Progress of the LUNEX5 Project

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Abstract

LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) aims at investigating the production of short, intense, and coherent pulses in the soft X-ray region. A 400 MeV superconducting linear accelerator and a laser wakefield accelerator (LWFA), will feed a single Free Electron Laser line with High order Harmonic in Gas and Echo Enable Harmonic Generation seeding. After the Conceptual Design Report (CDR), R&D has been launched on specific magnetic elements (cryo-ready 3 m long in-vacuum undulator, a variable strong permanent magnet quadrupoles), on diagnostics (Smith-Purcell, electro-optics). In recent transport studies of a LWFA based on more realistic beam parameters (1 % energy spread, 1 μm beam size and 1 mrad divergence) than the ones assumed in the CDR, a longitudinal and transverse manipulation enables to provide theoretical amplification. A test experiment is under preparation. It is noted in this context that among the French scientific community's interest in experiments at operating FELs is increasing.

INTRODUCTION

Fifty years after the laser discovery, the emergence of several mJ femtosecond X-ray lasers for users in the Angström range at LCLS (USA) in 2009 [1] and in SACLA (Japan) [2] and in the VUV/soft X-ray at FLASH(Germany) [3], SCSS Test Accelerator (Japan) [4] and FERMI (Italy) [5] constitutes a major breakthrough and open unexplored multidisciplinary investigations of matter. Because of the small mirror reflectivity at short wavelength limiting FEL oscillators to the VUV [6], short wavelength FELs are usually operated in the so-called SASE scheme. Though efficient in terms of power, emitted radiation is constituted of random spikes, giving a poor temporal coherence. After the first Coherent Harmonic generation experiments in the VUV [7, 8, 9], since more than one decade ago, seeding with conventional laser has demonstrated the suppression of the spikes, the reduction in gain length and an increase in coherence [10]. FERMI@ELETTRA is the first seeded FEL open for users in the soft X-ray region. It also efficiently up-frequency converts the wavelength along different stages. Short wavelength seeding with High order Harmonics generated in Gas (HHG), demonstrated on the Japanese SCSS FEL [11], on SPARC (Italy) [12], and on FLASH (Germany) [13] enables to decrease the FEL wavelength. The recently proposed self-seeding in particular with a crystal monochromator efficiently cleans the SASE spectrum [14, 15, 16]. The Echo-Enabled Harmonic Generation (EEHG) [17] enabling to generate short wavelengths has been experimentally evidenced so far in the UV [18, 19], opening perspectives for very short wavelength (Å) and short duration at moderate cost.

Present FEL user facilities usually provide only a restricted number of beamlines, making the acceptance of user proposals quite difficult. Superconducting technology enables to produce long electron macro-pulses which can be split into different FEL branches, approaching thus a multi-user facility such as synchrotron radiation light sources. In addition, a superconducting linac enables the operation of the FEL at high repetition rate, beneficial for coincidence experiments for example. The European XFEL, when coming to operation, will provide a major step in this direction [20].

In parallel, novel acceleration schemes such as dielectric ones [21], inverse FELs [22] and Laser Wakefield acceleration [23] are actively developed. Laser Wakefield Acceleration (LWFA) by using intense laser beams interacting with cm long plasmas can now provide high quality electron beams of very short bunches (few fs) with high peak currents (few kA) [24]. Indeed, spontaneous emission from LWFA has already been observed [25], but the presently still rather large energy spread (~1 %) and divergence (mrad) prevent from a straightforward FEL amplification.

