OPTIMIZED DESIGN OF AN ULTRA-LOW EMITTANCE INJECTOR FOR FUTURE X-RAY FEL OSCILLATOR*

P.N. Ostroumov[#], D. Capatina, K.-J. Kim, S.A. Kondrashev, B. Mustapha, A. Nassiri,
ANL, Argonne, IL 60439, U.S.A

Abstract

The concept of an ultra-low transverse emittance injector operating in CW mode for an XFELO [1] was discussed at LINAC-08 [2]. Here we will report the design optimization of the injector, which includes a 100 MHz RF-gun with thermionic cathode, an energy filter to produce short bunches (~0.5 nsec), a velocity bunching section, higher harmonic cavities to minimize the longitudinal emittance, two bunch compressors and accelerating sections operating at 400 MHz and 1300 MHz to obtain 546 MeV electrons. The proposed design is capable of producing 40 pC bunches with 0.5 psec rms time width and 0.7 MeV rms energy spread. Most significantly, the effective transverse rms emittance of the bunch is kept below 0.13 μm. The longitudinal emittance and bunch time width can be substantially reduced for low charge bunches of few pC.

INJECTOR DESIGN

The concept of a 7 GeV CW SC linac which includes an Ultra-Low Emittance Injector (ULEI) based on a thermionic RF-gun was discussed in [2]. The 7 GeV electron beam must be delivered with the parameters listed in Table 1. The beam parameters achieved as a result of multiple iterations of injector design and optimization are listed in the "Design" column of Table 1. The general layout of the 546 MeV injector is given in Figure 1.

The following design modifications have been implemented since the previous design [2]:

- To limit electron beam power on the slits of the energy filter, the beam repetition rate must be reduced to 3 MHz. To reduce the bunch repetition rate, an RF chopper (pos. 3 in Fig. 1) is added with a beam dump.
- To compensate the Twiss parameters variation along the bunch, a 100 MHz RF cavity is used (pos. 9 in Fig. 1).

The phase and voltage of the cavity are optimized to minimize the effective emittance growth in the following accelerator system.

- An energy filter forms a short ~ 0.5 nsec bunch with 50 pC charge which is required to deliver 40 pC (80% of the bunch) bunches within the specifications of Table 1.
- A 13th harmonic RF cavity (1300 MHz) is introduced upstream of the first bunch compressor (positions 14 in Fig. 1) to linearize the energy of the electron beam as a function of time.
- The beam energy upstream of each bunch compressor is optimized to maintain low transverse emittance and minimize the longitudinal emittance.
- A final acceleration of electron beam up to 7 GeV using SC ILC cavities (1300 MHz) is discussed elsewhere [3].

Table 1: Main Beam Parameters.

Parameter	Required	Current design	Unit
Transverse rms emit., X &Y	≤0.1	0.13&0.1	μm*
Bunch charge	40	40	pC
Bunch rms time width	2	0.5	psec
Bunch rms energy spread	1.4	0.7	MeV
Bunch repetition rate	1-3	-	MHz

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

CW acceleration is provided by 400 MHz SC cavities up to 66 MeV and 1300 MHz SC cavities up to 546 MeV. The low frequency section of the linac up to 66 MeV is required to maintain low emittance in the longitudinal phase space.

NEW COMPONENTS OF THE INJECTOR

Compared to the preliminary design of the ULEI reported at LINAC-08 [2], several modifications have
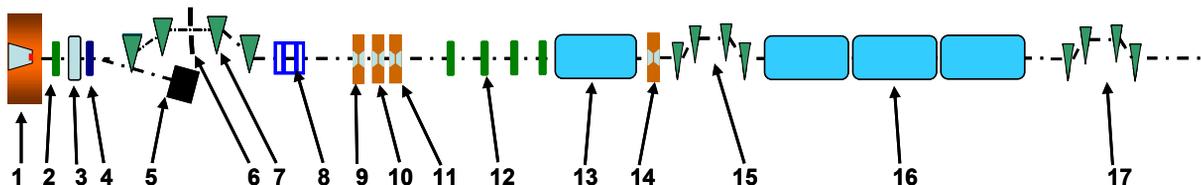
Figure 1: General layout of the injector. 1 – RF cavity with thermionic cathode, 100 MHz, 1 MV; 2 – focusing solenoid; 3 - RF chopper to form bunch repetition rate 1 MHz to 3 MHz; 4 – quadrupole; 5 – beam dump; 7 – chicane and slits (6) as an energy filter; 8 – quadrupole triplet; 9 – 100 MHz rf cavity; 10 - monochromator of the beam energy, f=600 MHz; 11 – buncher, f=300 MHz; 12 – focusing solenoids; 13 – booster linac section, f=400 MHz; 14 – high-harmonic cavity (1300 MHz); 15 – bunch compressor – I; 16 –SC linac section, 546 MeV, f=1300 MHz; 17 – bunch compressor – II.

been implemented in new optimized design layout and are discussed below.

