

“Intense pulsed ion beam generation investigation”

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Abstract

The achievement of high current density of the generated intense pulsed ion beams (IPIBs) with low diode impedance is critical towards efficient surface modification of materials. This thesis determines the impact of the triple-junction (ATJ) geometry on the ion beam current density in a dielectric-coated, externally magnetically insulated (B -applied) ion diode with the specific goal of increasing the output without raising the accelerating voltage. Anode configurations

A total of four anode designs was made based on the i-NURA accelerator: three with continuous liquid-dielectric (epoxy) grooves of 1, 2, and 4 rings, and a novel design with polylactic acid (PLA) segments inserted into the grooves, forming multiple discontinuous triple junctions. The time variation of the diode voltage, time-integrated current and ion current density were recorded at magnetic field settings between 2kA and 5kA. The diode perveance, the impedance and the peak beam parameters were determined out of these waveforms. To identify the beam composition of anode of choice, time-of-flight spectrometry was used to resolve the beam composition of selected anodes. The results show that the 3D-printed anode made of PLA exhibits the highest peak ion current density and beam power, as well as the largest beam-to-diode current ratio, giving its best performance at a current in B-field coils of 4kA. The single-groove design of the continuous anodes surprisingly achieves higher ion efficiency than the multi-groove designs, in spite of the shortest ATJ line. The lowest impedance ($7.65 \cdot 10^{-1}$ vs. $18.57 \cdot 10^{-1}$ at $I = 2\text{kA}$) is in the 4 -groove anode, but at the cost of a lower ion fraction. The total ATJ length by itself does not control beam quality; the uniformity of the plasma initiation is equally important. The analysis by time-of-flight shows that the first current peak of the 3D-printed anode is dominated by protons, whereas the second peak of the anode is dominated by carbon and oxygen ion. The results show that a triple-junction geometry of anode can be carefully engineered and optimized, especially with the use of segmented dielectric inserts, to achieve significantly higher ion beam current density and lower the effective diode

impedance with no change in the accelerating voltage. This method offers a straightforward and robust solution to a more efficient IPIB source to industrial surface modification and future studies will expand the 3D-printed concept to further enhance the plasma uniformity and explore specific applications such as the post-treatment of silver nanowire transparent electrodes.

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Introduction

Intense pulsed ion beams (IPIBs) have emerged as a flexible instrument in surface modification of materials and are able to provide rapid thermal processing with heating and cooling rates of about 10^9 - 10^{10} K/s [1]. It is the highly localized energy deposition, coupled with the capacity to penetrate surface layers regardless of optical reflectivity, that makes IPIB treatment appealing to a very broad range of target materials. Applications that have been successful include the improvement of tribological performance of cemented carbides [2], the enhancement of hydrogen embrittlement resistance in high-strength martensitic steels [3], the surface hardening of additively manufactured Ti-6Al-4V alloy [4], the modification of metallic glasses and their crystalline counterparts [5,6], the controlled fracture analysis of single-crystal silicon [7] and the increase of radiation resistance in ceramic materials [8]. Once the beam is produced, efficient transportation of the beam to the target is dependent on proper space-charge neutralization [9] and more beam focusing can be obtained through exploitation of the beam space charge [10] or by geometrical and magnetic means.

Two conditions are critical to the production of an IPIB with the energy density and reliability it needs: that the electron component of the total diode current be suppressed, and that a dense, uniform anode plasma be produced, which will serve as the ion source [11,1]. In magnetically insulated ion diodes, the electrons flowing off the cathode are confined by a transverse magnetic field - either self-generated [12,1] or externally applied [11,13] - and the heavier ions pass through the gap. A popular ion source in B-applied diodes is the flashover discharge plasma: anode is made by narrow grooves filled with a polymer dielectric and the high electric field at the triple junction where the metal, dielectric, and vacuum meet causes surface breakdown, creating a dense plasma in which the ion beam is extracted [11,13]. The overall energy transfer efficiency of the accelerator, between the pulsed power system and the diode and then to the beam has been studied in detail with

self-magnetically insulated designs in mind [14, 27], and the importance of the impedance matching and minimization of parasitic losses.

In many materials processing applications, a greater ion beam current density is desirable, to either increase the treatment throughput or to exceed the ablation threshold of refractory materials. Increasing the current density by merely increasing the accelerating voltage is frequently not practical since it increases the impedance of the diode and imposes additional demands on the pulsed power system. [13] demonstrated that over a wide range the diode impedance and the resulting beam current density can be tuned by changing the timing of the magnetic field pulse relative to the accelerating voltage. Nonetheless, this strategy adds additional complexity of control and fails to enhance the natural emissivity of the anode plasma source. Another way to directly get to higher current density at constant voltage is to seek to improve the anode design so that the flashover plasma becomes more dense, more homogeneous, and more reproducible. The number and spatial density of flashover initiation sites and hence is likely to have a strong influence on the plasma generation process.

Although much research has been conducted on the dynamics of plasma formation and the resultant ion beam current density[12,13,15], the effect of the anode triple-junction geometry on the dynamics of the plasma formation, and on the outcome ion beam current density, has been largely unexplored. [13] observed that the non-uniformity and the variation in the density of the beam current by the anode can be caused by the non-uniformity of the anode emitting surface and the variation of the density of the beam current by the anode. Up to now, no experiment has been able to vary the length of the anode triple-junction lines in a flashover-source B-applied diode and correlate this geometrical parameter to the ion beam performance.

To produce intense pulsed ion beams, two basic problems must be addressed: (1) how to suppress the electron component of the diode current, and (2) how to produce a dense plasma

($n_i > 10^{14} \text{ cm}^{-3}$) on the anode surface [15]. The Child-Langmuir law limits the ion current density in planar diodes without magnetic insulation to about 2.3% of the electron current density in protons, i.e. nearly 98% of the energy supplied is wasted on accelerating electrons instead of ions [15].

The most common way of reducing the flow of electrons is magnetic insulation, either externally applied or self-generated. Ion generation efficiencies of up to 80-90 J - are achievable with externally applied magnetic field diodes [28], but these require more energy sources, up to 500 J -, to provide a total ion beam energy of 80-90 J - significantly increasing the complexity and power consumption of the system [16, 17]. By contrast, self-magnetically insulated diodes eliminate the need to provide external sources of magnetic fields to generate the transverse magnetic field by using the current flowing through the cathode to create the transverse magnetic field. With much lower degradation of graphite electrodes, such diodes have simpler construction, longer operational life (up to 10^6 - 10^7 shots due to minimal degradation of graphite electrodes), and are promising in industrial applications, although their ion generation efficiency is typically only 5-10% [16,18].

In self-magnetically insulated diodes, the anode plasma is often made by coating the anode surface with a dielectric polymer (e.g., polyethylene). Plasma formation is started by dielectric surface breakdown when the high-voltage pulse is applied, a process known as flashover [18]. The quality of this plasma anode source such as its density, uniformity, and reproducibility is critical to the efficiency and stability of ion beam generation [15].

Although much has been done in HIPIB generation, there are still a few gap areas that remain regarding the optimization of anode polymer filaments. First, the traditional polyethylene coating applied to self-magnetically insulated diodes has a relatively short lifetime in comparison to long-lasting graphite anodes, and ablated particles of the target can land on the anode surface, causing surface shorting and poorer plasma production [18]. Second, the ion beam

composition from polyethylene anodes is approximately 70% H^+ and 30% C^+ which may not be best for specific surface modification applications [18]. Third, although the efficiency of self-magnetically insulated strip and planar diodes is a subject of extensive research, the dependence between the anode polymer properties (e.g., surface morphology, dielectric strength, hole geometry) and the ion beam current density is not well characterized [18, 19].

Notably, it has been conventionally assumed that it is necessary to increase the accelerating voltage to achieve higher ion beam current density, which also increases diode impedance and power consumption. However, when using thin films and nanostructured materials (characteristic dimensions less than 500 nm) excessively high current densities may cause the destruction of the material instead of beneficial modification, as is the case with the transformation of 10 nm gold films into spherical particles when irradiated with a single pulse at 20 A/cm², but retained the film integrity when the same fluence was applied at 4 A/cm² in five pulses [13]. Therefore, a way of managing and optimizing ion beam current density without changing voltage is much desirable.

Recent experiments by [13] demonstrated that ion beam current density in a B-applied ion diode can be adjusted from 100 A/cm² down to 4 A/cm² by varying the diode impedance by controlling the triggering delay relative to the magnetic field generator, and keeping charging voltages fixed. This method, however, is limited to externally magnetically insulated diodes. In the case of self-magnetically insulated diodes, which do not have an independent magnetic field generator, an alternative approach is required.

In the literature, the anode plasma source is a major factor that influences the properties of ion beams such as their current density, composition and stability [18, 19]. Thus, the current study seeks to enhance the anode polymer filament in a magnetically insulated diode in order

to increase the ion beam current density without raising the accelerating voltage, thus reducing the diode impedance.

Particularly, this research will concentrate on:

1. Characterization of the dynamics of flashover plasma formation on altered polymer anode surfaces.
2. Determining the influence of polymer filament design (e.g., hole geometry, material composition, surface treatment) on ion current density, and beam uniformity.
3. Displaying the correlation of anode characteristics, diode impedance and ion beam output parameter.
4. Demonstrating enhanced efficiency with surface modification applications at lower impedance.

The diode impedance (defined as $Z_d = V_d / I_d$) will be lower by achieving higher current density at constant voltage, making more efficient energy transfer between the pulse-forming line and the ion beam and possibly improving the overall energy efficiency of the HIPIB generation system. This method directly responds to the industrial requirement of strong, efficient and controllable ion sources to large-scale materials processing.

