DESIGN AND OPTIMIZATION OF AN S-BAND PHOTOINJECTOR

Jang-Hui Han, Diamond Light Source, Oxfordshire, United Kingdom

Abstract

Several X-ray Free Electron Laser (XFEL) projects are under construction or are being proposed over the world. For successful XFEL operations photoinjectors with low transverse emittance are one of the key elements. For the European XFEL and LCLS projects, photoinjectors have been developed to reach their requirements, typically with a normalised emittance of 1 mm mrad for a 1 nC beam. Here, we make a further optimization of an S-band photoinjector to achieve 0.4 mm mrad for a 1 nC bunch in a structure that should permit high repetition rates operation. Optimizations for alternative operation conditions with a 0.2 nC bunch charge for lower emittance and a 10 pC charge for ultrashort pulse (< 100 fs) generation are also shown.

INTRODUCTION

Two kinds of photocathode RF guns are successfully used as injectors for VUV or X-ray FELs. LCLS [1] uses a gun improved from the BNL/SLAC/UCLA guns which operate with a 2.856 GHz resonant frequency. The FLASH gun [2] operates at 1.3 GHz. Both gun cavities are composed of a first half cell and a second full cell. In the LCLS gun, RF power is coupled to the cavity through the side of the second cell and the focusing solenoid is located downstream of the cavity. In the FLASH gun, RF power is coupled coaxially through the exit of the second cell and the solenoid surrounds the cavity. In general, S-band guns provide a shorter pulse length and lower transverse emittance beam thanks to the higher accelerating field compared to L-band guns. Typically, the maximum field is 40 to 60 MV/m in L-band guns but 120 MV/m or higher in S-band guns. With a coaxial RF coupler, the RF field in the cavity is axisymmetric and the focusing solenoid can be located close to the cathode. In addition, the coaxial coupler allows more cooling-water channels around the cavity symmetrically. Here, we show a new design of an S-band photocathode RF gun with a coaxial coupler.

GUN DESIGN AND OPTIMIZATION

In an RF gun cavity, an electron beam is generated by a drive laser pulse illuminated at a photocathode located on the back plane of the first cell. When the photon energy of the laser pulse excites electrons in the cathode so to overcome the potential barrier, the electrons are emitted into the vacuum. Depending on the direction of the RF field the electrons can be accelerated downstream. When the accelerated beam reaches the second cell the direction of the RF field is reversed and therefore the beam can be further accelerated. Since the beam starts at the first cell with almost zero velocity, there exists a large phase slippage. In order for the beam to get accelerated in sequence the beam must start earlier than maximum acceleration phase (90°) at the first cell depending on the first cell length and the accelerating field strength. For example, for a lower field strength or for a longer first cell length, the flight time in the first cell is longer, the phase slippage is higher, and the phase of beam emission for an optimum acceleration is shifted towards 0°. The beam dynamics (emittance and bunch length) of the beam strongly depends on the emission phase.

A new S-band gun was designed adopting the advanced features of the DESY gun [3], like the coaxial RF coupler and the cooling-water channels over the entire cavity surface. The resonant frequency was chosen as 2.998 GHz. Compared to the Eindhoven gun [4], which is another S-band gun with a coaxial coupler, the first cell length has been optimized for smaller emittance and the possibility of further cooling channel installation has been considered here. A focusing solenoid is located around the gun cavity (see Fig. 1). Another solenoid upstream of the gun compensates the magnetic field at the cathode. Even if the resonant frequency of the cavity is fixed as 2.998 GHz, the lengths of the first and second cells are slightly variable while keeping the cavity in resonance. The radii of the cells should be adjusted when the cell lengths are changed. The length of the first cell dramatically influences the beam dynamics while the length of the second cell does not visibly affect the beam dynamics. A shorter first cell length allows a higher acceleration field during beam emission at the cathode and a shorter electron flight time between the cathode and the second cell. A higher acceleration field minimize the beam quality degradation caused by the space charge force. The first cell length was set to 0.54 times a half of the RF wavelength and the second cell set to 0.98 times a half wavelength. The RF field in the cavity were calculated by SUPERFISH [5] (Fig. 2). After scaling down from the DESY L-band gun to the S-band, the iris thickness was changed thicker for allowing cooling channels inside the iris and the diameter of the coupler antenna was enlarged for a weaker interaction with electron beams. The π-mode of the RF is utilized for the beam acceleration. Even if the 0-mode is separated from the π-mode, the tail of the 0-mode peak is still activated at the resonant frequency of the π-mode, 2.998 GHz. When the 0-mode is activated, the electron beam is affected by the unwanted 0-mode field in a wrong phase. If the 0-mode is separated far from the π-mode, the unwanted effect is reduced. In this design, the mode separation is 18.25 MHz, which is larger than those of the other S-band guns [1, 4].