RF Chopper

The total beam power extracted form the RF-gun can reach ~20 kW. The simulations show that the slits of the energy filter can not withstand such a high power. Therefore, the bunch repetition rate must be reduced upstream of the energy filter. We plan to investigate an RF chopper located immediately after the RF-gun to select bunch repetition rate from 1 MHz to 3 MHz by deflecting extra bunches to a beam dump. The beam dump requires a beam sweeper to reduce the power density on the electron collector.

100 MHz RF Cavity

There is a correlation between the normalized transverse emittance of an electron bunch and RF phase. To minimize the effective emittance for the whole bunch, we have introduced a 100 MHz RF cavity (position 9 in Fig. 1) operating in a debunching mode to de-couple the transverse emittance and time along the bunch. After optimization of the cavity voltage, the transverse emittance growth in the following beam transport and acceleration system is minimal.

High-Harmonic RF Cavity

The left plot in Fig. 2 shows the electron beam energy along the bunch upstream of the first bunch compressor. We have noticed that the "linearization" of the energy as a function of time (or phase) by applying higher harmonic voltage helps to maintain very low longitudinal emittance in the following accelerator sections. The effect of the high-harmonic cavity is shown on the right picture of Fig. 2. Thanks to the harmonic cavity and appropriate phase of the accelerating field in the standing-wave SC linac, it is possible to maintain extremely low longitudinal emittance which results in a small time width and energy spread of the bunch. As is shown in Table 1, the application of high harmonic cavity allows us to achieve an rms bunch width which is a factor of 4 lower than the specified value. Similarly, the beam energy spread is lower by a factor of 2 than the specified value.
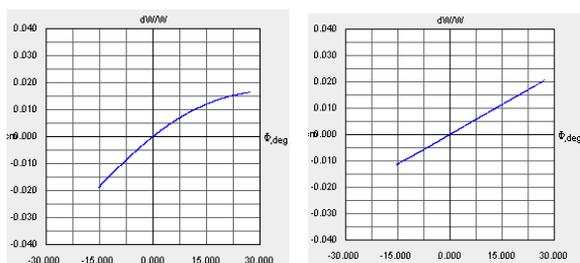
Figure 2: Beam phase space plots in the longitudinal plane before (on the left) an after the harmonic cavity.

BEAM DYNAMICS

The physics design of the injector has been performed using the TRACK [4] code. The simulations of 3D beam dynamics include space charge effects and realistic field distributions in all injector elements. The evolution of the RMS energy spread and bunch width along the 546 MeV linac is shown in Fig. 3. Although, the longitudinal emittance of the 546 MeV beam is much lower than the specified value, more optimization is required to reduce the horizontal emittance of the accelerated beam by ~30%. The latter is shown in Fig. 4. To achieve the required bunch length, two magnetic chicanes are used. The final current distribution of the accelerated bunch is shown in Fig. 5.

Optimization via Evolutionary 3D Algorithm

A genetic optimization algorithm similar to [5] has been implemented into the 3D tracking code TRACK. The code TRACK has been also updated from its original version to simulate high-energy electrons. The genetic optimization has been applied to the sections of the ULEI. An initial optimization of the energy filter including upstream and downstream beam optics elements improved the transverse emittance by 10%. Currently, extensive genetic optimization on BlueGene supercomputer at ANL is being performed for the downstream section of the injector starting from the velocity buncher.