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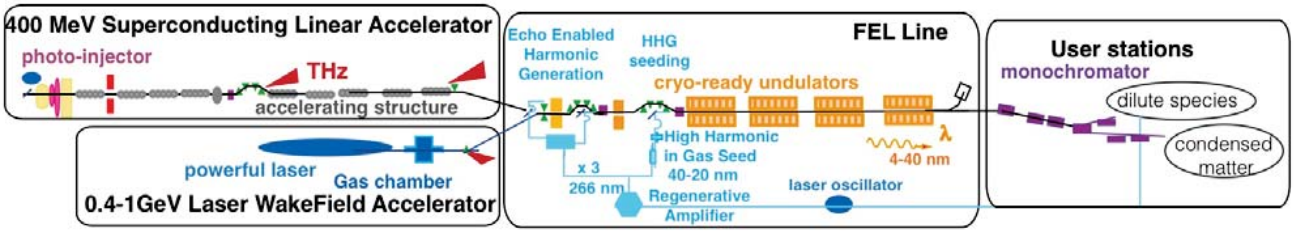

Figure 1: LUNEX5 scheme.

GENERAL PRESENTATION OF LUNEX5

In this context, LUNEX5 [26] proposes to develop a demonstrator for investigating the production of short, intense, and coherent pulses in the soft X-ray region. It will comprise two types of accelerators (see fig. 1) : a superconducting linac for enabling high repetition rate and multi-user operation and a low repetition rate LWFA, to be qualified in view of FEL application. The common FEL line will apply the most advanced seeding configurations (HHG seeding, EEHG) and provide flexibility. To assess the performance of these sources from a users' perspective, the facility will include a photon transport beamline equipped with an optional monochromator. This bemaline will serve two end stations, which are optimized for experiments on gazeous and solid samples, respectively. The precise equipment will be identified in close collaboration with the growing French XFEL user community, which is organized within the XFEL-Science research network and financially supported by the CNRS. User representatives will also participate in defining the science vision going beyond the LUNEX5 demonstrator project towards the needs for a further full scale facility.

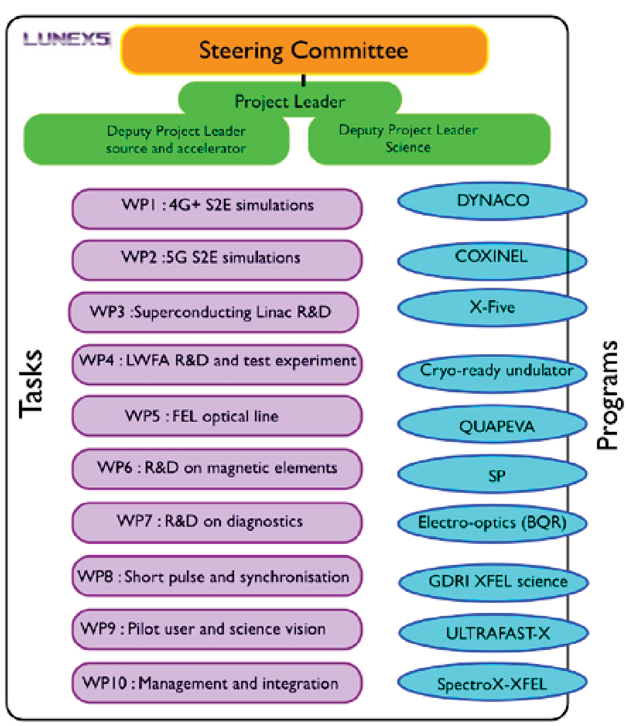

Figure 2: LUNEX5 organisation.

LUNEX5 Conceptual Design Report has been completed [27] and the project has entered the next phase of targeted complementary studies and associated R&D. The organizational structure is shown in Fig. 1 where tasks deal with the main subjects of studies whereas specific programs are funded actions relevant to some particular aspects. These programs involve additional partners as compared to the ones of the original LUNEX5 collaboration.

STUDIES TOWARDS A LWFA BASED FEL DEMONSTRATION

With respect to conventional accelerators, LWFA beams exhibit very different characteristics of phase space: in longitudinal, short bunch duration and large relative energy spread and in transverse, large divergence and micrometer size.

