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A MODEL FOR PARTICLE CONFINEMENT IN A TOROIDAL PLASMA SUBJECT TO STRONG RADIAL ELECTRIC FIELDS

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ABSTRACT

The approach adopted in the NASA Lewis Bumpy Torus experiment is to confine and heat a toroidal plasma by the simultaneous application of strong d.c. magnetic fields and electric fields. Strong radial electric fields (about 1 Kilovolt per centimeter) are imposed by biasing the plasma with up to 12 negative electrode rings which surround its minor circumference. The plasma containment is consistent with a balance of two processes: a radial infusion of ions in those sectors not containing electrode rings, resulting from the radially inward electric fields; and ion losses to the electrode rings, each of which acts as a sink and draws ions out the the plasma in the manner of a Langmuir probe in the ion saturation regime. The highest density on axis which has been observed so far in this steady-state plasma is 6.2×10^{12} particles per cubic centimeter, for which the particle containment time is 2.5 milliseconds. The deuterium ion kinetic temperature for these conditions was in the range of 360 to 520 eV.

INTRODUCTION

Pure magnetic containment, in which a plasma is contained solely by strong magnetic fields, has been the dominant approach to plasma confinement since the beginning of controlled fusion research. The principle of enhancing magnetic containment by applying strong d. c. electric fields seems to have been first applied to an open-ended mangetic geometry by George in 1961 (ref. 1). Several investigators have since applied strong electric fields to plasma in cusp (refs. 2-4) or mirror (refs. 5,6) configurations in an effort to enhance the otherwise poor containment of these open-ended geometries. In other experiments, (refs. 7, 8) strong radial electric fields have been applied to a plasma in mirror geometries for the primary purpose of heating the ions to high energies.

Externally applied electric fields have not thus far played a role in toroidal plasma confinement. It was suggested by Roth in 1967 (ref.9) that a toroidal plasma could be heated and confined in a modified Penning discharge configuration. Theoretical papers by Kovrizhnykh (refs. 10,11) and Stix (refs. 12,13) have examined the confinement implications of ambipolar electric fields in toroidal geometries. There does not appear to be relevant theoretical literature on the subject of transport in the presence of imposed, nonambipolar electric fields acting on a toroidal plasma.

The approach taken in the NASA Lewis Bumpy Torus experiment is to confine and heat a toroidal plasma by the simultaneous application of strong magnetic and electric fields. The toroidal ring of plasma is biased to high negative potentials by applying negative d.c. voltage to 12 or fewer midplane electrode rings which encircle the minor circumference of the plasma. The resulting electric fields point radially inward from the grounded walls of the coils to the plasma, in the manner illustrated schematically in Fig. 1. The radial electric fields acting on the plasma have been observed to exceed values of 1 kV/cm (ref. 15).

Previous investigations of the Bumpy Torus plasma (refs. 14-17) have shown that, in common with Penning discharges and magnetron-like devices, the plasma forms rotating spokes which gyrate around the minor circumference of the plasma with velocities comparable to the E/B drift velocity. The ions in the rotating spokes form an energy reservoir which is thermalized to the high kinetic temperatures observed. Ion kinetic temperatures up to 2.5 keV have been measured in deuterium. The thermal velocity of these hot ions is proportional to the spoke rotational velocity (ref. 15).

Previous work reported in ref. 15 has shown that the ion population can be heated equally well by positive or negative electrode polarities. However, investigations reported in refs. 16 and 18 indicated that the polarity of the electric field has a profound effect on the density and particle containment time. Both are substantially greater when the electric fields point radially into the plasma than they are when the electric fields point outward and push ions out of the plasma.

The greatly enhanced densities and containment times which result from negative bias of the plasma and radially inward electric fields strongly suggest that further investigation of a positive bias on the toroidal plasma is not likely to be as productive as optimization of the negatively biased plasma with the resulting radially inward electric fields.

The physical picture of the electric field distribution which emerged from the investigations described in refs. 14 - 18 is summarized in schematic form in figure 1. The electrode rings at the magnetic field midplanes bias the entire plasma to potentials approaching those of the midplane electrode rings. The electric field is strongest in the annular region between the grounded inner bores of the superconducting magnets and the plasma.

