DEVELOPMENT OF ULTRA-LOW EMITTANCE INJECTOR FOR FUTURE X-RAY FEL OSCILLATOR*

P.N. Ostroumov#, K.-J. Kim, ANL, Argonne, IL 60439, U.S.A
Ph. Piot, Northern Illinois University, DeKalb, IL, U.S.A.

Abstract

An XFELO proposed recently [1] requires a continuous sequence of electron bunches with ultra-low transverse emittance of less than 0.1 µm, a bunch charge of 40 pC, an rms energy spread of 1.4 MeV, repeating at a rate between 1 MHz to 100 MHz. The bunches are to be compressed to rms lengths less than 2 ps at the final energy of 7 GeV. Following the successful commissioning of the pulsed injector based on a thermionic gun [2] we discuss a concept for ultra-low emittance injector to produce 100 MHz CW electron bunches. The electron beam is extracted by ~ 1MV RF voltage using low frequency ~100 MHz room temperature RF cavity [3]. The injector also includes a chicane and slits to form a short ~0.5 nsec bunch, a buncher to form low longitudinal emittance of the bunched beam, an accelerating section to ~20 MeV using higher harmonic cavities, and an RF cosine-wave chopper to form any required bunch repetition rate between 1 MHz and 100 MHz. The results of initial optimizations of the beam dynamics with the focus on extracting and preserving ultra-low emittance will be presented.

GENERAL LAYOUT

The 7 GeV electron beam must be delivered with the parameters listed in Table 1. We propose 7 GeV CW SC linac which includes Ultra-Low Emittance Injector (ULEI) based on a thermionic RF-gun as a solution to deliver an electron beam as specified in Table 1.

The proposed electron linac includes the following main systems:

- An RF-gun with a small diameter thermionic cathode to extract ultra-low emittance beam. The latter is possible primarily due to the low equivalent DC current which is ~80 mA for 0.5 nsec bunches and high extraction voltage.
- A low-frequency RF cavity capable to provide ~ 1.0 MV extracting voltage. The highest possible extraction voltage should suppress beam space charge in the following sections of the injector.
- An energy filter which includes a magnetic chicane and slits to form a short, ~ 0.5 nsec bunch.
- A 6th harmonic RF cavity (600 MHz) as a monochromator to minimize momentum spread of the electron beam.
- A velocity buncher (300 MHz) to form low longitudinal emittance of the bunched beam.
- A booster acceleration up to ~20 MeV using higher harmonic cavities (400 MHz).
- An RF cosine-wave chopper to form any required bunch repetition rate between 1 MHz and 100 MHz.
- Two chicanes along the linac for bunch compression.
- A final acceleration using SC ILC cavities (1300 MHz) with 20 MV/m accelerating field.

Table 1: Main Beam Parameters.

Parameter	Value	Unit
Transverse rms emittance	<0.1	µm*
Bunch charge	40	pC
Bunch rms time width	2	psec
Bunch rms energy spread	1.4	MeV
Bunch repetition rate	1-100	MHz

*The emittance defined as the area must be multiplied by π.

The layout of the injector and the 1.6 GeV section of the linac is shown in Fig. 1.

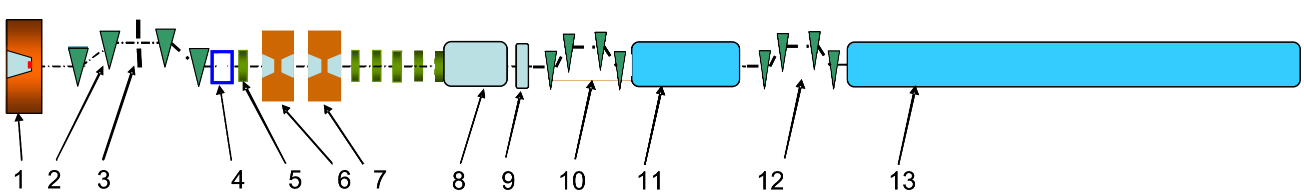

Figure 1: General layout of the linac for XFELO. 1 – RF cavity with thermionic cathode, 100 MHz, 1 MV; 2 – chicane and slits (3) as an energy filter; 4 – quadrupole triplet; 5 – focusing solenoid; 6 – monochromator of the beam energy, f=600 MHz; 7 –buncher, f=300 MHz; 8 – booster linac section, f=400 MHz; 9 –RF cosine-chopper to form rep. rate 1 MHz to 100 MHz; 10 – bunch compressor – I; 11 –SC linac section, 460 MeV, f=1300 MHz; 12 – bunch compressor – II; 13 – initial section of the SC linac, f=1300 MHz.

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#ostroumov@anl.gov

THERMIONIC RF GUN

The normalized RMS emittance of an electron beam emitted from a hot cathode is described by the well-known formula $\varepsilon_{n,RMS} = \frac{r_C}{2}\sqrt{\frac{kT}{m_0 c^2}}$, where r_C is the cathode radius and T is the cathode temperature, k is the Boltzmann constant, m_0 is the electron rest mass and c is the speed of light. To obtain a low emittance beam, a small diameter cathode is required. Initial simulations of a 1 MeV DC electron beam produced by a thermionic cathode in a 100 MHz VHF gun similar to ref. [3] have been performed. The results, shown in Fig. 2, demonstrate that about a 50 mA DC beam can be extracted with an rms emittance less than 0.1 µm. These simulations are also consistent with the measurements performed at the Spring-8 injector [2].

