Polarized Electron Gun Beam Tests in mA range

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The high intensity polarized electron gun at MIT-Bates was designed as a prototype injector for the linac-ring version of eRHIC. The design implements a separate preparation chamber, load lock, large area cathode, ring-shaped beam and active cathode cooling. Very good vacuum conditions have been achieved in both the gun chamber and the preparation chamber. Reliable cathode transfer between the load lock, the preparation chamber and the gun chamber has been demonstrated. Beam tests have been conducted with currents from 50 nA to 5 mA. The results of these tests are discussed.

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1.   Introduction

MIT-Bates is investigating the possibility of building a very high intensity polarized electron gun for an Electron-Ion Collider. This development is crucial for the eRHIC project [1], as noted in the 2007 and 2015 NSAC Long Range Plans and the November 2009 report of the Electron-Ion-Collider Advisory Committee.

Modern polarized electron sources routinely produce average currents of hundreds of μA with a polarization approaching 90%. This intensity satisfies the requirements of the existing accelerator facilities. New advances in nuclear physics are expected with the development of the high luminosity electron-ion collider (EIC). The concept of such a collider has been discussed in the nuclear physics communities around the world for the past decade. One of the most advanced concepts for an EIC is eRHIC, based on the existing Relativistic Heavy Ion Collider (RHIC) complex located at Brookhaven National Laboratory (BNL).

Two alternative versions of the eRHIC collider have been developed. The ring-ring version is based on construction of an electron storage ring which will intersect the RHIC ion ring in one of the existing interaction regions. The linac-ring version of eRHIC offers the possibility of achieving a higher luminosity. This version is based on the construction of a very high intensity energy recovery linac (ERL). The linac version excludes the possibility of stacking bunches of electrons to achieve very high current. Therefore, the polarized electron source must be able to provide very high average current. In order to achieve a luminosity of $1 \cdot 10^{33} \, cm^{-2} s^{-1}$ an average current of at least $I_{av} \approx 50 \, mA$ is required. Meanwhile, the highest average current produced in existing polarized electron guns on test benches is in the mA region, but with rather low lifetimes.

One of the reasons for a short lifetime is the fact that all existing guns have a rather poor thermal connection to the cathode. A laser beam with very significant laser power has to be used for the photoemission and it overheats the crystal.

However, the most challenging problem for the lifetime is produced by ion back-bombardment. The electron beam ionizes the molecules of the residual gases in the cathode-anode gap, ions accelerate toward the cathode and damage it on impact. Tremendous efforts have been applied to improve the vacuum inside gun chambers, but ion back-bombardment remains the main limiting factor in gun intensity.

It has been shown that the ion damage depends on the size of the active area of the photocathode. With large photocathodes the damage is spread over a large area, allowing for longer lifetimes. It was also demonstrated [2,3] that the ions tend to damage mostly the central area of the cathode due to the focusing properties of the anode.

A large area cathode is used in the MIT-Bates gun. The new feature of the installation is the annular shape of the beam. A ring-shaped laser beam is formed with an axicon lens. The central area of the cathode, where most of the damage is concentrated, is not used at all. Also, active cathode cooling is implemented.

2. Gun layout

The installation consists of three chambers: the gun chamber, the preparation chamber and the load-lock chamber (Figure 1). The new cathodes are placed into the load-lock chamber, and after this chamber is pumped out, the valve between the load-lock and the preparation chamber

is opened and the cathodes are transferred into the preparation chamber with a magnetically-coupled manipulator. Heat cleaning and activation take place in the preparation chamber, and then the activated cathode is transferred into the gun chamber with a similar manipulator.

The GaAs crystal is mounted on a molybdenum puck with a tantalum cup pressing it to the puck. An indium foil is inserted between the puck and the crystal. During the first activation the foil melts and solders the crystal to the puck, providing a very good thermal connection.

