IMPROVEMENTS ON THE DESIGN OF AN ULTRA-LOW EMITTANCE INJECTOR FOR A FUTURE X-RAY FEL OSCILLATOR*

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Abstract

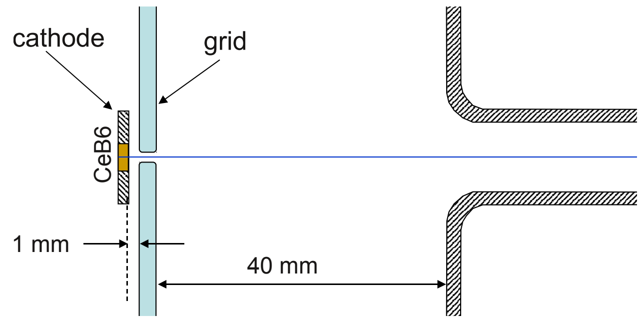
The concept of an ultra-low transverse emittance injector for the x-ray free-electron laser oscillator [1] (XFEL-O) was discussed at PAC09 [2]. Two problems come to mind. A dual-frequency rf chopper for reducing the beam rate from 100 MHz to 1 ∼ 3 MHz would limit our choice of the beam repetition rate. The electron back-bombardment could be solved by embedding a three-pole wiggler [3] in the nose cone of the gun cavity, but that results in increased emittance. Inspired by the concept of a triode gun [4], the injector now includes a gated 100-MHz rf gun with thermionic cathode to avoid those limitations. The design has been studied and is capable of producing 40-pC bunches with 0.1- μm effective transverse rms emittance.

INTRODUCTION

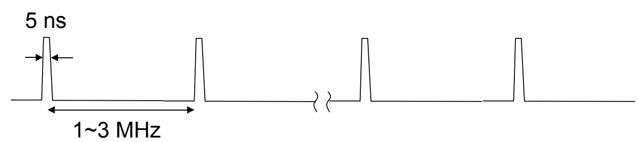
The injector discussed in [2] and [5] includes a 100-MHz rf gun with thermionic cathode, an energy filter to produce short bunches (0.5 ns), a velocity-bunching section, higher harmonic cavities to minimize the longitudinal emittance, two bunch compressors, and accelerating sections operating at 400 MHz and 1300 MHz to obtain 542-MeV electrons. The proposed design is capable of producing 40-pC bunches with 0.13- μm effective transverse rms emittance, 0.5-ps rms bunch length, and 0.7-MeV rms energy spread.

Because the injector must operate continuously, back-bombardment (BB) of the thermionic cathode is a serious concern [3]. In order to reduce the BB power hitting the 0.6 mm cathode from 60 W to a safe range of several Watts, an additional magnetic system will be needed, which may increase the beam emittance. In addition, to reduce the beam rate from 100 MHz to 1 ∼ 3 MHz, an rf chopper located immediately after the rf gun is needed. This is essential, because the total beam power extracted from the rf gun can easily exceed 20 kW, beyond the capability of the energy filter slits. However, the number of workable beam repetition rates determined by a dual-frequency rf chopper at a reasonable bias voltage is very limited.

Our simulations show that a gated rf-gun-based injector could meet the requirements for XFEL-O, addressing several of the above-mentioned limitations. Figure 1 illustrates an rf gun with a pulsed gate electrode, to be referred to as a grid, 1 mm from the cathode. The grid has a single on-axis circular opening that allows the electron beam to flow



(a) Schematic drawing of the rf gun with gate electrode.



(b) Grid-to-cathode potential difference, generated by a fast pulser.

Figure 1: Concept of a gated rf gun.

through during the flattop of a waveform generated by a fast pulser. The grid is normally held at a small retarding voltage relative to the cathode to "turn off" the beam.

CATHODE AND GUN

Minimizing thermal emittance is critical for achieving submicron emittance. The normalized rms emittance of an electron beam emitted from a thermionic cathode is described by the equation [8]

$$\varepsilon_{n,rms}^{th} = \frac{r_c}{2}\sqrt{\frac{k_B T_c}{m_e c^2}} \qquad (1)$$

where r_c is the cathode radius, T_c is the cathode temperature, k_B is the Boltzmann's constant, m_e is the electron rest mass and c is the speed of light. The emission current density is governed by Richardson's equation:

$$J = AT^2 \exp(-\frac{\phi_{eff}}{k_B T}) \quad \phi_{eff} = \phi - \frac{e}{2}\sqrt{\frac{eE_s}{\pi\epsilon_0}} \qquad (2)$$

where A is the Richardson constant, ϕ is the work function of the cathode material, ϕ_{eff} is the effective work function reduced by Schottky effect, and E_s is the electric field on the cathode surface. A measurement [9] at SPring-8 gives $A = 19.1A/cm^2/K^2$ and $\phi = 2.39V$ for a single-crystal CeB_6 thermionic cathode.

