RF PRODUCTION OF LONG, DENSE PLASMA COLUMNS

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Novel accelerator concepts /1/ such as wake-field accelerators, plasma lenses, and inverse free-electron lasers, often call for uniform plasma sources of high, controllable densities of order 10^{14} cm^{-3} or above. The beat-wave concept, which needs the order of 10^{17} cm^{-3}, falls in a different category /2/. To produce 10^{14} cm^{-3} plasmas, we have been studying the use of helicon waves, which themselves are accelerators, in this case bringing primary electrons to their optimum energy by Landau damping /3/. Evidence for this absorption mechanism has been given previously /4/. Measurements on 4- and 2-cm diameter tubes /5/ showed that a right-hand helical antenna is more efficient than others, and that densities of order 10^{14} cm^{-3} can be attained at 60 mTorr of A and a field of 1.2 kG, using 2 kW of rf power at 27.12 MHz.

Creation of a plasma of 10^{14} cm^{-3} density is facilitated by experimental techniques not easily foreseen from theory. Ions are confined in a radial potential well but escape freely along the axial magnetic field B at the acoustic speed c_s. Electrons are confined by an axial potential well and are scattered out radially. To supply the ion losses, neutral gas must be injected into the discharge at a fast enough rate. We have previously found /5/ that a 4-cm diam tube housing a 2-cm diam plasma acts as a reservoir of gas which can feed radially into the plasma. The constriction of the plasma can be accomplished in three ways. An antenna wound helically in a direction to launch a right-hand polarized wave toward the midplane tends to produce a peaked density profile /5/. By reversing the endcoils and producing a cusp field at the antenna, we can produce a magnetic aperture limiter which is very effective in narrowing the column. We can also insert a carbon limiter into the tube to constrict the plasma directly. To optimize these effects, the apparatus was configured as shown in Fig. 1.

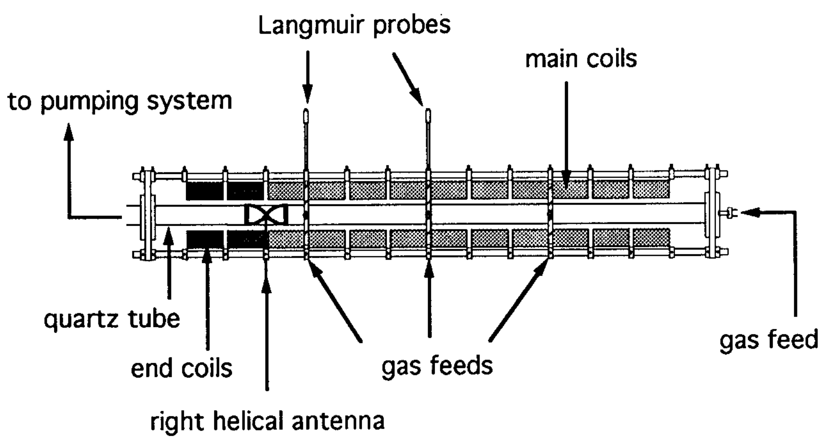

Fig. 1

Argon gas was fed in at four places along the tube. The endcoils near the antenna were controlled independently to shape the magnetic field there. To avoid overheating, both the field and the rf power were pulsed for 100-150 msec, with less than 5% duty factor. At these densities, the sputtering of tungsten probe tips would change the collection area during a run. This was remedied by using carbon tips (0.3 mm pencil lead), 1.5 mm long, centered in an alumina tube of 1.6 mm o.d. The probe was biased at −130 V with floating batteries, and it was made to follow potential fluctuations at the rf frequency by an rf choke with a resonance frequency around 30 MHz, connected within 5 cm of the probe tip. The probe was thus effectively terminated in 200 KΩ at rf frequencies, and in 50 Ω at low frequencies. Though the ion saturation current was calibrated against the density measured by microwave interferometry, the densities reported here are uncertain by ±10%, mainly due to variations in probe area.

The effect of varying the magnetic field shape is shown in Fig. 2, which gives the density on axis vs. voltage on the end coils for two antennas – a right-hand helical (R.H.) and a plane-polarized Nagoya Type III. The standard conditions were B = 600 G, p = 5.5 mTorr of argon, and P_{rf} = 1.9 kW at 27.12 MHz. A voltage of +40 gives a nearly uniform field; and −40, a strongly cusped field. The density from a plane-polarized antenna increases about a factor of 5 with a cusp field. Fig. 3 shows the density profiles with a uniform field, with the end coils off, and with the end coils reversed. At least part of the density increase is due to the peaking of the profile with cusped fields. The density increase is smaller with the R.H. antenna (Fig. 2), because this gives a peaked profile even in a uniform field.

