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# Performance of two helium ion diodes

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Two magnetically insulated gas-puff diodes were tested. In one design the plasma source was a fast inductive coil; in the other a coaxial gun created the plasma. The plasma current density from both sources, as well as the accelerated beam from each, was comparable to the Child-Langmuir limit of  $\sim 10 \text{ A/cm}^2$ .

## I. INTRODUCTION

We attempted to build a plasma injector capable of producing a neutralized beam of helium ions with a current density of  $100 \text{ A/cm}^2$ . The original intent was to inject alpha particles into a tokamak.<sup>1</sup> Beams of this intensity have been reported for hydrogen and other gases<sup>2,3</sup> but not helium, which is expected to be more difficult due to its high ionization potential. Two approaches were tried; the maximum current density achieved was  $\approx 20 \text{ A/cm}^2$ .

## II. INDUCTIVE DRIVER

The first device we built<sup>1</sup> was patterned after the gas-puff diode developed by Greenly *et al.*<sup>3</sup> Our design, shown in Fig. 1, was intended to be simpler. It had fewer insulation-field coils, spark preionization, a simple, spring-loaded puff valve, and lower operating voltages than the Cornell design.

The critical magnetic field that prevents electron current from short circuiting the anode-cathode gap, expressed as the integral of  $B^*$  across the anode-cathode gap, is  $1.2 \text{ kG cm}$  for a  $200 \text{ kV}$  diode voltage.<sup>2</sup> In our design, the radial field that provides the magnetic insulation was created by two annular coaxial field coils mounted on the cathode (Fig. 1) and the A-K gap was  $1.3 \text{ cm}$ . The coils had an inner to outer coil turns ratio of 7:3 and were energized by a  $500 \mu\text{F}$  capacitor that was typically charged to  $3.5 \text{ kV}$ . We measured the magnetic field produced by this coil at three radial locations in the anode-cathode gap using a square coil that exactly filled the gap. At the outer ring of the cathode (where shorting due to electron flow is most likely to occur),  $B/B^*$  was equal to 1.1. Computer simulations of the magnetic field<sup>4</sup> predicted a value  $\sim 30\%$  smaller than the measurement. Empirically, with a flashover source,<sup>2</sup> performance is optimized for  $B/B^* \approx 1.3$ .

While the cathode coils were being energized, a puff of helium gas was injected through a fast, inductively driven valve. It took about  $100 \mu\text{s}$  for the valve to open and gas to reach the chamber. The gas pressure varied from 15 to 30 psi absolute. Both ion sources were dependent on the symmetry of the gas puff, which turned out to be unsatisfactory. Measurements were made with a piezoresistive pressure sensor. We observed a strong dipole pattern in the emerging gas, with a maximum-to-minimum ratio as high as 3; the results varied considerably from shot to shot. The velocity of the emerging gas front was about  $0.1 \text{ cm}/\mu\text{s}$  for

helium, preventing equilibration on diode time scales. In the coaxial-gun source (Sec. III), the valve assembly was reconfigured to introduce a right-angle bend in the flow path to make the gas stagnate before entering the gun, but this had little effect.

The gas was preionized by a symmetric array of eight spark gaps placed next to the face of the driver coil (Fig. 1). The spark gaps were driven by a single  $580 \mu\text{F}$  capacitor charged to  $3.5 \text{ kV}$ ; they were isolated from each other by  $2.2 \Omega$  resistors. This was a simple, easy-to-build method and used a much lower voltage than an inductive preionizer. The reliability and uniformity of our preionizer was not as good as reported<sup>5</sup> for inductive preionization, however. We used a gas mixture containing  $0.5\%$  argon to enhance ionization through the Penning effect.<sup>6</sup>

After preionization, a coaxial coil mounted within the anode was fired to further ionize the plasma and to drive it into the anode-cathode gap (Fig. 1). This "breakdown" coil was driven by three  $0.75 \mu\text{F}$ ,  $75 \text{ kV}$  capacitors connected in parallel. This circuit operated at  $25 \text{ kV}$  with a quarter-period of  $3 \mu\text{s}$  and a total inductance of  $1.7 \mu\text{H}$ . The efficiency of such a circuit is measured by the voltage induced around a loop in a plane parallel to the anode, which is proportional to  $dV/dt$  of the driver. Our loop voltage was  $4.0 \text{ kV}$ , compared to  $17 \text{ kV}$  for the Cornell unit,<sup>3</sup> which operated at  $100 \text{ kV}$  with a  $1 \mu\text{s}$  period.

