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High Intensity Polarized Electron Gun

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Abstract

A proposed new high-luminosity electron-ion collider requires a polarized electron source of extremely high intensity. The MIT-Bates Laboratory in collaboration with Brookhaven National Laboratory (BNL), developed a new polarized electron gun that can be operated at currents in the mA range and possibly higher. This paper describes the design of the gun and beam line and also presents the results of the beam tests.

Keywords: Polarized electron source.

1. Introduction

The development of highly polarized electron beams has led to many advances in nuclear and particle physics in recent decades. Polarized electron beams evolved from the development of the laser and semiconducting materials in the 1970's, when research in electron spin-polarization from III-V based photoemitters made it possible to produce electron beams with polarization using bulk GaAs photocathodes [1]. Since that time polarized electron sources have been established at numerous facilities worldwide [2-5].

Modern polarized electron sources routinely produce average currents of hundreds of µA with a polarization approaching 90%. This intensity satisfies the requirements of existing accelerator facilities. New advances in nuclear physics are expected with the development of a 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 decades. One of the most advanced concepts of an EIC is eRHIC [6], based on the existing Relativistic Heavy Ion Collider (RHIC) complex located at BNL.

Two versions of an eRHIC collider have been developed. The ring-ring version is based on the construction of the electron storage ring which would intersect the RHIC ion ring in one of the existing interaction regions. This project uses existing technology and does not require major R&D. However the maximum luminosity that could be achieved in this design is limited to approximately $1-2\cdot 10^{32}\, cm^{-2}s^{-1}$. Such luminosity is insufficient for the most exciting experiments planned for EIC.

The linac-ring version of eRHIC provides the possibility to achieve 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. 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 10 mA is required.

MIT-Bates, in collaboration with BNL, has investigated the possibility of building a very high intensity polarized electron gun. This paper reports the development of a prototype gun and the first results on studies of ion-induced damage of the photocathode. Ion-induced damage is the most crucial issue to address for this next generation gun.

2. High Intensity Gun - Major Challenges

Three main problems must be solved in order to build a polarized electron gun suitable for an EIC. Let us consider the requirements for the linac-ring version of eRHIC.

The first challenge is to achieve the necessary peak current. The time structure of the electron beam should match the structure of the ion beam, which has a duty factor of less than 1%. Taking into account a higher RF frequency for the electron accelerator, the duty factor of the electron beam is expected to be about 0.25%. With an average current of $I_{av} \approx 50\ mA$ this translates into a peak current $I_{peak} \approx 20\ A$. Fortunately, the gun doesn't have to produce such a tremendous peak current. The pulses generated by the gun could be much longer and then be compressed using appropriate RF techniques. However, the compression usually leads to emittance growth, so it is desirable to keep the compression factor low and generate the highest possible peak current in the gun. A gun that produces a peak current of several Amps will provide a good compromise. Such a current has already been achieved at SLAC (at much lower duty factor), and the problem of high peak current appears to be the least challenging one.

The second challenge is the heat load on the cathode. High average current means that a laser power up to several tens of Watts would be applied to the cathode. All existing polarized guns have a rather poor thermal connection to the outside world and can absorb less than 1W. Active cooling of the cathode is necessary to avoid overheating of the crystal. The cooling system must be compatible with the high voltage applied to the cathode and with UHV conditions of a polarized electron gun, and therefore presents a formidable engineering challenge.

The most difficult task is to achieve the high average current. The main problem is ion back bombardment. An electron beam ionizes molecules of the residual gases in the vacuum chamber; positive ions accelerate in the cathode-anode gap and strike the cathode, damaging the surface of the crystal. The effect is proportional to the product of the average electron current and the pressure in the gun chamber. It is difficult to expect a significant improvement of the vacuum conditions over present state-of-the-art installations, and the ion back bombardment effect limits the average current in existing guns to several hundreds of µA.

3. Large Area Cathode

Noticeably, all three problems could be addressed with increased cathode area. A large area cathode can produce a higher peak current since both space charge effects and surface charge effects [8,9] become less significant, and the heat transfer can be done more efficiently. Most importantly, the ion damage will be distributed over a larger area, resulting in a higher lifetime of the cathode.

Measurements conducted at TJNAF [10] with a green laser indicated that the lifetime increased by a factor of ~10 when the laser spot diameter was increased by factor of 4.

In a simplified model, the average current that could be extracted from the cathode, with the same lifetime, is proportional to the emitting area. In reality, the picture is more complicated. The anode hole acts as a focusing lens for the positive ions, and ions tend to do the most damage to the central area of the cathode. Existing electron guns use Gaussian shaped laser beams, with the maximum beam intensity near the cathode center, which is where the ion damage is most significant. For a high-intensity gun, it could be beneficial to form a ring-shaped laser beam, so the majority of the laser power is applied to the peripheral area of the cathode. The major difficulty in this approach is to avoid beam losses in the gun and its vicinity. Very detailed simulations including space charge effects must be conducted to design a large area cathode with a ring-shaped emission.

