Operation of a 0.2–1.1 keV ion source within a magnetized laboratory plasma

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To study the physics of energetic ions in magnetized plasma, a rf ion beam is inserted into the 1 kG, \( \sim 3 \) eV, \( \sim 10^{12} \) cm\(^{-3}\) plasma produced by the upgraded LASe Plasma Device (LAPD). The commercial 100–1000 eV argon source normally operates in an unmagnetized microelectronics production environment. Successful operation in the LAPD requires numerous modifications, including electrical isolation of the source housing, relocation of the matching network for the rf, reduction of the gas pressure, pulsed operation to avoid overheating, and care to preserve current neutralization in the presence of a strong magnetic field. With these modifications, a \( \sim 500 \) eV, milliampere beam that propagates axially more than 6 m is obtained. © 2004 American Institute of Physics. [DOI: 10.1063/1.1646766]

I. INTRODUCTION

Fast ions (FIs) that have energies much larger than the thermal, bulk-ion population are pervasive in astrophysical, space, and fusion plasmas. Unfortunately, FI physics studies are challenging in both space and laboratory plasmas. Detailed measurements of the plasma properties, the FI velocities and spatial profile, and the spectrum of any waves or instabilities are required for a full characterization. In space, the spatial scales are daunting. In a hot fusion plasma such as a tokamak, the plasma profiles are well characterized, but the high temperatures complicate measurements of the fluctuations (particularly at the most relevant, relatively long, spatial scales) and FI properties are inferred indirectly from external measurements. The objective of the work reported here is to develop a FI source that can be inserted into a relatively cool laboratory plasma that is accessible to probes and FI diagnostics. This source is being employed in studies of wave–particle interactions and of collisional and fluctuation-induced transport of FIs.

The upgraded LASe Plasma Device (LAPD)\(^1\) at the University of California, Los Angeles (UCLA) is well suited for laboratory studies of FI physics. The 1-m-diam, 18-m-long cylindrical vacuum chamber is sufficiently large to confine FI orbits. The excellent plasma reproducibility and automated data collection facilitate thorough characterization of the properties of both the FIs and the background plasma. The apparatus is illustrated in Fig. 1(a). The background argon plasma is produced by a 75-cm-diam cathode at one end of the LAPD. The plasma is confined by a uniform 1 kG solenoidal field. At the other end of the device, a source is inserted into the plasma and injects FIs on orbits that spiral toward the distant cathode. A gridded energy analyzer detects the FIs at intermediate distances from the source.

As illustrated in Fig. 1(b), the properties of the source also are characterized on a smaller (0.3-m-diam, 3.6-m-long) testbed at the University of California, Irvine (UCI). This testbed is a mirror machine; the ion source is mounted along the axis beyond the field coils in a region with a strong field gradient. Background electrons for charge neutralization of the beam are produced by a filament source. Laser-induced fluorescence (LIF) of the argon ions\(^2\) and an energy analyzer diagnose the ion beam.

The ideal source for this experiment has the following properties.

1. A wide energy range (100–1000 eV) to study the energy dependence of transport.
2. Operation at variable angles with respect to the field, \( \chi = \cos^{-1}(v_i/v_0) = 0^\circ–70^\circ \), and operation in fields up to 4 kG.
3. Milliamp beam current to facilitate observation.
4. Atomic physics that accommodates diagnosis with LIF.
5. Modest energy spread (<10\%), small divergence (<3\°), and a 2 mm spot size in one direction in order to measure plasma-induced beam spreading accurately.
7. Small overall size to minimize the perturbation of the background plasma; no magnetic materials.

These are demanding requirements. We briefly investigated a compact barium source based on ion emission from a tungsten surface,\(^3\) but the beam current was inadequate. We then purchased a commercial rf source from Veeco Instruments/Ion Tech\(^4\) that is normally used for plasma processing of silicon wafers. This source is a rf Kaufman source\(^5\) with continued proprietary development that extends improvements reported by Reader et al.\(^6\) After modification, the Ion Tech source meets most of the ideal requirements. The most notable deficiency is that operation is limited to angles of \( \chi \leq 25^\circ \) in a 1 kG magnetic field.

