High Voltage Design of the BNL EIC Polarized Electron Source

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Introduction and Outline

This presentation will describe the development of the high voltage system for the prototype EIC polarized electron gun.

Several innovations were required along the way, including a semiconducting jacket to control stored energy in the cable between the power supply and gun, and a modification of the HV plug to allow for liquid cooling of the cathode.

Topics include:

- The HV system as part of the polarized electron gun development laboratory at Stony Brook University.
- The HV plug and the modification to allow for liquid cooling of the cathode
- The ceramic receptacles – both slightly conductive (brown) and non-conductive (white).
- Testing of the connected plug / receptacle

The Development Lab at Stony Brook University

The polarized e-gun development lab is located at Stony Brook University.

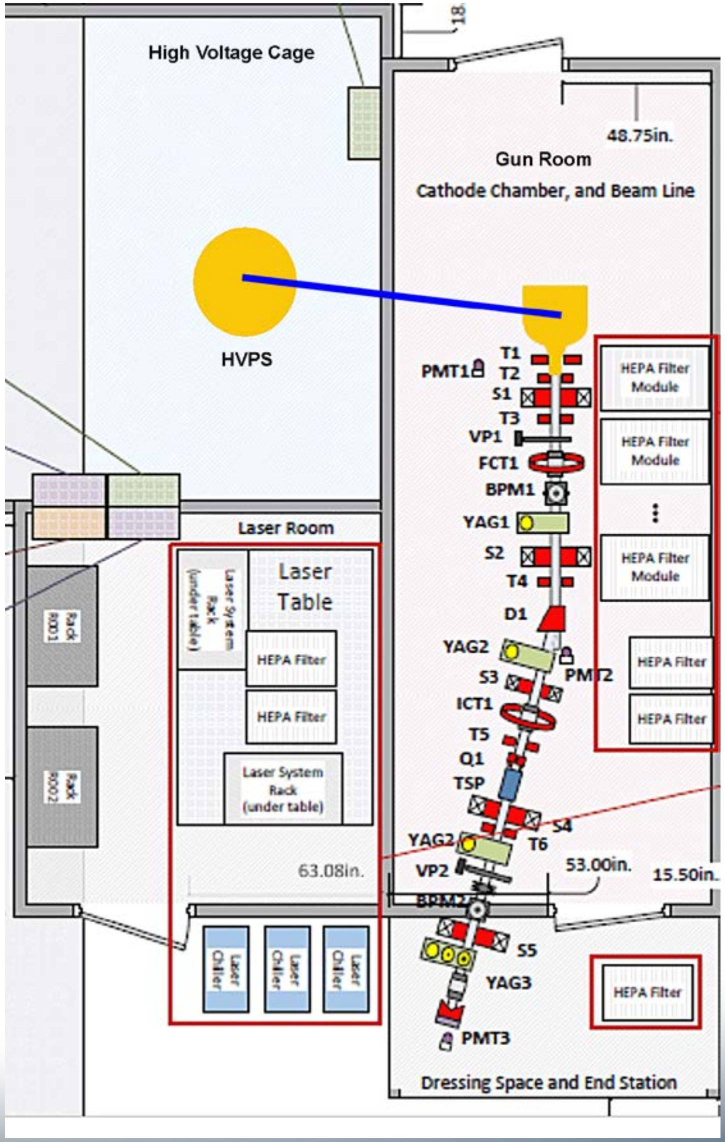
The layout is roughly in three parts:

1. The gun room with the e-gun and beam line.
2. The high voltage cage with the -400kV power supply.
3. The laser room, which also contains some magnet power supplies.

This lab had two constraints that affected the HV system design:

1. Oil could not be used because of the sensitive laser optics and ultra high vacuum.
2. SF6 could not be used because it was not permitted at the University.

