Inductively driven gas-breakdown plasma source for intense ion beam production

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A plasma source based on an inductive breakdown of a supersonic gas puff is described. The source was developed to provide an anode plasma for an annular, extraction geometry, magnetically insulated ion diode. In this source, plasmas with densities of 10^{13} cm^{-3} were generated and accelerated to velocities of 20–30 cm/ μs ; plasma fluxes of 10–40 A/ cm^2 were obtained. Operating the source under the diode insulating field effect, plasma fluxes above 100 A/ cm^2 were observed. When the plasma source was used in conjunction with a magnetically insulated diode gap, intense ion beams with proton fluxes of more than 100 A/ cm^2 , energies of 100 keV, and beam pulses longer than 1 μs were extracted.

I. INTRODUCTION

Recently, there has been a renewed interest in the experimental results on intense ion beam (IIB) generation due to the potential application of these powerful beams for inertial confinement fusion,¹ material processing,² and fusion condition Tokamak diagnostics.³

A crucial issue in the research of IIB generation is the production of an appropriate anode plasma that acts as the source of ions to be accelerated in the diode gap. Conventional anode plasmas for IIB are generated by the process of flashover of plastic materials aided by leakage electron deposition.^{4,5} Diodes based on such flashboard anode sources are known to have certain drawbacks including: diode closure initiated by excessive amount of neutrals in the gap,⁶ unnecessary expenditure of the injector electrical energy to form the anode plasma, outputs with high impurity content, poor impedance history, and damage after a few shots (a single shot for high power diodes). In order to solve these problems, ion diodes based on nonflashboard anode plasma, produced independently from the injector voltage or leakage current, have been studied experimentally. Diodes with anode plasmas produced by lasers,⁷ deuterated washer guns,⁸ and Mendel guns⁹ have been successfully operated. The anode plasma sources described in this paper are based on the breakdown of an annular gas puff using an inductive voltage produced by a single turn coil. By properly adjusting the amount and position of the anode plasma so obtained with respect to the gap of a MID, it was possible to extract ion beams with characteristics that were superior (except divergence angle which remained the same 3°) to the ones obtained with a surface flashover anode when the diode is operated with the same low voltage (200 kV), long pulse (1 μs) power generator (LONGSHOT II).¹⁰

In this paper, we will mainly discuss the characteristics and operational aspects of the plasma source and only slightly mention the diode results which will be detailed in a future paper.

II. EXPERIMENTAL APPARATUS AND ITS OPERATION

The objective of the present experiments was to develop a nonflashboard plasma source that could be used in conjunction with a magnetically insulated diode (MID) gap. The source had to provide an anode plasma that could be used in an annular geometry MID, driven by the LONGSHOT II pulse generator. The scale drawing of the plasma source is illustrated in Fig. 1, where the diode gap and the coils for the diode gap insulation are also shown. The anode contact is necessary for diode current contact and to prevent damage of the coil caused by electron bombardment as well as due to voltages induced by the fast coil. The back slow coil was added to the standard annular MID coil system (inner and outer coils) in order to earn a low field region behind the anode of the accelerating gap into which the plasma source was inserted. A preionizer was incorporated to the source to preionize the gas for the production of a sufficiently dense and uniform plasma when field induced by the fast coil is applied. The nozzle system and the puff valve are utilized to deliver a gas cloud with a very steep pressure gradient in the axial direction of the source such that we obtain enough pressure near the fast coil for breakdown of the feed gas and simultaneously a sufficiently low pressure at the gap of the diode to avoid short circuit.

Our gas-breakdown plasma source is a variation of one that was previously used in other experiments, one intended for beam production¹¹ and another for plasma propulsion.¹² However, as is apparent from Fig. 1 and supported by experimental results, our source behaves entirely in a different way from its predecessors because it is located inside the diode structure. The performance of the source is closely related to the mode of operation of the diode. In particular, the diode insulating field strongly influences the anode plasma production and its injection into the gap. The plasma source is operated with the following timing sequence: the slow field coils are energized first, producing a quasistatic magnetic field configuration (relative to the

