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E. Wang
Peking University, China

J. Kewisch, I. Ben-Zvi, A. Burrill, T. Rao,
Q. Wu, A. Jain, R. Gupta
Brookhaven National Laboratory Upton, NY

D. Holmes
AES Medford, NY

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Collider-Accelerator Department

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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HEAT LOAD OF A P-DOPED GAAS PHOTOCATHODE IN AN SRF ELECTRON GUN

Erdong Wang, Peking University, China

Jörg Kewisch, Ilan Ben-Zvi, Andrew Burrill, Trivini Rao,Qiong Wu, Animesh Jain, Ramesh Gupta, BNL, Upton, NY11973,U.S.A

Doug Holmes,AES, Medford, NY

Abstract

Many efforts were made over the last decades to develop a better polarized electron source for the high energy physics. Several laboratories operate DC guns with the Gallium-Arsenide photo-cathode, which yield a highly polarized electron beam. However, the beam's emittance might well be improved using a Superconducting RF electron gun, which delivers beams of higher brightness than DC guns does, because the field gradient at the cathode is higher. SRF guns with metal cathodes and CsTe cathodes have been tested successfully.[1] To produce polarized electrons, a Gallium-Arsenide photo-cathode must be used: an experiment to do so in a superconducting RF gun is under way at BNL. Since the cathode will be normal conducting, the problem about the heat load stemming from the cathode arises.[2] We present our measurements of the electrical resistance of GaAs at cryogenic temperatures, a prediction of the heat load and the verification by measuring the quality factor of the gun with and without cathode.

INTRODUCTION

The ILC and similar applications require low emittance, highly polarized electron sources. Previous, traditional DC guns were employed to generate polarized electron beams. The ILC demand the vertical emittance at the entrance of the main linac is 0.02um; if the DC polarization electron gun is used, a damping ring will be needed which will incur further expenditures. Our simulations show SRF injector can exceed the ILC's requirement for vertical beam emittance by a factor of 2 without a damping ring when an ellipsoid charge-distribution is used.

Although RF electron guns typically provide higher brightness than the DC guns, in the past only the latter were used to generate polarized electron beams. One reason is that a very good vacuum is essential for operating of the GaAs photo-cathode to minimize the destruction of the cathode surface by ion back-bombardment. DC guns typically have vacuum pressure lower than 10^{-11} torr, compared to 10^{-9} torr in a normal conducting RF gun.

Experiments at BINP Novosibirsk in the late 1990s demonstrated that quantum efficiency of GaAs in a pulsed normal conducting RF gun was quickly destroyed[3]. Instead of using a normal conducting gun, Brookhaven National Laboratory (in collaboration with Advanced Energy Systems Inc) is using a superconducting gun to repeat that experiment,[4] because the superconductor surface acts as a cryogenic pump so that the vacuum pressure can be maintained at better than 10-11 torr.

Figure 1: The cathode plug with original and recessed GaAs crystal.

The BNL's plug gun is a 0.6 cell 1.3 GHz SRF gun. It got its name from a removable niobium plug, located in the back of the gun which holds the GaAs cathode. Figure 1 shows the plug, the original design and the improved one that allows the rapid exchange of the cathode. The cavity was fabricated and modified to accept the plug by AES. The surface of the cavity was treated at the Thomas Jefferson National Laboratory by buffered chemical polishing (BCP with an HF: HNO3:H3PO4=1:1:1 ratio) followed by high pressure rinsing. The cavity wall was etched to remove10um, the plug was etched 20um and two probes were etched 5um at room temperature. The cavity was tested in a vertical cold test [5].

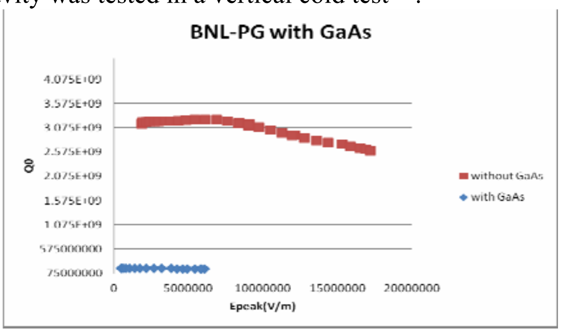

Figure 2: Quality factor vs. gradient with and without GaAs cathode at 2k.

The plug gun was tested first without a GaAs cathode. After cooling it down to 2K, we measured the Q factor As shown in Figure 2. During the second cool-down, we inserted the cathode plug. The Q dropped from $3*10^9$ to $1.78*10^8$ because of the electric losses in the GaAs cathode. Unlike a DC gun the RF electric field penetrates into the GaAs cathode, causing dielectric losses. The flatness of the Q_0 curve with the cathode indicated that the cavity did not quench. However, the drop was much larger than initially estimated. A careful analysis was necessary.

