# NORMAL CONDUCTING CW RF GUN DESIGN FOR HIGH PERFORMANCE ELECTRON BEAM*

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## *Abstract*

High repetition rate (>1 MHz), high charge (1 nC), low emittance (1 micron) electron beams are an important enabling technology for next generation light sources. Advanced Energy Systems has begun the development of an advanced, continuous-wave, normal-conducting radio frequency electron gun. This gun is designed to minimize thermal stress, allowing fabrication in copper, while providing low emittance electron beams. Beam dynamics performance will be presented along with thermal and stress analysis of the gun cavity design.

## INTRODUCTION

Normal-conducting Radio Frequency (NCRF) photocathode guns have been very successful in producing low emittance beams in pulsed, low duty-factor operation. For high duty factor or CW operation wall losses quickly become the limiting factor, so the problem becomes one of optimizing both the overall losses for a given cathode surface electric field as well as reducing the peak surface losses at local hot-spots. For conventional copper accelerating cavities the most efficient design is a re-entrant shape which has a high shunt impedance and reasonably evenly distributed wall losses. This shape has tapered nose cones on either side of the interaction gap. The taper is important to spread the wall currents through a larger surface area to improve efficiency and manage the local heat load. The highest heat load for an axis-symmetric structure is typically near the base of the nose cone. Cutting ports into this geometry breaks the symmetry and leads to local current concentrations, but if the port openings are suitably blended, the local power density can be maintained to not exceed the previous peak value on the nose.

Applying a re-entrant geometry to an NCRF gun can significantly improve the efficiency and allow a higher cathode gradient than would be possible with a pillbox design at the same frequency. Previous studies [1,2] have shown that a re-entrant gun cavity with the cathode mounted in one nose cone is a promising configuration for CW operation.

The goal of this research was to demonstrate the feasibility of developing a copper NCRF gun that can operate at cathode gradients in excess of 15 MV/m and provide 1 nC electron bunches at 1 micron transverse emittance. The beam dynamics calculations and thermal/stress analysis for the gun are discussed in the following sections.

Our chosen frequency is 1.5 GHz to allow thermal testing at JLab of the prototype, although thermal issues would probably be less at a lower frequency

## BEAM DYNAMICS

The beam dynamics were simulated using TStep [3], which is a derivative of PARMELA [4]. The simulation included the cathode cavity closely followed by a second independent cavity. The cathode cavity is surrounded by an emittance compensating solenoid with a bucking coil behind the cathode to zero out the magnetic field at the cathode. The simulation also includes a booster accelerating structure, which is not part of the present design, but is used to show that the emittance of the beam can be brought to ~ 1 mm-mrad at a higher energy.

A Cfish simulation of one of the cavity geometries explored is shown in Figure 1. In this figure, the cathode is on an independent stalk with the RF input being accomplished on-axis. The coupling factor can be varied across a very broad range by changing the geometry of the cathode stalk.

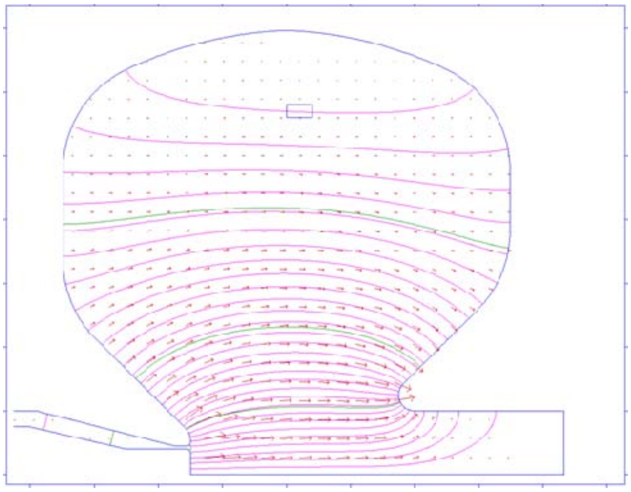

Figure 1: Cfish simulation of gun cavity with cathode gradient of 23 MV/m.

The emittance evolution seen in Figure 2 is from the simulation of the photoinjector cavity shown in Figure 1, closely followed by a similar single cell cavity as described before and a booster accelerator structure. At the end of the booster accelerator, the beam energy is almost 6 MeV. The simulation was done with 100,000 particles and the same 3d space charge routine that is used in the code Impact.

The beam dynamics simulations indicate that our re-entrant gun design is capable of achieving an emittance of

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1 mm-mrad at bunch charges of 1 nC. The longitudinal emittance from the simulations is only 15 keV-ps. With a cathode gradient of 23 MV/m, the peak surface field is 37 MV/m. Subsequent thermal analysis has shown that the gun can support a field gradient at the cathode of 23 MV/m as will be described in the following paragraphs. The cathode radius for these simulations was 3 mm.