FIG. 1. Plasma source and diode components. (1) Outer cathode. (2) Inner cathode. (3) Anode contact and outer field excluder for fast field. (4) Inner field excluder for fast field. (5) Outer diode insulating coil. (6) Inner diode insulating coil. (7) Back slow coil. (8) Fast coil. (9) Back field excluder for fast field. (10) Diode support. (11) Preionizer support. (12) Mylar collar shield. (13) Stainless-steel sheet. (14) Front nozzle structure. (15) Fast coil insulator. (16) Puff valve. (17) Gas mixing section.

times of the source components) shown in Fig. 2. Next the puff valve is energized, and the gas that is ejected from the plenum is guided by the nozzle reaching the annular region in front of the fast coil. The axial puff pressure profile can be made sufficiently sharp that the gas pressure 1 cm in front of the average radius of the fast coil can be up to 100 mTorr while the pressure in the diode accelerating gap 4 cm away (to the right in Fig. 1 is below 0.5 mTorr). When such gas profile is achieved, the preionizer is fired producing a low density seed plasma. Then, the induced E -field generated by the fast coil breaks down the preionized gas; as soon as the plasma is formed, it is driven away by the $J \times B$ force, due to the current in the plasma and the field generated by the fast coil, toward the diode gap. The

FIG. 2. Constant flux surfaces generated by diode insulating coils and field excluders. Numbers indicate the diode components described in Fig. 1.

FIG. 3. Geometry of the spark preionizer gap in detail. Plasma source front view.

plasma stagnates against the magnetic field produced by the slow coils which serves to magnetically insulate the diode accelerating gap. The position of the plasma stagnation is determined by the relative magnitudes of the fast and slow magnetic fields and can be chosen to be near the axial position of the metal anode contact.

The slow field is produced by a current flowing in the coils 5, 6, 7 shown in Fig. 1. The current is supplied to the coils by discharging two capacitors of 100 μF each, typically charged to 3–7 kV and connected in parallel and via ignitron switching. The total inductance of the slow coil circuit was measured to be 125 μH , the contribution of the coil section being about 100 μH . The peak current flowing in the coils can reach 5 kA in the normal operation. The coils produce radial B fields in the anode-cathode gap of 2–3 kG typically, with a rise time of about 200–300 μs .

The geometry of the setup for the spark preionizer gaps is shown in Fig. 3. The seed ionization of the gas in our preionizer occurs presumably via UV light or by injection of few electrons into the region of interest. The light and electrons are here generated by spark sources distributed symmetrically around the plasma source. The electrodes were made of copper strip tape with sharp edges and glued to an acrylic base. The individual gaps were about 0.3 cm wide and the six groups of sparkers were positioned about 1.5 cm from the outer edge of the fast coil. To avoid unnecessary illumination of the ion diode gap, UV shielding Mylar strips were included. The six spark channel groups were charged in parallel and ballasted so that all channels would fire independently at nearly the same time, while the individual gaps of each group would discharge in series. The primary energy source was a 1 μF capacitor, charged typically to 20–30 kV. It was discharged through a spark gap switch using a PT-55 trigger source. The voltage pulse was sent through an isolation inductor consisting of a 75 foot long RG-8 cable (to isolate against the injector high voltage pulse). On the other side of the isolation inductor, a capacitor was used to store the energy until the pulse sharpening switch breakdown occurred. Then the power was evenly distributed into the group of six channels with similar inductances.

The plasma in the present source is produced by the

FIG. 4. Diagram of the fast coil driver circuit. A top view of the system, and its position relative to injector components, is also shown.

