A plasma source for mirror physics simulation experiments

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A low density, cold lithium plasma source with cross field injection operates with neutral gas density sufficiently low for studies that simulate certain low frequency waves in a mirror fusion reactor.

I. INTRODUCTION

Magnetohydrodynamic (MHD) waves relevant to magnetic mirror fusion can be investigated in a modestly funded device with almost zero β, where $\beta = 8\pi P/B^2$ is the ratio of plasma pressure to magnetic pressure. One unstable MHD wave is called the "flute mode" if it is driven by magnetic field curvature, and a "Kelvin–Helmholtz mode" if it is driven by a radial electric field.[1] The influence of the endwalls on these modes, ("linetying"), is of special interest because theory indicates the presence of interesting non-linearities at low amplitude and because it might be possible to linetie the outer region of a fusion reactor.[2]

This report focuses on our efforts to construct a low cost plasma source suitable for these studies. In order to "mimic" a fusion reactor, certain parameters must be achieved: the plasma must have both Debye length and ion gyroradius small compared the plasma radius.[3] The plasma must be dense enough so that the ion plasma frequency exceeds the ion cyclotron frequency.[3] Finally, the plasma should be collisionless (mean-free-path much longer than machine length) and mirror trapped.[4,5]

These latter two conditions pose the greatest difficulty for a small device because the collisionless criteria demands that the background pressure be near 10^{-6} Torr, and because it is difficult to produce ions in the mirror trapped state. Most plasma sources using discharges or low power rf require background pressures of at least 10^{-5} Torr.[6–9] The Q machine[10] produces ideal plasma and vacuum parameters, but the ions acquire too much axial velocity at the hot plate to be mirror trapped.[11,12] Also the electron emitting hot plate lineties flute modes.[1] Sources that have been developed by other groups either required equipment that was unavailable to us,[11,13] required too much background gas,[6–9] or linetied the plasma.[12]

II. DESCRIPTION OF SOURCE

The experimental setup consists of an axisymmetric magnetic mirror and a 15.2-cm-diam stainless steel vacuum chamber that can be easily taken apart and cleaned (Fig. 1). The plasma source (Fig. 2) contains an ohmically heated, electron emitting filament aligned parallel to the magnetic field. The filament is inside a grounded box consisting of a block of stainless steel with the center milled out. Some of the plasma escapes out of the box through a rectangular slot along the top of one side. Two guide plates produce an $E \times B$ drift of the plasma into the center of the chamber. The bottom plate is grounded, and the top plate ("anode plate") is biased at positive voltage. The source is located on the midplane of the mirror.

The box has dimensions $3.8 \times 3.8 \times 5.1$ cm, with the magnetic field parallel to the 5.1 cm side. The plasma escapes from a 5.1×1.3 cm aperture between the top of the box and the anode plate. The filament (0.08 cm diameter) is crimped at each end to 0.3-cm-thick oxygen free copper wires that are supported by alumina cylinders on the outside of the box. One end of the filament is biased at 4–5 V, drawing 30–35 a. If the filament current exceeds 35–40 A, the copper leads melt at the point of contact. About one gram of lithium is placed inside the box, where it is heated by the filament. In order to avoid overheating the lithium, a plate with small holes was often placed inside the box, between the lithium and the filament.

It is important to note that when the lithium is exhausted, most of it does not leave the box, but migrates to the top of the box which is kept cool because the anode plate shields the top from the heat of the filament, and because the "roof" of the box is a large copper plate ($10.2 \times 15.2 \times 0.6$ cm). This "roof" is an effective radiator of heat. The purpose of this design is to create a high density of lithium neutrals inside the box, while the neutral density outside the box remains low. Also, lithium neutrals that do exit the box will stick to the walls of the vacuum chamber, further reducing the neutral gas density in the chamber.

In order to reduce the amount of neutral lithium that leaves the box, the two guide plates are designed to collect lithium vapor. Also, lithium traps on three sides of the copper "roof" serve to condense lithium. The material and thickness of these plates and traps are critical to the design. Consider a thin plate held at temperature T_0 at $x = 0$, and assume that at $x > 0$ the temperature is determined by heat conduction along the plate and black body radiation from the plate. The temperature $T(x)$ obeys

$$s\kappa d^2T/dx^2 + 2\epsilon\sigma T^4 = 0,$$

where s and κ are the plate thickness and heat conductivity, respectively, and $\epsilon\sigma$ is the Stephan–Boltzmann constant times the emissivity which we take to be 0.3 for steel.[14] Dimensional analysis and numerical computation of this equation show that the temperature begins to drop within a distance x_0 of $x = 0$, where

$$x_0 = s^{0.5}\kappa^{0.5}\epsilon^{-0.5}\sigma^{-0.5}T_0^{-1.5}.$$

Both guide plates and lithium traps were made 0.0076-cm-thick nonmagnetic stainless steel. If we take $\kappa = 0.3$

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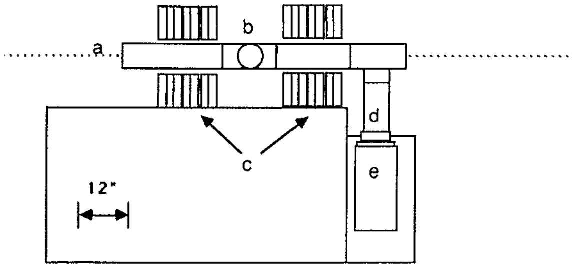

FIG. 1. Schematic of dickinson mirror: (a) end-loss-analyzer, (b) source and Langmuir probe, (c) electromagnets, (d) baffle, (e) oil diffusion pump.