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the quartz chamber. Some of the ions that are produced in the rf discharge reach the two grids of the accelerator system. The grid closest to the rf discharge, called the screen grid, is biased positively relative to the cylindrical metal shroud that houses the source. The second grid, called the accelerator grid, is biased negatively. The source normally produces a 3-cm-diam beam. For some experiments, a rectangular mask reduces the beam cross section.

The source is inserted into the LAPD vacuum chamber through a rectangular vertical port (Fig. 3). The source is supported on a 1.5-m-long, 1-in.-diameter stainless steel shaft; a chevron seal at the vacuum flange allows the shaft to slide and rotate to alter the vertical position and orientation of the source. For efficient rf power handling, the matching network must be near the discharge chamber, but the capacitors in the matching network overheat in vacuum. Accordingly, the matching circuit is mounted in a sealed reentrant box. The vacuum feedthroughs for the electrical connections are mounted on the matching circuit box and the box and the interior of the steel shaft are at atmospheric pressure. In addition, compressed air flows through the shaft to provide further cooling. The entire apparatus presents a large electrical perturbation to the LAPD plasma. To reduce this perturbation, the apparatus is electrically isolated from the vacuum chamber by a Teflon™ flange.

The matching network consists of a 170 pF capacitor that is in parallel with the series combination of a 25 pF capacitor and the source inductance. The shield cable for the rf power is electrically connected to the source can. In this configuration, the source resonance occurs at 18.55 MHz (Fig. 4). Because it is desirable to increase the rf frequency $f$ relative to the electron cyclotron frequency (Sec. IV), the resonant frequency is higher than the nominal operating frequency recommended by the manufacturer of 13.6 MHz.

The dc power supplies that bias the screen and accelerator grids are referenced electrically to the (floating) potential of the source can (Fig. 5). A dc break electrically isolates the rf power. Signals that monitor the source performance are isolated inductively. The rf power is modulated in amplitude to avoid overheating.

Typical signals during operation in the LAPD are shown in Fig. 6. The background plasma is formed by biasing the LAPD anode relative to the cathode. The density increases during this “active” phase of the discharge and the maximum discharge current reaches 7.2 kA. After the active
phase, the density steadily decreases in a plasma “afterglow” phase. Active plasmas are formed at a repetition rate of 1 Hz. Both the LAPD plasma and the source rf discharge are sustained at low power between active pulses. The high-power phase for the rf discharge is initiated when the anode bias is applied and persists 70 ms. If the full power is applied continuously, the source overheats within a minute and ceases to operate. The LAPD plasma and the rf discharge share responsibility for this thermal overload: at the UCI testbed, continuous full-power operation is possible, while at UCLA, the source will restart if the rf is turned off for 10 min. The purpose of the low-power phase is to maintain an ample supply of seed electrons for the rf discharge, improving source reliability.

In a normal plasma-processing operation, a “plasma bridge neutralizer” supplies electrons to maintain charge balance outside the source. Within the source, the positive extracted ion current is balanced by a negative current to the screen grid. Indeed, at the UCI testbed, the electron current to the screen grid is a reliable monitor of the ion current extracted from the source. This is not always the case at the LAPD, however. The dense LAPD plasma often alters the charge and current balance in the source, particularly early in the pulse (when the density is high) or when the source is aligned along the magnetic field (χ≈0) (so that external LAPD electrons flow readily into the discharge chamber). Under some conditions with the source parallel to the magnetic field, a beam is transiently extracted even without the application of rf power; apparently, some of the gas in the discharge chamber is ionized by the LAPD plasma. Current balance is an important consideration for operation at steep angles of χ (Sec. IV).

The gridded energy analyzer illustrated in Fig. 2 is the principal ion-beam diagnostic. The analyzer housing is usually referenced to the potential of the vacuum vessel. A 0.46-cm-diam mesh with transparency of 29% is biased negatively to \(-2.45\) V to repel electrons. The collector cup is usually biased positively to \(-72\) V to repel thermal ions and reabsorb secondary electrons. It also is possible to increase the cup bias to \(-1\) keV to measure the beam energy. The analyzer is usually aligned nearly parallel to the magnetic field, facing the source. At the LAPD, it is mounted on a computer-controlled probe drive to measure two-dimensional planes of the beam profile. Typical signals with and without rf power are shown in Fig. 6(c). Large negative signals are often observed early in the discharge when the plasma density is large. These signals are independent of source conditions and are probably caused by electrons that “leak through” the repelling mesh when the Debye length is smaller than the openings in the mesh. Later in the discharge, the difference between the with-rf and no-rf signals is caused by the ion beam.

