DEVELOPMENTS OF A HIGH-AVERAGE-CURRENT THERMIONIC RF GUN FOR ERLS AND FELS*

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Abstract

The development of a high-average-current thermionic RF gun with the required beam performance for lasing would provide significant cost of ownership and reliability gains for high-average-power energy recovery linac (ERL) and free electron laser (FEL) devices. The beam for these applications requires high quality and high performance, specifically: low transverse emittance, short pulse duration and high average current. We are developing a gridded thermionic cathode embedded in a copper one-and-half cell UHF cavity to generate the electron beam. The fundamental RF and higher harmonics are combined on the grid and a gated DC voltage controls the beam emission from the cathode. Simulations indicate that short pulse ~ 10 psec, < 1 MeV electron beams with low-emittance ~ 15 mm-mrad at currents ≥ 100 mA can be generated. The elimination of sensitive photocathodes and their drive laser systems would provide significant capital cost saving, improved reliability and uptime due to increased robustness and hence operating and lifecycle cost savings as well. We will present the gun design and performance simulations and the progress achieved to date in optimizing the device.

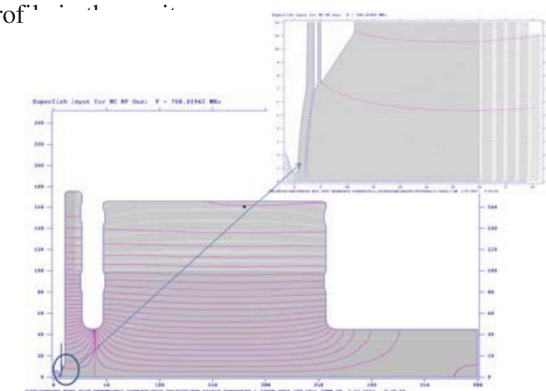
INTRODUCTIONS

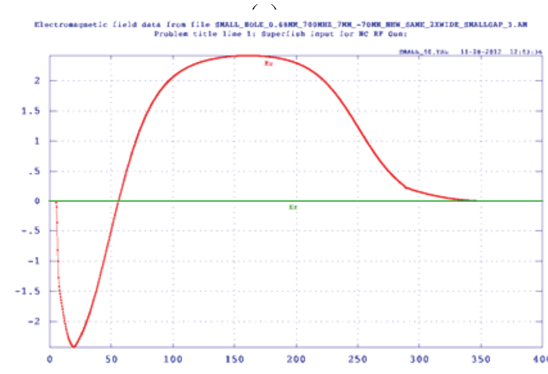
In order to develop high-average power IR free electron laser (FEL) and energy recovery linac (ERL), high brightness, high-average-current electron beam is required. There are several approaches to generate high-average-current electron beam. One example is JLAB's GaAs DC photocathode gun that makes high average current, high brightness electron beam sources for the development of 100 mA class injectors for ERLs and FELs [1-2]. Photocathode guns are employed in the majority of FELs and are capable of generating short, high-quality, and high-charge electron bunches However, photocathodes have some drawbacks when operated at high-average power values due to excessive cathode heating, short cathode lifetimes, and high-average power drive laser requirements. Thermionic cathodes have demonstrated long lifetime operation high-peak-current densities without the need of drive lasers. Several FELs have used thermionic gun technology, however, these guns generate bunches at a subharmonic of the linac frequency and cannot be used for high-average-power IR FELs because of their low repetition rates.

To resolve this issue, AES, here, proposed a thermionic rf gun with gridded cathode driven with harmonics of the main linac rf frequency. When the grid is negatively biased with respect to the cathode, emission is restricted to a small portion of the RF phase [3], thereby generating short bunches at a repetition rate equal to the gun rf frequency.

CAVITY DESIGN

The proposed gun cavity is shown in Figure 1(a). The thermionic cathode is hollowed slightly from the body of a 700-MHz RF cavity. Fields from the RF cavity slightly decrease into the gridded cathode gap, reaching a nonzero value at the cathode surface. After injecting RF power at the 3rd and 5th harmonics of the fundamental cavity frequency into the gridded cathode gap, the longitudinal electric field at the cathode surface takes the superposition of those mentioned fields could control the beam emission. Figure 1(b) shows the fundamental field prof[illegible]





(b)

Figure 1: (a) Thermionic rf gun cavity with grid control mesh in the cathode region and (b) fundamental field profile of the cavity.