Research methodology

1) Theoretical background

The high-intensity pulsed ion beams (HIPIB) characterization necessitates the measurement of a number of interrelated electrical and physical parameters that define the energy content, composition and material interaction potential of the beam. The diagnostics and the optimization of the ion diode work are possible only when the accurate diagnostics are provided [1]. Accelerating voltage, total diode current, current density, diode impedance, perveance, ion fluence, and beam composition are the main parameters of interest.

A basic parameter that determines the kinetic energy that is imparted to ions is the accelerating voltage U_d applied to the ion diode. In pulsed power systems, high frequency, high voltage resistive or capacitive dividers are often installed near the diode, to measure the voltage [18,19]. In the case of the TEMP-series accelerators, resistive-capacitive divider, with division ratios of about 1500:1, is used, with calibration accuracy of about 3% [18].

A voltage waveform accelerating to a second positive pulse (120-150 ns duration, 200-300 kV amplitude) during which ions are extracted and accelerated [20] is found in the operation of bipolar-pulse mode diodes, which are typical of self-magnetically insulated diodes. The primary interest of the ion beam generation is the second pulse which determines the ion kinetic energy as $E_i = zeU$, where z is the ion charge state.

A Rogowski coil is used to measure the total current flowing in the diode circuit in a non-inductive, wideband measurement. The Rogowski coil gives an output voltage proportional to the time derivative of the current [18], which is then integrated to obtain the current waveform. The common Rogowski coil sensitivities are approximately 200-300 A/V [18]. The total diode current is

the sum of electron and ion components, but the electron component is the dominant component since the electrons are the most mobile.

The time-dependent changes in the diode current give information on the dynamics of the anode-cathode (A–K) gap. At the beginning, prior to the formation of plasma, the impedance is high and the current increases slowly. When plasma is formed, the effective AK gap will be reduced because of the expansion of plasma resulting in a higher current [20]. In self-magnetically insulated diodes operated without an external magnetic field, diode current can be up to 94 kA, but with efficient magnetic insulation this can be reduced to only a few tens of kiloampere, and ion current density is also increased [18].

The ion current density J_i is normally measured by a collimated Faraday cup (CFC) located downstream of the diode (at the target position). There are two major configurations: the CFC with magnetic cutoff and the CFC with electric bias [19].

In this design, a transverse magnetic field ($B = 0.20.4$ T) is generated by permanent magnets placed around the collimating aperture. The low-energy electrons neutralizing the ion beam space charge are deflected by the magnetic field and will not reach the collector. The Larmor radius of electrons is [19]:

$$R_L = \frac{\sqrt{(2m_e E)}}{eB}$$

where E is the electron kinetic energy (usually less than 10 keV to neutralize electrons). The Larmor radius of a magnetic field of 0.3 T is less than 1 mm, which is sufficiently small to ensure successful electron suppression. Current density ion beam current density is then calculated as the measured collector current/aperture area. The diameter of the collimating aperture is usually 4-8 mm and the limitation here is that the aperture size must be greater than the skin depth of the magnetic field penetration into the plasma beam [21].

[1] have demonstrated that measurements of the amplitude of ion current densities alone cannot be used to provide an accurate characterization of beam-target interactions. The correlation coefficient between the amplitude of ion current density and the total charge density per pulse is only $R = 0.83$, indicating that up to 100% change in charge density is possible at constant amplitude. This is due to several factors: (1) the complicated ion energy spectrum, (2) the presence of accelerated neutrals due to charge-exchange reactions, (3) asynchronous generation of ions across the beam cross-section, and (4) variations in accelerating voltage.

Diode impedance is $Z_d = U_d / I_d$ and is an important parameter in matching the pulsed power generator to the diode load. A characteristic impedance of the double forming line (DFL) in the TEMP-4M accelerator is approximately 5Ω , and the gap between the A and K is adjusted (usually 8-9 mm) to fit this impedance [16].

The space-charge-limited current can be calculated using the Child-Langmuir relation, which is time-dependent, and using the plasma expansion and the plasma erosion effect [21,22,29]. The current of electrons flowing through the circuit in the first (negative) pulse is:

$$Z_{calc}(t) = \frac{U}{I_e} = \frac{(d_0 - vt)^2}{2.33 * 10^{-6} S U^{\frac{1}{2}}}$$

where d_0 is the initial A-K gap, v is the expansion velocity of the plasma (usually 1.3-1.5 cm/ μ s) and S is the area of the emitting surface. In the second (ion extraction) pulse, the electron current is increased by a factor of about 1.86 due to bipolar flow, and the impedance is correspondingly lowered [21].

In diodes with self-magnetically insulated diodes, the impedance changes considerably during the pulse. It is initially high (hundreds of ohms) but decreases to a fairly flat

plateau (5-15 Ω) when the plasma is formed and finally drops to near zero when the A-K gap is closed by the plasma expansion [18]. When an external magnetic field is applied, the first impedance is increased by inhibiting the flow of electrons.

Perveance P is a figure of merit which characterizes the space-charge-limited current-carrying capacity of a diode, defined as $P=I/U^{3/2}$. In the case of a perfect planar diode in vacuum, the Child-Langmuir perveance is [22,30]:

$$P_{Ch-L} = \frac{4\epsilon_0}{9} \sqrt{\frac{2e}{m}} \frac{S}{d^2} = 2.33 * 10^{-6} \frac{S}{d^2}$$

In the case of ion diodes, the experimental perveance can easily exceed the ChildLangmuir value because of the formation of virtual cathodes and plasma effects. [13] have demonstrated that when the ion diodes are applied with a B-field, the amplification factor K (the ratio of experimental to theoretical perveance) varies between 1.2 and 4 depending on the strength of the magnetic field [31]. The factor of current amplification is:

$$P_{exp} = \frac{4K\epsilon_0}{\sqrt{m_i}} \frac{\pi[(R + vt)^2 - (r - vt)^2]}{(d_0 - vt)^2}$$

in which R and r are the outer and inner radii of the annular anode, respectively. When magnetic insulation is weakest (i.e., when the virtual cathode is closest to the anode) the amplification factor is largest [13].

The time-integral of the density of the ion current is the ion fluence per pulse (ϕ):

$$\phi = \int \frac{J_i(t)dt}{e}$$

For typical HIPIB parameters (200–250 kV, 100–150 ns pulse duration, 40–70 A/cm²), the fluence is approximately $1.3\text{--}2.5 \times 10^{13}$ cm⁻² per pulse [1]. The energy density q that corresponds is:

$$q = \int U(t) * J_i(t) dt$$

The most common energy densities of the surface modification are 110 J/cm², with higher values (10-12 J/cm²) possible in focusing diode geometries [20].

[1] strongly encourage energy density measurement over current density measurement as the primary diagnostic to beam-target interactions, since energy density is the direct measure of the thermal effect causing material modification, and is independent of ion species and kinetic energy spread, and superior shot-to-shot reproducibility (standard deviation of 10-11% compared to 20-30% with current density).

Time-of-flight (TOF) is an effective method of determining the composition and energy spectrum of HIPIB with a single Faraday cup sensor [19]. The principle is based on the fact that the ions of various mass to charge ratios accelerated by the same voltage pulse receive the same kinetic energies but different velocities.

When a pulsed accelerating voltage $U(t)$ is applied to the diode, an ion of mass m_i and charge state z gets kinetic energy:

$$E = \frac{m_i v_i^2}{2} = zeU$$

The velocity of the ion is thus:

$$v_i = \sqrt{\frac{2zeU}{m_i}}$$

The ion time lag to move a distance of D (diode to Faraday cup) is:

$$\Delta t = \frac{D}{v_i} = D \sqrt{\frac{m_i}{2zeU}}$$

Therefore, in a given accelerating voltage, lighter ions (protons) reach the target sooner than heavier ions (carbon) and higher charge states arrive sooner than lower charge states of the same species.

The TOF method goes ahead as follows [19]:

1. The voltage waveform $U(t)$ is sampled at a very high temporal resolution (0.4 ns step).
2. The current density of each species at each instant is computed using the space-charge-limited Child-Langmuir relation, considering the effects of expansion of the plasma and the plasma erosion effect:

$$j_k(t) = \frac{4K\epsilon_0\sqrt{2z_k}}{9\sqrt{m_k}} \frac{U(t)^{3/2}}{[d_0 - v(t - t_0)]^2}$$

where K is the amplification coefficient of the ion current (including the focusing or virtual cathode effect) and t_0 is the polarity reversal time.

3. The arrival time for the Faraday cup is computed in each region, which results in a time-shifted signal:

$$t_{arrival,k} = t + \Delta t_k(t)$$

4. The overall computed current density is the sum of all species and compared with the experimentally determined signal of the Faraday cup.

TOF method has been validated on various accelerator configurations [19, 32]:

- Self-magnetically insulated diode with graphite anode (TEMP-4M, bipolar mode):

The beam consists of about 80-85% C^+ ions and 15-20% protons. Amplification effects have increased the current density of C^+ ions by 5-10 times that of the Child-Langmuir calculation.

- External magnetic insulation diode with polyethylene anode (TEMP-6, unipolar mode): This beam consists of approximately 50% protons and 50% C^+ ions, with the former of these coming not only from hydrogen in the polyethylene but also from hydrogen in the hydrogen peroxide. The focusing geometry is reflected in the amplification factor of protons is $K_H = 7$ and of C^+ is $K_C = 25$ [18,19].

- Barrel diode with dielectric anode (BIPPAB-450): At magnetic fields above critical ($B > B_{crit}$), the beam is mainly C^+ . Fields near critical, doubly and triply ionized carbon are observed, and the proton fraction is elevated.