electric field induced from a rapid variation of the magnetic field generated by a single turn coil. The radial component of the same magnetic field is responsible for the acceleration of the plasma. The E field required to breakdown an annular gas region with 30–70 mTorr pressure around the 100 cm circular path can be estimated to be roughly 100–200 V/cm. In order to reach such fields, we designed a fast coil circuit able to provide 20–40 kV pulses. Concomitantly, in order to maximize dB/dt , the total inductance of the fast coil driving circuit had to be as low as possible (450 nH was achieved). The diagram in Fig. 4 shows the experimental setup of the fast coil. To minimize the inductance of the system, the fast coil driving capacitor was placed inside the Marx generator tank, as close as possible to the (oil/vacuum) interface. The electrical feed to the fast coil passed through this interface and was connected to the flat, ring shaped, single turn coil, potted in epoxy. To connect the switch (placed on top of the capacitor) to the coaxial feed through a parallel strip line consisting of two brass sheets 6/1000 of an inch thick, 5 in. wide, and 50 cm long was used. They were separated by five layers of 0.25-mm-thick Mylar to ensure voltage hold-off. The coaxial feedthrough was 50 cm long. Its external conductor was 1.73 cm in diameter and its center conductor 1.03 cm in diameter, the space between them filled with epoxy to assure 50 kV insulation. The connection between the coaxial feed and the single turn coil as well as the coil itself were cast in epoxy for insulation. The resulting external inductance of the fast coil driving circuit was as low as 150 nH. Since the single turn coil (fast coil) inductance was 300 nH, the loop voltage would reach 17 kV when the capacitor was charged to 25 kV. This would result in the required 160 V/cm E field, 0.5 cm from the fast coil surface, at an average radius of 15 cm. The $1.8 \mu\text{F}$ capacitor was dc charged through the isolation inductor cable and the fast coil spark gap switch fired using a 20 kV trigger pulse sent through the same isolation cable. The rise time of the oscillating current in the fast coil was typically $1.5 \mu\text{s}$ and its total period was $6 \mu\text{s}$. The typical operating peak current in the coil reached 50 kA.

The puff valve and the nozzle system that delivers a supersonic gas flow are depicted in the diagram of Fig. 5. The flux excluding aluminum diaphragm bends as a result

FIG. 5. Puff valve and nozzle configuration.

of the electromagnetic force applied on it and the gas can escape from the plenum region. The gas passes through a carefully shaped nozzle system in the expansion region of which the flow becomes supersonic. The rise time of the current in the valve solenoid is about $6 \mu\text{s}$ with a peak current of 4.0 kA. The puff valve inductance is $3 \mu\text{H}$ while the total inductance of the valve driving circuit is $5.7 \mu\text{H}$. The valve power supply was a $4 \mu\text{F}$ capacitor charged to 5–7 kV and switched via an ignitron. A key feature of the present valve is the inclusion of a “secondary” plenum region which served the purpose of remixing the gas coming out of the primary plenum, thereby making it possible to obtain a symmetric gas output from the throat of the nozzle even if the gas ejected from the valve itself was not that symmetric.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Puff valve performance

The puff gas pressure was measured with a fast ionization gauge (FIG), described by Pedrow.¹³ A 6AU6A pentode (1 cm in diameter and 2 cm in length) was used without the glass envelope and also without 40% of the plate suppressor. The control circuit of the pentode, its operation, and calibration for 5 mTorr pressures are described in the same reference. The calibration curve for lower pressures (down to about 0.5 mTorr) is given in another work.¹⁴

Two gas output measurements relevant for diode applications of this plasma source will be presented. One is the measurement of the azimuthal uniformity of the puffed gas and the other is the measurement of the gas distribution in the diode axial direction. The first is important because it is one of the determining factors of the anode plasma uniformity, hence of the beam uniformity, while the second will indicate the magnitude of the axial pressure gradient. A very steep variation of the gas pressure in the

FIG. 6. Variation of the gas puff pressure: (a) in the azimuthal direction (arrows represent position of the inner coil supporting structures) and (b) in the axial direction (ac represents the anode contact axial position). The four cases in (b) are described in the text.

axial direction is essential to produce sufficiently dense anode plasmas and to simultaneously avoid diode breakdown caused by excessive amounts of neutral gas in the gap. The variation of the gas output in the azimuthal direction is shown in Fig. 6(a). The measurement was performed by rotating the FIG around the axis of the plasma source while keeping its radial position at 15 cm and its axial position at about 0.5 cm from the fast coil surface. It can be seen that the overall nonuniformity of the gas output in the azimuthal direction is less than $\pm 30\%$. The nonuniformity is caused mainly by the presence of the inner coil and nozzle supporting structures which intersect the radial gas flow path. The position of these structures is indicated by arrows in the figure. When regions behind the supporting structures are excluded, the nonuniformity is as low as $\pm 5\%$. This optimized uniformity was achieved aligning the front nozzle axis (No. 14 in Fig. 1) with the axis of the gas mixing nozzle section (No. 17 in Fig. 1) to within 0.5 mm. The axial position of the front nozzle with respect to the fast coil surface was not so critical (within 2–3 mm). It is worth noting that the gas uniformity did not change with the amount of the puffed gas.