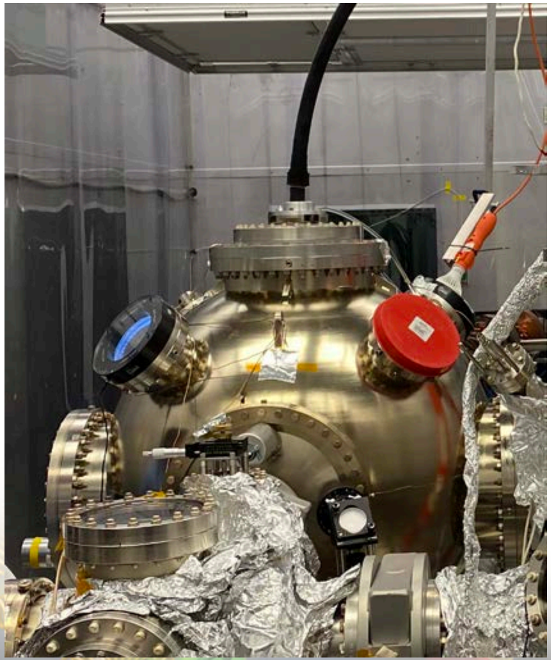
This led to a design without a resistor assembly right at the gun. Without this resistor and with the HVPS about five meters away, the stored energy in the cable between the HVPS and the gun had to be controlled a different way.



The High Voltage System

The HV system consists of:

1. A -450 kV Glassman power supply. We've used it with one of two stacks, which gives a rating of 6.5mA of 13mA at -350 kV.
2. A 105 MΩ conditioning resistor assembly.
3. An Arduino based Power over Fiber (PoF) current sensor at the HVPS output.



4. A high voltage cable, which can be connected to the corona ring on either side of the conditioning resistor. The output connection is repositioned with a pull cord.
5. A penetration through the aluminum wall between the power supply cage and the gun room.
6. A plug and receptacle connection to the gun.
7. A liquid cooling system for the cathode.

Each of these elements required detailed design and testing at every stage. We will now examine each of these elements in more detail.

The R30 Plug

The design starts with a spring loaded R30 plug. The R30 plug is a standard X-Ray machine connector, which has a nominal operating voltage ratine of 300kV, but with the possibility of being operated at higher voltages. We have tested the R30 at our required voltage of 350kV and above.

The reasons a spring loaded plug is essential are:

1. The calibrated mismatch in conical angle between the plug and the receptacle ensures that any voids between the plug and the receptacle are pushed up and out by plug deformation.
2. The known spring constant makes it simple to apply the correct deformation force.
3. The spring maintains pressure on the surface between the plug and receptacle, even after the elastic characteristics of the plug change with time.

The spring does apply a force which places the ceramic receptacle in tension. This is not the preferred state for ceramic. But that is addressed in the receptacle design.

Modifying the Plug for Liquid Cooling

This standard R30 design is then modified with spiral grooves to deliver cooling liquid to the tip of the plug. This is needed as this gun is designed for high current polarized beam.

The cooling liquid chosen in 3M FC-72 Fluorinert with the properties:

- Dielectric Strength: 38 kV for a 0.1” gap
- Electrical Resistivity: 1.0 x 10^{15} Ω-cm
- Specific Heat: 1100 J kg^{-1} $°C^{-1}$

Preliminary Testing of the Plugs

The connector tests were performed at the Dielectric Sciences facility.

The goal was to see if the plug could be run at 350kV. Then, we could condition at 350kV and run at 300kV. The standard R30 spring loaded plug without cooling grooves was tested first. This verified it could be operated at higher voltages. It also established a performance baseline that could be compared to the plug that was modified for liquid cooling

To test the liquid cooled plug, a Fluorinert circulation system needed to be added. This included a pump, flow monitor, pressure gauges, and a bubble trap / filling port. Because Fluorinert is difficult to seal, the pump / heat exchanger system needed to be designed to be compatible.