Whereas in the LUNEX5 CDR, rather optimistic LWFA performance had been anticipated, more recent LUNEX5 studies have been devoted to the optimization of the electron beam transport from the gas cell to the undulator, with currently achieved parameters, as given in Table 1. Electron beam distributions calculated with PIC or CALDER-PIC codes have been calculated independently [28]. However, the Table 1 baseline parameters have been mainly used first for designing the transfer line. They typically correspond to what is expected with the 60 TW laser of the Lab. d'Optique Appliquée, to be used for a demonstration of LWFA-based FEL amplification in the frame of LUNEX5, as a step before the use of a dedicated laser. Typical U15 LUNEX5 undulators are considered [29] as well as a spare U20 undulator of SOLEIL [30]. Considered wavelengths are 200 and 40 nm.

The design of electron transfer lines aims at an electron beam longitudinal and transverse manipulation. In a first step, the divergence can be handled by strong quadrupoles located very close to the electron source [31]. Then, electrons are sorted in energy by a "demixing" (decompression) chicane [32, 33], reducing the slice energy spread from 1 % to 0.1%. In a third step, the transverse density is maintained constant all along the undulator (supermatching) thanks to the particular energy position correlation in the electron beam phase space [34]. This chicane scheme has been studied, even though the transverse gradient undulator [35] approach is also

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considered [36, 37]. Finally, in the case of 200 nm wavelength, seeding enables to avoid a long lethargy and limitations due to slippage. First series of simulations suggest that the conditions for lasing are fulfilled.

Table 1: LWFA Parameter Set for Electron Beam Transport

Parameter	Unit	Value
Energy	MeV	400, 200
Length	µm RMS	1
Relative energy spread	%	1
Divergence	mrad RMS	1
Normalised emùitta,ce	π mm.mrad	1
Peak current	kA	4

MAGNETIC ELEMENTS STUDIES

Permanent magnet quadrupoles are of interest for different types of applications, such as colliders, low betatron function optics and LWFA transport. Designs derived from the Halhach configuration are under way, in particular to introduce a variability of the strength. The requested gradient is 200 T/m for the LWFA based FEL test experiment while maintaining the bore radius at 10 mm.

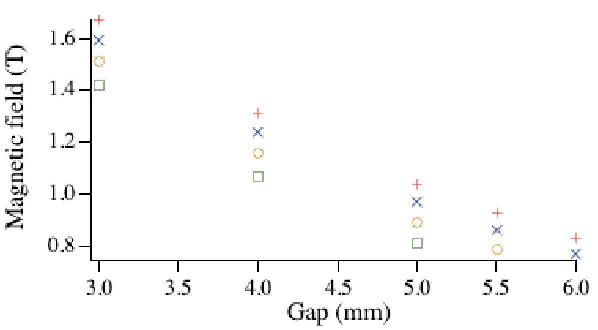

Figure 3: Expected magnetic field calculated with RADIA versus gap for various radiator periods : 15 mm (+), 14 mm (x), 13 mm (o), 12 mm (square).

A prototype of the 3 m long PrFeB [38] cryo-ready LUNEX5 radiator is under study. First, various studies have been carried out to confirm the period choice. Indeed, the magnetic field has been calculated for periods ranging from 12 mm to 15 mm, as shown in Fig.3. Whatever the linac choice, the tuneability is reduced with shorter periods. In the case of the superconducting linear accelerator, only 14 and 15 mm periods enable the cascade configuration. Higher power is obtained with a 14 mm period, but 15 mm is chosen to keep a safety margin.

With respect to the usual magnet holder design of the in-vacuum 20 mm period undulators, the design is under revision for ensuring a proper holding and an easier swapping of the modules.

DIAGNOSTICS STUDIES

Figure 4: Smith-Purcell apparatus installed in the SOLEIL injector linac.

Strategies for electro-optic sampling diagnostic are currently investigated by the PhLAM and SOLEIL teams. The tested options include scanning setups, which are expected to yield high temporal resolution diagnostics. Single-shot strategies based on spectral encoding are also tested [39]. Both types of strategies are tested using TiSa lasers as well as Yb fiber lasers.