4. Ring-shaped laser beam

In the studies reported here, a fiber-coupled diode laser with a wavelength of λ=808nm was used for photoemission. The optical system is shown in Figure 1. The laser beam coming out of the fiber (0.4 mm diameter) has a very large divergence (full open angle $\approx$25°). The first focusing lens L1 produced an almost parallel laser beam. An axicon (conical lens) in conjunction with the second focusing lens L2 formed a ring-shaped laser beam at the location of the cathode. With the axicon removed from the system, lenses L1 and L2 formed point-to-point focusing between the output of the laser fiber and the cathode, resulting in a very small laser spot. A longitudinal translation of L2 allowed varying of the beam spot size. The L2 lens was mounted on a translation stage for precise translation in both transverse directions. With the axicon removed and the laser beam focused, one could scan the surface of the cathode using these translations and map the Quantum Efficiency (QE) of the crystal. .

5. The apparatus

The installation consisted of several chambers and the beam line. The gun chamber contained the anode and cathode assembly. The crystal activation procedure included heating the cathode to about 600^{o} C and deposition of Cesium and Fluorine on the atomically clean surface. This operation always led to some vacuum degradation therefore we conduct activation in a separate chamber (preparation chamber). It was separated from the gun chamber with a gate valve, and the cathodes could be moved between the two chambers in vacuum by a magnetically coupled manipulator.

It takes a long time to achieve a very good vacuum, and it was undesirable to vent the gun chamber or preparation chamber every time new cathodes were inserted into the installation. The load-lock chamber was used for this purpose. It was separated from the preparation chamber with a gate valve, and the cathodes could be moved between the two chambers in vacuum by a magnetically coupled manipulator.

The beam line consisted of two dipole magnets, three solenoidal lenses, several pairs of x-y correction coils, several BeO targets for the beam diagnostics and the beam dump.

Figure 2 shows a 3-D model of the installation.

5.1 The gun chamber

The gun implemented a so-called "inverse geometry" (see Figure 3). There were no outside ceramics and the gun chamber was manufactured from 316L stainless steel. The cathode assembly was suspended on three long ceramic tubes. Two of these tubes served as pipes to deliver cooling agent to and from the cathode. Fluorinert was used as a cooling agent. This liquid has virtually zero conductivity and very good electrical strength. The third tube served as a conduit for the high voltage (HV) cable. The working voltage of the cathode was 120 kV.

The GaAs crystal was mounted on a molybdenum puck with a tantalum retainer holding it onto the puck. To maximize conduction an indium foil was inserted between the puck and the crystal. During the first activation this foil melted and soldered the crystal to the puck providing a very good thermal connection. An additional ceramic rod attached to a Linear Transfer Mechanism (LTM) at the top of the chamber moved the cathode in the vertical direction, allowing a gap to open between the cathode and the heat exchanger. The puck with a crystal was inserted into this gap through the side port using a magnetically coupled manipulator. The conical shape of the interface between the puck and heat exchanger ensured self-centering as well as a good thermal connection (see Figure 4).

The cathode cooling tests were conducted with a thermocouple attached to the outer edge of the molybdenum puck. This part of the puck was the farthest from the cooling surfaces and it was expected that the temperature of the thermocouple is close to the temperature of the crystal. The tests were conducted in vacuum. The ring-shaped laser beam was directed to the crystal through a viewport at the bottom of the chamber. We found that we could apply at least 35 W of laser power to the cathode and keep it at room temperature by adjusting the temperature of the cooling agent.

The gun chamber was pumped by a 100 l/s ion pump and five 400 l/s NEG (Non Evaporative Getter) pumps. The chamber walls were made from thin (3 mm) stainless steel to reduce wall outgassing. The main body and all large metal parts were prebaked at 400°C. After that the chamber was fully assembled and baked at 200°C. The resulting vacuum was in the low 10^{-12} mbar scale, dominated by hydrogen. In fact, the evidence suggests that the main gas load was produced by the Residual Gas Analyzer (RGA) itself and when the RGA was off the vacuum was better.

The cathode assembly was surrounded by a polished stainless steel field shield to prevent field emission. The gun was processed to 150 kV. After the processing there was no sign of activity (measurable dark current or vacuum excursions) at the working voltage of 120 kV. The anode was disconnected from ground potential and biased to 1 kV in order to reflect the ions that were produced outside the cathode-anode gap and trapped in the electron beam [11].

5.2 The preparation chamber

The heart of the preparation chamber was a carousel that could be rotated and moved vertically. The interface between the carousel and the holding rod was lubricated with dichronite. The carousel could hold up to four pucks with crystals. The preparation chamber had two heat-cleaning stations and two activation stations. Each heat cleaning station was equipped with a PBN heater, a thermocouple for reference measurements and a view port for a pyrometer. The activation stations were equipped with cooling rods, Cesium dispensers, a NF^3 leak valve and windows for the laser light. The cooling rods could be biased to apply negative voltage to the crystals so the QE could be monitored during the activation.

The preparation chamber was pumped by a 100 l/s ion pump and two 400 l/s NEG pumps. The resulting vacuum was slightly worse than in the gun chamber, and dominated by hydrogen. During heat cleaning the pressure climbed into the 10^{-9}scale, but it recovered in 2-3 hours.

Activated crystals were moved into the gun chamber using a magnetically coupled manipulator.

5.3 The load-lock chamber

The load-lock chamber was the only unbaked chamber in the system. The load-lock chamber had a rack that could hold up to four molybdenum pucks. The rack could be moved vertically. After pucks were loaded and good vacuum conditions established in the load-lock chamber, the pucks were moved into the preparation chamber with a magnetically coupled manipulator. When the valve between the load-lock and preparation chamber was open, the pressure in the preparation chamber increased by factor of 10, but with the valve closed the vacuum restored in several hours.

