HIGH-AVERAGE-CURRENT, HIGH-BRIGHTNESS HVDC ELECTRON GUN DEVELOPMENT FOR EIC HADRON COOLING[*]

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Abstract

The hadron cooler is an essential system for achieving high luminosity in the Electron-Ion Collider (EIC). The required electron source parameters exceed the current state of the art. We are conducting an electron-source R&D program aimed at producing an average current above 75 mA with bunch charges of 1 nC to 3 nC. This proceeding outlines the high-voltage design of a DC gun operating at 500 kV, with conditioning capability up to 600 kV. The design incorporates several unique features, including an inverted ceramic insulator at this voltage level, active cathode cooling, and large single-crystal multi-alkali photocathodes grown on silicon carbide substrates. We are developing the AI conditioning based on the convolution neutroal network. This paper presents recent progress on gun construction, AI conditioning development and preliminary major components test results.

INTRODUCTION

To achieve and sustain the high-luminosity target of $1 \times 10^{34}\,\mathrm{s^{-1}\,cm^{-2}}$, the Electron-Ion Collider (EIC) requires advanced hadron-cooling capabilities. A high-energy cooler for collision energies was designed between 2020 and 2024, but that project was terminated because the high-risk items could not be retired within the EIC project schedule [1]. A low-energy cooler is therefore being designed to cool hadrons at the injection energy of 24.5 GeV. Building on the successful polarized-gun R&D at the EIC [2], we are developing an HVDC gun to serve as the electron source for the hadron cooler. This gun is designed to deliver up to 98.5 mA of average current at voltages exceeding 500 kV to meet the requirements of various hadron cooling schemes for the EIC [3]. The design incorporates several advanced features, including an inverted feedthrough structure and an upgraded active cathode-cooling system using Fluorinert (FC72). To achieve high brightness, the gun will use novel large-crystal K_2CsSb photocathodes grown on 4H-SiC substrates. The design and analysis of the HVDC gun have been completed, and the gun assembly is currently underway. We are aiming for gun conditioning and beam tests in the next few years. In this paper, we discuss the HVDC gun design concepts, key considerations, and novel features. In addition, the major components of the HVDC gun are described in detail, and the AI-driven gun-conditioning approach is presented.

HVDC GUN DEVELOPMENT

Electron Source Requirements

The hadron cooler requires an electron source with high brightness, high average current, and high bunch charge. The electron-source requirements for several cooler schemes are listed in Table 1.

Table 1: Comparison of various hadron-cooling electron-source requirements.

Parameter	Precooler	SHC-CeC	HEC-Rec.
I_{ave} [mA]	> 70	90 to 100	60 to 100
ϵ_n [mm mrad]	1.5	3	2
C [nC]	1.2	1	4
Lifetime	1 week	> 3 days	> 3 days

The HVDC gun R&D is guided by the following requirements:

- Development of an electron source capable of delivering a 98 mA beam with a single operational lifetime charge of 60 000 C.
- Operation at voltages exceeding 500 kV with an electric-field gradient on the cathode surface of more than $5\,\mathrm{MV\,m^{-1}}$.

The primary challenges of this R&D effort include developing an efficient cathode-cooling mechanism, achieving long-term stable operation at high voltage, reducing emittance,develop advanced AI enhanced control system, and generating high-bunch-charge beams [4].

Gun Geometry

The inverted structure of the HVDC gun is more compact because both sides of the ceramic are enclosed and are not exposed to either the atmosphere or SF_6 [5]. This design allows for a shorter ceramic feedthrough. A polarized gun using this configuration achieved 350 kV after only 20 h of conditioning [2]. However, scaling this design to higher voltages, such as 500 kV, remains challenging because the potential distribution along the ceramic is difficult to control. The Pierce-shaped cathode and anode system were optimized to minimize emittance and maximize the laser spot size. Applying 550 kV to the electrode results in a cathode-surface gradient of $5.4\,\mathrm{MV\,m^{-1}}$, while all other surfaces maintain gradients below $10\,\mathrm{MV\,m^{-1}}$.With a well-polished surface, field emission can be effectively mitigated. The optimized normalized emittance is 1.02 mm mrad for a bunch length of 250 ps. The field gradient along the electrodes and on axis

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is shown in Fig. 1 To prevent gun trips caused by ion back-bombardment, offsetting the laser from the center is essential. Our cathode size with the laser achieved size is 2.6 cm in diameter. A laser offset of 3.5 mm results in approximately 3% emittance degradation.

