SEEDING THE FEL OF THE SCSS PHASE 1 FACILITY WITH THE 13TH LASER HARMONIC OF A TI: SA LASER PRODUCED IN XE GAS

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Abstract

In order to reach very short wavelengths in FEL, and to have a more compact, fully coherent and tunable source, a particular seeding configuration is foreseen to be tested as a demonstration experiment in 2006 into the SCSS phase 1 facility (Spring-8 Compact Sase Source, Japan). The external source is the 13th harmonic (61.5 nm) of a Ti: Sa laser (25 mJ, 10 Hz, 100 fs) generated in 10 Hz pulsed Xe gas cell. The harmonic generation process provides us with an intense (1 µJ) and ultra-short (50 fs) VUV beam. The design of the experiment implantation is discussed, taken into account the performances of the generation process, the focusing of the selected harmonic into the modulator, and the resistance of the optical components. Besides, one should consider the vacuum needs, the geometrical problems and the mechanics for the under UHV mirrors translation. One first chamber is dedicated to the harmonic generation. A second one is used for spectral selection and adaptation of the harmonic in the modulator. Finally theoretical estimates of the performances relying on 1D simulations using PERSEO code and 3D simulations using GENESIS code are also given.

INTRODUCTION

A seeding experiment on the SCSS prototype [1] is proposed here, in order to achieve more compact and fully coherence on a Free Electrons Laser (FEL) based light source at short wavelength, with respect to the simple scheme based Self Amplified Spontaneous Emission (*SASE*). Seeded FEL at 1.06 µm combined to the generation of coherent harmonics has already been demonstrated experimentally in Brookhaven, using the High Gain Harmonics Generation (HGHG) configuration [2]. 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, allowing to obtain high pulse energy radiation down to 10 nm [3]. It is 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 and to extract the Non-linear Harmonics Generated (NHG) [4,5,6]. Recently such a seeding experiment with high harmonics produced in gases was performed in an X-ray laser [7].

The basic layout of a seeding experiment with high harmonics generation in gases is given in Figure 1. It comports a laser, a delivering gas system, a telescope, a periscope and a magnetic chicane. The laser is focused in the gas system, by means of a lens in order to generate harmonics. It requires intensity of the order of 10^{14} W/cm^2 in the focal region (saturation intensity for which ionization becomes important). For the SCSS phase 1 case and a laser pulse of 15 mJ, the above intensity is achieved within a focal spot of 215 µm, corresponding to an "aperture number" f#=280 (beam diameter of 2.5 cm focused with a 7 m focal length).

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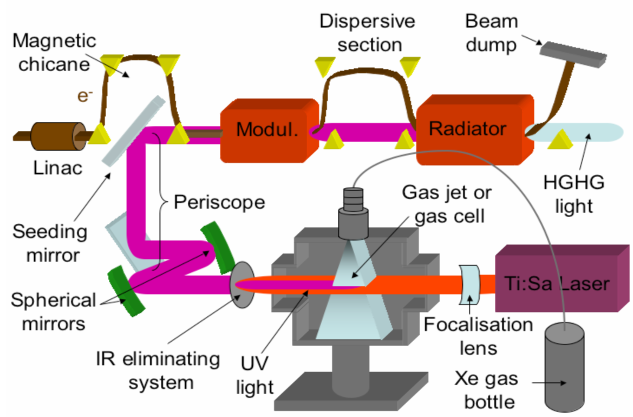

Figure 1: General layout of the seeding experiment with harmonics generated in gases.

The harmonic generation in gas results from the strong non linear polarization 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 radiation spectrum is completely tunable in the VUV-XUV region by means of frequency-mixing techniques applied on the pump laser [8]. High order harmonics are linearly polarized sources between 100 and 3 nm (12-400 eV), of high temporal [9] and spatial [10] coherence, emitting very short pulses (less than 100 fs), with a relatively high repetition rate (up to few kHz). The harmonic radiation is emitted on the axis of the laser propagation with a small divergence (1 to 10 mrad).

