ADVANCES ON THE LUNEX5 AND COXINEL PROJECTS

M. E. Couprie, C. Benabderrahmane, P. Berteaud, C. Bourassin-Bouchet, F. Bouvet, J. Bozek, F. Briquez, L. Cassinari, L. Chapuis, J. Daillant, J. Da Silva, D. Dennetière, Y. Dietrich, M. Diop, J. P. Duval, M. El Ajjouri, T. El Ajjouri, C. Herbeaux, N. Hubert, M. Khojoyan, M. Labat, N. Leclercq, A. Lestrade, A. Loulergue, P. Marchand, O. Marcouillé, J. L. Marlats, F. Marteau, C. Miron, P. Morin, A. Nadji, R. Nagaoka, F. Polack, F. Ribeiro, J. P. Ricaud, G. Sharma, P. Rommeluère, P. Roy, K. Tavakoli, M. Thomasset, M. Tilmont, M. A. Tordeux, M. Valléau, J. Vétéran, W. Yang, D. Zerbib, Synchrotron SOLEIL, France
S. Bielawski, C. Evain, M. Le Parquier, C. Szwaj, PhLAM/ CERLA, Lille, France
E. Roussel, FERMI@ELETTRA, Sincrotrone Trieste, Basovizza, Italy
G. Lambert, V. Malka, A. Rousse, C. Thaury, Lab. d'Optique Appliquée, Palaiseau, France
G. Devanz, C. Madec, A. Mosnier, CEA/DSM/IRFU/SACM, Saclay, France
D. Garzella, CEA/DSM/IRAMIS/ LIDyL, Saclay, France
N. Delerue, M. El Khaldi, W. Kaabi, F. Wicek, Laboratoire de l'Accélérateur Linéaire, Orsay, France
X. Davoine, CEA/DAM/DIF, Bruyère-Le-Châtel, France
A. Dubois, J. Lüning, LCPMR, Paris-VI, France

Abstract

LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) aims at investigating compact and advanced Free Electron Laser (FEL). It comprises one one hand a 400 MeV superconducting linac for studies of advanced FEL schemes, high repetition rate operation (10 kHz), multi-FEL lines, and one the other hand a Laser Wake Field Accelerator (LWFA) for its qualification by a FEL application, an undulator line enabling advanced seeding and pilot user applications in the 40-4 nm spectral range. Following the CDR completion, different R&D programs were launched, as for instance on FEL pulse duration measurement, high repetition rate electro-optical sampling. The COXINEL ERC Advanced Grant aims at demonstrating LWFA based FEL amplification, thanks to a proper electron beam manipulation, with a test experiment under preparation. As a specific hardware is also under development such as a cryo-ready 3 m long undulator of 15 mm period is under development.

INTRODUCTION

Since the laser discovery [1] and the first FEL [2] in the infra-red in Stanford on MARK III, followed by the ACO FEL in Orsay [3] in the visible and UV, and then in the VUV using harmonic generation [4] in the VUV, free electron lasers count nowadays as unique light sources in terms of their properties. Since the early FEL times, performance characterisation and quest for improvement was one of the major concerns. For example, in the case of the Super-ACO storage ring based FEL in France [5,6], the FEL dynamics was actively studied [7-10] and led to the first use of a UV FEL, even in combination with synchrotron radiation for pump-probe two-color experiments [11-16]. Oscillators and coherent harmonic generation also enable adjustable polarisation thanks to the use of elliptically polarised undulators [17-18]. So far, FEL oscillators have been limited to the VUV [19] because of the issues related to the mirror performance and degradation at short wavelengths [20-21]. Short-wavelength FELs then evolved towards high-gain single-pass-based systems [22] in the SASE [23] and seeded [24] configurations. Presently, VUV-X tuneable coherent sub-ps pulses FEL light sources around the word provide record peak powers (typically GW), peak and average brilliance at short wavelengths. FEL user facilities (FLASH1, FLASH2 [25-26], FERMI@ELETTRA in the seeded configuration [27], LCLS [28] and SACLA [29] in the hard X-ray) enable to explore unknown phenomena in various scientific domains. Different directions are now explored for performance improvement.