The load-lock chamber is equipped with a rack that can hold up to four pucks. The rack can be moved in the vertical direction to place the desired puck against the fork of the manipulator.
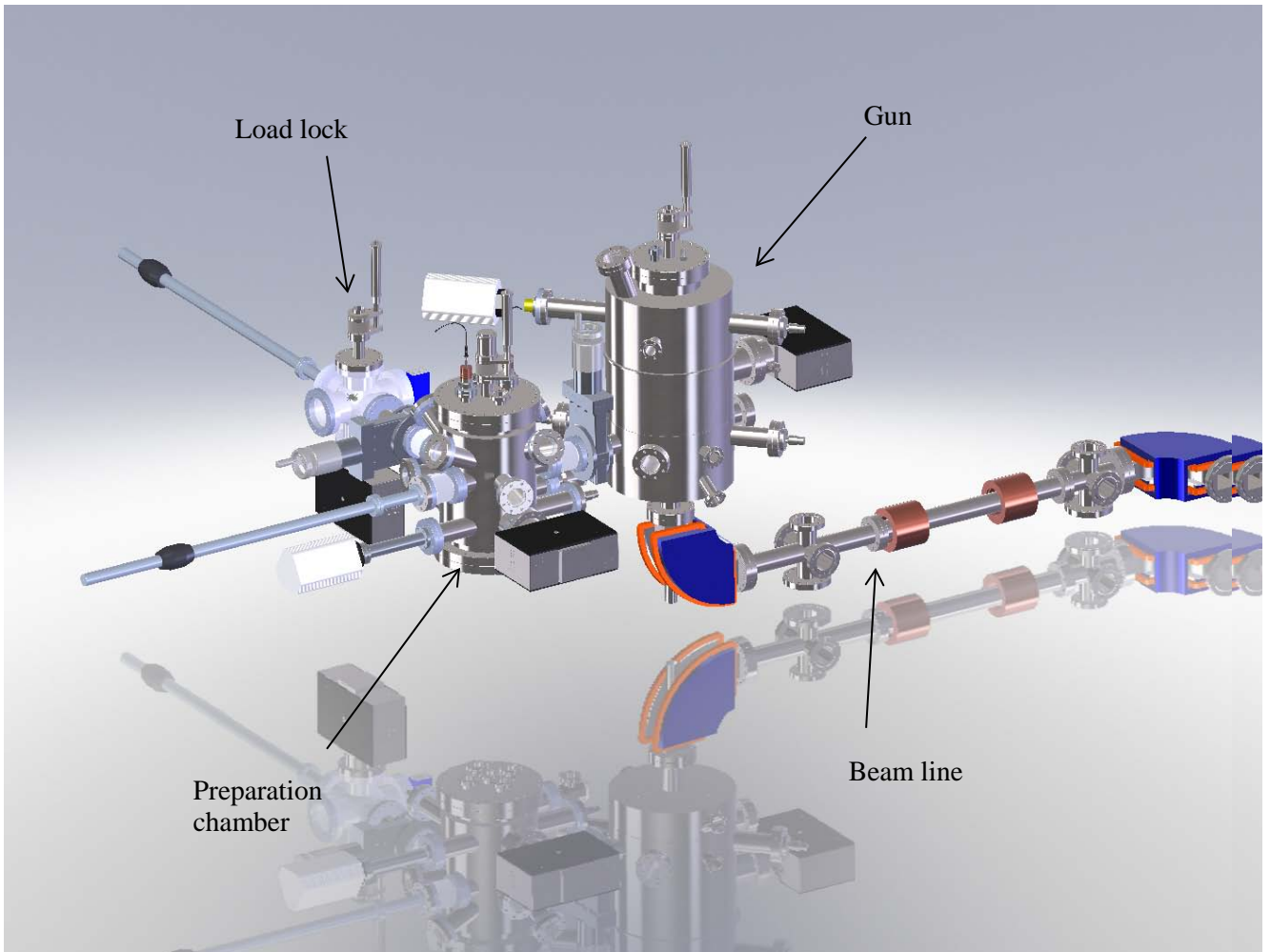

Figure 1. Gun and beam line layout.

