X-FEL CONCEPT BASED ON A LOW EMITTANCE GUN

R.J. Bakker, R. Ganter, G. Ingold, M. Pedrozzi, L. Rivkin, A. Wrulich

Free-Electron Lasers (FELs) are a promising concept to extend the capabilities of 3rd generation synchrotron light-sources like the SLS. Compared to these, an FEL can produce fully coherent, short-pulsed (femto-second) radiation with selectable wavelength at orders of magnitude higher brightness. FELs are, however, costly and this is particularly true for those that aim for X-rays. In that case the performance of state-of-the art electron-beam sources is a major cost-driving factor. These costs may significantly be reduced if a future electron source can operate with a higher brightness combined with sufficient peak-current. The LEG project at the PSI aims for these goals. The success of this project thus enables the construction of a cost-effective X-ray FEL user-facility. A conceptional design study has been initiated to explore the options.

INTRODUCTION

The wavelength λ_s of a free-electron laser (FEL) is tuned in exactly the same way as that of an insertion-device (ID):

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \qquad (1)$$

where γ relates to the electron-beam energy (E/0.511 [MeV]), λ_u is the undulator period, and K to the magnetic field strength of the undulator (K = 0.93 $B\,\lambda_u$ [T cm]). Unlike an ID, the successful operation also depends on the combination of a high peak-current and a high brightness of the electron beam. Operation in the X-ray spectral range (0.1 nm or 12 keV) typically requires a peak current of a few kA and a low transverse emittance:

$$\varepsilon_{x.y} = \sigma_{x,y}\sigma'_{x,y} = \frac{\varepsilon_n}{\gamma} < \frac{\lambda_s}{4\pi}, \qquad (2)$$

where ε_n is the normalized transverse emittance of the electron beam source, and σ_{xy} and σ'_{xy} are the rms transverse beam-size and divergence, respectively. The squared dependence of the wavelength on beam energy in Eq. (1), and the linear dependence in Eq. (2) make the operation of an FEL at extreme by short wavelengths challenging. In other words, the state of the art electron-gun technology is a limiting factor for the operation in the X-ray spectral range with a short undulator period and a low beam-energy. Projects like the European X-FEL [1] and the American LCLS [2] therefore opt for operation at increased beam-energy with extended undulator periods. Such an option is expensive and the costs of construction may be reduced significantly if a more adequate electron source is developed.

The LEG project involves the development of an electron source that enables the operation of an FEL at 0.1 nm with permanent-magnet undulator technology and minimum beam energy, i.e., a cost-effective way to obtain laser-like light beams in the X-ray spectral region. This sets the project apart from other European projects that aim at operation at longer wavelengths [3-8] and puts it in line with the SCSS project in Japan [9].

CHALLENGES OF THE PROJECT

Construction of a single-pass FEL at short wavelength is non-trivial. Already in the design phase, many issues must be addressed, which merit an extensive study. Some issues, e.g., the development of diagnostics and stability issues, are common to most projects. The specifics of the electron source developed at the PSI also raise some specific technical challenges. As a first step we try to identify and study these issues. The most obvious ones are:

- Realistic target specifications (peak current, bunch charge, emittance and energy spread) for LEG, compatible with FEL operation.
- Preservation of the emittance and control of the energy-spread while the electrons are accelerated out of the space-charge dominated regime (E < 0.2 GeV).
- Preservation of the emittance and control of the energy spread while the peak-current is increased, i.e., during bunch compression.
- Identification of a minimum undulator period.
- Tolerance studies on the main electron beam and undulator parameters.