In France, activity has been performed in the frame of international collaborations on seeding, enabling to reduce the intensity fluctuations, jitter, the saturation length, in particular with a seed being generated from high-order harmonics generated in gas [30-32]. There is also interest for two-color operation, with first studies on CLIO [33] and in the pulse splitting configuration [34]. Characterisation of FEL properties is also of concern, both transversally [35] and longitudinally [36].

LUNEX5 PROJECT

The LUNEX5 [37-41] demonstrator project (shown in Fig. 1) aims at exploring several directions for the production of short, intense, and coherent pulses between 40 and 4 nm on the first, third and fifth harmonics. It relies first on a 400-MeV superconducting linac (SC) with two to three modified XFEL-type cryomodules at 1.3 GHz for high repetition rate CW and thus multiple user operation. The electron bunch is compressed due to a dogleg with sextupoles, enabling phase space linearization and cancellation of the second order dispersion [41].

Copyright © 2015 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-134-2

The FEL line is made of two modulators (period 30 mm) and four cryo-ready radiators (15-mm period) for the comparison of Echo Enabled Harmonic Generation (echo) [42] and HHG seeding in terms of FEL spectral and temporal properties. Two pilot user experiments in gas phase and condensed matter will qualify the FEL performance in the different cases.

In addition, another direction will explore the qualification of a laser plasma acceleration process [43] by a FEL application, using the same FEL line components and a specific transport line for handling the plasma electron beam properties (divergence (1 mrad) and energy spread (1%)) to enable FEL amplification [44-45].

The LUNEX5 R&D and complementary studies to the Conceptual Design Report are carried out on specific programs with their own funding. The progresses on the different R&D programs are described below.

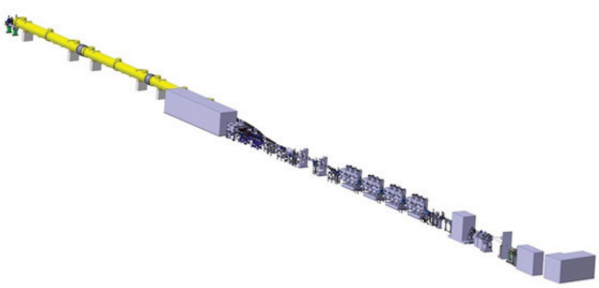

Figure 1: LUNEX5 sketch: cryomodules (yellow), LWFA laser hutch (grey), undulators (4 radiators and 2 echo modulators), pilot user experimental sections.

PARTIAL COHERENCE FEL PULSE MESUREMENT

Measuring and controlling the temporal properties of the radiation emitted by LUNEX5 is essential. A new method called MIX-FROG enabling to characterize these properties even in the presence of partial longitudinal coherence has been proposed and developed [36]. It is an extension of the FROG (Frequency Resolved Optical Gating) technique [46]. The measurement scheme relies on laser-dressed XUV photoionization: the evolution of the shot-averaged photoelectron spectrum with the laser/XUV delay provides a two-dimensional spectrogram (see Fig. 2a). The statistical properties of the XUV pulses accumulated during the measurement are then extracted from this spectrogram considering a superposition of coherent states [47] using a phase-retrieval algorithm, inspired from ptychography [48]. The ability of the technique to measure the pulses produced by LUNEX5 has been validated numerically. Fig. 2a shows the spectrogram expected in the EEHG configuration of LUNEX5 [49]. In this regime, partial longitudinal coherence will arise from the unavoidable arrival time jitter that exists between the laser and FEL pulses. The simulations show an impact of jitter on the spectrogram. The proposed technique however properly retrieves the LUNEX5 pulse, (see Fig. 2b), as well as the laser pulse and the envelope of the arrival time jitter (see Fig. 2c).

This technique provides a diagnostic for shot-to-shot pulse fluctuations, but it also enables the characterization of other phenomena that can reduce the pulse coherence, including the spatio-temporal pulse distortions or the limited resolution of the detection device.