The load lock chamber, the preparation chamber and the gun chamber were all equipped with view ports to control the vacuum manipulation and multiple halogen bulbs for illumination.

5.4 The beam line

It was extremely important to minimize beam losses near the gun. Extensive simulations have been conducted to design the gun and the beam line in such a way that the beam losses in the gun and in the first section of the beam line were significantly less than 10^{-6}. Special attention was paid to “extreme” rays – trajectory of electrons emitted at the very edge of the crystal.

The beam dump was located at the end of the beam line and the dump absorbs 100% of the beam. The vacuum in the beam dump was expected to be at least 100 times worse than in the gun. One of the main purposes of the beam line was to separate bad vacuum in the beam dump from good vacuum in the gun. The beam line was designed to be as long as our physical room space permitted. It had two 90º dipole magnets to minimize “direct view” effect. The poles of the magnets were designed in such a way that the magnets had the same focusing properties in both directions.

Two solenoidal lenses were used to control the beam size in the beam line. The beam line had a large aperture (50 mm) to minimize beam losses. The only small aperture – a tube 10 mm long and 15 mm in diameter was installed in the entrance of the beam dump to limit conductance between the beam dump and beam line. A third solenoidal lens focused the beam into the aperture making it small enough that less than 1% of the beam was lost at the aperture. After this aperture the beam size increased fast, making it more efficient to absorb the beam power in the dump.

Three 100 l/s ion pumps and six 400 l/s NEQ pumps were distributed along the beam line for effective differential pumping.

Several sets of steering coils controlled the beam location in the beam line. A set of retractable BeO targets were used to detect beam location, size and shape during the tuning. They were only used at low current (20-100 nA). Figure 5 shows the beam image on one of the targets.

5.5 The beam dump

The beam dump was a large chamber equipped with one 100 l/s ion pump and six 400 l/s NEG pumps. The end flange of the chamber was isolated from the ground so the beam current could be measured. A water cooled copper spiral was installed on the end flange to absorb the beam power. The dump was designed to absorb up to 6 kW of beam power (50 mA, 120 kV beam).

6. The test results

Cathode heat-cleaning and activation were conducted a number of times, and high Quantum Efficiency was demonstrated with a bulk GaAs crystal (about 2% at λ=804 nm; the QE for a high-polarization crystal should be similar). Transport in vacuum of the crystals between load-lock chamber, preparation chamber and gun chamber was performed routinely.

CW beam tests were conducted. The beam was successfully guided through both dipoles and into the beam dump, and the beam shape and size was in good agreement with the simulation results (Figure 5). A very good tune was established, with very small (if any) beam losses. These tests were performed at a low CW current (~100 nA) so as to be cautious during tuning.

Next, we conducted lifetime tests with a current varying from 0 to 10 μA (Figure 6). The lifetime at all currents was the same as the dark lifetime (about 200 hours). This was a clear indication that ion back bombardment produced a very insignificant contribution to the lifetime at these currents. However, the dark lifetime of 200 hours was lower than expected. We improved vacuum conditions in the gun by fixing an extremely small leak in the Fluorinert conduit. At the same time, we added additional NEG pumps in the beam line and the beam dump. As a result, the dark lifetime increased dramatically (too long to measure).

The lifetime was measured at currents from 1 to 5 mA (Figure 7). We achieved lifetimes of about 170 hours at 1 mA, 60 hours at 3 mA and 30 hours at 5 mA.

We believe the lifetime was dominated by outgassing in the beam dump, which was relatively close to the gun. When we ran beam in the mA range, the pressure in the beam dump increased to the 10^{-9} scale, at least 100 times higher than the gun pressure. The pressure in the beam line increased significantly as well. However, as we ran high current beam into the beam dump, the vacuum conditions slowly but steadily improved (Figure 8). The lifetime improved accordingly (Figure 9). It indicated that the beam dump surfaces were slowly outgassing and one could expect further improvement with time.

The indications that the lifetime was dominated by outgassing in the beam dump were very strong:

- When we ran the RGA in the beam line it showed a significant increase in pressure at high current, especially for hydrogen. This is natural since the aperture conductance for hydrogen is 3.5 times higher than for air. But when we steered the beam anywhere in the beam line, the RGA readings did not change. This was a strong indication that we had little if any beam scraping in the beam line.
- We mapped the cathode QE after the long run and found that the QE degradation was uniform across the crystal. This fact indicated that the degradation was caused by cathode poisoning, not by ion back bombardment.
- During the long tests we lost 99% of the 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 was 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.

7. Conclusion

MIT-Bates Laboratory in collaboration with BNL developed polarized electron gun that can produce at least several mA of beam current. Lifetime of the cathode was dominated by the outgazing in the beam dump and it was improving slowly as the beam cleaned the surfaces of the beam dump. Even a relatively short run (accumulated charge 150 C) improved the vacuum in the beam dump and the lifetime of the cathode by a factor of 3 (Figures 8 and 9).

We expect the effect of beam dump outgassing will be much lower, and therefore the lifetime will be much higher, when the gun is connected to a real beam line.

At 5 mA current the lifetime of 30 hours was measured. With a fresh crystal, the gun produced 5 mA current with laser power of about 0.15 W. The gun was designed to take up to 40 W of laser power. This means that even in the current configuration we could run 5 mA for about 300 hours before the cathode needs to be reactivated.

