GENERATION OF ULTRAFAST, HIGH-BRIGHTNESS ELECTRON BEAMS*

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Abstract

The production and preservation of ultrafast, high-brightness electron beams is a major R&D challenge for free electron laser (FEL) and ultrafast electron diffraction (UED) because transverse and longitudinal space charge forces drive emittance dilution and bunch lengthening in such beams. Several approaches, such as velocity bunching and magnetic compression, have been considered to solve this problem but each has drawbacks. We present a concept that uses radial bunch compression in an X-band photocathode radio frequency electron gun. By compensating for the path length differential with a curved cathode in an extremely high acceleration gradient cavity, we have demonstrated numerically the possibility of achieving more than an order of magnitude increase in beam brightness over existing electron guns. The initial thermo-structural analysis and mechanical conceptual design of this electron source are presented.

INTRODUCTION

Ultrafast high-brightness electron beams are desired as injectors for many accelerator-driven facilities such as light sources, including free-electron lasers (FEL), and medical applications. Brightness is the holy grail of most light sources and brighter, short-pulse electron injectors are to be prized where there are no downstream transport consequences of the short bunches such as microbunching instabilities that can result from transport interactions with the energy modulations induced by the longitudinal space charge (LSC) forces in the bunches. Beam brightness is also of value in medical applications including monochromatic X-ray sources utilizing Compton back-scattering that can result in reduced dose with higher resolution images, and also tomographic imaging systems. Additionally, these sources find direct application in advanced accelerators like the plasma wake-field accelerator (PWFA) and ultrafast electron diffraction (UED) [1]. Plasma accelerators promise orders-of magnitude increases in accelerating gradient to greater than 100 GeV/m and could lead to very compact and economical systems for those many accelerator applications that require high particle energies. Ultrafast diffraction techniques, which provide information about atomic-scale molecular structure, are critical to chemists and material scientist in their research and development activities.

In the generation of ultrafast, high-brightness electron beams, space-charge forces play a fundamental role in emittance dilution and bunch lengthening within the gun and subsequent emittance compensation drift. In order to generate and preserve the beam brightness, transverse and longitudinal space charge effects have to be precisely managed. Several different approaches have been reported and are being actively pursued within the worldwide accelerator community. These include various velocity bunching and magnetic compression techniques. However, each option suffers drawbacks that must be overcome in order to deliver a compact and economic ultrafast, high-brightness source.

In recent years, due to a better understanding and improved control of the propagation dynamics in the non-relativistic electron guns used to date for high-brightness electron source, sub-picosecond level temporal structures have been achieved. In order to develop an improved ultrafast high-brightness electron source, we have proposed a scheme that compensates for path length differences by using a curved cathode [2] to introduce radial compression that compensates for geometric bunch lengthening effects when coupled with extremely high acceleration gradient that minimizes the impact of space-charge forces. AES patented cathode rear feeding coaxial coupling also eliminates contributions to transverse emittance from non-axisymmetric modes [3]. We show that combining these two effects is feasible and does indeed deliver a more compact, economic, ultrafast high-brightness electron beam for various applications such as FEL and advanced accelerator injector and UED.

CAVITY DESIGN

For a high-aspect-ratio (short bunch length) electron bunch, the asymptotic bunch length due to the space charge forces of a uniformly accelerated bunch, ignoring the drive laser duration and assuming prompt response from a copper cathode where the laser spot radius (R) is kept constant, is expressed by:

$$\Delta t_{sc}(\infty) = \frac{mc^2}{e}\frac{Q}{\pi R^2 \varepsilon_0 c E^2}. \quad (1)$$

Here, bunch lengthening due to space charge is inversely proportion to the square of the bunch radius (R) and the square of the accelerating field (E). Bunch length stretches due to the longer path lengths of the outer particles compared to electrons emitted closer to the axis. Bunch lengthening due to geometrical effects is proportional to the square of the beam radius.

Use of a coaxial waveguide feeding the front of the gun cavity has the drawback that radial space for electron beam emission and drive laser insertion is relatively small from the previous cavity design [4]. We have completed

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the RF analysis for a coaxial RF feed from the rear of the gun. Standard codes like SUPERFISH and SLAC developed S3P code [5] has been used to complete the RF design that has been handed of to the beam dynamics analysis. The RF design also has visited with the design of Ref. [3]. It focuses on the geometry of the coaxial coupler and iris between the cells in order to maximize shunt impedance, thereby minimizing losses for a given cathode voltage. The coaxial coupler and the iris also require adjustment to distribute thermal stress appropriately or to provide for routing of cooling channels. The RF design in the cathode area also affects the beam dynamics design. To allow flexibility in cathode materials, the cathode has been designed as a detachable and adjustable structure. A completely axisymmetric gun delivers improved emittance and permits optimal placement of the emittance compensating solenoid. We explore applying the same RF design concept as our patented axisymmetric coupling gun in this new X-band concept [3-4].