The measurement of the axial gas distribution was performed with the FIG held at the same azimuthal and radial positions and varying its axial position with respect to the fast coil surface. The results of this measurement for different puff valve conditions are shown in Fig. 6(b). Here, case A corresponds to using 6.5 kV puff valve charge with a 5 psig plenum pressure and measuring the puffed gas pressure 190 μ s after firing the valve. In case B, we used the same valve conditions but measured the pressure 175 μ s after firing the valve. In case C, we charged the valve to 7 kV, used a plenum pressure of 2.5 psig, and measured the puffed gas pressure 180 μ s after firing the valve. For case D, we also used 7 kV charging voltage but 10 psig plenum pressure and measured the output gas 170 μ s after firing

FIG. 7. Measured fast field intensity vs distance to fast coil. The data points represent the first peak B -field intensity for different fast coil driving capacitor charging voltages: open circles are for 20 kV charge, filled circles for 25 kV charge, and + for 30 kV charge. Square points represent the calculated fields assuming a $1/D$ drop in the field normalized to the 30 kV curve at $D=1$ cm.

the valve. In cases C and D, we used a slightly different diaphragm setup from cases A and B. The experimental results show that the gradient in the gas pressure is compatible with diode operation, i.e., high pressure (up to 70 mTorr) near the fast coil and less than 1 mTorr in the diode gap, over a wide range of puff valve conditions. Furthermore, it should be noted that the actual puff gas pressure gradient could be larger than the observed with the FIG because of its finite size which reduces the gradient.

We also measured the radial distribution of the gas puff near the fast coil surface. The peak pressure (gas front) did not change noticeably between 13 and 14 cm radius but it was reduced by 1/2 at 15 cm and by a further factor of 2/3 at 16 cm radius. The radial velocity of the puffed gas was determined to be about 0.15 cm/ μ s.

The amount of the puffed gas provided in the source region can be varied in four ways: (1) by changing the plenum pressure, (2) the puff valve charging voltage, (3) the diaphragm thickness, or (4) by choosing a different relative timing between firing the puff valve and the rest of the system. The gas output varied unintentionally as much as 30% as a result of disassembling and then assembling the valve without changing other valve conditions. If we did not open the valve or touch the nozzle assembly, the output varied less than 20% over a month long experimental run.

B. Plasma source characterization

The magnetic field generated by the fast coil was mapped using a calibrated B -dot loop. The peak values of the B field as a function of distance D from the fast coil, at the average radius of the coil (15 cm), for different coil charging voltages, are plotted in Fig. 7. The peak field intensities drop with distance from the fast coil approxi-

mately as $1/D$ over the range of interest. For plasma source operation in which only the fast coil was used, we obtained the following results:

(1) A variation of 55% in the puffed pressure (40 to 90 mTorr 0.5 cm from the fast coil surface) resulted in a comparable change in the extracted plasma flux (17–43 A/cm² at 10 cm from the coil surface) measured with a biased Faraday cup.

(2) When the fast coil charging voltage was varied over 15–33 kV range, the output changed proportionally (8–23 A/cm²).

(3) The optimum delay between energizing the puff valve and firing the preionizer and the fast coil was measured to be about 200 μ s. For longer delays the plasma flux remained constant at 15 A/cm².

(4) Preionization of the gas puff prior to its inductive breakdown was observed to be indispensable for the production of the plasma in the first maximum of dB/dt generated by the fast coil. The experimental data indicated that about a 2 μ s delay between discharging the preionizer and firing the fast coil circuit is required to obtain the optimum plasma output of about 20 A/cm².

(5) The azimuthal uniformity of the plasma from our source not only depended on the gas distribution uniformity but also on the uniformity of the preionizer illumination.

(6) Time-of-flight measurements with two Faraday cup detectors indicated that the velocity of the output plasma (taking the peak of the plasma fluxes as references) is 20–30 cm/ μ s. This measurement, associated with the peak flux measurement, allowed us to estimate the plasma density to be about 1×10^{13} cm⁻³.