The next step is to apply the technique on FEL experimental data. It can also be used for the characterisation of attosecond high-order harmonics or for infrared lasers.

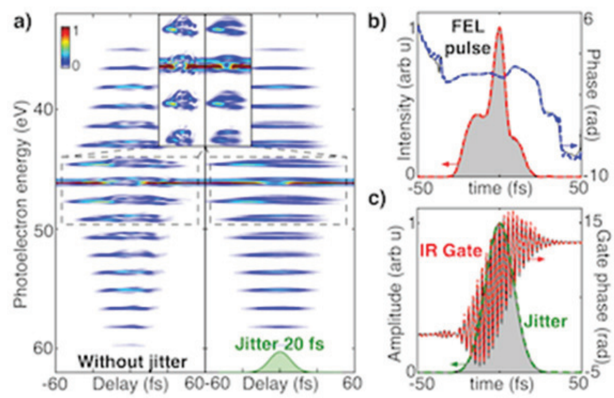

Figure 2: a) Photoelectrons spectra vs laser/FEL delay with and without arrival time jitter. In the presence of jitter, the new technique allows for the retrieval of b) the LUNEX5 pulse and of c) the laser pulse and the jitter envelop.

HIGH REPETITION RATE ELECTRO-OPTICAL SAMPLING

Operation of the LUNEX5 [37-41] demonstrator at high repetition rate (shown in Fig. 1) will also present challenges from the diagnostics point of view. This is particularly true for shot-by-shot electron bunch shape characterization.

Classical single-shot electro-optical sampling (EOS) schemes consist in encoding the electron bunch shape in the spectrum of a laser pulse. Then an optical spectrum analyzer (i.e., a grating and camera system) is used for the final detection. Though very efficient in the low-repetition case, this method cannot be directly applied to high repetition rates, because of the limited speed of current cameras (typically in the hundreds of kHz range).

We have tested an alternate method enabling to perform EOS at high repetition rates (88 MHz for the moment), using the so-called *time-stretch* strategy illustrated in Fig. 3 [50]. The principle is to slow down the EOS signal (with ps/sub-ps duration) down the nanosecond range, using dispersion in optical fibers. Eventually, the output of the system is a replica of the EOS signal (i.e., the bunch shape), magnified down to the nanosecond scale, and which can be recorded by an oscilloscope.

We performed a feasibility demonstration of this method, using Coherent Synchrotron Radiation (CSR) THz pulses (instead of bunch shapes). The EOS was performed in a GaP crystal, and the CSR pulses were

ISBN 978-3-95450-134-2

Copyright © 2015 CC-BY-3.0 and by the respective authors

produced at the AILES beamline of the SOLEIL storage ring. Our EOS setup [51] was able to characterize individual THz CSR pulses emitted by the electron bunch at MHz rates. This strategy will thus be foreseen for the high repetition rate operation of LUNEX5.

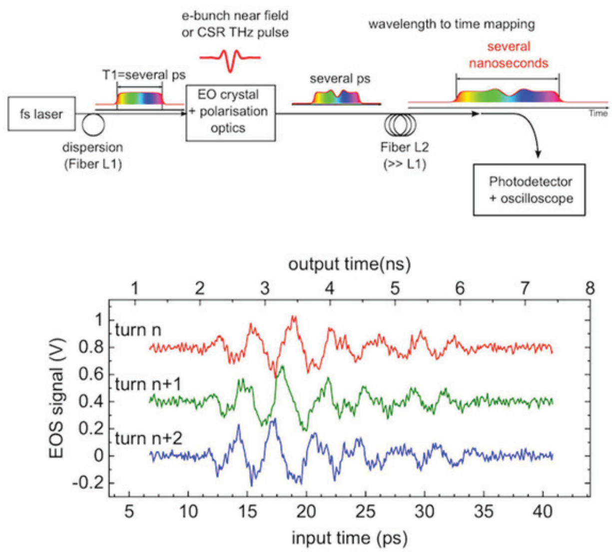

Figure 3: Time-stretched electro-optical sampling. Upper part: general principle (see Ref. 51 for the detailed setup). Lower part: typical series of single-shot EOS pulses. Note that the repetition rate of the pulses is ~1 MHz, but the EOS system is actually acquiring at 88 MHz acquisition rate.

