

Large-area helicon plasma source with permanent magnets

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Received 22 May 2006, in final form 22 July 2006

Published 27 March 2007

Online at stacks.iop.org/PPCF/49/A81

Abstract

A helicon plasma source has been designed using annular permanent magnets to produce the required DC magnetic field (B -field). With the discharge tube located in the remote field, rather than the internal field of the magnet rings, the plasma can be injected into a processing chamber containing the substrate to be treated. The discharge tube, radiofrequency (RF) antenna and magnet size were optimized by computation and tested by experiment. A distributed source comprising eight individual discharges was constructed and tested. Such sources are capable of producing downstream densities $>10^{12} \text{ cm}^{-3}$ (in argon) over an arbitrarily large area for high-flux applications.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Unlike other radiofrequency (RF) plasma sources, helicon sources, invented by Boswell [1], depend on the excitation of waves, namely, helicon waves, which are whistler waves bounded within a cylinder. The behaviour of these waves and of the discharges they produce has provided numerous challenges to our intuition. Foremost among these is the efficient ionization mechanism which causes the density to be as much as an order of magnitude higher than that in other plasma generators at a given power. In 1991 Chen [2] suggested that ionizing electrons were accelerated by Landau damping. Though a small number of such electrons has been detected, the Landau damping hypothesis was later disproved by Chen and Blackwell [3], who showed that these electrons were too few to produce the high observed densities. Meanwhile Shamrai and Taranov [4] proposed that electron cyclotron waves in the Trivelpiece–Gould (TG) mode could be generated by mode-coupling at the radial boundary. These electrostatic modes rapidly convert RF energy into electron heat. The existence of TG modes was confirmed in the experiment of Blackwell *et al* [5], and computations [6] support the dominance of this mechanism in the far-field region downstream from the antenna. Near the antenna the fields are so strong that they cannot be measured easily. Nonlinear or parametric coupling to ion acoustic or lower-hybrid waves has been suggested. Using correlation techniques, Lorenz *et al* [7] proved the existence of parametric decay of helicons into ion acoustic and TG modes. Energy deposition in helicon discharges is, therefore, very complicated, but it works.

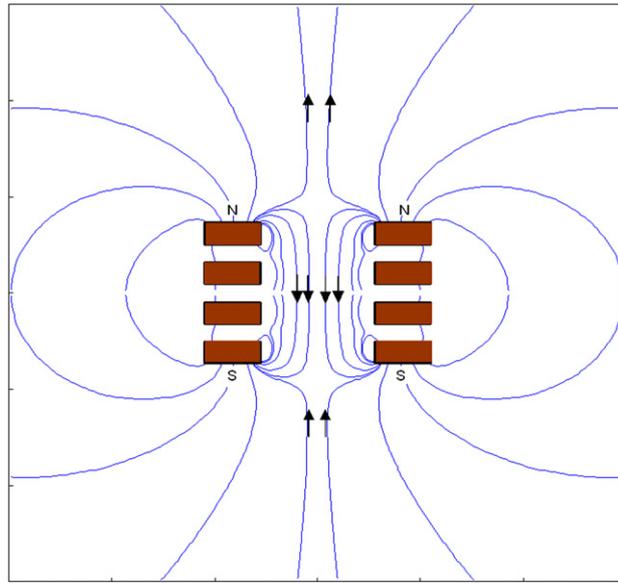


Figure 1. Field lines around a stack of annular ceramic magnets 2.2 cm thick and 1.9 cm apart.

At least two companies have tried to commercialize helicon sources for plasma processing. The device of Chapman *et al* [8] employed a Boswell [9] antenna to create an $m = 1$ helicon wave, where m is the azimuthal wave number. The device of Campbell *et al* [10], described by Tynan *et al* [11], used a dual $m = 0$ antenna with opposite currents. Though both sources performed well, they were not readily accepted by the semiconductor industry, which found that simpler RF sources not requiring dc B -fields were satisfactory for substrates up to 300–400 mm in diameter.

