SEEDING SCHEMES ON THE FRENCH FEL PROJECT LUNEX5

C. Evain, M. Labat, M.E. Couprie, F. Briquez, A. Loulergue
Synchrotron SOLEIL, Saint Aubin, France
V. Malka, Laboratoire d'Optique Appliquée, Palaiseau, France

Abstract

LUNEX5 is a single pass FEL project aims at producing coherent synchrotron radiation with, in a first step, an electron bunch accelerated in conventional RF cavities up to 300 MeV [1]. It is planned to work in a seeded configuration where the longitudinal coherence of the emitted light is improved and the gain length reduced [2], compared to the SASE configuration (Self-Amplified Spontaneous Emission). Two seeding schemes are considered: High order Harmonics in Gas (HHG) seeding [3] and EEHG scheme (Echo Enabled Harmonic Generation) [4]. Preliminary simulation results indicate that these two schemes permit to reach the saturation below a wavelength of 7 nm, and with less undulator periods for the EEHG scheme. HHG seeding with plasma acceleration based FEL is also considered.

GENERAL PARAMETERS AND LAYOUT

Electron Bunch Parameters

After acceleration in a 3 GHz warm Radio-Frequency gun and linac up to 300 MeV, the 1 nC bunches are compressed. Their main characteristics are:

Table 1: Electron Bunch Parameters

Energy (MeV)	300
Slice relative energy spread	2×10^{-4}
Emittance $\epsilon_{x,y}$ (π.mm.mrad)	2
Peak current (A)	400
Charge (nC)	1
RMS Length (ps)	1

FODO Lattice and Undulators

The electron-bunch is guided along the undulators in a FODO lattice. The parameters are given in the Table 2. Each section is composed of a 3 meter undulator and of a horizontal focusing quadrupole (Fig. 2). Focusing in the vertical plane is achieved by the undulators. Figure 1 shows typical transverse beam-size along the FODO lattice. The RMS width is about 100 μm in the horizontal and vertical planes.

It is planned to use 15 mm period in vacuum undulators with a magnetic field standing between 0.3 and 1.5 T [1], i.e. fundamental resonant wavelength stands between 24 nm and 70 nm.

We study here two seeding schemes (direct seeding with HHG source [3] and EEHG scheme [4]) to get FEL radiation at short-wavelength with good coherence properties [2, 5]. To compare the two schemes, we focus on the emission at 38 nm and on its third and fifth harmonic (12.76 nm and 7.6 nm respectively).

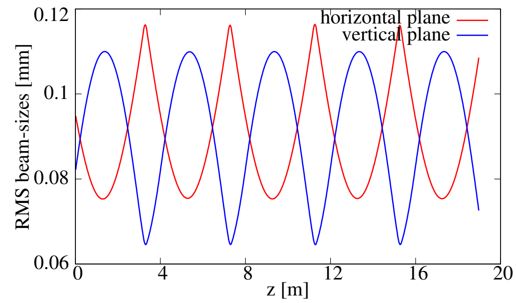

Figure 1: Horizontal σ_x and vertical σ_y beam sizes along the FODO lattice from GENESIS simulation.

Table 2: FODO Lattice and Undulators Parameters

Undulator period (mm)	15
Number of undulator periods	200
Magnetic field (T)	0.3-1.5
Undulator parameter K	0.45-2.1
Resonant wavelength (nm)	24-70
Number of sections	5
Length of quadrupole (m)	0.15
Typical quadrupole field (T/m)	4

SEEDING WITH HARMONICS IN GAS SOURCE

The first studied seeding scheme is direct seeding, i.e. FEL amplification of a harmonics generated in gas source (Fig. 2) [3, 5].

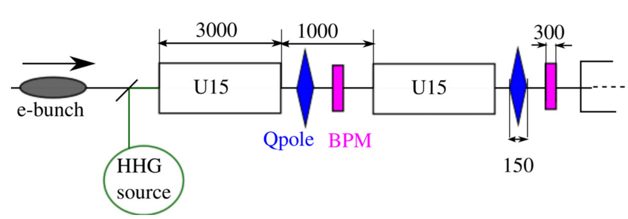

Figure 2: Layout of the FEL amplifier scheme with Harmonic in Gas Source. Distance in mm.

HHG pulses at 38 nm are obtained using the 21^{th} harmonic of a 800 nm of the Ti:Sa laser. Parameters of the seed pulse are presented in Table 3 [6].

To estimate the output power, GENESIS simulations in

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Table 3: Seeding Source Parameters

Wavelength (nm)	38
Peak power (kW)	1
FWHM width (fs)	100

the steady-state mode [7] have been performed. Figure 3 shows the output power along the FODO lattice at 38 nm, 12.67 nm (harmonic 3) and 7.6 nm (harmonic 5), for undulators tuned at 38 nm. At 38 nm, an output peak power of 0.1 GW is expected after $z = 10$ m. Saturation occurs nearly at the same position for the third and fifth harmonics with an emitted peak power of 3×10^5 W at 12.67 nm and of 3×10^4 W at 7.6 nm.

