POTENTIAL FOR AN ULTRA-LOW EMITTANCE THERMIONIC TRIODE GUN*

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Abstract

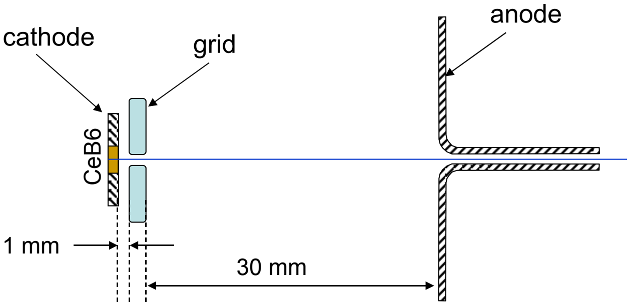
The proposed X-ray Free Electron Laser Oscillator [1] (XFEL-O) requires an ultra-low emittance gun that generates continuous electron bunches at 1 to 10 MHz. Recently, T. Shintake raised the possibility of using a pulsed triode gun with a thermionic cathode. In this paper, we investigate the feasibility of such a gun as part of an injector producing normalized core emittance in the 0.1 µm range with ∼1 ps rms duration for 50 pC/bunch.

INTRODUCTION

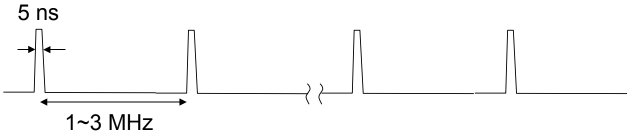
The injector discussed in [2] and [3] includes a 100 MHz RF-gun with thermionic cathode, an energy filter to produce short bunches (0.5 nsec), a velocity bunching section, higher harmonic cavities to minimize the longitudinal emittance, two bunch compressors, and accelerating sections operating at 400 MHz and 1300 MHz to obtain 542 MeV electrons. The proposed design is capable of producing 40 pC bunches with 0.13 µm effective transverse rms emittance, 0.5 psec 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 [4]. In order to reduce the BB power hitting the 0.6 mm cathode from 60 W to a safe range of several Watt, 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.

T. Shintake [5] proposed an alternative to the 100MHz rf gun for the XFEL-O injector, namely, a DC gun with a pulsed gate electrode, also known as a grid, 1 mm from the cathode, as illustrated in Fig. 1(a). The grid has a single on-axis, 1-mm-diameter circular opening that allows the electron beam to flow through on the flattop of a waveform generated by a fast pulser. The grid is normally held at a small retarding voltage relative the cathode to “turn off” the beam. Our simulations show that a triode gun based injector could meet the requirements for XFEL-O, addressing several of the above-mentioned limitations.

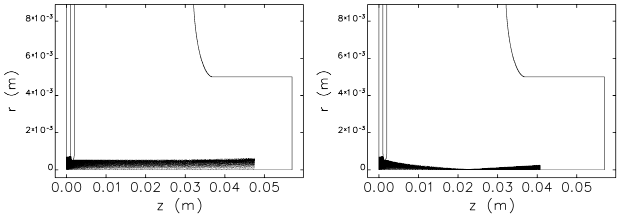


(a) Schematic drawing of the proposed triode gun.



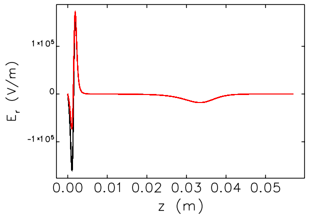
(b) Grid-to-cathode potential difference, generated by a fast pulser.

Figure 1: Concept of triode gun.



(a) Snapshot from a basic simulation without space charge.

(b) Snapshot from a basic simulation without space charge. In this case, the grid-to-cathode voltage is reduced from 10 kV to 5 kV



(c) Radial electric field at $r = 50\mu m$ for 10 kV (black) and 5 kV (red) case.

Figure 2: The choice of gap potential.

INITIAL STUDY OF TRIODE GUN

We simulated the gun using `spiffe` [6]. The various structures were assigned DC potentials for either the beam-retarding or beam-accelerating configuration. We did not simulate the transient behavior. The cathode is assumed to be at a potential of -300 kV. The grid is pulsed to an accelerating voltage of -290 kV for 1 ns to create the beam.

