Development and Testing of a new Current-Regulated Arc Modulator for the LINAC

Nathan Campos

Supervisors: Ralista Sharankova, Dan Bollinger

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Abstract

In this study, the performance of a current-regulated arc modulator was investigated with a focus on its role in initiating and sustaining plasma discharge within the Magnetron Body of the LINAC system. The analysis centered on how switching components, circuit topology, and feedback loop architecture influence critical factors such as energy efficiency, discharge stability, and long-term plasma containment. Particular attention was given to variations in pulse termination behavior, as observed through oscilloscope traces, which revealed inconsistencies affecting the duty factor and cathode temperature. These fluctuations have downstream effects on the cesium-coated cathode surface, thereby impacting H^- ion production and beam reliability. Simulation-based testing in LTspice was used to evaluate noise suppression techniques and arc current regulation schemes, revealing how optimized snubber networks, improved pulse shaping, and feedback stability can mitigate modulator-induced noise. The results identified hardware-level parameters that significantly enhance discharge repeatability and improve overall plasma performance under operational conditions.

Contents

1 Introduction

1.1 High-Energy Beamlines and Particle Production

Fermi National Accelerator Laboratory is the premier accelerator research laboratory dedicated to understanding the building blocks of matter and energy within the universe. Within this environment, engineers & accelerator operators ensure that machines found within the accelerator complex function smoothly and safely to deliver beams to various scientific experiments. Particle accelerators work by boosting the kinetic energy of a tightly packed stream of charged particles called a beam. These beams are directed toward a target, where high-energy collisions generate particles that weren't originally present before, or they could be collided head on with another beam. For example, Fermilab often uses proton beams to hit targets made from graphite, producing pions and kaons. These decay into neutrinos, which scientists use to investigate the properties of these fundamental particles.

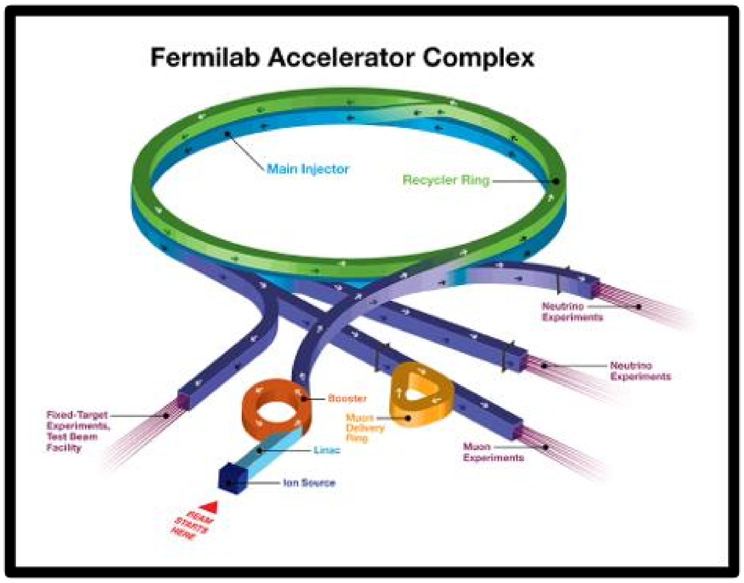

Fig. 1: Diagram of the Fermilab Accelerator Complex, detailing the particle acceleration pathway from ion source through the Linac, Booster, and Main Injector, with dedicated rings and facilities for muon, neutrino, and fixed target experiments

1.2 Role of LINAC

The linear accelerator (LINAC) plays a crucial role in the 1st stage of the particle acceleration process by accelerating the H^- ions to an energy of 401.5 MeV. This is achieved through the use of standing waves radio-frequency fields (EMF), which resonate inside copper cavities called RF cavities. A consistent supply of H^- ions is essential for the LINAC to operate effectively, and their generation involves a carefully controlled sequence of steps.