For applications to larger substrates, the idea of distributed sources using multiple discharges has been tried with both magnetic and field-free systems. In particular, Chen *et al* [12] made extensive measurements of a seven-tube helicon source, proving the principle that uniform plasmas can be produced with a finite number of discrete sources. However, the magnetic field was still a problem. If the field was produced by a small coil around each tube, the field lines diverged so rapidly that most of the plasma was carried into the entrance flange and lost there before reaching the processing chamber [13]. To avoid this, a uniform B -field was produced with a large electromagnet surrounding the entire array. Also, the discharge tube and the antenna were shortened to reduce the wall loss. This device [12] produced a plasma of nearly 10^{12} cm^{-3} density, uniform to 3% over 400 mm. However, this concept cannot be extended. Similar results have been reported by Kim *et al* [14] in a 12-tube linear array to much larger areas, and the large, expensive magnet and its power supply make the device uneconomical for commercial purposes. The use of permanent magnets (PMs) alleviates this problem.

2. Characteristics of toroidal PMs

Consider a stack of ring magnets magnetized vertically, as shown in figure 1. A uniform downward B -field exists inside the hole of the stack, and strong helicon discharges can be

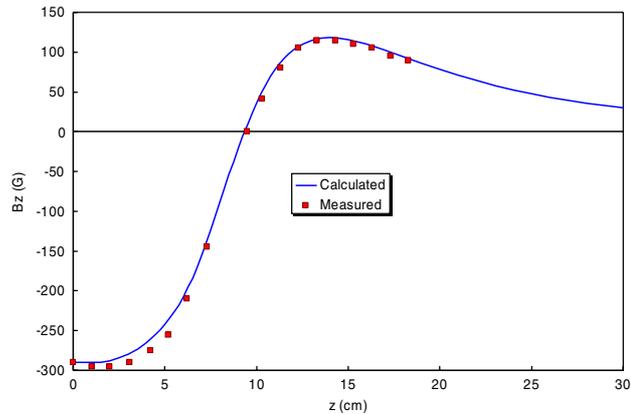


Figure 2. Computed $B_z(z)$ on axis compared with measurements, where z is measured from the midplane of the magnet stack.

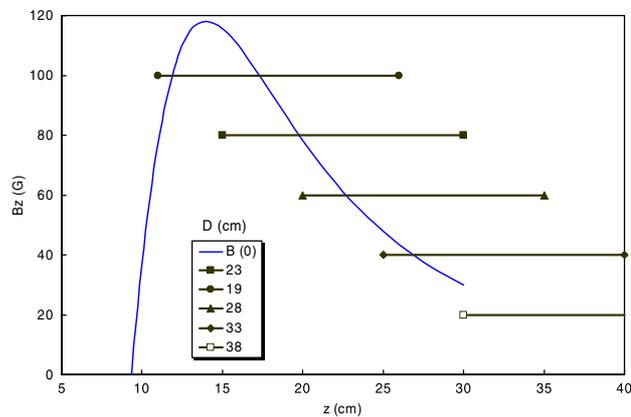


Figure 3. $B_z(z)$ in the remote region. The lines represent the length of the discharge tube as it is placed at various distances below the magnets. Here D is the distance between the bottom of the magnet stack and the bottom of the discharge tube.

produced there. However, the plasma cannot escape from the hole, since those field lines end on the magnets. At large distances, the hole is insignificant, and the stack appears as a simple dipole, with the field pointing upwards. Thus, there must be a stagnation point on axis where the field reverses sign. If the plasma is created in the external field beyond the null, the field is weaker and not as uniform, but it extends to infinity. In practice, the null point occurs very close to the magnets, and a compact system can still be designed.

Figure 2 shows the computed and measured B -fields on axis, showing the field reversal at $z \sim 10$ cm below the midplane of the stack. The reverse-field, remote region is shown in figure 3, together with different test positions of the discharge tube, showing the field gradients. These positions sampled B -fields of ~ 100 G down to below 20 G. Calculations were made to optimize the shape of the magnets as their inner and outer diameters (ID, OD) and their thickness and spacing were varied. The results showed that field strength increased more or less with the total volume of the magnets and decreased with the spacing. Uniformity of the