In subsequent steps the cathode size was chosen to ensure that the slice (or uncorrelated) emittance is ~ 0.08 µm at the gun exit. The e-gun RF frequency and voltage were optimized from start-to-end simulations of the low energy transport line (including bunching and acceleration up to ~20 MeV) Among the considered frequency (50, 100 and 186 MHz), the 100 MHz case provided best results so far. The 100 MHz RF cavity creates ~20 MV/m across the accelerating gap with 1 MV total voltage. This cavity will require ~150 kW RF power.

Fig. 3 shows the electron beam momentum along the bunch for three different RF voltages. The energy filter will "chop" the top of the curve within the ±0.25 nsec time window to deliver 40 pC bunches from 80 mA DC beam.

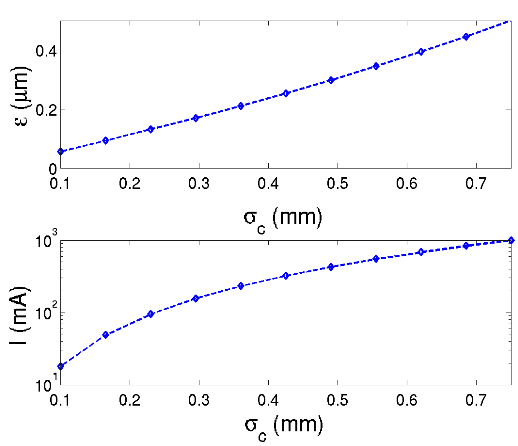

Figure 2: Electron beam slice emittance and current as a function of the cathode RMS radius (σ_c=$0.5r_C$) for the 100 MHz gun.

PHYSICS DESIGN AND START-TO-END SIMULATIONS

The physics design of the injector and initial section of the main linac up to 1.6 GeV has been performed using

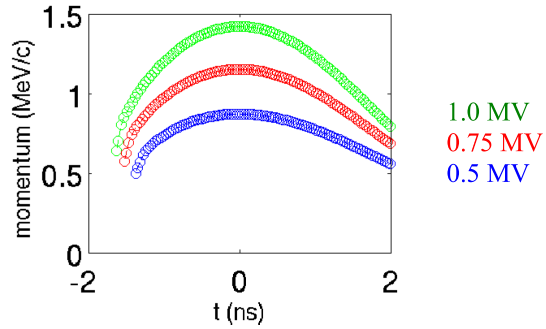

Figure 3: Electron beam momentum along the bunch for three different RF voltages in the 100 MHz cavity.

TRACK [4] and ASTRA [5] tracking codes. The simulations of 3D beam dynamics include space charge effects and realistic field distributions in all injector and linac elements. In addition, PARMELA is being used to verify the beam dynamics in some sections of the linac.

Originally the linac design has been performed by optimization of each subsystem such as the RF-gun, energy filter, monochromator, velocity buncher, booster acceleration and bunch compressors. For example, the monochromator, the velocity buncher and booster linac were optimized to minimize emittance growth due to space charge and chromatic aberrations.

The simulations indicate that all functional elements of the layout shown in Fig. 1 provide the expected performance. For example, the chicane and slits serve as a perfect energy filter and form 0.5 nsec bunch without any transverse emittance growth. The RF cavity (element 6 in Fig. 1) operating at 600 MHz can reduce the total energy spread down to 0.07%. The buncher and booster section reduce the rms bunch time width below 30 ps. The current configuration of the linac is not yet finalized: overall, we observe ~60% growth of the transverse rms emittance derived from 90% of particles.

The evolution of the RMS energy spread and bunch width along the 1.6 GeV linac is shown in Fig. 4. Although, the longitudinal emittance of the 1.6 GeV beam is within specifications, more optimization is required to reduce energy spread by the factor of 2. To achieve required bunch length, two magnetic chicanes are used. The final current distribution of the accelerated bunch is shown in Fig. 6.

We are developing a chopper system which allows us to produce a bunch sequence with any frequency between 1 to 100 MHz. The system is based on a combination of cosine-wave chopper [6] with a fast kicker (~20 nsec). The kicker can be used at low energy while cosine-wave chopper should be installed after the 20 MeV section to suppress any space charge effects.

