OVERVIEW OF PROPOSALS FOR MAJOR FEL FACILITIES

H.H. Braun, PSI, Switzerland

Abstract

The X-ray FEL facilities in an advanced stage of planning worldwide can be grouped in two categories. Those with normal conducting driver linacs aiming to bring the XFEL technology, after the impressive feasibility prove at LCLS, to regional user communities at affordable cost, and those with superconducting driver linacs capable to serve several photon hungry users simultaneously. The talk will review the rationales, technical choices and status of the main proposals and discuss some key R&D issues.

INTRODUCTION

The first and still only operating hard X-ray FEL, LCLS at SLAC, is based on a large existing 2.85 GHz S-band linac, giving a beam energy of 13.4GeV with a gradient of about 17MV/m. Because of the existing linac compactness was not a real design issue. Moreover, safe design margins have been taken for the total undulator length, due to the uncertainties for a first machine of its kind. The measured performance of LCLS lasing in SASE mode at 1.5Å has demonstrated very good agreement with simulation codes [1]. This gives confidence for the expected performance of future facilities, which are presently in planning or construction stage.

The VUV FEL FLASH in operation at DESY has over the past years grown to a 1.2GeV accelerator lasing at wavelengths as short as 4.45nm [2]. Besides being a very successful user facility FLASH has established the injector know-how and superconducting linac technology required for the European XFEL presently under construction in Hamburg [3]. Both FLASH and Eu-XFEL employ a pulsed superconducting RF accelerating systems at 1.3 GHz with an accelerating field of up to 24 MV/m, delivering trains of 2700 bunches per pulse with a repetition rate of 10 Hz and an RF duty cycle of about 1%.

The next facilities which will come online are the hard X-ray FEL SCSS of RIKEN/Spring8 [4] and the soft X-ray FEL FERMI@ELETTRA [5]. Both facilities use a pulsed normal conducting linac. However, SCSS is the first large scale facility to adopt a C-band RF frequency of 5.72 GHz. This allows for a gradient of 40MV/m. The feasibility of this gradient has been demonstrated. The SCSS has a maximum electron energy of 8 GeV. To reach with this energy a wavelength of 1Å SCSS employs variable gap in-vacuum undulators with 18 mm period length. SCSS is presently the only hard X-ray FEL using a thermionic electron gun with subharmonic bunching system and chopper to produce the electron beam. The feasibility of this type of injector is already demonstrated with the SCSS test facility. FERMI@ELETTRA will be the first X-ray FEL facility to use laser FEL seeding as the baseline operation mode. The commissioning results of both SCSS and FERMI@ELETTRA together with the progress on the already operational LCLS and FLASH facilities will have a major influence on the concepts of future FEL facilities.

The main components of an XFEL are the electron injector, the main linac with bunch compressors and the string of undulators, where the FEL lasing process takes place. Assuming a given wavelength goal for the XFEL, compactness of the overall facility can be achieved by reducing the electron beam energy and by increasing the accelerating field in the main linac. Furthermore can the length of the undulator string be substantially reduced by applying seeding techniques instead of SASE for the XFEL operation. Reducing beam energy reduces the linear accelerator length in proportion but requires undulators with shorter magnet period. Since the saturation length of an FEL is roughly proportional to the number of magnet periods the required length of the undulator string is also reduced for machines of lower energy. To keep the undulaotr length constant the beam emittance has also to be reduced in proportion with the beam energy. Therefore lower energy machines require better injector performance and more advanced undulator technology. Raising the accelerating field reduces the overall linac length, but requires an increase of the installed RF power in proportion to the square root of the gradient. Moreover, the maximum accelerating field is limited by RF breakdown phenomena. This power increase can be compensated with a higher RF frequency. The higher frequency structures profit also from higher achievable accelerating field.