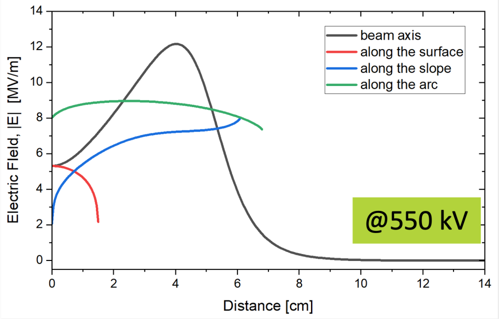

Figure 1: Electric field along the HVDC gun surfaces at 550 kV after optimization.

Cathode Cooling Setup

Characterization of the K_2CsSb cathode material revealed that both the quantum efficiency (QE) and lifetime of the cathode decrease significantly above 80 °C, particularly when the laser power exceeds 5 W, with the QE dropping below 1 % [6]. Cathode cooling is therefore essential for generating average currents in the 100 mA range, where the laser power typically exceeds 12 W. We tested a cathode-cooling scheme at BNL's polarized gun, which successfully maintained voltages above 300 kV for more than two years without failure [2]. However, the cooling system, which uses FC72 as the fluid, increased maintenance complexity because FC72 can dissolve the grease typically used to seal HV cable plugs and feedthroughs. Grease is commonly employed in industry to prevent air from being trapped between these components. To mitigate the maintenance challenges and enhance cooling efficiency, our new approach creates a small gap between the ceramic feedthrough and the HV plug, which is filled with FC72. This not only prevents air entrapment but also provides cooling to the cathode. FC72 has a dielectric strength of 80 kV cm^{-1}, allowing a length of 7.5 cm to withstand 600 kV. This setup is currently being tested and has already reached voltage levels between 530 kV and 570 kV. Further tests focused on stability and reliability are planned. The cathode puck, designed with a large-waisted base, is tightly attached to the cathode heat sink, which is made of oxygen-free copper. After several improvements, the cooling fluid reaches the heat sink and efficiently removes more than 20 W of thermal power, maintaining the cathode temperature at about 30 °C, as illustrated in Fig. 2.

Epitaxially Grown Large-Crystal Photocathode

K2CsSb typically forms polycrystalline films on Moly pucks. The used cathode material must then be removed, and the substrate repolished to restore a mirror-like surface. Recently, the BNL team developed a large-crystal K_2CsSb cathode, epitaxially grown on lattice-matched 4H-SiC wafers, which demonstrates exceptional crystal quality, including ultra-smooth surfaces [7, 8]. Using 4H-SiC as the cathode substrate simplifies the replacement process, making it quick, cost-effective, and straightforward. The 4H-SiC substrate can potentially mitigate high-voltage breakdowns and reduce field emission. In addition, doped 4H-SiC exhibits excellent thermal conductivity (4.2 W cm^{-1} K^{-1}), surpassing that of copper. This property aids efficient heat transfer from the laser-heated cathode to the heat sink, helping to maintain the cathode temperature during high-current operation. The intrinsic emittance is also expected to be smaller than that of polycrystalline cathodes. The QE of these photocathodes can reach approximately 9% when illuminated with a 532 nm laser, which satisfies the operational requirements of the gun.

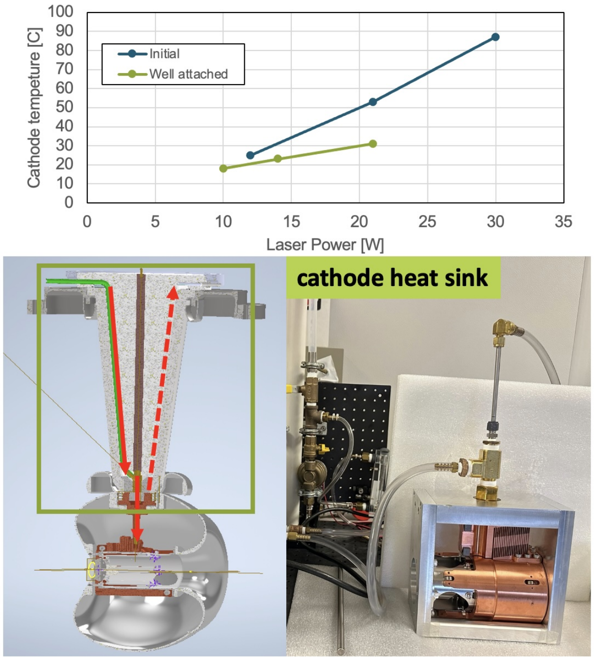

Figure 2: Cathode-cooling setup. Top: cathode temperature as a function of laser power. Left: model showing how the cooling fluid flows to and from the cathode heat sink. Right: cathode-temperature test setup using a heater and cooling fluid.