Acknowledgements

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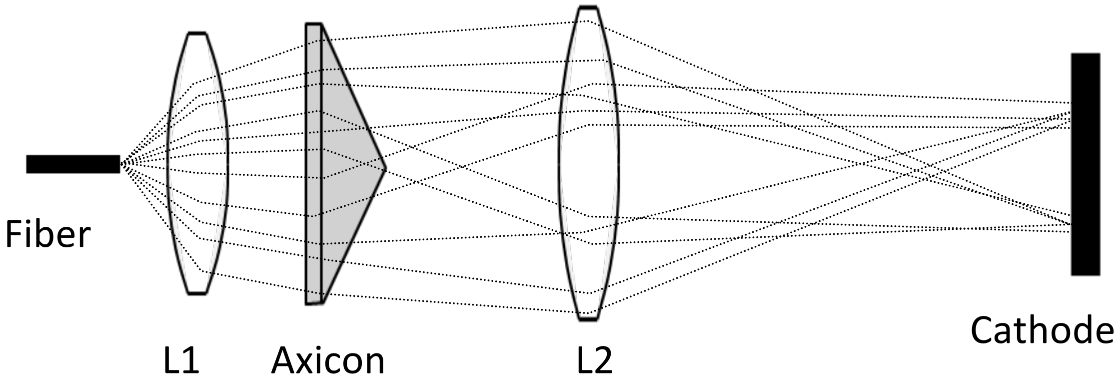

Figure 1. The optical system to form a ring-shaped laser beam.

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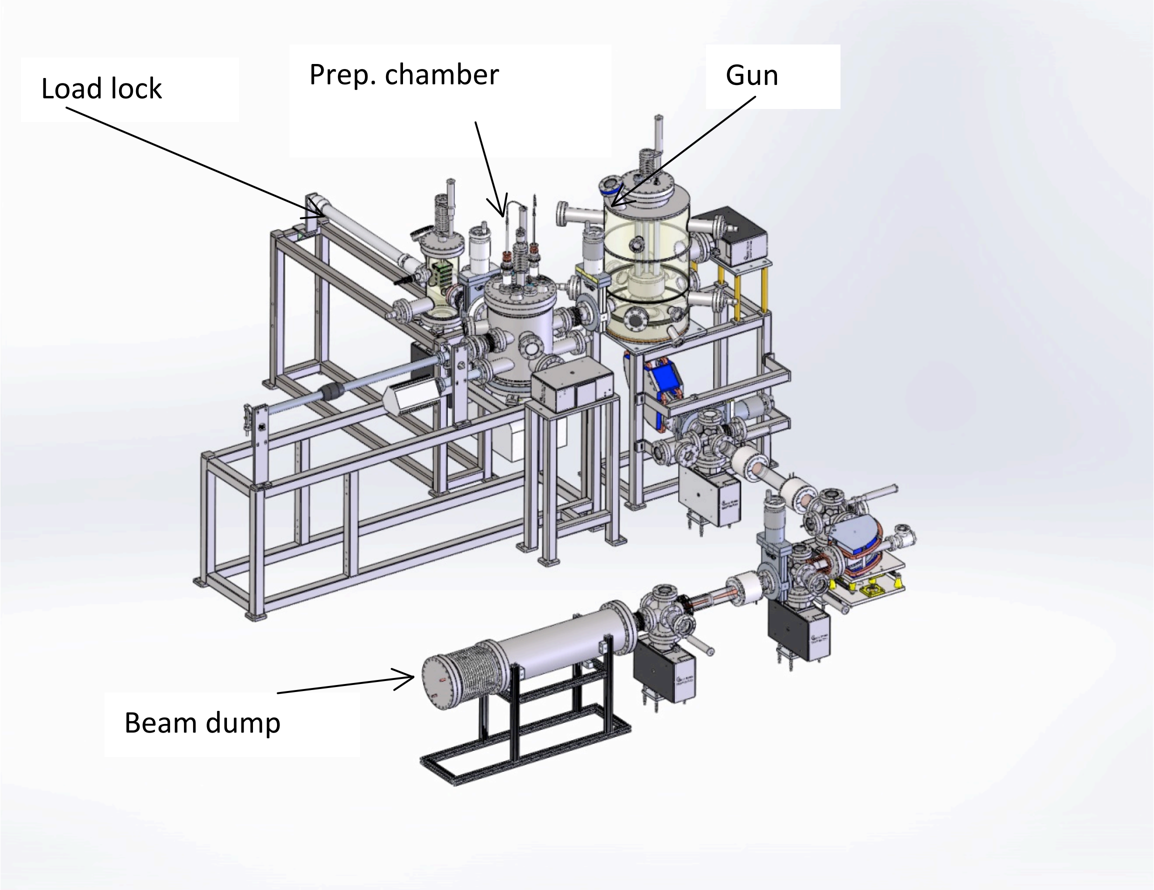