OVERVIEW OF PROJECT PROPOSALS

Key decisions for every new XFEL facility are the choice of the shortest lasing wavelength and the choice of linac technology, because these factors have the strongest influence on the overall facility complexity and cost. The facilities presently proposed can be placed in two main groups. The first one are soft X-ray FELs with superconducting linacs running in c.w. mode. These facilities try to maximize average photon flux and the number of beamlines. Part of the rational for these facilities is that the future users like to have a photon pulse repetition rate and number of beamlines similar to nowadays 3rd generation synchrotron radiation sources. The facilities in this group are:

NLS

The New Light Source (NLS) planned in the United Kingdom is a soft X-ray facility with a 2.25 GeV superconducting driver linac with an RF frequency of 1.3 GHz in c.w. operation [6]. The NLS is planned to start with a 1 kHz bunch repetition rate with the possibility to increase with an upgraded injector to 1 MHz bunch

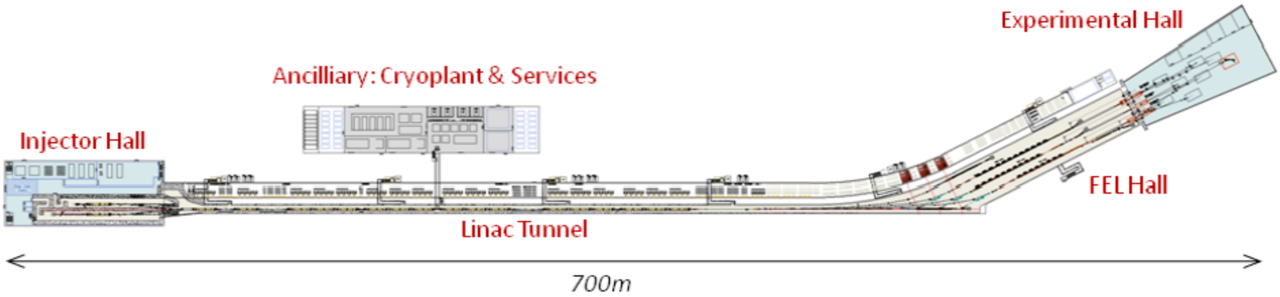

Figure 1: Footprint of NLS.

repetition rate.The baseline design foresees three FEL lines with Apple II undulators and initially a shortest wavelength of 12 Å for 32.2 mm undulator period. All three FEL lines operate with HHG seeding. Figure 1 shows the footprint of NLS.

NGLS at LBNL

LBL has plans for a soft-X-RAY FEL NGLS with c.w. operation [7]. The superconducting linac technology is similar to European XFEL but uses c.w. operation with a gradient of about 14MV/m. The final energy is 2.4GeV. The NGLS has planned for 10 FEL lines, such serving a large user community simultaneously.

BESSY soft X-ray FEL

The BESSY soft X-ray FEL project has definitely been put on hold, but is still worth mentioning because of the valuable R&D [8] which had been performed for this project. This XFEL intended also to use a superconducting 1.3 GHz linac with c.w. operation and a maximum electron beam energy of 2.3 GeV.

The second group of proposed facilities are based on normal conducting, pulsed linac drivers with repetition rates in the 50-100Hz range. For these facilities the rational is to achieve a very short wavelength as required for high resolution X-ray imaging applications with a reasonable facility size and cost frame. Imaging applications require complex 2D detectors with the requirement to read large amount of data every pulse. Therefore a pulse spacing of several ms is well matched to the experimental needs. Planned facilities in this group are:

SwissFEL at PSI

The SwissFEL project at PSI [9] aims like SCSS at a wavelength of 1Å but with an even lower beam energy of 5.8GeV. A schematic view of this facility is shown in figure 2. For the linac the same frequency as SCSS is adopted, however, SwissFEL rather looks for an overall cost optimum than for the shortest possible facility. Therefore the nominal gradient is only 26.5 MV/m. The undulator period length is 15mm. SwissFEL uses a RF gun injector with photocathode. A set-up to test the SwissFEL injector up to the first bunch compressor has just been put into operation [10,11]. The present planning foresees start of construction of the main linac and undulator lines 2012 with first FEL beam in 2016.

