SEEDING HIGH GAIN HARMONIC GENERATION WITH LASER HARMONICS PRODUCED IN GASES

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Abstract

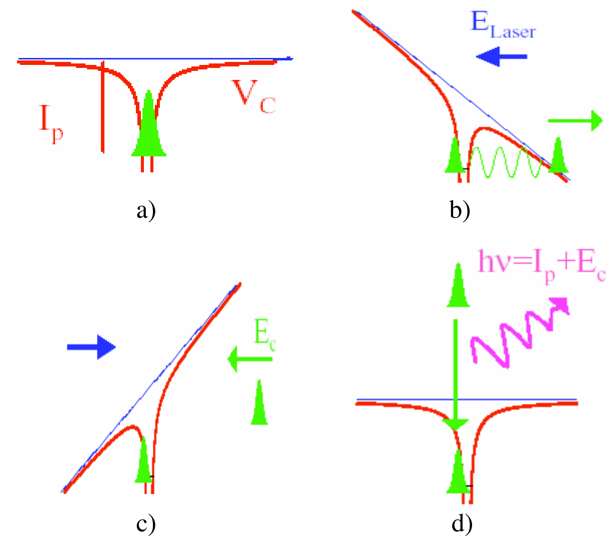
Free electron Lasers employing High Gain Harmonic generation (HGHG) schemes are very promising coherent light sources for the soft X-ray regime. They offer both transverse and longitudinal coherence, inversely to Self Amplified Spontaneous Emission schemes, where the longitudinal coherence is limited.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

INTRODUCTION

During the last years, new schemes other than the Self Amplified Spontaneous Emission (SASE) have been proposed for reaching very short wavelengths in systems based on Free Electrons Laser (FEL) [1,2,3], where the main need is to have more compact and fully temporally coherent sources. We consider here the High Gain Harmonics Generation (HGHG) configuration, first proposed by L. Hua Yu [2]. In this arrangement, an external laser source is seeded into a modulator, i.e. an undulator where a periodic energy modulation is induced in the electron beam. This modulation occurs with the periodicity of the seeding source wavelength, the successive beam evolution in a dispersive section induces the conversion of the energy modulation into a density modulation and of consistent emission of radiation at higher order harmonics with longitudinal and transverse coherence reproducing the laser's one. In parallel, important progress in strong laser-matter interaction have been made, leading to the generation of the high harmonics of intense laser pulses in gases. This technique is being now well-controlled. It is possible to obtain high pulse energy radiation down to 10 nm [4]. It has been proposed to use these High order Harmonics of a laser, generated in a Gas (HHG), as a seed to inject a high gain FEL amplifier, which radiates at $\lambda/3$ or $\lambda/5$, and to extract the Non-linear Harmonics Generated (NHG) [5]. This scheme is studied for different installations: SCSS (Spring-8 Compact Sase Source, Japan) [6], SPARC (Sorgente Pulsata e Amplificata di Radiazione Coerente, Italy) [7] for demonstration experiments and as a source of radiation for ARC-EN-CIEL (Accelerator-Radiation Complex for ENhanced Coherent Intense Extended Light, France) [8], and BATES (MIT, USA) [9]. It would allow shorter and more coherent wavelengths to be reached. We present here a first analysis of the prototype experiments on SCSS, and ARC-EN-CIEL including the experimental set up and theoretical estimations based on analytical formulae from ref.[1,10], and one dimensional simulations using PERSEO [11].

THEORY OF HIGH ORDER HARMONICS IN GASES

The harmonic generation in gas results from the strong non linear polarisation induced on the rare gases atoms, such as Ar, Xe, Ne and He, by the focused intense electromagnetic field E_{Laser} of a "pump" laser. The most important characteristics of the process are given by the three-step semi-classical model [12,13] illustrated in fig. 1



a) b) c) d)

Figure 1: Three-step semi-classical model a) initial state of the gas atom b) electron tunnelling c) gain of kinetic energy E_C d) electron absorption and photon emission. V_P is the gas medium ionization potential.

As the external electromagnetic field strength is comparable to the internal static field V_c of the atom in the interaction region close to laser focus, atoms ionize by tunnelling of the electrons. The ejected free electrons, far from the core, are then accelerated in the external laser field and gain in kinetic energy E_C. Those which are driven back close to the core can either be scattered or recombine to the ground state emitting a burst of XUV photons every half-optical cycle.

EXPERIMENTAL SET UP

High Order Harmonics in Gases Characteristics

A typical spectrum of harmonics generation in gas (see fig. 2) looks like a train of XUV bursts, superposition of the high order odd harmonics, separated by twice the fundamental energy.