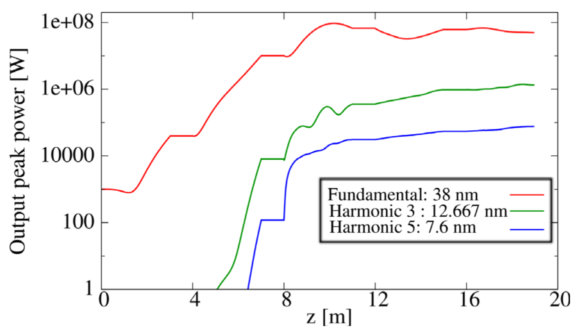

Figure 3: Output peak power along the undulators at 38 nm (red line), 12.67 nm (blue line) and 7.6 nm (green line) with direct seeding at 38 nm (from GENESIS simulation).

SEEDING WITH ECHO SCHEME

The EEHG scheme, proposed in 2009 [4] and validated experimentally in 2010 [8], permits to seed free-electron laser at very high harmonics of an external laser wavelength. It includes two laser-electron interactions in tuned undulators, called modulators (M1 and M2), and two dispersive sections (DS1 and DS2) (Fig. 4). At the end of the second dispersive section and with a proper set of parameters, the longitudinal charge distribution can be modulated at a harmonic of the laser wavelength [4]. The so-called "bunched electrons" can then initialize the coherent radiation in the tuned radiator (R).

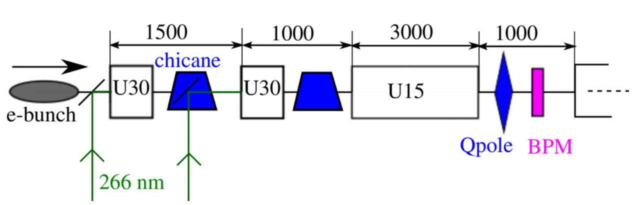

Figure 4: Layout of the seeding with the EEHG scheme. Distance in mm.

The first laser/electron interaction is designed to provide an electron bunch energy modulation at 266 nm (third harmonic of the Ti:Sa wavelength) of about 5 times the energy spread value since it has been shown that the final bunching factor saturates at about this value [9]. Chosen parameters are presented in Table 4.

Table 4: Laser/Electron Interactions Parameters

	First interaction	Second interaction
Undulator period (mm)	30	30
Number of periods	9	5
Resonant wavelength (nm)	266	266
Laser peak power (MW)	100	<500

The first dispersive section is a chicane composed of 4 bending magnets. Choice of the parameters is a compromise between dimensions (total length and free-space to accommodate the second seeding mirror) and longitudinal dispersive value $R_{56}^{(1)}$. $R_{56}^{(1)}$ should not be too high to prevent the induced fine structures in the longitudinal phase-space to be too sensitive to noise (induced by Incoherent Synchrotron Radiation in bending magnets) [9]. The chosen parameters are presented in Table 5.

Table 5: First Chicane Parameters

Total length (m)	1.2
Dispersive strength $R_{56}^{(1)}$ (mm)	2
Dipole length (m)	0.25
Dipole field (T)	0.25

Parameters of the second modulator and of the second dispersive section are tuned in function of the final wanted wavelength (38, 12.67 or 7.6 nm). Fixed parameters of the second modulator are presented in Table 4. The second dispersive section is also composed by 4 bending magnets, but with lower dimensions than the first one since the required $R_{56}^{(2)}$ value is lower than $R_{56}^{(1)}$.

To estimate the output peak power emitted with this configuration, steady-state GENESIS simulations have been performed. The simulations are done in three steps: (i) the first energy modulation; (ii) the first dispersive section and the second modulation; (iii) the second dispersive section and the radiation in the undulators previously described. Frequency conversion between the second and third step is obtained thanks to the CONVHARM option of GENESIS. Dispersive section are modeled using transport matrix in GENESIS (ITRAM option). Only the longitudinal dispersion is considered here. For each wavelength, the second laser power and the second dispersive strength $R_{56}^{(2)}$ are tuned to obtained the maximum output peak power for a minimum undulator length. Output peak powers emitted along the radiator at 38 nm, 12.62 nm and 7.6 nm are presented Figure 5, and results are summarized in Table 6.

For these three wavelengths, the saturation is reached within the first undulator: at about 3 m for the fundamental

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Table 6: Characteristics of the Emitted Power Using the EEHG Scheme (from GENESIS Simulations)

Harmonic number of the 266 nm	Wavelength (nm)	Maximum bunching factor at the input of the radiator	Saturation length (m)	Peak power at the saturation length (MW)
k=7	38	0.16	3	50
k=21	12.67	0.10	1	1.2
k=35	7.6	0.06	0.75	0.35