The TOF technique is also able to reconstruct the ion energy spectrum [19]. The kinetic energy of a given ion species at a certain step of the accelerating voltage waveform is:

$$E_k(t) = z_k e U(t)$$

Correlation of the time of arrival at the Faraday cup with $U(t)$ yields the energy distribution of each species. In the case of self-magnetically insulated diodes, with matched Blumlein loads, the accelerating voltage pulse is roughly rectangular, which results in a narrow energy spectrum, where >80 percent of ions have kinetic energies in excess of 150 keV [19].

The single CFC TOF method has a number of benefits [19]: (1) fast, real-time monitoring of beam composition, (2) determination of the absolute ion current densities with an error of $\pm 10\%$, (3) separation of the contributions of the various ion species, and (4) simultaneous reconstruction of the energy spectrum. The main constraint is that it requires high bandwidth oscilloscopes (at least 200 MHz, at least 5 GS/s), and precise synchronization (error 200 MHz).

2) Experimental background

All the experiments were carried out on the i-NURA pulsed ion accelerator (Figure 1) at Nazarbayev University, a high-voltage pulsed generator system designed to produce intense pulsed ion beam (IPIB) and modify materials [13]. The accelerator has two independent high-voltage generators (HV_1 and HV_2), one of which produces the accelerating voltage pulse (HV_1), and the other of which supplies current to the B-field coils of the magnetically insulated ion diode. The HV_1 generator is made of 3 μF capacitive storage, a step-up pulse transformer, a spark-gap switch, and an inductive voltage adder, which delivers a voltage pulse of 180-200 kV under equal conditions. The HV_2 generator consists of a capacitor bank of 50 μF capacitors and a pseudo-spark switcher, which generates a 110 μs pulse of current to the B-field coils [13].

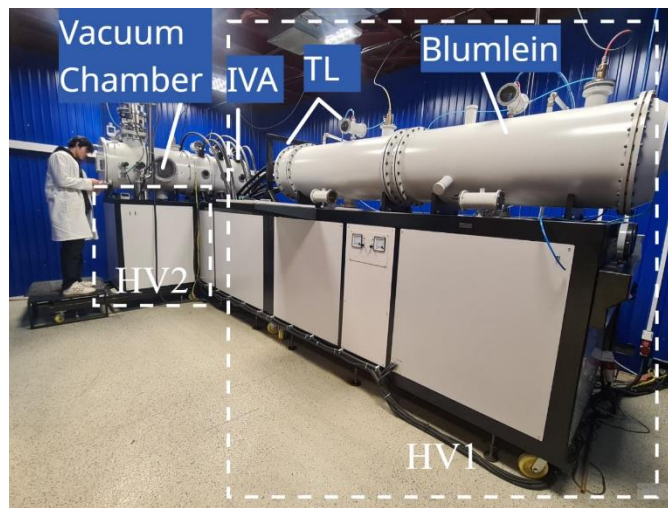


Figure 1. i-NURA accelerator schematic

The diode is an externally magnetically insulated (B-applied) ion diode with radial (B_r) field configuration and focusing geometry. The annular anode (outer diameter 24.5 cm, inner diameter 20 cm) is made of copper with 1 mm deep annular grooves filled with a polymer dielectric to serve as the ion source. The cathode is made of two truncated stainless-steel cones (0.5mm thick) attached to an aluminum supporting disk. All experiments set the anode cathode (A-K) gap to 7 -

mm, with the diode operated in the matched mode at a Blumlein breakdown voltage of 120 -mm with the current density being around 70 A/cm^2 [13].

The basic physics of plasma formation in a dielectric-coated anode is the surface flashover that occurs at the triple junction between the anode metal, the dielectric, and vacuum [23,24]. The flashover processes and the effectiveness of the plasma formation depend strongly on the local electric field in the triple junction of anode and cathode, and increasing the effective length of the anode triple junction (ATJ) line can modify the flashover processes and the efficiency of the plasma formation [16]. It was based on this principle that four different anode configurations were fabricated, each with a different ATJ line length, the total anode surface area and A-K gap kept constant.

An anode with four annular grooves (depth 1mm) cut into the copper surface. The grooves were filled with a liquid dielectric (hot glue resin) that was cured at room temperature for 24 h. The overall ATJ line length was estimated as the sum of the circumferences of all groove edges (both inner and outer boundaries).



Figure 2. 4 grooved anode filled with liquid dielectric

Two identical annular grooves, filled with the same cured epoxy, were made on an anode. The line length of the ATJ was about half the line length of the four-groove anode.



Figure 3. 2 grooved anode filled with liquid dielectric

With a single annular groove filled with cured epoxy, the anode has the shortest ATJ line length of the liquid-dielectric-filled anodes.

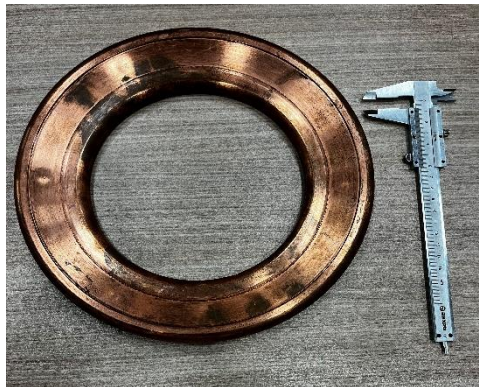


Figure 4. 1 grooved anode filled with liquid dielectric

A grooved anode of the same size but filled with segmented inserts produced using fused deposition modelling with polylactic acid (PLA) filament. The inserts were discrete 5mm long segments that are inserted into each groove, with small gaps between them. The design resulted in a discontinuous ATJ line, with an effective length between the two-groove and four-groove anodes and also introduced several additional triple junctions at the interfaces between the segments.

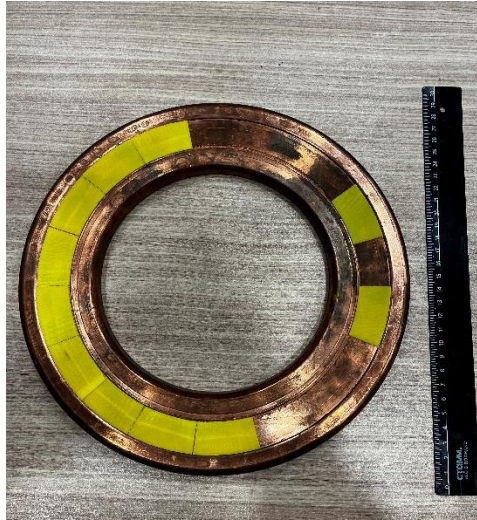


Figure 5. 3D printed anode

Each anode configuration was operated in four different settings of the accelerator, where the value of current applied to the B-field coils: 2, 3, 4 and 5 kA [13]. A small number of pulses were discharged, and all the parameters of the combinations of the anode type and operating condition were recorded.

- Accelerating voltage (U_a): Measured by a resistive voltage divider placed in the transition chamber between the induction voltage adder and the diode. The divider had a division ratio of $10^4:1$ and a bandwidth of 100 MHz [13].

- Total diode current (I_a): Measured with a Rogowski coil that was placed around the cathode feed [13].

- Current in B field coils (IBF): Measured with a second Rogowski coil on the output of HV_2 generator.

- Two Agilent DSO5034A oscilloscopes (300 MHz bandwidth, 2GS/s) were connected to a common trigger to record all signals.

The ion current density (J_i) was measured with a collimated Faraday cup, which has a magnetic cutoff of low-energy electrons [19]. The Faraday cup was attached to a rotary table within

the vacuum chamber with a distance of 28 cm between the diode and the Faraday cup, which was located at the geometric focal plane of the focusing electrode set. The waveform of the ion current density was corrected with the time-of-flight delay of ions between the diode and the collector using the method described by [19].

Based on the measured waveforms, the following parameters were estimated of each pulse:

- Pulsed power (instantaneous power supplied by the HV¹ generator to the diode):
- Diode power (average power of the accelerating pulse):
- Diode impedance (dynamic impedance at the maximum of the accelerating voltage)

[13].

- Perveance (space-charge-limited current capability):

The experimental perveance was compared with the theoretical Child-Langmuir perveance for a planar diode: [13,22].

- Ion current density (maximum value): J_i^{peak} in A/cm², determined by the signal of the Faraday cup after time-of-flight correction.

- Ion fluence/ pulse: (in cm⁻²).

The justification of the changing ATJ line length is premised on known physics of flashover. [23,24] showed that flashover initiation in vacuum can either occur at the cathode or at the anode triple junction depending on the local electric field distribution, and that increasing the effective triple junction length increases the probability of a plasma initiation at lower electric fields. With a dielectric-coated anode, a longer ATJ line offers more sites of field-enhanced electron emission and dielectric surface flashover, which in turn results in faster and more uniform anode

plasma formation [16,33]. The lower delay between the application of accelerating voltage and the onset of full space-charge-limited ion current, in turn, leads to a reduction in the delay between the application of accelerating voltage and the onset of full space-charge-limited ion current, which may in turn increase the effective ion current density at a given voltage.

[18] demonstrated that the stability and density of plasma anode is critical in the efficiency of ion beam generation in a unipolar-mode MID that directly depends on the dielectric surface breakdown properties. We are looking to encourage more vigorous and reproducible flashover by increasing the line length of the ATJ line, and this will lead to a higher ion current density without increasing the accelerating voltage. A systematic variation of the length of ATJ is provided by the use of various groove numbers (1, 2, 4), and not only a different ATJ length is introduced but also other discontinuous triple junctions that can further enhance the formation of plasma through micro-discharges at the interfaces between segments.