The best Lawson parameters achieved to date are listed in Table I. Data on the radial profile of plasma number density (ref. 14) indicate that the plasma has a linear radial profile, for which the axial density is twice the average electron number density. The highest ion kinetic temperature ever observed in this deuterium plasma was 2500 eV, although this was measured at densities much lower than those shown in Table I. For these conditions, the electron temperatures were in the range between 2-10 electron volts. The highest electron temperature ever observed, under much lower density conditions, was about 150 eV. The ions in this plasma are approximately a factor of 100 hotter than the electrons, as a result of E/B drift which is the basis for the ion heating, and which tends to put the input power into the heavier species. At the maximum electron density listed above, the ratio of charged to neutral particles in the plasma volume was slightly more than 3 to 1. As has been shown in previous work (refs. 15, 18) the ion heating efficiencies are typically between 20-30% in this plasma have been observed to be as high as 45%. These ion heating efficiencies represent a lower bound on the power into the ion population divided by the total DC power into the plasma.

EXPERIMENTAL APPARATUS

The Bumpy Torus magnet facility is described elsewhere (ref. 19-20) and consists of 12 superconducting coils equally spaced around a toroidal volume of 1.52 meters in major diameter. An isometric cutaway drawing of the Bumpy Torus facility is shown in Figure 2. Each coil has a minor diameter of 19 cm, and the maximum magnetic field on the magnetic axis during the experiments reported in this paper was 2.4 tesla. The minimum magnetic field on the magnetic axis between coils is 40% of the maximum magnetic field. The coil array is located in a single vacuum tank 2.6 meters in major diameter.

The plasma number density was measured with a polarization diplexing microwave interferometer (ref. 18) which was located halfway between the minimum and maximum magnetic field points in one sector of the bumpy torus. The microwave interferometer measured the time and space averaged plasma number density across a plasma diameter in the equatorial plane of the torus.

MEASUREMENT OF PARTICLE CONTAINMENT TIME

In this steady-state plasma, it is easy to obtain the particle containment time provided that two conditions are met: 1) that there are no parasitic currents flowing outside the plasma volume which might short-circuit the power supply to ground; and 2) that no ambipolar currents flow to either electrode. The latter condition requires that the cathode not emit electrons to the plasma, and that all ion-electron pairs be created by volume ionization within the bulk of the plasma. A series of investigations were carried out which showed that these two conditions are met (ref. 18) and that parasitic or ambipolar currents cannot be contributing more than 1 percent of the current flowing to the power supply.

Since the d.c. current flowing to the power supply is a measure of the charge losses of the plasma, and since the above two conditions require that all ions flow to the cathodes and all electrons flow to the anodes, the power supply current can be written in the form:

$$I_a = \frac{\bar{n}_e\ e\ V_p}{\tau_p} \text{ amps} \quad (1)$$

where $\bar{n}_e$ is the average number density measured by the microwave interferometer, e is the electronic charge, V_p is the plasma volume, (82 liters for the bumpy torus plasma), and τ_p is the particle containment time. Equation 1 can be rearranged to yield

$$\tau_p = \frac{\bar{n}_e\ e\ V_p}{I_a} \text{ sec.} \quad (2)$$

so that a measurement of the average number density and the d.c. current flowing to the power supply yields a measurement of the particle containment time.

THE SINK MODEL OF CONFINEMENT

Recent measurements have shown that the radial transport spectrum is dominated by a large peak in the vicinity of the frequency of the rotating spokes (ref. 21). If the geometric and other variables discussed in ref. 17 are properly optimized, the transport of plasma in sectors not containing electrode rings is radially inward (ref. 21). This inward transport is consistent with the large improvement in containment obtained by electric fields that push the ions radially inward, as reported in refs. 16 and 18. The electron temperatures in this plasma are typically less than 30 eV (ref. 14), and the ion kinetic temperatures are between one and two orders of magnitude higher. The ions are the most mobile species in this plasma, and tend to migrate to the bottom of the toroidal electrostatic potential well whenever they are subject to any stochastic process. This radial infusion of ions is interrupted in those sectors containing negative electrode rings, because, as is illustrated in figure 1, the electric field under the electrode rings is radially outward, and the electrode rings gather ions from the plasma.

A simple physical model appears to explain the confinement of the Bumpy Torus plasma in both qualitative and quantitative terms.