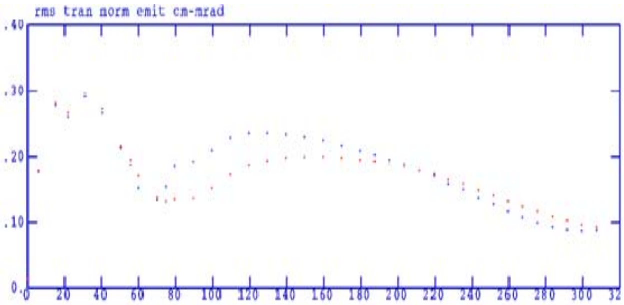

Figure 2: Emittance evolution through simulation using gun cavity shown in Fig. 1.

Table 1: Electron bunch parameters at end of simulation.

| Parameter | Value | Units |
|---|---|---|
| Charge | 1.00 | nC |
| Beam Radius | 2 | mm rms |
| $\varepsilon_{nx}$ | 1 | microns rms |
| Bunch length | 2 | mm rms |
| $\varepsilon_{nz}$ | 15 | keV ps |
| Energy | 6 | MeV |

## THERMAL/STRESS ANALYSIS

Based on our understanding of the operational experience with the Stanford Linear Accelerator PEP II copper cavities and on analytic elastic studies performed on these cavities stresses as high as 7300 psi in a copper cavity can be tolerated without operational problems as long as the peak stresses are compressive and are localized. Therefore, the goal of the thermal studies was to design a cooling scheme for the cavity of Fig. 1 with a stress limit of 7300 psi. The initial thermal design was developed using elastic material properties with a high density of coolant channels in the high heat load regions. The density of channels was increased until the general stresses on the RF surface were below 7300 psi. Presently there are small regions of stress within the cooling channels that are above the limit, however, they are at the intersection of the inlet/outlet channels and main cooling channels and can be decreased by adding a local radius to the intersection which we will consider later. In addition, it is expected that the stress at these locations will have little influence on the performance of the cavity since they are far from the RF surface. Besides the elastic stress study, inelastic analysis was completed with multiple cycles and the subsequent RF frequency shift was calculated. The resulting frequency shift arose from residual stress during cycling that occurs on the RF surface. Repeated cycling showed that after just five cycles the change in frequency shift was less than 50 Hz/cycle and was within the capabilities of the RF system. The thermal analysis results indicate that this low emittance CW NCRF gun can be operated at a cathode gradient of at least 23 MV/m.

The thermal analysis was completed assuming that the velocity in the main coolant channels was 5 m/s. The inlet channels have slightly higher velocities, up to about 5.9 m/s. The coolant temperature is assumed to be 20ºC throughout the channels. Coolant heat up, which would tend to increase temperatures, and coolant entrance length effects, which would tend to increase the heat transfer coefficients and therefore decrease temperatures, have not been included in this first phase of the analysis. However, RF heat loads and RF surface temperature have been iterated to give heat loads at temperature. The maximum temperature is 49.6ºC and occurs on the longer nose at the RF surface above the inlet channel.

Based upon the thermal analysis results, a structural/stress analysis was completed on the ¼ model using the elastic properties of the material. The temperatures from the thermal model are mapped directly to the structural model. Node and element connectivity are the same for both models. Ambient pressure of 14.7 psi was applied to the outer surface, since the RF volume is evacuated. A pressure of 70 psi is assumed in the cooling channels. Symmetric boundary conditions are applied to the two cut surfaces of the model. The model is then held in the axial direction. The stress is less than 7300 psi for all RF surfaces. This was the main goal of the design. Figure 3 shows the stress contour results.

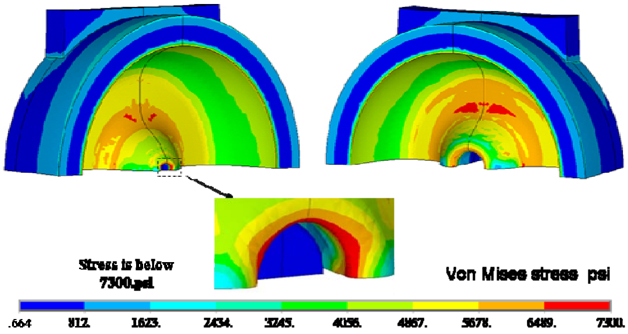

Figure 3: Stress contours on the cavity surface.

