

# DEVELOPMENT OF AN ULTRA-LOW-EMITTANCE RF PHOTOINJECTOR FOR A FUTURE X-RAY FEL OSCILLATOR\*

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## Abstract

The proposed X-ray free-electron laser oscillator [1] (XFEL-O) requires continuous electron bunches with ultra-low normalized transverse emittance of less than  $0.1 \mu\text{m}$ , a bunch charge of 40 pC, an rms uncorrelated energy spread of less than 1.4 MeV, produced at a rate between 1 MHz to 10 MHz. The bunches are to be compressed to an rms length of  $\sim 1$  ps and accelerated to the final energy of 7 GeV. In this paper, we discuss a design for an ultra-low-emittance injector based on a 325-MHz room-temperature rf cavity and a  $\text{Cs}_2\text{Te}$  photocathode. The results of initial optimizations of the beam dynamics with a focus on extracting and preserving ultra-low emittance will be presented.

## DESIGN OF THE XFEL-O RF PHOTOINJECTOR

Our design follows the original proposal of VHF cw rf gun [2], and employs a 325-MHz normal conducting rf (NCRF) gun [3] as shown in Figure 1. A low-frequency NCRF gun can use long bunches near cathodes similar to that of DC guns to reduce transverse space-charge forces. Unlike a superconducting rf (SCRF) gun, an NCRF gun can use solenoids focusing adjacent to the cavity for emittance compensation. The Kilpatrick's empirical breakdown limit  $E_K$  [MV/m] at rf frequency  $f_{rf}$  [MHz] is given by  $f_{rf} = 1.64E_K^2 e^{-8.5/E_K}$ , which yields  $E_K \simeq 18\text{MV/m}$  at 325 MHz. Present-day rf technology can often reach over  $1.5 E_K$  before breakdown. Thus we used a 25-MV/m cathode field for this study, and the beam energy at gun cavity exit is  $\sim 890$  keV.

The semi-conductive alkali telluride  $\text{Cs}_2\text{Te}$  shows high quantum efficiency, high robustness, and long lifetime and therefore has been chosen for many other photoinjectors. A cesium-telluride-based photoemitter is also a reasonable choice for our design, because rf field induced heat load in a 325-MHz rf cavity makes it very difficult to keep the vacuum level as low as required by a GaAs cathode from which the thermal energy of emitted electrons is much lower. According to the measurements at the Photo Injector Test Facility at the DESY location in Zeuthen [4], a 0.8-eV thermal energy has been used as an initial condition for our simulation. The thermal emittance of the photocathode is  $\epsilon_{n,rms} = \sigma \sqrt{2E_{th}/3m_0c^2}$  [5], where  $\sigma$  is the rms laser spot size,  $E_{th}$  is the effective thermal energy of the pho-

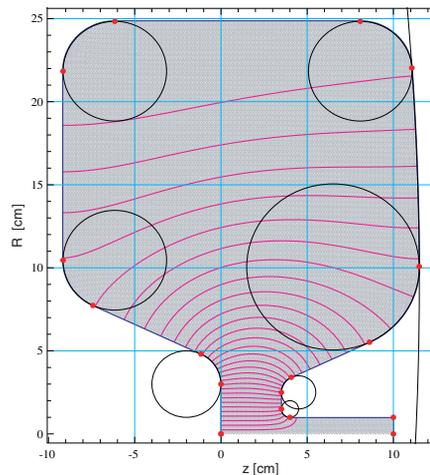


Figure 1: Geometry and field pattern of a 325-MHz gun cavity, adopted from an LBNL design by courtesy of J. Staple. The meshed area is the cross section of the cavity interior, outlined by lines and arcs joined at the red dots. The purple lines are the field pattern generated with LANL Superfish software. The cathode is located at the origin.

tocathode, and  $m_0c^2$  is the rest mass of the electron. The thermal emittance adds in quadrature to the other emittance contributions, thus it sets the lower limit for the transverse emittance of injectors. A “beer can” laser pulse with 10% rise/fall time has been assumed in this design to avoid complex laser shaping. In order to achieve  $\sim 0.1 \mu\text{m}$  final emittance, the diameter of laser spot on the cathode surface must be smaller than 0.4 mm. A long laser pulse duration at the order of tens of picoseconds is another prerequisite, otherwise the space-charge emittance growth becomes significant.