W/deg/cm[14] and $T_0 = 780$ K, we obtain $x_0 = 1.7$ cm. Numerical calculation of the above box indicates that the temperature falls to the melting point of lithium (454 K) within 2 cm. Lithium deposits were found in the lithium traps and on both guide plates about 1 cm from the box.

The plasma density and temperature was measured with a retractable Langmuir probe located midplane in the vacuum chamber, opposite the source. We also used an end-loss analyzer[15] which gave us the magnitude of the radial electric field, as well as time-resolved density profiles. The end-loss analyzer was used as a Langmuir probe of area 0.45 cm^2 that consisted of a machine screw located at the end wall.

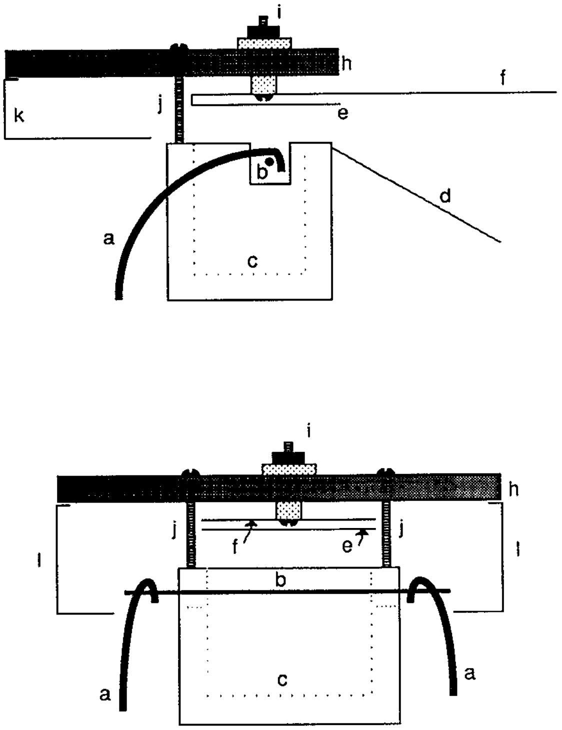

FIG. 2. Sketch of source: In top view, magnetic field points into paper; in bottom view, plasma streams out of the paper. (a) Copper lead to filament, (b) filament, (c) location of lithium pool, (d) grounded guide plate, (e) heat shield (anode), (f) anode guide plate, (g) magnetic axis, (h) copper "roof" to radiate heat, (i) Maycore and steatite insulation with anode lead screw, (j) roof support, (k) rear lithium trap, (l) side lithium traps.

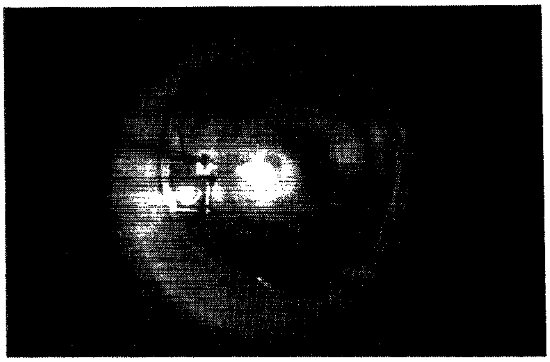

FIG. 3. Photograph of a similar source in the PIG mode with argon. The source is viewed through a plexiglass plate at the usual location of the end-loss analyzer.

The end-loss-analyzer (and to a lesser extent the retractable probe) often showed poor ion-saturation. This is probably due to the large Debye length associated with the low densities. Therefore our temperature and density measurements are estimates. The ion-saturation current was taken to be nev_i, and was evaluated at the "knee" of the curve, which is the transition between exponential dependence on voltage due to electrons and linear region where ions were collected. The temperatures quoted below are electron temperatures based on the Langmuir probe's curves of I vs V.

III. THE PIG MODE

The source can operate in two different modes. The original intent was for it to resemble a penning ion gauge[9] (PIG), using a tantalum filament. The anode plate was biased to about 150–250 V, so that primary electrons gain enough energy to ionize neutral lithium ions. The magnetic field assures a long path length for the electrons as they presumably take a helical path from a filament wire to the anode plate. The source worked quite well in this PIG mode when we filled the chamber with argon to a pressure of 10^{-2}–10^{-1} Torr. When the end-loss analyzer was replaced by a plexiglass plate, the discharge could be seen and photographed as shown in Fig. 3. On two occasions, the source was inadvertently placed upside down or on the wrong side of the chamber. This reverses the direction of the $E \times B$ flow, and the plasma was not seen between the plates, but observed to be flowing backwards through cracks in the box.

