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Heat load of a GaAs photocathode in an SRF electron gun*

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Abstract: A great deal of effort has been made over the last decades to develop a better polarized electron source for high energy physics. Several laboratories operate DC guns with a gallium arsenide photocathode, which yield a highly polarized electron beam. However, the beam's emittance might well be improved by using a superconducting radio frequency (SRF) electron gun, which delivers beams of a higher brightness than that from DC guns because the field gradient at the cathode is higher. SRF guns with metal and CsTe cathodes have been tested successfully. 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 a bulk gallium arsenide (GaAs) photocathode is normal conducting, a problem arises from the heat load stemming from the cathode. We present our measurements of the electrical resistance of GaAs at cryogenic temperatures, a prediction of the heat load and verification by measuring the quality factor of the gun with and without the cathode at 2 K. We simulate heat generation and flow from the GaAs cathode using the ANSYS program. By following the findings with the heat load model, we designed and fabricated a new cathode holder (plug) to decrease the heat load from GaAs.

Key words: SRF gun, GaAs photocathode, heat load, 2 K test

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1 Introduction

The International Linear Collider (ILC) and similar projects require low emittance, highly polarized electron sources. Previously, traditional DC guns were employed to generate polarized electron beams. The ILC demands that the vertical emittance at the entrance of the main linac is 0.02 μm; if a DC polarization electron gun is used, a damping ring will be needed, which will incur further expenditure. Our simulations show that the 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 a higher brightness than DC guns, in the past only the latter have been used to generate polarized electron beams. One reason is that a very good vacuum is essential for operating the GaAs photocathode to minimize the destruction of the cathode surface by ion back-bombardment. DC guns typically have vacuum pressure lower than 10^{-9} Pa, compared with 10^{-7} Pa in a normal conducting RF gun.

Experiments at BINP Novosibirsk in the late 1990 s demonstrated that the quantum efficiency of GaAs in a pulsed normal-conducting RF gun was quickly destroyed [1]. 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 [2, 3] because the superconductor surface acts as a cryogenic pump so that the vacuum pressure can be maintained at better than 10^{-9} Pa.

The SRF gun with and without a bulk GaAs

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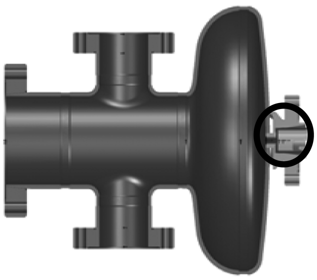
crystal was tested at the Jlab. A heat load model of GaAs in the microwave field was made. It matches the measurement result well. The heat generation and flow from the GaAs cathode simulated using the ANSYS program. Following the findings with the heat load model, a new cathode holder (plug) was designed and fabricated to decrease the heat load from GaAs.

2 SRF gun 2 K test

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 at the back of the gun which holds the GaAs cathode. Fig. 1 shows the BNL plug gun with the plug's geometry, 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: HNO_3: H_3PO_4 = 1:1:1 ratio) followed by high pressure rinsing. The cavity wall was etched to remove 10 μm, the plug was etched 20 μm and two probes were etched 5 μm at 15 ℃. The cavity was tested in a vertical cold test at JLab [4].



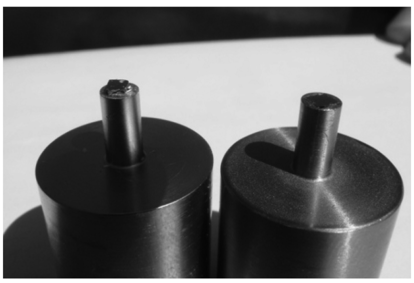


Fig. 1. The top picture is the geometry of BNL half cell 1.3 GHz plug gun. The Nb plug is located inside the circle. The bottom picture is the fabricated Nb plugs. The GaAs crystal is welded on the top of Nb plugs. The left one is of flat tip design. The right one has a recessed structure that the GaAs crystal merges into the Nb plug, which is different from the original design shown on the left. The GaAs crystal size is 2 mm × 2 mm × 0.6 mm.

The plug gun was first tested without a GaAs cathode. After cooling it down to 2 K, the Q_0 factor was measured (shown in Fig. 2), the square point shows that the Q_0 factor in the flat range is 3×10^9. During the second cool-down, a GaAs cathode of 2 mm × 2 mm × 0.6 mm in size was used and the Q_0 dropped from 3×10^9 to 1.78×10^8. In the DC gun, the temperature increase of the GaAs photocathode comes from the laser power. In the RF gun, not only does the laser power induce an increase in heat, but also as the electric field penetrates into the GaAs cathode, causing dielectric losses, the magnetic field induces the surface current to generate heat. That is the reason why Q_0 is low in a SRF gun with a GaAs crystal. The flatness of the Q_0 curve with the GaAs cathode indicates that the cavity and the plug did not quench in the field lower than 7 MV/m. However, the drop was much larger than initially estimated. Careful analysis is necessary. The heat load model is shown in the next two sections.