For bunch length measurement, analysis of the Smith Purcell (SP) radiation spectrum produced by the bunch itself can be used [40]. SP radiation is emitted when a charged beam travels close to a metallic grating and becomes coherent when the bunch length is about the grating period. SP monitors are intensively studied since they may allow single-shot, fs-short, low-charge bunch length measurements. Currently, in the framework of an ANR project, several monitors are under study. A first one is installed at FACET (USA) for the measurement of few hundred fs bunch lengths and enables already to confront experiment to theory [41]. A second one has just been installed in the SOLEIL injector linac, for the measurement of ps bunch lengths. This device is aimed at systematic studies for detector optimization and confrontation to theory. Two additional monitors are foreseen: for SPARC (Italy) and finally for a Laser Wake Field Accelerator in France, aiming at the measurement of few pC, few fs bunches. Those monitors should benefit of the preliminary work done at SOLEIL.

CONCLUSION

LUNEX5 R&D with specific funding has started. Complementary studies with respect to the CDR include sensitivity to the parameters and an electron beam transport from a LWFA to the undulator enabling FEL amplification with more realistic parameters. Parameter studies continue for a better design of the test experiment under preparation.

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REFERENCES

[1] First lasing and operation of an Angstrom-wavelength free-electron laser, P. Emma et al., Nature Photonics 4, 641 (2010)
[2] A compact X-ray free-electron laser emitting in the sub-ångström region, T. Ishikawa et al., Nature Photonics **6**, 540–544 (2012)
[3] Operation of a FEL from the extreme UV to the water window, W. Ackermann et al., Nature Photonics **1**, 336 - 342 (2007)
[4] *A compact FEL for generating coherent radiation in the extreme u ltraviolet region*, T. Shintake et al. Nature Photonics **2** (9), 555—559, (2008)
[5] E.. Allaria et al., *Nature Photonics* 6, 699-704 (2012)
[6] Operation of the European storage ring FEL at ELETTRA down to 190 nm, M. Trovò, M. Marsi, R. P. Walker, J. A. Clarke, M. W. Poole, M. E. Couprie, D. Garzella, G. Dattoli, L. Giannessi, A. Gatto, N. Kaiser, S. Günster, Nucl. Inst. Meth. A 483, 1-2, (2002) 157-161
[7] B. Girard, Y. Lapierre, J. M. Ortéga, C. Bazin, M. Billardon, P. Elleaume, M. Bergher, M. Velghe, Y. Petroff, Opitcal frequency multiplication by an optical klystron, Phys. Rev. Lett. 53 (25) 2405-2408 (1984)
[8] First Production of Vacuum-Ultraviolet Coherent Light by Frequency Multiplication in a Relativistic Electron Beam, R.Prazeres, J.M.Ortéga, C.Bazin, M.Bergher, M.Billardon, M.E. Couprie, H.Fang, M.Velghe and Y.Petroff, Europys. Lett., 4 (7), (1987), 817-822