With this gun, the beam dynamics was calculated with ASTRA [6]. Parameters for optimization were the laser beam size and pulse length, the RF gun phase, and the solenoid field distribution and strength and the location.

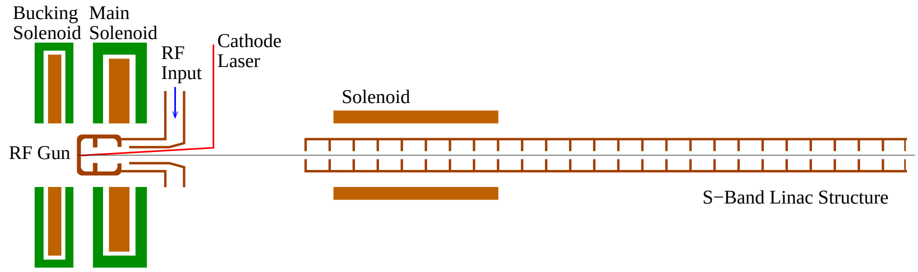

Figure 1: Injector layout. The injector consists of a gun and six 3.1 m long linacs. 1 m long solenoids are installed around first three linacs.

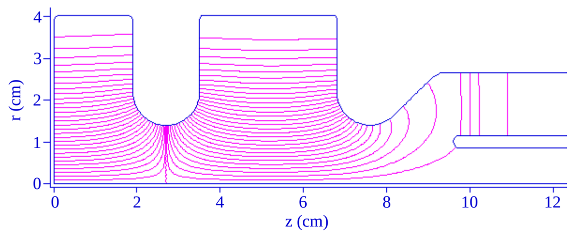

Figure 2: Gun cavity geometry and SUPERFISH calculation of the RF field.

The solenoid field was calculated with POISSON [5]. The center of the main solenoid was set to 9.5 cm from the cathode. The maximum field strength at the cathode was fixed as 120 MV/m which corresponds to an RF peak power of 7.5 MW in the cavity operating at 50 °C. In the case of 120 MV/m, a beam has a highest energy after the gun when the beam starts at a 50° RF phase at the cathode. The field strength at the emission phase is about 90 MV/m (120 MV/m $\times$ sin 50°). When a beam is emitted at the cathode, the beam is highly space-charge dominated and each slice of the beam experiences a different strength of the space charge force, which results in a misalignment of the beam slices in the phase space. With a solenoid field we are able to re-align the slices on a line in the phase space so that the projected emittance becomes small [7]. With the gun cavity only this alignment process takes place in the space-charge dominated region because the beam energy is not high enough. Therefore, the projected emittance blows up after a minimum (see Fig. 3).