Figure 2. The 3-D model of the installation

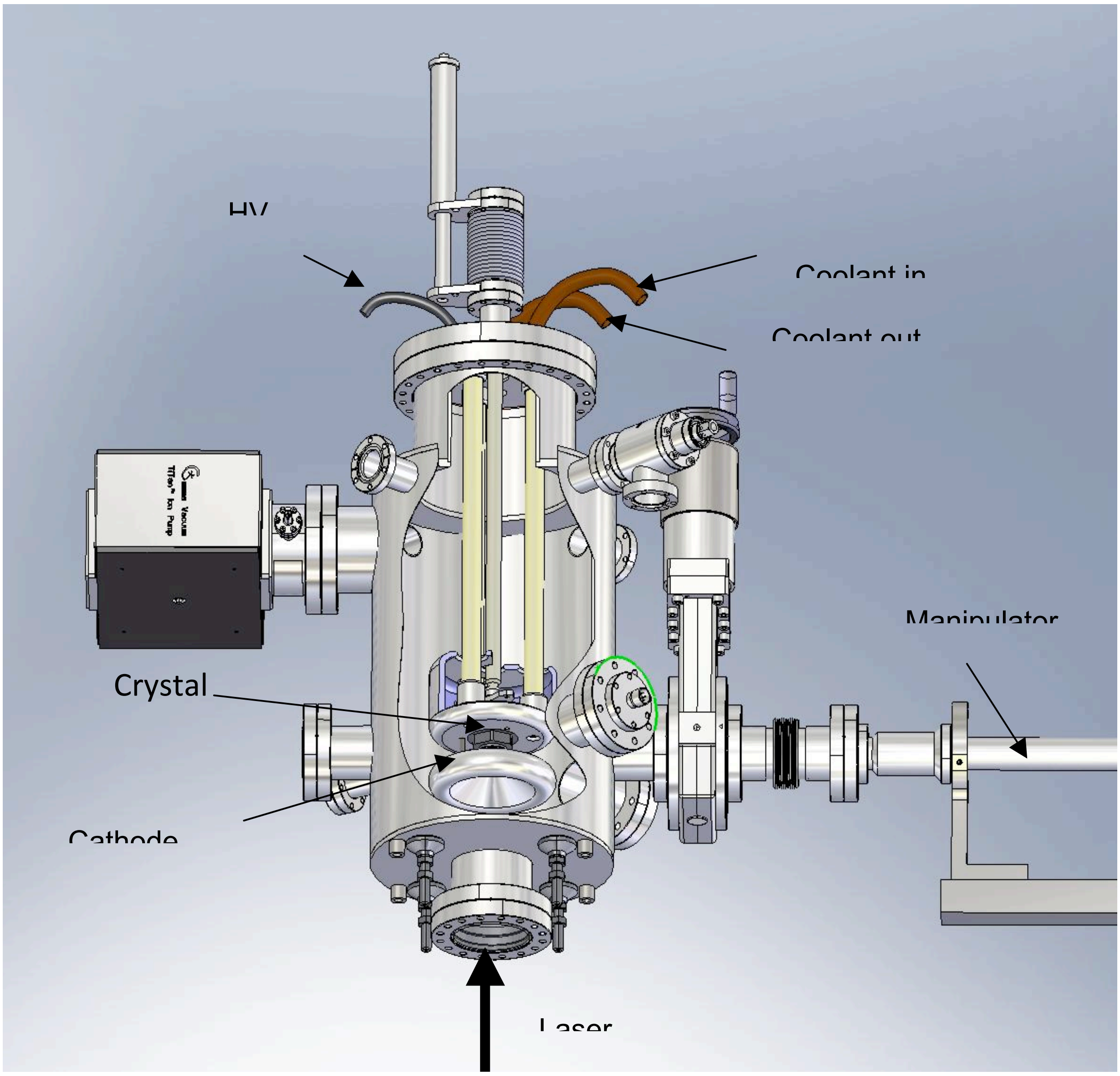

Figure 3. The gun chamber

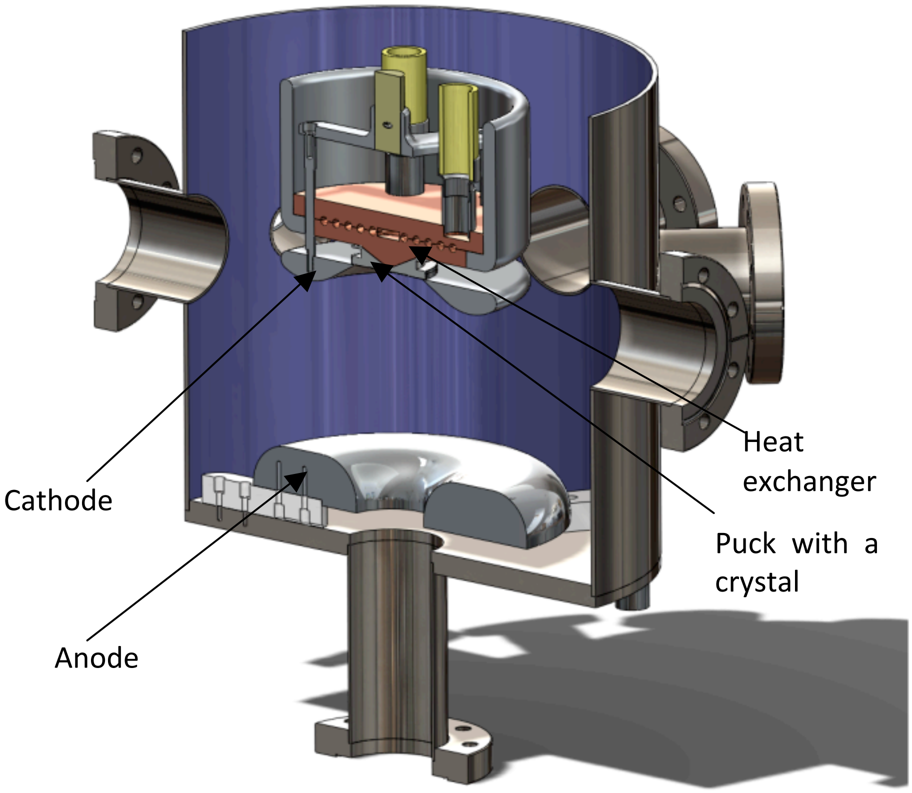

Figure 4. Anode and cathode assembly