[9] Coherent Harmonic Generation in VUV with the optical klystron on the storage ring Super-ACO, R. Prazeres, P. Guyot-Sionnnest, D. Jaroszynski, J.M. Ortéga, M. Billardon, M. E. Couprie, M. Velghe *Nucl.Inst. Meth.* **A 304** (1991) 72-76
[10] High-Gain Harmonic-Generation Free-Electron Laser, L. H. Yu et al., Science 11, 289 no. 5481, 932-934 (2000)
[11] Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme ultraviolet light, G. Lambert et al., Nature Physics 4, 296-30 (2008)
[12] High-Gain Harmonic-Generation Free-Electron Laser Seeded by Harmonics Generated in Gas, M. Labat, M. Bellaveglia, M. Bougeard, B. Carré, F. Ciocci, E. Chiadroni,A. Cianchi, M. E. Couprie, L. Cultrera, M. Del Franco, G. Di Pirro, A. Drago, M. Ferrario, D. Filippetto, F. Frassetto, A. Gallo, D. Garzella, G. Gatti, L. Giannessi, G. Lambert, A. Mostacci, A. Petralia, V. Petrillo, L. Poletto, M. Quattromini, J.V. Rau, C. Ronsivalle, E. Sabia, M. Serluca, I. Spassovsky, V. Surrenti, C. Vaccarezza, and C. Vicario, Phys. Rev. Lett. 107, 224801 (2011)
[13] S. Achermann et al. , S-FLASH, present status and commissioning results, Proced. FEL conf. 2011, Shangahi, 194-197
[14] A novel self-seeding scheme for hard X-ray FELs, Geloni, Journal of Modern Optics 58 (16), 1391-1403 (2011)
[15] Demonstration of self-seeding in a hard-X-ray free-electron laser, J. Amann et al. , Nature Photonics 6, 693–698 (2012)
[16] X-Rays: Self-seeded FEL emits hard X-rays, M. Yabashi, T. Tanaka, Nature Photonics 6, 648–649 (2012)
[17] Echo-enabled harmonic generation free-electron laser, D. Xiang and G. Stupakov, Phys. Rev. STAB 12, 070302 (2009)
[18] D. Xiang et al., Phys. Rev. Lett. 105, 114801 (2010)
[19] First lasing of an echo-enabled harmonic generation free-electron laser, Z. T. Zhao et al., Nature Photonics **6**, 360–363 (2012)
[20] The European X-Ray Laser Project XFEL, TDR, July 2006, http://www.xfel.desy.de
[21] B. Naranjo, A. Valloni, S. Putterman, J. B. Rosenzweig, stable charge-particle accleration and focusing in an laser accelerator using spatial harmonics, Phys. Rev. Lett. 109, 176803 (2012)
[22] W. Kimura et al. PHys. Rev. Lett. 92, 154801 (2004), P. Musumeci et al. Phys. Rev. Lett.94, 154801 (2005), P. Musumeci Proceeding EAAC , Elba, May 2013
[23] T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979) 267
[24] S. Mangles et al., Nature 431, 535 (2004)., C.G.R. Geddes et al., Nature 431, 538 (2004), J. Faure et al., Nature 431, 541 (2004), O. Lundh et al., Nat. Phys 7, 219 (2011), W.P. Leemans et al., Nature Phys. 2, 696 (2006), J. Faure et al., Nature 444, 737 (2006), C. Rechatin et al., Phys. Rev. Lett. 102, 164801 (2009), S. Fritzler et al., Phys. Rev. Lett. 92, 165006 (2004), C. M. S. Sears et al., Phys. Rev. ST Accel. Beams 13, 092803 (2010)., E. Brunetti et al., Phys. Rev. Lett. 105, 215007 (2010).