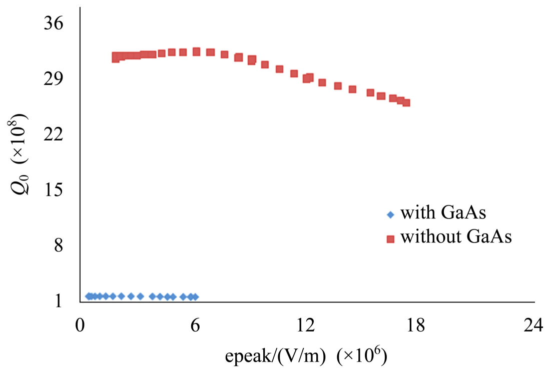


Fig. 2. Quality factor vs. gradient of BNL plug gun at 2 K. The triangle points represent the gun without GaAs, the Q_0 factor in flat range is 3×10^9, the square points show the Q_0 factor of the gun with a 2 mm × 2 mm GaAs crystal.

3 GaAs surface heat load

The GaAs crystal used for the photocathode is zinc doped (p type) 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 2 mm by 2 mm and is 0.6 mm thick. The resistive heat load of the GaAs crystal can not be neglected due to the high p-doping of the crystal. The dissipated power per unit area due to Joule heating is Ref. [5]

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

The surface resistance $R_s = \dfrac{1}{\sigma\delta}$ 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 it is essential to know the resistivity of GaAs at 4 K. The manufacturer specifies it as 3.4×10^{-2} Ω·cm at 290 K. The GaAs photocathode resistivity measurement was performed by the Magnet Division of BNL. To get an accurate result, the temperature of GaAs drop is very carefully measured. The temperature drop from 300 K to 4 K takes 6 h, and the temperature increased all through the night. The result measured from the processing of the temperature drop has vibration because of controlling difficulties. Then the GaAs resistivity curve was measured when the temperature increased.

The resistivity at 4 K was measured 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, it is independent of the temperature. The factor is obtained for our device via taking a measurement at room temperature and comparing it with the manufacturer's specification.

Figure 3 shows the measured resistivity during the cool-down to 4 K. 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. There is little variation in temperature, as in GaAs the Fermi level is below the valance level. At 4 K, the resistivity is 1.1×10^{-2} Ω·cm.

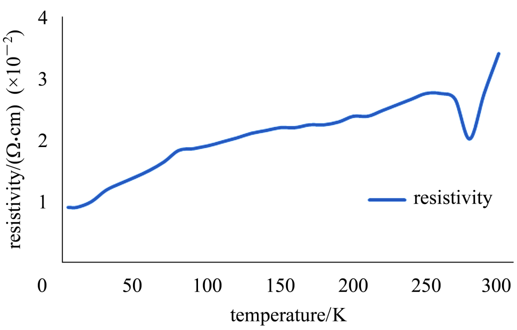


Fig. 3. The GaAs resistivity in temperatures from 300 K to 4 K. At 300 K, the resistivity of 3E18 Zn doping GaAs is 3.4×10^{-2} Ω·cm. The resistivity of GaAs decreases to 1.1×10^{-2} Ω·cm at 4 K.

Knowing the resistivity of the gun's boundary and geometry, the surface magnetic field can be calculated using the SUPERFISH computer code [6]. To compare these findings with the experimental ones, the peak field is normalized to 5 MV/m. Table 1 shows the GaAs parameters used in the simulation and calculation.

Table 1. GaAs photocathode parameter.

name	parameter
thickness	0.6 mm
carrier concentration	3×10^{18}/c.c(Zn)
surface peak field	5 MV/m
size	2 mm × 2 mm
loss tangent	0.06
permeability	12.9
permittivity	12.36

The magnet field increases linearly from the center of the crystal to its edges. With the value of the magnetic field and surface resistance, the resistive heat load is calculated and it is found that a 200 mW heat load is generated from the emission surface of the GaAs crystal and 1 W from its edge. The GaAs surface heat load in the RF field depends on the doping level. The total heat generated from the GaAs surface is 1.2 W when the gun's peak field is 5 MV/m.

4 GaAs body heat load

GaAs experiences a dielectric loss (independent of the doping level) when the RF field penetrates into the crystal. So the heat load due to dielectric loss is called body heat load.

The power loss in the semiconductor body is

$$P=\int_0^d \omega\cdot\varepsilon\cdot A\cdot E(x)^2\cdot\frac{\varepsilon_1}{\varepsilon_2}\mathrm{d}x\,, \qquad (2)$$

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

$$E(x)=E_0\mathrm{e}^{-\frac{x}{\delta}}\,. \qquad (3)$$

With the photo cathode peak field $E_0=5$ MV/m and the parameter in Table 1, 230 mW of heat will be generated inside the GaAs wafer. The total heat load due to resistive and dielectric losses in GaAs is 1.43 W at 5 MV/m. The gun's stored energy is 3.25×10^{-2} J, so Q_0 will drop to 1.8×10^{8}, which matches the test results well. The detail heat load results are shown on Table 2.