SHORT PERIOD COMPACT UNDULATOR

SOLEIL has been pioneering in the development of $Pr_2Fe_{14}B$ based cryogenic undulators [52-55]. Cooling down the permanent magnet increases both the remanence and the coercivity. Because of the absence of Spin Reorientation Transition at 77 K, such a magnetic grade can also be directly used at the liquid nitrogen temperature. A first 2-meter long U18 undulator (18-mm period) is installed since 4 years on SOLEIL storage ring and operates successfully for the Nanoscopium long beamline with a gap of 5.5 mm. Performance are pushed further on LUNEX5 with a cryo-ready U15 (15-mm period) undulator of 3-m long and 3-mm gap for the FEL application.

The selected $Pr_2Fe_{14}B$ magnets with a coercivity of 1900 kA/m at 300 K and a remanence of 1.31 T enables operation at room temperature with a peak magnetic field of 1.59 T, and a cold regime at 77 K with a field of 1.74 T at 3-mm gap thanks to the increase of the remanence up to 1.55 T. The undulator construction is under progress.

TOWARDS CW OPERATION

There is a clear need for high repetition rate operation from the LUNEX5 user side, e.g. for coincidence experiment, photoemission and imaging.

In its last phase, the 400 MeV superconducting linac of LUNEX5 shall allow for a high repetition rate (10 kHz) multi-user operation by multiplexing the electron beam towards different FEL lines. That requires designing the RF system for continuous (CW) operation and the R&D programme LUCRECE was launched for this purpose. Within this framework, a 1.3-GHz superconducting accelerating structure and its related components (tuner, fundamental and HOM couplers, Helium manifold), based on the TESLA technology will be upgraded for CW operation. In parallel, a 1.3-GHz 20-kW CW solid state amplifier (SSA) will be developed, on the base of the SOLEIL technology already in use at lower frequencies (350 MHz and 500 MHz). The 20-kW CW operation of the complete RF unit including the cavity, the power source, as well as the associated LLRF and control systems, will then be validated in the CEA CryHoLab test station from high rate pulsed to CW operation. Performance will be compared at 1.8 K and at 2 K. LUCRECE will gather the three key laboratories of the Ile-de-France area, Synchrotron SOLEIL, CEA-IRFU and LAL with three industrial partners, Sigmaphi Electronics (SPE), ALSYOM and THALES. The joint work from CEA-IRFU & ALSYOM for the assembly of 103 cryomodules and from LAL & THALES for the supply of 800 couplers, as in-kind contribution to the European XFEL, will be extended to upgrade the equipment for use in CW regime. SOLEIL and SPE, which are already linked by an agreement of transfer of know-how in the domain of SSAs, will explore together the possibility of applying new emerging technologies. Finally, LUCRECE project aims at closely linking laboratories and companies in a process of technical valorisation with the aim to LUNEX5.

TOWARDS A DEMONSTRATION OF FEL AMPLIFICATION WITH ELECTRONS GENERATED WITH LASER PLASMA ACCELERATION

Laser Plasma Accelerator (LPA) presently provides an electron beam with a typical current of a few kA, a bunch length of a few fs, an energy in the few hundreds of MeV to several GeV range, a divergence of typically 1 mrad, an energy spread on the order of 1%, and a normalized emittance on the order of 1 π·mm·mrad. It is considered to use them to drive a FEL but a particular beam handling is necessary.

In a laser plasma wakefield accelerator [56-58], an intense laser pulse is focused in a light gas or in a mixture of heavy and light gases [59]. The rising edge of the laser ionizes the gas and creates a plasma. As the laser pulse propagates in the plasma, the ponderomotive force expels electrons from the optical axis, thus forming a cavity free of electrons in the laser wake, with large fields enabling electrons to be accelerated. The best electron beam performance has been achieved with colliding injection [60] and density transition injection [61].

