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Particles scattering in a HVDC gun

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Electron-Ion Collider

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Introduction

The Electron Ion Collider (EIC) hadron cooling electron source will utilize a high average current, high voltage DC gun ,aiming to generate 1nC, 100 mA average current, and 1mm-mrad normalized emittance[1]. One of the challenges in designing and operating the HVDC gun is the occurrence of undesired "ghost" particles that disrupt the gun's operation. In other words, the high voltage power supply (HVPS) trips more frequently when pushing to higher current.

Several mechanisms have been proposed to explain the generation of these particles, which includes ions originating downstream, such as cluster ions emitted from the beam dump, and emitter bursts from the cathode causing strong field emission. The back bombardment of ions can be described in the following sequence: 1. Electrons beam ionize residual gases downstream; 2. Ions or clusters with positive charges flow back towards the cathode; 3. Ions possessing energies in the hundreds of kilovolts halt at the cathode's center, fracturing the cathode material and producing a highly irregular surface; 4. The roughened cathode surface leads to field emission, thereby tripping the power supply. This sequence can explain the increased probability of trips with rising average current, as well as the concentration of damage spots at the cathode's center. Multiple strategies have been employed to mitigate downstream ions, such as biasing the anode and incorporating ion kicker electrodes. While effective in reducing trip probability below 10 mA of average current, these approaches face challenges in surpassing the 30-50 mA range. Moreover, ions generated from the DC gap cannot be removed through the above methods. There is one contradiction where some of the cathode's damage spots are located away from its center, which is the only location that downstream ions can reach.

Another explanation involves the formation of sharp geometries on the cathode in a high-gradient environment, delineated as follows: 1. The fine crystal cathode exhibits roughness of approximately 10s nm [2] or contains particulates during transfer as shown in Figure 2 [3]; 2. The cathode features a low electron affinity, resulting in a field emission threshold significantly lower than that of the substrate or stainless steel; 3. At high gradient operation, field emission (or dark current) may be present; 4. Field emission on the tips can further sharpen them and increase the field enhancement as shown in Figure 1; 5. The localized temperature elevation due to high-power lasers enhances the field emission; 6. The field emission experiences a sudden exponential increase when the field enhancement surpasses the threshold. This mechanism can explain the occurrence of spots away from the cathode's center and the heightened trip probability associated with increased current levels. With smoother cathode and smoother substrate, such as a single crystal cathode on the atomic smooth substrate can reduce this effect. The extra particulates on the substrate can be removed by the high-pressure rising and the particulates generated from transferring can be eliminated by installing the cathode in a clean room.