The heart of the preparation chamber is a carousel that can be rotated and also moved in the vertical direction. The pucks are placed into receptacles on the wings of the carousel. The carousel moves the photocathodes to either heat-cleaning or activation stations. There are two heat cleaning stations and two activation stations in the preparation chamber. Each heating station is equipped with a PBN heater, a thermocouple for the reference measurements and a view port for a pyrometer. The activation stations are equipped with cooling rods, Cesium dispensers,

NF3 leak valves and windows for laser light. The cooling rods can be biased to apply negative voltage to the crystals.

The gun chamber is manufactured from stainless steel. The so-call "inverted gun" geometry is implemented. The cathode assembly is suspended on three long ceramic tubes. Two of these tubes serve as pipes to deliver the cooling agent to and from the cathode. Fluorinert is used as the cooling agent. This liquid has virtually zero conductivity and very good electrical strength. Our measurements demonstrated that by varying the temperature of the cooling agent, we can apply up to 40 W of laser power to the GaAs crystal while keeping the cathode at room temperature.

The third tube serves as a conduit for the HV cable. The working voltage of the cathode is 120 kV. An additional ceramic rod attached to a Linear Transfer Mechanism (LTM) at the top of the gun chamber moves the cathode in the vertical direction, allowing a gap to open between the cathode and the heat exchanger, so that the puck with a crystal can be inserted through the side port using a magnetic-coupled manipulator. The conical shape of the interface between the puck and heat exchanger ensures self-centering and a good thermal connection.

The cathode assembly is surrounded by a polished field shield to prevent field emission. The gun was processed to 150 kV. After processing there are no signs of activity (measurable dark current or vacuum excursions) at the working voltage of 120 kV.

The anode is disconnected from ground potential and is biased to 1 kV in order to reflect the ions produced outside the cathode-anode gap that are trapped in the electron beam.

All three chambers are equipped with multiple view ports for observation during vacuum manipulation. Halogen bulbs installed in the vacuum chambers provide excellent illumination.

The beam line consists of two 90° dipole magnets, several focusing solenoids, steering coils and a beam dump. The beam propagation in the beam line was carefully modelled. It is extremely important to minimize the beam losses near the gun. At such high intensity even 10^{-6} losses could be fatal for the crystal. The simulations indicated that our losses will be much smaller than 10^{-6} up to the second dipole. Special attention was given to the "extreme" rays - electrons produced at the very edge of the crystal. Although the simulation suggested that even these electrons will not hit the walls, it is unclear how accurately the calculations include the influence of the tantalum cup, which produces a tiny step on the flat surface. In order to minimize the risk produced by the "extreme" electrons, the outer 1 mm of the crystal is screened during the activation, so the quantum efficiency of this area is very low.

The main feature of the beam dump is a water-cooled copper spiral that intercepts the beam. The spiral is electrically insulated from the ground to allow measurements of the current of the electron beam.

3. Vacuum conditions

The gun chamber is equiped with a 100 l/s ion pump and five 400 l/s NEG pumps. The preparation chamber has a 100 l/s ion pump and three 400 l/s NEG pumps. Additional ion and NEG pumps are distributed along the beam line and in the beam dump. All metal parts of the gun (including the chamber itself) were pre-baked to 400ºC, and baked to 200ºC after the final assembly. All other chambers were baked at 200ºC.

The pressure in both gun and preparation chambers is better than $1 \cdot 10^{-11}$ torr, dominated by hydrogen.

4. Beam tests

Freshly activated cathodes (bulk GaAs) have a QE of about 2 % at λ=804 nm. The ring-shaped laser beam is produced with an axicon (conical) lens.

The beam was tuned through the beam line and into the beam dump. The location, the shape and the size of the beam were measured in different location in the beam line using BeO targets at low (~100 nA) current. The data are in excellent agreement with the simulation results.