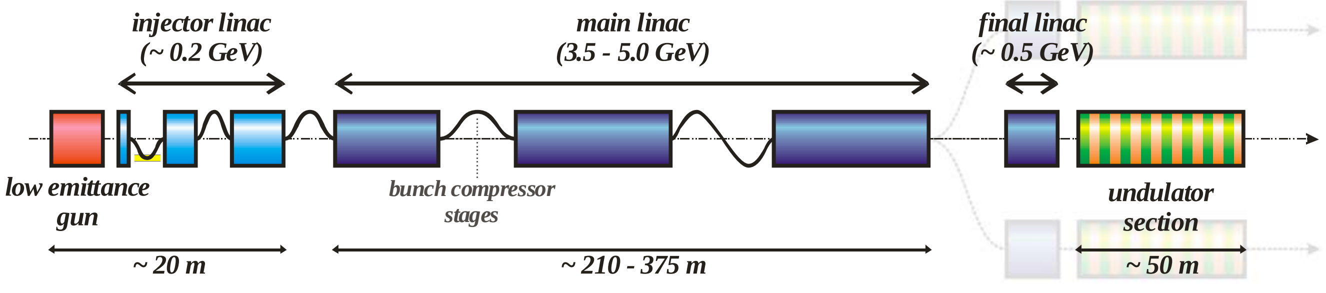

Fig. 1: Schematic layout of a possible single-pass X-ray FEL. Dimensions at the bottom are indicative only and depend on the choice of accelerator technology. See text for details on the design.

SYSTEM LAYOUT

As a reference we assume a linear system that targets a fundamental wavelength of 0.1 nm. Since operation becomes more challenging at shorter wavelength, the target of 0.1 nm reflects the short wavelength limit of a wavelength range. The long wavelength limit of the tuning range will be specified in close collaboration with potential users of the facility.

A schematic sketch is presented in Fig. 1. The scheme is based on design considerations published elsewhere [10-12]. In the figure the electron gun is followed by a 0.2 GeV injection linac system, designed to boost sufficient charge out of the space-charge limited regime. The LEG electron gun target specifications are summarized in Tab. 1. Details of the injector design are under development.

Peak current	I	≥ 5	A
Pulse duration (FWHM)	τ	2	ns
Beam energy	E	500	kV
Energy spread (FWHM)	δE	0.5	eV
Emittance (normalized)	ε_n	$0.5 \cdot 10^{-7}$	m rad
Repetition rate	f	10	Hz

Table 1: Electron gun specifications (LEG).

The main accelerator serves to accelerate the beam to its target energy. Since operation of the FEL is only possible with a sufficiently high peak current, we anticipate the use of up to three magnetic bunch compressors. Because of the nature of the LEG gun, i.e., pulsed DC gun with a low repetition rate, we consider normal conducting accelerator technology only, since superconducting technology appears to be inefficient due to the long filling time of the RF structures. As a reference we assume S-band (3-GHz) accelerator technology. Other technologies, such as C-band (6 GHz) or X-band (12 GHz) are still under consideration as they might permit a higher accelerator gradient and hence, a reduction of the total accelerator and facility length. For any of the technologies we intend to accelerate a single electron bunch per RF macro-pulse.

Wavelength	λ_s	0.1	nm
Photon energy	$\hbar\omega_s$	12.4	keV
Beam energy	E	5.8	GeV
Peak current	I	1.5	kA
Bunch charge	Q	0.5	nC
Emittance (normalized)	ε_n	$1 \cdot 10^{-7}$	m rad
Energy spread (rms)	σ_E	0.6	MeV
Undulator period	λ_u	15	mm
Undulator type		planar	
Undulator strength	K	1.19	

Table 2: FEL input specifications

Target parameters for FEL operation are summarized in Table 2. To reduce both the required beam energy and the total length of the undulator, we aim for a short undulator period (15 mm or less). This choice makes tuning of the wavelength by means of undulator gap variations inefficient. Instead, the wavelength will be tuned with the electron beam energy. The final linac section sketched in Fig. 1 permits a 40 % tuning range of the wavelength. This is particularly interesting as it enables the option of parallel FEL beamlines that share most of the linac (blended undulator lines in Fig. 1). Note that the values quoted in Table 2 are preliminary and serve as a starting point only.