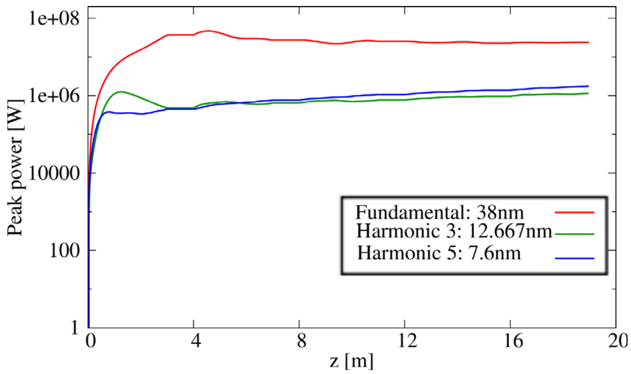

Figure 5: Output power along the radiators at 38 nm (red line), 12.67 nm (blue line) and 7.6 nm (green line) with the echo scheme, from GENESIS simulations. Parameters: Second laser peak power=22 MW (38 nm), 120 MW (12.667 nm), 300 MW (7.6 nm). $R_{56}^{(2)}$=0.29 mm (38 nm), 0.092 mm (12.667 nm), 0.052 mm (7.6 nm).

undulator wavelength (38 nm), at about 1 m for the third harmonic (12.667 nm) and at about 0.75 m for the fifth harmonic (7.6 nm). At these distances, the output peak power is 50 MW at 38 nm, 1.2 MW at 12.667 nm and 0.35 MW at 6.7 nm. The first two values are in the same order that with the direct seeding scheme with HHG source, whereas a substantial gain is obtained at 7.6 nm with the EEHG scheme (350 kW with EEHG against 30 kW with direct seeding).

HHG SEEDING USING A LASER WAKEFIELD ACCELERATOR

One part of LUNEX5 project is composed by a Laser WakeField Accelerator (LWFA) [1, 10] instead of a Conventional Linear Accelerator (CLA). With the same undulator and seed pulse parameters than for the CLA (Table 2 and 3), and with the electron-bunch parameters given in Table 7, it is possible to reach the saturation (Fig. 6). It is worth to notice that at the output of the LWFA the electron-bunch length is 2 fs RMS [11], but for numerical simulations a value of 20 fs has been used.

Table 7: Electron Bunch Parameters with a LWFA

Energy (MeV)	300
Relative energy spread	10^{-3}
Emittance π.mm.mrad	1
Bunch charge (pC)	50
RMS bunch length (fs)	20

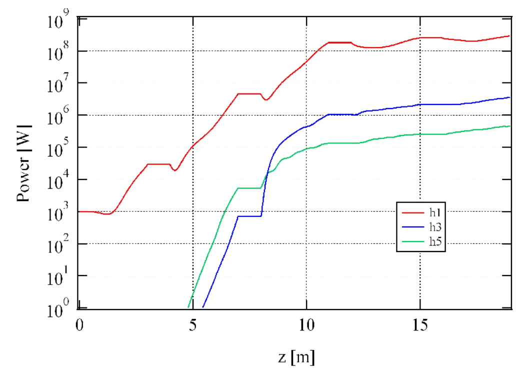

Figure 6: Output power along the radiators at 38 nm (red line), 12.67 nm (blue line) and 7.6 nm (green line) with HHG seeding using a Laser WakeField Accelerator, from GENESIS simulations (steady-state mode).

CONCLUSION

With a 300 MeV electron bunch (from conventional linear accelerator) radiated in U15 undulators, seeding with HHG source and EEHG scheme permits to reach saturation at 7.6 nm. Seeding with HHG is more straightforward, but EEHG scheme enables to reach the saturation with shorter undulator length. Also, numerical simulations indicate that at 7.6 nm, EEGH scheme permits to obtain higher output peak power. Application of HHG seeding scheme using a electron-bunch produced by a laser-wakefield accelerator would also permit to reach the saturation. Future studies will focus on temporal and spectral characteristics of the emitted pulses and on a 1 GeV electron-bunch from a laser-wakefield accelerator.

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REFERENCES

[1] M.-E. Couprie et. al., “LUNEX5: an FEL project towards the fifth generation in France”, FEL’11 (2011)

[2] Yu et. al., “High-Gain Harmonic-Generation Free-Electron Laser”, Science **289**, 932 (2000)

[3] G. Lambert et. al., “Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light”, Nature Physics **4**, 296 (2009)

[4] G. Stupakov, “Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation”, Phys. Rev. Lett. **102**, 074801 (2009)

[5] T. Togashi et. al, “Extreme ultraviolet free electron laser seeded with high-order harmonic of Ti:sapphire laser”, Optics Express **1**, 317 (2011)

[6] Mc Pherson et. al., J. Opt. Soc. Am. **4**, 585 (1987)

[7] S. Reiche, GENESIS 1.3: a fully 3D time-dependent FEL simulation code, Nucl. Inst. Meth. A **429**, 243 (1999)

[8] D. Xiang et. al., “Demonstration of the Echo-Enabled Harmonic Generation Technique for Short-Wavelength Seeded Free Electron Lasers”, Phys. Rev. Lett. **105**, 114801 (2010)

[9] D. Xiang and G. Stupakov, Echo-enabled harmonic generation free electron laser, Phys. Rev. ST Accel. Beams **12**, 030702 (2009)

[10] V. Malka et. al., “Principle and applications of compact laser-plasma electron accelerator”, Nature Physics **4**, 447 (2008)

[11] O. Lundh et. al., Nature Physics **7**, 219 (2011)

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