All other diode parameters (A -K gap, magnetic field coil current, Blumlein charging voltage, and triggering delay range) were held constant across types of anode to isolate the effect of the ATJ line length on beam parameters. The difference between the HV_1 charging voltage and the triggering delay enabled the accelerator to be operated at different impedance matching conditions, providing a range of baseline ion current densities against which the improvement due to the anode design could be evaluated [13].

The following metrics were calculated and compared depending on the type of anode and the operating conditions:

- Peak ion current density J_i^{peak} .
- Diode impedance Z_d
- Experimental perveance P_{exp}

- Experimental to Child-Langmuir perveance $P_{\text{exp}}/P_{\text{Ch-L}}$, which is a measure of space-charge neutralization and virtual cathode effects [13]

- Pulse power and diode power.

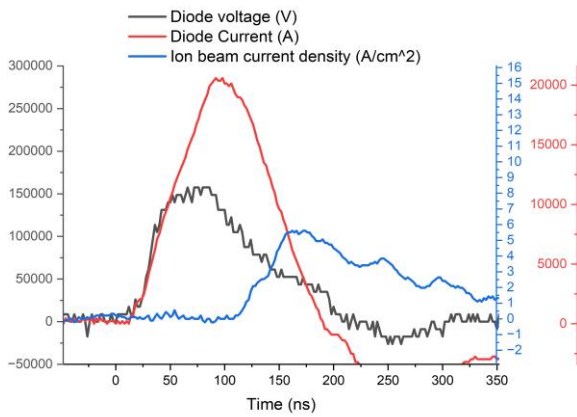
- Shot-to-shot variability (relative standard deviation) of J_i^{peak}

Graphical comparisons were made between each metric as a function of ATJ line length and as a function of triggering delay (i.e., the strength of the magnetic field at which the accelerating pulse occurs). The aim was to find anode designs that would give the highest ion current density at the lowest possible diode impedance, thus demonstrating an increase in beam current density without an increase in voltage [1,13].

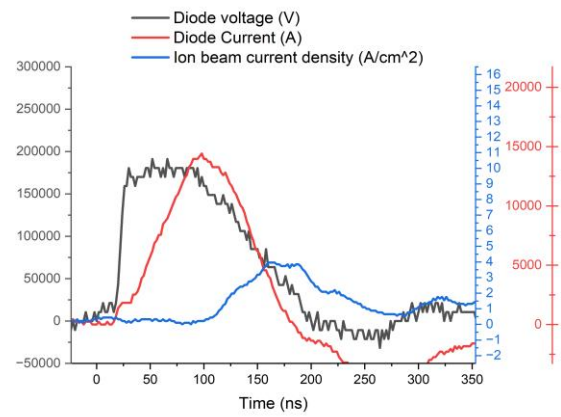
Results analysis

1) Diode Voltage, Total Current, and Ion Beam Current Density Waveforms

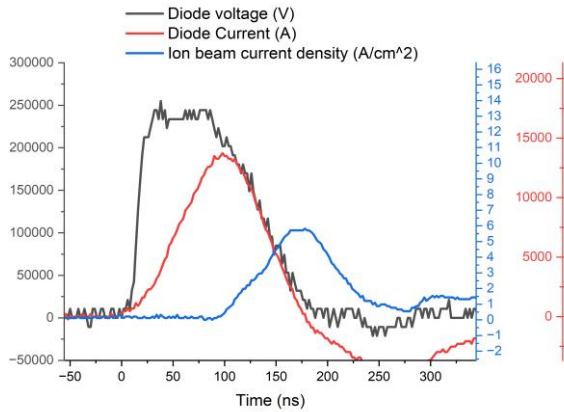
The temporal evolution of the accelerating voltage, the total diode current, and the ion beam current density was recorded for each anode configuration (4 grooves, 2 grooves, 1 groove, and 3D-printed PLA segmented) at the four magnetic field settings (values of current in B-field coils: 2, 3, 4, 5 kA). The complete set of waveforms is presented in Figures 6–9.



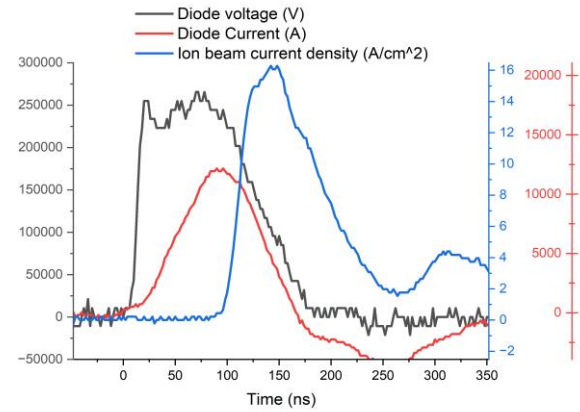
a. 4 groove



b. 2 groove

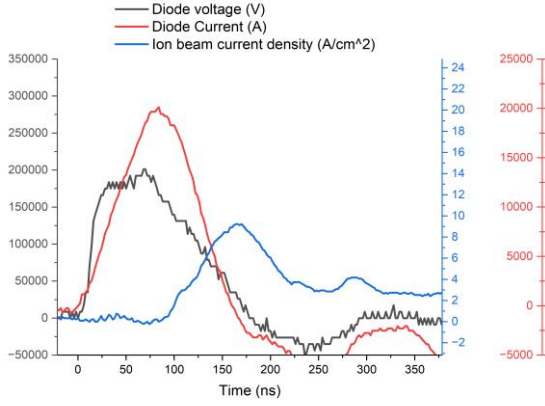


c. 1 groove

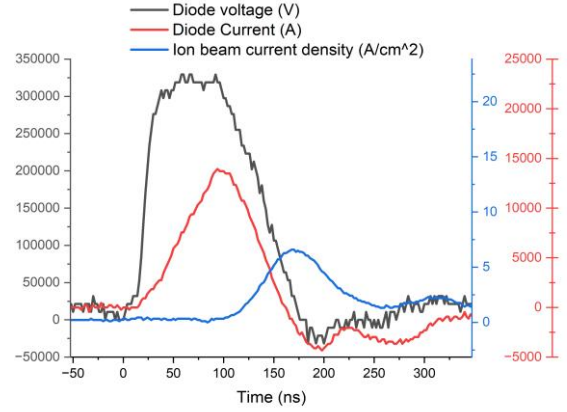


d. 3D printed

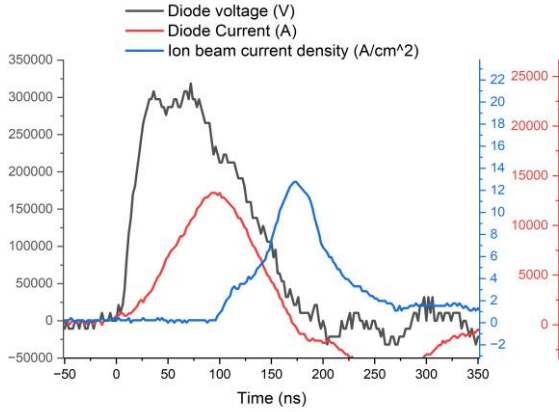
Figure 6 (a-d). Diode voltage, diode current and ion beam current density of 4 anodes at 2kA – current in B-field coils



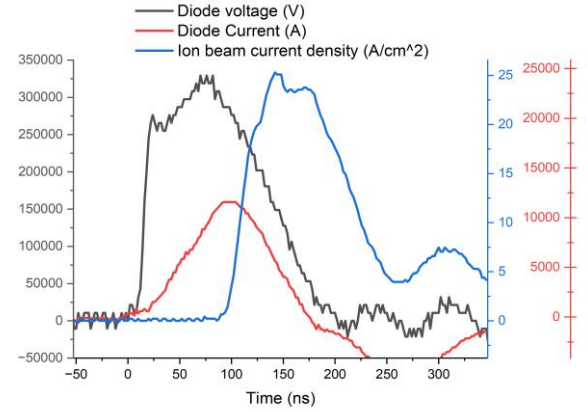
a. 4 groove



b. 2 groove

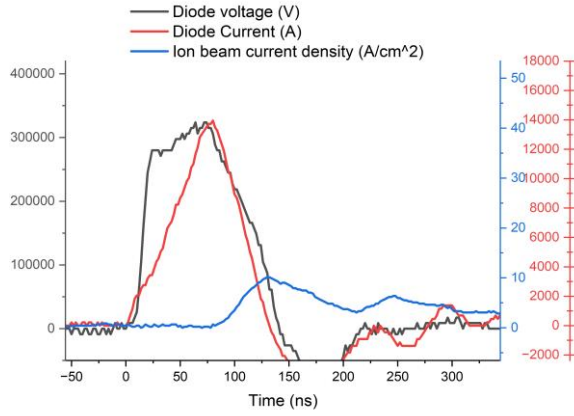


c. 1 groove

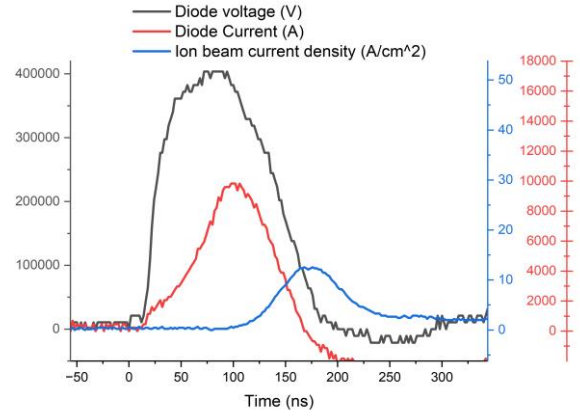


d. 3D printed

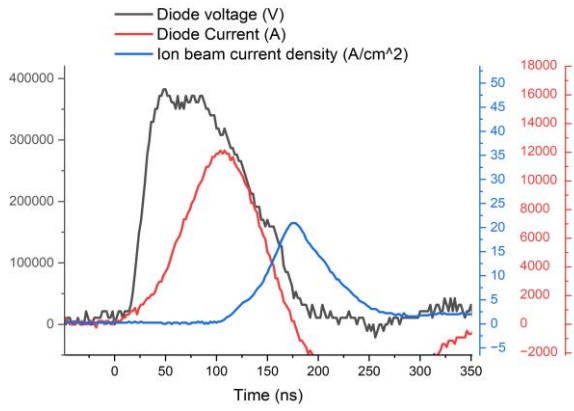
Figure 7 (a-d). Diode voltage, diode current and ion beam current density of 4 anodes at 3kA – current in B-field coils