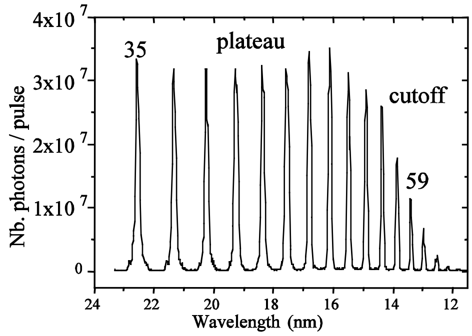


Figure 2: High Order Harmonics spectrum in Ne.

Even if the conversion rate of this technique is relatively weak (10^{-4}-10^{-7}), the characteristic distribution of intensities is almost constant with harmonic order into the "plateau" region. For higher orders, the conversion rate and consequently the intensities decrease rapidly in a zone called "cut-off" region. Its upper spectral limit is given by $E_{cutoff} = V_P + 3.2\ U_P$. E_{cutoff} is the "cut-off" photon energy, V_P is the gas medium ionization potential, U_P is the ponderomotive potential and $U_P \propto I_{pump}\ \lambda^2_{pump}$, with I_{pump} the focused intensity, λ_{pump} the wavelength of the pump and finally 3.2 corresponds to the maximum of kinetic energy which can be reached by the electron. In the regime, where atoms are not ionized, the lighter the gas, the higher the ionization potential and the laser intensity, and consequently the higher the cut-off energy. The maximum number N_{max} of orders can be deduced by: $N_{max} \approx E_{cutoff}/h\nu_{pump}$, where ν_{pump} is the pump frequency.

Moreover, the radiation spectrum is completely tuneable in the VUV-XUV region by means of frequency-mixing techniques applied on the pump laser [14]. High order harmonics are linearly polarized sources [15] between 100 and 3 nm (12-400 eV), of high temporal [16] and spatial [17] coherence, emitting very short pulses (less than 100 fs), with a relatively high repetition rate (up to few KHz). The harmonic radiation is emitted in the axis of the laser propagation with a small divergence (1 to 10 mrad).

Finally, table 1 gives the Harmonics parameters used for the seeding.

Table 1: Harmonics parameters: λ (nm), Pulse Length τ (fs), Energy E_H (μJ), Number of 10^{11}ph/pulse N, Intensity I (10^{10} W/cm^2), Spot Diameter D (μm)

	λ	τ	E_H	N	I	D
H1	800	60	15000	80.4	1.25 10^4	500
H3	266	30	2	26.8	17	250
H19	42	30	2	4.24	17	250
H57	14	30	2	1.41	17	250

Electron Beam and Undulators Parameters

SCSS is a project of a Linac based FEL, providing compact SASE source with high brightness in X-ray range. ARC-EN-CIEL (AEC) is a proposal of a Linac based FEL, which would bring an innovative coherent light source in the UV-X ray range, and would begin with a first phase to reach VUV range.

Table 2: Electron beam characteristics: Beam Energy E (GeV), Energy Spread Σ_γ, Bunch Length τ_e (rms, fs), Bunch Charge Q (nC), Normal Emittance ε (π mm-mrad), Peak Current I_P (kA), and Transverse Dimension σ (μm)

Projects	AEC Phase I	AEC	SCSS
E	0.22	1	1
Σ_γ	0.001	0.001	0.0002
τ_e	300	200	250
Q	1	1	0.5
ε	1.7	1.5-2	2
I_P	0.8	0.6	2
σ	100	150	100

For the seed experiment, an 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), which radiates on the third harmonic and proving a high gain.

Table 3: Undulators characteristics: Resonant Wavelength λ_R (nm), Period λ_U (mm), Deflection Parameter K, Periods/Section N_P, Number of Sections N_S

Proj.	AEC Phase I		AEC		SCSS	SPARC
Und.	mod	rad	mod	rad	mod+rad	mod+rad
λ_R	267	89	14	4,64	14	160-53.33
λ_U	38.9	20	30	20	15	28
K	1.76	1.14	2.27	1.26	1.25	1.36
N_P	34	450	160	1000	500	487
N_S	1	1	1	1	5	6

Layout of the HGHG Configuration Seeded by Harmonics Produced in Gases

Before the modulator section, a Ti:Sa laser system is intended to deliver radiation at 800 nm (E_{ph}=1.55eV). In the gas jet vessel, the Ti:Sa radiation is converted in order to obtain harmonics, which can be then injected into the modulator either by a chicane or a holed mirror.

The first system of implementation (fig. 3) consists in deflecting the electrons from the axis of the undulators with a chicane, which is composed of magnetic dipoles. It allows the harmonics beam to be injected into the modulator thanks to a mirror and providing the possibility to adjust the position and the angle at the modulator entrance. The chicane drives, in fact, the electrons around this mirror of seeding until the modulator. Nevertheless, enough space should be available in order to accommodate the magnetic elements. Finally, this technique will be probably used in SCSS and ARC-EN-CIEL projects.