CHARACTERISTICS

Table 2 gives the characteristics of the SCSS prototype experiment electron beam and undulators. The system is optimized for a seeding experiment at 60 nm but other harmonics (coming from gas like 72.7 nm and 53.3 nm and for crystals like 266 nm and 160 nm) could be injected by changing a little bit the gap and the energy.

Table 1: Beam parameters. E is the energy, σγ the slice energy spread, τ_e the bunch length, ε the slice emittance, I_P the peak current and β the beta function.

E (MeV)	σγ (%)	τ_e rms (fs)	Q (nC)	ε (π mm. mrad)	I_P (kA)	βx/βy (m)
250	0.004	200	1	1	0.3	4.7/0.5

Table 2: Undulators characteristics. λ_R the resonant wavelength, λ_U the undulator period, K the deflexion parameter, N_P the period number, and N_S the section number

λ_R (mm)	λ_U (mm)	K	N_P	N_S
60	15	1.389	300	1

Table 3 presents the Ti:Sa laser and harmonic main optical parameters known or estimated for the seeding experiment.

Table 3: Laser and harmonics characteristics. λ is the wavelength, τ the pulse duration, M^2 the Gaussian beam quality factor, P the peak power and Pol the polarization, with V for vertical and H for horizontal.

λ (nm)	E /pulse (mJ)	Rep. rate (Hz)	τ_{FWHM} (fs)	M^2	P (MW)	Pol
750-850	0.5-50	10	130	1.5	$4\ 10^3$-$4\ 10^5$	V or H
61.5	10^{-4}-10^{-3}	10	55	3.5	2-20	H

IMPLANTATION

The experiment consists into two chambers. The first one is dedicated to the harmonic generation in xenon, which is a well-adapted gas for the generation of 60 nm radiation (H13). The second one is used for the spectral selection (residual IR elimination) and the adaptation of the harmonic beam at the focusing point in the centre of the first undulator (modulator). The choice of two chambers results from a vacuum adaptation with a differential pumping and from power density considerations on the optical components. A periscope system, composed of two VUV flat mirrors (FM1 and FM2) with adjustments, is used to align the harmonic beam with the e-beam, which is seeded by a magnetic chicane.

The harmonic generation experiment will be located in the SCSS tunnel, together with the accelerator and the undulators, (Figure 2) between the chicane and the shielding wall. Implementation in the radiation zone imposes remote control of several elements. In the laser hutch, the laser system provides the IR beam, which is then adapted for harmonic generation optimization and synchronized with the e-beam. A pass through the shielding wall for injecting the IR-beam inside the interaction chamber takes place at a 2.3 m high for radioprotection safety reasons. After a first IR periscope, on which the 7 m length focal lens is installed, it goes through the hole, enters the vacuum tube and goes down to 80 cm of high before passing into the two chambers system with a second IR periscope. After passing through the two chambers, the harmonic beam is seeded into the chicane thanks to the VUV periscope. The alignment of the beam harmonic in the modulator is done by a He-Ne laser, as planed for SCSS [11].

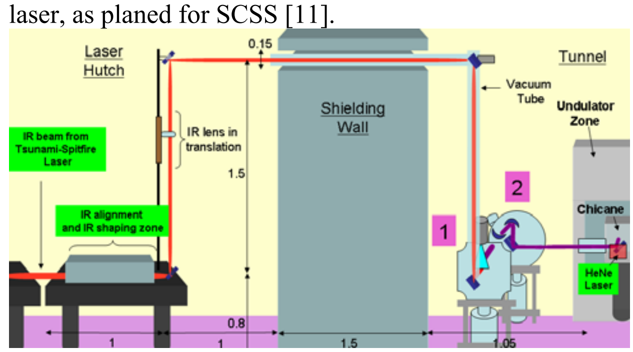

Figure 2: Transversal view of the seeding experiment implantation. 1. Interaction chamber 2. Optical chamber

Figure 3 illustrates the experiment from the tunnel side. It shows the real implantation of the system and makes appear clearly the different parts.