The physics design of an X-band RF gun cavity with a curved cathode and a coaxial RF coupling scheme, embedded in an emittance compensating magnetic field has been optimized. Various curved and flat cathode geometric models have been visited using SUPERFISH code. We varied the radius of curvature to optimize the beam dynamics output. The resultant SUPERFISH output field files were translated into input files for the TStep beam dynamics code. Figure 1 shows a cavity cross-section with field lines from SUPERFISH. Radius of coaxial coupler has been chosen to prevent the transmission of the lowest high-order TE01 mode through the coaxial waveguide.

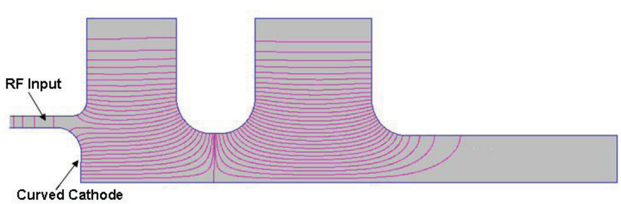
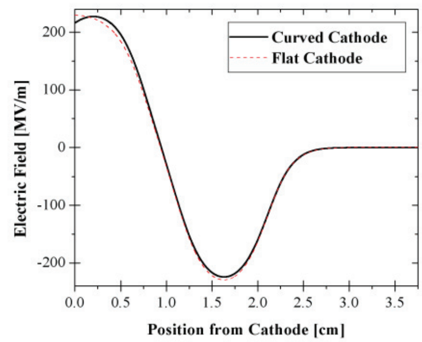
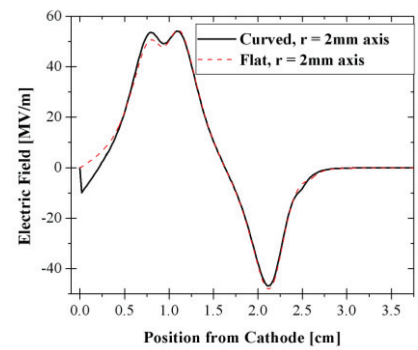


Figure 1: SUPERFISH model of the 1.6 cell, X-band, π-mode, RF gun cavity with backward coaxial coupling (not to scale).

The longitudinal electric field profiles on axis for flat and curved cathodes that illustrate the differences in the near cathode region are shown in Figure 2(a). The difference derives from the field modification caused by the curvature. Off-axis, the cathode region has radial focusing, as shown in Figure 2(b), and this focusing can deliver a smaller radial output beam at the gun output than can be achieved with a flat cathode. In a cavity with a flat cathode, the beam is initially affected by a defocusing force in the first half cell before the beam is respectively focused and defocused at the entry and exit of the second cell around the 1 and 2 cm points from the cathode.



(a)



(b)

Figure 2: (a) Logitudinal electric field profile on axis, (b) radial electric field profile at r = 2 mm. The curved cathode (black lines) field peaks slightly ahead of the surface and the electron bunch is initiated in a radial focusing region. Red dots are the flat cathode.

BEAM DYNAMICS CACULATION

The beam dynamics analysis addressed several aspects of the gun design. Firstly, we anticipated that the higher accelerating field in the X-band cavity would reduce the longitudinal and transverse emittance growth produced by space charge forces, thereby contributing to the satisfaction of our goal of an ultrafast high-brightness electron bunch. Secondly, by utilizing a curved cathode, we expected that the focusing field near the cathode surface would lead to improved integrated transverse beam focusing and improved beam brightness. Finally, we believed that the curved cathode would compensate for the bunch lengthening induced by path length variation across the cathode due to the combined effect of the focusing elements and the RF in the cavity.

Various simulations were performed using TStep [6], an evolved version of PARMELA, to investigate the effect of the bunch charge on the bunch length and beam brightness. Figure 3 shows an evolution of the bunch length, beam size and emittance along the beam. The result of the beam profile is similar result as the previous design [4].

