LOW EMITTANCE X-FEL DEVELOPMENT

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Abstract

Paul Scherrer Institut (PSI) in Villigen, Switzerland, is developing a Low Emittance Electron Gun (LEG) based on field-emitter technology [1]. The goal is to achieve a normalized transverse emittance of $\varepsilon_n \leq 0.05$ mm mrad at a bunch charge of 0.2 nC. Such a source is particularly interesting for FELs that target wavelengths below 0.3 nm since it permits a reduction of the required electron beam energy and hence a reduction of the construction and operational costs of an X-ray FEL. An important issue here is to take care that the initially low emittance can be preserved throughout the accelerator. We present a concept for a 0.1 nm X-FEL based on LEG, which could be located in the vicinity of the Swiss Light Source (SLS). Special attention is given to the preservation of the emittance during the acceleration and compression process.

INTRODUCTION

Free Electron Lasers (FELs) may be large machines and their construction generally costly. This is especially true for FELs operating in the hard X-ray regime. One approach to significantly reduce the costs for the construction of an X-ray FEL would be the use of new electron sources with higher transverse brightness combined with sufficient peak current of the kind targeted at in the Low Emittance Gun (LEG) project at PSI in Switzerland. With this starting point a feasibility study has been initiated to explore the options for an economic X-Ray laser facility at PSI.

MOTIVATION FOR LOW EMITTANCE

The output radiation of an FEL is given by:

$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{1}$$

where λ_u is the undulator wavelength and K is the dimensionless undulator strength: $K \approx 0.93\lambda_u$ [cm] B_u [T], with B_u the peak magnetic field strength on axis.

An approximate requirement for efficient FEL operation is given by the diffraction limit:

$$\varepsilon = \frac{\varepsilon_n}{\gamma} < \frac{\lambda_{rad}}{4\pi} \tag{2}$$

where ε_n is the normalized transverse emittance of the electron beam source and γ is the relativistic Lorentz factor. At very short wavelengths operation becomes challenging since the wavelength has squared dependence with the beam energy while the emittance only scales linear. Hence, the demand for a small normalized emittance becomes stronger as the wavelength decreases.

State of the art electron sources like an RF photo-cathode gun typically provide a normalized emittance of 1 mm mrad. For this purpose projects like the European X-FEL [2] or the American LCLS [3] include a long accelerator and a long undulator section. Both projects will set the reference for future developments and will be the first to provide X-Ray laser light.

As a future alternative, PSI will first attempt to develop an electron source with a much lower transverse emittance to allow for an X-FEL design with reduced beam energy, peak current and undulator length. This approach has a similar philosophy as the one behind the SCSS project in Japan [4]. However, the PSI approach aims at an order of magnitude lower emittance, both from the electron gun and after acceleration.

Table 1: The parameters of the beam expected from LEG.

Peak current	I	≥ 5	A
Pulse duration (FWHM)[a]	τ	35	ps
Bunch charge[a]	Q	0.2	nC
Beam energy	E	1.0	MeV
Energy spread (FWHM)	σ_E	0.5	eV
Emittance (normalized)[b]	ε_n	0.05	mm mrad
Repetition rate	f	10	Hz

[a] defined by parametric FEL studies [5].
[b] Sliced parameter

FEASIBILITY STUDY

The LEG X-FEL proposal targets a normalized emittance of $\varepsilon_n \leq 0.1$ mm mrad at the entrance of the undulator section. The value is based on the expected performance of LEG [1], which is presently in development at PSI. Performance parameters are summarized in Tab. 1 Here the following issues are important

Preservation of emittance X-FELs are mostly designed for a target normalized beam emittance of 1.0 mm mrad or more. Any distortions leading to emittance growths within some 0.01 mm mrad are then negligible. The accelerator proposed here however, will be sensitive to such distortions since it needs to be designed in a way to maintain an emittance lower than 0.1 mm mrad, up to the injection of the beam into the undulator.