OPTIMIZATION VIA EVOLUTIONARY ALGORITHM

We have also started to use a genetic optimization code [7] in conjunction with ASTRA as done in ref. [8]. For the preliminary optimization (ASTRA does not yet include the space charge force in dipole magnets), a simplified approach was followed. The energy filter was idealized (by numerically chopping the distribution out of the gun), and the distribution was tracked in a cylindrical-symmetric beamline (to increase the simulation speed). Currently we considered the 100 MHz RF gun with an accelerating voltage of 1 MV and the ideal chopper was set such that 50 pC was transmitted. Our simplified beamline incorporates solenoids similar to the JLAB IR-FEL. The multi-objective optimization included the minimization of the transverse emittance and the bunch length. The positions and settings of all the elements in the beamline were optimization variables. The evolution of the transverse emittance along the optimized beamline is shown in Fig. 5, the 80 % rms emittance, i.e. corresponding to targeted 40 pC, is below 0.08 µm. The corresponding rms bunch length ~20 m downstream of the cathode is 27 mm (rms).

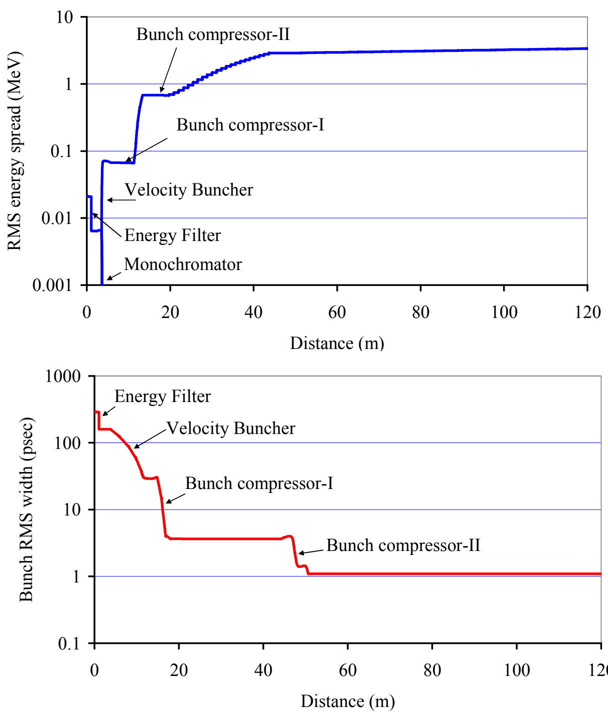

Figure 4: Evolution of RMS energy spread and bunch width along the linac.

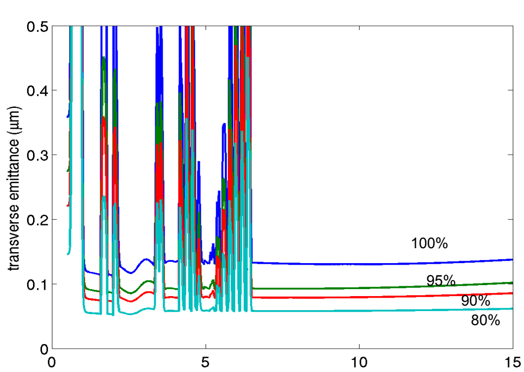

Figure 5: Electron beam emittance vs distance.

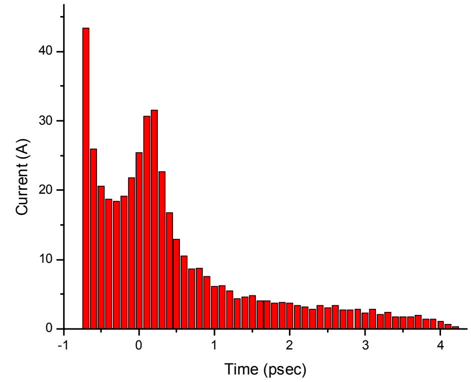

Figure 6: Current distribution in the accelerated bunch.

CONCLUSION AND OUTLOOK

Preliminary "manual" design of the ULEI and CW accelerator has been developed without genetic optimization codes. 3D simulations show that the energy filter does not produce any transverse emittance growth. Two bunch compressors are required to achieve specified longitudinal beam parameters at the end of linac. Start-to-end simulations have been performed in realistic external and space charge 3D fields. These simulations show that the longitudinal emittance is within specifications while the transverse rms emittance (normalized and defined for 90% of particles) is 0.16 µm. Application of a genetic optimization code in a currently simplified injector section results in improved performance capable to maintain the emittance unchanged and equal to ~0.08 µm.

We plan to extend the genetic optimization of the injector and define cost-effective accelerating systems for the whole linac up to 7 GeV.

REFERENCES

[1] K.-J. Kim, Y. Shvyd'ko, and S. Reiche, Phys. Rev. Lett., 100 244802 (2008).

[2] K. Togawa, et al., Phys. Rev. STAB 10, 020703 (2007)

[3] J.W. Staples, et al., Proceedings of the PAC 2007, p. 2990.

[4] http://www.phy.anl.gov/atlas/TRACK/

[5] K. Flottmann, ASTRA user manual available at: http://www.desy.de/ ˜mpyflo/Astra dokumentation/

[6] R. E. Laxdal, M. Pasini, L. Root, Proceedings of LINAC 2002, Gyeongju, Korea, p. 409.

[7] M. Borland, H.Shang, GeneticOptimizer unpublished program.

[8] I.V. Bazarov and C.K. Sinclair, PRST-AB, 8, 034202 (2005).