Various grid spacing and cavity length have visited to get optimized cavity design. The resulted cavity design

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forwarded to TSTEP code [4] for the beam dynamics simulations. The TSTEP code can combine three field profiles (1st, 3rd, and 5th harmonic) and the DC bias voltage in one running.

BEAM DYNAMICS

To generate a gated beam, the fundamental, 3rd harmonic and 5th harmonic of the cavity frequency are superposition in the grid plus a bias voltage is applied in to grid respect to proper phase to accelerate electron beam through the cavity without back-bombardment to avoid cathode damage. Figure 2 shows fundamental and superposition field of 1st, 3rd and 5th harmonic with several different rf phases. Once the DC bias of 3.3 MV/m is applied in to the grid then less than gradient of 3.3 MV/m will not emit electrons from the cathode grid.

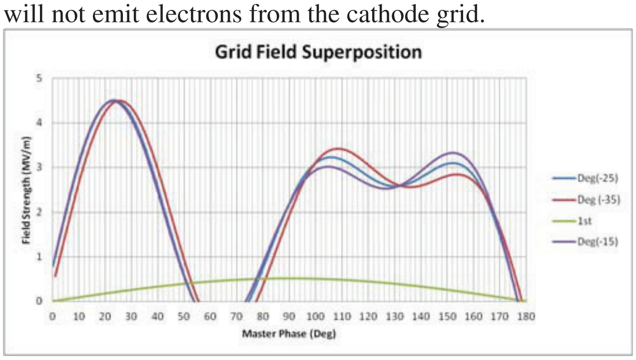

Figure 2: Grid control field of fundamental and superposition field of 1st, 3rd and 5th harmonic in several different rf phases. Positive field is acceleration in the TSTEP code.

The TSTEP code [4] has CELL3 command that could make one superposition field with the separated input files of fundamental, 3rd, and 5th harmonics. The POISSON command could provide DC bias in the grid region. The combined field has visited with different higher harmonic phases as shown in Figure 2. One of the beam dynamics results is shown in Figure 3. The bunch length is 17ps and transverse emittance is 15 mm-mrad at 70cm position.

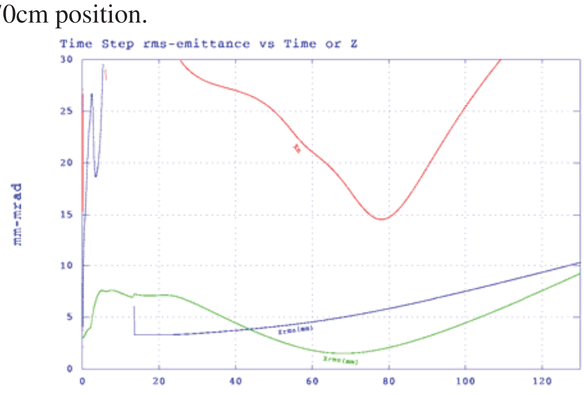

Figure 3: Beam profile evolutes along the beam axis that. (Red) transverse beam emittance, (blue) longitudinal bunch length and (green) transverse beam size are represented.

THERMAL ANALYSIS

The wall power losses are shown in figure 4. The losses are mapped from SUPERFISH output to the surface of a 2-D axi-symmetric ANSYS model. These losses are determined assuming a wall temperature of 20ºC. Cell 1 fields and power densities are considerably higher than in cell 2. The power loss in cell 1 is higher than the cell 2 losses even though cell 2 has considerably more surface area than cell 1. The total power loss on both the cells is 691 kW, this is even higher than the total power loss of the 2.5 cell gun at LANL that has a power loss of 660 kW at wall temperatures of 20 ºC.

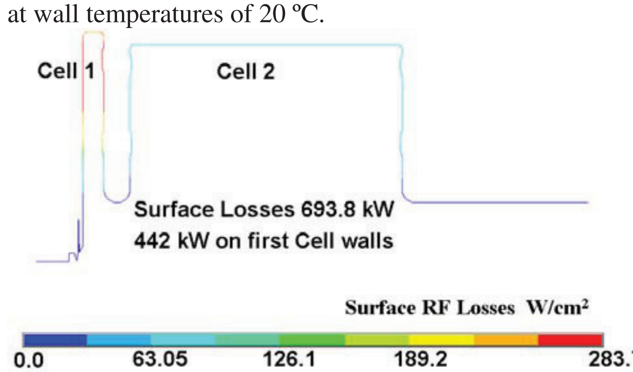

Figure 4: The wall power losses from each cavity. The total wall loss is 693.8W and the first cell loss is 442 kW. The top portion of first cell shows high loss that represent as red color.