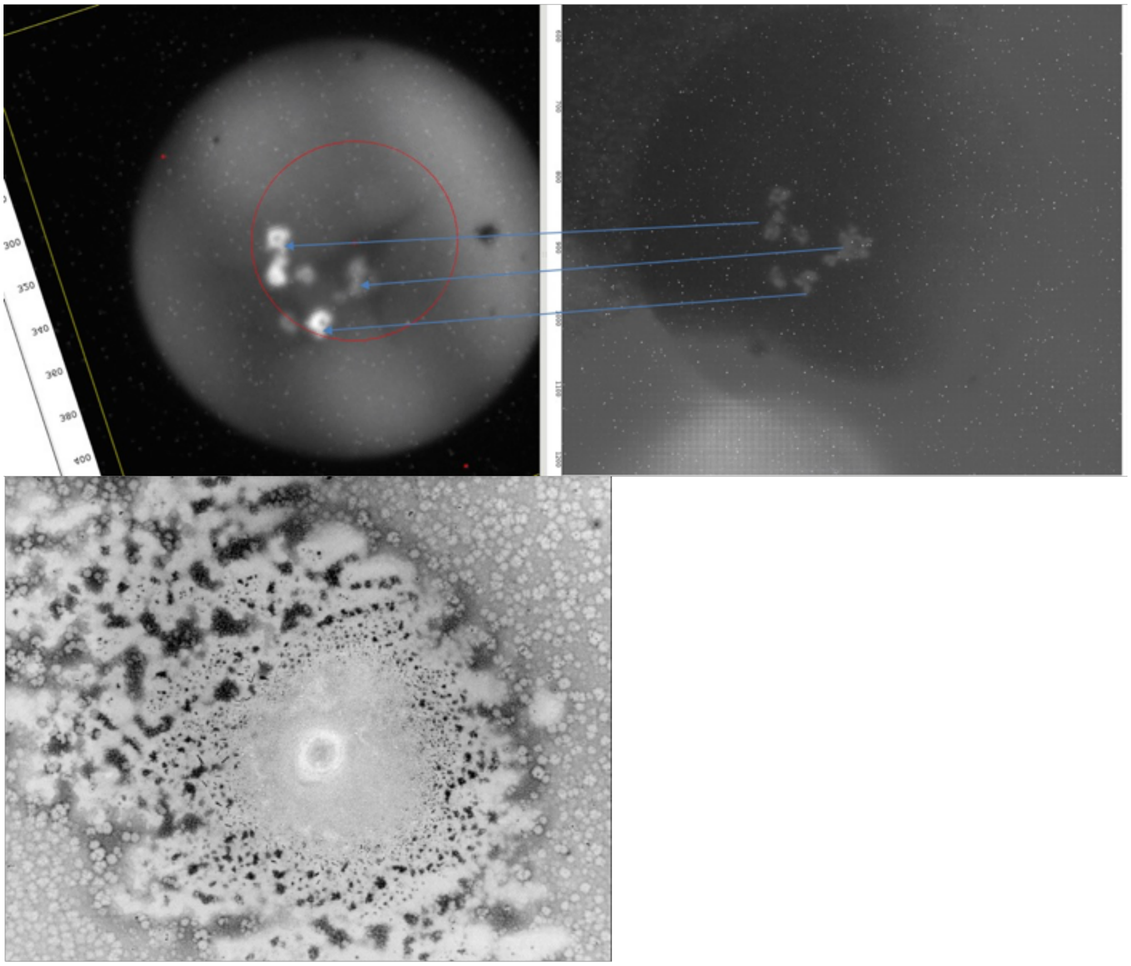

Figure 1. The gun trips leaves white spots on the cathode. SEM studies show the cathode material was redistributed and made a crater shape with large roughness.

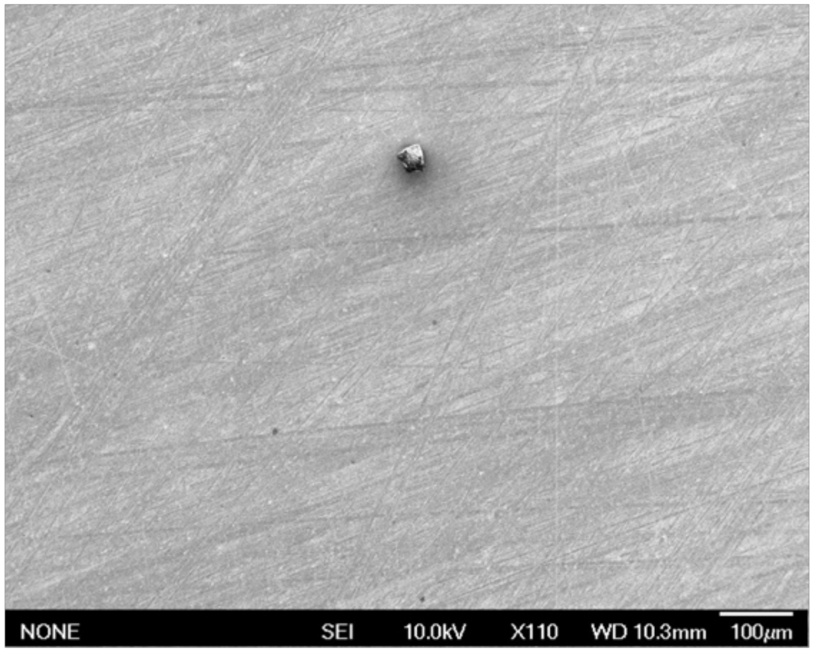

Figure 2. The particulates are left on the cathode substrate, mainly from polishing or transferring.

Despite numerous attempts to mitigate these effects, the HVDC gun still faces obstacles in reaching 100 mA. Other factors likely contribute to the high voltage trip during high current operation. This note aims to explore an additional mechanism: Part of the electrons beam loss on the anode, interacting with the monolayer on the anode or degas the anode and generating ions. These ions halt at the cathode and prompt the emission of secondary electrons. This cycle may iterate and intensify, like the phenomenon of multipacting in RF cavities. Ultimately, this process results in a substantial increase in emission current, potentially leading to the tripping of the high-voltage power supply (HVPS). I developed a scattering particles tracking code to analyze the ions and electron trajectory. And use this code to address the issue of the arrangement of the NEG (Non-Evaporable Getter) pump.