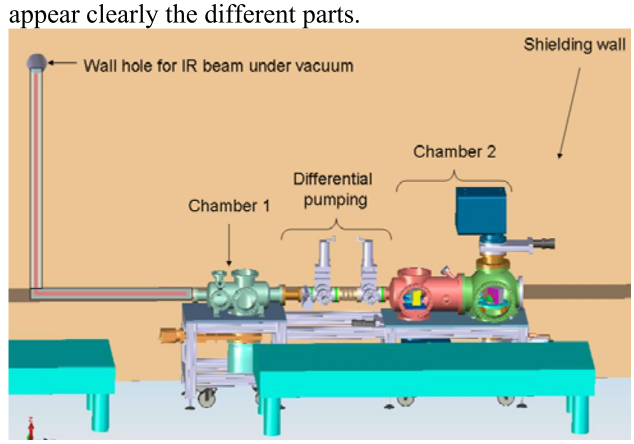

Figure 3: CATIA software 3D drawing view of the experiment implantation from the tunnel side.

The second chamber, the optical chamber (Figure 4), contains a system of two reflective concave spherical mirrors (SM_1 and SM_2) in SiC, with 35% of reflectivity.

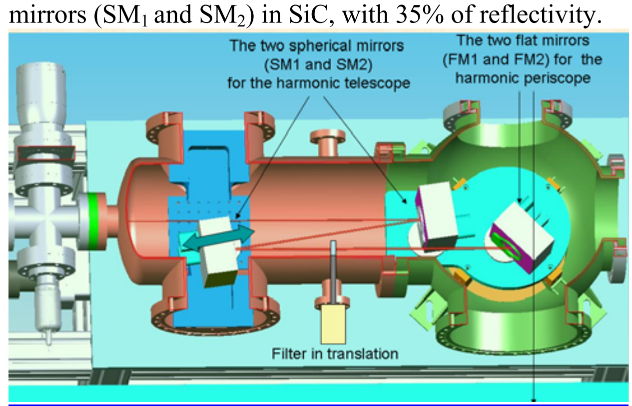

Figure 4: CATIA software 3D drawing view of the second chamber: spectral selection, beam shaping.

It provides a spectral selection of the chosen harmonic (H13: 60 nm) and focuses the UV beam into the modulator at the correct position and with the desired waist, in order to have a proper interaction with the e-beam. The spherical mirrors are moveable to compensate all the variations of the system (position of the IR lens, errors on the spherical mirrors radius of curvature and on the evaluation of the harmonic waist…). The adjustment is realized with under vacuum remote controlled stepping motors providing translations and tilts.

In option, a Sn filter could be added. It would definitively cut the residual IR light, when it is needed, and select a certain part of the spectrum around the 60 nm radiation.

Concerning the diagnostics of the harmonic spectrum and energy, beam position and shape, one XUV photodiode and microchannel plates will be used and located in one last chamber. This latter, which is not yet completely designed, will contained the last mirror of the VUV periscope, the seeding mirror, for injecting the harmonic beam into the modulator. For a perfect alignment of the harmonic beam in the modulator during the shifts, a system of one translation on the seeding mirror could be added. In a first position the harmonic beam and the residual IR beam are driven into the modulator. The second position lets pass a He-Ne light into the modulator for the alignment or the harmonic beam to the microchannel plates.

PROPAGATION OPTICAL CALCULATIONS

The IR evolution after the focusing lens is calculated. One should maintain the energy density of the IR beam on each optic in order not to pass beyond 100 mJ. cm^{-2} for avoiding optical damages and prevent from the self phase modulation, destroying the beam Gaussian distribution in air, by setting transport tubes when the power density limit is reached. Besides, the evaluation of the waist size on the gas cell determines the conversion rate of the harmonic generation process. The propagation formulas used here are those of a non-purely Gaussian mode (with M^2). The evolution of the transverse size of the beam, W_p (Z) as a function of the longitudinal coordinate Z, is given by equation 1.

$$w_p(Z) = w_o \times \sqrt{1 + \left\{\frac{Z}{Z_R}\right\}^2} \qquad (1)$$

with w_0 the laser waist, Z_R the Rayleigh range.