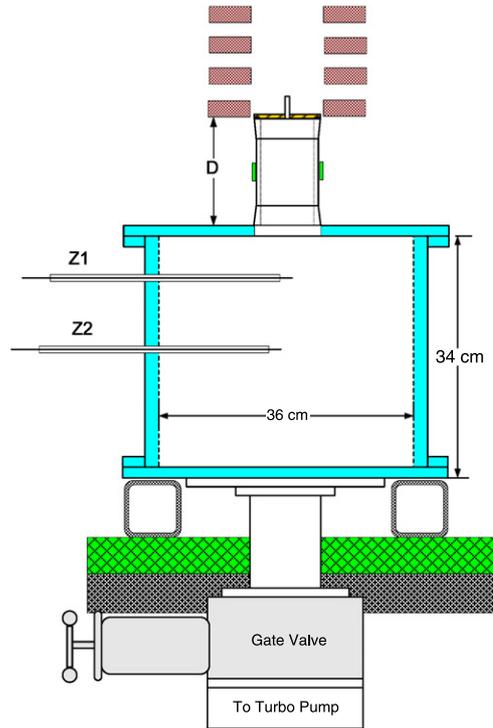


Figure 4. Schematic of apparatus for first tests of helicon discharges in the remote field.

remote field improved with spacing, and hence the configuration of figure 1 was chosen for our tests.

3. Preliminary tests in the remote field

Tests with these magnets were made with the apparatus shown in figure 4. The discharge tube was a 7.6 cm ID pyrex pipe 15.2 cm long. Up to 500 W of RF at 2 or 13.56 MHz was applied to an $m = 0$ loop antenna at the midplane of the tube. The gas was 1–10 mTorr of argon. Density profiles were measured with two Langmuir probes located at $Z1 = 7.4$ cm and $Z2 = 17.6$ cm below the top flange.

Radial density profiles $n(r)$ for various heights D are shown in figure 5 for 2 MHz, 1 mTorr and 500 W. The low density at $D = 1$ cm proved that putting the discharge inside the magnets produces low n downstream, though that inside the tube was high. Though the densities were much higher than with $\mathbf{B} = 0$, they were only in the mid- 10^{10} cm^{-3} range, rather than in the high 10^{11} cm^{-3} range, as obtained previously [12]. The density increased with increasing D , where \mathbf{B} was weakest. This was probably caused by the difference in field line divergence, which also could have caused the large change in profile between $Z1$ and $Z2$. Increasing the pressure to 10 mTorr had little effect.

To recover previous results, we replaced the 7.6 cm diameter tube with the short, 5 cm-diameter tube used in [12] and shown in figure 6. As seen in figure 7, $n(r)$ increased by an order of magnitude, and the behaviour with radius and pressure was more reasonable. This is because the antenna created a plasma close to the exit aperture, with little loss to the sidewalls

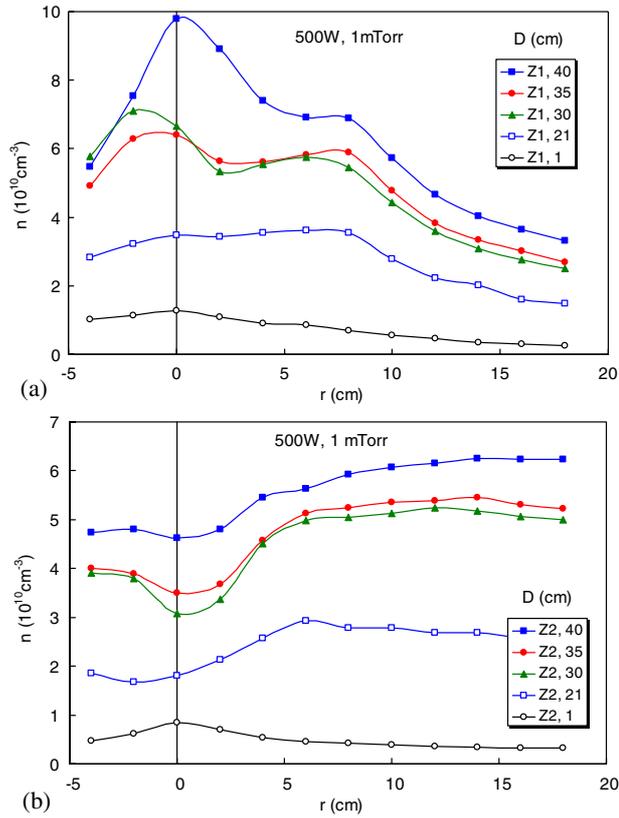


Figure 5. Radial density profiles at (a) Z1 and (b) Z2 for various magnet positions D . Conditions: 500 W at 2 MHz, 1 mTorr.