Comparing these power densities to the gun at LANL one concludes that an increase in the coolant channel density on the order of or greater than the power density ratio is required. The gun at LANL has channels with widths of .1 inches and power densities as high as 103 W/cm2 on the rf surface (20ºC). This compares to 283 W/cm2 for this thermionic gun. Cooling channels .025 inches wide were used. Figure 5, shows the general layout of the channels. The channels are predominantly .025" x .150" long. This aspect ratio is 1 to 6 which is above the 1 to 4 that we generally design to for manufacturing reasons. However, if we design to 1 to 4 the amount of coolant will be more limited and the rise in coolant temperature will increase. In the region near the tuning ring the temperatures and stresses were too high for a 1 to 6 aspect ratio. In this region the depth of the cooling channels was increased to .200 inches. These extreme aspect ratio coolant channels add risk to manufacturing. The dimension between the rf surface and cooling channels was maintained at .075 inches except in the tuning ring region. It may be beneficial to decrease the wall thickness, and if a detail design of a high current thermionic gun is pursued we would consider decreasing the wall thickness to .050 inches and below. Another important design item for the high current gun is the glidcop material used for the gun body. Glidcop has 3 to 5 times the yield strength of OFE copper with 92% of the thermal conductivity. This makes it an ideal material for this application. This is the material used to fabricate the 2.5 cell AES gun presently being tested at LANL. AES has extensive experience fabricating with glidcop.

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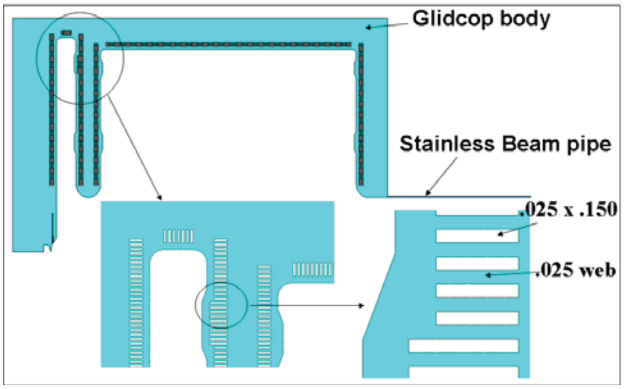

Figure 5: The general layout of the glidcop cooling channels that the glidcop has 3 to 5 times the yield strength of OFE copper with 92% of the thermal conductivity.

An axi-symmetric thermal model was developed to determine the temperature distribution. The model is set up to iterate the heat load and surface temperature so that the surface heat loads are consistent with the surface temperatures. This is done by simply using the temperature results and calculating new heat loads from the magnetic field which was mapped to the thermal model. The results are iterated upon until the temperatures converge. The effect of the surface temperature was to increase the peak power density by up to 14% with the largest increase in cell 1, whereas the total power loss increased by only 10% due to the lower temperatures of cell 2. The total surface loss at temperature was calculated as 761 kW with 499 kW lost in cell 1. The cooling flow rate given in the figure is 39 gpm in cell 1 and 64 gpm in cell 2. This is determined by taking the flow area and allowing for a flow velocity of 15 ft/sec. This flow velocity limits erosion and allows for long life of the gun. Ideally we would want significantly more flow in cell 1 than cell 2, this could be accomplished by increasing the depth of all the channels in cell 1, however, it would require an aspect ratio of 1 to 8 or more, which may make manufacturing more difficult.

