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STUDY OF AN ECHO-ENABLED HARMONIC GENERATION SCHEME FOR THE FRENCH FEL PROJECT LUNEX5

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Abstract

In the French LUNEX5 projet (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation), a compact advanced Free-Electron Laser (FEL) is driven by either a superconducting linac or a laser-plasma accelerator that can deliver a 400 MeV electron beam. LUNEX5 aims to produce FEL radiation in the ultraviolet and extreme ultraviolet (EUV) range. To improve the longitudinal coherence of the FEL pulses and reduce the gain length, it will operate in Echo-Enabled Harmonic Generation (EEHG) seeding configuration [1]. EEHG is a strongly nonlinear harmonic up-conversion process based on a two seed laser interaction that enables to reach very high harmonics of the seed laser. Recent experimental demonstration of ECHO75, starting from an infrared seed laser, was recently achieved at SLAC [2] and opened the way for EEHG scheme in the EUV and soft x-ray range. Furthermore, FELs are promising candidates for the next generation lithography technology using EUV light. In this work, we report a preliminary study of EEHG scheme for LUNEX5 in order to reach the target wavelength of 13.5 nm, currently expected for application to lithography.

INTRODUCTION

More than fifty years after the discovery of the laser [3], the Free-Electron Lasers (FELs) are nowadays the brightest sources in the extreme ultraviolet (EUV) and x-ray domains [4]. Thanks to the remarkable properties of the FEL pulses, like the spatial coherence, the high peak brightness, the narrow bandwidth spectrum and the ultra short duration in the sub-100 fs range, the operational FEL facilities [5–9] have opened the way to new possibilities in ultrafast dynamic of excited systems and in imaging. Besides the unprecedented capabilities of FEL lightsources, new researches are going towards the generation of even shorter FEL pulses and Fourier limits over a wide spectral range. An other trend is investigating the possibility to reduce the size of the FEL facilities by means of seeding schemes, like the echo-enabled harmonic generation (EEHG) scheme [1, 10] that enables to reach very high harmonic of the seed laser, or by replacing one of the components by an alternative, e.g. the use of cryogenic permanent magnet-based undulator (CPMU) [11, 12] or the use of new accelerator concepts like the laser-plasma acceleration (LWFA: Laser WakeField Acceleration) [13].

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LUNEX5 PROJECT

The LUNEX5 [14, 15] is an advanced and compact FEL demonstrator project (shown in Fig. 1) that aims at producing ultra short, coherent and intense pulses in the EUV domain. A 400-MeV electron beam will be delivered by two XFEL-type cryomodules (Fig. 1, yellow) for high repetition rate operation (see Table 1 for electron beam parameters), to a FEL line (Fig. 1, purple) composed of two modulators and four radiators based on the cryogenic permanent magnet technology for compactness. Two pilot user experiments (Fig. 1, green) in gas phase and condensed matter will qualify the FEL performance in the different cases. Measuring and controlling the temporal properties of the radiation emitted by LUNEX5 is essential for users application. A new method called MIX-FROG, based on the FROG (Frequency Resolved Optical Gating) technique, enabling to characterize these properties even in the presence of partial longitudinal coherence has been proposed and developed [16].

Table 1: Electron Beam Parameters

Beam energy	400	MeV
Bunch charge	1	nC
Bunch length	1	ps (RMS)
Peak current	400	A
Normalized slice emittance	1.5	mm.mrad
Energy spread	80	keV

The construction is not launched yet, but Research and Development programs are underway. The LUCRECE project aims at developing elementary RF cell with a 20-kW solid state amplifier. The operation at high repetition rate will also present challenges from the diagnostics point of view. This is particularly true for shot-by-shot electron bunch shape characterization. For that purpose, an original single-shot detection has been developed based on the electro-optic sampling that consists in encoding the electron bunch shape in the spectrum of a laser pulse, coupled to a photonic-time stretch strategy that slows down the signal to be detected. The feasibility of the method has been verified and applied on the detection of coherent THz pulses in synchrotron lightsources [17, 18].