The breakdown coil pushes magnetic flux, along with

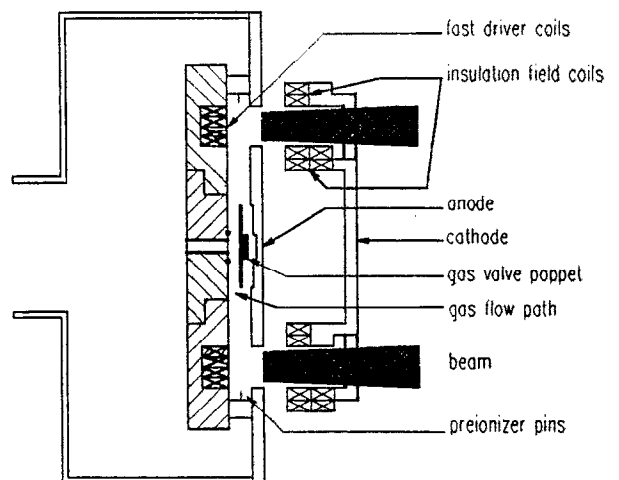


FIG. 1. Schematic of the inductive driver.

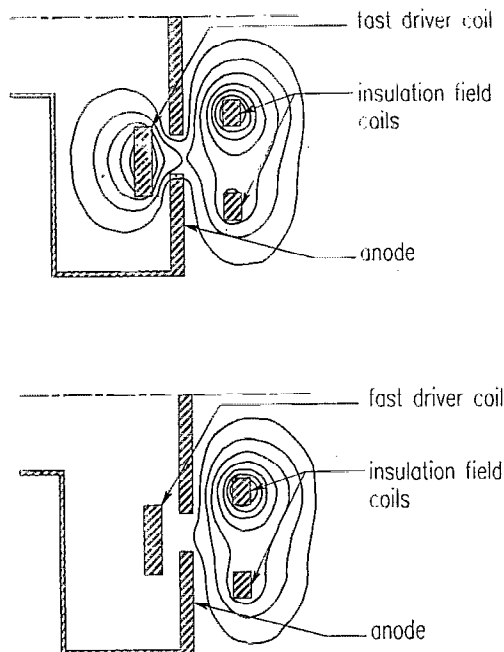


FIG. 2. Magnetic field lines (contours of  $rA_\theta$ ) for the anode faceplate with an annular gap. (a) Maximum current in the fast driver coil. (b) Null current in the fast driver coil.

trapped plasma, into the A-K gap; the insulating field resists this. A field null, as seen in Fig. 2(a), provides both axial and radial confinement of the electrons. The Cornell group's three-coil design produced such a null.<sup>3,5</sup> The ions, with a gyroradius of  $\sim 0.5$  cm, penetrate the gap, allowing currents in excess of the Child-Langmuir limit.

We tested our inductive source with two different anode faceplates. In one configuration, the plasma was pushed through a gridded anode structure into the A-K gap. With this faceplate, the magnetic fields created by the cathode coils and by the anode coils were completely independent. In the second configuration, the plasma entered the A-K gap through a 2.3 cm annular gap in the anode faceplate. With this faceplate, the field produced by the cathode coils pushed the plasma away from the A-K gap during the time of maximum flux swing of the driver coil [Fig. 2(b)]. When the current in the driver coil had built up to its maximum value, a field null existed near the anode surface [Fig. 2(a)].