Table 2. Heat load from the SRF gun with GaAs.

heat load/mW	
name	parameter
GaAs emission surface	196.8
GaAs edge surface	928.1
GaAs body	231
Nb	89
total	1462
Q_0	1.82×10^8

From this table, one can see that the heat generated at the GaAs edge is dominant in the gun heat load model.

5 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 (Fig. 4). The recess was machined into the plug's surface by electron discharge machining. The GaAs crystal is mounted onto the plug with a small amount of Indium solder, carefully limiting it to the rear side of the crystal so that no indium is exposed to the RF field.

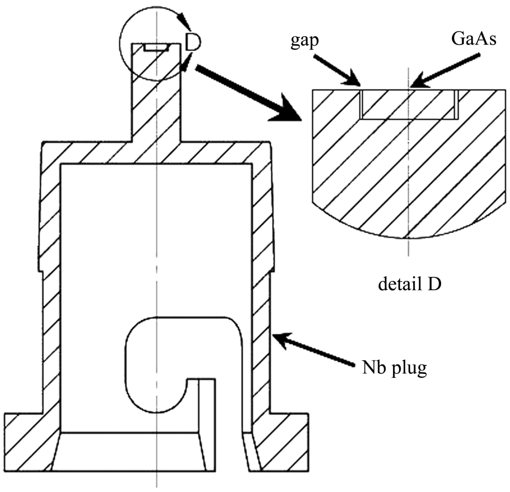


Fig. 4. The drawing of the Nb plug with a GaAs photocathode. The top right drawing is the detail of recess structure. There is a 200 μm gap left between the GaAs edge and niobium due to machine tolerance.

Because of machining tolerances, a small gap remains 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 machine tolerance. The best method is to first cut the GaAs crystal and then machine the recess to match the crystal size. In this way the gap can be as small as 200 μm and Q_0 can reach 6×10^8. The procedure of plug making has been proved.

6 Simulation of the thermal flow

For the SRF gun, the gradient at the cathode is limited by the superconductor quench around the cathode. The cathode's emission surface has a high electric field that generates the heat power on the photocathode, as discussed earlier. The heat from the cathode flows to the Nb plug and if the plug temperature rises above the critical temperature, Q_0 will drop. If the heat power from the GaAs can not be absorbed by the LHe effectively, the quench area will be increased and the whole gun will be quenched.

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

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

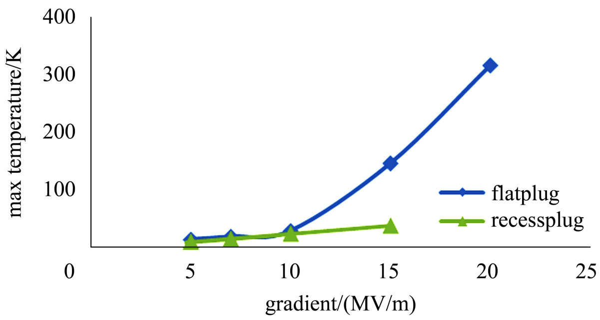


Fig. 5. The GaAs crystal temperature simulation with two kinds of plug design. The square curve shows the GaAs's peak temperature from the original plug design. The GaAs peak temperature reaches 150 K at 15 MV/m, which is the design peak field. The triangle curve is the peak temperature from the recess structure design. The GaAs peak temperature is 38 K at 15 MV/m.

4.536 kg on the contact surface.

Our analysis indicates that at a temperature of 4 K, the original plug design will quench when the cathode is above a 6 MV/m peak field. The new, recessed cathode plug can operate up to 13 MV/m, which is the design gradient for this experiment (Fig. 5). For higher gradients, a gun with a choke structure should be used as it allows the cathode to reach at higher temperatures and can be cooled with liquid nitrogen.

7 Conclusions

A GaAs polarized photocathode can be used in the superconductor RF environment and the measurement of Q_0 factor at 2 K shows the GaAs will generate heat from the RF field. The heat load from the cathode shows a combination of doping and dielectric heat load. The doping heat load from the crystal surface and the dielectric loss come from the crystal body. Our model shows that heavy doping generates much more heat than dielectric loss tangent. We conclude that to keep the gun operating in high Q_0, one must assure that the sides of the bulk crystal must be shielded from the RF field when designing the recess holder in which to place the photocathode. The simulation indicates that for a low-current plug gun, the quench will occur at the cavity wall around the cathode. Quenching limits the gun's peak electrical field.

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