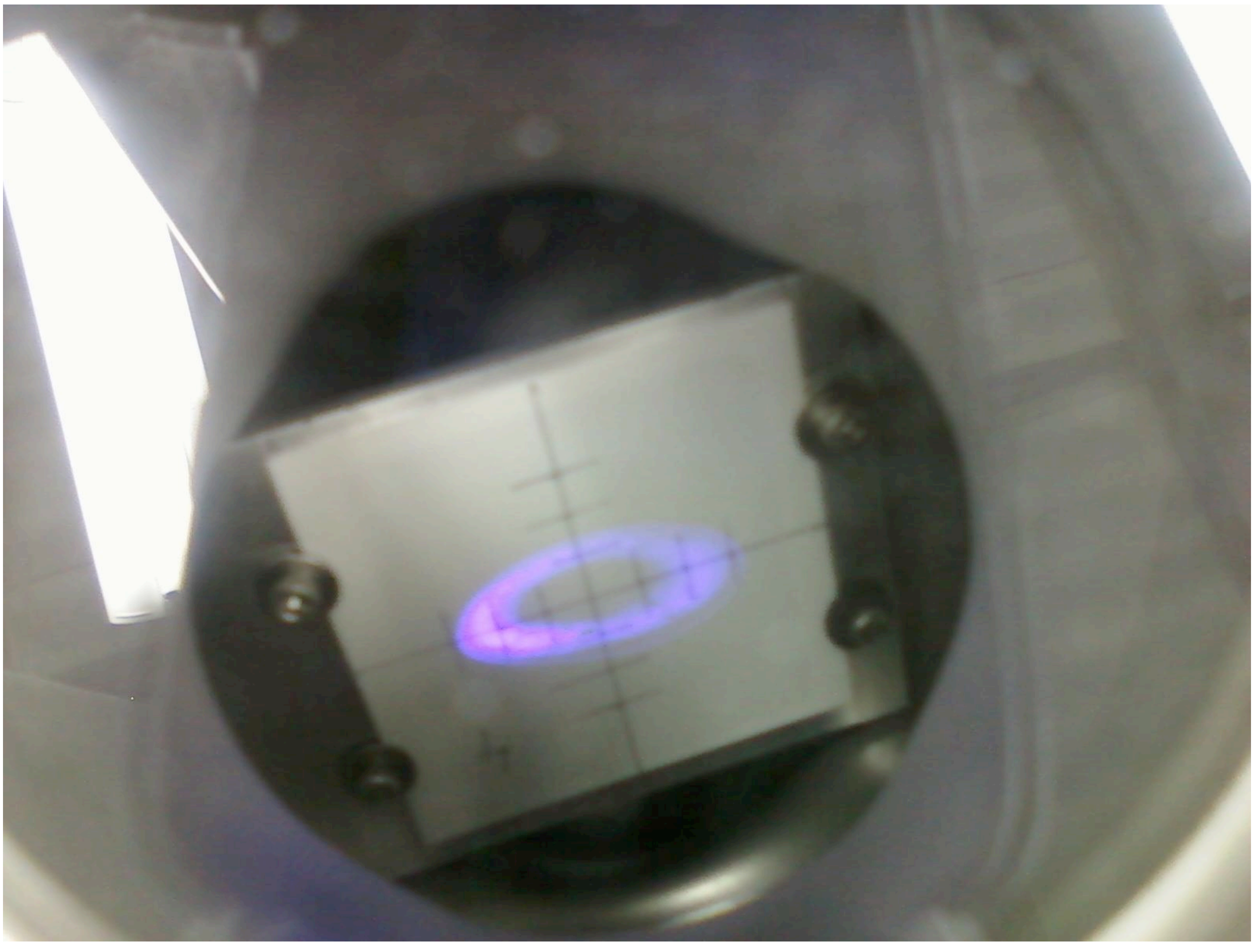

Figure 5. Ring shaped beam on BeO target after the second dipole magnet. The distance between the hush marks is 5 mm

