HIGH-CHARGE FEMTOSECOND ELECTRON GENERATIONS FOR ULTRAFAST, HIGH-BRIGHTNESS ELECTRON BEAM APPLICATIONS*

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Abstract

Generation and preservation of ultrafast, high-brightness electron beams is one of the major challenges in accelerator research and development (R&D) for beam applications such as free electron lasers (FEL) and ultrafast electron diffraction (UED). Transverse and longitudinal space charge forces play a key role in emittance dilution and bunch lengthening respectively, for all high-brightness beams. We present a newly-designed, X-band, photocathode, radio frequency (RF), electron gun that utilizes radial bunch compression to deliver a compact ultrafast, high-brightness source. By compensating for the path length difference in an extremely-high-acceleration-gradient cavity with a curved cathode, we numerically demonstrate the potential for achieving more than an order of magnitude increase in beam brightness over existing electron guns. The thermo-mechanical analysis and conceptual design that demonstrate the viability and reliability of the concept are also presented.

INTRODUCTION

Ultrafast high-brightness electron beams are desired as injectors for light sources, including FELs, energy recovery linacs (ERL) and medical devices, amongst other 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. An example is micro bunching instabilities that can result from transport interactions with the energy modulations induced by the longitudinal space charge (LSC) forces in the bunches. These sources may also 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 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]. This introduces radial compression that compensates for geometric bunch lengthening effects when coupled with extremely-high-acceleration-gradient to minimize the impact of space-charge forces. The AES-patented rear-fed coaxial cathode coupling eliminates contributions to transverse emittance from non-axisymmetric modes [3]. We show that combining these effects is feasible and does indeed deliver a more compact, economic, ultrafast high-brightness electron beam for the identified applications.

CAVITY AND COUPLING 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 is expressed by:

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

This ignores the drive laser duration and assumes prompt response from a copper cathode with a constant laser spot radius (R). 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). The bunch lengthens due to the longer trajectories of the outer particles, compared to electrons emitted closer to the axis, and is proportional to the square of the beam radius.

Our previous upstream, coaxial, waveguide-fed gun cavity design had the drawback that the radial space for electron beam emission and drive laser insertion was relatively small [4]. We have now completed the RF analysis for a coaxial RF feed from the rear of the gun. Standard codes like the SLAC-developed S3P code [5] and SUPERFISH have been used to complete the RF design used in the reported beam dynamics analysis. Following Ref. [3], we focused on the geometry of the coaxial coupler and the iris between the cells, in order to maximize shunt impedance and thus minimize losses for a given cathode voltage. The coaxial coupler and the iris

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* This work was supported by the U.S. Department of Energy, under Contract No. DE-SC0009556.

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ISBN 978-3-95450-138-0

changes required adjustment of the thermal stress analysis and the location of the cooling channels. The RF design in the cathode area also affects the beam dynamics design. To allow for 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.

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 studied using the SUPERFISH. 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 [6] beam dynamics code. Figure 1 shows a cavity cross-section with field lines from SUPERFISH. The radius of the coaxial coupler has been chosen to prevent the transmission of the lowest high-order TE01 mode through the coaxial waveguide.

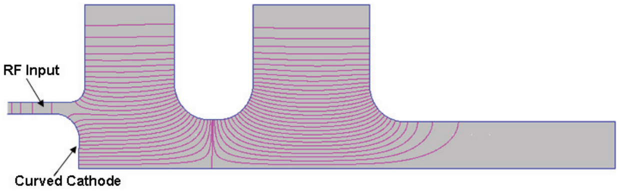

Figure 1: SUPERFISH model of the 1.6 cell, X-band, π-mode, RF gun cavity with rear-fed coaxial coupling.

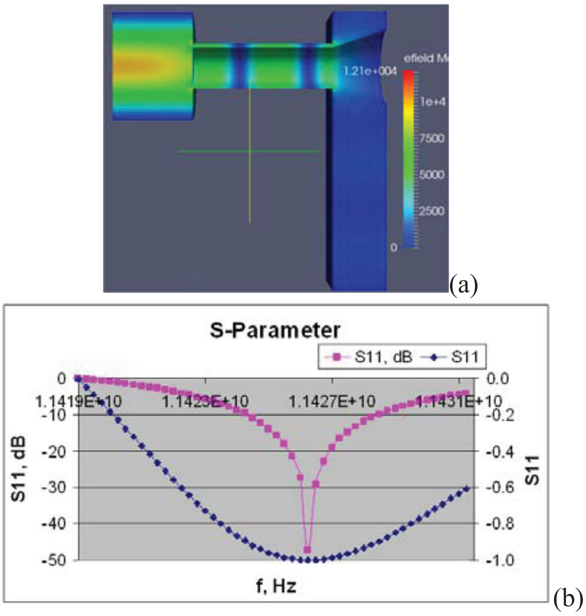

Figure 2: (a) Coupling structure electric fields in the rectangular to coaxial waveguide transition, and (b) the normalized S11 parameter for the coupling structure.

The waveguide to coaxial cavity coupling transition has been designed using by SLAC developed S3P code [5]. Figure 2(a) shows that WR-90 rectangular to coaxial waveguide transition. The coaxial waveguide and the cavity resonate as TEM and TM modes, respectively. Figure 2(b) shows the normalized S-parameter - the transmission/reflection coefficient for the coupling structure. The cavity resonant frequency is 11.426 GHz for the geometry shown.

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 delivering 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 predicted 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.