ISBN 978-3-95450-126-7

[25] *A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator,* H.-P. Schlenvoigt et al. Nature Physics, 4, 130-133, (2008), *Laser-driven soft-X-ray undulator source,* M. Fuchs et al., Nature Physics, 5, 826 (2009)
[26] M. E. Couprie et al., *The LUNEX5 project*, Proced. FEL conf., Nara, Japan, Aug. 2012
[27] The LUNEX5 project in France, M. E. Couprie, C. Benabderrahmane, P. Betinelli, F. Bouvet, A. Buteau, L. Cassinari, J. Daillant, J. C. Denard, P. Eymard, B. Gagey, C. Herbeaux, M. Labat, A. Lestrade, A. Loulergue, P. Marchand, J. L. Marlats, C. Miron, P. Morin, A. Nadji, F. Polack, J. B. Pruvost, F. Ribeiro, J. P. Ricaud, P. Roy, T. Tanikawa, R. Roux, S. Bielawski, C. Evain, C. Szwaj, G. Lambert, A. Lifschitz, V. Malka, R. Lehe, A. Rousse, K. Ta Phuoc, C. Thaury, G. Devanz, M. Luong, B. Carré, G. LeBec, L. Farvacque, A. Dubois, J. Lüning, Proceeding of ICXRL, Paris, 2013-08-27; edited by S. Sebban, to appear in SPRINGER PROCEEDINGS IN PHYSICS.
[28] M. E. Couprie, C. Benabderrahmane, P. Betinelli, F. Bouvet, A. Buteau, L. Cassinari, J. Daillant, J. C. Denard, P. Eymard, B. Gagey, C. Herbeaux, M. Labat, A. Lestrade, A. Loulergue, P. Marchand, J. L. Marlats, C. Miron, P. Morin, A. Nadji, F. Polack, J. B. Pruvost, F. Ribeiro, J. P. Ricaud, P. Roy, T. Tanikawa, R. Roux, S. Bielawski, C. Evain, C. Szwaj, G. Lambert, A. Lifschitz, V. Malka, R. Lehe, A. Rousse, K. Ta Phuoc, C. Thaury, G. Devanz, M. Luong, B. Carré, G. LeBec, L. Farvacque, A. Dubois, J. Lüning, The LUNEX5 project in France, Proced. 11th International Conference on Synchrotron Radiation Instrumentation, Lyon, July 9-13, 2012 Journal of Physics Conferences Series, 2013, 425: art.n° 072001 - (SRI2012)
[29] LUNEX5 CDR, www.lunex5.com
[30] A. Lifshitz, X. Davoine, E. Lefebvre, J. Faure, C. Rechatin, and V. Malka, Particle in cell modelling of laser plasma interaction using Fourier decomposition, J. Comput Phys. 228, 1803-1814 (2009).
[31] C. Benabderrahmane, M. Labat, A. Loulergue, F. Marteau, M. Valléau, M.E. Couprie, G. Le Bec, J. Chavanne; LUNEX5 FEL line undulators and magnetic elements; International Free Electron Laser Conference, Nara, Japan, 2012, Aug 26-31
[32] M.E. Couprie C. Benabderrahmane, P. Berteaud, F. Briquez, L. Chapuis, O. Chubar, T. Elajjouri, F. Marteau, J. M. Filhol, C. Kitegi, O. Marcouillé, M. Massal, M. Valleau, J. Vétéran, A panoply of insertion devices at SOLEIL for a wide spectral range and flexible polarisation,Synchrotron Radiation Instrumentation Melbourne, Australia, 27 Sept.- 2 Oct. 2009, AIP Conference Proceedings 2010, 1234, 519-522
[33] M.P. Anania et al. Proceed. SPIE 7359, 735916 (2009)
[34] A. R. Maier et al., Phys. Rev. X 2, 031019 (2012) ; C. B. Schroeder et al., Proc. of FEL Conf. (to be published)(2012)
[35] A. Loulergue, workshop HBEB, Puerto Rico;
[36] Z. Huang et al., Phys. Rev. Lett. 109, 204801 (2012), T. Smith et al. J. Appl. Phys; 50, 4580 (1979)
[37] O. Marcouillé et al., these proceedings
[38] C. Benabderrahmane, P. Berteaud, M. Valléau, C. Kitegi, K. Tavakoli, N. Béchu, A. Mary, J. M. Filhol, M. E. Couprie, Nuclear Instruments and Methods in Physics Research A 669 (2012) 1-6
[39] F. Muller et al., Phys. Rev. Spec. Topics AB 15, 070701, 2012
[40] S. Smith and E.M. Purcell, Phys. Rev. 92, (1953) 1069 ; S.E. Korbly et al., Phys.Rev. Lett. 94 (2005) 054803 ; A.S. Kesar et al., Phys. Rev. ST. Accel. Beams 9 (2006) 022801.
[41] R. Bartolini, C. Clarke, N. Delerue, G. Doucas and A. Reichold, *JINST* 7 P01009, (2012).

ISBN 978-3-95450-126-7