Copyright © 2015 CC-BY-3.0 and by the respective authors

One considers here in the LUNEX5 case (and in the COXINEL R&D program) electrons of several hundreds of MeV, dozens of pC charge, with 1-µm transverse size, 1-mrad divergence, and 1-µm longitudinal size (normalized emittance of ~1 π·mm·mrad), few-femtosecond duration and 1% energy spread. These values are close to what has been achieved but they require a specific handling to preserve the emittance and the bunch length in the transport. The proposed beam manipulation for COXINEL is the following: The beam is first strongly focused with adapted quadrupoles of high gradient close to the electron source and/or with a plasma lens [62]. The energy spread is handled in passing the electron beam through a decompression chicane, which sorts them in energy and can reduce typically the slice energy spread by one order of magnitude [63]. In addition, because of the energy-position correlation, the slices can be focused in synchronization with the optical wave advance, in the so-called chromatic matching scheme [64]. An example of FEL simulation in the seeded configuration is shown in Fig. 4. Further start-to-end simulations, starting from CALDER-PIC simulations, are also under way.

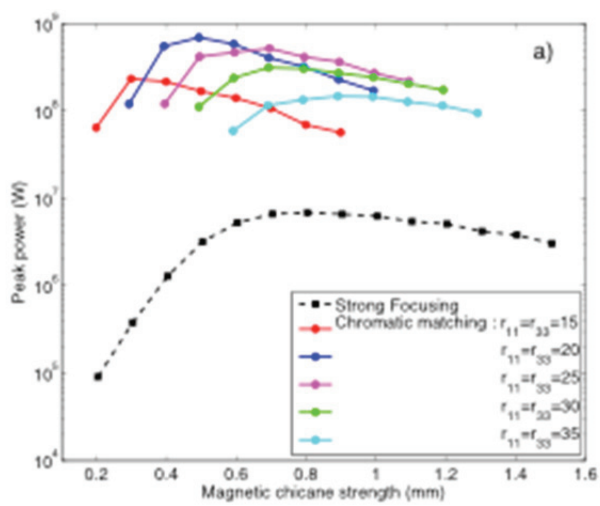

Figure 4: FEL peak power comparison versus chicane strength. Case of a 5-m undulator of 15-mm period and 1.5-T maximum field seeded with 10 kW at 40-nm wavelength and 400-MeV beam energy.

A test demonstration experiment is under preparation under the COXINEL and X-Five programs [65-67].

Electrons will be generated with the 2x60 TW laser at Lab. d'Optique Appliquée and equipment is under preparation at SOLEIL. The majority of the magnetic elements (see Fig. 5) of the transport line and their power supplies are under measurements. The cavity Beam Position Monitors (SwissFEL) and Turbo-Integrated Current Transformer (Bergoz) are under test on the SOLEIL linac. The profile meters are under design. The experiment of FEL amplification will be started at 200 nm with a 2-m long U20 undulator (which is ready) and a spectrometer (IHR320 Horiba), presently under test. The pumping system has been designed and is under procurement. Control will be performed with TANGO. This activity sets a first step within a larger prospect offer by the EuPRAXIA program on laser-plasma acceleration applications.

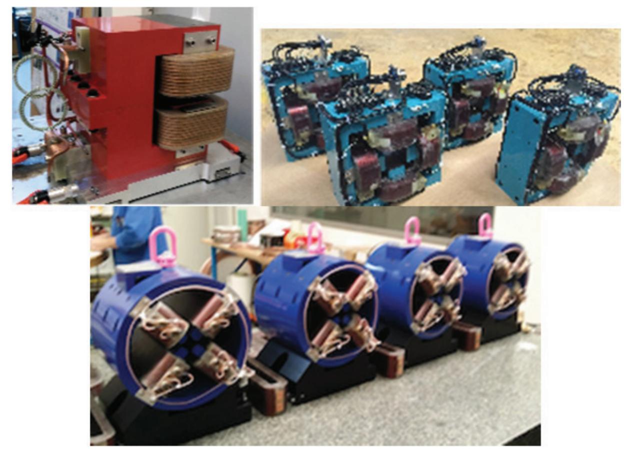

Figure 5: Picture of the COXINEL chicane dipoles, steerers and quadrupoles of the second refocusing set (manufactured by SEF).