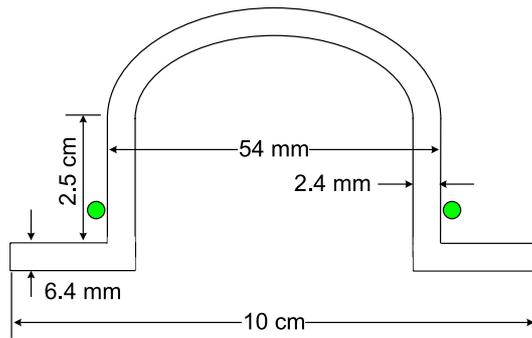


Figure 6. Diagram of the short 'stubby' tube.

in spite of the diverging B -field. Furthermore, the added flat section moved the plasma farther from the metal flange, minimizing image currents and electron losses. The insulating corner also mitigates these losses by charging to a negative floating potential. A small $m = 0$ antenna is essential. Helical or Nagoya Type III $m = 1$ antennas require long tubes and

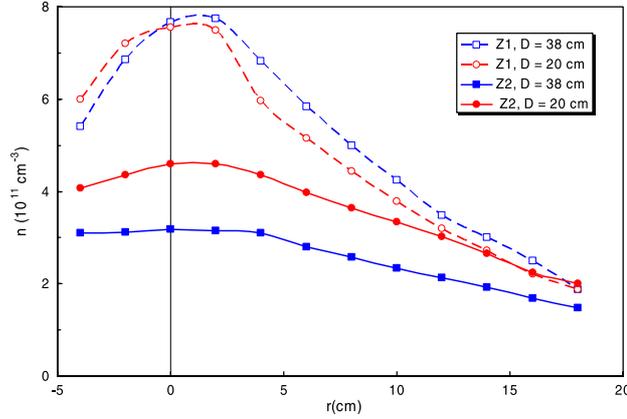


Figure 7. Density profiles with the ‘stubby’ tube at 500 W and 10 mTorr. Dashed (---) curves are for probe position Z1, and solid (—) curves for Z2. Squares (\square) are for $D = 38$ cm and circles (\circ) for $D = 20$ cm.

create the plasma far from the exit hole. Experiments with other antennas yielded poor results downstream.

4. Optimization

4.1. The low-field peak and plasma loading

To optimize the discharge tube, numerous computations were made with the HELIC code of Arnush [15]. This code yields the plasma resistance R of a coupled helicon-TG wave in an infinite or finite-length cylinder for specified B , $n(r)$, pressure and antenna type. However, B and n are assumed uniform in the axial (z) direction. To simulate injection from a short tube into a large space, a 2 m long cylinder is assumed, and the antenna is placed a small, set distance from one endplate. A typical $n(r)$ profile is assumed.

Since B in the far-field region of a PM is likely to be weak, we take advantage of the density peak found at low B in helicon discharges [16]. This has been explained by constructive reflection from the endplate [17]. The location of this peak depends on the density, plasma radius and endplate conductivity. Since B is fixed while n varies in an experiment, it is convenient to show the peak as a function of n rather than of B . An example of R versus n is shown in figure 8. The density at the peak varies linearly with B , as in simple helicon theory.

The value of R is related to the RF power absorption P_{in} , and hence to n , as follows. If P_{rf} is the power out of the generator and R_c is the circuit resistance, P_{in} is given by

$$P_{\text{in}} = P_{\text{rf}} \frac{R_p}{R_p + R_c}. \quad (1)$$

If $R_p \ll R_c$, $P_{\text{in}} \propto R_p$, and both stable and unstable intersections with the loss curve can occur [18]. We desire $R_p \gg R_c$, so that $P_{\text{in}} \approx P_{\text{rf}}$. Power balance determines n . Consider a discharge 5 cm in diameter and 5 cm long, with surface area $S \sim 122 \text{ cm}^2$. At low pressure the ion flux to the walls is $\Gamma_i \approx \frac{1}{2} n c_s$, where the acoustic velocity c_s is $1.7 \times 10^5 \text{ cm s}^{-1}$ at $K T_e = 3 \text{ eV}$ in argon. The particle loss rate is then

