LARGE-AREA PLASMA SOURCES


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LARGE-AREA PLASMA SOURCES

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

High-current ion sources for neutral-beam injection into controlled-fusion experiments require large-area uniform high-density plasmas from which to extract the ions. Three types of such sources have been constructed for use with several injection experiments. All generate the plasma by a diffuse low-pressure high-current discharge from distributed thermionically emitting cathodes, without the use of externally applied magnetic fields. Two are short pulse (t = 30 and 10 msec, power supply limited) sources from which deuterium ion-current densities of ~0.5 A/cm² are extracted from a 7-× 7-cm square array and from a 7-× 35-cm rectangular array. The third operates for 10 sec and gives a hydrogen ion-current density of 0.25 A/cm² over a 10-cm diameter. The design differences for long- and short-pulse operation, as well as the operating characteristics of each, will be discussed.

Introduction

One of the more promising methods for heating and fueling the plasma for a number of large controlled-fusion experiments is the injection of intense energetic neutral beams. To obtain the multiampere beams required (deuterium in most cases), plasma sources that can generate a high ion-current density over very large extraction areas are needed. The ion optics of the extraction system are very sensitive to plasma density, thus one prime requirement is that the source be capable of generating a high-density plasma that is spatially uniform over the entire extraction region. In addition, temporal plasma density fluctuations, including those indicated by noise or hash of the type and frequency encountered in most source geometries, in which magnetic fields are used, must be avoided. Our aim has been to limit plasma density variations of all types to less than ±10%.

We describe three different plasma sources: a cylindrical pulsed source which produces a uniform plasma (up to 0.5 A/cm² of deuterium ions) over a 12-cm diameter for a time of 30 msec (set by the duration of the pulse line); a scaled-up pulsed rectangular source which supplies 0.5 A/cm² of deuterium ions uniformly over a 7-cm by 35-cm area for 10-msec pulses (again, power supply limited); and a long-pulse cylindrical source which produces 0.25 A/cm² of hydrogen ions over a 10-cm diameter for 10-sec pulses.

Cylindrical Pulsed Source

The cylindrical pulsed source will be discussed first; it will be recognized as an improved version of our initial model, which was described at the first meeting of this Symposium in Brookhaven [1]. A block diagram of this source and its associated electronics is shown in Fig. 1.

FIG. 1. Block diagram of the plasma source. The solid sections are insulators, 1) tungsten filaments, 2) cathode mounting plates (one +, one -), 3) filament cover plate (floating), 4) wall electrode (floating), 5) anode, 6) movable probes (4 total), 7) grid support plate (floating), 8) back plate (floating), 9) pulsed gas valve.

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The plasma is produced by a diffuse low-pressure high-current discharge with a distributed thermionically emitting cathode which consists of a ring of hot tungsten filaments [2,3]. Pulsed dc heater power is used (about 12 V, 25 A per filament) to avoid ac modulation of source potentials and plasma density. No externally applied magnetic fields are added, so the fluctuations associated with cross-field transport are avoided.

We have found empirically that for short-pulse operation (tens of milliseconds) the emission current drawn from each filament must be no more than twice the filament heater-current, otherwise the filaments will be destroyed by hot spots. This source, designed to operate with currents up to 1400 A, has 28 hairpin filaments, 0.5-mm diameter and 10-cm long, inserted into molybdenum chucks and connected electrically in parallel. The filaments reach thermal equilibrium approximately 1.5 sec after the heater power is applied.

In our initial source [1] the gas was pulsed through a small cylindrical anode; however, the plasma profile was peaked on axis, and the effect was enhanced as the arc current was increased. By operating a portion of the cylindrical chamber wall as the anode, we obtained a considerable improvement in the uniformity of the radial profile which, in addition, did not change with increasing arc current. This larger anode area eliminated the existence of anode sheaths as well as troublesome magnetic fields resulting from concentrated arc currents.

The remaining parts of the source, including the first extractor electrode, are allowed to float electrically, and a number of movable probes are used to indicate the saturated ion-current density immediately behind this electrode.

Gas flow is controlled by a specially constructed combination of a needle and solenoid valve connected to a regulated 15-psi deuterium reservoir. This unit also incorporates a small plenum, which is effective in rapidly bringing the source pressure to its proper operating level. Gas flow changes are made either by varying the setting of the needle valve or by altering the reservoir pressure.

Arc power is supplied from a 30-msec pulse line; Fig. 2 is a plot of the arc current, arc voltage, and ion current density vs pulse-line voltage for the pulsed cylindrical source.

Figure 3 is a plot of the saturated ion-current density profile for two levels of operation as indicated by the movable probes. Although this source was designed for use with a 7 X 7-cm square extraction grid, it can be seen that a larger extracting area could be utilized, as the profile shown here is flat to ± 6% to a diameter of 12 cm. The location of the filament ring and anode wall are also indicated in Fig. 3, demonstrating that nearly the entire source diameter should be available for extraction.
Photographs of the source interior minus the extractor electrode, as well as the source exterior, including the pulsed gas valve, are shown in Fig. 4.

When the filament and arc currents become as large as those in these sources, currents flowing through the source structure can produce unwanted magnetic fields, and special care must be taken in making the connection to the electrodes. Multiple parallel connections are made to each current-carrying element to minimize and distribute this effect. The top view of Fig. 4 shows four bars that are used to make the anode connection.