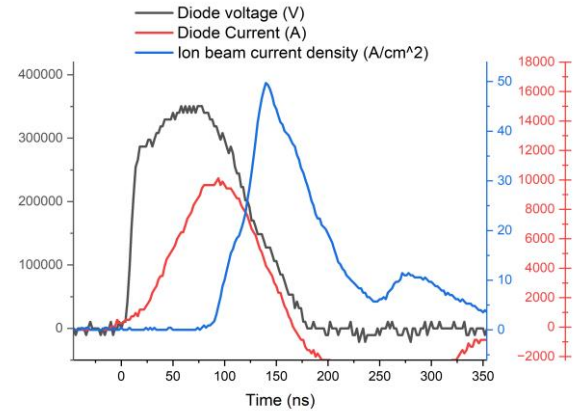
a. 4 groove



b. 2 groove

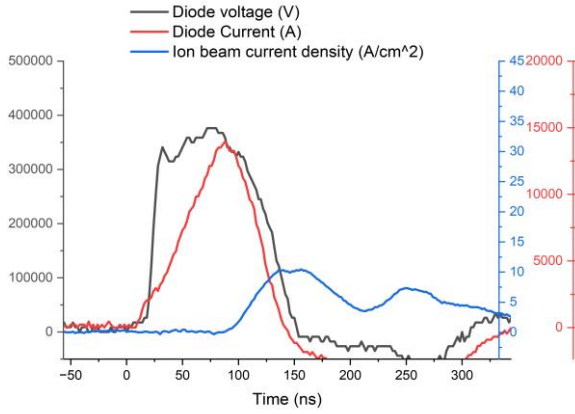


c. 1 groove

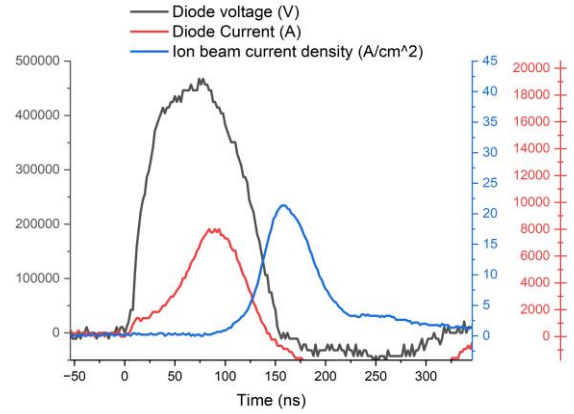


d. 3D printed

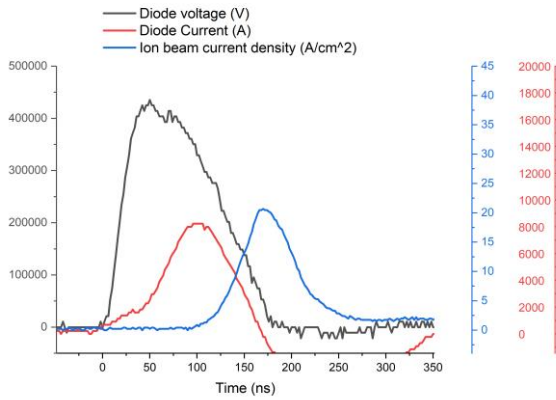
Figure 8 (a-d). Diode voltage, diode current and ion beam current density of 4 anodes at 4kA – current in B-field coils



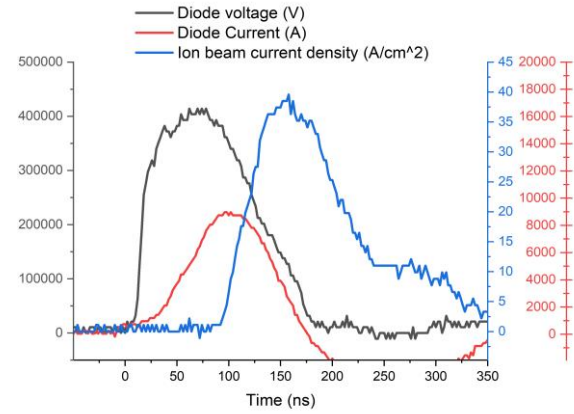
a. 4 groove



b. 2 groove



c. 1 groove



d. 3D printed

Figure 9 (a-d). Diode voltage, diode current and ion beam current density of 4 anodes at 5kA – current in B-field coils

Across all anodes and B-field settings, the diode voltage waveform displayed a characteristic fast-rising pulse with a duration of approximately 150 ns at full-width-half-maximum. The peak voltage varied by around 25% between the different anode configurations at a given current in the B-field coils.

The total diode current waveform generally followed the voltage rise, although a measurable delay between the onset of voltage and the onset of appreciable current was observed for all anodes. This delay, attributed to the time needed for flashover plasma formation and expansion across the anode–cathode gap, was shortest for the 3D-printed anode and longest for the 2-groove and 4-groove liquid-dielectric anodes, particularly at the lower magnetic field settings.

The ion beam's current density, as measured by the magnetically insulated Faraday cup, rose more slowly than the total diode current and peaked after the voltage maximum. The peak ion current density increased with the B-field coil current setting from 2kA to 4kA for all anodes and then declined slightly at the 5kA setting. The highest peak ion current density at the optimal setting of 4kA was recorded for the 3D-printed anode, followed in order by the 1-groove, 2-groove, and 4-groove anodes. This ordering was preserved at all B-field coil current values.

The shape of the ion current density pulse also varied systematically with anode type: the 4-groove anode, 2-groove anode and the 1-groove anode exhibited a single, relatively symmetric peak, whereas the 3D printed anode tended to produce 2 peaks in the waveform.

At the lowest B-field current (2kA), the ion current density was noticeably lower for all anodes, and the electron contribution to the total diode current was higher, as indicated by the larger difference between the total current and the ion current signals. As the B-field was increased to 4kA, the ion current density rose while the total diode current remained comparable, reflecting improved electron suppression and a higher proportion of ion current. At 5kA, the total current decreased slightly without a further increase in ion current, indicating that the magnetic insulation was already sufficient at 4kA.

No abnormal waveforms, such as premature shorting or late-time breakdown, were observed for any anode. The shot-to-shot reproducibility of the waveform shapes was qualitatively

good over the several pulses recorded per configuration; a more quantitative statistical analysis of the peak values has been presented in the following sections.

2) Diode perveance

To further quantify the effect of anode geometry on ion beam generation, the diode perveance $P = I / U^{3/2}$ was calculated from the measured voltage and current waveforms, more precisely the peak values were considered. Perveance values were compared at four fixed currents in the magnetic field coils, corresponding to the values of current B-field coils of 2, 3, 4, and 5 kA, respectively.