$$-dN/dt = \frac{1}{2} S n c_s = 1.0 \times 10^7 n \text{ s}^{-1}. \quad (2)$$

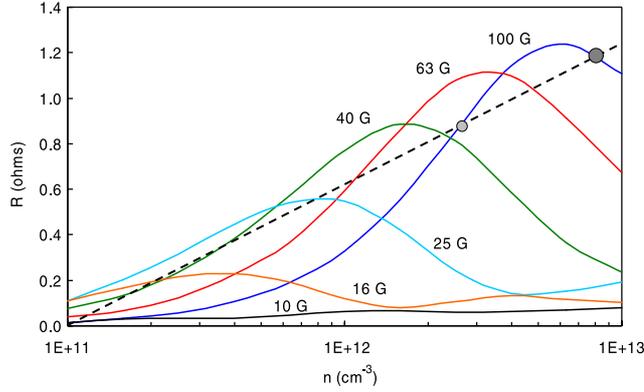


Figure 8. Plasma resistance versus density at various B -fields at 1 mTorr for a 5 cm diameter tube, 5 cm long, with a conducting endplate. The dashed line represents losses proportional to n , intersecting the 100 G curve at two points, the leftmost one being unstable.

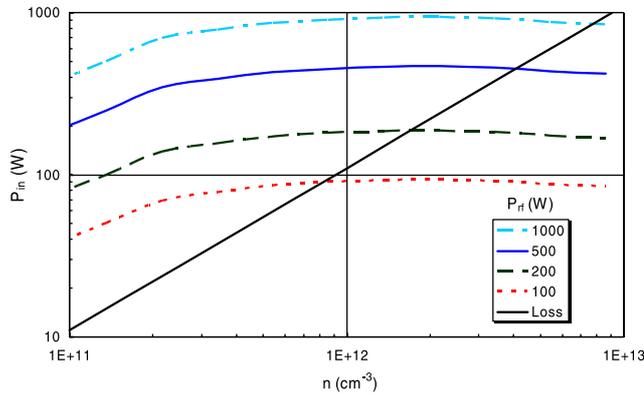


Figure 9. Absorbed power for various applied powers versus density. The diagonal line is the computed energy loss rate.

The energy loss is the sum of three terms [19, 20]:

$$W = E_c + W_i + W_e, \quad (3)$$

where W_i and W_e are the ion and electron energies carried out and E_c is the energy lost to radiation in each ionization, as computed by Vahedi [21]. Each escaping ion loses its energy gained in the presheath ($\frac{1}{2}K T_e$) and that gained in the wall sheath ($\sim 5K T_e$), a total of $W_i \sim 5.5K T_e$. The accompanying electron loses $2K T_e$ [19, 20]. Equations (2) and (3) then yield

$$P_{\text{out}} \approx 1.1 \times 10^{-10} n W. \quad (4)$$

This line is shown in figure 9 together with P_{in} computed from equation (1) and the 100 G curve of figure 8, assuming $R_c = 0.1 \Omega$. We see that P_{in} is close to P_{rf} , and unstable intersections have been eliminated as long as R_p/R_c is greater than about 10.

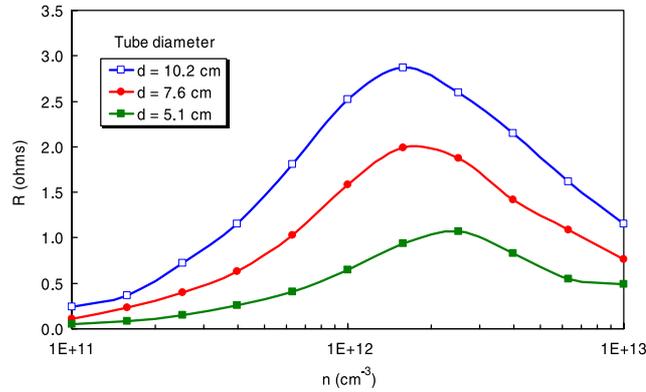


Figure 10. R versus peak density n for various diameters d at 13.56 MHz and 3 mTorr. The antenna is a simple loop located 5 cm from a conducting endplate. Parabolic $n(r)$ profile; $KT_e = 2.5$ eV.