An alternative accelerator line is also considered (Fig. 1) that will explore the qualification of a laser plasma acceleration process by a FEL application, using the same FEL line components and a specific transport line for handling the

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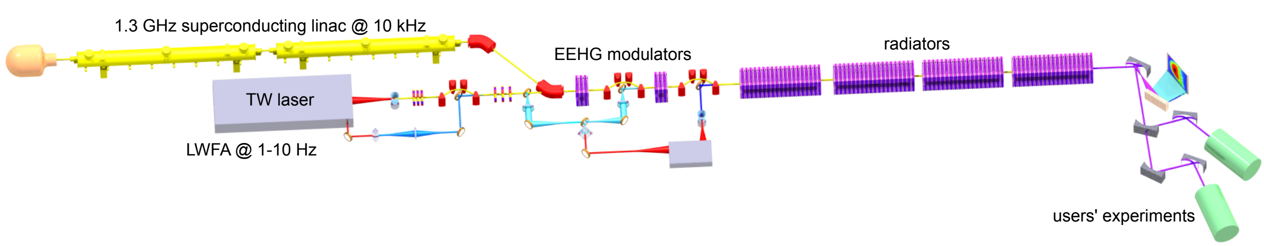

Figure 1: Layout of LUNEX5. It comprises two accelerators: a superconducting linac (yellow) and a laser-plasma accelerator (grey), and a single FEL line (purple) composed of two modulators (for EEHG seeding scheme) and four radiators. Two pilot users' experiments (green) will characterize the FEL performances from a user perspective.

plasma electron beam properties (divergence: 1 mrad, and energy spread: 1%) to enable FEL amplification [19,20]. A test experiment with a dedicated funding (ERC), called COXINEL (COherent Xray source INferred from Electrons accelerated by Laser), is on-going at the Laboratoire d'Optique Appliquée (LOA, France), where the laser-plasma accelerator (LPA) has been equipped with a FEL transport line designed and prepared at Synchrotron SOLEIL [21, 22]. Recently, the transport and control of the electron beam from the LPA source to the entrance of the undulator has been achieved and first spontaneous emission has been observed [12,23].

In order to control the spectral-properties and shorten the FEL amplification process, LUNEX5 will operate in seeding configuration, either by direct seeding using a HHG (High harmonic generation in gas) source [24, 25] or by taking advantage of the highly nonlinear frequency up-conversion process of the EEHG scheme [1,25] in order to reach short wavelengths in the tens of nm range starting from a UV seed laser.

LUNEX5 FOR EUV LITHOGRAPHY

UV lithography (EUVL) using a wavelength of 13.5 nm is a leading candidate among the next generation lithography technologies to continue the Moore's law scaling of devices, but only if the lightsource produces enough EUV photons per second to satisfy the hundreds of wafers per hour required for high volume manufacturing. The typical requirement for EUVL is a compact EUV source of 1 kW average power within 2% spectral bandwidth. The choice of FEL sources for EUVL appears to be an alternative to laser-produced plasma (LPP) EUV sources to overcome the source power limit.

CPMU Undulators

CPMUs take advantage of the enhanced field performance of permanent magnets when cooled down to low temperature, enabling shorter period with sufficient magnetic field [11,12]. The EUV lithography community is currently focused on the wavelength of 13.5 nm. For a planar undulator, the wavelength of the FEL is given by: $\lambda_{\mathrm{FEL}} = \lambda_u/(2\gamma^2)\left(1 + K^2/2\right)$, where γ is the relativistic factor, K is the deflection parameter, and λ_u is the undulator period. For a small beam energy, one need an undulator with a short period to maintain a K-value closed to one, The undulator configuration considered for LUNEX5 at 13.5 nm is summarized in Table 2.

Table 2: Undulator parameters

Magnetic Period	10	mm
Number of periods	300	
Undulator type	planar	
Resonant wavelength	13.5	nm
Deflection parameter	1.14	
Peak field	1.23	T
Gap	3.17	mm

EEHG Seeding Scheme

The EEHG is based on a two-seed laser interaction that takes place in the modulators. The two modulators are followed by two dispersive sections ($R_{56}^{(1)}$ and $R_{56}^{(2)}$) and FEL amplification develops in the radiators. The two seed lasers required for the EEHG seeding scheme are "twin" seeds. The output of a Ti:Sa laser is used to produce Third Harmonic Generation (THG). The layout of the line is shown in Fig. 2.