The process begins with the introduction of pure hydrogen gas into a vacuum chamber. Inside this chamber, the hydrogen is subjected to ionizing conditions using arc discharge, converting the hydrogen gas into plasma. To enhance the production of H^- ions, hydrogen atoms with an extra electron, cesium vapor is introduced. To enhance H^- ion production, cesium vapor is introduced to coat the cathode surface. This coating lowers the work function, making it easier for hydrogen atoms to acquire an extra electron through surface conversion

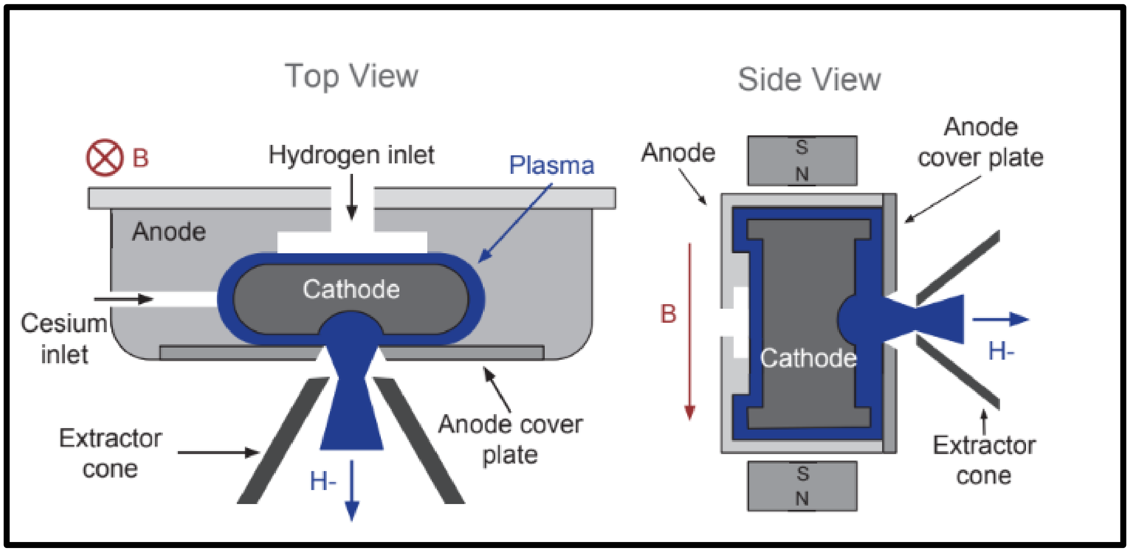

Fig. 2: Internal structure of the Magnetron Body integrated within the LINAC, highlighting the active regions responsible for H^- ion generation, acceleration and containment.

The arc modulator is posted at 15Hz to produce an arc that discharges to produce the plasma. Once formed, these negatively charged ions are extracted from the plasma using an externally applied electric field. This field pulls the H^- ions out of the source region and injects them into the front end of the LINAC, where they begin their journey through progressively accelerating RF cavities. This entire system forms the first stage of Fermilab’s high-energy beamline infrastructure.

1.3 Role of Arc Modulator

The arc modulator is a critical subsystem responsible for initiating plasma discharge within the ion source. Internally, it’s composed of several specialized components that work together to deliver precise, high-voltage pulses required for stable ionization. As explained by the image below, at the heart of the energy delivery system lies the high-voltage (HV) card, equipped with eight 100 µF capacitors that store and release energy rapidly to ignite the hydrogen gas & convert it into plasma. These capacitors help form sharp, well-defined pulses while suppressing unwanted overshoot and electrical ringing within the system. Supporting the control circuitry are two dedicated DC power supplies—a +15 V supply for driving gate logic and high-level control circuits, and a +5 V supply for lower-voltage elements such as signal processing and feedback control.