We simulate heat generation and flow from the GaAs cathode using the ANSYS program. The results match the measurements well. Following from the findings with the heat load model, we designed and fabricated a new cathode holder (plug).

HEAT LOAD DUE TO RESISTIVE LOSSES DUE TO THE DOPING

The GaAs crystal used for the photocathode is a zinc doped (p type) one with a heavy doping of 10^{18} cm^{-3} to prevent the build-up of charge on the surface, viz, NEA surface. The GaAs wafer has an active area of 2mm by 2 mm and is of 0.6mm thick. We cannot neglect the resistive heat load due to the high p-doping of the GaAs crystal. The dissipated power per unit area due to Joule heating is [6]:

$$P_c = \frac{1}{2} R_s \int_s |H|^2 ds \quad (1)$$

The surface resistance $R_s = \frac{1}{\sigma\delta}$ can be calculated from the skin's depth $\delta = \sqrt{\frac{2}{\sigma\mu\omega}}$ and the resistivity of GaAs. To model the heat load from the GaAs crystal correctly tt is essential that we know the resistivity of GaAs at 4k. The manufacturer specifies it as $3.4*10^{-2}$ ohm-cm at 290K.

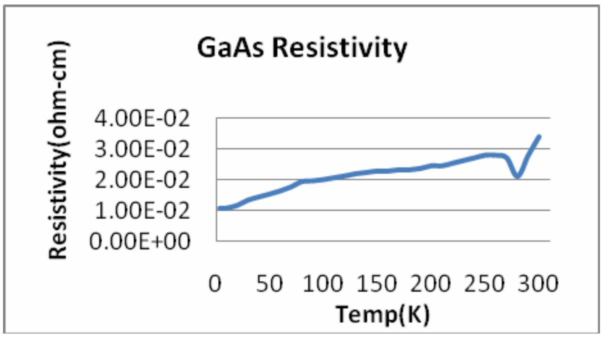

Figure 3: The GaAs resistivity by the temperature from 300K to 4K

We measured the resistivity at 4K using the four-point method, which avoids the impedance of the connection of the probe to the GaAs wafer. It is calculated using the formula $R = g\frac{U}{I}$, where g is the geometric factor of the GaAs crystal. We obtained that factor for our device via taking a measurement at room temperature and comparing it to the manufacturer's specification.

Figure 3 shows the measured resistivity during the cool-down to 4k. As the doping increases, a larger number of holes are forbidden to participate in hole-electron scattering because the Fermi level moves deeper into the valance band with most states below the Fermi energy being occupied. So, there is little variation with the temperature we explained this by the fact that in GaAs the Fermi level is below the conduction level. At 4K and the resistivity is $1.1*10^{-2}$ ohm-cm.

Knowing the resistivity and gun's geometry, we can calculate the magnetic field, for which we used the computer code SUPERFISH. To compare these finding to the experimental ones, we normalized the peak field to 5 MV/m.

The magnet field increases linearly from the center of crystal to its edges. With the value of the magnet field and surface resistance that we obtained from measuring the GaAs resistivity, we calculated the resistive heat load. We found that a 200mW heat load is generated from the emission surface of GaAs crystal and 1W from its edge.

HEAT LOAD DUE TO DIELECTRIC LOSS

GaAs experiences a dielectric loss (independent of the doping level) when the RF field penetrates into the crystal. The power loss is

$$P = \int \omega \cdot \varepsilon \cdot A \cdot E(x)^2 \cdot \frac{\varepsilon_1}{\varepsilon_2} dx \quad (2)$$

A is area and *d* is the thickness of GaAs surface. *E* is the electrical field, ω is the frequency of the field. $\varepsilon_1 / \varepsilon_2$ is the loss tangent of GaAs. There also is a magnetic component to the power loss, but it is much smaller than the electric part and can be neglected. The electrical field drops exponential with the depth:

$$E(x) = E_0 e^{-\frac{x}{\delta}} \quad (3)$$

With the peak field E_0= 5 MV/m, 230mW of heat will be generated in the GaAS. the total heat load due to resistive and dielectric losses in GaAs is 1.46W at 5MV/m. The Q will drop to 1.8E8, which matches the test results well.

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#wedwrd@gmail.com

IMPROVED NIOBIUM PLUG

The model shows that a large part of the heat load comes from the edge of GaAs crystal. The plug therefore can be improved by shielding the crystal's edges from the RF fields. In our new design, the GaAs crystal is recessed into the niobium plug (Figure 1). The recess was machined into the plug's surface by EDM. We attached the GaAs crystal to the plug with a small amount of Indium solder, carefully limiting it to the back side of the crystal so that no indium is exposed to the RF field.

Because of machining tolerances, there is a small gap remaining between the edge of the crystal and the niobium. Depending on the gap's size, a magnetic field exists there and generates heat. The simulation estimated the heat load due to the machine tolerance. We found that the best methods was first to cut the GaAs crystal and then machine the recess to match the crystal size. This way the gap can be as small as 200 μm and the Q can reach $6*10^8$.