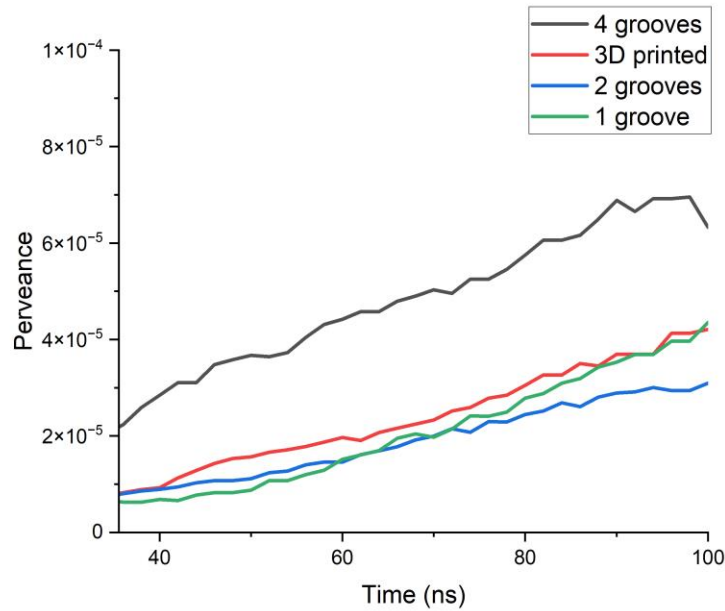


Figure 10. Comparison of perveances at 5 kA current in B-field coils

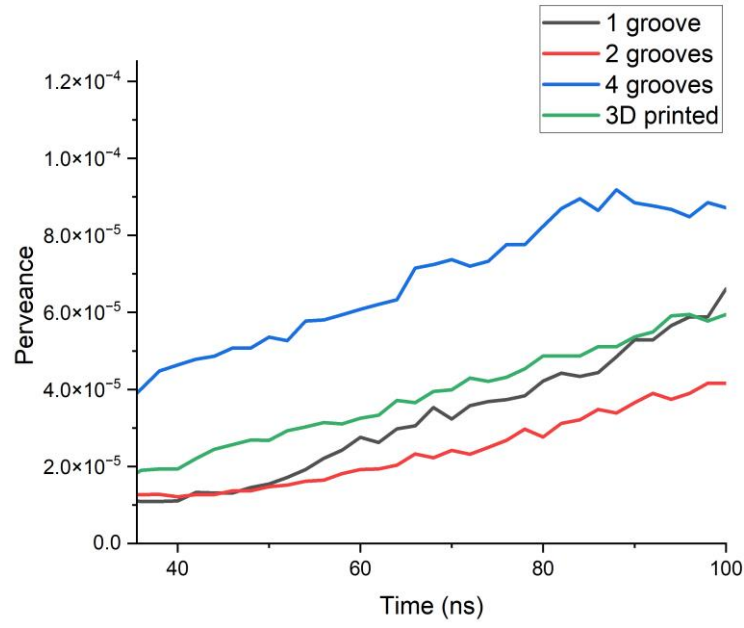


Figure 11. Comparison of perveances at 4 kA current in B-field coils

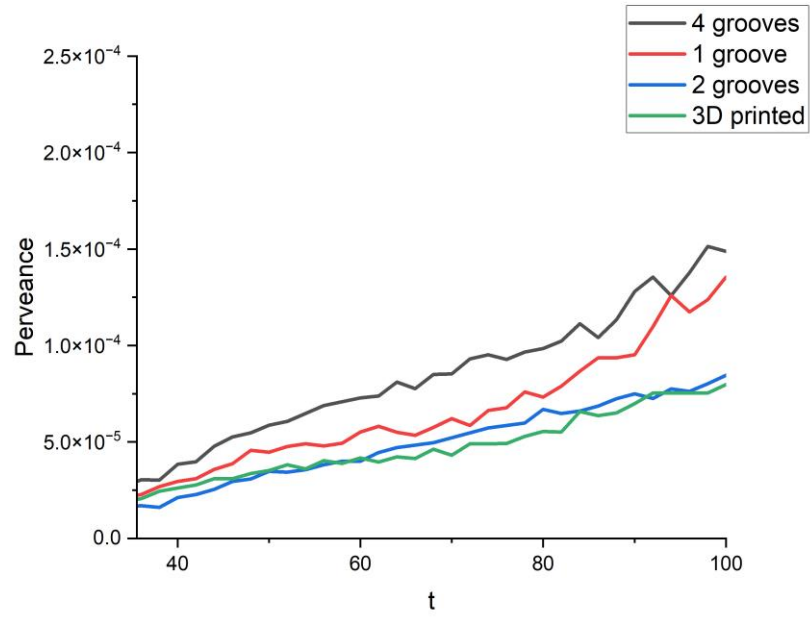


Figure 12. Comparison of perveances at 3 kA current in B-field coils

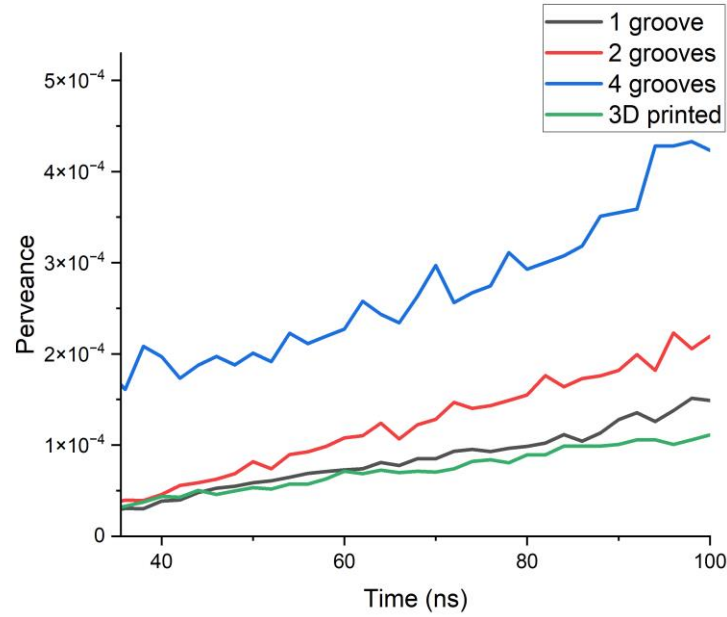


Figure 13. Comparison of perveances at 2 kA current in B-field coils

Figures 10–13 display the perveance of each anode type at the four B-field settings. Across all settings, the perveance was highest for the anodes with the longest triple-junction lines. The difference in perveance between the most and the least emissive anode grew as the B-field setting was reduced, indicating that the benefit of an extended triple-junction length becomes more pronounced under weaker magnetic insulation.

The relative ordering of the anodes by perveance was preserved across all accelerator settings and B-field values, with the anode having the greatest total triple-junction length consistently yielding the highest perveance, and the reference anode with the shortest triple-junction length yielding the lowest.

3) Diode impedance

The impedance of the ion diode was calculated from the recorded accelerating voltage and total diode current waveforms for each anode type and for each of the four magnetic field settings. The resulting impedance values are presented in Figures 14-17.

