THE FUTURE OF X-RAY FELS

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Abstract

Recent years have brought enormous progress with X-ray FELs. With LCLS and SACLA two facilities with quite different technological approaches have shown the feasibility of SASE FELs in the hard X-ray regime while the SASE FEL FLASH and the recently commissioned laser seeded FEL FERMI@ELETTRA provide coherent light beams of unprecedented brightness at EUV and soft X-ray wavelength. First user experiments at these facilities demonstrate the vast scientific potential of this new type of instrument and have accelerated and triggered R&D and planning for other facilities of its kind worldwide. Projects under construction or in advanced stage of planning are European XFEL, LCLS II, SwissFEL, PAL XFEL, Shanghai XFEL and NGLS. Worldwide R&D efforts for XFELs try to improve performance and reduce size and cost. Focuses are on injector, linac and undulator technologies as well as on FEL seeding methods.

RECENT PROGRESS IN X-RAY FELS

The last three years have seen an exceptionally fast progress in the development of a novel photon source with unprecedented performance figures, the X-ray FEL. A milestone of paramount importance for these developments was the first lasing of LCLS in self amplified stimulated emission mode (SASE) at 1.5 Å in 2009 [1], just three years ago. Before this it was not at all certain if the SASE operation mode can be achieved at such short wavelength. Now LCLS is a well established user facility with an exciting experimental program [2].

The importance of SASE stems from two key features. Firstly it allows FEL operation in single pass mode, i.e. without mirrors. Secondly the amplification process uses the shot noise of the electron beam as input, i.e. no external seeding source is required. These two features allow application of the SASE FEL mode over an extremely large wavelength range, spanning more than five orders of magnitude from infrared light to hard X-rays. More important, SASE holds presently a monopoly for the production of intense laser radiation for the EUV to hard X-rays wavelength domain. An excellent overview of the theory of SASE and the theoretical, technical and experimental developments towards its realization can be found in [3]. The first implementation of SASE for a photon-science user facility is FLASH at DESY [4-5], an EUV/soft X-ray FEL.

In June 2011 the second hard X-ray FEL, SACLA, saw its first SASE photon beam with a wavelength of 1.2 Å [6]. SACLA uses technical solutions quite different from LCLS featuring C-band RF for the linac, in-vacuum undulators and a unique diode electron gun design with thermionic cathode. In particular the linac and undulator technology of SACLA allows for a total facility length as short as 800m, which is less than half the length of LCLS.

The biggest and most powerful amongst presently funded FEL projects is the European XFEL presently under construction [7]. Its 17 GeV superconducting linac will distribute ten times per second a train of 2200 electron bunches into three FEL lines and produce FEL radiation with wavelength as short as 0.5 Å.

SEEDING

Although SASE has paved the way for X-ray FELs and is the baseline mode of operation for most facilities in operation or under construction it has disadvantages inherent to the stochastic nature of the shot noise starting the FEL amplification process. Since different time slices of the electron pulse start the lasing process independently SASE FEL pulses consist of a number of radiation spikes with a time and spectral distribution which changes randomly from pulse to pulse. The duration of the spikes is of the order of the FEL cooperation length. As a consequence pulse energy and spectral shape fluctuates from pulse to pulse no matter how stable the initial electron beam is. Even though the transverse coherence of SASE FELs is very good, the longitudinal coherence is limited to the time of individual spikes. These inherent drawbacks of SASE can be overcome either by seeding the FEL process with a coherent external radiation source, i.e. a laser, or by "selfseeding" with a spectral filter introduced in the SASE gain process.