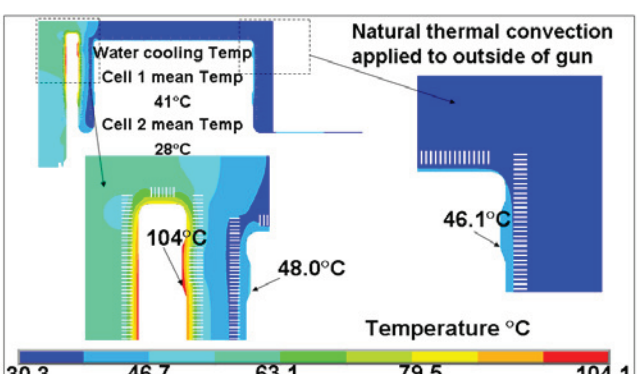

Figure 6: Cavity temperature distribution after applying coolant at 20ºC. A maximum model temperature of 104ºC was determined on first cell for the inner part of the outer tuning ring.

Ambient thermal conditions were applied to the outside surface of the thermal model. These include both natural convection and thermal radiation. Though radiation is small due to low temperatures on the surface it was easy to include and makes the model more complete. The steady state temperature results are shown in figure 6. A mean water cooling temperature was used for the heat transfer cooling boundary. The mean water temperature in cell 1 was determined to be 41ºC. A total water temperature rise of 42ºC was determined from the heat load and flow rate and the inlet temperature was assumed to be 20ºC. The mean coolant temperature was applied to all cooling channels in cell 1. The same methodology was applied to cell 2. The mean water temperature in cell 2 was determined to be 28ºC and applied to all cooling channels of cell 2. The temperature results of the steady state thermal solution are shown in the figure. A maximum model temperature of 104ºC was determined on cell 1 for the inner part of the outer tuning ring. On the other side of the cell 1-to-cell 2 septum, at the inner part of the outer tuning ring, the maximum temperature of cell 2 was determined as 48.0ºC. This results in a significant temperature gradient across this septum. This temperature gradient causes the septum to "bow" and increase stresses on the cell 1 walls. To decrease these stresses the local cooling channel depths near the outer tuning ring were increased. Again, increasing all cooling channel depths would decrease the coolant temperature and with it decrease stresses.

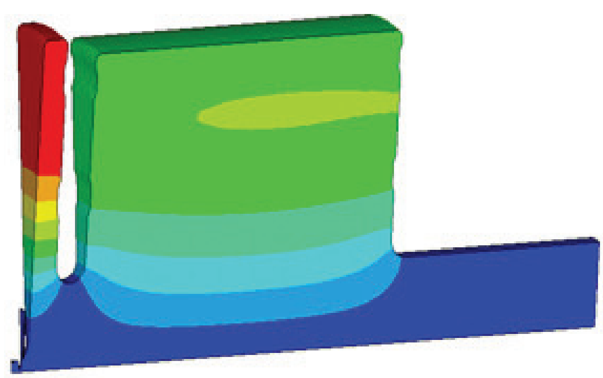

Figure 7: Frequency shift primarily from temperature distribution. Red color represent higher frequency shift than other color because the higher temperature shift the more frequency shift.

Figure 7 shows the frequency shift along the beam axis for wall temperatures of 20ºC and for the displaced structure at steady state temperatures. The field is nearly the same showing that the thermal management results in nearly identical fields at room temperature and operating conditions. The frequency shift of the cavity was determined at temperature to be -166. kHz. This shift can be offset by designing the gun to +166. kHz at 20ºC.

The thermal management design presented here shows traceability to high current CW application. The high fields that the gun is designed for requires glidcop as the

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gun body material. The high fields also introduce risk into the design, the fields result in rf surface power densities that are 3 times higher than the cw rf gun at LANL and transient stresses above 2/3 yield. The frequency shift resulting from the rf losses is manageable.

SUMMARY

AES is developing a high-average-current thermionic RF injector for ERL and FEL applications. For quality electron beam generation, beam emission can be controlled by superposition of 1st, 3rd, 5th harmonic and DC bias in the gridded cathode in thermionic RF gun. Simulations indicate that short pulse 17 psec, < 1 MeV electron beams with low-emittance 15 mm-mrad at currents of 1.0 A can be generated. Conceptual thermal design is developed for the Thermionic Gun that traceability to high-average current CW gun with high fields requires the Glidcop cooling mechanism. The frequency shift from rf losses can be offset with starting geometry at +166 kHz. Transient stresses well above 2/3 yield but less than yield that typically get other than hipped Glidcop with yield near or above 40 ksi. It would require manufacture with rolled plate and extruded material for high stress regions. Thermal stresses can go near yield but adds significant risk. It is still needs to modify in physics design to lower the DC bias less than target of 1 MV/m.

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