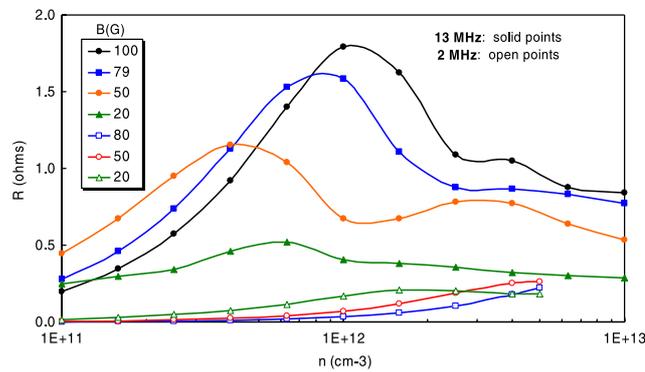


Figure 11. R versus n at various B -fields for a 7.6 cm diameter tube at 2 and 13.56 MHz.

4.2. Tube design

HELIC calculations of loading resistance versus tube diameter d are shown in figure 10. It appears that larger diameters are better, but this is illusory. First, the large R can be achieved only by increasing the power more than the volume ratio. More importantly, the larger antenna has such a high inductance even for a single turn that very large capacitors are required in the matching circuit. With small d , the inductance can be varied to suit the matching network by varying the number of turns in the $m = 0$ antenna. Experiments with a 15 cm diameter tube at 500 W produced only a faint glow under the antenna, with densities at Z1 in the mid- 10^{10} cm^{-3} range. Similarly, computations varying the distance between the antenna and the endplate were deceptive. Density was always higher when the antenna is placed near the exit aperture.

Frequency dependence is shown in figure 11. For the range of n and B being considered, the higher frequency gives much larger loading. The harmonic at 27.12 MHz is advantageous only at much higher B and n . Figure 12 shows the effect of endplate material. Conducting endplates are generally better for our range of parameters. As a result of these studies, the tube design of figure 13 was adopted. It is very similar to the intuitive design of figure 6.

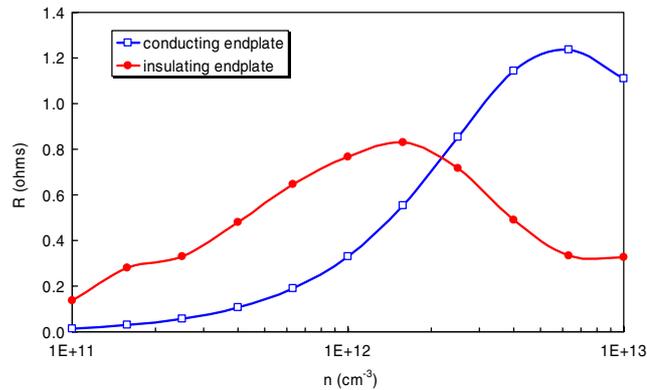


Figure 12. Comparison of endplates for a 5 cm diameter tube at 100 G.

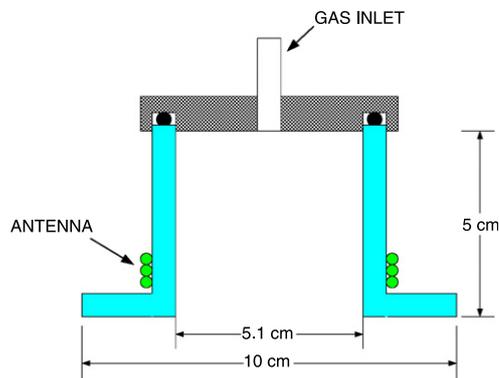


Figure 13. Optimized design of discharge tube.