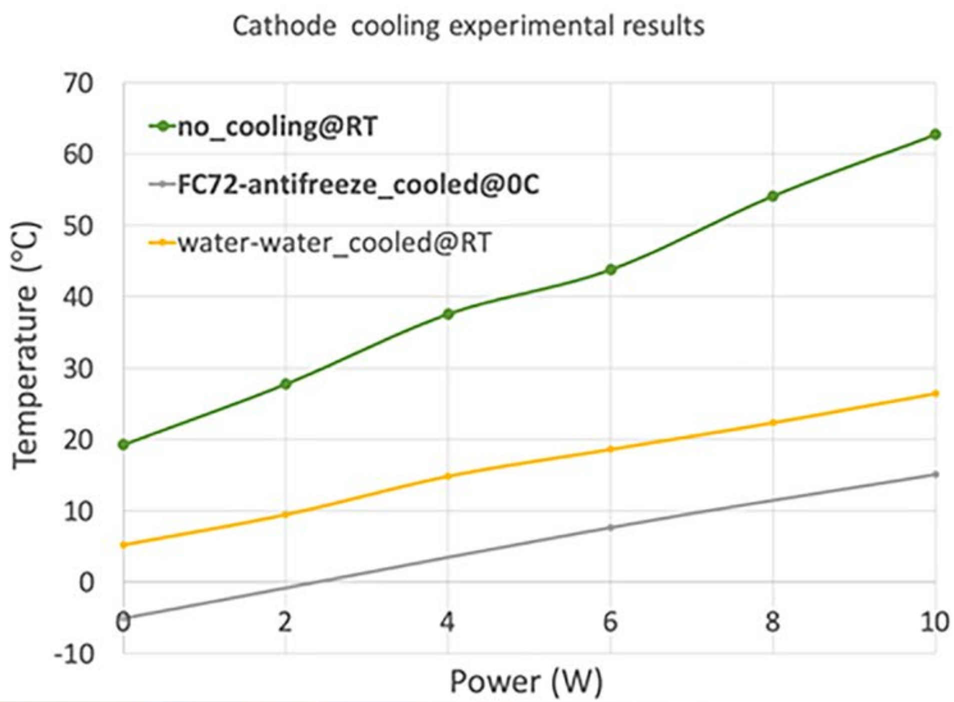
To minimize the amount of silicone grease that got into the grooves, rubber O-ring stock was put into the grooves prior to applying the grease, and then removed after. To see if the grooves were clear of grease and bubbles, a clear acrylic receptacle was built.

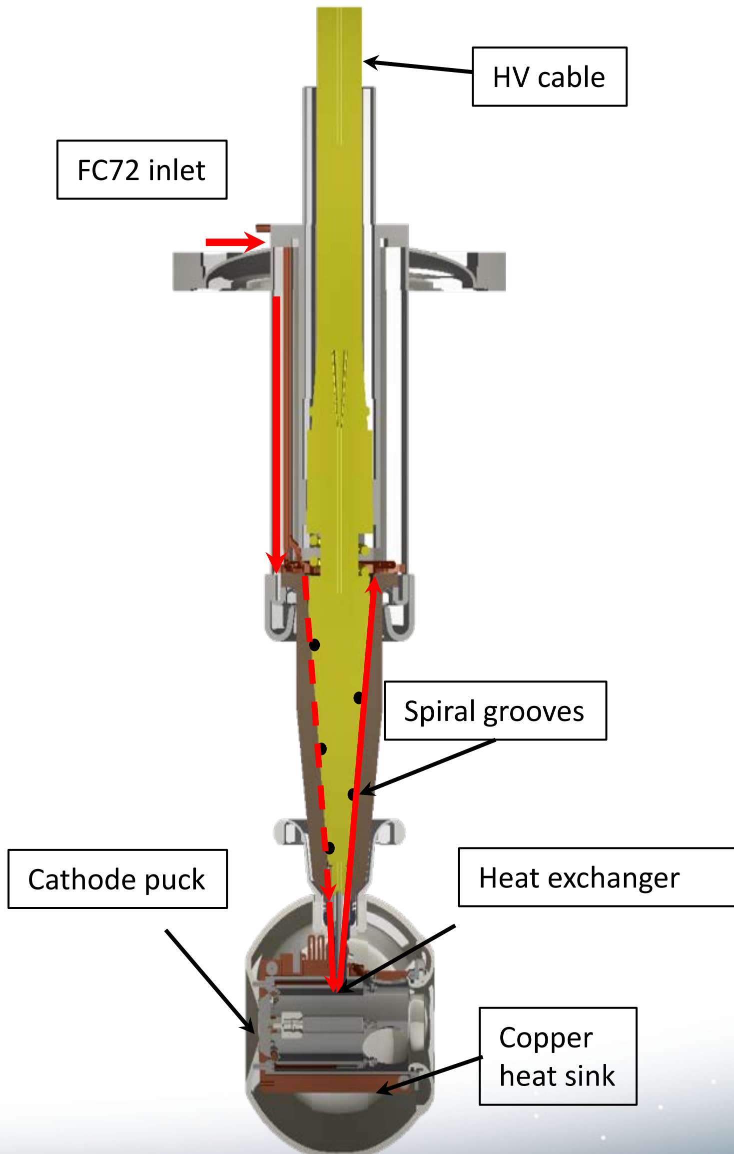
It was demonstrated, by bench testing, that by cooling the Fluorinert to ambient temperature, 10W of power can be removed from a cathode by our cooling system. It seems very possible that 25W can be removed operating a chiller to cool to below ambient temperature. The heat removed is from the absorbed laser power. Knowing what percentage of the laser power is reflected, makes calculating the upper limit of laser power possible.