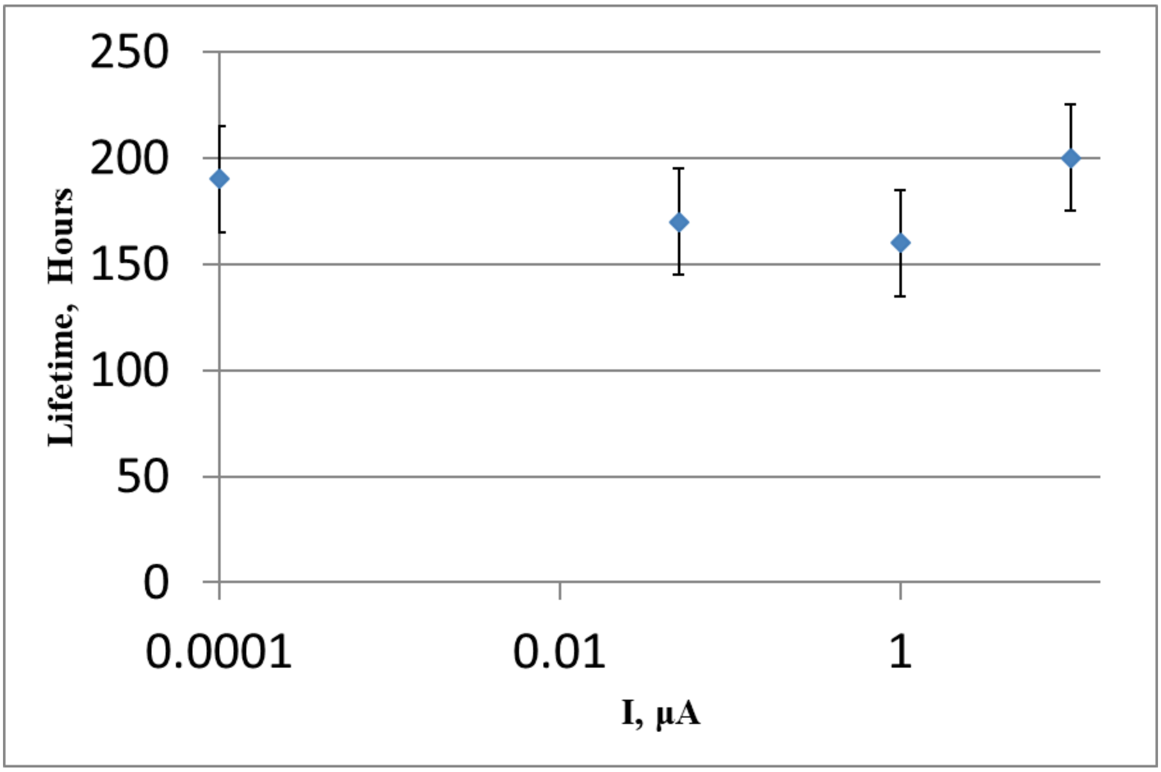

Figure 6. Lifetime at currents from 0 to 10 μA

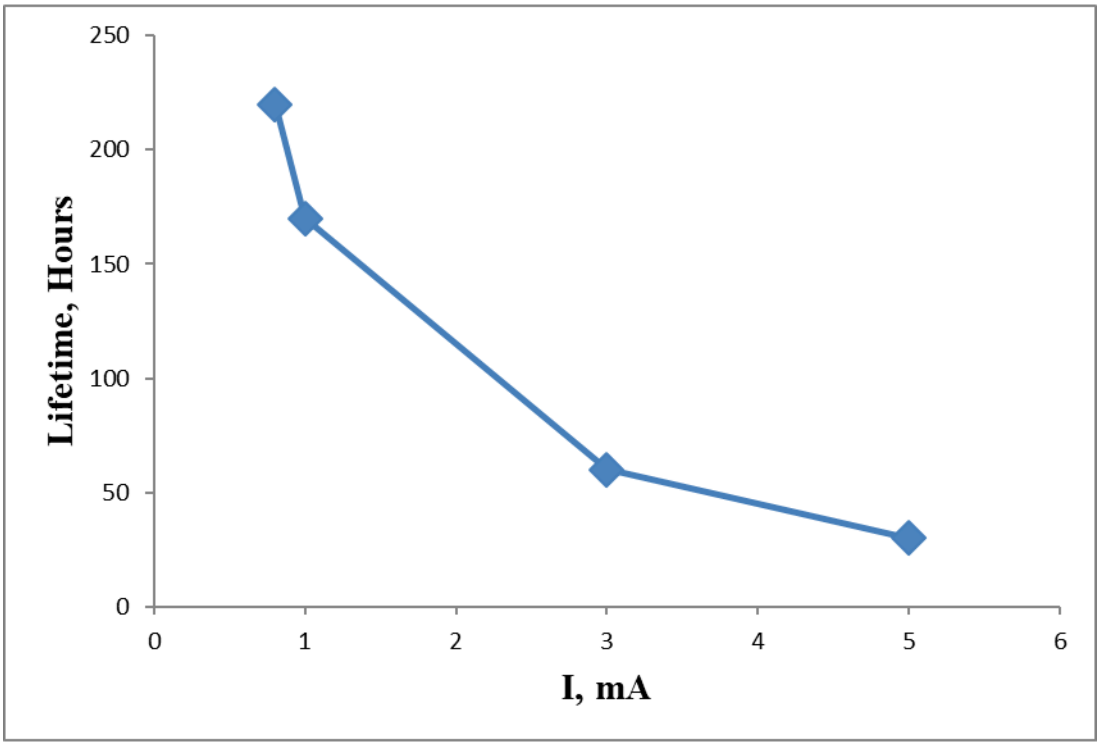

Figure 7. Lifetime at currents from 1 to 5 mA

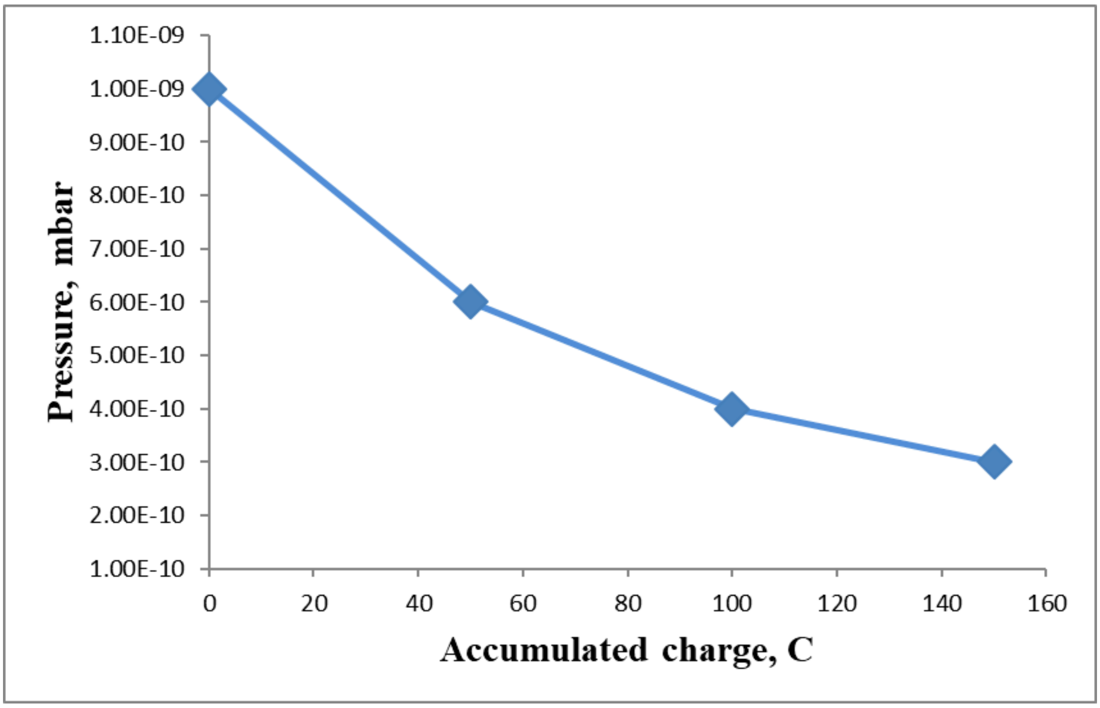