Physics model

Operating at high currents, such as 100 mA, even a small beam loss of 10^{-5} would generate an amount of 1 μA beam loss. At 550 kV, the beam power loss is about 0.55 W which can cause outgassing or generating X ray. The outgassing rate is determined by the material property and post-treatment. The X-ray generated from the scattering electron can be estimated by[4,5]

$$W = \epsilon VI = 0.33 \times 10^{-9} V^2 ZI \quad (1)$$

where V is beam kinetic energy in eV, Z is the atomic number of the material stopping the electrons and I is the beam current. For the titanium anode with Z of 22, and 550 kV DC gap voltage, the lost electron generating X-ray power is about 2 mW.

When employing a mask during cathode growth in the DC gun, the cathode's size is constrained. However, the diffusion of cathode growth material vapor can extend beyond the cathode area. When the laser halo or scattered light illuminates the photocathode, electrons can be generated from unexpected regions. These electrons, subject to nonlinear strong focusing, are prone to loss on the anode tube or aperture. Utilizing a scattering particle tracking code, we aim to assess the location of beam loss.

Within the DC gun, the initial aperture encountered by the beam is the anode, where electrons at rest can generate hydrogen (H) or hydrogen gas molecules (H_2). These ions, commonly trapped in materials or present as a monolayer coating on metal surfaces, are accelerated by the DC electric field, reaching the cathode electrode surface and initiating the generation of secondary electrons.

Another mechanism involves X-rays generated from the anode, which can also produce secondary electrons. Cathode materials containing alkali metals exhibit a notably high secondary electron yield, often exceeding 100. Consequently, the secondary electrons originating from the cathode surpass incident ions in quantity. These secondary electrons are susceptible to loss on the anode, further generating more ions as depicted in Figure 3.

Given the complex configuration of the anode and cathode, electrons and ions oscillate between these elements, extending over a larger area. When the secondary yield exceeds one, multiple iterations result in an instantaneous surge in peak current. This process can increasing the outgassing and increase the intensity ion backbombardment. Meanwhile, the ionized gas moves back toward the electrode, frequently leading to power supply failure. Detailed simulation results are elaborated in the subsequent section.

The methods to reduce this effect could be : 1) Anodize the cathode substrate, only expose the metal substrate to the cathode coating area. That can eliminate unwanted electron emission; 2) Use low secondary yield material like BN or SiC as the substrate or coating on the electrodes; 3) Optimize the anode geometry to break the ions trajectory back to the cathode electrode.

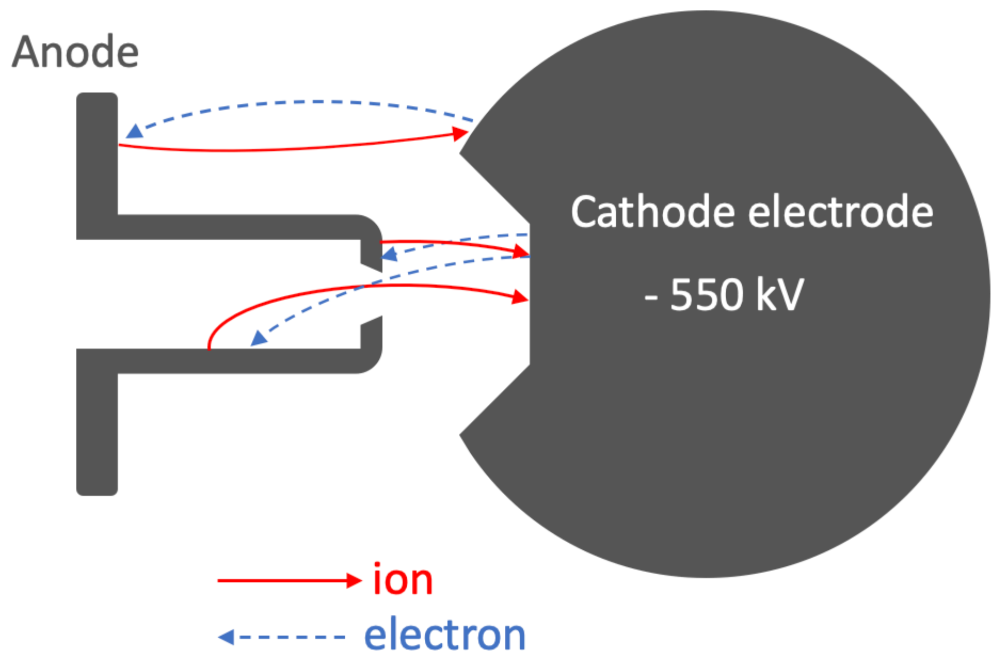

Figure 3. The schematic drawing of electrons and ions trajectories in cathode and anode gap