Active Cooling of HVDC Guns

The EIC gun prototype was originally designed for high current operation and 10W of heat removal.

The chart below is the results of bench testing at our flow rate of 0.5gpm.





Liquid, Bubbles, and Grease

The rubber groove tubes did not prevent grease from going into the grooves after insertion. We ran the pumping system overnight to clear the grease and the bubbles.

The silicone grease in the grooves went into solution with the FC-72, saturating at about 3%. We had this solution tested by 3M who confirmed the electrical properties were not degraded.

Bubbles needed to be avoided. The liquid circulating system had two bubble traps – the fill tube and the flow meter. Bubbles were sometimes formed after the initial clearing by cavitation in the pump and at constrictions caused by pressure gauges. But these bubbles never reached the plug.

This system was run continuously for about six months without maintenance. A maintenance schedule will be developed.

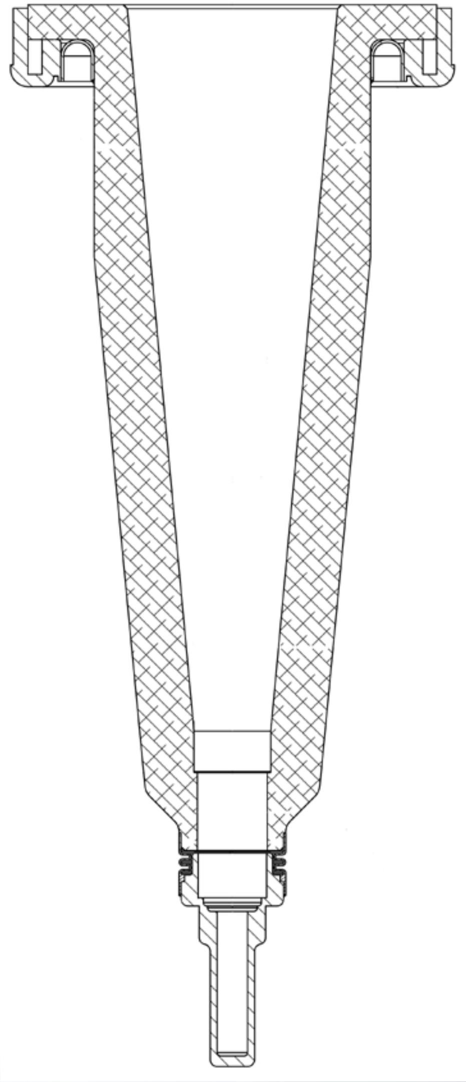
The Ceramic Receptacle

Two types of receptacles were tested – a brown ceramic with some conductive material, and a white ceramic with no conductive material added.

The idea behind the brown ceramic was that the trapped electrons can discharge, resulting in a more uniform potential distribution. But there were problems in manufacturing. The resistivity of the brown material was not well controlled during manufacturing and varied widely. Manufacturing six ceramic elements only produced one viable receptacle. Fortunately, one was all we needed.

After two years of intermittent operation, we are still using the same receptacle we first installed.

In use, the brown ceramic had one other problem. It absorbed the heat of the Non Evaporative Getter Pump (NEG) bakeout much more than the white ceramic would have. Because of this, the NEGs were baked at a lower temperature to prevent the weakening of the brazed joints tip.



Ceramic Receptacle Factory Tests

To accommodate the force of the plug spring, the walls of the ceramic receptacle were made thicker, up to the internal step where much of the force is applied.

To test the strength of the ceramic in tension, we compressed the plug string to twice the normal value, which resulted in twice the operating force. There was no damage to the ceramic.