The study of the harmonic beam propagation has been done in parallel to the chamber design. The harmonic beam evolution is calculated using equations 1 with M^2= 3.5 and the wavelength λ= 60 nm and with a beam waist w_0 approximately half of the IR one. The harmonic beam propagation is only modified by the two spherical mirrors (SM_1 and SM_2). As the spherical mirrors are regarded as lenses of f focal length, in the paraxial approximation, the characteristics of the transmitted beam can be calculated using:

$$s' = f \times \left[1 + \frac{\left(\frac{s}{f} - 1\right)}{\left(\frac{s}{f} - 1\right)^2 + \left(\frac{Z_R}{f}\right)^2} \right] \qquad (2)$$

$$w_0' = \frac{w_0}{\sqrt{\left(\frac{s}{f} - 1\right)^2 + \left(\frac{Z_R}{f}\right)^2}} \qquad (3)$$

s is the object distance and s' is the image distance. w_o' is the image waist.

Figure 5 illustrates the longitudinal evolution of the IR and high harmonic beams from the IR lens of 7 m of focal length to the centre of the modulator.

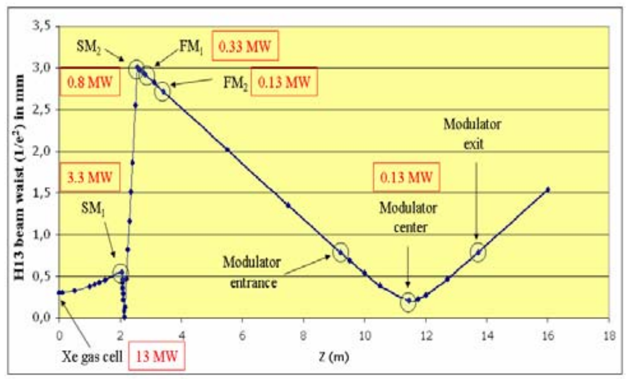

Figure 5: Longitudinal evolution of the beam radius size (waist in $1/e^2$). Peak power in square boxes for each position.

Figure 6 zooms on the undulator zone. The e-beam radius sizes are added in order to see the overlap between the harmonic beam and the two dimensions of the e-beam.

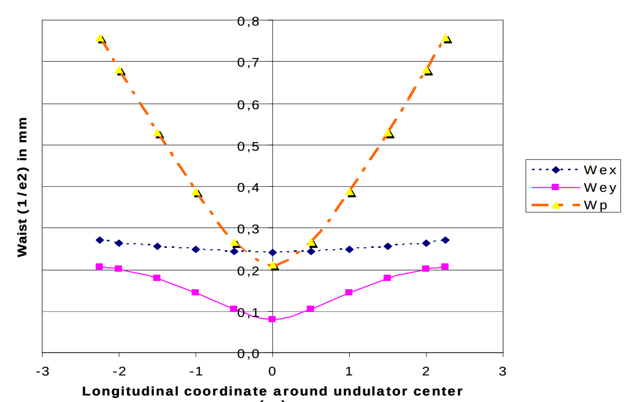

Figure 6: Evolution of the beam radius sizes (in mm and in $1/e^2$) for the harmonic beam (Wp) and for the e-beams in x (Wex) and y (Wey), as function of the longitudinal coordinate, which the origin is taken at the focussing point in the middle of the modulator.

SIMULATIONS

Genesis calculations [12]

With the values of Tables 1, 2 and 3, some Genesis calculations (Figure 7) have been done for comparing the SASE and the seeding HGHG configurations. The fundamental peak power evolutions and the saturation lengths are observed on the total length of the undulators.