When the plasma reached the A-K gap, the main accelerating pulse was applied to the anode. The pulse was produced by a Marx generator consisting of ten  $0.7 \mu\text{F}$ , 75 kV capacitors connected in series through spark-gap switches. The total inductance was  $1.8 \mu\text{H}$ , the operating range was 150–500 kV, and the pulse duration was  $\sim 0.5 \mu\text{s}$ . The field coils on the cathode were coated with a 1 mm thick graphite layer to define a planar cathode surface and to minimize ablation. The beam formed an annulus with inner and outer diameters of 11.4 and 15.9 cm, respectively.

The gas-valve, preionizer, and driver-coil discharge circuits were mounted in the Marx tank and floated up to

the main (accelerating) voltage when the Marx was fired. To isolate these circuits from the charging supplies and trigger circuitry (which were referenced to ground), the charging supplies were isolated through 20 cm long water resistors ( $R = 50 \text{ k}\Omega$ ) and the cables for the triggering pulses were wound 200 times around an iron-core inductor with a  $50 \text{ cm}^2$  cross section. The measured current that flowed back through the trigger cables was only  $\sim 100 \text{ A}$ , corresponding to an effective impedance of  $1 \text{ k}\Omega$ .

### III. INDUCTIVE DRIVER RESULTS

With the Marx accelerating voltage off but all other circuits energized, the device produced about  $20 \text{ A/cm}^2$  current density at the anode face. Plasma production was optimized for a gas valve preionizer delay of  $100 \mu\text{s}$  and for a preionizer-breakdown coil delay of  $1.3 \mu\text{s}$ . Plasma production was similar for hydrogen and helium. Measurements of visible light showed that ionization occurred when the emf produced by the breakdown coil was largest; the Faraday cup signal at the anode gap peaked  $\sim 0.5 \mu\text{s}$  later. Thus, the plasma was formed in the magnetic field configuration of Fig. 2(b), which provides no radial confinement. As the current in the cathode coils was increased, the ion density at the anode decreased for both polarities of the cathode field.

The timing of the Marx relative to the inductive driver was varied. The maximum current density occurred when the Marx erected concurrently with the arrival of the plasma at the A-K gap; shorter delays produced little current and longer delays produced rapid collapse of the Marx voltage.

The highest accelerated current density from our inductive device was about  $10 \text{ A/cm}^2$ , for accelerating voltages in the 150–250 kV range, with a beam divergence of  $\sim 5^\circ$ . Performance was similar with both the gridded anode and the anode with a 2.3 cm annular gap. The optimized current density from the accelerated beam was typically one-half of the current density produced by the inductive driver. Thus the plasma source was the main factor that limited diode performance.

### IV. COAXIAL GUN

Rather than extensively redesign the inductive source, we switched to a Marshall gun<sup>7</sup> (Fig. 3). While not as clean a source we hoped it would be simpler and more robust, as well as being less sensitive to azimuthal nonuniformities. A Marshall gun operates at much lower voltages than an inductive driver, making the circuit more reliable. Also, the operating parameters can be varied over a much larger range. The Marshall gun design focuses the beam; we felt that this would overcome the main flaw of the inductive driver, the lack of radial confinement of the injected plasma.

The gun had an inner/outer radius of 11.4 cm/15.9 cm and was 12 cm long. An aluminum faceplate was placed 6 mm from the gun's muzzle to create a magnetic-flux-excluding surface (Fig. 3). The gun was driven up to 30 kV, the limiting factor on the voltage being the feeds. The

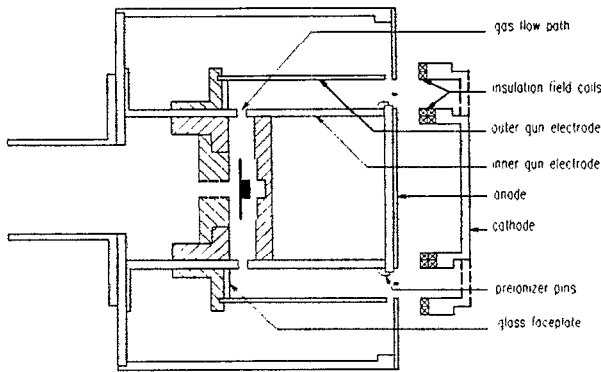


FIG. 3. Schematic of the coaxial gun. The gun shoots the plasma through a gap in the anode faceplate. (There is a small annular ring in the center of the gap.)

