ULTRA HIGH BRIGHTNESS ACCELERATOR DESIGN

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Abstract

The PSI FEL Project at the Paul Scherrer Institute in Switzerland incorporates the development of a low emittance gun as a driver for a cost-effective X-ray free-electron laser user facility ($\lambda_s \geq 0.1$ nm, $\hbar\omega_s \leq 12.4$ keV). We investigate sources based on field-emitter technology and photoemission, followed by high gradient ($\Gamma \geq 0.25$ GV/m) acceleration up to 1 MeV. We present a concept to preserve the emittance in the acceleration process where the first 250 MeV of acceleration is the most delicate. Experimentally we intend to verify the validity of ultra-high brightness acceleration over this energy range in the period 2008-2011.

INTRODUCTION

In a free-electron laser (FEL) the resonant wavelength (λ_s) is given by:

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

where λ_u is the undulator period, γ the Lorenz factor corresponding to the beam energy (γ = E [Mev]/0.511), and K the dimensionless undulator strength ($K \approx 0.66\, \lambda_u \cdot B_u$ [cm] [T]). It follows that the X-ray regime (0.1 nm) is accessible with conventional undulator technology ($\lambda_u \geq 0.8$ cm) and a beam-energy as low as 4 GeV. Lasing at such a wavelength is more restrictive, however, since it is fundamental to control the transverse emittance (ε), the energy spread (σ_γ) and the current (I) of the electron-beam. An estimate for the critical wavelength limit λ_{cr} for sufficient gain in the FEL is [1]:

$$\lambda_{cr} \cong 18\pi\varepsilon_n \frac{\sigma_\gamma}{\gamma}\sqrt{\frac{1}{\gamma}\frac{I_A}{I}}, \tag{2}$$

where ε_n, σ_γ/γ, and I_A are the normalized emittance, the relative energy-spread, and the Alfèn current ($\approx$ 17 kA) respectively. For typical electron beam parameters for short wavelength operation (Q = 1 nC, $\varepsilon_n \approx 1$ mm mrad) λ_{cr} is then reduced by increasing beam-energy combined with an increased undulator period and length.

As a future alternative, the PSI-FEL project at the Paul Scherrer Institute in Switzerland attempts to develop an electron source with a significantly lower transverse emittance as a basis to develop a cost-effective X-ray FEL user facility [2] by pushing the beam-energy as low as technological possible. That is, for the case with $\varepsilon_n \leq 0.1$ mm mrad, parameter studies [2] suggest that the beam energy and peak current may be limited to 6 GeV and 1.5 kA, respectively.

In this paper we present a concept for an ultra-high brilliance 6-GeV accelerator. Starting point is the performance expectations of the Low Emittance Gun (LEG) [3], which is under construction at PSI. The first 250 MeV deserves special attention since emittance preservation proves to be most challenging in this part of the machine. It is our intention to test the concept of emittance conservation in this part of the machine experimentally. If successful, it should then serve as an injector for a linac that feeds a cost-effective X-FEL. An outlook follows at the end of this paper.

Table 1. Electron Source Parameters for the PSI FEL.

Peak current	I	≥ 5	A
Bunch charge	Q	0.2	nC
Bunch length (full width)	τ	≤ 40	ps
Bunch shape	-	uniform	-
Normalized emittance*	ε_n	≤ 0.05	mm mrad
Repetition rate#	f	10	Hz

* Slice parameter of a field-emitter at E=1 MeV and a slice-charge of 1 pC, i.e., the charge in the FEL-corporation length [2].
\# Limited by high-gradient pulser technology.

THE ELECTRON SOURCE

In a linac the emittance is limited by the intrinsic emittance at the electron source, which can be expressed as [4]:

$$\varepsilon_n = \frac{R}{2}\sqrt{\frac{2}{3}\frac{E_{kin}}{mc^2}} \tag{3}$$

where R is the beam radius in the case of a uniform radial distribution and E_{kin} is the mean kinetic energy of emitted electrons. With Eq. (3) in mind two strategies are persued: laser assisted Field Emission and photo-emission. Both technologies rely on laser-illumination to shape the temporal profile of the pulse.

With field emission electrons are drawn from sharp tips that are exposed to high gradient electric fields ($\Gamma \approx 6$ GV/m). Normally the emitting radius is small ($R \leq 5$ μm) and the field-emission process keeps the kinetic energy of the emitted electrons low ($E_{kin} \approx$.0.15 eV), which suggests a normalized emittance below 10^{-3} mm mrad. However, with increasing current the required electrical field-strength goes up followed by increased space-charge forces. This makes the combination of high-current and low-emittance challenging, both from technological and operational point of view. To reach ultra-low emittance two types of field emitters (FE) are under investigation: (*i*) a macroscopic single-tip FE and (*ii*) Field-Emitter Arrays (FEA). Construction of the former is technologically less demanding but the latter permits a reduction of the current density and most likely a lower emittance. The status and performance are discussed in detail in [3]. Target specifications are summarized in Tab. 1, where the emittance refers to the slice-value after acceleration up to 1 MeV.