XFEL at PAL

PAL intends to build an X-ray FEL with a 10 GeV linac, a 20mm undulator period and a the capability to provide wavelengths as short as 0.6 Å in a facility of about 900m total length [12]. Although the baseline design foresees a linac with standard 2.85GHz S-band frequency and 27MV/m gradient, PAL considers switching to C-band with higher gradient for better space economy.

SXFEL and Shanghai XFEL

SINAP/Shanghai has a staged approach. Starting from the experience with the existing SDUV test accelerator [13] they intend to build the SXFEL soft X-ray FEL user facility next to the SSRF synchrotron, adding the 1Å class Shanghai XFEL next to it later. The Shanghai XFEL plans for an energy of 6.4 GeV and an undulator period length of 16mm [14]. Since the maximum site length is SXFEL C-band technology is presently favoured

SPARX-FEL

The SPARX-FEL proposed by a consortium of Italian institutes is aiming for a 5Å FEL with a normal conducting 2.6 GeV driver linac. SPARX uses an S-band linac system as design baseline, but considers also C-band and X-band options [15]. The SPARC facility in Frascati is the main test bed for SPARX injector, linac and FEL technology [16]. Among the many developments at SPARC is the experimental characterisation of the ballistic bunching concept and a prototype C-band acceleration system [17].

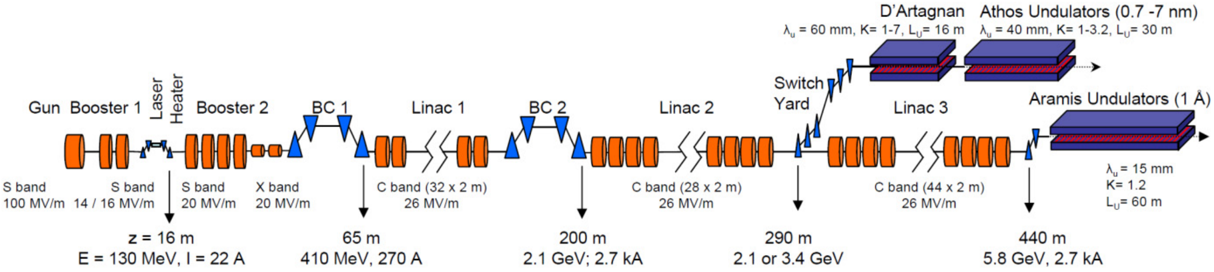

Figure 2: Schematic of SwissFEL. The overall facility length including the experimental halls is about 700m.

MAX IV

The MAX IV facility in Sweden is a electron storage ring facilityfor synchrotron radiation research with a full energy,3.5 Gev injector linac based on S-band technology [18]. Construction of MAX IV is just starting. The linac is from the beginning build with bunch compression and 100Hz repetition rate, allowing an experimental program on short pulse physics in parallel with top-up operation of the storage rings. Space reservations allow a later extension of this linac to about twice the energy and a use of this linac as a driver for a hard X-ray FEL.

R&D ISSUES

Injectors

For injectors the RF-guns at S-band of LCLS/SLAC and at L-band of PITZ/DESY define presently the state of the art. Normalized emittances in the order of 0.4µm for a bunch charge of 250pC (LCLS) and 1.0µm for 1nC (PITZ) have been achieved. Key elements to realize these values are a careful RF and solenoid magnet design in order to avoid all deviations from circular symmetry around the beam axis, a good control of RF field pollution with transient modes, high electric field on the cathode and good control of laser spot and cathode uniformity. A very interesting recent observation from LCLS shows, that laser pulse temporal uniformity seems to be much less important than what was generally believed so far. The present state of the art for injectors requires about 6 GeV minimum electron energy for FEL lasing at 1Å. Progress on injectors allows reducing this energy further. This minimum energy is for a given bunch charge proportional to the inverse FEL wavelength divided by the emittance. Further progress in injector electron beam brightness is expected from a better matching of the cathode-laser wavelength to the cathode materials work-function [19] and from RF guns working at X-band frequency with higher cathode field [20]. Both methods are particular interesting for achieving low emittances with small bunch charges (1-100pC range). Field emitter arrays presently under development at PSI (fig. 3) may will provide in the future cathodes with even lower intrinsic emittance [21], if present limitations of current density and other still existing practical difficulties with these FEAs can be overcome. Another approach to high brightness electron guns is the use of a cathode in a pulsed diode with high field and voltage, followed by an accelerating RF cavity. Such a concept has been experimental verified [22] and electron beam performances similar to RF guns have been achieved. However, these experiments showed also that the pulsed diode-RF cavity combination is more complex than an RF gun, without providing a clear performance advantage.