We require an $I_r = 0.10$ A beam with minimal thermal emittance. E_s is 18.5 MV/m, giving $\phi_{eff} = 2.23eV$. For a given T_c, the emission density is determined by Eq. 2, which determines the cathode radius r_c needed to give

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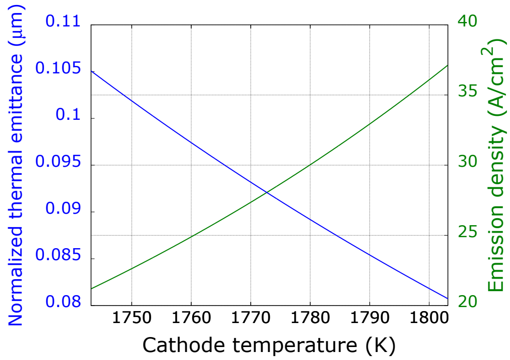


Figure 2: Normalized thermal emittance and electron emission density vs cathode temperature. See text for details.

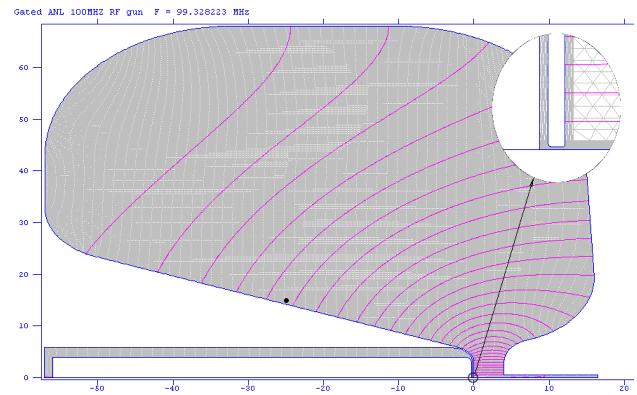
$I = I_r$ through the relation $I_r = \pi r_c^2 J$. Given r_c and T_c, Eq. 1 gives the emittance $\varepsilon^{th}_{n,rms}$. Thus, we get a curve of $\varepsilon^{th}_{n,rms}$ as a function of the cathode temperature subject to $I = I_r$, as shown in Fig. 2. We see that lower thermal emittance can be obtained at higher cathode temperature, a surprising conclusion. 1773 K has proved to be safe for a CeB_6 cathode [10] during a long-term run of 2000 hours, giving $J = 28A/cm^2$ which we used in our simulations. Thus the thermal emittance of the electron beam from a $r_c = 0.35$ mm cathode is 0.09 μm.

The geometry of the APS 100-MHz rf gun [6] was first input to a SUPERFISH [7] model. The original cathode surface was modified to form a gate electrode, and a cavity for the new cathode stem was attached. The dark part in the vicinity of the grid and the beam orbit in the magnified view on Figure 3(a) represents enhanced mesh to improve the field accuracy. The grid is 2 mm thick and the beam aperture is rounded with a 0.5 mm radius. In order to get sufficient beam current from a cathode with above-mentioned emission density and temperature while a fraction of particles can be stopped on the inner wall of the beam aperture, the radius of the beam aperture is 0.4 mm, slightly larger than 0.35 mm. We did not simulate the transient behavior. The model was converted into a POISSON/electrostatics problem by assigning a potential difference of 20 kV over the cathode-grid gap. Here we got a field map for beam-on mode as shown in Figure 3(b).

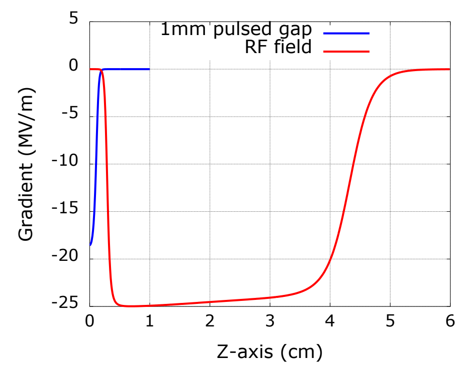
ASTRA [11], used for simulation of the rf gun, calculates off-axis fields from the derivative of the on-axis field. This method will certainly cause an error in the vicinity of the grid aperture. However, the good agreement between ASTRA and GPT [12], which supports 2D or 3D field map and an accurate, but relatively slow 3D space-charge solver, implies that this has an insignificant effect on the beam dynamics results.

INJECTOR DESIGN AND OPTIMIZATION

During the beam dynamics optimization using simulation code TRACK [13], a special effort has been made to deliver proper longitudinal shaping of the simulated bunch.



(a) Geometry and field pattern of APS 100-MHz rf gun with gate electrode. The meshed area is the cross section of cavity interior. The gate electrode structure is magnified due to its tiny size.



(b) Field map for ASTRA, generated with LANL Superfish software from above geometry.

Figure 3: Superfish model of gated APS 100-MHz rf gun.

An increase in slice emittance in the bunch head has always been observed. This is mainly due to the stronger space-charge effects in the peak current region during the velocity bunching at low beam energy. It is also due to a larger residual slice energy spread that affects the distribution of the transverse momenta at the horizontal kicker and thus the slice emittance. The monochromator cavity (#7 in Fig. 4) was therefore moved to the immediate downstream of the energy filter to minimize such an effect. With the aid of `geneticOptimizer` [14] based on the non-dominated sorting genetic algorithm II [15], the quadrupole triplet (#8 in Fig. 4) was in turn optimized to restore the axial symmetry of the beam and avoid any additional emittance growth due to X-Y coupling, and the locations and the strengths of four solenoids (#10 in Fig. 4) were optimized to compensate space-charge emittance growth during the compression of 1-MeV beam.