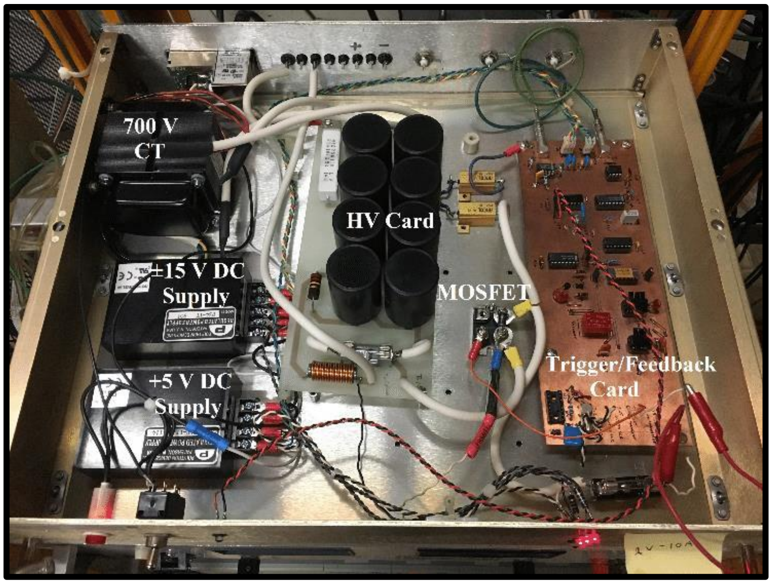

Fig. 3: Internal components of a similar Arc Modulator

To ensure accurate pulse modulation, a MOSFET is used as the primary switching device. Its fast response allows tight control over pulse timing and protects the system from erratic discharge. Real-time monitoring is handled by a 700 V-rated current transformer, which feeds data into the Trigger/Feedback card—a module that initiates discharge cycles and adjusts parameters based on feedback from previous pulses. A rectifier is also integrated within the circuit to shape the DC supply output into a controlled, pulsed output, mimicking aspects of AC behavior such as frequency and duration, to regulate the discharge cycle. Meanwhile, a protective fuse safeguards the circuit against overcurrent events or component failure, preserving the integrity of the system.

Together, these components enable the arc modulator to deliver consistent, clean pulses that stabilize plasma conditions inside the ion source. Beyond ignition, operational reliability depends on meticulous fine-tuning of multiple parameters. Cesium vapor delivery reduces the surface work function, enabling efficient H^- ion formation via surface conversion. Hydrogen pressure directly influences the plasma's density and collision rates, while arc current regulates overall discharge stability. Pulse timing, in turn, governs how energy is distributed across each cycle, affecting both plasma uniformity and source longevity. By fine-tuning cesium delivery, hydrogen pressure, arc current, and pulse timing, while also suppressing electrical noise, the arc modulator ensures stable plasma conditions in the ion source. Through carefully timed and shaped electrical pulses, the arc modulator controls how much energy enters the system. Its precision in adjusting pulse width, frequency, and amplitude ensures a stable environment that doesn't oscillate or extinguish, which could disrupt H^- ion production as the plasma would become unstable. Additionally, by suppressing unwanted electrical noise, the modulator prevents fluctuations that might otherwise degrade plasma quality or introduce beam instabilities downstream.

This controlled environment enables consistent generation of H^- ions, which are subsequently extracted by an electric field and injected into the LINAC, where they're accelerated to high energies. Without the arc modulator's ability to fine-tune the ignition of the plasma, the entire chain of beam formation could become compromised. It plays a key element in maintaining beamline reliability and repeatable ion source performance across accelerator operations.

2 Arc Modulator & Experimental Setup

2.1 Instability within the Arc Modulator

The production of plasma becomes critically dependent on the arc modulator's ability to deliver precise, high-voltage electrical pulses. These pulses inject energy into the ion source, helping maintain the energy required to generate plasma. Ideally, the modulator should generate well-timed and cleanly terminated pulses with stable amplitude and frequency, enabling consistent plasma behavior and reliable downstream ion production.

However, oscilloscope measurements reveal that the arc modulator's high-voltage pulses often fail to terminate cleanly, with trailing edges that fluctuate from cycle to cycle. This pulse instability generates electrical noise, which in turn causes variations in the angular frequency ω. Since impedance depends on ω as shown by the formula $Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$, as impedance shifts unpredictably, energy coupling into the plasma becomes unstable. This results in a less reliable arc discharge, hampering the conditions required for controlled H^- ion production.

Taken together, these fluctuations undermine plasma generation, compromise H^- ion yield, and introduce variability that can degrade beam quality once the ions are injected into the LINAC. Addressing these pulse instabilities is essential—not only to protect the plasma environment but also to maintain the integrity of the entire accelerator chain.