This has been designated the "sink" model of confinement, and is predicated on the experimental observation that the ions are transported radially inward in sectors which do not contain electrode rings, and are lost to the electrode rings as though the individual negative electrode rings were Langmuir probes operating in the ion saturation regime. Five conditions, all of which are supported by experimental data, are incorporated into the sink model. 1) The electrode rings are negatively biased to high potentials, resulting in radially inward electric fields acting between the plasma and the surrounding walls. 2) The ions are the most mobile species in the plasma, and determine the rate of charge transport across the magnetic field to the electrodes. 3) The ions are transported radially inward in sectors which contain no electrode rings. This condition is consistent with direct measurements of the radial transport spectrum reported in ref. 21. 4) Ions are lost to each electrode ring at a rate which yields a particle confinement time of τ_0 milliseconds. 5) All ion loss processes other than withdrawal of ions by the electrode rings are lumped together in an "intrinsic" containment time, τ_{in}.

Since τ_0 is the containment time which would result in withdrawal of ions by a single electrode, the containment time resulting from ion loss to N electrodes is equal to:

$$\tau_e = \frac{\tau_0}{N} \tag{3}$$

thus predicting that the greater the number of electrodes, the shorter the particle containment time because of the greater ion loss. This expression is consistent with the idea that the individual electrode rings are acting as Langmuir probes, since the total particle interception by such probes is directly proportional to the probe area, and to the number of identical electrodes. If one allows the possibility of additonal loss processes, not involving interception of ions by the negative electrodes, the total particle containment time may be written:

$$\frac{1}{\tau_p} \quad \frac{1}{\tau_e} \quad \frac{1}{\tau_{in}} \tag{4}$$

where τ_{in} is the intrinsic containment time due to all other loss processes. Substituting equation 3 into equation 4, the particle containment time may be written:

$$\tau_p = \frac{\tau_o \, \tau_{in}}{\tau_o + N \, \tau_{in}} \tag{5}$$

Equation 5 predicts that the particle containment time will improve if the number of electrodes is reduced, and if one were to entirely avoid interception of ions by the electrodes, N = 0, the particle containment time would equal the intrinsic containment time.

The sink model can also be used to obtain an expression for the plasma number density. Equation 1 can be solved for the average electron number density in the plasma. By substituting equation 5 for the particle containment time one obtains:

$$N_e = \frac{I_a \tau_p}{e V_p} = \frac{I_a \tau_o \tau_{in}}{e V_p (\tau_o + N \tau_{in})} \qquad (6)$$

The average electron number density is directly proportional to the electrode current, and inverscly proportional to the number of electrode rings for those cases in which the interception rate of the electrode rings dominates the intrinsic losses, $\tau_{in} \gg \tau_o$.

EXPERIMENTAL EVIDENCE FOR THE SINK MODEL

A series of measurements were carried out to test the sink model of confinement. These consisted of measurements of the average electron number density as a function of the electrode current, for several arrangements of negatively biased electrode rings. On figures 3 and 4 are shown the particle containment time and average electron number density plotted as functions of electrode current for 12, 6, 4, and 2 electrode rings, respectively. The six electrode rings were located in alternate sectors around the torus; the four electrode rings were arranged in two symmetric pairs in sectors 5 and 6 and 11 and 12; and the two electrode rings were in sectors 5 and 6.

The solid lines in figures 3 and 4 are drawn on the assumption that electrode losses are the sole particle loss mechanism, and that a particle containment time of 4.92 milliseconds would result if the plasma could be generated with a single electrode ring, τ_0 = 4.92 msec. As is evident, the experimental data lie somewhat below the solid line, suggesting that an additional, "intrinsic" loss process occurs in this plasma. The dotted lines on figures 3 and 4 are based on the particle containment time given by equation 5, with N assuming the appropriate number of electrode rings. The best-fitting intrinsic containment time for these data is τ_{in} = 12.4 milliseconds. The experimental data therefore indicate that total particle containment times of at least 12.4 milliseconds should be possible if one could eliminate ion losses to the electrodes.

The data shown on figures 3 and 4 were taken with the electrode rings 93 millimeters from a fiducial reference on the superconducting magnet spacer-bars. Some data that were taken at a position 1.5 cm radially outward from the data in figures 3 and 4 are shown in figures 5 and 6 for N equal to 12, 9, 6, 4, 3, and 2 electrode rings. The array of 9 electrode rings consisted of three triads of electrode rings with a missing electrode ring in sectors 120^{o} apart around the torus. The three electrode configuration consisted of electrodes 5, 6, and 12. It is interesting that this different radial position resulted in the same value of τ_0, 4.92 msec, as was observed for the data in figures 3 and 4. The containment time that would result from losses to the electrodes only is predicted by equation 3, and is indicated by the arrows pointing to the ordinate axis. The experimental data lie somewhat further below these predictions than was the case previously, implying a shorter intrinsic containment time. The dotted lines are the total particle containment time, given by equation 5, for τ_{in} = 4.92 msec. By a numerical coincidence, the amount of loss to an individual electrode ring happens to equal the losses due to all other causes.