CONCLUSION

The LUNEX5 R&D is under progress under various specific programs.

ACKNOWLEDGMENT

The work is supported by the European Commission (European Research Council Advanced Grants (COXINEL (340015), X-Five (339128), and Design studies EuPRAXIA), the Agence Nationale de la Recherche (Laboratoire d'Excellence Physique Atomes Lumière Matière- ANR-10-LABEX-0039 (FEL shaping, Ultrafast-X), IDEX Paris-Saclay (OPT2X), ANR (SP, DYNACO)), Labex CEMPI, the "Triangle de la Physique" (QUAPEVA) with collaborators from Sigmaphi (J.L. Lancelot, O. Cosson, F. Forest), the French Ministère chargé de la Recherche, Région Nord-Pas de Calais and FEDER, and the "region Ile-de-France" for the LUCRECE contract (partners Pascal Dupire (Sigmaphi Electronics), Thales Serge Sierra (THALES), Eric Giguet (Alsyom)), and the SOLEIL-VR collaboration (SP3-ID).

REFERENCES

[1] C.H. Townes, in L. Garwin *et al*., Univ. of Chicago Press, 107-112 (2003).
[2] D.A.G. Deacon *et al*., Phys. Rev. Lett. 38, 892-894 (1977).
[3] M. Billardon *et al*., Phys. Rev. Lett. 51, 1652, (1983).
[4] B. Girard *et al*., Phys. Rev. Lett. 53 (25) 2405-2408 (1984).
[5] M.E. Couprie *et al*., Nucl.Inst. Meth. A 296, 13-19 (1990).
[6] M.E. Couprie *et al*., Europhysics Letters 21(9), 909-914 (1993).