4.3. Magnet design

PMs can be made of ceramic, Alnico, SmCo or NdFeB (the strongest). Ceramic magnets are cheapest, but when the tooling cost is included, Nd magnets are actually cheaper. These have an internal field of 12 kG and therefore need not be thick. They can also be small to go with the 5 cm diameter tubes. We therefore decided on Nd magnets of 7.6 cm ID and 12.7 cm OD, 2.54 cm thick. Their field lines are shown in figure 14, together with positions of the discharge tube to adjust field strength and uniformity. Figure 15 plots B versus r at various distances z below the magnet. At the indicated position of the tube, the field is very uniform radially but varies from 175 to 75 G from top to bottom.

The magnets are so strong that one can jump 30 cm upwards to attach to another. At a separation of 1 cm, the attractive force is of order 50 kg weight.

5. An array of optimized sources

The spacing between tubes was determined by superposing $n(r)$ s from neighbouring tubes to obtain the total density. The measured $n(r)$ from a single tube and its magnet is shown in figure 16; it cannot be calculated because the diffusion mechanism in the nonuniform field is

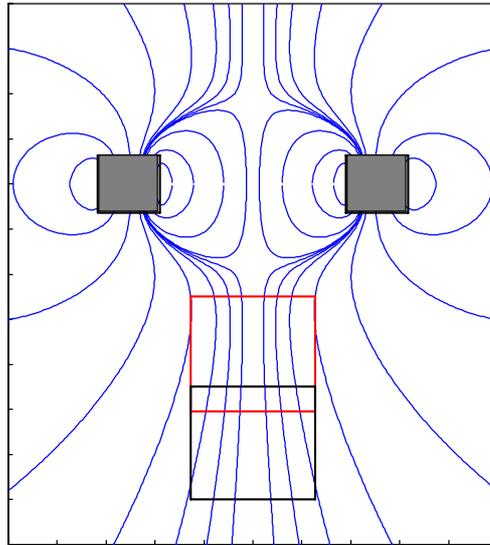


Figure 14. Field pattern of Nd magnets. The rectangles below them represent possible positions of the discharge tube.

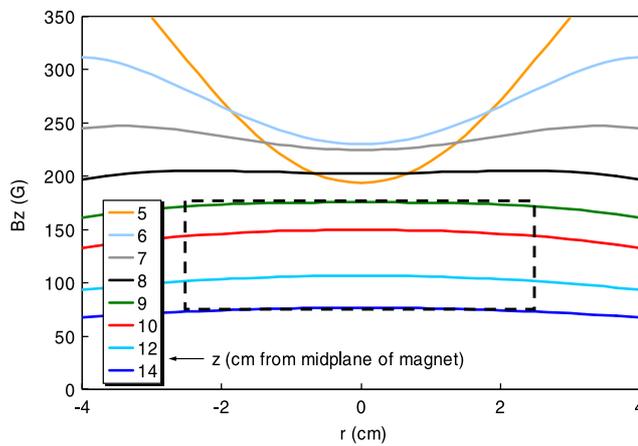


Figure 15. B_z versus r at various z below the midplane of the magnet. The curves are in the same order as the in the legend. The dashed rectangle is the possible position of a 5 cm diameter \times 5 cm long discharge.

unknown. The disturbance from neighbouring magnets is minimal. The density at substrate level, $Z_2 = 17.6$ cm below the tubes, is calculated from a fit to the lower curves in figure 16. The calculated ripple between tubes is shown in figure 17 versus the distance L between tubes. It is seen that $L = 17.5$ cm gives a ripple of $\pm 2\%$. A test facility was built to accommodate two rows of sources separated by about 15 cm. For application to web-coaters, in which the moving substrate sees only the average density from the two rows, every other source can be omitted, creating a staggered array.

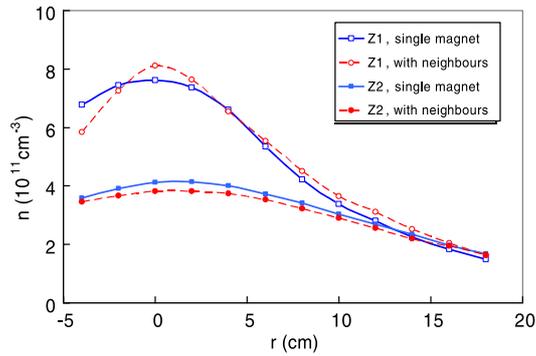


Figure 16. Density profiles (—) for a single tube and magnet at probe positions Z1 and Z2. The dashed curves (- - -) are for a single tube in the presence of the other magnets (500 W, 15 mTorr).