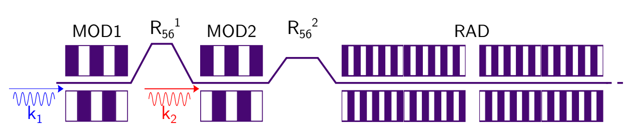

Figure 2: EEHG scheme of LUNEX5

According to [10], the bunching factor at the wavenumber $k_E = nk_1 + mk_2 = (n + Km)k_1$ is given by:

$$b_{n,m} = \left| e^{-(1/2)\xi_{n,m}^2} J_n\left[-A_1\xi_{n,m}\right] J_m\left[-(Km + n)A_2B_2\right] \right|, \quad (1)$$

with

$$\xi_{n,m} = nB_1 + (Km + n)B_2. \quad (2)$$

$A_{1,2} = \Delta E_{1,2}/\sigma_E$ are the dimensionless modulation amplitudes from the first and second laser interaction, and $B_{1,2} = R_{56}^{(1,2)} k_1\sigma_E/E_0$ are the dimensionless dispersive strengths.

It follows from the optimization of Eq. (1), that the maximum bunching at 13.5 nm is obtained for the combination

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$m = 20$ and $n = -1$, that corresponds to the harmonic 19$^{\text{th}}$ of the seed laser. A bunching factor of 10.3% (Fig. 3a) is reached for a first energy modulation A_1 equal to 2, a first dispersive section of 2 mm and a second modulation of 1.9 and a second dispersion of 124.1 µm.

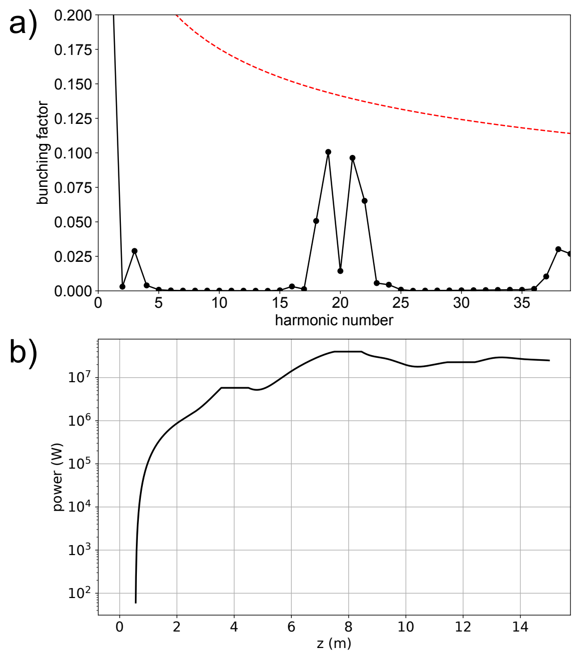

Figure 3: a) Bunching factor (black line) and maximum bunching factor (red dashed line). b) Peak power along the undulator at 13.5 nm.

A preliminary FEL simulation using GENESIS code [26] shows that the undulator radiation can reach a peak power of about 40 MW after 8 m of propagation. Thus, an average power of 0.4 kW can be obtained with a repetition rate of 10 MHz and an electron bunch length of 1 ps, that corresponds to a duty cycle of 1×10^{-6}.

The limit of the seeding schemes at high repetition rate may come from the lack of powerful laser source at this repetition rate. An alternative to single-pass seeded FELs is the FEL in oscillator configuration. Despite a still low reflectance of the mirrors in the EUV range, of the order of 70% [27], the oscillator configuration combined with an energy recovery linac will allow high repetition rate to be reached.

CONCLUSION

The LUNEX5 project is a demonstrator of advanced and compact FEL based on R&D technology. Its advanced and compact design makes it suitable for the generation of intense, coherent EUV pulses for lithography application. Moreover, the use of a superconducting linac and cryogenic undulators opens the way for FEL with high average power level.

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