High-Voltage Cable and HVPS

The gun is designed to operate at 550 kV and to be conditioned up to 600 kV. A 1 MV HV cable made by Dielectric sciences,Inc. will be used to deliver power, which simplifies the configuration compared with the case in which both the power supply (PS) and the gun share the same SF_6 tank. However, the stored energy in the HVPS and the high-voltage cable can potentially damage the gun if arcing occurs. For instance, the HVPS has a stored energy of 3.5 kJ, and a 9 m cable at 600 kV contains about 80 J of stored energy. We therefore place a resistor between the gun and the HV cable. During conditioning, the field-emission current is uncontrollable. To mitigate this, we employ 66.7 MΩ voltage-dividing resistors to form a negative-feedback loop, thereby protecting the gun. In high-current operation, the current becomes more controllable. To prevent the resistor from absorbing too much voltage drop, we use a 500 Ω resistor, which provides protection in the event of a high-current HV trip. These resistors are capable of handling energies above 4 kJ, which is sufficient for both conditioning and operation of the gun. They are mounted in cylindrical assemblies designed to be directly affixed to the gun assembly. The energy storage between the resistor tank and the gun is negligible. The HVPS is designed as a two-phase Cockcroft–Walton voltage multiplier, housed within a vessel that can be pressurized with N_2, depending on the requirements. It can provide an average current of 150 mA at 400 kV, 120 mA at 550 kV, and 12 mA at 600 kV. We completed HVPS commissioning up to the full voltage of 600 kV. The HVPS, designed and manufactured by DTI, has been installed and commissioned in the gun experimental hall as shown in fig. 3. It reached 600 kV.The voltage multiplier is driven by an external power inverter that operates at a nominal frequency of 20 kHz and an output voltage of 50 kV. In pulsed mode, the voltage droop is less than 0.16%, and the ripple is 0.03% operating at 150 mA.

Figure 3: The assembled DTI power supply operated at 600 kV.

AI for HV Conditioning

HVDC conditioning is a highly operator -dependent process that relies on experience and real-time interpreation of diagnostic signals. To reduce operator workload and improve consistency, we developed a Convolutional Neural Network (CNN)-based model that learns operator action patterns from historical data and predicts voltage actions (hold vs ramp-up) [9, 10]. We used BNL gun-conditioning data to develop the AI model. Prior to training, diagnostic inputs (radiation, pressure, and current) were z-score normalized to account for differences in scale, while the previous voltage ramp action and the binary voltage ramp decisions were left unchanged. The model architecture is shown in Fig. 4. The network outputs a single logit, which is used to determine the ramp decisions. To address class imbalance, a weighted binary cross-entropy loss with logits was employed, with the class weight defined as the ratio of hold to ramp-up samples. The model was trained using the Adam optimizer with a learning rate of 5×10^{-6}. Early stopping based on validation loss with a patience of 15 epochs was applied to mitigate overfitting. The trained model was evaluated on a held-out test set and achieved an accuracy of 98.7% and a recall of 89.3%, indicating strong performance in offline evaluation as shown in Fig.5. The model is currently being prepared for real-time deployment and hardware integration.

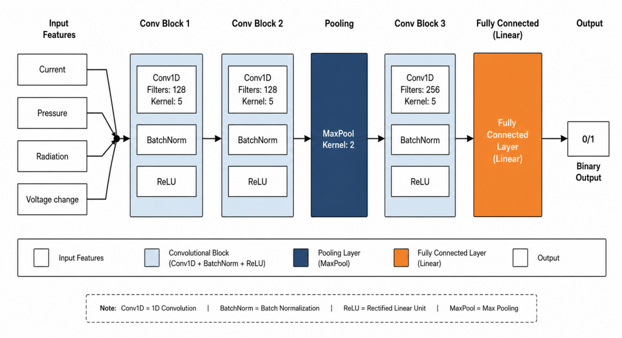

Figure 4: CNN model architecture used for HVDC conditioning.

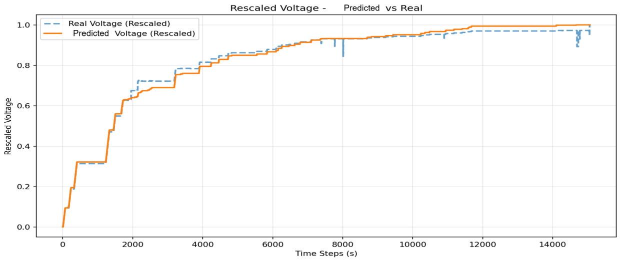

Figure 5: Predicted ramp-up (solid) using CNN versus actual ramp-up (dashed) for the test set.

CONCLUSION

As part of the EIC R&D effort, we are developing an HVDC gun to be operated a 550 kV with a novel cathode-cooling mechanism. In addition, a single-crystal or large-crystal multialkali photocathode is being implemented. We are also developing an AI-based high-voltage conditioning algorithm. The project is currently in the construction phase, with high-voltage conditioning planned for 2026 and beam commissioning scheduled to begin in 2027.

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