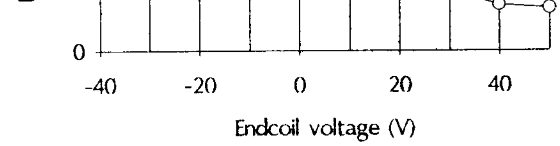

Fig. 2

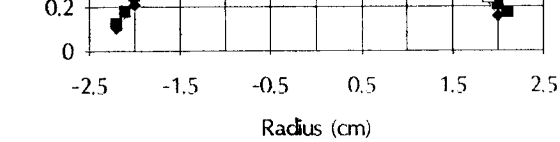

Fig. 3

We next investigated the effect of material limiters, carbon disks with holes of 1.2 and 2.0 cm. The density profiles with the 1.2-cm limiter are shown in Fig. 4 for a uniform B-field, and in Fig. 5 for a cusped B-field (end coils reversed). Other conditions were the same as above. Fig. 4 shows that the density was sensitive to the position of the limiter; a large increase in density occurred when the limiter was located just under the rear loop of the antenna, at −6 cm from the midplane of the antenna. When a cusped field was added (Fig. 5), the profile was more sharply peaked, and the density further increased, showing that a magnetic limiter is more effective. In this case, the position of the limiter was not important, except when it is located well downstream, near the probe (+22 cm). Restricting the column at that point decreased the density.

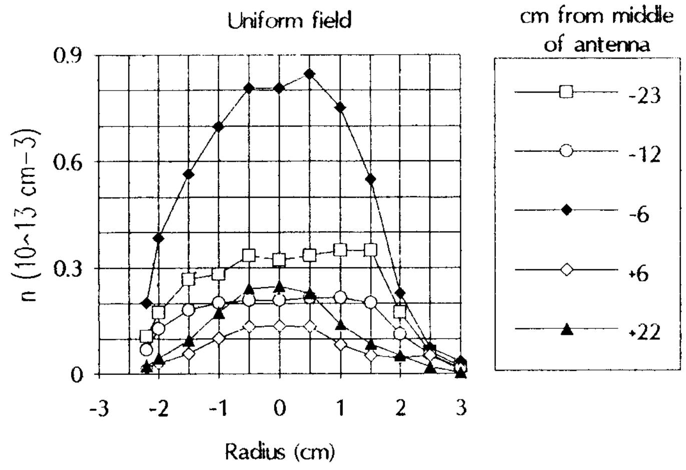

Fig. 4

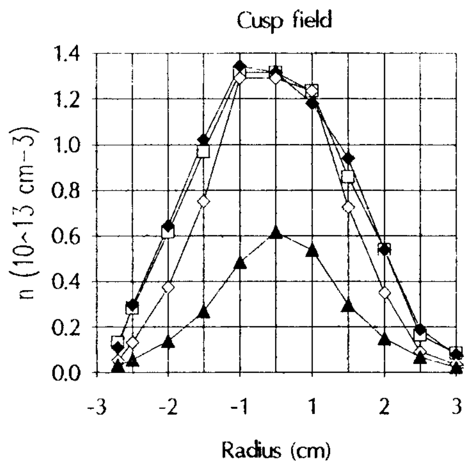

Fig. 5

The combined effect of magnetic and material limiters is shown in Fig. 6, which shows the density on axis under standard conditions for different positions of the 1.2-cm limiter as the endcoil voltage is varied. Since the limiter is effective at the rear end of the antenna (-6 cm), there is relatively little improvement with a cusp field. When the limiter is at the front end of the antenna, however, there is a great improvement with a cusped field, because the performance in a uniform field is so poor. These observations are not yet understood.

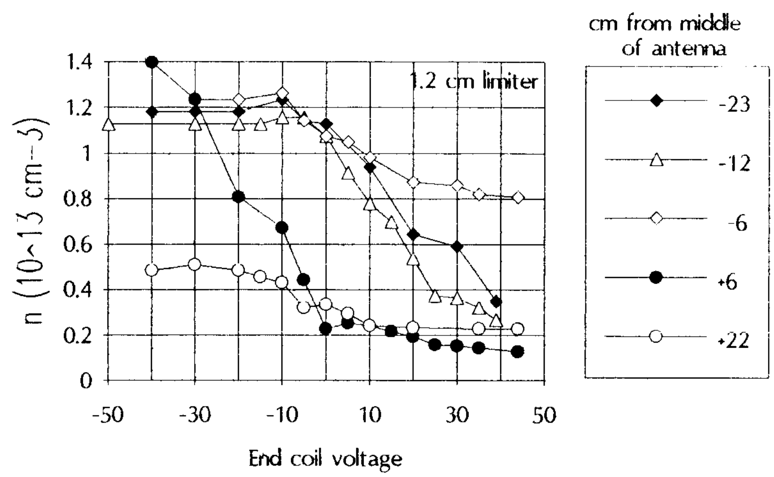

Fig. 6

Even a solid carbon block has an effect on the density, depending on its position. Fig. 7 shows density profiles with the block at the rear end of the antenna (-6 cm), far back near the pump (-22 cm), and in between (-12 cm). There is an increase in density at the -6 cm position. Possible explanations include image currents in the limiter, reflection of helicon waves by the limiter, and the recirculation of neutral atoms formed by recombination of ions on the surface. By comparison, Fig. 8 shows the performance of the limiter with a 2-cm diam hole. These data were for a uniform B-field.