Measurements of the beam profile \(\Delta z = 0.32\) m from the source are shown in Fig. 7. For these data, the source is at an angle χ≈20° with respect to the 1 kG axial magnetic field.
The plotted data are from relatively late in the discharge (45 ms) when collisional scattering of the beam by the background afterglow plasma is expected to be negligible. The plane of probe data is acquired twice: once with rf power in the source and once with the rf power off to obtain background signal levels. Without a mask, the beam profile is circular with a full width at half-maximum (FWHM) that is about 50% larger than the source aperture [Fig. 7(a)]. Figure 7(b) show the profile with the rectangular mask in place. At the source, the mask is oriented horizontally, but the beam profile rotates as the FIs spiral along their helical trajectories. The FWHM of the beam profile is about twice as wide as the mask.

Beam divergence depends on several factors. The plasma boundary at the openings in the screen grid can be convex or concave, depending on the grid biases and the plasma potential. The source manufacturer states that maximum collimation is achieved when the current to the accelerator grid is minimized. In a study at the UCI testbed, the divergence of the beam decreases as the rf power is increased (Fig. 8). The divergence also depends on the screen bias. In a LAPD experiment with accelerator bias of −10 V, rf power of 80 W, $\chi = 22^\circ$, and a 0.5-cm-wide rectangular mask, the beam width 30 cm from the source is 1.6 cm for a screen bias of 390 V, but increases to 2.1 cm for $V_{\text{screen}} = 250$ V.

The flat, collimating mask employed in these tests has not been optimized. We tested another mask with a 0.16 cm slit in two configurations: with the slit 0.8 cm farther from the source and with the slit 0.8 cm closer to the accelerating grid. (The flat mask is 0.9 cm from the accelerating grid.) With the more distant, narrow mask, the source performance was unreliable in the LAPD, perhaps because neutralizing electrons could not reach the screen grid. With the mask close to the accelerating grid, arcing occurred in the presence of a background plasma. In contrast, the flat, 0.5-cm-wide collimating mask had the desired effect of limiting the cross section of the extracted beam without any adverse impact on source performance.

### III. BEAM ENERGY AT RELATIVELY LOW PRESSURE

The energy of the beam ions is the sum of the screen grid potential, which biases the rf source plasma above ground potential, and the energy of the ions reaching the grid through the source plasma sheath. The accelerator grid potential serves three functions: as a barrier for background plasma electrons, as an accelerator–decelerator stage to increase the extracted ion current, and as an aid in shaping the plasma meniscus at the screen grid holes which, in turn, is important for beam focusing. The accelerator grid potential does not change the beam energy.

The beam energy is measured using two techniques. At the UCI testbed, with the source oriented parallel to the field ($\chi = 0$), a ring laser with a variable frequency (manufactured by Coherent) injects axially antiparallel to the beam. Meta-stable argon ions in the $3d^2G_{9/2}$ state are excited to the $4p^2F_{7/2}$ state when the Doppler-shifted wave frequency
The energy can also be measured by varying the bias voltage on the energy analyzer [Fig. 9(b)]. When the bias voltage exceeds the beam energy, the beam ions are repelled by the collector and the analyzer current drops. The derivative of the analyzer current as a function of bias voltage can be interpreted as an energy distribution of the beam. The maximum derivative is interpreted as the beam energy.