Magnetic fields produced by the slow coils at different axial positions (at a fixed azimuthal position and radius of about 15 cm) were measured also with a calibrated B -dot loop. The obtained results are plotted in Fig. 8, where fast field values were included for comparison. Here, we note two important points: (1) The B -field null occurs about 2 cm from the fast coil and there is an inversion in the field direction at positions closer to the fast coil; (2) the fast and slow field amplitudes can be made equal near the anode contact. Since this axial position is where the plasma tends to stop (stagnation point), it defines roughly where the anode plasma front surface can be initially placed for beam extraction in the actual diode shot.

The radial variation of the slow field intensity in the accelerating gap was also measured. The field was two times larger at 18 cm radius and three times larger at 11 cm radius than the value measured at the average radius of the fast coil (15 cm). Typical constant flux surfaces, obtained by calculation with R -super code,¹⁵ for current flowing in both the fast and slow coils are shown in Fig. 9; no plasma current is included in the calculations.

When the diode insulating field is applied, the source plasma characteristics change dramatically. Plasma production efficiency and the subsequent plasma dynamics are strongly affected by the insulating field. When this field is used, as indicated by the result of Fig. 8, a preapplied magnetic field of about 0.5 kG is present in front of the fast

FIG. 8. Measured slow field intensity vs distance to fast coil. The data points represent the first peak B -field intensity for different slow coil driving capacitor charge: open circles are for 3 kV charge, triangles for 4 kV charge, and filled circles for 6 kV charge. Fast field curves (dashed) are also included for comparison of the fields.

coil (at about 1 cm from fast coil surface) when it is energized. The pre-existing field is opposite in direction from the fast field produced during the first 1/2 cycle of the current oscillation. In fact, the $J \times B$ force on the plasma is toward the fast coil at that time. Only after the fast field has overcome the preapplied 0.5 kG slow field can the plasma start moving away from the fast coil in the axial direction. Moreover, as the plasma moves toward the gap, it is also confined radially because the insulating field intensity increases both in the radially inward and outward directions as the magnetic flux mapping in Fig. 9 shows.

FIG. 9. Constant flux surfaces generated by the fast and slow coils calculated with the R -super code. The various coils and flux excluders considered in the calculation are indicated in the figure.

FIG. 10. Plasma output vs delay 1 using the slow coil. The Faraday cups FC1, FC2, FC3, and FC4 were placed 90° apart and 1.5 cm from the cathode towards the fast coil at a radius of 15 cm.

This confinement of the plasma near the fast coil during the gas breakdown phase is evidently responsible for substantially increasing the efficiency of plasma production when compared to the situation without the slow field, as we shall shortly see.

Two source parameters influence drastically the plasma output: (1) the time delay between puff valve and the preionizer/fast coil firing (delay 1); and (2) the time delay between preionizer and fast coil firing (delay 2). To study the effect of these parameters, the other plasma source parameters were fixed at 25 kV fast coil charge, 28 kV preionizer charge, 4 kV slow coil charge, and 6.5 kV puff valve charge with 10 psig plenum pressure. When we varied delay 1, we held delay 2 at 1.5 μ s. The plasma fluxes were measured using four Faraday cups which were placed 90° apart and at the same radial positions (15 cm) and about 1.5 cm from the cathode position (toward the fast coil), hence deep into the plasma confining field configuration. This positioning of the cups was chosen to measure the moving plasma before it stagnated against the insulating field. The graph of Fig. 10 shows that the average plasma flux can change from about 50 to more than 200 A/cm² when delay 1 is changed from 150 to 180 μ s. After reaching peak values at delay 1 of about 180 μ s, the measured flux drops to 100 A/cm² in an additional 40 μ s. Therefore the delay 1 for which we obtain a maximum plasma output when operating the source in the presence of the insulating field is around 180 μ s. This coincides with the time at which we observe the peak of the puffed pressure at the average radius of the fast coil, after energizing the valve. The measured gas velocity in the radial direction is about 1.5 mm/ μ s (for gas flowing near the fast coil surface). Therefore, if we were to fire the fast coil 20–30 μ s earlier than the optimized timing, the peak of the puffed gas cloud would be 3–4.5 cm further inward from the average radius of 15 cm. This suggests that a delay 1 smaller than 180 μ s could indeed affect the preionizer efficiency and/or breakdown mechanism which are evidently hampered by insufficient gas pressure at the average radius of the fast coil. On the other hand, if we fire the preionizer/fast coil too late, the resulting excessive gas pressure at the gaps of the preionizer starts to influence sparking which