Copyright © 2015 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-134-2

[7] M. Billardon, D. Garzella, M.E. Couprie, Phys. Rev. Lett. vol 69 (16), 2368-2371 (1992).
[8] T. Hara *et al*., Nucl.Inst. Meth. A 341, 21-23 (1994).
[9] M.E. Couprie *et al*., Phys. Rev E 53 (2), 1871-1889 (1996).
[10] M.E. Couprie *et al*., Nucl. Instr. Meth. A 407, 215-220 (1998).
[11] M.E. Couprie *et al*., Rev. of Scient. Inst. 65, 1495-1495, (1994).
[12] M. Marsi *et al*., Appl. Phys. Lett. 70, 895-897, (1997).
[13] M. Marsi *et al*., Journal of Electron Spectroscopy and Related Phenomena 94, 149-157 (1998).
[14] M.Marsi *et al*., Phys. Rev. B 61, R5070-R5073 (2000).
[15] L. Nahon *et al*., Nuclear Instr. Meth. A 429, 489-496 (1999).
[16] E. Renault *et al*., Nucl. Inst. Meth. A 475 (1-3), 617-624 (2001).
[17] M. Labat *et al*., Phys. Rev. Lett. 101, 164803 (2008).
[18] E. Allaria *et al*., Phys. Rev. Lett. 100, 174801 (2008).
[19] M. Trovo *et al*., A 483, 1-2, 157-161 (2002).
[20] M. Velghe *et al*., Nucl.Inst. Meth. A 296, 666-671 (1990).
[21] M.E. Couprie *et al*., Nucl. Instr. Meth. A 272 (1-2), 166-173 (1988).
[22] M.E. Couprie, J. M. Filhol, 2008 C. R. Physique 9, 487-506.
[23] A.M. Kondratenko, E.L. Saldin, Part. Acc. 10, 207 (1980).
[24] L.H. Yu *et al*., Science 289(5481), 932 (2000).
[25] W. Ackermann *et al*., Nature Photonics 1, 336-342 (2007).
[26] K. Honkavaara *et al*., Proceeding FEL Conf, Basel, Switzerland, Aug. 2014.
[27] E. Allaria *et al*., Nature Photon. 6 699–704 (2012).
[28] P. Emma *et al*., Nature Photonics 4, 641 (2010).
[29] T. Ishikawa *et al*., Nature Photonics 6, 540–544 (2012).
[30] G. Lambert *et al*. Nature Physics 4, (2008), 296-300.
[31] T. Togashi *et al*., Optics Express, 1, 317-324 (2011).
[32] M. Labat *et al*., Phys. Rev. Lett. 107, 224801 (2011).
[33] R. Prazeres *et al*., Eur. Phys. J. D3, 87 (1998).
[34] M. Labat *et al*, Phys. Rev. Lett. 103, 264801 (2009).
[35] R. Bachelard *et al*., Phys. Rev. Lett. 106, 234801 (2011).
[36] C. Bourassin-Bouchet and M. E. Couprie, Nature Communications 6, 6465 doi:10.1038 /ncomms7465 (2015).
[37] M.E. Couprie *et al*., J. of Phys. Conf. Series 425, 072001 (2013).
[38] M.E. Couprie *et al*., accepted in Review of Modern Optics.
[39] http://www.lunex5.com/spip.php?article34.
[40] M.E. Couprie *et al*. Proceeding FEL conf, Basel (2014).
[41] M.E. Couprie *et al*. Proceed. IPAC conf, Dresden, (2014).
[42] G. Stupakov, Phys. Rev. Lett., 102, 074801 (2009).
[43] T. Tajima *et al*., Phys. Rev. Lett. 43, 267 (1979).
[44] A. Loulergue *et al*. New J. Phys. 17 (2015) 023028 (2015).
[45] M.E. Couprie *et al*. J. Physics B: At., Mol., Opt. Phys. 47 234001 (2014).
[46] R. Trebino *et al*, Rev. of Scient. Inst., 68 3277-3295, (1997).
[47] D.T. Smithley *et al*., Phys. Rev. Lett. 70, 1244-1247 (1993).
[48] P. Thibault *et al*., Science 321, 379-382 (2008).
[49] C. Evain *et al*., Proceeding IPAC 2012, New Orleans, USA, 1611-1613 (2012).
[50] F. Coppinger *et al*., IEEE Transactions on Microwave Theory and Techniques 47, 1309 (1999).
[51] E. Roussel *et al*., Scientific Reports 5, 10330 (2015).
[52] C. Benabderrahmane *et al*. Nucl. Instr. Meth. Phys. Res. 669, 1-6 (2012).
[53] C. Benabderrahmane *et al*., Journal of Physics: Conference Series 425, 032019 (2013).
[54] M.E. Couprie *et al*. Proceeding of the SPIE conf, Praha, April 2015, to appear in IEEE.
[55] M. Valléau *et al*., Proceeding SRI 2015, New York.
[56] S. Mangles *et al*., Nature 431, 535 (2004).
[57] J. Faure *et al*., Nature 431, 541 (2004).
[58] C.G.R. Geddes *et al*., Nature, 431, 7008, 538-541(2004).
[59] M. Chen, *et al*., Journal of Applied Physics 99, 056109 (2006).
[60] J. Faure *et al*., Nature 444, 737 (2006).
[61] K. Schmid *et al*., Phys. Rev. ST Accel. Beams 13, 091301 (2010).
[62] C. Thaury *et al*., Demonstration of relativistic electron beam focusing by a laser-plasma lens, Nature Comm. 6, 6860 (2015).
[63] M.E. Couprie *et al*., Towards Free Electron Laser with Laser Plasma Accelerators, J. Physics B : At., Mol. Opt. Phys. 47 (2014) 234001 (12 pp) Special issues on compact x-ray sources (2014).
[64] A. Loulergue *et al*., Beam manipulation for compact laser wakefield accelerator based free-electron lasers, New J. Phys. 17 (2015) 023028 (2015).
[65] M.E. Couprie *et al*., Proceedings FEL'14, Basel, Switzerland 574-579 (2014).
[66] M.E. Couprie *et al*., Proceedings FEL'14, Basel, Switzerland 569-573 (2014).
[67] A. Loulergue *et al*. Proceeding SPIE, Prague, April 2015.

Copyright © 2015 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-134-2