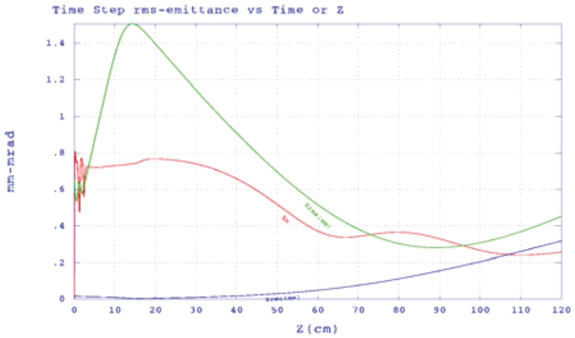

Figure 3: Evolution of the bunch length (blue), beam size (green) and emittance (red) along the beam axis.

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 the evolution of the bunch length, beam size and emittance along the beam axis. At the interaction point 45 cm from the cathode, we deliver a 2.5 MeV, 20 pC bunch with a transverse rms emittance of 0.81 π mm-mrad. The 82 fsec FWHM bunch has a transverse rms beam spot of 0.71 mm with an energy spread of 0.6 %. These results are very similar to those achieved with the upstream-fed coaxial RF design [4].

THERMAL DESIGN

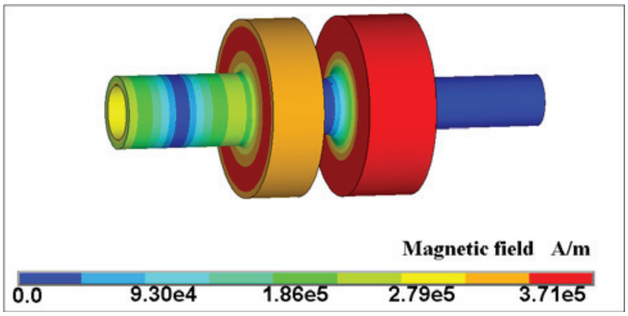

Figure 4: Magnetic field values during an RF pulse.

SUPERFISH normalizes electric fields to a maximum of 1 MV/m. Our design maximum electric field is 250 MV/m in the gun. The wall losses thus scale from the indicated 467 watts to 4.23 MW, thus requiring pulsed RF power. Figure 4 shows the RF surface magnetic fields. The proposed RF pulse duration is 200 nsec and the repetition rate is 200 Hz, resulting in a duty factor of 4.0 x 10^{-5}. This low duty factor enables the adoption of a simplified cooling scheme for the design.

The magnetic fields in the waveguide and coaxial feed were determined from the geometry and the operating point power. The magnetic fields along with wall and the resistance were used to determine the local power loss on the walls, where the power loss is iterated to reflect the temperature dependent resistance of the walls. Figure 5 shows the resistive wall power densities.

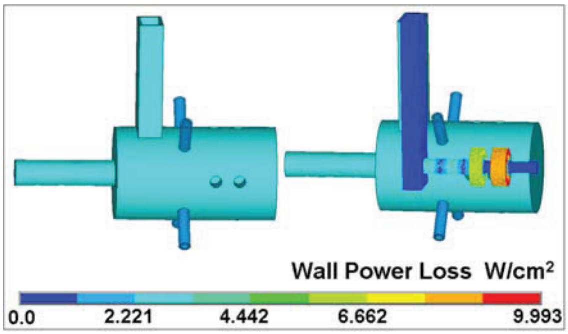

Figure 5: Average power loss on the cavity walls with a duty factor of 4.0 x 10^{-5}.

A cooling water flow rate of 2.3 gpm through the eight cooling channels is used to keep the temperatures within the acceptable range. Figure 6 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.

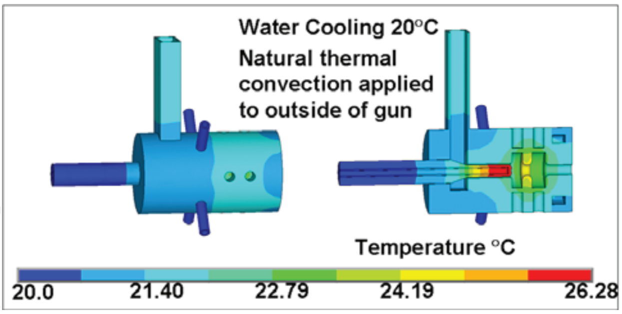

Figure 6: Temperature distribution in the gun body. The supplied water cooling temperature is 20ºC. Natural thermal convection is applied outside of the gun.

The displacements derived from the temperature variation were then applied to the RF model. The RF model was then rerun to determine a frequency comparison with the original geometry. This showed a shift of -644. kHz. This can easily be compensated by developing the geometry to be at the design frequency for an elevated design temperature. The inlet cooling temperature would then need to be about 3.4ºC below this design temperature to operate at the design frequency.

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 rise was not significant. The thermo-structural and RF frequency shift analysis demonstrates that the design of this electron gun running at 4.0 x 10^{-5} duty factor is robust. The temperature rise of the gun body is small, less than 5ºC, the displacements are small, less than 0.8 x 10^{-4} inches, the Von Mises stresses are low, less than 1100 psi, and the frequency shift is manageable. Hence the design and thermal management of this gun have adequate head room for robust operation.

SUMMARY

AES has recently completed the design of an ultrafast, high-brightness, electron source for FEL, ERL and advanced accelerator injectors. The gun is particularly suited to UED analysis. The beam dynamics analysis of such an X-band, ultrafast, RF gun with a curved copper cathode has been demonstrated to deliver an order of magnitude increase in beam brightness over existing S-band electron guns. Thermo-structural analysis and mechanical design shows the achievement of robust operation at a duty factor of 4.0 x 10^{-5}. Proposals have been submitted to perform the experimental validation of the device at the BNL Accelerator Test Facility (ATF).

ACKNOWLEDGMENT

The authors would like to thank Dr. Ng of SLAC for permitting the use of and providing assistance with the ACE3P code.

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