One application of this concept is explaining beam stops on the NEG pump and generates outgassing. As description above, some electrons excited by the back ions emit out from the electrode or some ions emit from the anode can stop on the NEG pump. The NEG material trapped gas molecules will have significant outgassing when energied particles halt on them. To prevent the generation and emission of ionized gas, we have implemented a metal mesh on top of the NEG pump in the SBU polarized gun as depicted as Figure 4. The idea behind this approach is that when electrons come to rest on the NEG material, gas molecules are generated. These molecules can be ionized by the scattered electrons. Since the metal mesh and NEG modules are at the same potential, the ionized molecules do not experience acceleration and are eventually absorbed by the NEG pump.[6].

Figure 4. The circled area shows the mesh covering the top of the NEG pump.

This approach effectively functions when the electron beam current is low (<1 mA) since the number of ionized gas molecules produced is negligible. Our testing confirms that no instances of the beam-induced gun trip have occurred in the gun in the last two years of operation while employing this method.

However, at high current HVDC gun, there is a possibility of ionized gas molecules escaping the NEG mesh due to random movement. Therefore, an improved design should aim to prevent any electrons from coming to rest on the NEG pump. We use this approach in design strong hadron cooling (SHC) R&D gun.

For the high current gun such as the Cornell gun which locates the NEG pump at out of main gun vessel. The advantage is the scattering particles can not see the NEG material and the fracture of the NEG material will not drop into the gun. The cons is flange aperture limited the pumping rate and the volume of the sub-vessel also limited the number of NEG modules. So far, this kind of gun hasn't achieved 10^{-12} torr vacuum.

Scattering particles tracking code

I have developed a particle tracking code called "scattering particles tracking" for the HVDC gun field emission, secondary electrons and ions tracking[7]. This code allows for the emission of charged particles at various locations and their tracking in the DC field. It reads the 2D Poisson field information (SF7 grid) and boundary segments (SFO seg #) from Possion [8].

Here are some key features of the code:

- The initial particles are defined by charge and mass. The electron, proton, H_2^+ and H_2^{+2} have been predefined in the code. More charged particles/clusters can be defined in the code.
- The field is interpreted by the field Er, Ez in grids. (Using scipy.interpolate.RectBivariateSpline)
- The particle tracking is time domine. First define total time, then time step for motion calculation and output time. Time step value has to be pre-tested and make sure the results will be converged.
- The motion equations are

$$
\begin{gathered}
cdp_r = ecErdt \rightarrow p_r = p_{r0} + dpr \\
cdp_z = ecEzdt \rightarrow p_z = p_{z0} + dpz \\
\gamma = (1 - \frac{cp_r^2 + cp_z^2}{(mc^2)^2})^{1/2} \\
E = \gamma mc^2 \\
\beta_r = cp_r/E \\
\beta_z = cp_z/E \\
v_r = \beta_r c \\
v_z = \beta_z c
\end{gathered} \tag{2}
$$

- If the particles go beyond the boundary, their position on the boundary is marked. These positions can emit particulates in the next iteration
- The new particles or say secondary particles can be generated by set conditions, such as location, gradient, and voltage

- The code is capable of generating figures of field map, ion/electron trajectories, and particle-generating locations.

Simulation results discussion

Here use EIC-SHC HVDC R&D gun as an example. The gun field was simulated using Possion and input into the code. The SHC cooling gun field gradient 2D map as the Figure 5:

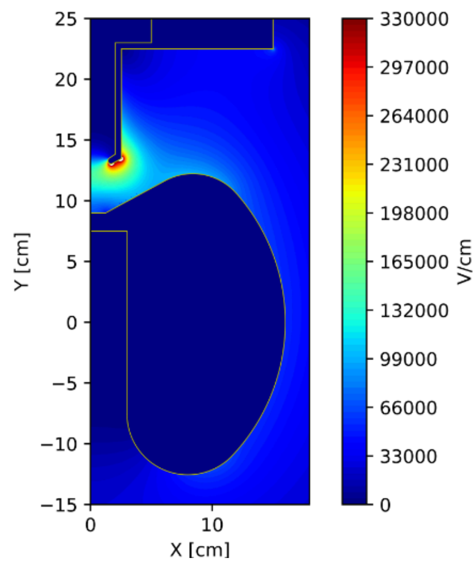

Figure 5. The field gradient in the SHC HVDC gun

We set the field emission criteria is 10 MV/m. Then we have a field emitter when set the gun voltage at -550 kV as shown in Figure 5. We will not have field emission when applying -500 kV on the gun. But 10 MV/m is not a hard limit, with better polish it is possible to achieve 12 MV/m threshed.

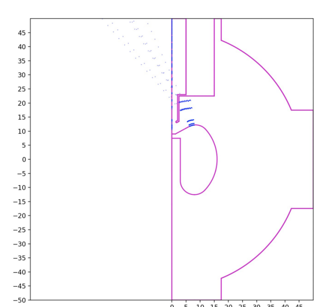

Figure 5. Field emission from the electrode where the field gradient higher than field emission threhold.

The trajectories of ions (H_2^{+2} or H^+ and H_2^+) emitted from the anode can be seen as Figure 6. When the electrons and ions oscillate between the cathode and anodes, they eventually cover the entire anode surface facing the electrodes. There is a possibility of electron beam loss on the anode tube caused by the beam halo, these ions can be emitted and traced back to the cathode as shown in Figure 6. Most of the ions stop on the electrodes, but some of them pass by the electrodes and arrive at the chamber wall, particularly, on to the flange.

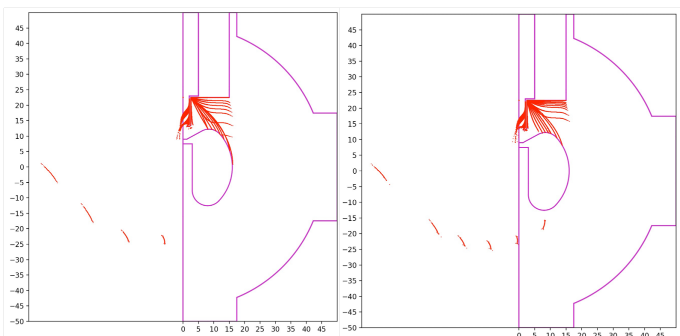

Figure 6. H_2^{+2} or H^+ (left) and H_2^+ (right) trajectory from the anode towards the electrode and gun vessel.

The ions stop on the cathode electrode can generate secondary electrons with trajectories as Figure 7. The electrons can halt on the anode and vacuum chamber. Part of the electrons can reach the flange where we intend to install the NEG pump.

- H_2^{+2} or H^+

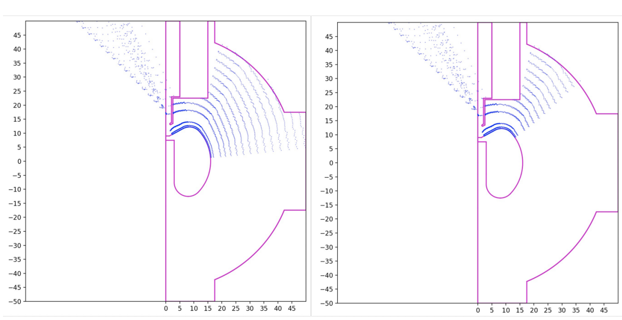

Figure 7. Secondary electrons trajectory excited by H_2^{+2} or H^+ (left) and H_2^+ (right)from the electrode.

From the simulation, we can see the ions or the scattering of electrons can achieve the flange where we intend to mount the NEG pump. The outgassing can intensify the ion back bombardment, finally causing the HVPS trip. That can explain the observation of the trip rate increasing if the NEG pump is placed inside the vacuum chamber. One solution is installing the NEG pump in an individual chamber with a nipple connect to the main vessel. However, it limits the conduction and causes gun chamber pressure cannot achieve the requirement level. There are two ways to lay out the NEG pumps inside the chamber. One is installed on the flange(Figure 8 left) which is much easier to assemble. Alternatively, we can mount NEG lay on the chamber as in figure 8 right. It will increase the distance between the NEG pump and the electrode and reduce the gradient on the electrode. However, simulation results as discussed at Figure 7 show both H_2^+ and H_2^{+2} have more chance to achieve the NEG location.