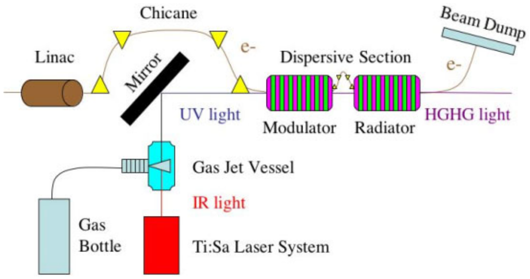


Figure 3: Layout of the seeding system with a chicane.

The alternative solution, chosen for SPARC, is a holed mirror allowing the electron beam to pass through and the harmonic light to be injected (see fig. 4). It can provide a spectral selection for the given harmonic in gas, and can be rather small and thus easily added on installations.

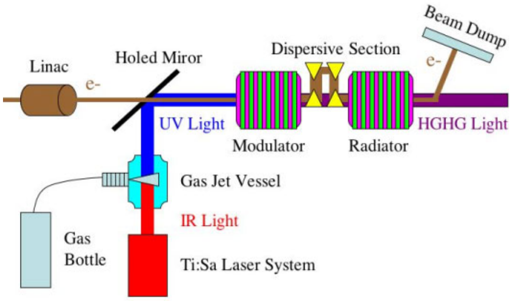


Figure 4: Layout of the seeding system with a holed mirror.

Different types of mirrors will be used, according to the seed wavelength, and also in order to optimize the optical properties of transport. Concerning the UV range, multidielectric mirrors such as oxides and fluorides can be used. Si/C would be useful for a reflectivity around 80-40 nm. In the 50-40 nm spectral region, Sc/Si could be used, and at 14 nm Mo/Si [18, 19]. To improve the focalisation into the modulator and the overlap the harmonic pulse with the electron beam, a spherical mirror with a radius of curvature of 10 m at 42 nm is available.

EXPECTED PERFORMANCES

Analytical Simulation [10]

A first estimate of the $\lambda_{Rmod}/3$ harmonics performances (see fig. 5) can be obtained in static mode, averaging on the transverse and longitudinal coordinates.

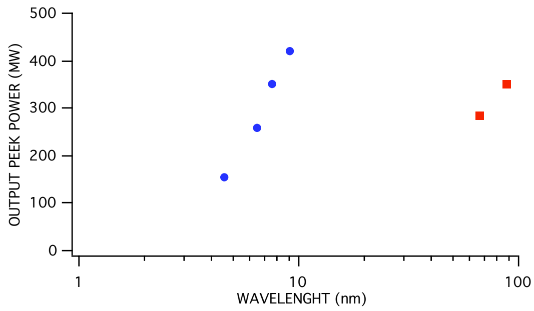


Figure 5: Output peek powers of the $\lambda_{Rmod}/3$ harmonics performances with a 1MW seed power and with beam parameters coming from Table 2, for AEC (●), and AEC phase 1 (■). <P>≈0.1-0.5 W, Flux ≈1-6 10^{16} ph/s.

One Dimensional Code PERSEO [11]

Perseo is a library of functions, which reproduce the main properties of the desired FEL configuration in a 1D simulation. In this example, Perseo has been used to show the evolution of the electrons bunching for different e-beam parameters and the growth of the peak power of the radiated wavelength, on the fundamental on the third and fifth non-linear harmonics, as a function of the longitudinal coordinate. Fig. 6 shows the expected results in terms of output power. In the SCSS project, one seeds at 14 nm and extracts its non-linear harmonics. In the AEC and AEC phase 1 cases, one seeds at 22 nm, radiates at its third linear harmonic and extracts its non-linear harmonics.

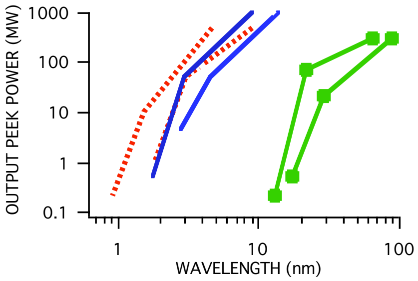


Figure 6: Output peek powers of λ_{Rrad}, its third and fifth non-linear harmonics for AEC (----), SCSS (—), and AEC phase 1 (-●-), for seed powers less than 1MW. $<P_{\lambda Rrad}>$≈0.1-0.5 W.

The results between 0D and 1D analysis roughly agree. Estimations carried out have shown that high peak power could be obtained with this scheme.

CONCLUSIONS

Using state-of-the-art High Order Harmonics in gas for seeding High Gain FEL amplifiers appears very interesting, because the seed radiation is fully coherent and tuneable in the VUV-XUV range. Such a seeding can reduce saturation lengths giving a more compact source.

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