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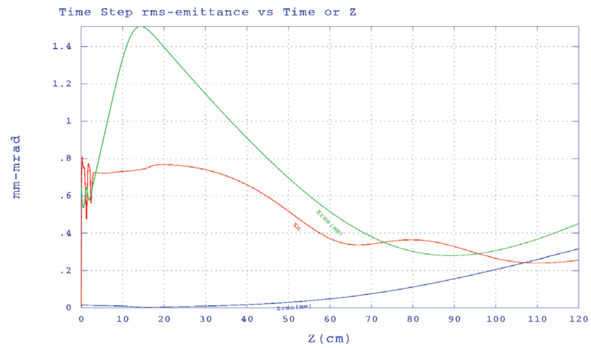
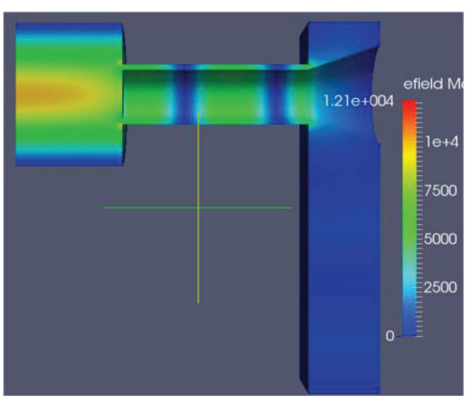


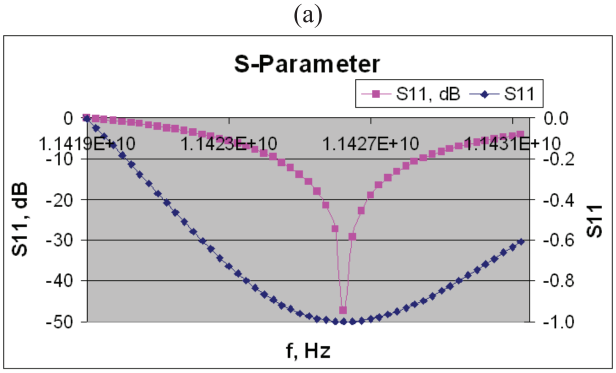
Figure 3: SUPERFISH model of the 1.6 cell, X-band, π-mode, RF gun cavity with backward coaxial coupling (not to scale).

RF COUPLING DESIGN

Waveguide to coaxial cavity coupling structure has been designed using by SLAC developed S3P code [5]. Figure 4 (a) shows that WR-90 rectangular waveguide to coaxial waveguide coupling with a resonant cavity that resonant through the coupling. The coaxial waveguide and the cavity are resonant as TEM mode and TM mode, respectively. Figure 4 (b) shows normalized S-parameter as a transmission/reflection coefficient for the coupling structure. The cavity resonant frequency is 11.426GHz with a trial cavity.



(a)



(b)

Figure 4: (a) Coupling structure from rectangular waveguide to coaxial waveguide and (b) normalized S11 parameter of the coupling structure.

THERMAL DESIGN

Within the SUPERFISH code the fields were normalized to an electric field of 1 MV/m. The gun is planned to be run with a maximum electric field of 250 MV/m in the cavity. The wall losses scale from 467 watts to 4.23 MW requiring that the real RF power is pulsed. Figure 5 shows the magnetic field on the RF surfaces. The planned RF pulse duration is 200 nsec and the repetition rate is 200 Hz resulting in a duty factor of 4.0e-5. This low duty factor enables the simplified cooling scheme developed for this design.

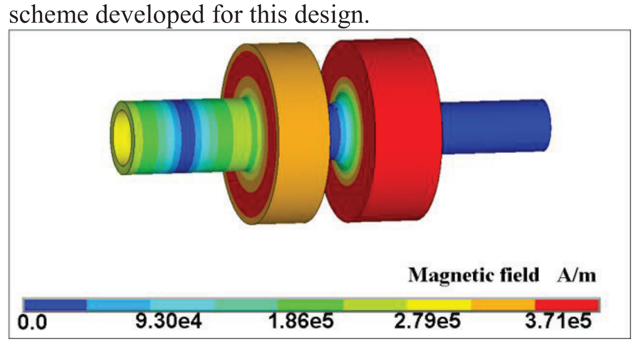


Figure 5: Magnetic Field values during an RF pulse.

The magnetic fields in the waveguide and coaxial space were determined from the geometry and the power through of 4.23 MW. These magnetic fields and those shown in Figure 5 along with wall resistance were used to determine the local power loss on the walls. This power loss is modified to reflect the temperature dependent resistance of the walls. An iterative solution is used to update the wall resistance from the calculated temperature. Figure 6 shows the resistive wall power densities after multiplication by the RF duty factor.