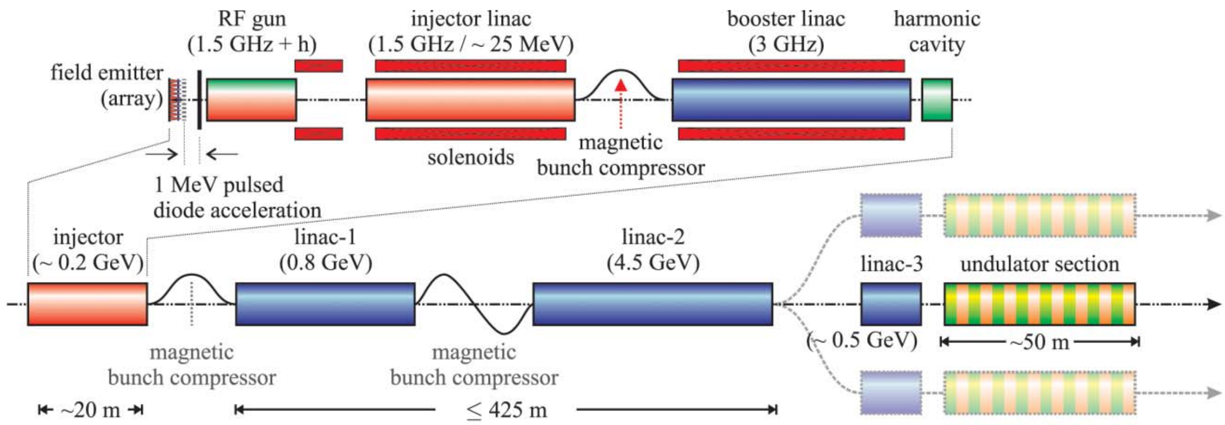

Figure 1: Layout of an X-FEL for a feasibility study. Details of the injector are shown at the top. The main linac and undulator beamlines are shown at the bottom. See text for details. Note that the conceptional phase consists of a single undulator beam-line only. For a future user-facility more beamlines are foreseen as indicated by the shaded area in the lower-right side of the figure. In this case linac-3 enables independent wavelength tuning of each beamline.

Electron beam compression The required peak current for an X-FEL can go up to a few kA and generally exceeds the current, which can be drawn from an electron source without compromising the emittance. To increase the current, it is necessary to compress the electron bunches, which may have a negative effect on the emittance or energy spread of the beam. This is specifically important for the LEG X-FEL design because of the motivations discussed in the previous paragraph.

In addition the following boundary conditions have been considered

PSI User Facility and Spectral Range The FEL will be designed to serve the research activities of the SLS user community by providing scientists access to two complementary light sources in a similar spectral domain, i.e. the SLS with a high average brilliance and picosecond pulses, and an X-FEL with a high peak brilliance and femtosecond pulses. To match the demands of this community a shortest target wavelength of 0.1 nm has been specified for the FEL. At the same time a wide spectral tuning range will be kept accessible.

MACHINE LAYOUT AND MOTIVATION

A machine layout for the feasibility study is shown in Fig. 1. Target specification of the electron source, the linac, and the FEL are summarized in Tab. 1 and Tab. 2. Note that the scheme serves as a base reference for the feasibility studies only and is due for modifications once the basic concept is established.

Machine aspects

The concept foresees emission from field emitters (either as a single tip or as an array of tips) [1] followed by a high-gradient pulsed 1 MV diode $|\vec{E}| \geq 250$ MV/m [6] and an RF gun [7]. Since LEG provides a fairly low peak current, the bunch length is stretched. This ensures sufficient bunch charge at the target peak current of 1.5 kA, which is important to obtain a fairly long bunch, and hence, control possible coherent synchrotron (CSR) effects in the final

Table 2: The FEL input parameters along with the expected performance. A verification of this performance forms the core of the feasibility study and is presently in progress.

Wavelength	λ_{rad}	0.1	nm
Photon energy	$\hbar\omega_{rad}$	12.4	keV
Electron Beam			
Beam energy	E	~ 6	GeV
Peak current	I	1.5	kA
Bunch charge	Q	0.2	nC
Norm. Emittance^a	ε_n	≤ 0.1	mm mrad
Energy spread^a	σ_E	≤ 0.6	MeV
Undulator Section			
Undulator period	λ_u	15 (12)	mm
Undulator type		planar	-
Undulator strength	K	1.19	-
Average β-function	β	15	m
FEL Performance^b			
Pierce parameter	ρ_{1D}	$5.4 \cdot 10^{-4}$	-
Gain length	L_g	1.0	m
Saturation Length	L_{sat}	20	m
Peak power	P	6	GW
Pulse Energy	E_{ph}	0.4	mJ
Peak brilliance	B	$1.1 \cdot 10^{33}$	$-^c$
Photons per pulse	N	$1.9 \cdot 10^{11}$	-

^{a} Slice parameters at full energy
^{b} Based on analytical estimates [5]
^{c} photons/sec/mm^2/mrad^2/0.1% bw

stage of compression.