FIG. 11. Plasma output vs delay 2, using the slow coil. The data points represent averages of four Faraday cups, placed 90° apart and deep into the plasma confining field. Notice the steep increase in the plasma flux at a delay 2 of about 0.5 μ s.

may inhibit the production of shorter wavelength UV radiation. It is also worth noting that the azimuthal uniformity of the plasma is best when we use a delay 1 of 180 μ s, namely better than $\pm 10\%$. By contrast, by firing the preionizer/fast coil 20 μ s earlier or later, the uniformity is no better than $\pm 45\%$.

Another parameter that is critical to the plasma source performance is the delay time between firing the preionizer and the fast coil (delay 2). Here delay 1 was fixed to 180 μ s and other source parameters were kept fixed to previous measurement conditions. The firing times of fast coil and preionizer were monitored with *B*-dot loops and the plasma flux was measured with four Faraday cups mounted at the same radial position of 15 cm, and spaced 90° apart at a distance of 1.7 cm from the cathode (towards the source). The average of the peak values of the fluxes versus delay 2 is displayed in Fig. 11. This result clearly shows that the preionizer is required to produce plasma at the first maximum of dB/dt from the fast coil. The null output observed for less than zero delay 2 indicates this fact; this result is equivalent to not using the preionizer. We also find that about 1 μ s is needed for delay 2 to obtain maximum plasma flux (200 A/cm²) and that the output reduction is negligibly affected for larger delays. Figure 11 also indicates that a steep increase in the plasma flux, which occurs when delay 2 is about 0.5 μ s, may cause a drastic change of ion beam output due to jitter. This was indeed observed in the beam producing shots which will be described elsewhere.

Next, we will discuss two parameter variations that resulted in less drastic changes in the plasma output when operating the source in the parameter ranges of interest. Firstly, we show the dependence of the plasma output on the puffed pressure. Figure 12 shows the fluxes measured with four Faraday cups located in the previous source parameter study. The pressure indicated in the figure was measured with the FIG at 0.5 cm from the fast coil surface and at the radius of 15 cm. As we can see from the graph, the plasma output shows a tendency to increase with in-

FIG. 12. Plasma output vs gas puff pressure using the slow coil. The plotted data points were obtained with Faraday cups FC1, FC2, FC3, and FC4 at a distance 1.7 cm from the cathode (towards the plasma source).

creasing puff pressure; when the gas pressure is increased by 50%, the plasma output only increases by 25%. The other plasma source parameters were fixed at the following values: 25 kV, fast coil charge; 28 kV, preionizer charge; 4 kV, slow coil charge; 6.5 kV, puff valve voltage; 180 μ s, delay 1, and 1.7 μ s, delay 2. The improvement in the output uniformity for higher pressures indicates that a more azimuthally uniform preionization plasma takes place as we increase the puff gas pressure; this is due to the fact that the uniformity of the gas is not affected by the amount of the gas puff gas pressure as discussed previously.

The other parameter that affects the output is the loop voltage on the fast coil. The loop voltage can be changed experimentally by using different fast coil capacitor charging voltages. (The actual loop voltage is about 60% of the charging voltage because the inductance of the coil section is about 60% of the total inductance of the fast coil driving circuit.) In the series of shots taken to study the loop voltage effect on the output, the other source parameters were fixed at 28 kV preionizer charge, 4 kV slow coil charge, 6.5 kV puff valve charge with 10 psig plenum pressure, delay 1 of 180 μ s, and delay 2 of 1.7 μ s. The Faraday cups used in the flux measurements were located 1.7 cm from the cathode (towards the fast coil), at the same radius of 15 cm and 90° apart from each other. The experimental results are plotted in Fig. 13. There is a roughly linear increase in the output when we increase the loop voltage, namely a change of 40% in the loop voltage results in about a 30% increase in the plasma output. Also the uniformity of the plasma seems to be the best at 17 kV loop voltage (within $\pm 10\%$).