The longitudinal charge distribution obtained from the same bunch compressor design as in [2] is shown in Figure 5(a). The charge included in the bunch head where the slice current is much higher than 20 A or in the bunch tail where slice current is lower than 10 A don't help much for lasing. Such a longitudinal charge distribution was formed actually by folding the bunch, and then relatively large slice emittance was introduced into the peak current region. To

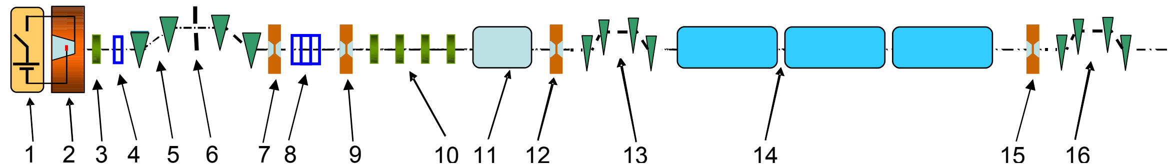


Figure 4: General layout of the injector. 1: 20-kV fast pulser; 2: 100-MHz rf gun with gate electrode and thermionic cathode; 3: focusing solenoid; 4: quadrupole; 5: chicane and energy slits (6); 7: 600-MHz energy monochromator; 8: quadrupole triplet; 9: 300-MHz buncher; 10: solenoids; 11: 400-MHz linac; 12: 1300-MHz high-harmonic cavity; 13: bunch compressor I; 14: 1.3-GHz SC linac; 15: 3.9-GHz high-harmonic cavity; 16: bunch compressor II.

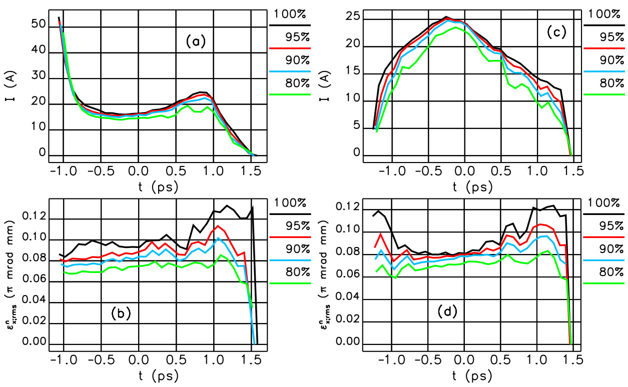


Figure 5: Slice current (top row) and emittance (bottom row) profile without (left column) / with (right column) additional 3.9-GHz cavities.

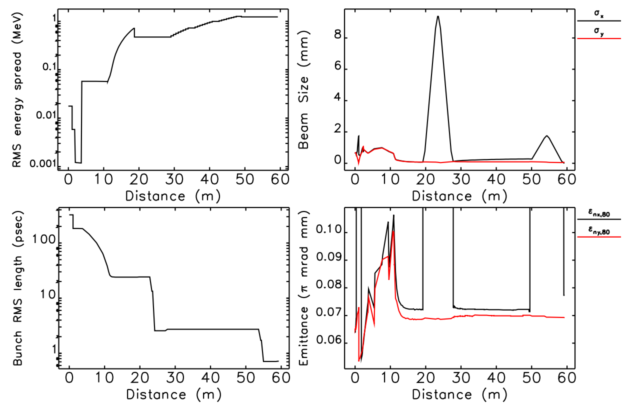


Figure 6: The evolution of key beam parameters.

Table 1: Performance of an Injector Based on Gated RF Gun and Requirements

	Design	Required
Normalized $\varepsilon_{x,80}/\varepsilon_{y,80}(\mu m)$	0.08/0.08	≤ 0.1
Bunch charge Q (pC)	51	40
rms bunch length (ps)	0.70	$\sim$1
Energy spread (MeV)	0.06	$\leq$1.4

improve the longitudinal bunch shaping, a set of 3.9-GHz cavities (#15 in Fig. 4) has been introduced. As shown in the right column of Figure 5, more charge is included in "good" slices, and the core emittances for the peak current region are even lower. The slice energy spread is also greatly reduced.

The beam parameters achieved as a result of injector design and optimization are listed in the "Design" column of Table 1, along with the requirements for comparison. The evolution of key beam parameters is depicted in Fig. 6.

CONCLUSION

We have modeled an injector design based on the APS 100-MHz rf gun with a gate electrode for XFEL-O using the beam dynamics programs ASTRA and TRACK. The introduction of the 3.9-GHz cavities upstream of the second bunch-compression chicane has led to an improvement in the bunch current profile. Extensive injector design and numerical optimization gives machine configurations for which the requirements of an XFEL-O are met. Most significantly, the effective transverse rms emittance defined for 80% particles is kept well below 0.1 μm.

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