FEL's operating at c.w. have another important injector feasibility issue to solve, since none of the electron gun currently used for the running VUV and X-ray FEL can be used in c.w. mode. Pulsed RF guns similar to the DESY type equipped with intense cooling can be considered up to a bunch repetition rate of about 1kHz. Such a gun is the baseline approach for NLS. For bunch repetition rates on a MHz scale LBNL studies [23] a RF gun operating continuously at very low RF frequency (fig. 4). Another alternative is the use of a superconducting RF gun. Such a superconducting gun is already in operation at the ELBE facility [24]. However, beam parameters as required for an X-ray FEL still remain to be demonstrated.

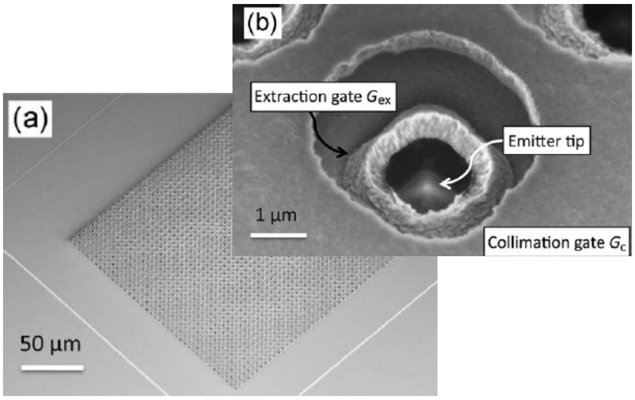

Figure 3: Double gate field emitter array cathode.

Linac RF

The FELs presently proposed with superconducting driver linacs assume a 1.3 GHz linac technology similar to FLASH and European XFEL but adapted for c.w. operation. The c.w. operation causes a massive increase of the dynamic losses in the cryogenic system of the s.c. accelerating modules in comparison with the pulsed RF operation of European XFEL. To keep these losses at a reasonable level the accelerating field has to be reduced.

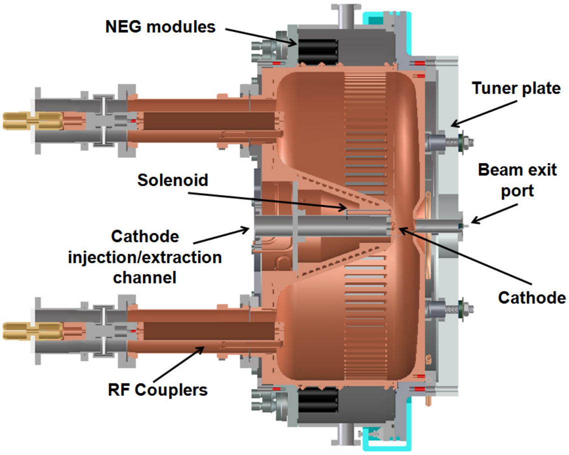

Figure 4: The VHF gun for c.w. operation of NGLS.

An extensive parametric study for the NLS Linac showed that an accelerating gradient of 15 MV/m provides the best compromise between investment cost, operation cost and operational reliability [6].