Initially a dark lifetime of ~200 hours was measured. Then the lifetime was measured with a beam current varying from 0 to 10 μA. We obtained the same lifetime of 200 hours at all currents. This is a very strong indication that ion back-bombardment plays a very small role in the crystal degradation. However, the dark lifetime of 200 hours was much shorter than expected. We found a very small leak in the Fluorinert delivery system and fixed it. The dark lifetime improved very significantly. In fact it was too long to measure.
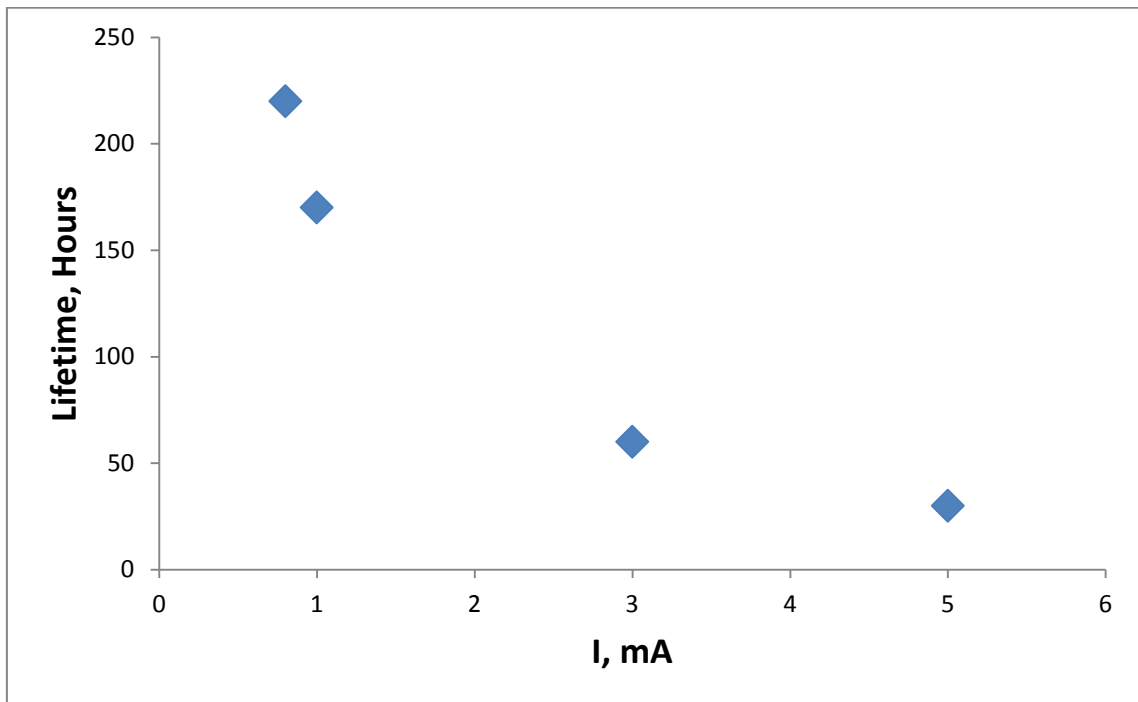

Figure 2. Lifetime measurements in mA range

Lifetime measurements were resumed at much higher currents. The results are presented in Figure 2. We measure lifetimes of about 170 hours at 1 mA and about 30 hours at 5 mA. We believe the lifetime is dominated by outgassing in the beam dump, which is relatively close to the gun.

- When we run the RGA in the beam line it shows a significant increase in pressure at high current, especially for hydrogen. But when we steer the beam anywhere in the beam line, the RGA readings do not change. This is a strong indication that we have little if any beam scraping in the beam line.
- We mapped the cathode QE after the long run and found that QE degradation is uniform across the crystal. This indicates that the degradation was caused by cathode poisoning, not by ion back-bombardment.

- During the long tests we lost 99% of QE of the cathode. But when we moved the cathode into the preparation chamber, several minutes of cesiation restored the QE to about 70% of its original value. This is another strong indication that ion back-bombardment plays a small role in cathode degradation. Ion back-bombardment damage usually can be fixed only by heat-cleaning.