Finally, we will discuss the experiments that showed that the plasma stagnates near the diode gap under certain plasma source and diode insulating field conditions. Plasma stagnation was inferred from an observation of a sudden reduction in the plasma flux measured with Far-

FIG. 13. Plasma output vs loop voltage with the slow field. Here we also indicate the fast coil charging voltage corresponding to the loop voltage. The Faraday cups FC1, FC2, FC3, and FC4 were placed 1.7 cm from the cathode (towards the fast coil).

day cups placed in different axial positions of the source and plasma density profile in the axial direction of the source measured with double Langmuir probe. A typical set of data from this experiment is shown in Fig. 14. The open circles are average values of fluxes measured when no insulating field was used. The source parameters here were fixed at 25 kV fast coil charge, 29 kV preionizer charge, 6.25 kV puff valve charge with 5 psig in the plenum, delay 1 of 190 μ s, and delay 2 of about 1 μ s. In this free-flowing plasma case, the flux change with axial position is negligible over the range 0.3–1.3 cm from the cathode (toward the fast coil). The fluxes so measured were about 30 A/cm². (The shots without slow field were taken between shots with the slow field present.) The filled circle points, obtained in the presence of the insulating field, are quite different in nature from the open circle ones. Here, as the Faraday cups were moved from 1.3 cm to zero, we ob-

FIG. 14. Plasma flux vs distance from the cathode. The data points represent the average plasma flux measured by four Faraday cups and were obtained using 25 kV fast coil and 4 kV slow coil charges. Filled circles represent plasma shots with the insulating field while the open circles represent shots without the insulating field.

served fluxes of 150 A/cm^2 until the position 0.9 cm from the cathode was reached. (The anode contact is located at about 1 cm from the cathode as indicated on the graph.) Moving the cups to a position of 0.6 cm resulted in a reduction of the flux to 50 A/cm^2 . The output dropped further when we moved the cups to the axial position of the cathode. The plasma source conditions for these data were the same as in the case of free-flowing plasma but with 4 kV slow coil charge. The drastic reduction in the plasma flux at about 0.8 cm from the cathode and the measured density profile of the plasma to be discussed later can be interpreted as the stagnation of the plasma against the insulating field. The exact mechanism of the plasma stagnation is not yet understood. However, an effect similar to the well studied process of plasma penetration perpendicular to B field by $E \times B$ drift of the plasma could be occurring in our system. The criterion $(\omega_{pi}/\Omega_i)^2 \gg 1$ for plasma penetration into a region with a magnetic field perpendicular to the plasma flow direction given by Schmidt¹⁶ indicates that our plasma should stop in the axial direction when it reaches the gap position. Here ω_{pi} is the plasma frequency and Ω_i the ion cyclotron frequency, and in our case $B = 1.5 \text{ kG}$ (in the gap) and $n_i \sim 10^{13} \text{ cm}^{-3}$ (before the stagnation point) which results in $(\omega_{pi}/\Omega_i)^2 \sim 8$. According to the experimental results of Wessel and Robertson¹⁷ there was no plasma penetration even for $(\omega_{pi}/\Omega_i)^2 \sim 26$. For regions closer to the fast coil than to the anode contact, the insulating field is much smaller and hence the plasma can flow unimpeded but when the plasma reaches the anode contact position it is forced to stop. The presence of the anode contact tip could also reduce the plasma flow by short circuiting the charge separation in the plasma which is needed for $E \times B$ drift of the plasma. Another important conclusion that can be drawn from Fig. 14 is that we can produce more plasma where it is required, i.e., at the gap (at least five times more) when the insulating field is applied. This increase in the plasma density before the stagnation point (toward the fast coil) is probably due to a more efficient plasma production and confinement resulting from the field configuration produced by energizing the insulating coils during the plasma formation. In the free-flowing case, the plasma can be driven away from the fast coil in all directions by the $J \times B$ force immediately after its formation. By contrast, when there is 0.5 kG applied in the opposite direction to the fast field prior to the plasma formation, the $J \times B$ force due to the fast field has to overcome the force due to the preapplied slow field. Therefore, we can infer that undesirable fast plasma blow-off is avoided, allowing extraction of a larger density plasma. The confinement (radial) of the plasma so obtained is an additional favorable feature of our design.