The data on figures 5 and 6 are practically straight lines out to ten amperes. It may be possible to achieve significantly higher plasma densities by boosting the amount of current flowing to the electrode rings. The vertical magnetic field is generated with two coils wrapped around the vacuum tank, and had to be altered by a few gauss as one increased the electrode current from 1 to 10 amperes. When this vertical magnetic field was correctly optimized, it reached the same highest possible value of containment time, independent of the electrode current.

On Figure 7 is shown the average electron number density plotted as a function of electrode voltage for the same subset of data used in figures 5 and 6. The electrode voltages corresponding to larger numbers of electrode rings are extremely low-electrode voltages of only 300-400 volts supplied densities approaching 10^{12} particles/cm^3. However, when the number of electrodes was reduced to four or below, the effective plasma impedance went up. With N = 2 electrodes, the average electrode voltage was about 3 kV or higher. The electrode voltage is an important factor because previous work (ref. 17) has shown that the ion kinetic temperature scales as the .7 power of the electrode voltage. These previously derived scaling laws indicate that the range of ion kinetic temperatures corresponding to the measurements taken for N = 2 electrode rings is 360 $\leq T_i \leq$ 520 eV. The observed rate of steady-state neutron emission from a deuterium plasma is consistent with ion kinetic temperatures at the high end of this range.

DISCUSSION AND CONCLUSIONS

The sink model of confinement seems to give a good fit to the experimental data on plasma containment in the NASA Lewis Bumpy Torus plasma. The processes underlying this model are fundamentally different from those which exist in pure magnetic containment devices. The latter are restricted to outward transport of the plasma only, at rates that are determined by some modification of classical diffusion. The use of strong radial electric fields in the Bumpy Torus plasma admits the possibility of radially inward particle transport, which has been observed by direct experimental measurement (ref. 21). The experimental data shown on figures 3-6 is consistent with the assumption that the dominant loss process in this plasma is withdrawal of ions by the negatively biased electrode rings. The particle containment time decreases as more electrodes are applied to withdraw ions from the plasma. It is also clear that there is an intrinsic loss process, not related to the electrode rings, which results in confinement times up to 12.4 msec. It has not thus far been possible to optimize the intrinsic containment time to obtain durations longer than 12.4 msec., because it represents a small difference of large numbers as long as the electrodes dominate plasma losses.

Thus far, a minimum of two negative electrode rings has been required to initiate the plasma. The particle containment time with two negative electrode rings in place has been observed to be as high as 2.8 msec. If the plasma could be initiated with a single negative electrode, this would be expected to improve to about 5 msec, based on the sink model. If the electrode geometry could be arranged so that no significant interception of the plasma occurred, particle containment times more than 10 msec should be possible.

The future direction of research on the Lewis Bumpy Torus plasma is clear from the considerations discussed above. The electrode rings as currently used serve two functions: They bias the plasma to high potentials, resulting in heating and radially inward transport of the ions, and they also intercept the ions in the manner of a biased Langmuir probe. If these two functions could be decoupled so the plasma could be biased while minimizing ion interception, very long containment times should result.

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Table I	Data from the Bumpy Torus plasma
Figure 1	A schematic of the electric field structure with negative electrode polarities and a negatively biased toroidal plasma.
Figure 2	An isometric cutaway drawing of the NASA Lewis Bumpy Torus superconducting magnet facility.
Figure 3	The particle containment time plotted as a function of electrode current for N = 2, 4, 6, and 12 electrode rings and a radial electrode position R = ΔR = 93 mm.
Figure 4	Average electron number density as a function of electrode current for N = 2,4,6 and 12 electrode rings and a radial electrode position of ΔR = 93 mm.
Figure 5	Particle containment time as a function of electrode current for N = 2, 3, 4, 6, 9, and 12 electrode rings and for a radial electrode position of ΔR = 108 mm.
Figure 6	The average electron number density as a function of electrode current for N = 2,3,4,6,9 and 12 electrode rings and for a radial electrode position of ΔR = 108 mm.
Figure 7	The average electron number density as a function of the electrode voltage for N = 2,3,4,6,9 and 12 electrode rings and for a radial electrode position of ΔR = 108 mm.