Low-frequency rf guns are expected to be similar to DC guns in terms of beam dynamic. In our benchmark study over various rf photoinjector layout, the “standard” features of both the Jefferson Lab and Cornell concepts, composed of a photocathode gun coupled with an rf buncher and TESLA-type 9-cell rf cavities operating at 1.3 GHz, show excellent performance in the ultra-low-emittance regime. A schematic of the injector is shown in Figure 2. We begin with the 325-MHz cw NCRF gun (1). The single-cell NCRF buncher cavity (3) based on designs from Cornell University [6] operates at 1.3 GHz with a maximum accelerating voltage of 200 kV. To be conservative we limited the accelerating gradient for the 1.3-GHz accelerating rf cavities (5,6) below 15 MV/m. The first solenoid (2) immediately following the gun cavity is responsible for transverse space-charge emittance compensation. The second

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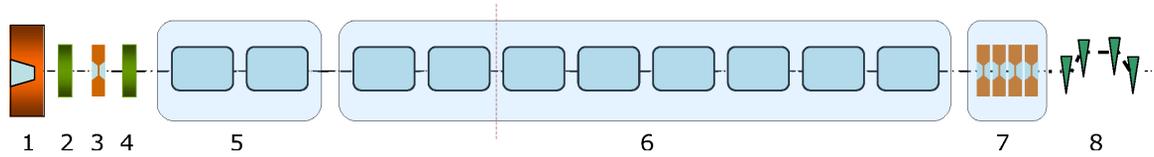


Figure 2: Schematic injector layout. 1) 325-MHz rf gun; 2) focusing solenoid; 3) 1.3-GHz buncher cavity; 4) focusing solenoid; 5) SCRF bi-cavity module containing two 1.3-GHz TESLA-type cavities; 6) Cryomodule containing eight 1.3-GHz TESLA-type cavities; 7) 3.9-GHz cryomodule containing four TTF 3.9-GHz SCRF cavities; 8) Symmetric chicane bunch compressor.

solenoid (4) located after the buncher matches the beam optics to the booster and also compensates emittance growth from space charge. The design of the solenoid is taken from [7].

In cooperation with the buncher cavity, a ballistic bunching section (5) reduces the rms length of electron bunches generated by laser pulses with duration between 40 and 80 ps to  $\sim 5$  ps before they enter a magnetic bunch compression section. The ballistic bunching section consists of two TESLA-type 1.3-GHz rf cavities encapsulated in a bi-cavity cryomodule.

The magnetic bunch compression section finally reduces the rms bunch length to  $\sim 1$  ps. This section consists of a set of 3.9-GHz SCRF cavities (7) and a symmetric 4-dipole chicane (8). Bunch compression is achieved by introducing an energy-time correlation using the rf cavities and by the bending section with energy-dependent path length.

## SIMULATION/OPTIMIZATION RESULTS

The beam transport from the gun cavity down to the end of the booster was simulated using ASTRA [8] while the entire magnetic compression process where the beam energy is larger than 80 MeV was modeled in eLégant [9]. Since eLégant does not include space-charge effects, the chicane was remodeled in IMPACT-T [10] with the same

parameters as in the eLégant simulation. IMPACT-T was adopted because it is able to model a wide range of beamline elements and calculate fully 3-dimensional space charge. The crosscheck shows very good agreement on the emittance evolution in the bending plane as well as final beam parameters. The space charge calculation results in an emittance growth of less than 1.5%.

The large number of variables and the complexity of the physics in the injector makes analytical optimization impossible. Hence, we used the multi-objective optimization technique that was used successfully for other injector projects [11]. The exact values of the magnitude and phases of the rf fields, as well as the initial spot size and pulse length of the laser that creates the electron beam at the photocathodes, are determined by the optimization process.

Two typical cases mainly distinguished by the laser pulse duration, which in turn determines the strength of ballistic bunching and the parameters for the magnetic compression, have been studied.

### 40-ps Laser Pulse Duration

Due to a relatively short initial bunch, the strength of ballistic bunching is weak. The evolution of bunch length is depicted in Figure 3(b). The total acceleration voltage

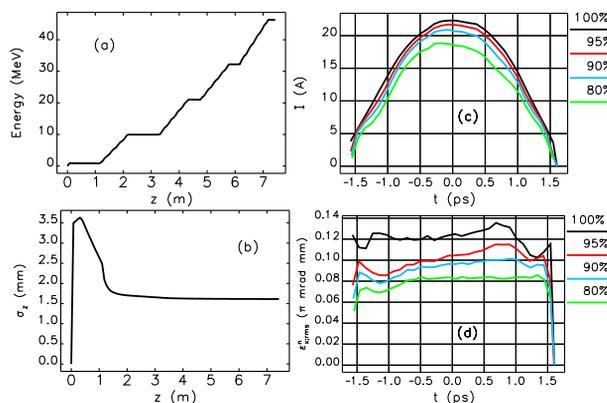


Figure 3: Simulation results for 40-ps laser duration.

Left column: beam energy (a) and bunch length (b) evolution from the cathode down to the dashed line in Figure 2. Right column: slice current (c) and slice emittance (d) profile of simulated bunch at the end of the injector.

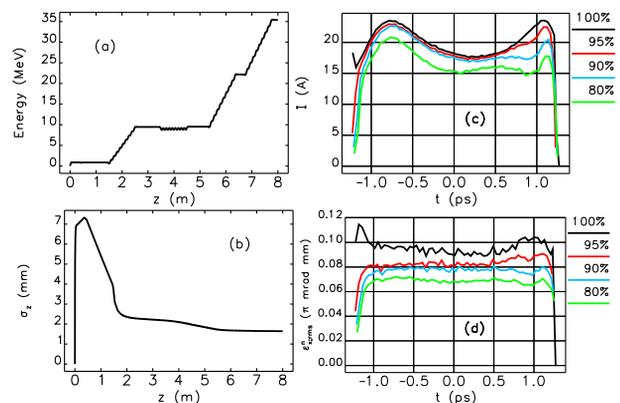


Figure 4: Simulation results for 80-ps laser duration.