Another important plasma source diagnostic, the results of which support the Faraday cup results, was a double Langmuir probe operating in the ion saturation regime.¹⁸ The probe was used to measure the plasma density profile in the axial direction of the source. The plasma source parameters here were similar to the ones used in measurements of the stagnated plasma with Faraday cups. The result is shown in Fig. 15 where the peak densities are

FIG. 15. Plasma density vs distance to the cathode. The anode contact position is indicated by ac. Here we used 25 kV fast coil charge and 5 kV slow coil charge.

plotted. The graph clearly shows the plasma pile-up effect at the stagnation point. At the plasma front surface (facing the cathode) the measured density drops from 2.5×10^{14} to $1 \times 10^{13} \text{ cm}^{-3}$ within 3 mm. The electron temperature of the plasma before it reaches the stagnation point was also inferred from the probe characteristic curve to be about 3 eV.

C. Gas puff diode outputs

In this paper, we will only present the basic characteristics of the gas puff diode. The preliminary results of this experiment has been published previously^{19,20} and the detailed results will be shown in another paper.

Here we recall the drawing in Fig. 1 which shows the details of the diode in scale. This annular extraction geometry, magnetically insulated diode has a beam extraction area of about 400 cm^2 . When a proton beam is desired, the diode is operated using the following optimized timing sequence for its components: First the slow coil is energized. About $40 \mu\text{s}$ later, the puff valve is fired followed by the preionizer $180\text{--}200 \mu\text{s}$ later. This sequence allows us to match the time needed for the hydrogen gas puff cloud to fill the region in front of the fast coil properly to the time of peak of amplitude of the slow field oscillation which is about $240 \mu\text{s}$. About $1 \mu\text{s}$ after the preionizer is fired, the fast coil is energized, producing the plasma. Then, the plasma is accelerated towards the diode gap where it stagnates against the diode insulating field. Choosing the position of stagnation to be near the axial position of the metal anode, the high voltage is applied to the gap $300\text{--}1500 \text{ ns}$ after the firing of the fast coil, depending on the other diode parameters used.

A typical voltage and current waveform and output beam characteristics are shown in Fig. 16. Specifically, these are: the inductively corrected diode voltage measured with a resistive voltage divider, diode total current consisting of electron leakage and ion current, measured with a Rogowski coil²¹ at the output switch, and traces from three Faraday cups positioned at 10 cm from the gap, indicating the current densities in different azimuthal positions (90°

FIG. 16. Typical diode output characteristics. Here we show from the top figure: inductively corrected diode voltage, total diode current, and current densities measured with three distinct Faraday cups at different azimuthal positions (90° apart) but all at a radius of 15 cm and positioned 10 cm from the ion diode gap.

apart) of the diode. In addition, a calorimeter and shadow plates with damage targets were used in this shot. A beam pulse of more than $1\ \mu\text{s}$ duration with peak current density over $200\ \text{A}/\text{cm}^2$ is indicated by the Faraday cup trace. More than 1×10^{17} ions with 50 keV (with peak energy over 120 keV) were extracted. The energy density measured with the calorimeter was $3.5\ \text{J}/\text{cm}^2$, and the divergence of the beam at positions far from the gap, estimated from damage targets, was about 3° . The system settings used to obtain this output were 50 kV Marx charge, 25 kV fast coil charge, 6 kV slow coil charge, 1.1 cm physical diode gap spacing, 7 kV puff valve charge with 10 psig pressure of hydrogen gas in the plenum, delay between firing puff valve and preionizer of $180\ \mu\text{s}$, between preionizer and the fast coil of 700 ns, and between fast coil and Marx of 450 ns.

Other hydrogen gas puff diode characteristics include¹⁴

the beginning of ion current extraction coincident with high voltage pulse under proper fast coil and Marx timings, pure proton beam within the 20% uncertainty of the measurement technique (foiled Faraday cups method), diode voltage shape and pulse length control by injection of hydrogen anode plasmas with different densities and/or timings, flat or increasing impedance in time during beam extraction, beam uniformity better than $\pm 35\%$ in both radial and azimuthal directions, realization of a sufficiently low neutral atom density at the diode gap so that the beam pulse duration is not harmed by the presence of the neutrals. Furthermore, when we used nitrogen gas puffs we obtained ion beams with current densities of $> 150\ \text{A}/\text{cm}^2$, over 700 ns duration, at voltages of 165 kV. The diode has survived for over 700 shots with minor maintenance.

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