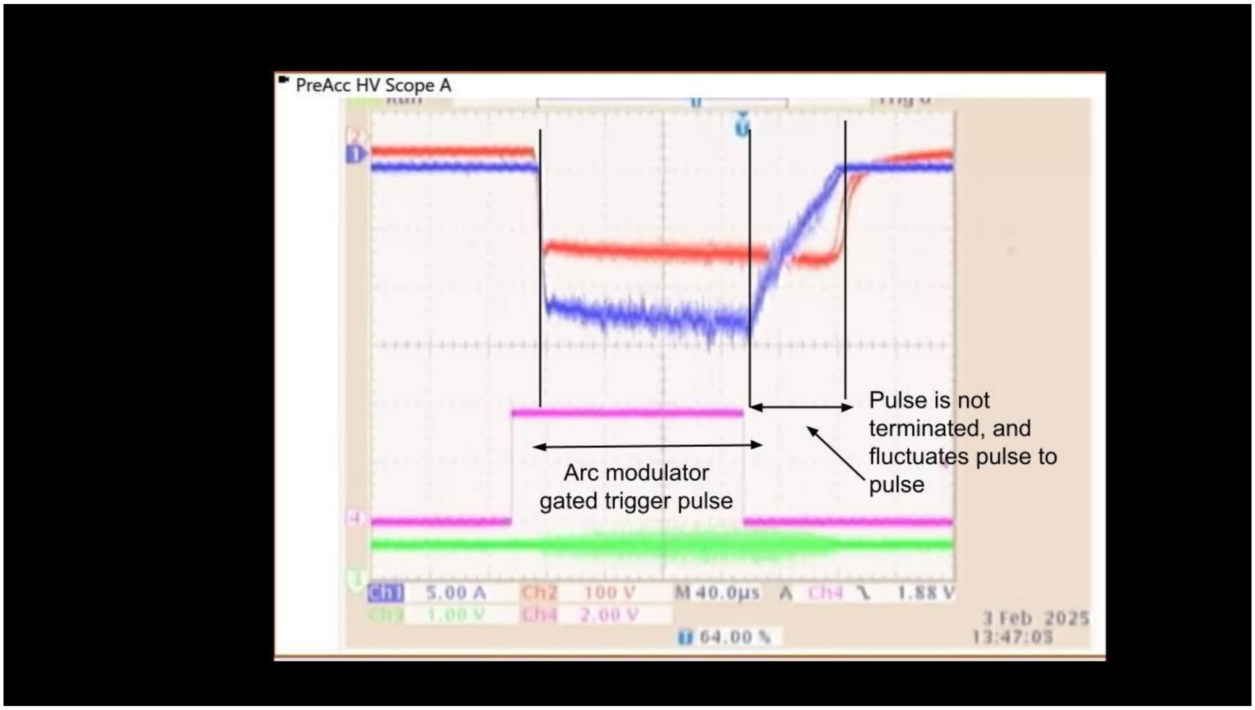

Fig. 4: Oscilloscope reading showing the gated trigger pulse and its fluctuating, unterminated signal(blue trace).

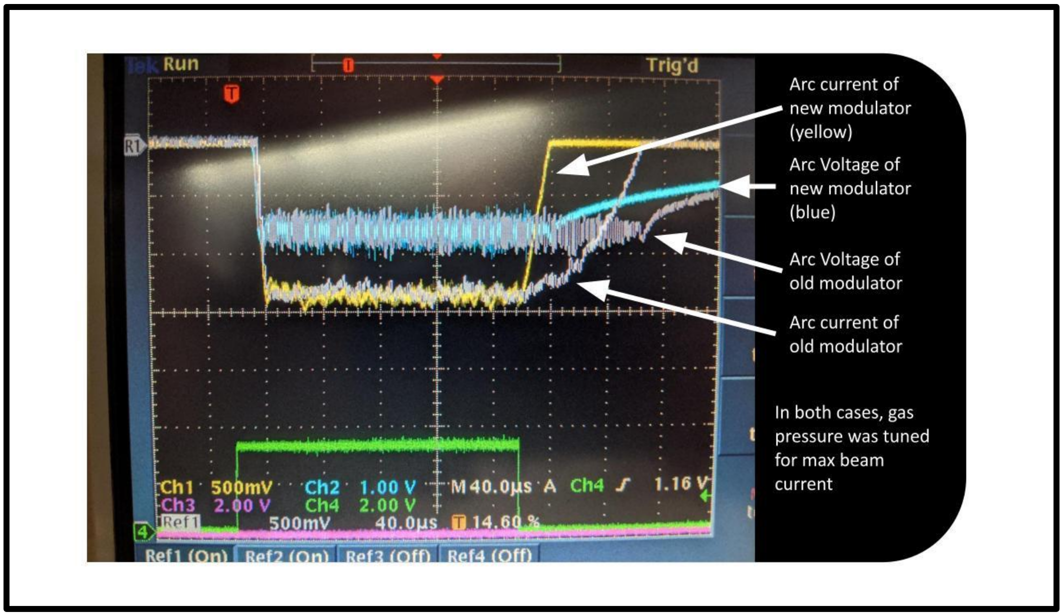

Figure 5: Oscilloscope reading of current-regulated arc modulator compared to the older model that was voltage regulated.