A possible implementation scenario based on 3 GHz accelerator technology is sketched in Fig. 2. In the figure the accelerator is located in a tunnel below the surface for radiation shielding purposes. After the accelerator, the electron beam is transported up to the surface into a hall, where it passes through the FEL before it is dumped. The experimental area is located on a straight line behind the undulator. The spacing between the undulator hall and the experimental area allows the photon beam to expand to power density levels, which can be handled by conventional grazing incidence optics. The sketch represents, in terms of the length, a non-optimized and conservative design. We note that the total length of it fits well within the flat area close to the SLS.

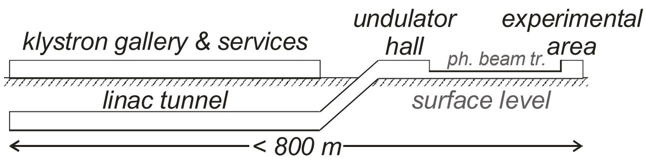

Fig. 2: Possible scenario for a facility layout based on 3-GHz accelerator technology. The vertical scale is multiplied by 10.

PERFORMANCE

The expected performance is benchmarked with two reference cases: 1) start-up from noise (the so-called SASE FEL), and 2) controlled start-up with an optical seed. The seed source for the latter has not been specified yet but could be a 2-stage FEL concept as proposed by Saldin et al. [13].

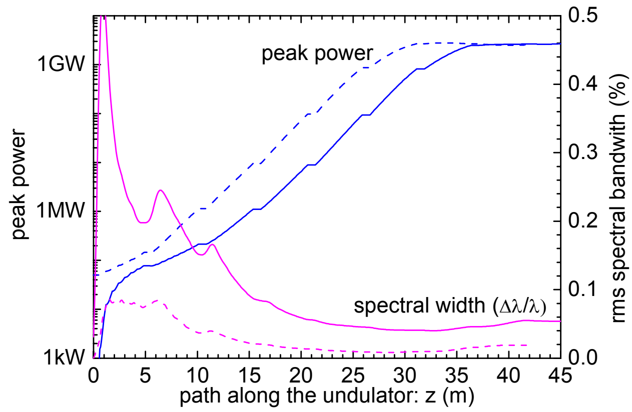

Fig. 3: Genesis 3D calculation [14] of the peak power and spectral width of a non-seeded FEL (solid lines) and a seeded FEL (dashed lines) with parameters specified in Table 2.

A performance estimate is presented in Fig. 3. The figure depicts the optical power growth and the spectral narrowing along the undulator. For the non-seeded case the latter depicts the increase in longitudinal coherence due to the FEL interaction. In this case, the left side of the plot corresponds to spontaneous emission from an undulator, similar to the radiation provided by IDs. For the seeded case we assumed a 50 kW seed on the fundamental with an rms duration of 35 fs, i.e., a short seed with a power 20 times above the level of spontaneous emission. Note that also this level is elevated by at least two orders of magnitude as compared to synchrotron light sources due to the brightness of the electron beam employed by the FEL.

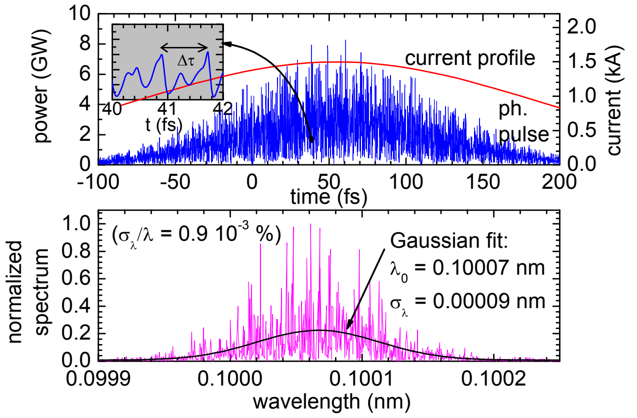

Fig. 4: Genesis 3D [14] calculation of the longitudinal pulse profile and spectrum for a non-seeded FEL and parameters specified in Tab. 2.