Left column: beam energy (a) and bunch length (b) evolution from the cathode down to the dashed line in Figure 2. Right column: slice current (c) and slice emittance (d) profile of simulated bunch at the end of the injector.

Table 1: Performance of Injector Using a Laser Pulse with 40-ps Duration and Requirements

|   | Design    | Required   |
|---|-----------|------------|
| Normalized $\varepsilon_{x,90}/\varepsilon_{y,90}(\mu m)$ | 0.10/0.10 | $\leq 0.1$ |
| Bunch charge Q (pC)                                       | 50        | 40         |
| rms bunch length (ps)                                     | 0.75      | $\sim 1$   |
| Energy spread (MeV)                                       | 0.0011    | $\leq 1.4$ |

for the 3.9-GHz cavities as well as the time-of-flight parameter R56 for the chicane compressor were estimated by following the methods described in [12]. The nonlinear energy-time correlations induced in the booster as well as that of the chicane is compensated by 18.8-MV voltage, which corresponds to an accelerating gradient of 13.6 MV/m if the number of the 3.9-GHz cavities is 4.

At the end of the injector, a cosine-like longitudinal charge distribution is obtained while the core emittance for 90% particles is 0.1  $\mu m$ . See plot (c) and (d) in Figure 3. The beam parameters are listed in the “Design” column of Table 1, along with the requirements for comparison. All key parameters are tabulated in Table 2.

### 80-ps Laser Pulse Duration

A laser pulse with 80-ps duration allows smaller laser spot size on the cathode, smaller thermal emittance, and weaker space-charge effects than in the 40-ps case. In order to compress the bunch length to 5 ps when the accelerating voltage for the buncher cavity is limited to 200 kV, the phase for the second 1.3-GHz SCRF cavity is set to -90 degrees from the crest to perform a strong ballistic bunching where the reduction of bunch length, as shown in Figure 4, mainly occurs in the drift downstream the cavity. Compared with the 40-ps case, the rms bunch length reduction from 2.5 mm to 1.5 mm occurs at 10-MeV beam energy rather than 1 MeV, thus the space-charge emittance growth is minimized. In this process, the first half of the bunch gets a stronger compression than the second half. In the 3.9-GHz cavities of the magnetic compression section, a stronger energy chirp is generated at the second half than the first half to balance the total compression over the

Table 2: Key Parameters Leading to Beam Parameters Shown in Tables 1 and 3

| Laser pulse duration (ps)                     | 40    | 80    |
|---|-------|-------|
| Laser spot size in diameter (mm)              | 0.34  | 0.28  |
| Thermal emittance ( $\mu m$ )                 | 0.087 | 0.071 |
| 1 <sup>st</sup> 1.3 GHz cavity phase (degree) | -30   | -30   |
| 2 <sup>nd</sup> 1.3 GHz cavity phase (degree) | -8    | -90   |
| 3.9 GHz cavity voltage (MV)                   | 18.8  | 36.4  |
| Chicane bending angle (degree)                | 20    | 8     |
| Chicane R56 (mm)                              | -172  | -92   |
| Final beam energy (MeV)                       | 117.2 | 82.3  |

Table 3: Performance of Injector Using a Laser Pulse with 80-ps Duration and Requirements

|   | Design    | Required   |
|---|-----------|------------|
| Normalized $\varepsilon_{x,90}/\varepsilon_{y,90}(\mu m)$ | 0.09/0.09 | $\leq 0.1$ |
| Bunch charge Q (pC)                                       | 50        | 40         |
| rms bunch length (ps)                                     | 0.73      | $\sim 1$   |
| Energy spread (MeV)                                       | 0.0018    | $\leq 1.4$ |

entire bunch. The slice current and normalized emittance profiles are depicted in the right column of Figure 4. The flattop longitudinal charge distribution is more desirable to the lasing process, and the core emittances for 90% of the particles in every slice are below 0.08  $\mu m$ . However, the number of 3.9-GHz cavities has to be double than in the 40-ps case to deliver 36.4-MV voltage.

The injector key parameters as well as beam parameters can be found in Table 2 and Table 3, respectively.

## CONCLUSION

Preliminary design of the ultra-low-emittance photoinjector equipped with a 325-MHz NCRF gun and Cs<sub>2</sub>Te photocathode has been developed with the aid of a genetic optimization code. A long laser pulse with small spot size has become the prerequisite for obtaining ultra-low-emittance beam from a Cs<sub>2</sub>Te photocathode whose thermal energy is fairly high. Therefore the proper bunch compression without evident emittance growth plays an important role in this design. In a machine configuration optimized for a relatively short (40-ps) laser pulse, the requirements of XFEL-O are met. An optimal configuration based on a longer (80-ps) laser pulse can deliver even better performance; however further study is necessary to justify the higher cost of the fabrication and operation.

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