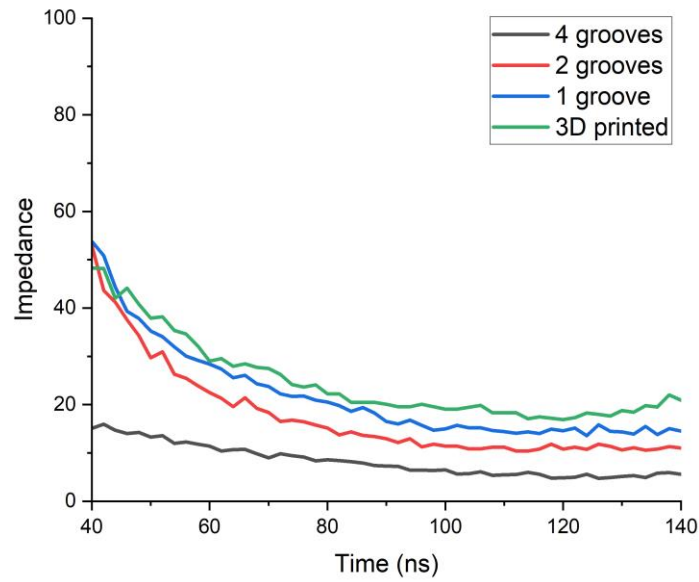


Figure 14. Comparison of impedances at 2kA current in B-field coils

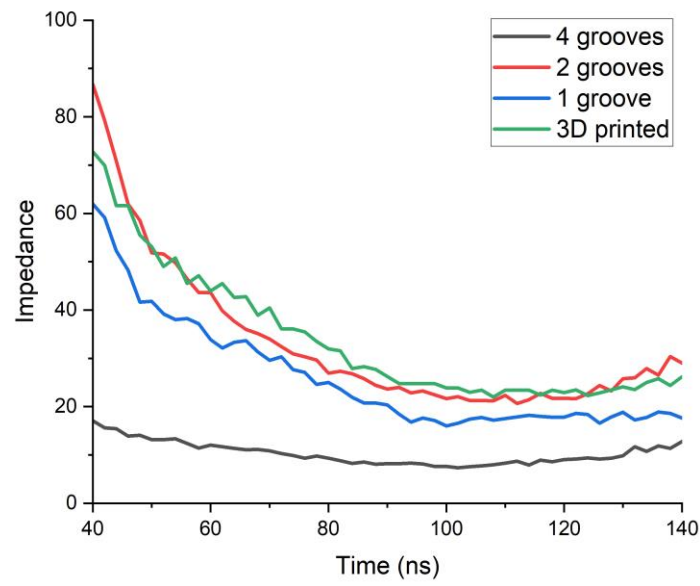


Figure 15. Comparison of impedances at 3kA current in B-field coils

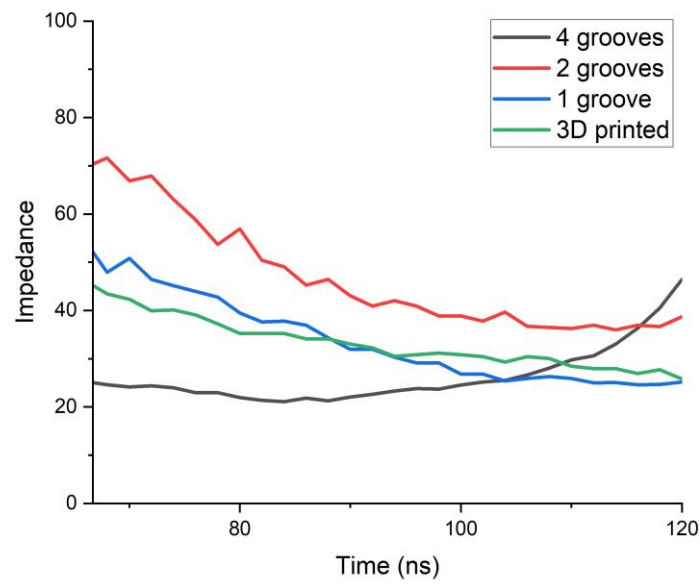


Figure 16. Comparison of impedances at 4kA current in B-field coils

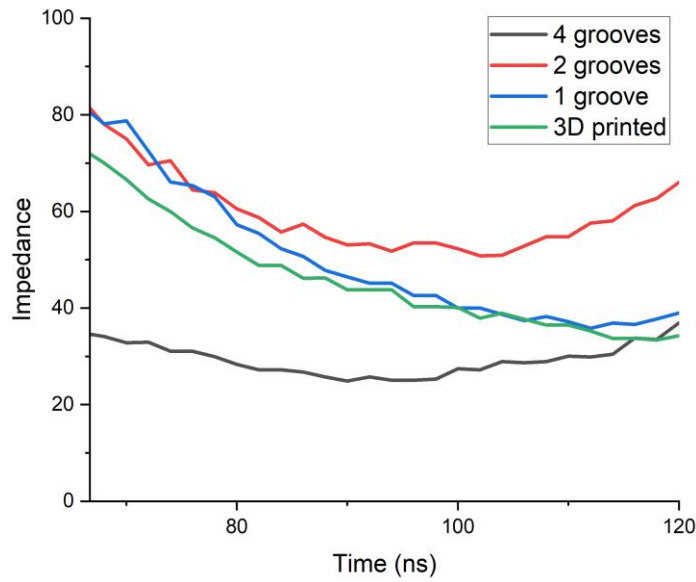


Figure 17. Comparison of impedances at 5kA current in B-field coils

Across all B-field settings a consistent ranking of the anodes was observed: the anode with the longest total triple-junction line exhibited the lowest diode impedance, while the reference anode with the shortest triple-junction length yielded the highest impedance. The difference in impedance between these two extreme designs was smallest at the lowest magnetic field ($I_{\text{coil}} = 2\text{kA}$) and became progressively higher as the B-field was increased. At $I_{\text{coil}} = 5\text{kA}$ the impedance values of all anodes converged, and the spread among the different designs was minimal.

At $I_{\text{coil}} = 2\text{kA}$, the impedance of the anode with the greatest triple-junction length was $7.65\ \Omega$, while that of the anode with only 1 groove was $18.57\ \Omega$. The intermediate anodes fell between these two values, with their impedance decreasing monotonically with increasing triple-junction length. As the I_{coil} was raised to 5kA , the absolute impedance of every anode increased 2-3 times and the range of variation across the anode types narrowed $20\ \Omega$.

No crossing of the impedance curves was observed; the anode that exhibited the lowest impedance at one B-field setting remained the lowest at all other settings, confirming that the effect of anode geometry on diode impedance is systematic and reproducible under the experimental conditions examined.

All the results are confirmed by Figure 18, which represents the peak values of Impedance across different anodes.

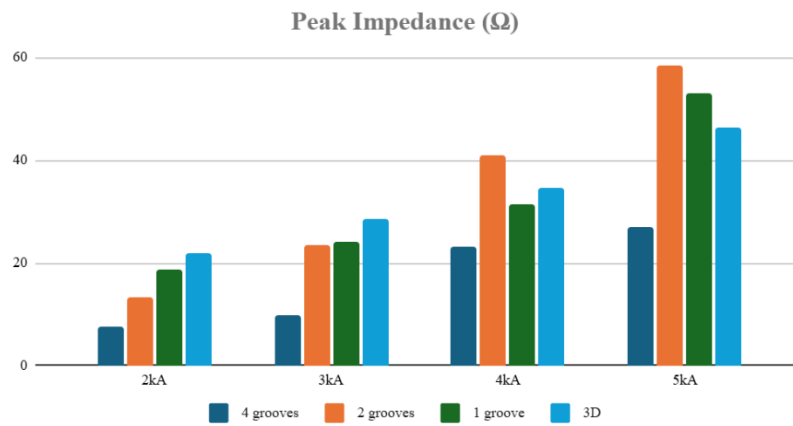


Figure 18. Peak impedances of different anodes at several accelerator settings

4) Peak values of beam parameters

The ion beam peak power, peak current density, power-to-current ratio, and peak supply voltage were measured for each anode configuration across the range of accelerator settings (charging voltage time gap of the Blumlein). The complete set of results is presented in Figure 19(a)–(d).

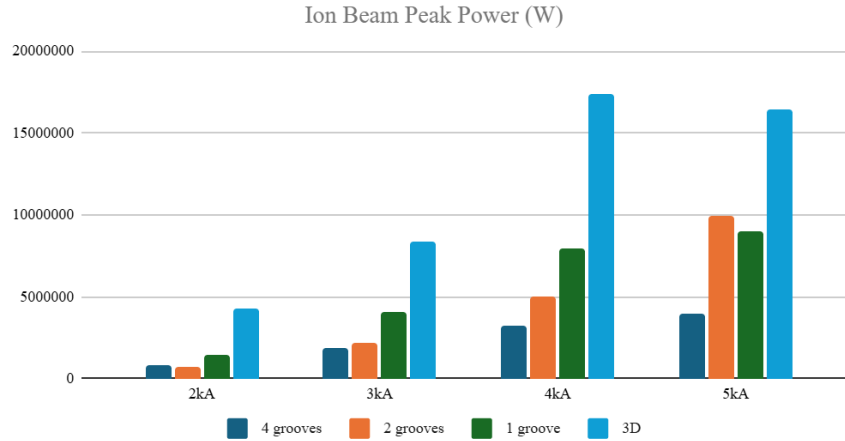


Figure 19a. Ion Beam Peak power across different accelerator settings for different anodes

It can be seen from Figures 1a-b., that the optimal setting for the accelerator's performance is 4kA of B-field coils. Moreover, the ion beam's peak current density as well as the beam's peak power are the highest for the 3D printed PLA anode. Across the number of ATJ lines, the best performing design of the anode turned out to be the anode with 1 groove, which provides continuous dielectric layer.

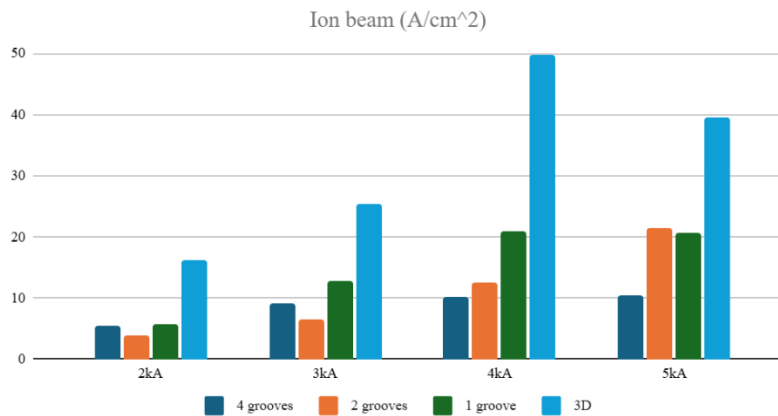


Figure 19b. Ion Beam Peak current density across different accelerator settings for different anodes

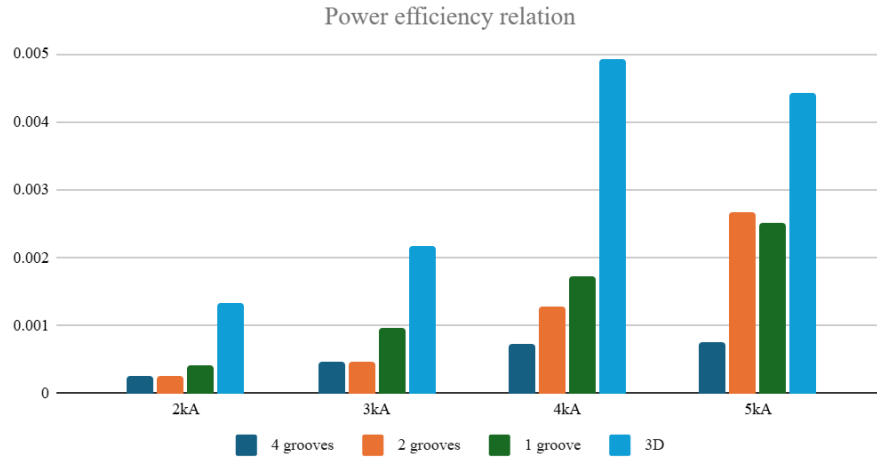


Figure 19c. Ion Beam power and current power ratio across different accelerator settings for different anodes

The beam-to-diode current ratio serves as an indicator of how effective plasma formation was. Figure 19c shows that the 3D printed 1 groove anode has the highest effectiveness among all of the anodes. Comparing the liquid filled anodes, 1 groove provides with slightly higher efficiency. Along with increased applied B-field, the efficiency increases, however after 120 it starts to decline.

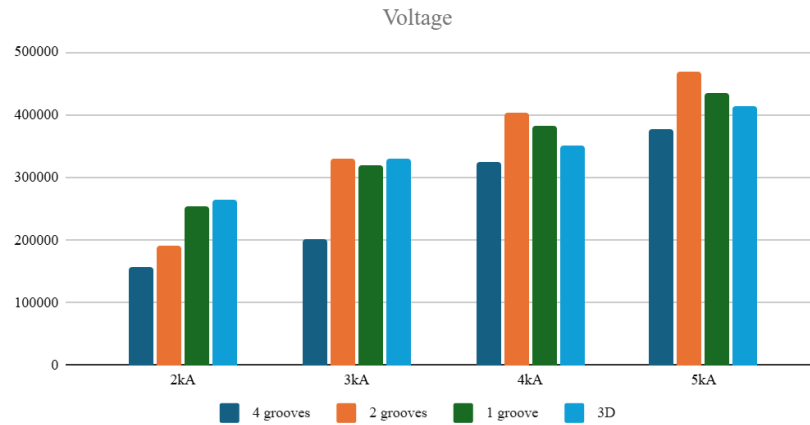


Figure 19d. Voltage across different accelerator settings for different anodes

The peak voltage supplied to the diode varied slightly with the anode type, reflecting changes in the impedance matching between the Blumlein generator and the diode load. The voltage remained within a 10–15 % range for all anode configurations at a given accelerator setting.