The transverse emittance of a photo-cathode for a 1 nC electron bunch typically is $\varepsilon_n \approx 1$ mm mrad. This value may become smaller with a reduced bunch-charge, a reduced peak-current, combined with an appropriate choice of cathode material. Optimizations based on Eq. (3) suggest that the slice emittance can reach $\varepsilon_n \leq 0.1$ mm mrad for a Cu cathode with beam parameters as quoted in Tab. 1 and an initial transverse radius $R = 0.25$ mm.

Since the fabrication and operation of a photo-cathode is less challenging then field emission, we anticipate commencing with a photo-cathode. A second stage based on field emission should then permit a lower initial emittance, which should permit a final value of 0.1 at the entrance of the undulator section of the FEL. Note that we have chosen the beam parameters identical for both types of cathodes such that the choice of cathode does not affect the design of the following accelerator structure.

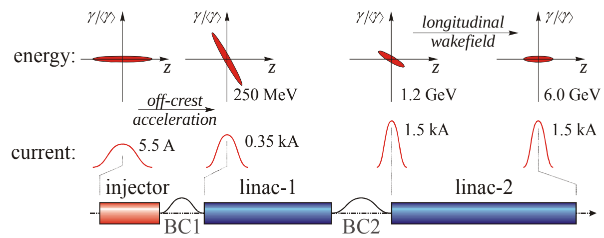

Figure 1. Functional layout of a low-emittance linac for an X-FEL. See text for details on the longitudinal shaping of the electron bunch.

ACCELERATOR CONCEPT

The performance parameters specified in Tab. 1 have, compared to more conventional RF photo-cathode designs, a low beam current and bunch charge at the cathode. This is beneficial to reduce the initial emittance and its dilution due to space charge in the region where the electron beam is sub-relativistic. The obvious drawback is the increased bunch compression ratio, which is required to obtain sufficient current for lasing. E.g., the LCLS [5] and the European X-FEL at DESY [6] have a total compression ratio of 70 and 100, respectively. The PSI-FEL aims for a ratio of 270.

The concept shown in Fig. 1 enables the increased compression ratio as it focuses on the control of the longitudinal phase-space. This is possible because we do not expect a significant emittance dilution in the bunch-compressors BC1 and BC2 [7]. Hence, the difficulties related to the emittance preservation are transferred to the design of the injector, which follows in the next section.

In terms of functionality the injector and BC1 accommodate most of the shaping of the longitudinal phase-space (γ,z). Similar to the design of the LCLS [5], linac-1 and linac-2 serve to boost the energy and allow of adiabatic damping of the emittance and relative energy spread. Deformation of the longitudinal phase-space, caused by wakefields in the linac structures, is controlled by off-crest acceleration in the injector and linac-1. In the present design both linac sections consist of 3-GHz room temperature (RT) traveling wave structures. We did not consider super-conducting technology because of the low repetition rate of the injector. Higher frequency RT will be considered later as an option to reduce the accelerator length.

THE INJECTOR

Fig. 2 shows a schematic of the injector. Details of the low-energy section are presented in Fig. 3.

Low Energy Acceleration

To minimize the initial blow-up of the emittance by space-charge, the cathode is positioned in a high-gradient field. The necessity of such a field is illustrated in Fig. 4, which shows a CAPONE [9] simulation of the slice-emittance of an ideal uniform beam with parameters as presented in Tab. 1. To obtain the gradient, the cathode is followed by a pulsed diode configuration as illustrated in Fig. 3. A 500 kV pulser has been constructed, which allows for initial tests with gradients up to 125 MV/m (top curve in Fig. 4). After sufficient operational experience the pulser will be upgraded to 1 MV to reach gradients up to 250 MV/m.

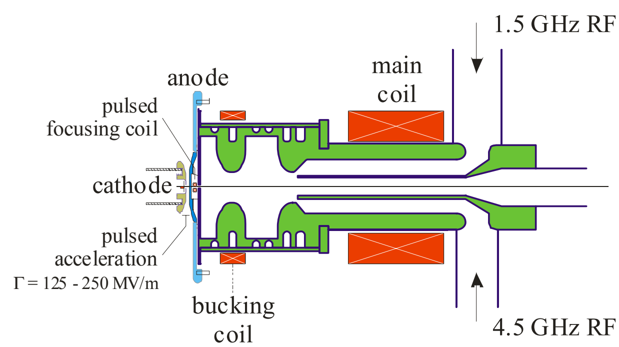

Figure 3. Layout of the high-gradient accelerating section followed by the initial RF acceleration [8].