The initial step for seeding a short wavelength FEL by an external laser is the modulation of the electron beam energy by overlapping laser and electron beam inside an undulator magnet called modulator. For direct seeding at the nominal FEL wavelength the initial laser has to be equipped with a high harmonic generation (HHG) frequency conversion in a gas cell. In this case the modulator has the same period as the FEL modulators. Alternatively the electron beam is energy modulated at the wavelength of the laser in a long period modulator and the longitudinal micro-bunching is generated by an R_{56} element downstream of the modulator. The harmonic content of the micro-bunching at the laser wavelength starts the FEL process at the nominal FEL wavelength in the undulators downstream of the R_{56} element. This scheme is called High Gain Harmonic Generation (HGHG) process. These seeding schemes can be cascaded by using a first FEL stage to generate the seed signal for a second stage at shorter wavelength. Echo enabled harmonic generation (EEHG) is a sophisticated new technique proposed in 2009 [8] where the beam is energy modulated twice using two R_{56} elements, one between modulators and one after the second modulator. All seeding methods with an external laser become with shorter FEL wavelength increasingly difficult not only because of the higher harmonic numbers, but also because the seed signal power has to overcome the shot noise power of the electron beam. The spectral power density of the shot noise increases with decreasing wavelength. A comparative study of the different seeding methods can be found in [9].

With FERMI@ELETTRA the first EUV/soft X-ray FEL user facility entirely based on laser seeded operation saw its first photon beam in December 2010 [10]. It is presently operating with a HGHG configuration and with minimum FEL wavelengths as short as 20 nm. For the next commissioning steps of FERMI@ELETTRA a substantial reduction of wavelength and introduction of a cascaded HGHG is foreseen. The shortest wavelength measured in a HHG laser seeded FEL is presently 38nm achieved end April 2012 at the sFLASH installation in FLASH [11]. The first lasing of an EEHG seeded FEL has recently been demonstrated at the SDUV facility in Shanghai at a lasing wavelength of 350nm [12].

In January 2012 the method of self-seeding was for the first time experimentally demonstrated at LCLS for a wavelength of 1.5 Å [13], shifting the wavelength frontier for seeding by five orders of magnitude in a single step. The basic concept of self seeding was already proposed in the last millennium but an improved variant [14], particularly well suited for the application of the scheme in the X-ray range, allowed the realisation of this landmark experiment. The self seeding set-up at LCLS consists of a first group of undulators operating in SASE centred at nominal wavelength. The SASE radiation generated in these undulators is send through a diamond crystal which is oriented with the nominal radiation wavelength at the Bragg angle. As a consequence narrow band frequency components just outside the Bragg reflection stop-band have a significantly reduced group velocity and the radiation is delayed while traversing the crystal. The electrons leaving the first group of undulators are delayed in a magnetic chicane so that they interact in the downstream group of undulators with the delayed fraction of the radiation only, thus getting bunched at only this wavelength. The self seeding does not only allow for a much better spectral definition of X-ray FELs compared with SASE but provides also longitudinal coherence.

In a tapered FEL undulator line following a self seeding stage FEL radiation can be extracted more efficiently from the electron beam than in a SASE FEL. In [15] an instantaneous FEL power of up to 1 TW has been anticipated for such a set-up.

XFELS IN CONSTRUCTION OR ADVANCED STATE OF PLANNING

The scientific output of the two X-ray FELs which have already accumulated significant amounts of user experiment time, FLASH and LCLS, is remarkable. A list of related publications can be found at [16,17]. The downside of this success is the overbooking of the FLASH and LCLS beam-lines, making access for experimentalists increasingly difficult. Both facilities have therefore launched projects to increase the number of end stations, beam capabilities and available beam time. The projects have been baptised FLASH II [18] and LCLS II [19].

For FLASH II a fraction of the bunches in the bunch train from the existing superconducting FLASH 1.2 GeV accelerator is extracted with a fast kicker to a new undulator line. This line is equipped with variable gap planar undulators, thus allowing independent wavelength control with respect to FLASH. Although FLASH II operation will start in SASE mode seeding with HHG is already planned and provisions have been taken to allow for other seeding methods as well. Construction work and procurement for FLASH II is ongoing and commissioning will start 2013.