LOW CHARGE MODE

Low charge CW bunches can be produced by adjusting the slits in the energy filter. In the following example, the slits are adjusted to obtain 3 pC total charge and Table 2 shows the parameters for 80% of particles in the bunch
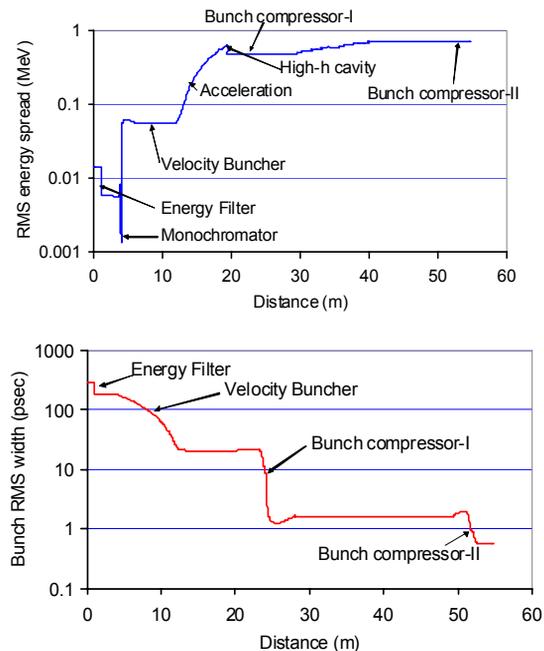
Figure 3: RMS energy spread and bunch width vs distance.
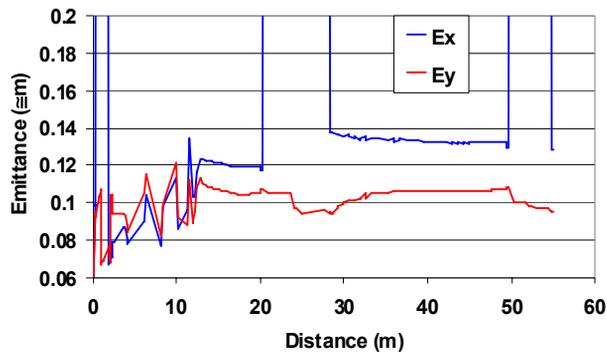
Figure 4: Electron beam emittance (80% of particles) vs distance.
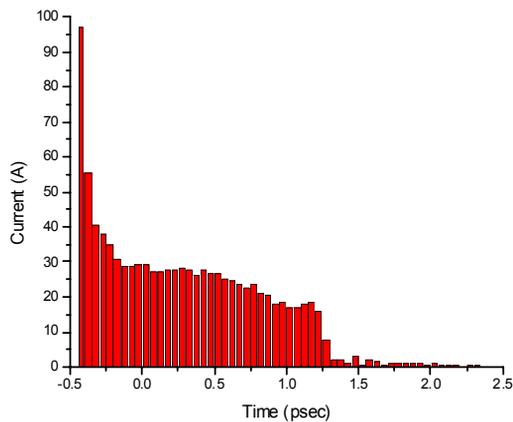
Figure 5: Current distribution in the accelerated bunch.

No additional parameters of the injector were changed to provide the beam properties listed in Table 2. The bunch may further be compressed so that the peak current is 500A or higher. The low charge mode will then be an excellent driver for temporally coherent, femtosecond SASE [6]

Table 2: Low-charge bunch parameters at 546 MeV.

Parameter	Value	Unit
Bunch charge	2.43	pC
Transverse rms emittance X & Y	0.087 & 0.079	μm
Bunch rms time width	11	fsec
Bunch rms energy spread	43	keV

DESIGN OF A PROTOTYPE ELECTRON GUN

The development and construction of a prototype RF e-gun is an expensive and long-term R&D work. The RF-gun will create high power 1 MV beam, the major fraction of which should be properly dumped in an electron collector. Therefore, as a first step of the R&D effort, we propose to develop and build a low duty factor pulsed e-gun with the parameters shown in Table 3. The main scope of the proposed R&D effort is to demonstrate a low-emittance electron beam using small (~1 mm diameter) thermionic cathode. The beam dynamics simulations show that 300 kV is sufficient to suppress beam space charge and preserve the thermal emittance in a short beam transport system where the emittance measurements should be performed. The 300-kV electron gun is based on a CeB_6 thermal cathode with diameter ~1 mm. The e-gun is followed by a beamline with the appropriate diagnostics to provide emittance measurements. We have developed the engineering design of such an electron gun in tight collaboration with the SPring-8 team [7]. The construction will start as soon as hardware funding becomes available.

Table 3: Beam parameters in the proposed e-gun test stand

Parameter	Value	Unit
CeB_6 cathode diameter	0.75-1.5	mm
Beam energy	300	keV
Peak current	Up to 200	mA
Pulse width (FWHM)	~ 2	μs
Rep-rate	1	Hz

CONCLUSION AND OUTLOOK

The design of an ULEI capable of producing 546 MeV electrons has been significantly improved in the past 6 months. The introduction of a high-harmonic cavity upstream of the first bunch compressor has resulted in very low longitudinal emittance. Start-to-end simulations have been performed in realistic external and space charge 3D fields. 3D genetic optimization algorithms have been applied to several sections of the linac. These simulations show that the transverse rms emittance (normalized and defined for 80% of particles) is below 0.13 μm and 0.10 μm in the horizontal and vertical planes respectively. The application of genetic optimizations is being pursued for longer sections of the linac.

ACKNOWLEDGEMENT

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