne is displayed in fig. 1, illustrating the characteristic distribution of the odd harmonics into the "plateau" region, where the conversion efficiency is almost constant, and the "cut-off" region where the conversion efficiency rapidly drops down. The conversion efficiency for high harmonic (HH) generation remains relatively weak, typically varying from 10^{-4} in the plateau to 10^{-7} in the cut-off.

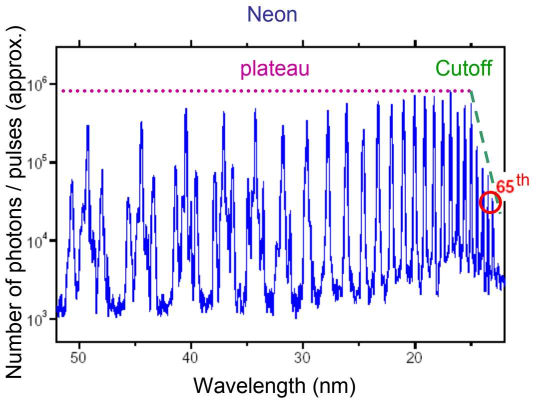

Fig. 1: High Harmonic spectrum in Ne.

The upper spectral limit is given by the "cut-off law" [5, 14]. It states that the lighter the gas, i.e. the higher the ionization potential and the laser intensity to which atom can be submitted without ionizing, the higher the cut-off energy. The HH therefore cover the 100^{-3} nm range (12-400 eV). They have remarkable properties of ultra-short duration (of a few 10 fs down to sub-fs), longitudinal [15] and transverse [16] coherence, good beam quality (small divergence ~ 1mrad on laser axis), easily rotatable linear polarization [17] and can be produced at relatively high repetition rate (up to KHz). Finally it is possible to continuously tune the HH, e.g. by manipulating the spectral phase of the driving laser or by starting from two driving frequencies [18].

Beams and undulators parameters

For the seed experiment, a HGHG configuration is foreseen with two undulators: the modulator (mod), which is chosen according to the wavelength of the seeded radiation, and the "radiator" (rad), providing a high gain. In SCSS and SPARC projects, the radiator emitted wavelength is matched on the fundamental of the modulator ($\lambda_{rad}=\lambda_{seed}$). In AEC and AEC Phase 1 projects it is matched on the third harmonic ($\lambda_{rad}=\lambda_{seed}/3$). The table 1 shows the electron beam parameters, where I_P is the peak current, the undulators parameters, where N_P is the number of periods per section and N_S the number of section, and the seeding parameters, where E_H is the harmonic energy per pulse, P_H the harmonic power and D the harmonic spot diameter.

Table 1: electron beam, undulator, and seeding characteristics.

Projects	AEC PhI	AEC	SCSS	SPARC
Electron Beam Characteristics				
E (GeV)	0.22	1	0.25	0.21
σ_γ	0.001	0.001	0.0002	0.002
Q (nC)	1	1	1	1
ε (π mm-mrad)	1.7	1.5-2	1.5	1
I_P (kA)	0.8	0.6	0.2	0.15
Undulators Characteristics (Mod/Rad)				
λ_R (nm)	267/89	14/4.64	60	160
λ_U (nm)	38.9/20	30/20	15	28
K	1.76/1.14	2.27/1.26	1.39	1.36
N_P	34/450	160/1000	300	487
N_S	1/1	1/1	2	6
Seeding Characteristics				
λ_{seed} (nm)	H3=267	H57=14	H13=60	H5=160
E_H (μJ)	5	1	5	5
P_H (MW)	50	10	50	50
D (μm)	250	250	250	250

Layout of the HGHG configuration seeded by harmonics produced in gases

A Ti:Sa laser system delivers pulses at 800 nm (E_{ph}=1.55eV), which are converted into harmonics in the gas jet vessel. The harmonic pulses are then injected into the modulator. In SCSS and ARC-EN-CIEL projects, a magnetic chicane is inserted on the electron bunch path to superimpose the bunch and the XUV pulse at entrance of the modulator (Fig. 1).