Figure 9(c) summarizes the various measurements. In one set of LIF measurements, the inferred energy increases linearly with screen voltage for $V_{\text{screen}}$ is $40-1000$ V with a constant energy offset of $130$ eV. In another set of measurements, the energy offset increased $35$ eV when the gas flow through the source was reduced to $\sim60\%$ of its previous value. The energy offsets inferred from the analyzer measurements at the UCI testbed with $\chi=0$ are similar to the LIF values. The offset increases with decreasing source pressure and with increasing source power [Fig. 9(b)]. With the source at $\chi=20^\circ$ at the LAPD for the conditions of Fig. 6, the energy offset measured by the analyzer is $80$ eV. Similar offsets and energy spreads were previously reported for a capacitive rf source with similar grid structure.\(^7\)

Collisions between the beam ions and argon neutrals attenuate and scatter the beam. For our experiments, which are conducted on length scales approaching $10$ m, it is important to minimize the neutral pressure in the main chamber. To that end, the source is operated with the lowest gas flow that is compatible with reliable performance. Without a collimating mask, a gas flow of $1.7$ sccm is typical. With the collimating mask, the flow can be further reduced to $1.3$ sccm, which gives a gas pressure in the LAPD main chamber of $2.3 \times 10^{-5}$ Torr. These flows are much lower than the manufacturer’s recommended flow for plasma processing applications of $6-12$ sccm.

The low gas pressure increases the electron temperature $T_e$ in the discharge chamber, which increases the energy offset. This can be understood using the formalism developed by Lieberman and Lichtenberg.\(^8\) The total energy of ions reaching the screen grid from the rf discharge chamber is the sum of the ion energy entering the sheath, which is associated with the Bohm velocity, $E_B=\frac{1}{2}T_e$, and the sheath potential, $V_s=\frac{1}{2}T_e \ln(\frac{M}{2m})=4.7T_e$. (The mass ratio $M/m=7.3 \times 10^4$ for argon.) Thus, the total ion energy at the screen grid surface is $E_s=E_B+V_s=5.2T_e$. Lieberman and Lichtenberg assert that the electron temperature can be estimated by equating the volume ionization to the total ion loss to all surfaces. This yields a transcendental expression for $T_e$ that depends on the gas pressure and the geometry of the discharge chamber. For chamber pressures of $2 \times 10^{-3}$ Torr, the expected energy offset is $\sim25$ eV, consistent with the manufacturer’s claim. However, if the gas pressure is four times lower, the predicted energy offset increases to $\sim120$ eV, which is comparable to the measured offset [Fig. 9(b)]. Evidently, the reduced gas pressure needed to minimize charge exchange losses of the beam in the main chamber produces a significant upshift of the extracted beam energy.

IV. EFFECT OF MAGNETIC FIELD

The ion gun performance in various magnetic field configurations was tested at the UCI testbed. To avoid ambigu-
ities due to beam focusing on a collector target during operation at different angles and magnetic fields, the screen grid current was used to determine gun performance. For the testbed conditions, this current is a direct measure of the emitted ion current, since for each emitted ion an electron has to be collected at the screen grid to maintain charge neutrality inside the gun plasma. In Fig. 10, the gun symmetry axis is parallel to the ambient magnetic field. Initially, the screen current increases with increasing magnetic field because a modest magnetic field \( (B \geq 10 \text{ G}) \) reduces electron transport and increases the source plasma density. On the other hand, at higher magnetic fields, the cyclotron motion becomes counterproductive. With the cyclotron frequency much larger than the rf frequency and with the rf-induced electric field perpendicular to the magnetic field, the average electron acceleration during one cyclotron orbit becomes small. Increasing the rf power level can partially compensate for this effect (Fig. 10).

When the gun is rotated perpendicular to the field, the gun performance rapidly degrades [Fig. 11(a)]. One factor that influences this degradation is the reduction of the plasma volume that is in contact with the screen grid since the electrons are strongly magnetized at high fields [Fig. 11(b)]. (The electron gyroradius is \( \sim 1 \text{ mm} \) at 100 G.) This plasma volume becomes considerably larger at low fields, where the diameter of the electron cyclotron orbit becomes comparable to the plasma dimensions. Consequently, at \( B \sim 20 \text{ G} \), the screen grid current is essentially the same for \( \chi = 0^\circ - 45^\circ \) [Fig. 11(a)].