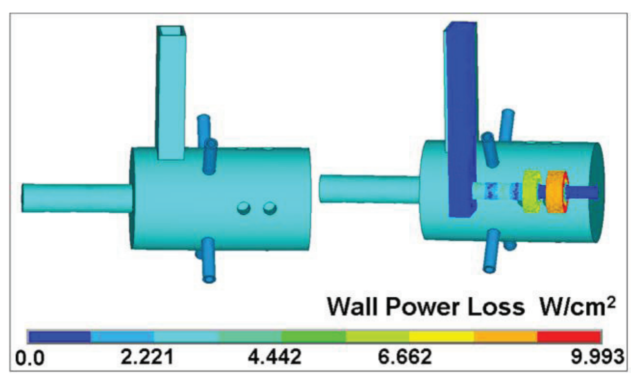


Figure 6: Average power loss on walls with a duty factor of 4.0e-5.

A cooling water flow rate of 2.3 gpm through the eight cooling channels used to keep the temperatures acceptable. Figure 7 shows the temperature distribution within the gun and on the cooling channel surfaces. The iris between the two cells is not cooled directly but is cooled with thermal conduction through the copper walls. The temperature rise between the inlet cooling water and the maximum copper surface temperature is only 6.3ºC.

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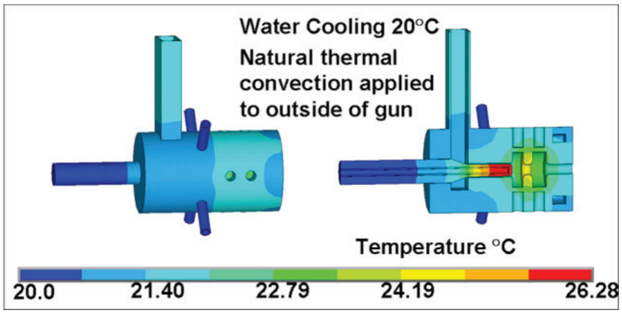

Figure 7: Temperature Distribution in Gun Body. Water cooling temperature of 20 ºC is supplied. Natural thermal convection is applied outside of the gun.

The displacements from the temperature variation were then applied to the RF model and the RF model was run again to determine a frequency comparison with the original geometry. The results are shown in figure 8, a shift of -644. kHz. This can be compensated for by developing the geometry to be at the design frequency at an elevated design temperature. The inlet cooling temperature would then need to be about 3.4 ºC below this design temperature to run at the design frequency.

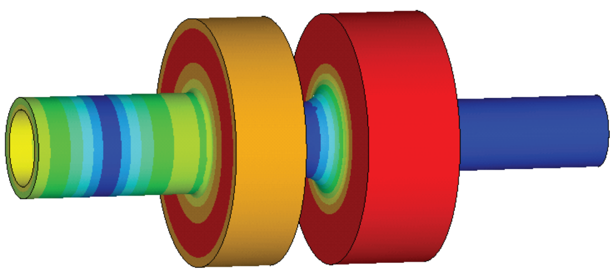

Figure 8: Frequency shift primarily from temperature distribution.

The waveguide and vacuum barrel were cooled by natural convection and conduction to the gun body. The rectangular waveguide was made of copper and the vacuum barrel and flanges were modelled as stainless steel. The ambient temperature was assumed to be 20ºC and the resulting temperature rising was only 1.2ºC. Thermal conduction in the waveguide was high enough and the field penetration of the perforations small enough that the temperature rising was not significant. Thermal-Structural and RF frequency shift analysis shows that the design of this electron gun running at 4.0e-5 duty factor is robust. The temperature rise of the gun body is small, less than 5ºC, the displacements are small, less than 0.8e-4 inches, the stresses are low, less than 1100 psi Von Mises stress and the frequency shift is manageable. The design and thermal management of this gun provide adequate head room.

SUMMARY

AES is newly developing an ultrafast, high-brightness, electron source for FEL and advanced accelerator injector and UED experiments. The feasibility of such an X-band, ultrafast, RF gun with a curved copper cathode has been demonstrated numerically in beam dynamics and thermal analysis. Simulations show a better brightness performance than S-band photocathode gun's performance. Thermo-structural and mechanical analysis shows that the gun design is robust for operation at a duty factor of 4.0 x 10^{-5}.

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REFERENCES

[1] X. J. Wang, D. Xiang, T. K. Kim and H. Ihee, J. Korean Phys. Soc. **48,** 390 (2006).
[2] M. J. de Loos et al., Phys. Rev. ST Accel. Beams **9**, 084201 (2006).
[3] H. Bluem et al., http://accelconf.web.cern.ch/accelconf/p07/PAPERS/THPMS070.pdf
[4] J. Park et. al., http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/tuppd080.pdf
[5] C.-K. Ng, et al., "State of the Art in EM Field Computation," Proc. EPAC06, Edinburg, Scotland.
[6] http://tstep.lmytechnology.com/

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