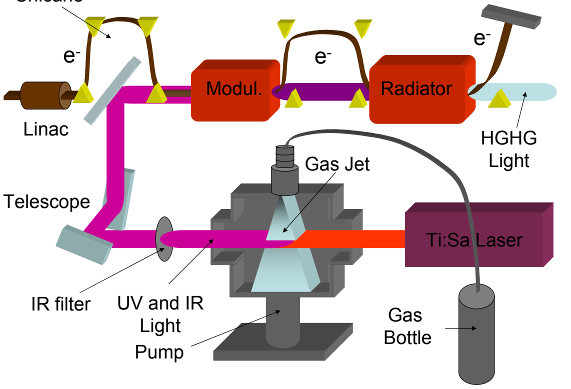

Fig. 1: Layout of the seeding system with a chicane.

A small size mirror serves to inject the XUV beam in the FEL cavity and to adjust its position. The advantage in this scheme is that all the XUV beam (~mm in diameter) is injected; the constraint is that enough room should be available to accommodate the magnetic elements. So, another arrangement, where the chicane is replaced by a holed mirror on the XUV beam, is envisaged in the SPARC project (Fig. 2).

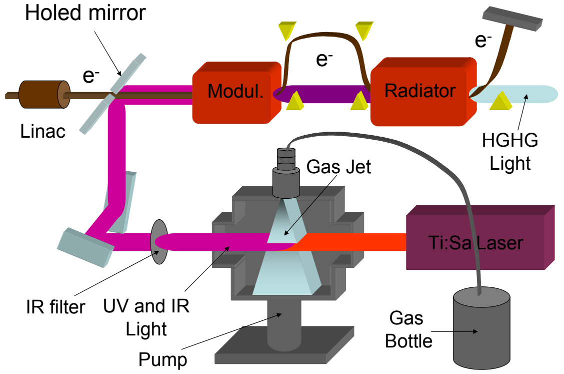

Fig. 2 : Layout of the seeding system with a holed mirror.

The constraint is now that the hole should be sufficiently small so that a high enough XUV energy is reflected.

In both schemes, the laser beam is eliminated using various metallic filters which further select a finite spectral range in the harmonic spectrum. Then the XUV beam should be collimated to a small diameter (mm) by means of a telescope (spherical mirrors in afocal geometry). The different mirrors should also improve, if needed, the spectral selection of a particular harmonic component, e.g. Mo/Si multilayer optics to select high orders in SCSS [19, 20]. The required multiple reflections should not reduce the XUV energy by more than 50%. Thus, if we consider a harmonics injection system based on five optics the global reflectivity falls around 3%.

CODES AND SIMULATIONS

One dimensional code PERSEO

Perseo [11] is a library of functions reproducing the main properties of the desired FEL configuration in a 1D simulation. The basic idea consists in the integration of the pendulum equation coupled to the fields equations. A typical simulation is shown in fig. 4.a,b where the growth of the output peak power on the fundamental and on the higher order non-linear harmonics is represented as function of the longitudinal coordinate in the radiator. The implementation of Perseo considered in this study allows to inspect the energy modulation (fig. 5a) and the associated bunching factor evolution (fig. 5b), during the parameters optimization. Finally in fig.6, the evolution of the output peak power on the harmonics is shown as a function of the seed power and the radiator length.