LCLS II will use the middle third of the SLAC linear accelerator (LCLS uses the last third of this accelerator), thus having the same 14 GeV energy capability as LCLS. A new injector and undulator lines will be built for LCLS II, thus making operation of LCLS II independent of LCLS. LCLS II will have two variable gap planar undulator-lines HXR and SXR. HXR is optimised for hard X-ray wavelength from 1-6 Å and SXR is optimised for soft X-rays from 6-50 Å. Ground breaking for LCLS buildings is planned for 2013 and first beam is expected for late 2017.

The Paul Scherrer Institut in Switzerland is preparing the construction of the X-ray FEL SwissFEL as its next large user facility [20]. The injector for SwissFEL is already been operated in a test-facility [21]. The 6 GeV main linac for SwissFEL uses normal conducting C-band technology. In a first construction stage from 2013-16 an undulator line for hard X-rays in the 1-7Å range will be built. This line uses planar variable gap in-vacuum undulators. The initial building has already space reservation for a soft X-ray undulator line optimised for 7-70 Å with Apple II undulators. The construction of this line is planed for 2018-19. Both SwissFEL lines can be operated in SASE or self seeding mode.

PAL in Korea is launching this year the construction of an X-ray FEL with a hard X-ray and a soft X-ray undulator line for 0.6-7 Å and 10-100 Å [22]. Space reservations allow adding two more undulator lines. A 10 GeV normal conducting S-band linac is foreseen as main accelerator. Completion of the PAL XFEL is planned for 2015.

SINAP/Shanghai has a staged approach. Starting from the experience with the existing SDUV test accelerator

Table 1: Overview of X-ray FELs facilities with key parameters and technology choices.
Facilities in operation are marked in blue, facilities under construction or in planning are marked in green.

	LCLS	LCLS II	Eu-XFEL	SACLA	FLASH	FLASH II	FERMI	SwissFEL	PAL XFEL	Shanghai XFEL	NGLS	MaRIE
Shortest wavelength	1.5 Å	1 Å	0.5 Å	1 Å	40 Å	40 Å	40 Å	1 Å	1 (0.6) Å	1 Å	10 Å	0.3 Å
Undulator type hard X-ray.	Fixed gap	Variable gap	Variable gap	In-vacuum Var. gap	n.a.	n.a.	n.a.	In-vacuum var. gap	Variable gap	Variable gap	n.a.	?
Undulator type soft X-ray.	n.a.	Variable gap	Variable gap	n.a.	Fixed gap	Variable gap	Apple II	Apple II	Apple II	?	Var. gap & Apple	n.a.
Injector	S-band RF gun	S-band RF gun	L-band RF gun	Pulsed Diode	L-band RF gun	L-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	VHF c.w. RF Gun	?
Cathode	Cu	Cu	Cs_2Te	CeB_6 (thermionic)	Cs_2Te	Cs_2Te	Cu	Cu	Cu	Cu	K_2CsSb	?
Main linac technology	n.c. Pulsed	n.c. pulsed	s.c. pulsed	n.c. pulsed	s.c. pulsed	s.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	s.c. c.w.	n.c. pulsed
RF frequency	S-band	S-band	L-band	C-band	L-band	L-band	S-band	C-band	S-band	C-band	L-band	S–band
RF Rep. rate	120 Hz	120 Hz	10 Hz	60 Hz	10 Hz	10 Hz	10-50 Hz	100 Hz	120 Hz	60 Hz	n.a.	60 Hz
FEL pulses/RF pulse	1	1	2700	1	2700	2700	1	2	1	1	1 MHz c.w.	100
max. bunch charge	0.25 nC	0.25 nC	1 nC	0.2 nC	1 nC	1 nC	0.5 nC	0.2 nC	0.2 nC	0.2 nC	0.3nC	0.1 nC
max. electron energy	13.6 GeV	14 GeV	17.5 GeV	8 GeV	1.2 GeV	1.2 GeV	1.5 GeV	5.8 GeV	10 GeV	6.4 GeV	2.4 GeV	12 GeV
No. RF stations	81	81	29	69	5	5	15	34	49	?	?	?
Approx. facility length	1.7km	1.7km	3.4 km	0.8km	0.32 km	0.32 km	0.5 km	0.7km	1.1 km	0.6 km	?	1.0 km
Start operation	2009	2017	2015	2011	2005	2013	2010	2016	2015	2019	2023	?