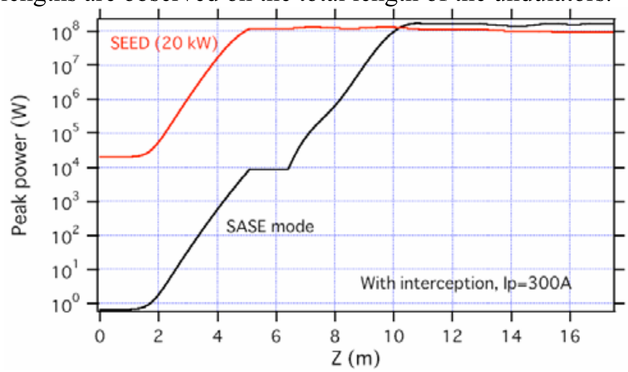

Figure 7: Comparison between SASE and Seeding HGHG configuration with 20 kW of seed.

Perseo calculations [13]

Figure 8 shows the evolution of the harmonic beam peak powers and of its third and fifth non linear harmonics in SASE and seeding case in the radiator section. A filling factor, calculated and corrected with Colson-Elleaume technique [14], has been taken into account by multiplying the small signal gain (go) in Perseo code with this factor (0.048). The levels of peak powers are very similar in Figure 7 and 8 (108 W). The saturation length for the SASE case is 9 m with Perseo and 10.5 m with Genesis. Concerning the seeding case, it is 7 m with Perseo and 7.5 m with Genesis.

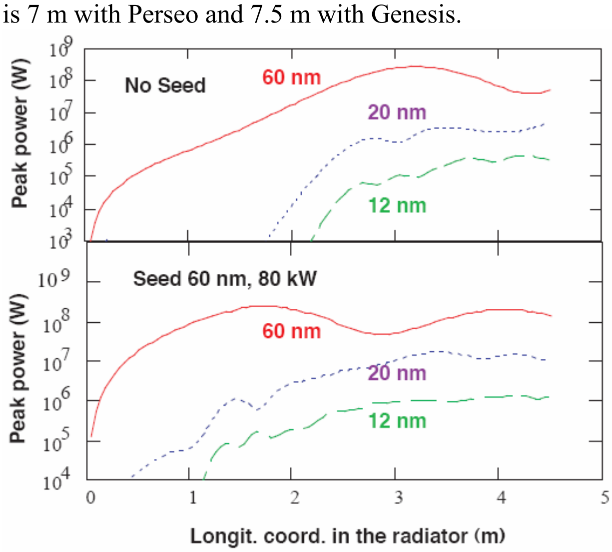

Figure 8: Comparison between SASE and Seeding HGHG configuration.

Finally, Figure 9 shows the evolution of the peak powers of the fundamental and of the third and fifth non linear harmonics inside the radiator, at three different peak currents 100 A, 200 A and 300 A.

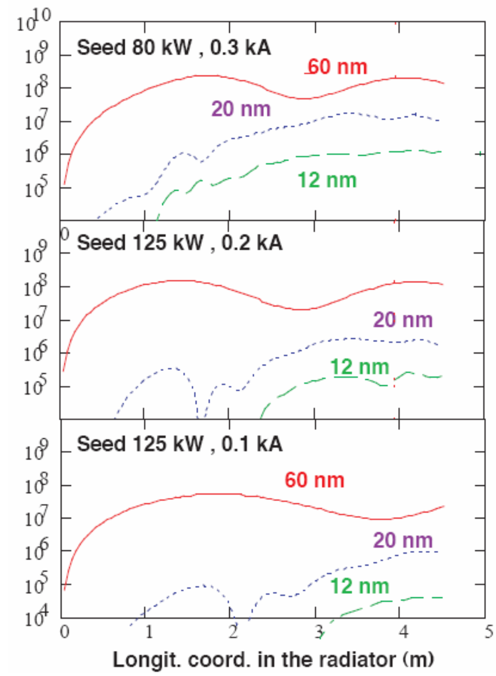

Figure 9: Comparison between SASE and Seeding HGHG configuration with the filling factor adding.

CONCLUSION

The seeding experiment is now ready to be tested. The different calculations show that high peak powers will be obtained in the seeding case, even for the third and fifth non linear harmonics, and the saturation length is reduced by approximately 30% compared to the SASE case. Finally, good agreements have been observed between Perseo with the implementation of the filling factor and Genesis.

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