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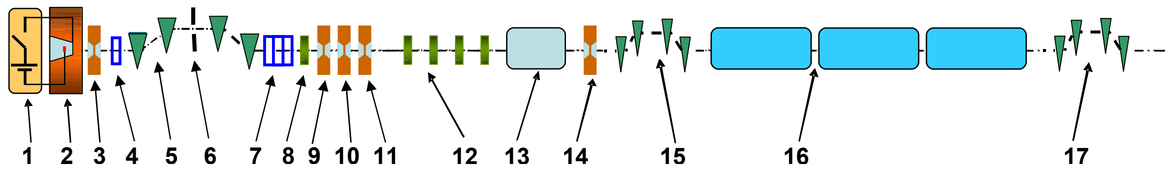

Figure 3: General injector layout. 1 : 10 kV fast pulser; 2 : 300 kV thermionic DC gun with gate electrode; 3 : 100 MHz RF cavitgy; 4 : quadrupole; 5 : chicane and energy slits (6); 7 : quadrupole triplet; 8 : Solenoid; 9 : 100 MHz RF cavity; 10 : 600 MHz energy monochromator; 11 : 300 MHz buncher; 12 : solenoids; 13 : 400 MHz linac; 14 : 1300 MHz high-harmonic cavity; 15 : bunch compressor I; 16 : 1.3 GHz SC linac; 17 : bunch compressor II.

The anode is of course at ground potential. The cathode radius is 0.7 mm, just slightly larger than the grid iris radius of 0.5 mm. The grid is 1 mm thick and the beam aperture is rounded with a 0.5 mm radius. The exit aperture has a 5 mm radius with a rounded entrance opening having a 5 mm radius. None of these parameters were optimized.

The first simulation was a basic beam-acceleration run without space charge to check the essential features of the design. Fig. 2(a) shows a snapshot of the beam. One might wonder if the potential difference between the cathode and grid can be reduced, which would relax the requirements on the pulser. Fig. 2(b) shows the results of reducing the potential difference from 10 kV to 5 kV. The beam is strongly focused, which results from lack of cancelation of the effects of the radial electric field in the two regions of the gun (see Fig. 2(c)). Hence, reducing the potential difference is not recommended for our current DC gun design.

Next we added space charge, assuming a current density of $1.3 \times 10^5 A/m^2$, giving an average current of about 100 mA through the iris. For a 1 ns pulse, the bunch charge will be about 100 pC. The assumed cathode temperature was 1673 K. Without thermal velocities, the normalized rms emittance is 0.04 µm and the rms energy spread is 0.005%. When thermal velocities are added, we get 0.12 µm emittance but essentially the same energy spread.

INJECTOR DESIGN AND OPTIMIZATION

To assess how the gun performs as part of a full injector, as shown in Fig. 3, we revised the injector design for the 1 MV RF gun. The 100 MHz RF gun has been replaced by the 300 kV triode gun (#2 in Fig. 3) followed immediately by a newly added 100 MHz accelerating cavity (#3) which brings the maximum beam energy to 1 MeV, as well as generates a momentum curve on the beam so that a ~50 pC bunch can be formed after the energy filter. The modification results in a longer bunch with smaller energy spread compared with the RF gun case. The strength of the monochromator therefore must be reduced by almost half to get beam energy spread properly linearized and avoid a large growth of beam energy spread in the booster section. Another modification is to add a focusing solenoid (#8) at ~0.6 meter upstream item 9, in order to match the beam to the velocity bunching section.

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 [7]

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

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 density is governed by Richardson's equation:

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

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 [8] 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 a $I_r = 0.08$ A beam with minimal thermal emittance. E_s is 9 MV/m, giving $\phi_{eff} = 2.28eV$. For a given T_c, the emission density is determined by Eq. 2, which determines the cathode radius r_c needed to give $I = I_r$. 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. 4. We see that lower thermal emittance can be obtained at higher cathode temperature, a surprising conclusion. 1773 K has proven to be safe for a CeB_6 cathode [9] during a long term run of 2000 hours, giving $J = 20.5A/cm^2$ which we used in our simulations.