A 1 nC beam with a 0.6 mm radius and a 10 ps fwhm length was numerically generated and tracked. The transverse and longitudinal electron distributions were assumed to be uniform. The rise/fall time of the pulse was 0.7 ps, which may be achievable with a Ti:Sapphire laser. The beam was emitted at 48° RF phase which is $-2°$ from the phase for the highest energy. The minimum emittance value is 0.51 mm mrad at z = 0.8 m. The minimum beam size is 0.094 mm at z = 0.73 m (Fig. 3). A 0.2 nC beam with a 0.28 mm radius and a 6 ps fwhm length was simulated also. The minimum emittance is 0.21 mm mrad at z = 0.96 m. The emission phase was 47°. For this emittance simulation, the thermal emittance depending on the cathode material was included. Assuming a Cu cathode, the kinetic energy of emitted electron was set to 0.5 eV, which corresponds to 0.4 mm mrad per 1 mm beam radius. This thermal emittance estimation is about 30% higher than the theoretical value calculated in Ref. [8] for a bare Cu at a room temperature condition and a 90 MV/m field. A thermal emittance of 0.24 mm mrad was used for the 1 nC case and 0.11 mm mrad for 0.2 nC.

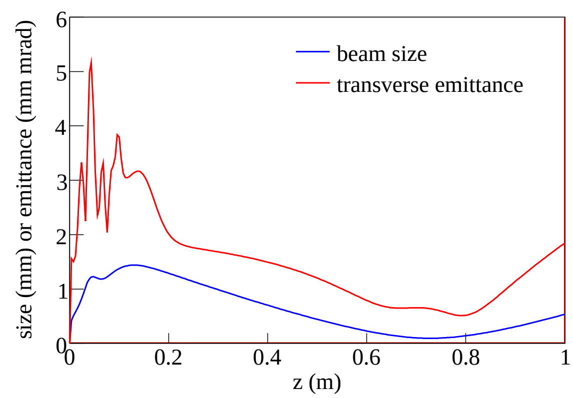

Figure 3: Beam size and transverse projected emittance evolution over the beam propagation for 1 nC beam.

INJECTOR OPTIMIZATION

This photoinjector consists of a gun, gun solenoids, six 3.1 m long S-band RF linacs with a $2\pi/3$ mode travelling wave structure, and three 1 m long focusing solenoids for the first three linacs (Fig. 1). The first linac starts at z = 1.02 m and has a gradient of 12.44 MV/m. The other five linacs have a gradient of 18.3 MV/m. The six linac structures accelerate a beam up to 320 MeV. For the 1 nC case, a driving laser pulse with a 0.76 mm radius and a 10 ps fwhm length (0.7 ps rise/fall time) was used to generate a beam at the cathode. The beam starts at a 48° RF phase. For the 0.2 nC case, a driving laser pulse with 0.4 mm radius and 6 ps fwhm length was used. The emission phase was 47°. The field strength of the solenoids and the accelerating field of the linacs were optimized for a lowest transverse emittance after the sixth linac. Due to the further acceleration by the linacs, the emittance does not blow up (Fig. 4). The simulated beam parameters are summarized in Table 1. The slice emittance of the simulated beam is shown in Fig. 5 for both bunch charge cases. The slice and core emittances are shown in Table 1.

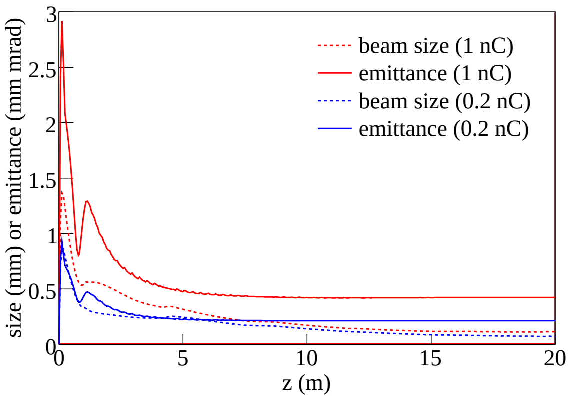

Figure 4: Beam size and transverse projected emittance including the linacs. ASTRA simulations for the 1 nC and 0.2 nC beam cases are shown.