During our investigations of this argon plasma, the end wall with the analyzer was moved to a position inside the mirror, 19 cm from the source. The source shown in Fig. 3 differs from that shown in Fig. 2 in that it is made of aluminum, and because alumina and steatite was used between the sides and top of the box. It became necessary to remove all aluminum oxide and steatite components from contact with the lithium vapor when we converted from argon to lithium vapor.

The plasma density and temperature for the argon discharge in the PIG mode were deduced from both the ELA and the Langmuir probe to be 1.6×10^{7} cm^{-3} and 15 eV, respectively. The floating potential was near 100 V. The large plasma potential indicates that the source actually works as a PIG, with primary electrons having enough energy to ionize, and also being electrostatically repelled by the walls of the box.

We also operated the source in the PIG mode using lithium vapor. The oven temperature was measured using a chromel-alumel thermocouple to be about 780 K. This temperature corresponds to a lithium vapor pressure of 3×10^{-3} Torr, and is consistent with calculations of temperature based on filament power and thermal radiation ($\sim T^4$) with an emissivity of 0.3.[14] In this mode, the cap above the lithium supply was absent, and the supply of 1 g of lithium was exhausted in about 2 h. This made the source unacceptable for our purposes because the run time was too short, and because too much lithium was dumped into the vacuum chamber. The density and temperature were measured to be 10^7 cm^{-3} and 20 eV, respectively.

IV. CONTACT IONIZATION MODE

It was discovered that the filament can contact ionize the plasma when tungsten or rhenium is used (the latter costing about $6 per filament and lasting for one or two days of operation). The anode plate voltage was 1.2 V, and could be pulsed to ground in order to shut off the source.

By operating at 30 A with a rhenium filament, we obtained 6.5 h of run time using only 0.5 g of lithium. The plasma radius, density, and temperature in this mode are 7 cm, 3×10^{6} cm^{-3}, and 1 eV, respectively.[7] The mirror ratio was 3.3 with a minimum magnetic field of 300. Thus at midplane, the Debye length is 0.4 cm, the ion gyroradius is 1.23 cm, and the ratio of ion plasma to ion cyclotron frequency is 2. These values are marginally acceptable. The ratio of ion plasma to ion cyclotron frequency should be higher in order to obtain "quasineutrality" for MHD modes, but this introduces only one extra linear term into the dispersion relation.[3]

A factor of 12 increase in plasma density occurs if we increased the filament current to 45 A. However, our filament leads do not work reliably at this level. Also, as we shall see below, the baffles would have to be redesigned to trap a higher fraction of the lithium vapor if the source is to operate in this high density regime.

V. NEUTRAL GAS PRESSURE

With careful outgassing of the source, we could achieve an operating pressure of 4×10^{-6} Torr, as measured by an ion gauge on the flange near the pump. However, this pressure neglects the scattering effect of neutral lithium atoms from the source.

In order to calculate the neutral flux from the source, we need to know the fraction of lithium that condenses inside the source. By weighing the source after operation we concluded that 95% ± 5% of the lithium remains trapped by the guide plates or lithium traps. We also measured the amount of lithium in the chamber by noting that most of the lithium in the chamber appeared on a vacuum flange opposite the source, forming a coating of lithium with an area of about 150 cm^2. The amount of lithium deposited was determined by placing a small sheet of stainless steel at the center of the flange. After operation, the amount of lithium on the sheet was determined by placing it in de-ionized water and measuring its *p*H value. This measurement yielded a value of 88% for the fraction of lithium trapped in the box.

In the contact ionization mode (with 30 A filament current), 0.5 g of lithium provided 6.5 h of operation at a plasma density of 3×10^{6} cm^{-3}. If we assume that this neutral lithium was part of a beam of area 10 cm^2 of atoms with energy corresponding to 780 K, we obtain a neutral density of 1.3×10^{11} cm^{-3}. (This density would represent a pressure of 4×10^{-6} Torr at room temperature.) The lithium cross section for charge exchange at 1 eV is roughly 10^{-13} cm^2, yields a meanfree path of 75 cm.[10] Since the beam is about 5 cm in diameter, a typical trapped ion will make about 15 passes through the beam before encountering a charge exchange collision.

VI. DISCUSSION

We have constructed a plasma source designed to mimic certain effects of interest in mirror fusion. When operated in the contact ionization mode, this source is marginally acceptable with respect to mean-free path, ion gyroradius, plasma density, and radius. The two big difficulties with this source are its low density and the fact that the plasma is hollow[15] in the contact ionization mode. A higher density is probably achievable if the filament leads and lithium traps were redesigned for hotter operation.

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