5) Composition analysis

Figure 20 shows the TOF analysis for a Proton (H^+) which perfectly matches the first peak of the ion beam. The peak of the beam current density at around $140 A/cm^2$ in a time interval of 100-300 ns mostly consists of proton.

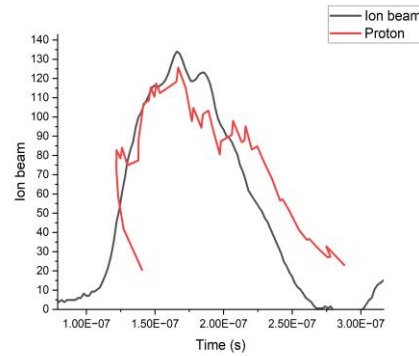


Figure 20. Ion beam's first peak and proton's TOF analysis

Figure 21 shows the second peak of the ion beam produced by the 3D printed anode and TOF analysis graphs of carbon (C^+), oxygen (O^{2+}), nitrogen (N^+) and Iron (Fe^{2+}). Peaks of carbon and oxygen are the closest to the second peak of around 40Ω at the time interval of 275-450 ns. Nitrogen's molar mass (14 g/mol) is too small, and the peak is rising too early compared to the

real peak. Iron's molar mass of 56 g/mol is too heavy for the accelerating voltage and the peak is falling behind the real peak.

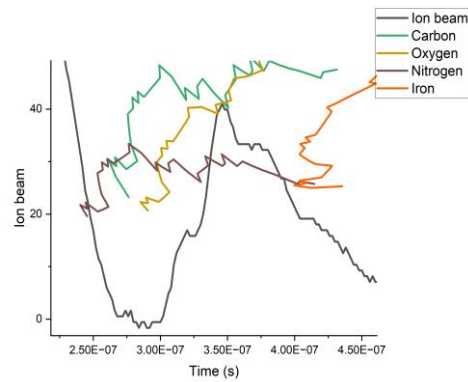


Figure 21. Ion beam second peak and TOF analysis of the most probable elements

From figure 22 the comparison with the liquid anode's ion beam's current density's waveforms tells that the epoxy filled anode has one symmetrical peak with one small peak following that might be consisted of carbon.

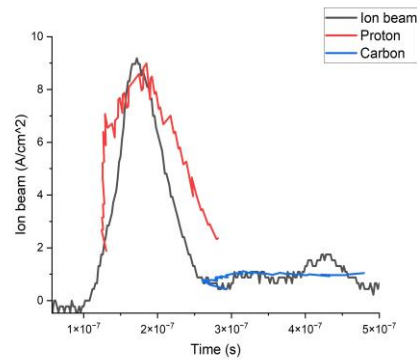


Figure 22. 1 groove anode's ion beam waveform with TOF analysis of proton and carbon

Conclusion

The overall goal of this thesis was to enhance the anode polymer filament in a magnetically insulated ion diode with the aim of increasing the ion beam current density without an increase in the accelerating voltage with the aim of reducing the diode impedance. Four anode configurations (with 4, 2, 1 and a new 3D-printed PLA with a segmented groove design) were systematically compared on the i-NURA B-applied ion accelerator at magnetic field settings between 2-5 kA, keeping the anode-cathode distance and the Blumlein charging voltage constant.

The experiments reveal that the anode triple-junction geometry has a decisive and reproducible effect on the electrical properties of the generated strong pulsed ion beam. The highest peak ion beam power, highest peak ion current density, and the highest ratio of beam to diode current were all achieved at a magnetic field setting of 4 kA with the 3D-printed PLA anode demonstrating the most favorable performance of all tested designs. The single-groove anode of the continuous liquid-dielectric anodes had the highest ion-to-electron current ratio compared to the 2-groove and 4-groove anodes, although the single-groove anode had the shortest total triple-junction line. The 4-groove anode, with the longest triple-junction length, achieved the lowest diode impedance (7.65Ω at $I_{\text{coil}} = 2\text{kA}$, compared with 18.57Ω for the 1-groove anode) but could not convert that low impedance into correspondingly higher ion current because a large fraction of the total diode current was evidently carried by electrons.

These observations confirm that the simple length of the triple-junction line is not the only determinant of the quality of the beam, the spatial distribution of the plasma initiation sites and the uniformity of the final anode plasma are also important. The multiple discontinuous triple junctions in the segmented PLA inserts provided many local field-enhancement points, thus generating a dense, homogeneous plasma that efficiently extracted ions. The single-groove design, by not requiring the mutual perturbation of the adjacent flashover plasmas, also enhanced the ion

fraction. The diode impedance was effectively decreased, and the ion beam current density was increased in both cases with no change in the accelerating voltage, fully satisfying the stated research aim.

The observed optimum at the intermediate setting of the B-field current at 4kA is in line with the previous reports that a moderate magnetic field offers the best compromise between electron suppression and the retention of a strong virtual cathode near the anode surface [13]. The fact that the highest field (5kA) shows a drop in efficiency confirms that over-insulation can push the virtual cathode away and reduce the space-charge-limited ion current.

The future work will take two directions. First, the segmented concept 3D-printed will be extended to other geometries (e.g., different lengths of segments, materials, and groove profiles) to further optimize the uniformity of the plasma and its lifetime. Second, time-of-flight spectrometry [19] will be used together with infrared imaging diagnostics [10] to find out the full ion composition and transverse beam homogeneity of beams produced by the optimized anodes. Such data will directly be applicable in applications in surface modification purposes, in which reproducible material modification requires a well-controlled, high-current-density ion beam of known species mix.

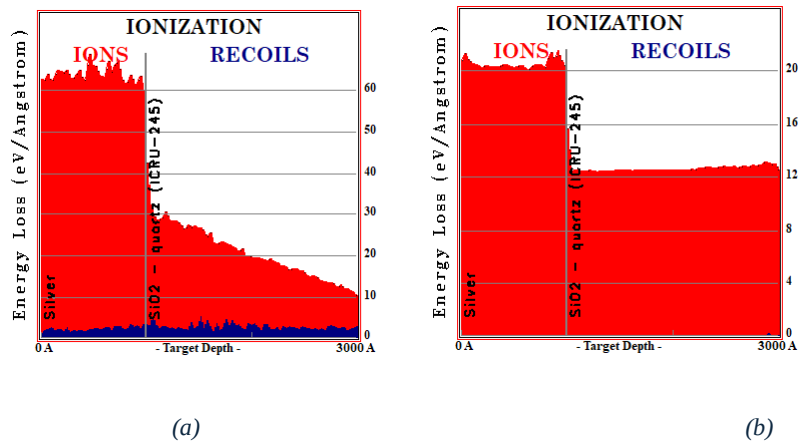


Figure 23. Ionization of C(a) and H(b) on silver nano-surface

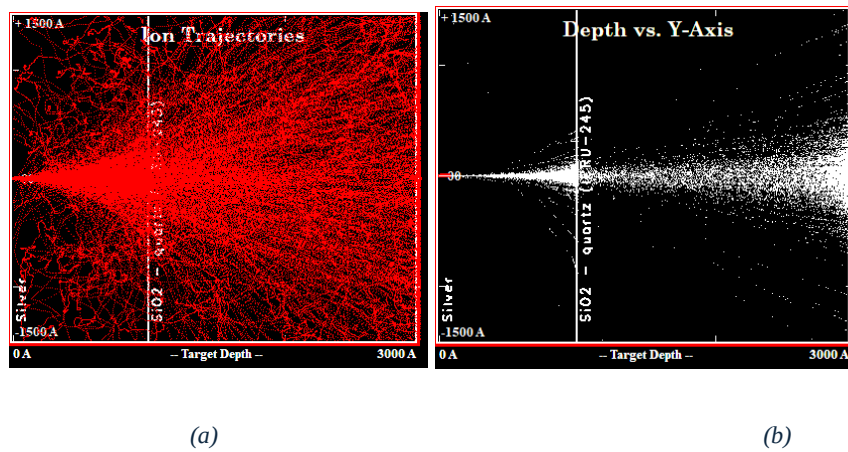


Figure 24. Ion trajectories of C(a) and H(b) on silver nano-surface

A future study will integrate optimized 3D-printed anode with the SRIM-based predictions to determine the appropriateness of generated ion beam to modify the silver nanowire (AgNW) networks on glass substrates. The SRIM calculations carried out to investigate the carbon (150-keV) and hydrogen ions (150-keV) as the dominant species in a PLA-based anode [18,19] have shown that the electronic energy loss of carbon in silver is around $58 \text{ eV } \text{\AA}^{-1}$ and the range of the ionization profile is only in a few tens of nanometres. This thin deposition of energy, which is practically confined to the film of AgNW and the near-surface area of the glass, is ideally matched to the film thickness of around 10-100 nm typically used in transparent conductive coating. Since the ion beam can transfer controlled heat and a thermal defect generation without acting upon the underlying substrate, previous research has already demonstrated that IPIB irradiation can enhance the electrical conductivity of silver nanowire films on temperature-sensitive flexible substrates and improve them in terms of their performance as transparent heaters [25,26]. With the new anode designs that provide higher and more reproducible ion current density at lower impedance, future experiments will systematically vary the fluence per pulse and the number of pulses, while using time-of-flight spectrometry and infrared imaging diagnostics to correlate the exact beam composition and energy density with the electrical sheet resistance, optical transmittance, and microstructural integrity of the AgNW films. By doing so, it will be possible to establish a strong

process window of IPIB-based post-treatment of nanowire transparent electrodes, which will directly relate the enhanced anode source characteristics to a potentially successful industrial application.

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