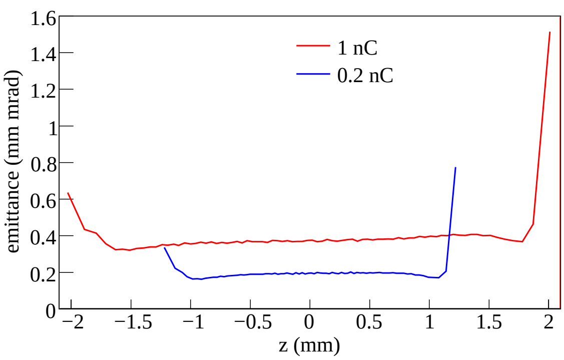

Figure 5: Slice emittances at the end of the injector.

SUB-PS BEAM GENERATION

For the NLS project [9], a relativistic electron beam source synchronized with the FEL laser is of interest. Such beams should be ultrashort (<100 fs) and in a MeV range. This requirement may be satisfied by installing one more RF gun in the user hall. If a beam generated at the main injector driving the FEL is transported to the experiment station downstream of the undulator, the beam spreads due to the space charge force. When the drive laser of this gun is synchronised with the laser system for the FEL seeding, the generated beams by this gun can be synchronised with the FEL photons. According to a simulation, this gun is able to generate a bunch with an 90 fs rms length for a 10 pC and 5 MeV beam when a drive laser pulse has a 100 fs rms length and a 2 mm radius. A target for experiment should be at 0.6 m downstream of the cathode. At the target, the rms beam size is 1 mm and the energy spread is 7 keV.

Table 1: Initial parameters and simulated beam parameters. The average slice emittances of the central 95% are shown.

bunch charge	**1 nC**	**0.2 nC**
initial parameters		
laser radius	0.76 mm	0.40 mm
laser fwhm length	10 ps	6 ps
thermal emittance	0.30 mm mrad	0.16 mm mrad
beam parameters at the end of the injector		
projected emittance	0.42 mm mrad	0.21 mm mrad
peak current	90 A	30 A
core emittances in 95/90/80%	0.33/0.28/0.21	0.17/0.14/0.11
95% slice emittance	0.37	0.19

GUN CAVITY COOLING

For the temperature control of the cavity, cooling-water channels are distributed over the cavity surface (see Fig. 6). The channel distribution is similar as that of the DESY L-band guns. The new DESY gun is designed for an average power of 100 kW and tested up to 50 kW [10]. A simple scaling as $(1/f)^2$ estimates that 9.4 kW may be possible at 2.998 GHz which should allow operation up to 400 Hz at a 120 MV/m field and a 3 μs pulse length. Even if the gun is operated with a low repetition rate, e.g. 100 Hz, the high capacity of cooling has advantages so that it enables a fast recovery of RF operations after any kind of interlocks and a fast change of operation modes.

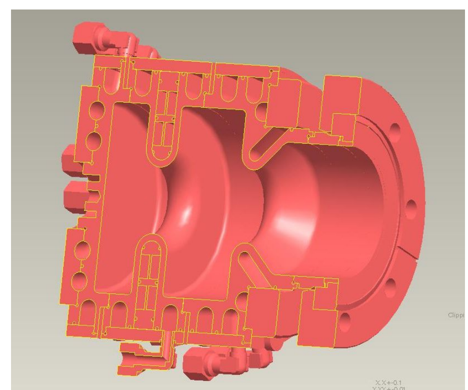

Figure 6: Designed gun cavity (drawing by L. Zaja).

REFERENCES

[1] R. Akre et al., Phys. Rev. ST Accel. Beams **11**, 030703 (2008).

[2] S. Schreiber, Proceedings of FEL 2005, p. 545.

[3] B. Dwersteg et al., Nucl. Instr. and meth. A **393**, 93 (1997).

[4] B. van der Geer et al., Proceedings of FLS 2006.

[5] J. H. Billen and L. M. Young, Poisson Superfish, LA-UR-96-1834.

[6] K. Föttmann, `http://www.desy.de/~mpyflo`.

[7] B. E. Carlsten, Nucl. Instr. and Meth. A **285**, 313 (1989).

[8] K. L. Jensen et al., J. Appl. Phys. **102**, 074902 (2007).

[9] `http://www.newlightsource.org`.

[10] S. Rimjaem et al., Proceedings of EPAC 2008, p. 244.