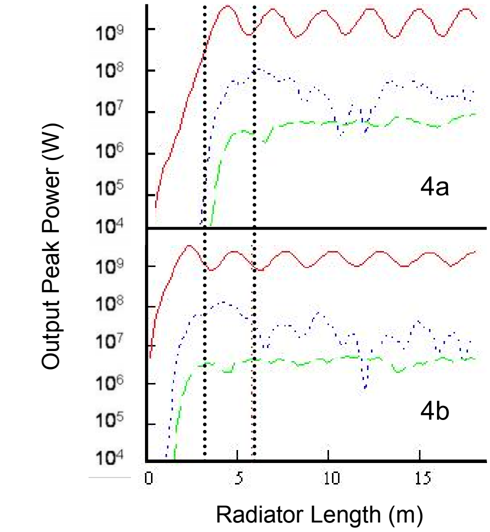

Fig. 4a, 4b: Evolution of the AEC SASE (a) and AEC Seeding HGHG (b) output peak power at 6.5nm (—) and at their third (…) and fifth (---) non linear harmonics.

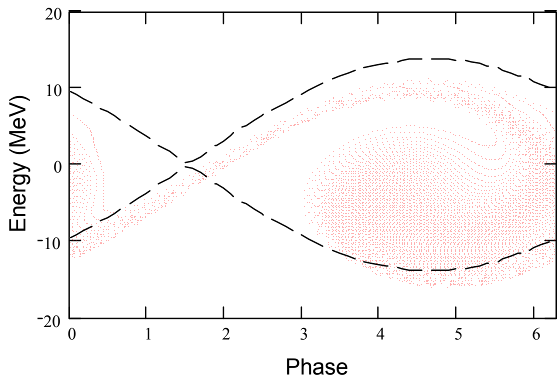

Fig. 5a: Evolution of the energy modulation before the drift section for SPARC project.

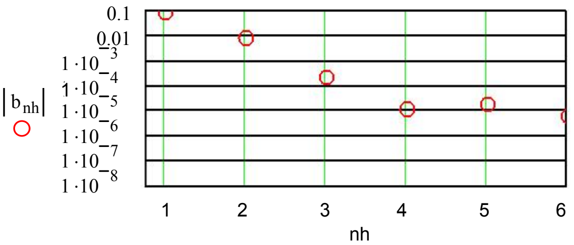

Fig. 5b: Evolution of the harmonics bunching factor (b_{nh}) before the drift section for SPARC project versus the order of harmonics (nh=1 is the fundamental).

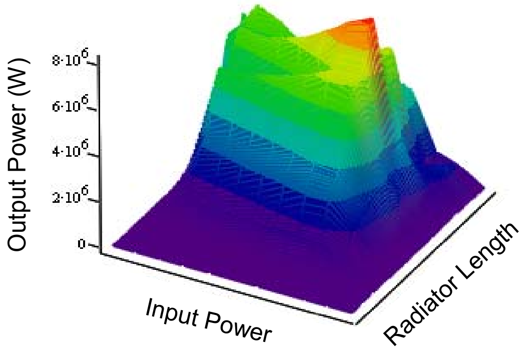

Fig. 6: Evolution of the SPARC Seeding HGHG output peak power for the third non linear harmonics (53.3 nm) versus input power and radiator length.

Analytical simulation

These simulations are based on an analytical 0D approach in static mode, that is to say, with an average on the transverse and longitudinal coordinates. The used FEL formula come from G. Dattoli and P. L. Ottaviani [10]. The simulations allow to investigate the exponential growth of the fundamental output peak power as a function of the radiator length.

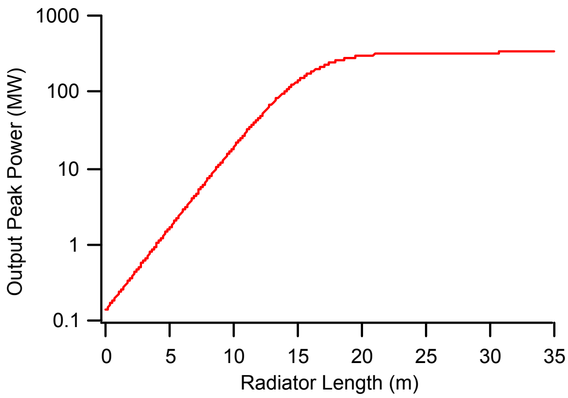

Fig. 7: Evolution of the AEC Seeding HGHG output peak power at 6.5nm.