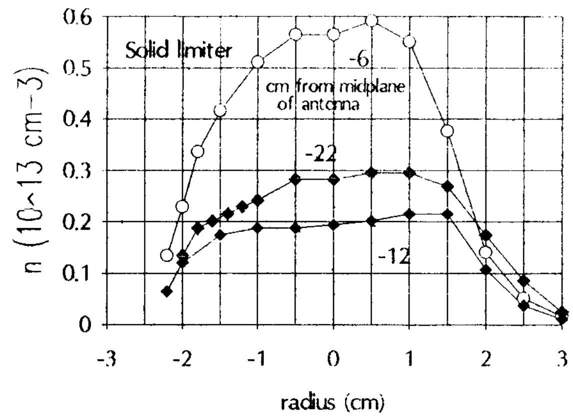

Fig. 7

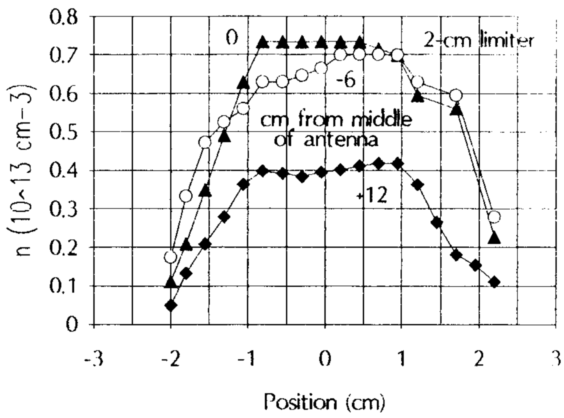

Fig. 8

To obtain the highest density with the available rf power, we operated at 1 kG with a cusped field, with no limiter, using a helical antenna and a probe located near it. The importance of gas feed is shown in the pressure scan of Fig. 9. The density pulse had a peak of about 5 msec, followed by a plateau for the remainder of the 100-msec pulse. The peak density did not vary with pressure above a few mTorr, but the plateau density fell off at low pressures, indicating a deficiency in neutral gas. Apparently, unless the flow rate is very high, densities of order 10^{14} cm^{-3} are sustained only by the gas stored inside the tube, feeding radially into the plasma. Fig. 10 shows radial profiles at the peak and the plateau for the upstream probe, as well as for the downstream probe, which does not show a density spike at the beginning of the pulse. The field was increased to 1.2 kG. There was a large axial density gradient because of the high pressure of 20-30 mTorr. At normal operating pressure, the plasma is much more uniform along the axis.

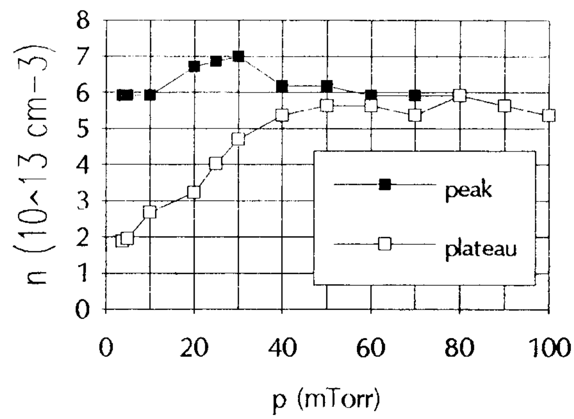

Fig. 9

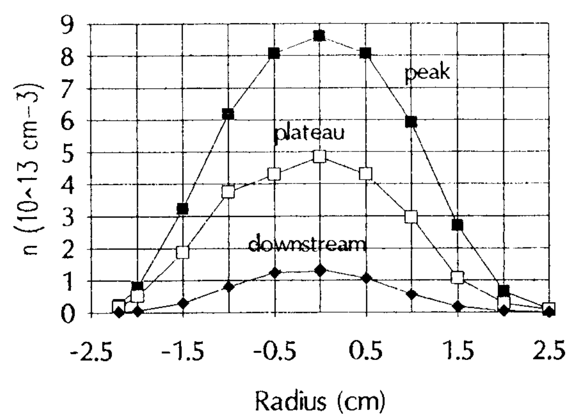

Fig. 10

Since there is no need for internal electrodes in this device, it should be possible to produce arbitrarily long plasma columns of density 10^{14} cm^{-3} by adding antennas periodically. This paper has shown the importance of magnetic field shaping near the antenna and of arranging for radial gas feed. Other investigators /6//7/ have found that, above a power threshold of 2-3 kW, the helicon discharge can burn out all the neutral atoms near the axis and constrict itself to a narrow, fully ionized column. We hope to add enough power to see this in the near future.

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