The beam dynamics optimization has been performed using TRACK [10] and ASTRA [11]. ASTRA, used for simulation of the triode gun and the first accelerating cavity, 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 maps and an accurate, but relatively slow, 3D space charge solver, implies that this has an insignificant effect on the beam dynamics results.

A 2-stage minimization of the 80% transverse emittance was performed with the aid of `geneticOptimizer` [13], which is based on the non-dominated sorting genetic algorithm II [14]. In the first stage, the quadruple triplet (#7

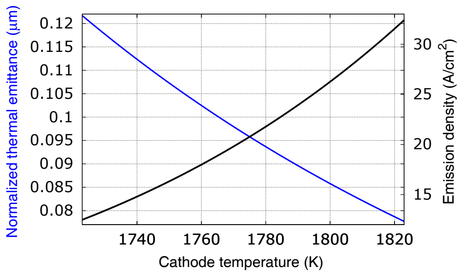

Figure 4: Normalized thermal emittance and electron emission density vs cathode temperature. See text for details.

Table 1: Performance of an Injector Based on 300 kV Triode Gun and Requirements

	Design	**Required**
Normalized $\varepsilon_{x,80}/\varepsilon_{y,80}$ (µm)	0.10/0.09	≤ 0.1
Bunch charge Q (pC)	55	50
rms bunch length (ps)	1.22	~1
Energy spread (MeV)	1.00	1.4

in Fig. 3) was optimized to restore the axial symmetry of the beam and avoid any additional emittance growth due to X-Y coupling. In the second stage, the locations and the strengths of four solenoids (#12) were optimized to compensate emittance growth due to space charge effect during the compression of 1 MeV beam from 220 ps to 30 ps. 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. 5.

IMPLEMENTATION CONCEPT

Although this concept performs well in simulation, a real-world implementation has significant challenges. Creating the required 10-kV, 5-ns pulses at a sustained 1 MHz repetition rate will require advances in pulser technology. This pulser will have to float at 300 kV. The geometry of the gun will have to be designed to preserve the pulse shape as it travels to the grid.

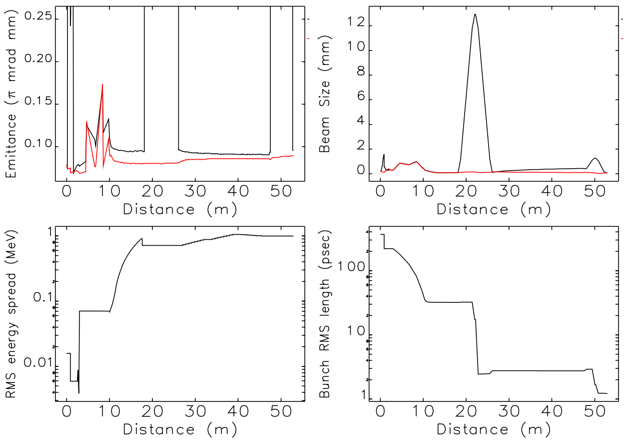

Figure 5: The evolution of key beam parameters.

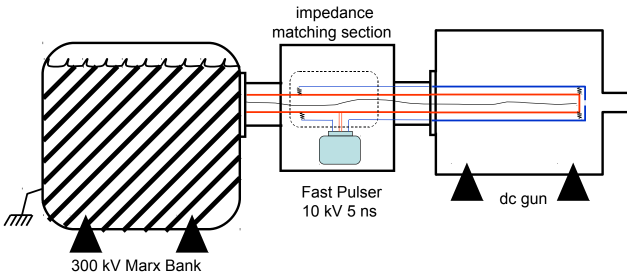

Figure 6: Concept for a pulsed DC gun to test the triode concept.

APS is developing a plan to test aspects of this design, based on a pulsed DC power supply and gun that are already in development. Fig. 6 illustrates the test configuration, in which a 300 kV long-pulse power supply is combined with a 10 kV short-pulse power supply to allow characterization of the essential features and beam dynamics.

CONCLUSION

We have modeled a injector design based on a high-brightness triode gun for XFEL-O using the beam dynamics program ASTRA and TRACK. Extensive injector design and numerical optimization gives machine configurations for which the requirements of XFEL-O are met. Most significantly, the effective transverse rms emittance of the bunch is kept below 0.1 µm. A plan is being developed to test the beam dynamics and required technology.

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