Experiments at the LAPD suggest that it is difficult to maintain a neutralizing electron current when the source is at a large angle with respect to the field. In these experiments, stable operation at \( \chi = 0^\circ \) is established, and the source is then gradually rotated until the source performance is intermittent. Source performance is readily monitored using either the screen current in the LAPD afterglow plasma or the visible light emitted by the discharge chamber. Depending on plasma conditions, intermittent operation occurs at angles between \( \chi = 20^\circ \) and \( 30^\circ \) when \( B = 1 \text{ kG} \). At this angle, modest \( (\sim 10 \text{ V}) \) changes in the accelerator bias have a strong effect on source operation. If the accelerator bias is reduced to allow more LAPD plasma electrons into the discharge chamber, the source operates more reliably. If the accelerator bias is increased, the discharge is completely extinguished. Apparently, at large angles in a strong magnetic field, both the plasma electrons and the discharge electrons are too highly magnetized to reach the screen grid, so that the current needed to preserve charge neutrality in the source is lost.

V. USE OF A GRADIENT FIELD

For studies of FI transport, source operation in strong fields \( (\approx 4 \text{ kG}) \) at steep angles \( (\chi \approx 70^\circ) \) is desirable but, as discussed in Sec. III, source performance degrades as \( B \) and \( \chi \) increase. A possible remedy is to create the FIs in a lower field region at modest \( \chi \), then launch them up a field gradient into a higher field region. If the first adiabatic invariant \( \mu = v_i^2 / B \) is conserved \( (v_i \) is the velocity component perpendicular to \( B \)), then the pitch of the FIs decreases as they move into the higher field region according to the formula

\[
\frac{v_{iH}}{v} = \sqrt{\frac{B_H}{B_L} \left( \frac{v_{iL}}{v} \right)^2 - \frac{B_H - B_L}{B_L}},
\]

where the subscripts \( H \) and \( L \) represent the values in the high- and low-field regions, respectively. For example, if the...
field strength is doubled so that $B_H/B_L = 2$ and the initial pitch angle $x_L = 30^\circ$. Eq. (1) indicates that the pitch angle $x_H$ increases to $45^\circ$.

Figure 12 shows the results of an experiment to test this idea in the LAPD. The current in the field coils at the end of the machine is lowered by a factor of 2, while the coil currents in the central portion of the machine are raised slightly. This produces a field of $\sim 0.6$ kG at the axial position of the source that increases steadily to a value of 1.1 kG 2.2 m away, where the beam is measured. For the conditions of this experiment, the ratio of the gyroradius to the gradient scale length of the magnetic field is $r_B/B = 0.1$ so that, theoretically, the magnetic moment $\mu$ is conserved and Eq. (1) is valid. In a uniform field in the absence of collisions, the FIs spiral on helical orbits. For a source of finite extent, the orbits cross a downstream plane in a pattern that depends on the initial gyrocenters of the orbits and the phase of the gynomotion. The expected pattern is modeled by solving the Lorentz force law $F = qv \times B$ for the ion orbits; the initial positions and velocities are determined by a Monte Carlo routine for assumed values of the source profile and divergence (Fig. 12). In a gradient field, a larger spread in gyrophase is predicted for a source of finite extent. The measured profile in the gradient field is at a position that is close to the expected location and is more elongated in gyroangle than the profiles in a uniform field, as theoretically expected. According to the modeling, the average pitch angle of the beam increases from $22^\circ$ to $28^\circ$ for these conditions. Based on the data of Fig. 11, we had hoped the beam would become more intense, but this is not observed.

VI. FUTURE IMPROVEMENTS

A rf plasma-processing source has produced a $\sim 10$ mA, 0.2–1.1 keV argon ion beam at an angle of $\chi = 20^\circ$ with respect to a 1 kG magnetic field in the LAPD device. This source is suitable for studies of collisional diffusion of fast ions.

The major limitation of this source is that the pitch angle is presently limited to $\chi \leq 25^\circ$. This limit can be relaxed by employing a field gradient, although this tends to increase the spot size of the beam. Increasing the radius of the discharge chamber might enable more electrons to reach the screen grid at larger values of $\chi$ (Fig. 11), which might extend the operational range.

The collimating mask could be optimized further for transport experiments. A smaller opening might further restrict the flow of neutral gas into the chamber and reduce the spot size without significantly weakening the extracted beam.

For some experiments, a more intense source is needed. If the pulse duration is shortened, the peak power could be increased without causing overheating.

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1 http://128.97.43.7/bapsf/pages/diagram.html
3 HeatWave HWIG-250 ion gun with one #1139-07 barium source.
4 IonTech 03RF ion source.