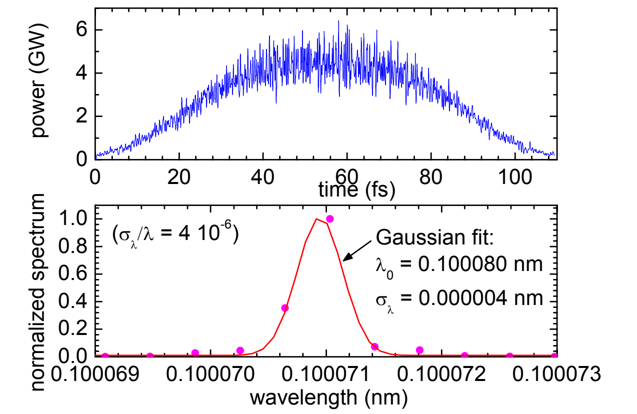

Fig. 5: Genesis 3D [14] calculation of the longitudinal pulse profile and spectrum for a seeded FEL with parameters specified in Tab. 2 and a 50 kW seed on the fundamental with an rms duration of 35 fs.

A simulated output pulse for the non-seeded FEL is depicted in Fig. 4. The spiky nature of the output is typical for such an FEL [15]. The spikes originate from the shot-noise of the spontaneous emission and the FEL amplifying mechanism. That is, the exact position and amplitude of each spike is purely statistical and varies from pulse to pulse. However, the distance between spikes, and hence the number of spikes, is stable and determined by the FEL process. For an X-FEL the number of spikes is large, thus making the number of photons per pulse rather constant. The example depicted in Fig. 4 corresponds to 4×10^{11} photons/pulse.

In a non-seeded FEL the longitudinal coherence is limited to a single spike. It may ultimately be extended to the transform limit, where the pulse duration determines the spectral width. Initial performance estimates for such a case are presented in Fig. 5 (note the difference in horizontal scale with Fig. 4). Note also that seeding partially suppresses the spiking in the temporal domain.

CONCLUSION AND OUTLOOK

The Figs. 3-5 indicate the validity of the parameter choice for an X-ray FEL facility. In Fig. 6 the performance is compared with beamlines at the SLS.

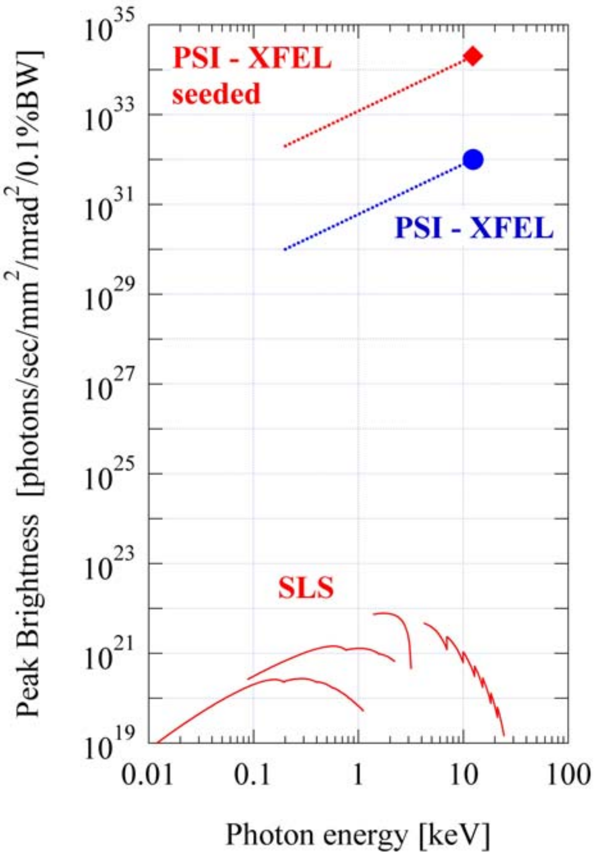

Fig. 6: The peak brightness compared to the SLS beamlines. The expected brightness is somewhat lower as compared to the other FEL sources because of the more moderate electron beam energies employed.