When coupled with a 60% transparent 7-×7-cm multiple-slot array [4], this source has produced a 20-keV deuterium ion beam of nearly 16 A. The extracted ion species mixture is typically 75% D⁺, 15% D⁻, and 10% D₀. The atomic output may well be enhanced by the dissociation of molecular deuterium by the hot tungsten filaments.

The source operating conditions for the 20-kV deuterium beam were as follows: 1.5 sec after the filament-heater power (≈8 kW) was applied, the gas valve was opened, admitting approximately 8 Torr-1/sec of D₂ gas. (We estimate the pressure in the source chamber to be 10 to 20 mTorr.) Ten milliseconds later the arc pulse-line was fired; the arc parameters were V = 60 volts, I = 800 amperes. A few milliseconds after the arc was established, the extraction voltage was applied. At the end of the extraction pulse the arc pulse-line was crowbarred and the gas valve was closed.

Sources of this type have been used successfully on the Lawrence Livermore Laboratory 2XII mirror confinement experiment, as well as on the ATC tokamak experiment at the Princeton Plasma Physics Laboratory [5].

**Pulsed Rectangular Source**

The larger of our two pulsed sources, an interior and exterior view of which are shown in Fig. 5, was designed and constructed as a prototype for injectors for the LLL 2XII-B experiment. The shape of the source was dictated by a combination of ion optics considerations, as well as the size of the proposed 2XII-B entrance aperture, and is rectangular to allow a number of similar units to be placed one above the other to inject into a common entrance port. This unit has an extraction area of 7 × 35 cm, five times that of the smaller source.

As the ion extraction area is increased, larger arc currents, hence a greater number of filaments, are required. Extrapolating the results obtained with the cylindrical source, we anticipated an arc current of 4000 A to obtain 0.5 A/cm²; therefore, 86 filaments similar to those already described were used.

For a given arc current, the required anode size becomes a function of the plasma density near the anode. To avoid the formation of an anode sheath, which tends to make the discharge noisy and wastes arc power, the anode should have enough area so that the arc current can be supplied entirely by the random-electron flux striking the anode. The anode area for this source is 350 cm².
Figure 6 is a plot of arc voltage and ion-current density as a function of arc current, indicating that the desired deuterium ion current density of 0.5 A/cm² is obtained with an arc current of about 3500 A, an arc voltage of 45 V, and a gas flow of 21 Torr-1/sec. Shown too are the 10-msec wave forms of arc current and voltage, as well as the ion-current density as indicated by four probes located at various positions throughout the extracting region. This photograph is actually an overlay of four shots, which shows that the shot-to-shot reproducibility is excellent, even in fine detail, and that there is complete freedom from noise or hash.

Though provisions were made for multiple gas feeds, as shown in the top view of Fig. 5, best operation and a flatter plasma-density profile result when the gas is fed through a single central port. This eliminates the external manifold structure; consequently, the initial rate of rise of the pressure in the source is increased. The gas is pulsed on 1.5 sec after the filaments are turned on, and the arc can be initiated within 1 msec after the gas valve has opened. The gas efficiency, or the fraction of the gas nuclei that are ionized and extracted, is 25 to 49%, depending on the arc conditions chosen by the operator. The composition of the ions extracted from this unit has not as yet been determined; however, we believe that it will be similar to that obtained from the smaller pulsed source.

Approximately 75 A of deuterium ions has been extracted from this unit, and despite its rectangular shape the plasma density variations can be held to less than the ± 10% desired. Twelve of these sources plus their associated extractor structures are now being constructed to inject 600 A of energetic deuterium neutrals into the plasma of the 2XII-B experiment.

Long-Pulse Source

Although we have been able to emit twice the heater current from the filaments for tens of milliseconds, this condition is intrinsically unstable for long pulses. This can be illustrated by the following oversimplified model: Consider the filament to be two equal resistors, one forming the positive leg of the hairpin and one forming the negative leg; furthermore, assume all the emission takes place at the tip of the hairpin (the junction of the resistors). When the emission current equals the heater current no current will flow in the positive leg; hence the positive leg will cool, whereas the negative leg will heat. Since our "resistors" are pieces of tungsten wire, the
negative leg will emit more electrons and the positive less. Hence a runaway situation develops.

To avoid this, one can heat the filaments with alternating current, so that the two legs of the hairpin switch roles. With hairpin filaments heated with 60 Hz power, there was considerable ripple (± 50%) in the plasma density at twice the heater frequency, presumably caused by the zero-crossings of the magnetic field created around the filament by the heater current. The use of counter-wound spiral filaments reduced the heater-induced ripple in the plasma density to less than ± 10%.

We have incorporated this filament configuration in the construction of a long-pulse (10-sec) plasma source. To be conservative, we also decided to limit the emission current to half the heater current for long-pulse operation. The source is similar to the pulsed cylindrical source, but has 56 counter-wound spiral filaments mounted on two concentric circles, 11.4 cm diam and 12.8 cm diam, with 28 filaments each.

Figure 7 is a plot of the saturated ion-current density vs arc current with the source operating with hydrogen. Shown too is a plot of the spatial ion-current profile. For 10-sec operation, this source is capable of generating a hydrogen ion-current density of 0.25 A/cm² as indicated by probes, and, including the variation caused by heating the filaments with 60-Hz current (~ 25 A rms/filament), has a plasma density that is flat to better than ± 10% throughout the region of extraction. As yet this source has not been operated with deuterium gas, nor with arc currents exceeding 600 A. Nor have we yet built an extractor for this source.

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References

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