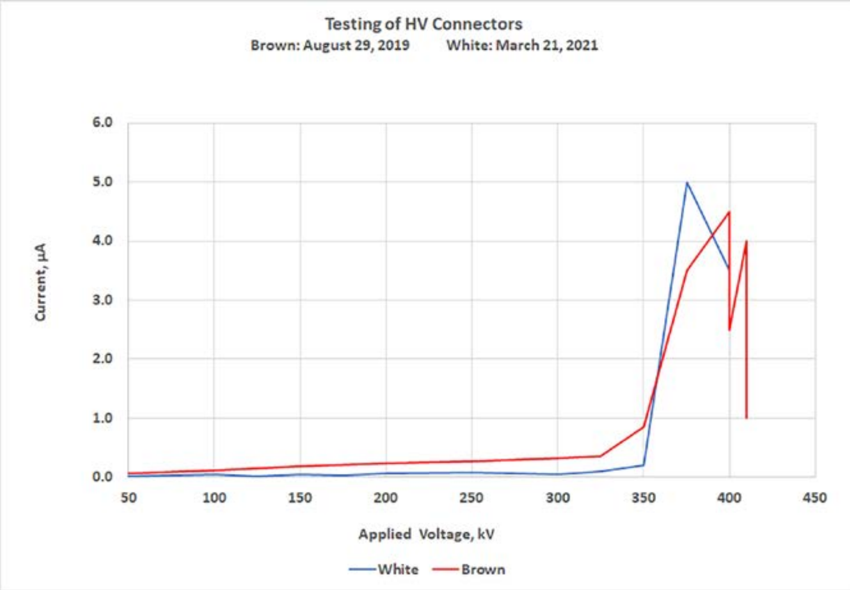
Accurate resistance tests at the factory were only useful to find ceramics where the resistivity was far too low.

Accurate tests of resistance were made during connector testing shown on the next slide.

Testing of the Plug with the Ceramic Receptacle

Both the brown and the white ceramic receptacles were tested with 20 psig SF6. A cathode shroud was placed at the tip of the receptacle and Fluorinert was flowing in the cooling channel in both cases.

The resistance of the brown receptacle in this test can be seen to be about 9 x 10^{11} Ω. Later testing in the gun at 350kV indicated a lower resistance of 3.2 x 10^{11} Ω.



The two resistance tests were taken three years apart, with the second test taken after many months of operation. Perhaps the resistance changed.

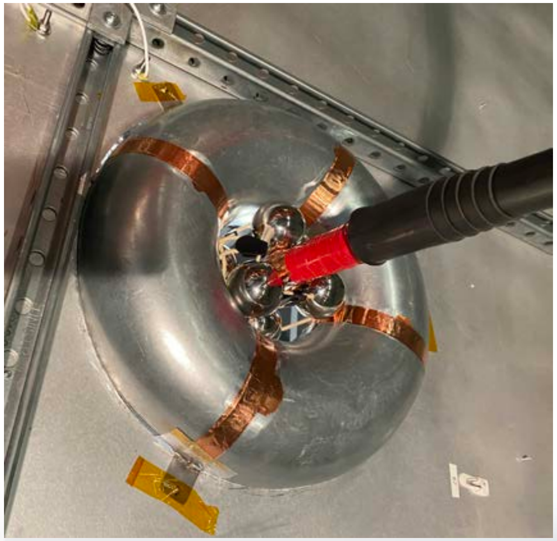
Both the brown and the white ceramics held off comparable voltages.

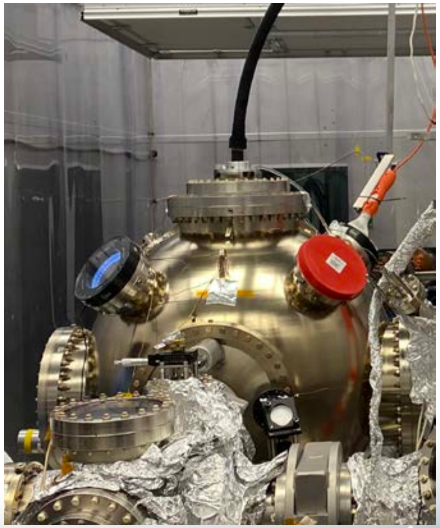
The Cable

There is a distance of about five meters between the HVPS and the gun. Being unable to use either SF6 or oil in a resistor box, the choice was to not use a shielded cable, but one with a slightly conducting (resistivity = 1×10^{10} Ω-cm) jacket.

A five-meter cable with an outer shield has about 150 pF per meter. At 300 kV, the stored energy is about 34 J. A slightly conducting jacket stores the same energy but cannot deliver that energy to an arc. But it can drain charge off the insulation surrounding the center conductor.

The jacket is connected at three points: the gun, the HVPS, and the wall between the gun and the HVPS. At these connection points, stepped cones were used to reduce the field gradients.





The Power Supply

The HVPS is a Glassman (now XP Power) model PS/LH450N013K20, which is rated for 13 mA at 350 kV when two stacks are used. We only used one of the two stacks. The single stack power supply is rated for 6 mA at 450 kV. The power supply was not used about 400 kV due to the height limitation of the HV cage.