From a comparison between Fig. 4 and Fig. 5 it follows that the seeded mode of operation is superior in terms of spectral brightness. However, the non-seeded mode might prove to be more flexible in terms of operation (e.g., fast tuning of the wavelength or pulse-duration). At present we consider all options, including the possibility to design a machine that permits both modes of operation. These options still need to be designed. For the near future we intend to concentrate on this. More important, a design that connects the parameters from Table 1 to Table 2 needs implementation and verification.

REFERENCES

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

[2] The LCLS Design Study Report, SLAC-R-521 (1998).

[3] SASE FEL at the TESLA Facility Phase2, TESLA internal note 2002-01, DESY, 2002.

[4] D. Krämer, E. Jaeschke, W. Eberhardt, *The BESSY Soft X-ray Free Electron Laser*, TDR BESSY, March 2004, eds.:, ISBN 3-9809534-08, BESSY, Berlin (2004).

[5] R.J. Bakker, C.J. Bocchetta, P. Craievich, M. Danailov, G. D'Auria, G. De Ninno, S. Di Mitri, B. Diviacco, G. Pangon, L. Rumiz, L. Tosi, V. Verzilov, D. Zangrando *FERMI@ELETTRA: 100 nm - 10 nm Single-Pass FEL User Facility*, Proc. EPAC'04, Lucerne, Switzerland, 387 (2004).

[6] D. Alesini, S. Bertolucci, M.E. Biagini, C. Biscari, R. Boni, M. Boscolo, M. Castellano, A. Clozza, G. Di Pirro, A. Drago, *Conceptual design of a high-brightness linac for soft X-ray SASE-FEL source*, et al., Nucl. Instr. and Meth. in Phys., A507, 502 (2003).

[7] M.E. Courpie, M. Desmons, B. Gilquin, D. Garzella, M. Jablonka, A. Loulergue, J.R. Marquès, J.M. rtega, F. Méot, P. Monot, A. Mosnier, L. Nahon, A. Rouse, *"ARC-EN-CIEL" a Proposal for a 4th Generation Light Source in France*, Proc. EPAC'04, Lucerne, Switzerland, 366 (2004).

[8] M.W. Poole, E.A. Seddon, *4GLS and the Prototype Energy Recovery Linac Project at Daresbury*, Proc. EPAC'04, Lucerne, Switzerland, 455 (2004).

[9] T. Shintake, *Status of the SCSS project*, Proc. Asian Particle Accelerator Conference 2004, Gyeongju, Korea (APAC2004).

[10] M. Pedrozzi, R. Ganter, L. Rivkin, A. Wrulich, *Motivations for- and Limitations of- the low Emittance Gun*, PSI Scientific and Technical Report 2003, Volume VI, 69.

[11] M. Pedrozzi, G. Ingold, *Expected Parametric Evaluation for 1Å FEL – Emittance and Current Requirements*, Proc. LINAC2004, Lübeck, Germany (2004).

[12] R. Ganter, J.-Y. Raguin, A. Candel, M. Dehler, J. Gobrecht, C. Gough, G. Ingold, S.C. Leemann, K. Li, M. Paraliev, M. Pedrozzi, L. Rivkin, H. Sehr, V. Schlott, A. Streun, A. Wrulich, S. Zelenika, *Low Emittance Gun Project Based on Field Emission*, Proc. 26th Int. FEL Conference, Trieste, Italy (2004).

[13] J. Feldhaus, E.L. Saldin, J.R. Schneider, E.A. Schneidmiller, M.V. Yurkov, *Possible application of X-ray optical elements for reducing the spectral bandwidth of an X-ray SASE FEL*, Opt. Commun. 140, 341 (1997).

[14] S. Reiche, *GENESIS 1.3: a fully 3D time-dependent FEL simulation code*, Nucl. Instrum. Meth. A429, 243 (1999).

[15] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, *The Physics of Free-electron Lasers*, Springr, Berlin-Heidelberg (2000).