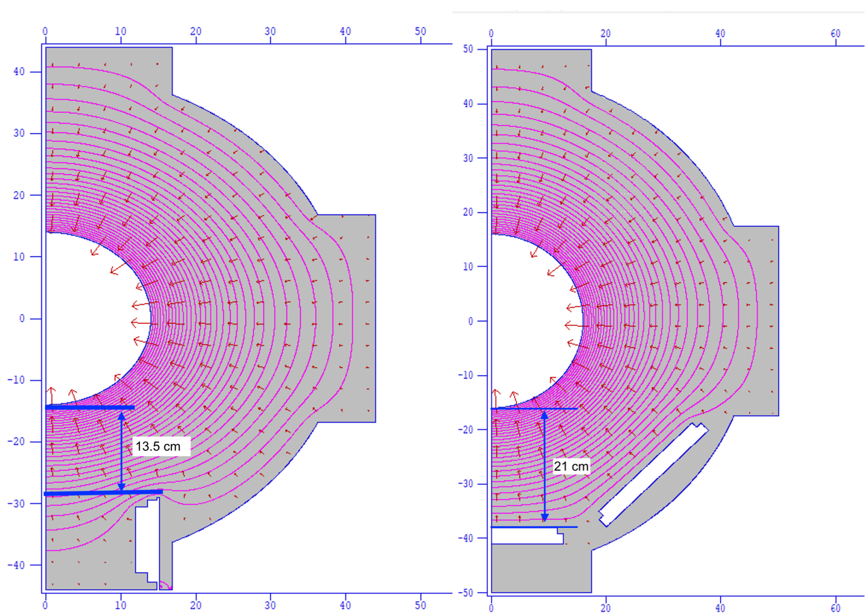

Figure 8. Two ways to install the NEG pump on the gun vessel. left: install the NEG on the flange; right: install the NEG lay down the chamber.

In order to prevent electrons from stopping on the NEG material, we use a solid titanium (Ti) sheet shield to cover the section of the electron path toward NEG and mesh to cover the rest of the NEG portion as shown in Figure 9. This arrangement helps ensure that the electrons do not come into direct contact with the NEG material, thereby avoiding any outgassing issue. It will not limit the conduction of pumping.

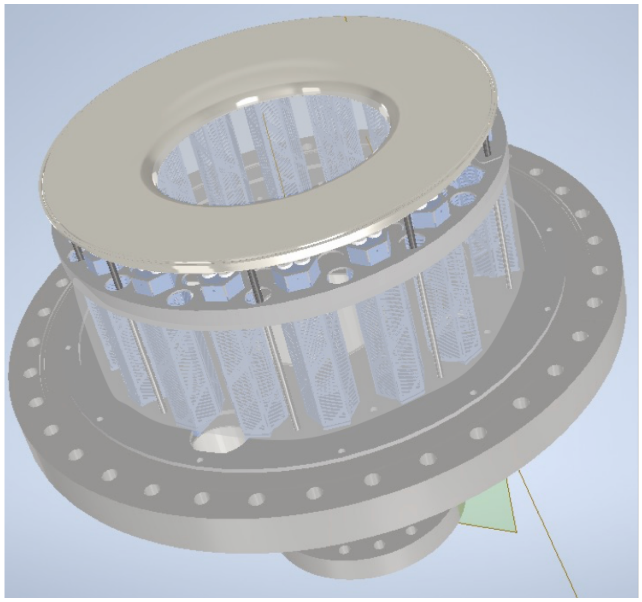

Figure 9. The NEG assembly for the EIC SHC gun.

Conclusion

This note discusses the potential mechanisms for HVPS tripping during high-voltage, high-current operation. I introduce a new mechanism, suggesting that the motion of halo electrons and ions between electrodes and the anode could significantly increase the current due to a high secondary yield, ultimately leading to HVPS tripping. Additionally, I propose and deliberate on potential approaches to mitigate these effects.

Subsequently, a dedicated charge particle tracking code for the DC gun was developed, showing that halo electrons and ions can reach the bad location, consequently triggering the current increase. Moreover, our observations indicate that scattering electrons and ions can access the NEG pump location, resulting in outgassing. By optimizing the NEG pump location and its geometry, it is feasible to prevent electrons or ions from reaching the NEG module.

Acknowledgment

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