TABLE I

BUMPY TORUS DATA

HIGHEST PLASMA DENSITIES:

$\bar{N}_E = 3.1\times10^{12}/\text{cm}^3$

$\tau_P = 2.52$ M SEC

$N_{E_{MAX}} = 6.2\times10^{12}/\text{cm}^3$

HIGHEST PARTICLE CONTAINMENT TIME:

$\tau_P = 2.78$ M SEC AT $N_{E_{MAX}} = 5.8\times10^{12}/\text{cm}^3$

HIGHEST SIMULTANEOUS $N_{E_{MAX}}\tau_P$:

$N_{E_{MAX}}\tau_P = 1.6\times10^{10}$ SEC/CM^3

ION KINETIC TEMPERATURES:

FOR ABOVE CONDITIONS, $360 \lesssim T_I \leq 520$ eV

HIGHEST EVER, $T_I = 2500$ eV

ELECTRON KINETIC TEMPERATURES:

FOR ABOVE CONDITIONS, $2 \lesssim T_E \lesssim 10$ eV

HIGHEST EVER OBSERVED, $T_E \approx 150$ eV

ELECTRIC FIELD STRUCTURE IN BUMPY TORUS
WITH NEGATIVE MIDPLANE ELECTRODES

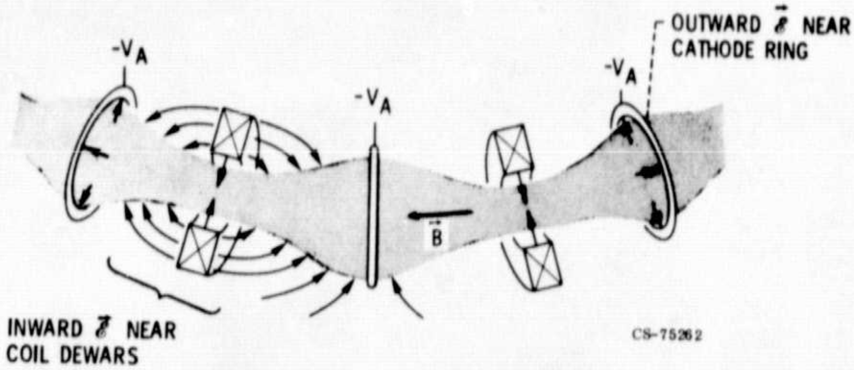

Figure 1.

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BUMPY TORUS SUPERCONDUCTING MAGNET FACILITY

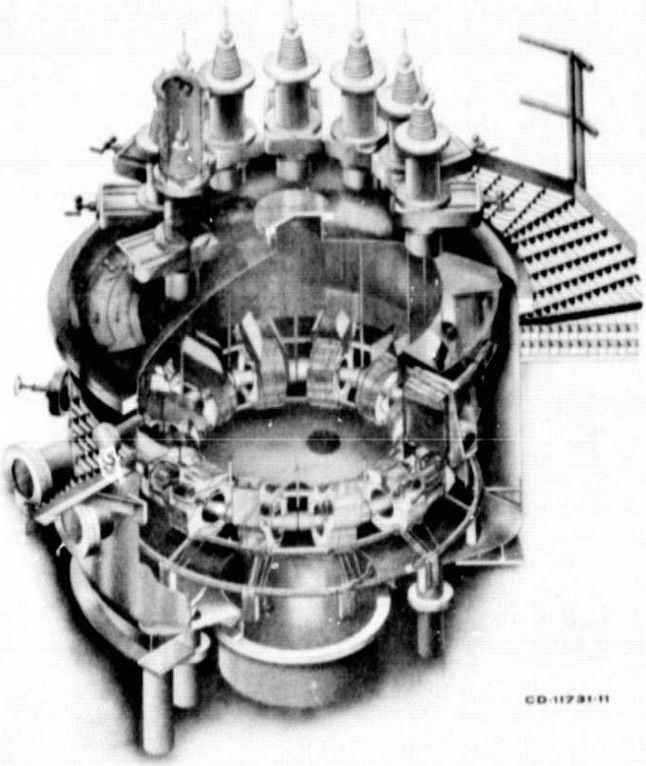

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Figure 2.