SIMULATION OF THE THERMAL FLOW

For the SRF gun, the gradient at the cathode is limited by the superconductor quench around the cathode and the gun's equator. The cathode's emission surface has a peak electric field that generates the heat load on the photocathode, as we have discussed earlier. The heat from the cathode flows to the Nb plug, should the plug's temperature rise above the critical temperature, Q will drop and the gun will be quenched.

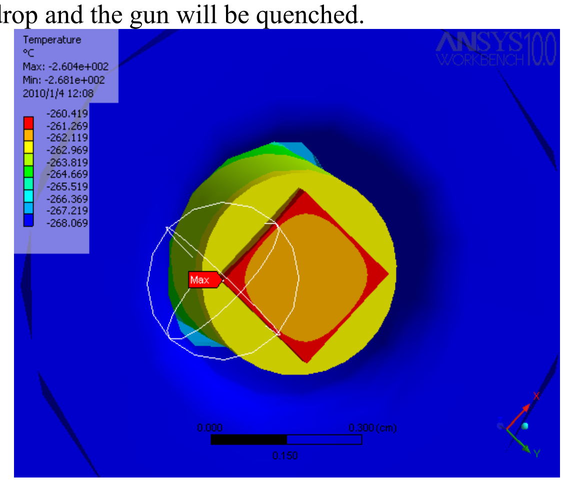

Figure 5: Temperature distribution at 5 MV/m, calculated with ANSYS. The picture shows the cavity walls (blue) , the tip of the plug (yellow) and the GaAs crystal (orange/red).

Our calculations showed that the power absorbed in the GaAs crystal dominates the heat load. Accordingly, the plug must be cooled sufficiently. The path length from the cathode to the liquid helium is about 1 cm. We undertook a thermal finite element analysis (FEA) using ANSYS10.0 to evaluate the relationship between the thermal flow to plug and the gun's geometry.

Since the RF loss on the cavity walls is 7% of it loss in the GaAs crystal, we ignored the former in the simulation. The heat load from the GaAs crystal depends on the stored energy in RF field. The FEA model included the cathode, half of the SRF cavity, and the geometry of the cathode's socket geometry. A mechanical clamp pressed the cathode plug against the cavity, we modelled the thermal contact resistance between the cathode and the cavity, assuming a pressure of 10 psi on the contact surface.

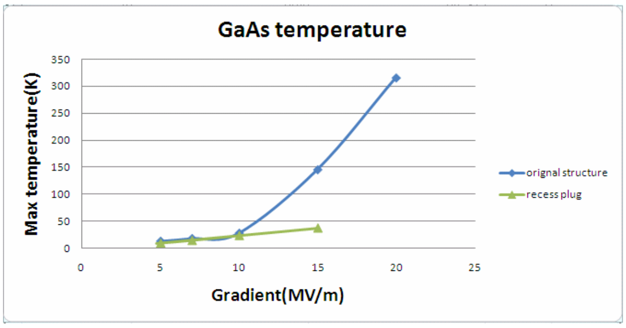

Figure 5: The GaAs crystal temperature simulation with two kind of plug designing.

Our analysis indicates that at a temperature of 4K, the original plug design will quench when the cathode above a 6 MV/m peak field. The new, recessed cathode plug can operate up to 13MV/m, which is the design gradient for this experiment. We consider that for higher gradients a gun with a choke structure should be used, it allows the cathode to reach at higher temperatures and be cooled with liquid nitrogen.

CONCLUSIONS

A GaAs polarized photocathode can be used in the superconductor RF environment and the 2K test show the GaAs will generate the heat from the RF field. The heat load from the cathode reflects a combination of doping and dielectric heat load. Our model shows that heavy doping generates much more heat than does dielectric tangent loss. We conclude that to keep the gun operation in high Q, we must assure that we shield the sides of the bulk crystal from the RF field when designing the recess holder in which to place the photocathode. For a low-current plug gun, the quench will occur at the cavity's wall around the cathode. Quenching limits the gun's peak electrical field.

REFERENCES

[1]R.Xiang et al" Low emittance polarized electron source base on superconducting RF gun" Proceedings of SRF2007,TUP66,Beijin,China

[2]J.Kewisch et al" The polarized SRF fun experiment" 2007 Particle Accelerator Conference,BNL-80018-2008-cp

[3] A. V. Aleksandrov et al.: "Experimental Study of GaAs Photocathode Performance in RF Gun", 1999 Particle Accelerator Conference,

[4]D.Homes et al "Superconducting RF photocathode gun for low emittance polarized electron beams" Proceedings of SRF2007,WEP02

[5] Tom Powers et al ”Theory and practice of cavity RF test system” Proceedings of the 12th international workshop on RF superconductivity,Newyork.US
[6] H. Padamsee, “RF Superconductivity for Accelerators”, Chapter. 5