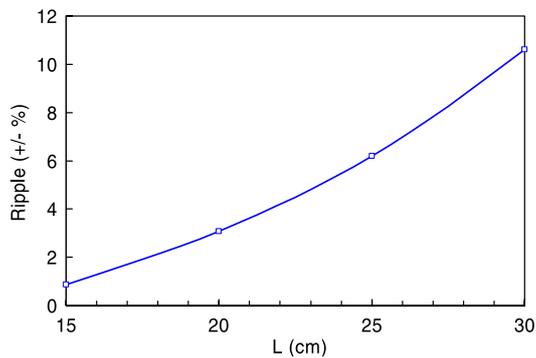


Figure 17. Computed ripple between tubes at Z2 versus tube separation L .

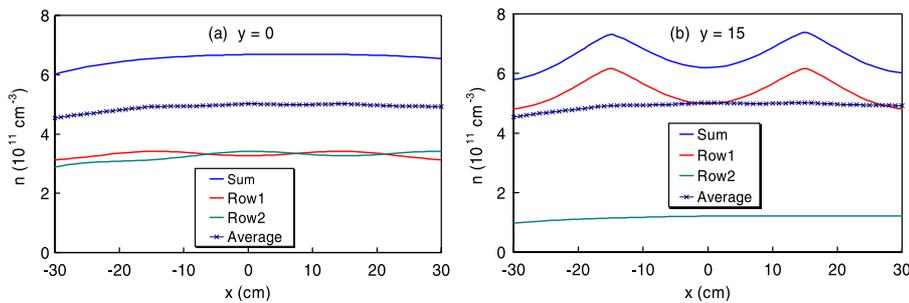


Figure 18. Predicted density distribution $n(x)$ at $y = 0$ and 15 cm for two staggered rows, 30 cm apart, each comprising two tubes separated by 30 cm. The bottom curves give the contribution from each row separately, and the top curve is the sum. The thick line, the same in (a) and (b), is the density averaged over all y . The roll-off at large x would not exist for a full row of tubes.

For this two-row staggered configuration, the predicted density $n(x)$ is in figure 18 for two values of y , the distance from the midplane between the rows. At $y = 0$ the ripple is very small, each row contributing equally to n . At $y = 15$, directly beneath one row, the ripple is large, and the other row contributes little. In a web-coater, as the substrate moving in the y

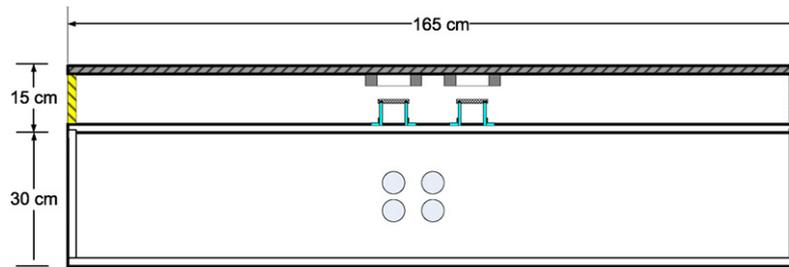


Figure 19. Side view of test device. The lower probe ports shown are at $Z_2 = 17.6$ cm below the tubes.

direction passes under both rows, it experiences an average density shown by the thick line in both graphs, and this is exceedingly uniform.

The great advantage in compactness of this system can be seen in figure 19, which shows two of the tubes in position under the magnets held by an iron plate. The B -field is controlled by the length of the four supports at the corners. Strong magnets cannot easily be moved, so in the experimental stage non-magnetic supports are used.

6. Conclusion

The use of the remote field of annular PMs enables uniform coverage of large substrates with high-density plasma in a vertically compact source. The degree of uniformity is computed from single-tube measurements but has not yet been measured. This device [22] can be used in web-coaters, for etching of flat panel displays and for deposition of optical coatings. This work was supported by the National Science Foundation, Grant No DMI-0115570.

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