At the beginning of the run the pressure in the beam dump was as high as $1 \cdot 10^{-9}$ torr at 1 mA beam current, at least 100 times worse than the gun vacuum. Apparently, some fraction of these gases travel through our rather short beam line into the gun, poisoning the GaAs cathode. However with time the vacuum in the beam dump improved, as the beam outgassed the beam dump surfaces. After an accumulated charge of 150 C was collected, the presure in the beam dump improved by a factor of 3 at the same 1 mA current. The lifetime improved accordingly (Figure 3).
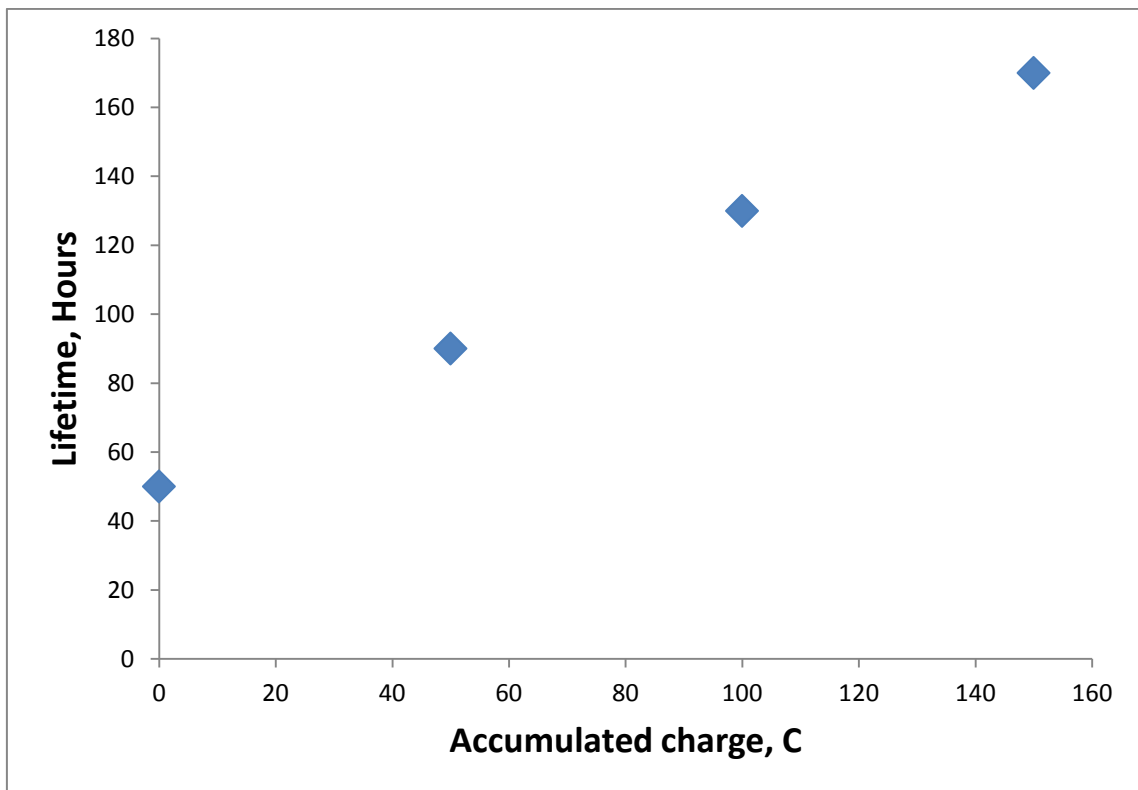

Figure 3. Lifetime at 1 mA beam current as a function of accumulated charge

We expect that the lifetime will continue to improve and we expect that the lifetime will be much higher when the gun is connected to a real, long beam line.

With a fresh crystal, the gun produces 5 mA current with a laser power of about 0.15 W. The gun is designed to take up 40 W of laser power. This means that even in the current configuration we can run 5 mA for about 300 hours before the cathode needs to be reactivated.

References

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