The RF frequency of both the RF gun and injector linac is lowered to 1.5 GHz to minimize the growth of emittance and energy spread. The enlarged irises of the accelerator structure helps to control the emittance growth by reducing the transverse wakefields. The lower frequency also reduces the effect of the curvature of the RF field and hence, the increase of the uncorrelated energy spread. The energy spread is further reduced with the addition of the 3rd harmonic in the RF gun. The option to add a harmonic cavity behind the injector linac has been discarded to minimize the effects of transverse wakes in this part of the machine [7]. The gun/injector combination also incorporates: (1) emittance compensation, (2) RF compression and (3) preparation for further magnetic compression.

After compression a 3 GHz booster accelerates the electrons out of the space charge dominated regime to about 200 MeV. The booster will be followed by a harmonic cavity to linearize the longitudinal phase space. After the booster the electron beam is compressed sufficiently to minimize a further increase of the energy spread in the main linac. The final compression is foreseen at an energy of 0.8 GeV. From here on the bunch will be accelerated in the main linac to an energy of 5.8 GeV. At the output of the last compressor the electron beam will be left with a small chirp to compensate for wakefield effects through the rest of the accelerating stage [3]. For the booster and the main linac the 3 GHz S-band technology serves as reference. Higher frequencies, such as C-band (6 GHz) or X-band (12 GHz) technology, are possible alternatives, which will be investigated at a later stage.

Both superconducting accelerator technology and plasma-wakefield accelerator technology were discarded. The former was not considered because of the nature of LEG, which is anticipated to run at a repetition rate of 10 Hz. This low frequency, in combination with the long filling time of superconducting cavities, makes the use of these cavities inefficient. Experiments on plasma-wakefield acceleration have demonstrated extremely high accelerating gradients ($>$ 1 GV/m compared to 20 MV/m for 3 GHz RF technology). However, this technology has not yet demonstrated compatibility with the stringent requirement of the electron beam quality set by the FEL process, and is considered insufficiently mature to serve the construction of a user facility [8].

Finally the beam will enter the undulator where the coherent synchrotron radiation will be generated. The undulator section consists of a chain of small-period, 4.5-m long permanent-magnet in-vacuum undulators, separated by 0.75 m drift sections to permit the installation of diagnostics, orbit correctors, and quadrupoles for a refocussing of the electron beam. Variable gaps will mainly serve for matching the sections rather than for wavelength tuning. The choice of undulator period and length are based on in-house expertise. New developments, e.g., smaller period permanent magnets undulators with cryo-cooled technology might permit a reduction of the period to 12 mm or below. This will consequently also reduce the target energy of the electron beam. The option of plasma- or laser-undulators has not been considered due to the lack of maturity if this technology.

Operational aspects

Operational aspects, which are not expected to cause restrictions to the design or operation, have been left open. For example, the long wavelength limit will be defined in close collaboration with potential users of the facility. Also no choice has been made whether SASE FEL operation (start up from shot noise) or laser seeded operation shall be employed. For a reference of the feasibility study, SASE operation has been chosen, since it is more straightforward to analyze in terms of performance, and it is not expected to underestimate the requirements of the electron beam properties such as peak current, energy spread and emittance.

Implementation

The dimensions of the X-FEL shown in Fig. 1 fit well within the compounds set by the flat area around the SLS, while at the same time still using S-band technology.

STATUS REPORT

While the LEG Project is progressing in both experimental methods and simulation results, first studies have been initiated on the accelerator section of the FEL.

Low Emittance Gun

The main components of LEG are the cathode, a high voltage pulser and a 1.5 GHz RF cavity [1].

The tests stands for the field emitter electron sources were upgraded. These upgrades include a Scanning Anode Field Emission Microscope (SAFEM), a 100 kV/1 ns pulser and a YAG-laser for tests on photo induced field emission to reduce the bunch length down to the picosecond range. A 100 kV DC-gun test-stand was also completed and is now under commissioning [9]. It will include optimized cathode gap geometries and a solenoid magnet for minimization of the emittance, which can be measured precisely within the test stand.

The construction of a first prototype of the high voltage pulser for the diode acceleration pointed out in Fig. 1 is going on. It will deliver 200 ns pulses of 500 kV using thyratrons as the switching device and a fast air-core resonant transformer to increase the voltage [6].

A combined fundamental and 3rd harmonic cavity is being designed to compensate for the RF induced emittance growth of the fairly long bunch, while at the same time minimizing transverse wakefield effects. First beam dynamic studies were made with this cavity to study the emittance growth caused by the RF fields. The results can be found in [7].

Accelerator section

In terms of electron dynamics the injector is the most complicated part of the accelerator. Simulations of this part of the machine are in progress. The diode acceleration and RF gun are simulated with MAFIA [10]. Several aspects of the performance of the RF gun, the injector linac and booster are simulated with PARMELA [11], GPT [12] and SPIFFE [13].