The SCSS C-band linac currently under construction provides presently the most advanced technology for normal conducting FEL driver linacs. This linac is capable to provide up to 40MV/m accelerating field. A SCSS linac module consists of a modulator klystron unit with a RF pulse compression system feeding two accelerating structures of 1.8m length each. Such a module provides an accelerating voltage of up to 144 MV. SCSS employs a total of 64 such linac modules. The accelerating structures use the so called choke mode design for damping of transverse modes excited by a beam. Such a damping scheme allows a later upgrade of SCSS for operation with multiple bunches per RF pulse at close bunch spacing. The PSI SwissFEL intends to use the same frequency and a similar klystron type as SCSS. However, contrary to SCSS the SwissFEL linac is not optimized for minimum length but for an overall minimum in investment and operation cost. The SwissFEL linac module consists of a modulator klystron unit with a RF pulse compression system feeding four accelerating structures of 2.0m length each. Such a module provides an accelerating voltage of up to 237MV. SwissFEL employs a total of 26 such linac modules. In comparison with SCSS SwissFEL uses a simpler structure design without dissipative HOM damping. Nevertheless, the natural dipole mode detuning of constant gradient structures provides sufficient damping for multibunch operation with moderate bunch spacing. The SwissFEL structure design has also a higher shunt impedance than the SCSS.

Accelerating fields of 65 MV/m and more can be achieved with X-band linac technology. A SLAC-LLNL collaboration will build a 250 MeV linac with this technology as driver for a Compton backscattering source [25]. However, to apply the X-band technology to FEL driver linacs a commercial supplier of high power klystrons in this frequency band has yet to be found.

It is, however, surprising, that presently no project seriously considers the use of normal conducting linac RF at repetition rates in the kHz scale, although this kind of technology had already been demonstrated in the late sixties of the last century [26]. In particular the combination of high frequency with moderate accelerating fields should allow for economically viable design concepts for FELs providing equally spaced hard X-ray pulses at kHz scale repetition rate. Such a time structure seems to be very attractive since it allows serving users at several beamlines simultaneously with a repetition rate and pulse spacing well adapted to their experimental needs.

Undulators

For compact hard X-ray FELs permanent magnet in-vacuum undulators with variable gap are currently the technology of choice because they give the best combined performance in terms of short period, field strength, gap width, field quality and flexibility. SCSS uses this technology, SwissFEL, PAL-XFEL and the Shanghai XFEL intend to implement it. As an example the SwissFEL undulators have a period length of 15mm, a K of 1.4 and a gap of 4mm. These values are feasible with present technology and room temperature operation. This performance can be pushed even further with permanent magnets operating at cryogenic temperatures (10-140K range). Depending on the permanent magnet material used this allows gaining 20%-50% in field strength or to increase the gap at fixed field strength. For the SINAP hard X-ray FEL the latter approach is considered. At BESSY recently a short fixed gap prototype undulator operating at 10K with a period length of 9mm, a K of 1.2 and a gap of 2mm has been realized [27], pushing this undulator type to its present technical limits. An even more advanced approach is the use of superconducting magnet undulators. In particular a novel approach to use high temperature superconductors with a production concept based on lithography seems to be promising in the long term. LBL is pursuing R&D on these devices [28].

FEL Seeding

FEL seeding with laser sources has not only the potential to improve the spectral quality, temporal control and pulse-to-pulse stability of FELs compared with SASE FELs but also to shorten the length of the undulator lines in comparison with SASE operation. While FEL seeding for FEL operation at optical wavelength is already a proven technique, seeding in the VUV and X-ray regime is currently an area of very active theoretical and experimental research worldwide. FERMI@ELETTRA will be commissioned with a laser seeded FEL line and experiments are underway at FLASH/DESY to demonstrate seeding with a HHG laser source. SINAP and SLAC are performing proof of principle experiments to demonstrate the feasibility of the novel EEHG seeding technique. The results of these experiments will strongly influence the further developments in this field and the application of seeding techniques for X-ray FELs.

OUTLOOK

The impressive number of major XFEL facilities presently under construction or in a planning stage show that the XFEL will become an as successful and widespread scientific research instrument as the 3rd generation light sources which nowadays are available for the scientific user communities all around the world.

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