they build on the Shanghai SSRF campus a Soft X-ray FEL, SXFEL, starting construction this year for commissioning 2015. This facility uses a C-band normal conducting linac with initially 840 MeV for a FEL wavelength of 88 Å. The purpose of this initial stage of SXFEL is the study of seeding schemes with emphasis on cascaded HGHG. An upgrade of SXFEL to an user facility with an electron energy of 1.3 GeV and a shortest wavelength of 38 Å wavelength is anticipated in the SXFEL design. A larger Shanghai XFEL facility with 6.4 GeV beam energy and wavelengths ranging to 1 Å is planned to be build next to SXFEL [23] from 2016 on with commissioning anticipated for 2019.

LBNL in California is planning for the Next Generation Light Source NGLS [24]. NGLS is a soft X-ray FEL with a superconducting 2.4 GeV L-band linac in superconducting technology. The NGLS would be the first X-ray FEL running in c.w. mode. Maximum envisaged bunch repetition rate is 1 MHz and initial wavelength range 10-46 Å. A superconducting 2.4 GeV c.w. linac is feeding 3 undulator lines simultaneously. The NGLS layout allows for extensions with up to 10 FEL lines featuring SASE and self seeded operation modes. The high repetition rate and the high beam power raise a number of R&D issues [25]. A particular challenge is the development of a low emittance gun for c.w. operation [26]. Presently first operation of NGLS is anticipated for 2023.

At LANL in New Mexico the concepts for the Matter-Radiation Interactions in Extremes facility MaRIE are taking shape. A key component of MaRIE is a X-ray FEL lasing at a wavelength of 0.3Å [27] using a 12 GeV normal conducting S-bandd linac. A specific challenge is the requirement for a train of 100 photon pulses in a 1.5µs time window. The timeline for MaRIE is not known yet, but a time span of 7 years is anticipated for the realisation of MaRIE.

Table 1 provides an overview of the various X-ray FEL facilities with key parameters and technological choices.

R&D CHALLENGES

The rapid progress of X-ray FEL facilities is only possible because of the intense R&D activities on critical FEL issues worldwide. A complete overview of these activities is beyond the scope of this paper, but reviews on the state of the art for X-ray FEL key technologies have been given at recent conferences. Here we list a few of them:

- Technology of short period undulators with permanent magnets [28]
- Technology of short period undulators with superconducting magnets [29].
- Lasers for photocathode guns and seeding [30]
- High precision RF distribution and timing [31,32]
- Main linac RF and electron guns [33]

Other developments which may have major impact for the future of X-ray FELs are the studies for an X-ray FEL oscillator XFELO [34,35] and for very compact X-ray FELs using laser acceleration instead of an RF linac [36].

CONCLUSIONS AND OUTLOOK

The last three years have seen enormous progress worldwide for the development and construction of X-ray FELs. Driven by the scientific successes of the facilities already in operation several new projects have been launched or are under consideration. While key technologies of X-ray FELs are established now, new developments will allow better performance and/or better economy for future facilities and upgrades of present facilities. Eventually the demands from the photon user community will decide if the number of X-ray FELs will grow to similar quantities as the present number of synchrotron radiation sources.

ACKNOWLEDGMENT

The author is very grateful to Paul Emma/LBL, Bart Faatz/DESY, In Soo Ko/PAL, Subrata Nath/LANL, Jörg Rossbach/Univ. Hamburg, Michele Svandrlik/ELETTRA, Hitoshi Tanaka/Spring-8, Dong Wang/SINAP for providing status information about their projects and R&D. Furthermore he acknowledges the inputs from his PSI colleagues in general and Sven Reiche in particular.

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