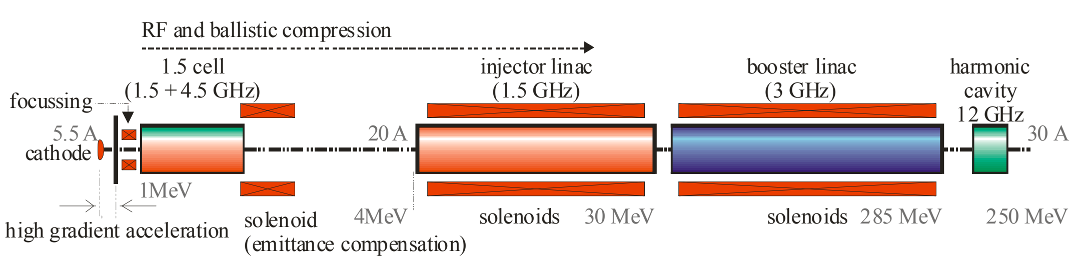

Figure 2. Schematic layout of the injector.

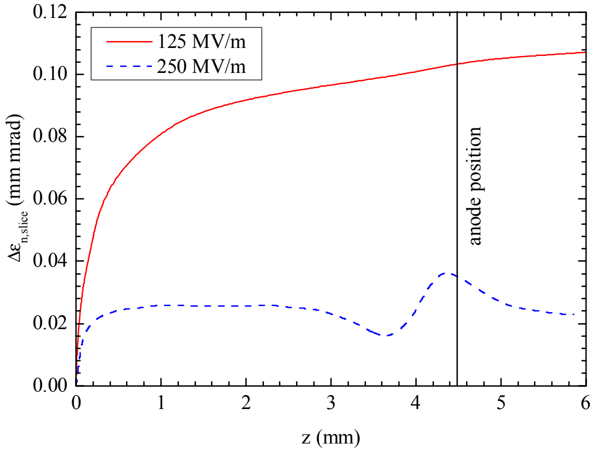

Figure 4. CAPONE [9] simulation of the slice emittance growth of a uniform electron bunch (Tab. 1) in a DC accelerator field (1 pC slice with an initial radius of 0.25 mm).

For further acceleration we have chosen an initial RF frequency of 1.5 GHz as a compromise between a high accelerating gradient (≥ 40 MV/m) and a large acceptance window to collect sufficient charge in a single bunch. A specially designed double-frequency 1.5-cell cavity [8] behind the diode further increases acceptance, see Fig. 3. Additional advantages of the double-frequency are: (*i*) a reduction of the emittance dilution caused by non-linear RF fields [8] and (*ii*) optimized RF compression. The latter is incorporated to reduce the bunch-length, see Fig. 2. We note that RF-compression is, in this part of the machine, the preferred choice as compared to magnetic compression since it maintains the cylindrical symmetry of the beam. That is, it avoids a break-up of the horizontal and vertical beam-optics in the space-charge dominated regime. For the similar reasons there are no quadrupoles included in the injector design.

During RF acceleration, it is important to control the transverse beam size since non-linear off-axis fields in the RF cavity may dilute the emittance otherwise. This is especially true in the first RF-structures where the beam-size may be blown up by a strong defocusing field as the beam passes the anode. For this reason, we plan to install a pulsed coil behind the anode to control the beam-size. We note that the pulsed technology has the advantage that the eddy-currents in the anode naturally shield the magnetic field from the cathode area.

Energy Booster

The RF compression is finalized in a 3-m long 1.5 GHz traveling wave structure. As soon as the electron bunches are short enough they enter a 3-GHz structures. A 12-GHz harmonic cavity at the end of the booster linearizes the longitudinal phase-space before further compression. All linac structures require additional focusing to control the electron beam-size. The final energy is 250 MeV. At this energy, the influence of space charge on the beam-optics is sufficiently reduced to permit the use of a chicane to reduce the bunch length.

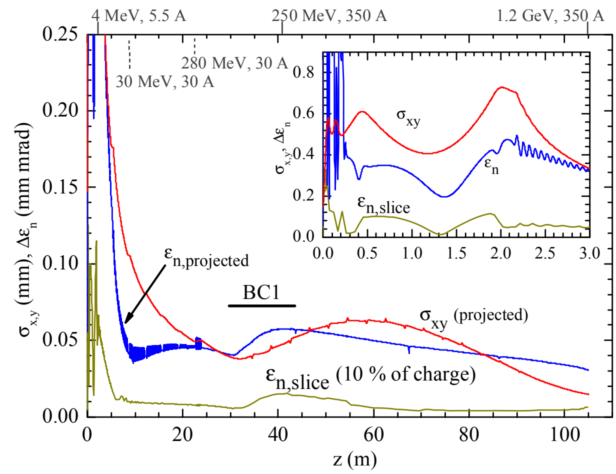

Figure 5. HOMDYN [10] simulation of the beam envelope and emittance dilution for the PSI FEL linac up to BC2, see Fig. 1. The inset is a zoom of the first 3 m.