Figure 8. Pressure in the beam dump with 1 mA of beam, as a function of accumulated charge (i.e. running time)

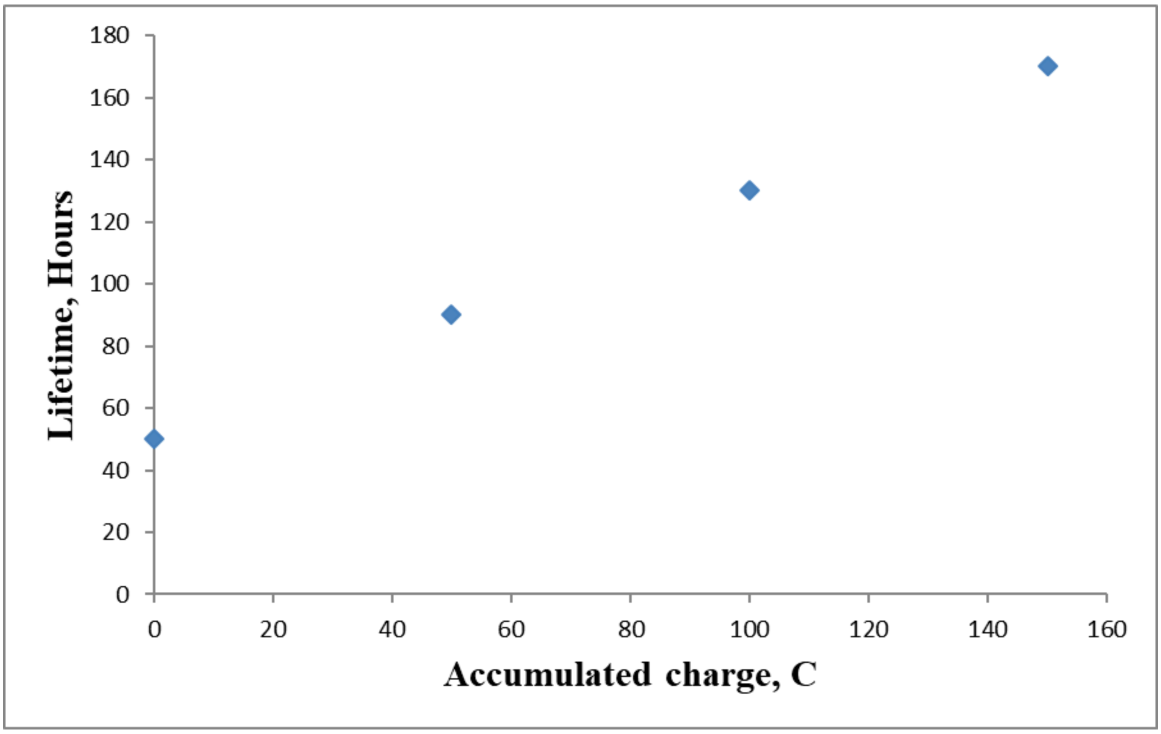

Figure 9. Lifetime with 1 mA of beam, as a function of accumulated charge (i.e. running time)