A helix of conditioning resistors (totaling 105 MΩ) rise up to a second corona ring. When this resistor was taken out of the circuit, the stored energy of the power supply is absorbed by a distributed internal resistance of 460 Ω.

The output cable could be connected to either corona ring by raising the connection by a cord, which is attached to a spring loaded handle.

Control and monitoring of the power supply is through the inverter box using a digital interface.

Monitoring the Current

Current is monitored at the output of the HVPS using a Power over Fiber Platform (POFP) manufactured by MH GoPower.

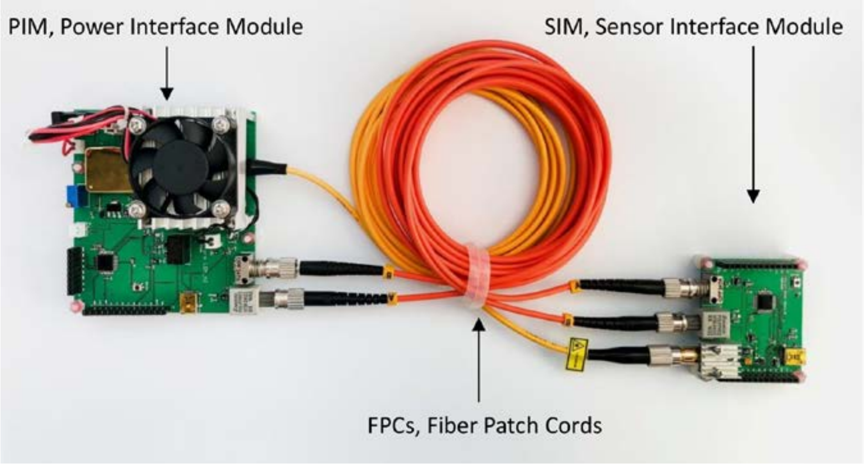
The Power Interface Module (PIM) operates at ground potential. It contains a laser with a 2.5W output. That laser powers the Sensor Interface Module (SIM) and up to 200mA @ 5V for external components which are connected to the SIM at high voltage potential.

Both the PIM and the SIM are programmed with Arduino development software. The SIM uses an external 22 bit ΔΣ A/D on a sensing resistor to increase the dynamic range and enable measuring both small currents and larger currents with out changing the sensing resistor.

Although the system has the capability to read data faster, the sample rate was set to 10 Hz to match the data readback rate of the other power supply parameters.

The input to the A/D is protected by a Zener network, and the Zener network is protected by a MOV network.

Extra safety requirements are required because of the power of the laser. The PIM and SIM are put in enclosures and fiber optic cables are run in non-conductive tube.



System Photograph from MH GoPower Operating Manual

The Next Challenge

Our next challenge is a non-polarized photo-cathode electron gun for hadron cooling in EIC. The short parameter list for the HVPS is:

- Voltage: -600 kV for conditioning, -550 kV for operation
- Current: -150 mA max
- Drop from Full Load Step: 1 kV

One would think that much of what was learned from our 350 kV gun would be directly applicable. Not exactly. It will be different.

- SF6 will be required and allowed.
- Power from the power supply to the gun will use a shielded MV cable.
- There will be resistor networks at the gun for running and operating.
- Spring loaded plugs are not compatible at the size required for a 600 kV system.
- With a different HV plug, a different Fluorinert system will need to be designed.

It is too soon to discuss a design for this system here. Perhaps at next year's workshop.

Summary

A 300 kV high voltage system was developed to support the prototype EIC polarized electron gun. It has been operating intermittently for about two years with continuous operation of up to six months.

Recently, the facility was paused for nine months to improve and update our safety procedures. We re-started the HV system at 350kV, quickly and without problems. The HV system is ready for beam operation.

Two key innovations were developed.

- A semiconducting jacket on the HV cable controlled the stored energy in the cable, while not requiring a resistor box near the cathode which would have required either SF6, oil, or a similar insulating media.
- A Fluorinert cooling system that can remove heat from the cathode deposited by the laser. Operating the cathode at lower temperatures extends its life.

  All high current high brightness sources may benefit from this important development. For example: PERL ERL, LHeC, JLab e+ project. It also may have industrial applications such as CW electron microscopy, ERL-based lithograph, medical radioisotopes(Mo99-Tc99) producing using high current beam, and leather tanning using an electron beam.