EXPECTED PERFORMANCES

We can see in table 2 that seeding HGHG configuration allows the saturations lengths to be reduced from a factor of 1.5 to 2.

Table 2: Saturation length (m) comparison with Perseo: Seeding HGHG/SASE.

Projects	Fundamental Output Radiation (nm)	Saturation Length (Seeding/SASE) (m)
ARC-EN-CIEL	9.2	2/7.5
	6.5	3.5/7.5
	5.5	7/12
ARC-EN-CIEL Phase 1	88.9	3.5/5.5
	66.7	4.5/7
	53	6/12
SCSS	60	4/7.5
SPARC	260	4/6
	160	6/8.5

Figure 8 shows the expected results in terms of output power made with Perseo.

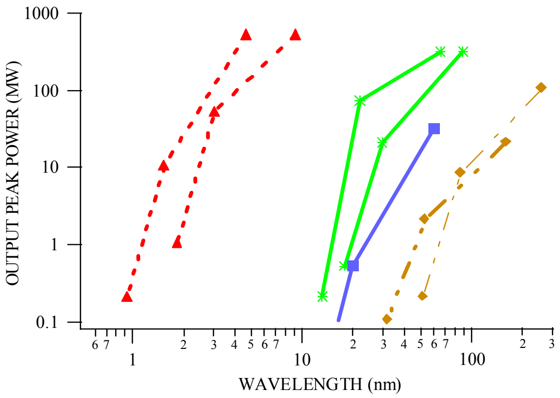

Fig. 8: Output peak power of λ_{rad}, its third and fifth non-linear harmonics for AEC (--▲--), AEC phase 1 (-*-), SCSS (-■-), SPARC (-♦-), and, for seed powers up to 1MW. $<P_{Rrad}>\approx0.1$-0.5 W.

As we can see on the figure 4a and 4b, the output peak power is lower by a factor of ~ 5 for a Seeding HGHG configuration than for a SASE configuration. However, it remains high and now corresponds to fully coherent XUV pulses. For instance, if we seed the SPARC experiment at 260 nm, the fifth harmonic at 52 nm is generated at 0.25 MW output level, whereas seeding at 160 nm gives a fifth harmonic at 32 nm of 0.15 MW peak power.

Figure 9 shows the expected results in terms of output power obtained by the analytical simulations.

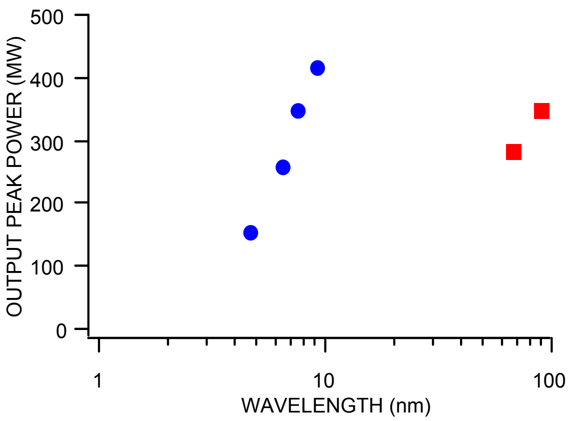

Fig. 9: Output peak power of the $\lambda_{seed}/3$ harmonics performances with a 1MW seed power and with beam parameters coming from Table 1, for AEC (●), and AEC phase 1 (■). $<P_{seed}>\approx0.1$-0.5 W.

CONCLUSIONS

Using high laser harmonics generated in gas for seeding High Gain FEL amplifiers appears very interesting, since the seed radiation is fully coherent, of ultra-short duration and tuneable in the XUV range. The seeding can reduce the saturation length, leading to a more compact source. The calculated performances roughly agree between 0 and 1D analysis. They show that high peak power (> MW) could be obtained with this scheme.

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