anode-cathode gap was again 1.3 cm reproducing the geometry of the inductive source. Gas was puffed in next to the breech face through 50 small holes. The breech face was made of quartz to prevent surface tracking. The gas pressure was varied from 300 to 1500 Torr. The same gas-puff valve was used in both sources. The circuit from the inductive "breakdown" coil was used to drive the plasma gun, but with one-third the capacitance. The insulating field and gas-puff circuits were the same.

A new preionizer circuit consisting of eight spark gaps placed at the gun's muzzle was built; it operated at 20–30 kV and had a 2 mm gap spacing. The voltage was high enough to produce vacuum arcing. The spark gaps were fired before gas reached the muzzle, preionizing the gas with UV radiation.

## V. COAXIAL GUN RESULTS

Gas reached the breech of the gun 85  $\mu\text{s}$  after the valve was fired. The gas front was found to expand at the sonic velocity for room temperature. Scans were taken varying gas pressure, delay time between the valve opening and the gun firing, and gun voltage. The timing showed the expected pattern. Below a critical delay setting no gas was present and the discharge was initiated at the same time on each shot relative to the gas valve trigger. At longer delays the current peaked quickly and then declined as the delay was increased. The gun produced a highly asymmetric beam, typically covering only two-thirds of the annulus of the gun's muzzle. Without the preionizer only one-fourth of the annulus flashed over. The highest current density of 25  $\text{A}/\text{cm}^2$  extended over one-half of the annulus. The addition of an aluminum faceplate to exclude magnetic flux from the gun barrel reduced this by one-half.

The gun voltage was varied from 10 to 30 kV. We hoped that the plasma current would scale rapidly with voltage; it did, in fact, increase as  $V^2$ , but the curve flattened out above 20 kV. The total current was linear with voltage up to 26 kV, indicating that there was no short circuit or arcing. The effective resistance of the circuit when firing was 1.1  $\Omega$  initially, later reconfigured to 0.9  $\Omega$ . Hydrogen and argon were also tried with similar results.

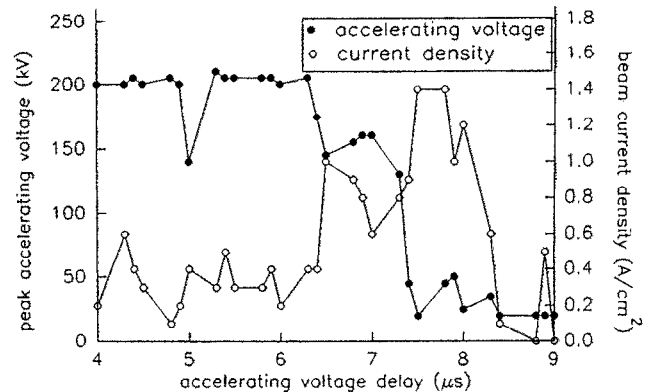


FIG. 4. Marx voltage and beam current density as a function of the delay between the firing of the coaxial gun and the triggering of the Marx.  $V_{\text{Marx}} = 200$  kV;  $V_{\text{gun}} = 15$  kV;  $B/B^* \approx 1.1$ . The Faraday cup was biased at  $-500$  V.

When the Marx voltage was applied, helium beams of 10–20  $\text{A}/\text{cm}^2$  were produced. The time delay between the gun breakdown and application of the accelerating voltage was varied for an accelerating voltage of 200 kV (Fig. 4). For long delays, the anode-cathode gap pre-filled with plasma. This produced a short-circuit effect and the accelerating voltage never erected fully. Shorter delays produced a flat-topped voltage trace. The peak plasma current density came when the accelerating voltage was triggered just after the plasma entered the gap (Fig. 4).

The main factor limiting the performance of the diode was the current density delivered by the gun. Better uniformity in the gas puff and more efficient preionization could improve performance.

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