Performance

As a first step, the emittance dilution has been tracked over the initial 1 GeV of acceleration (up to BC2) with HOMDYN [10], see Fig. 5. Initial conditions were an electron beam with the parameters presented in Tab. 1 with zero emittance at the cathode. It follows that a low emittance can be maintained during compression and acceleration. Verification of these results with more sophisticated codes is still in progress. Here we use MAFIA [11] to simulate the configuration presented in Fig. 3. Calculations are complemented with PARMELA [12] and GPT [13] simulations for tracking of the electron beam behind the diode. As a next step we will use IMPACT [14] for more elaborate calculations and tolerance studies.

Figure 6. Installation of the 500-kV pulser in the test-bunker OBLA.

STATUS AND OUTLOOK

The status of the field emitter development and the associated test stands are reported in [3]. As a first step towards the preservation of the emittance a 500 kV, 200-

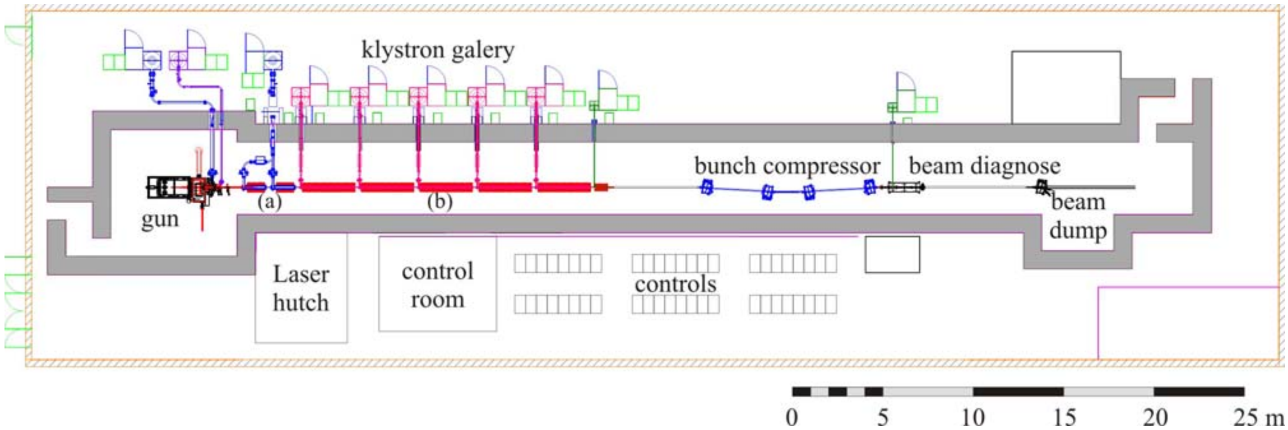

Figure 7. Layout of the 250 MeV test injector. The areas (a) and (b) mark the injector linac and booster linac as depicted in Fig. 2. The designed tunnel is sufficiently long to house the first bunch compressor (BC1 in Fig. 1).

ns pulser has been installed in a bunker at the PSI. It permits the operation of a diode configuration with a variable gap from 30 mm to 2 mm. A photo of the pulser is shown in Fig. 6. In fall of 2006 the pulser will be complemented with a diagnostic station for current and emittance measurements. First tests with pure field emitters (without laser illumination) are then foreseen for the end of the same year. In 2007 the experimental setup will be upgraded to permit laser assisted field emission and photo-emission combined with 1.5 cell RF cavity as depicted in Fig. 3. We note here the different laser systems. Laser assisted field emission has a high quantum efficiency (≈ 1) and requires a photon energy below the work function (λ > 400 nm). This can be a sub-system of the laser required for photo-emission, which typically has to deal with a low quantum efficiency at a wavelength of 266 nm.

In parallel surface cleaning techniques are studied to optimize the operation at high gradient and to minimize the occurrence of breakdowns in the high-gradient accelerator structure.

We plan to extend the experimental capabilities to a 250 MeV accelerator in the period 2008-2011. This linac should demonstrate low-emittance acceleration and bunch compression to reach a beam current of 350 A. In addition, it should serve as a test environment for the development of diagnose for an X-FEL. A possible layout is presented in Fig. 7. It includes the injector sketched schematically in Fig. 2 as well as the first bunch compressor, which is shown in Fig. 1.

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