A first lattice design was made for the accelerator section and was used for beam envelope simulations with MAD-8 [14]. The preliminary results are summarized in Tab. 3 and indicate that during bunch compression the absolute sliced emittance growth can be kept below 0.05 mm mrad.

Further studies are required and will include collective effects in more detail.

Table 3: The accelerator sections correspond to the sections in Fig. 1, where BC_2 is the magnetic bunch compressor after the injector and BC_3 is the magnetic bunch compressor between linac-1 and linac-2.

	BC_2	BC_3	
Length	14	14	m
Bending angle	3	2.9	deg
Compression factor	10	2.5	
${\sigma_{E_0}}^a$	0.5	0.16	eV
${\sigma_{E_c}}^b$	0.7	7.2	MeV/ps
${\Delta\varepsilon_n}^c$	≤ 0.05	≤ 0.02	mm mrad
	Linac-1	Linac-2	
Initial Energy	0.2	0.8	GeV
Final Energy	0.8	~ 6	GeV
Length	32.5	364	m
Mode	$\pi/2$	$\pi/2$	rad
Average β	8	7.5	m
Number of cavities	10	96	
Injection phase	40	5	deg

[a] Uncorrelated energy spread
[b] Correlated energy spread
[c] Absolute slice emittance growth

FEL simulations

Genesis 1.3 [15] simulations have been performed to verify the performance estimates, which were presented in Tab. 2 [5]. Further FEL simulations will be incorporated into start-to-end simulations as soon as the beam-dynamics of the injector is firmly established.

FUTURE DIRECTIONS

The plan for a compact X-ray FEL based on the technology of LEG has been made and target performance values have been specified. The boundary conditions are set and the critical aspects, like emittance preservation, beam orbit and energy stability and bunch compression are under investigation. Among the next tasks, linac feasibility studies will require further investigation since the FEL proposal incorporates several risk factors like the preservation of the emittance throughout the accelerator. The costs and the critical technologies that limit the operational range of the laser need to be evaluated where the outcome of the evaluation will be used to establish a realistic concept of a possible laser system, which can be used as a reference for discussions with potential users.

As an extension to the gun project we plan the construction of a 250 MeV injection test-facility, i.e. the top part depicted in Fig. 1. This phase is intended to: (1) experimentally verify critical aspects of the machine, (2) form a base to develop diagnostic tools relevant to the operation of X-FELs, (3) potentially become an electron source or photon source for user experiments, and (4) acquire the necessary linac technology experience for the X-FEL facility.

REFERENCES

[1] Nanoseconds field emitted current pulses from ZrC needles and field emitter arrays, R. Ganter et al, JVST-B, Special Issues (IVNC05), to be published.

[2] The European X-Ray Free Electron Laser Project at DESY, A.S. Schwarz, Proc. of the 26th Int. FEL Conference, Trieste, Italy (2004).

[3] An Optimized Low-Charge Configuration of the Linac Coherent Light Source, Paul Emma et al, Proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee, USA (2005).

[4] Status of SPring-8 compact SASE source FEL project, T. Shintake et al, Nucl. Instr. Meth. in Phys., **A507**, p. 382 (2003).

[5] http://leg.web.psi.ch/public/xfel/proposal.html

[6] Pulsed Power Techniques for the Low Emittance Gun (LEG), C. Gough, M. Paraliev, http://leg.web.psi.ch/public/publications/Gough-yr03.pdf.

[7] A Two-Frequency RF Cavity for the PSI Low Emittance Gun, J-Y. Raguin et al, these Proceedings.

[8] Mono-Energetic Beams from Laser Plasma Interactions, C.G.R. Geddes et al, Proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee, USA (2005).

[9] Design of the 100 keV DC Gun Test Stand, S. C. Leemann et al, http://leg.web.psi.ch/public/publications/Leemann-yr04.pdf.

[10] CST GmbH, Bad Nauheimer Strasse 19, D-64289 Darmstadt, http://www.cst.com

[11] L. Young, PARMELA, LA-UR-96-1835, LANL (1996)

[12] Pulsar Physics, De Bongerd 23, NL-3762 XA Soest, http://www.pulsar.nl/

[13] SDDS-Based Software Tools for Accelerator Design, M. Borland et al, Proc. of the 2003 Part. Accel. Conf. (PAC2003), Portland, USA, p. 3461 (2003)

[14] http://mad.home.cern.ch/mad/.

[15] http://corona.physics.ucla.edu/ reiche/