As shown above in (Figure 5), we can see that the older voltage-regulated arc modulator exhibits greater variation in arc behavior compared to the current-regulated design. Its inconsistent pulse profile across cycles signals unstable discharge conditions, which can compromise plasma reliability and reduce ion source performance.

2.2 Arc Modulator Optimization

To address pulse termination instability observed in the arc modulator, a prototype circuit was designed and simulated using LTspice [1] (Figure 2.2). The main goal was to identify hardware-level modifications that could reduce pulse distortion, suppress electrical noise, and improve consistency in discharge behavior.

The simulation incorporates critical components including a high-voltage MOSFET (AOD280A60) [2], a pulse generator synced to the trigger input, damping and gate protection networks, and current feedback mechanisms. To limit gate overshoot, a trans orb pair in anti-series was placed across the gate and source terminals, using an effective junction capacitance of 300 pF. The gate driver circuit was refined with adjustable resistors (R2, R3) and a snubber capacitor (C2). Simulation annotations such as “Increase C2 for stability” and “Increase R2 or R3 to reduce error” guided iterative parameter tuning.

Current feedback was modeled via a 700 V-rated transformer feeding into an OP27-based amplifier circuit, allowing responsive pulse shaping. The simulated ion source was represented as a simplified resistive load driven by a 15 Hz, 200 µs pulse input. A secondary measurement path incorporated realistic parasitic elements—wire resistance (R10), stray inductance ($L1 = 2$ µH), and capacitance to ground ($C3, C4 = 10$ nF)—to examine ripple behavior and trace energy leakage near the falling edge.

Transient analysis (.tran 1) revealed key insights: increasing snubber capacitance and fine-tuning gate resistor values helped sharpen the pulse termination, significantly reducing cycle-to-cycle jitter. Simulated waveforms showed cleaner trailing edges and more consistent fall characteristics, offering a viable pathway to mitigating instability in the physical modulator system.

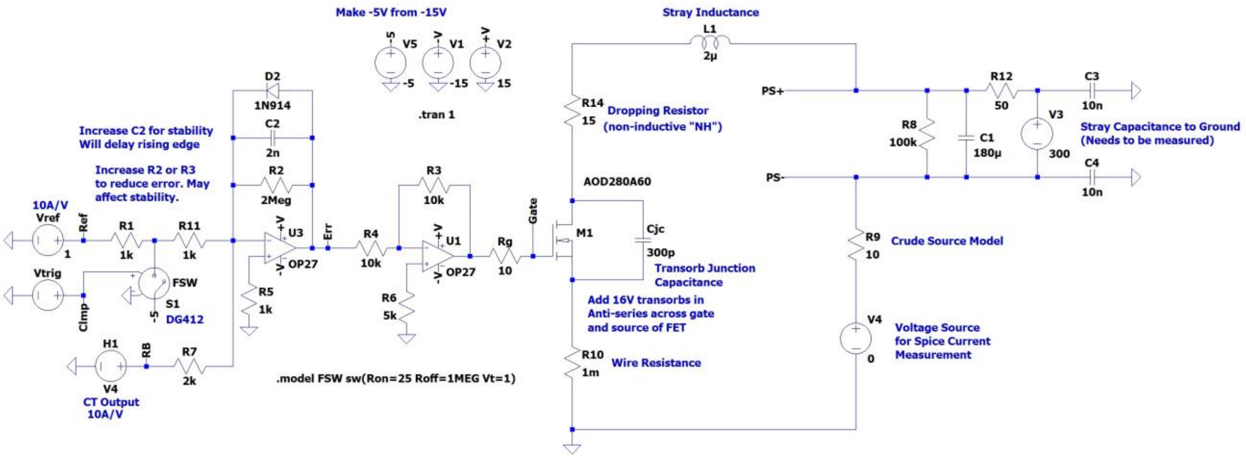

Figure 6: Conceptual circuit diagram for new current-regulated arc modulator designed by Matthew Kufer

3 Results & Discussion

Simulation results from the LTspice model show that the modified circuit successfully produces sharply terminated pulses with minimal overshoot, as illustrated in Figure 4. These improvements in waveform symmetry and fall-time behavior directly address the termination instability previously observed, supporting further refinement of the physical arc modulator.