Since copper has a relatively non-linear stress-strain curve at low strains, below 0.2%, inelastic analysis was performed to look at more realistic strains and to determine expected frequency shifts of the gun due to operating temperature, coolant pressure and ambient pressure. The proportional limit of copper is much less than the normal limit typically given by 0.2% strain. Since the greatest part of the strains is from thermal gradients, the stresses resulting from the nonlinear stress-strain curve used for the analysis will be much less than those resulting from an elastic modulus of 17.0e6 psi. Therefore, the model was run with this nonlinear stress-strain curve, and stresses and displacements were determined. Multiple cycles were run to determine the cyclic history, and displacements were then applied to the surface of an RF model to determine frequency shift and frequency shift for multiple cycles.

The resulting stresses after the ninth cycle, representing operating temperature, evacuated RF space (ambient pressure on the outside of the model), and 70 psi assumed in the cooling channels, have a maximum 6617 psi at the edge of the inlet channel on the large nose side of the gun. This stress is over a small region of the model and has little effect on the displacements of the RF surface. The stress on the RF surface is less than 4200 psi. This is not significantly different than the stresses from the first cycle.

After operation, with the RF off, the temperature everywhere in the gun converges to 20ºC. Since the analysis was performed in the in-elastic regime, residual stresses exist. These stresses are calculated at each RF off cycle. The resulting residuals show the peak stress is still at the wall of the inlet channel with a value of 2122 psi. The stresses on the RF surface are less than 1300 psi. These stresses are not significantly different from the residual stresses after the first cycle where the peak was 2131 psi.

Using the results from the in-elastic cyclic analysis the frequency shift before, during and after each cycle was determined. A model of the RF space was run, and the frequency was calculated. Using the displacements of the structural model, the RF surfaces were moved accordingly for each cycle's calculation, and the RF analysis was rerun to determine a new frequency. In Figure 4, the frequency shift from the original RF model is shown. On the left of Fig. 4, the frequency shift for each cycle, with RF power on, at temperature, is calculated. On the right of the figure, the frequency shift due to residual stresses is determined after the power is turned off, and the gun returns to 20ºC. The frequency shift at operating temperature is -350 kHz and changes a small amount after each cycle. The results indicate that the frequency shift is an additional -518 Hz after five cycles and -650 Hz after 9 cycles. Looking at the local change in frequency shift, one obtains -50 Hz/cycle at 5 cycles and -20 Hz/cycle at 9 cycles. The change in frequency shift is decreasing with increasing cycles, and it is well within the RF capabilities to track the frequency after each cycle.

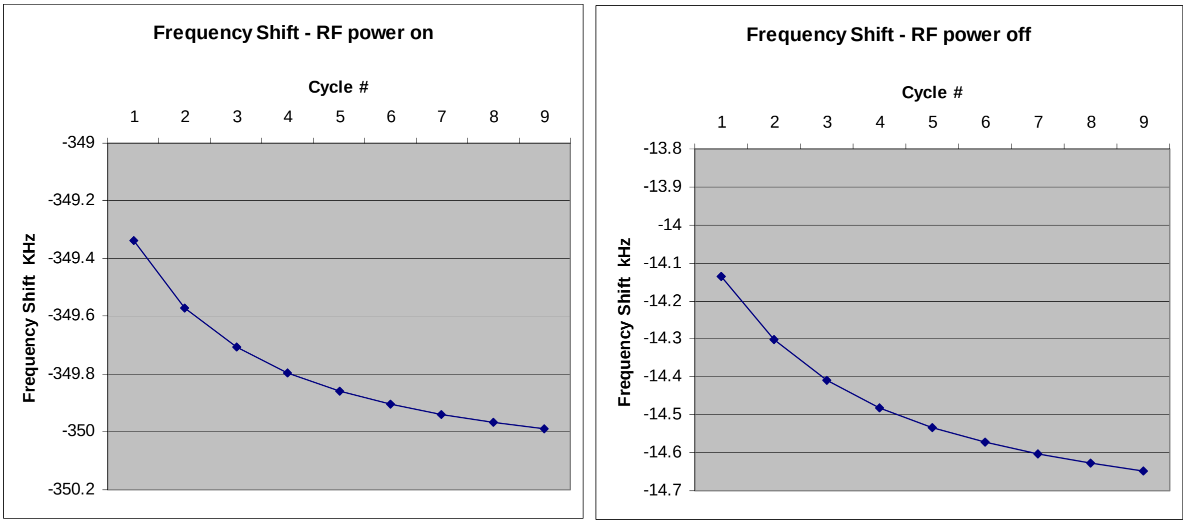

Figure 4: Frequency shift of cavity from cycling the RF on and off.

## SUMMARY

Although far from exhaustive, this study has shown that an all copper RF gun can be operated with CW power without excessive stresses and with low RF power induced frequency shifts. Cathode gradients in excess of 20 MV/m can be achieved, resulting in a 1 micron transverse beam emittance.

## REFERENCES

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