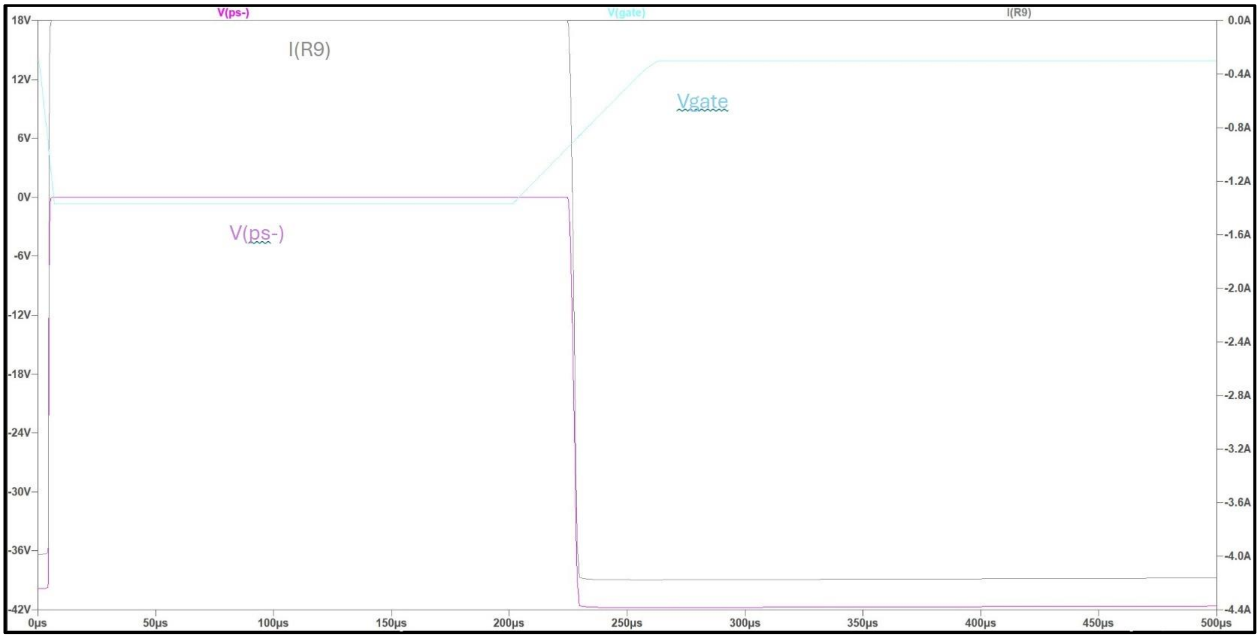

Figure 7: LTspice simulation of the prototype arc modulator circuit showing clean pulse termination across all channels

These results demonstrate that the prototype design significantly improves pulse stability and effectively suppresses AC signal noise within the ion source. This enhanced performance supports more consistent H^- ion generation, leading to improved beam quality and stability upon injection into the LINAC. The findings highlight the arc modulator's critical role in mitigating electrical instabilities within high-voltage systems, thereby enhancing the reliability of sustained H^- beam delivery. Such improvements are essential for supporting high-precision experimental operations at Fermi National Accelerator Laboratory.

4 Closing Remarks

The optimization of the arc modulator presented here demonstrates a viable path toward enhanced pulse stability and noise reduction in high-voltage plasma systems. By integrating targeted circuit improvements and validating their performance through simulation, the design offers a reliable means of addressing discharge variability that compromises ion source efficiency. These enhancements support sustained H^- beam delivery to the LINAC, aligning with the operational demands of the precision accelerator systems located at Fermi National Accelerator Laboratory. Continued refinement and integration of these approaches will be essential for achieving long-term reliability and advancing the performance of future ion source platforms.

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