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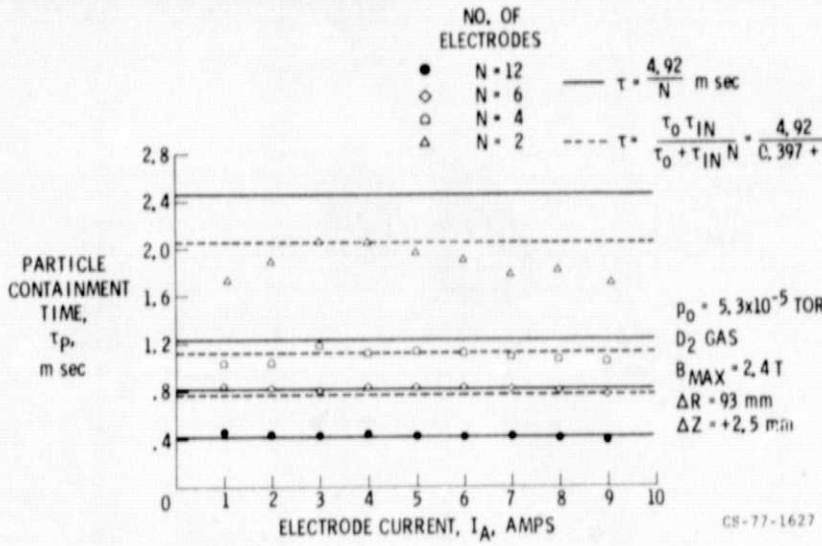

Figure 3.

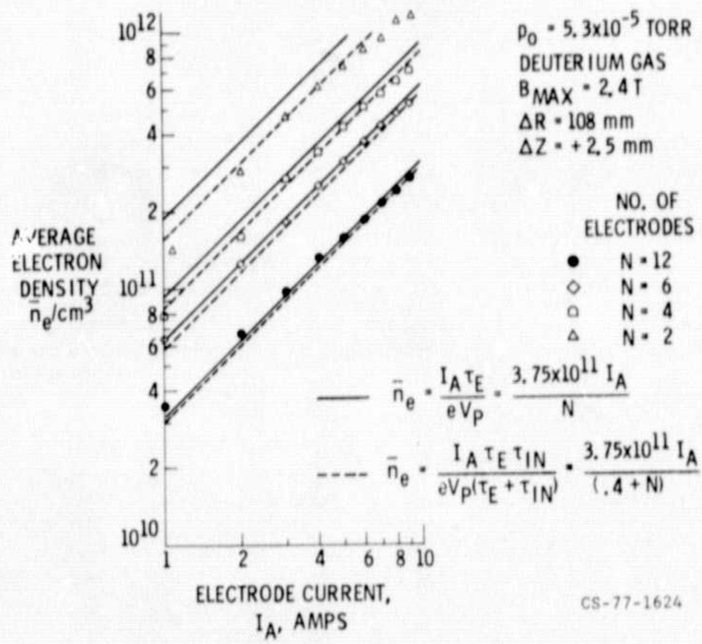

Figure 4.

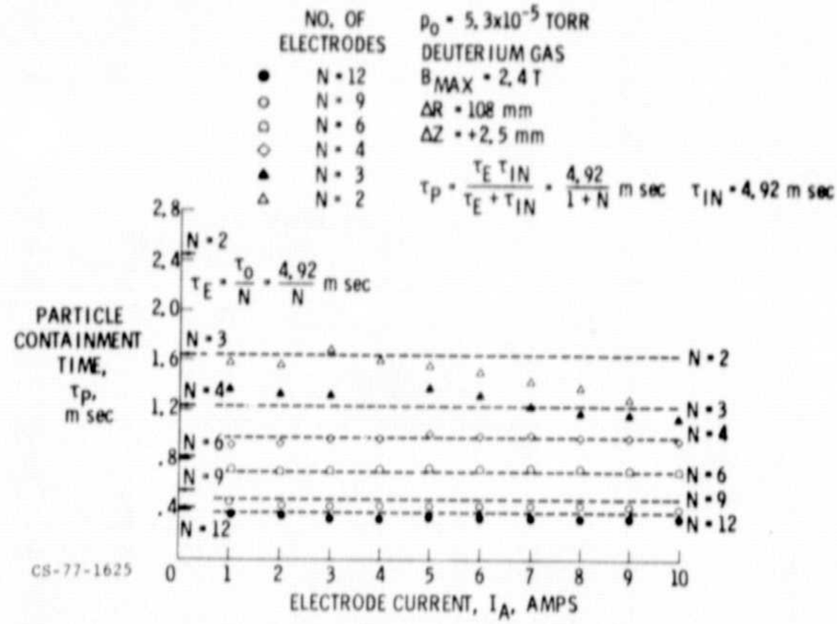

Figure 5.

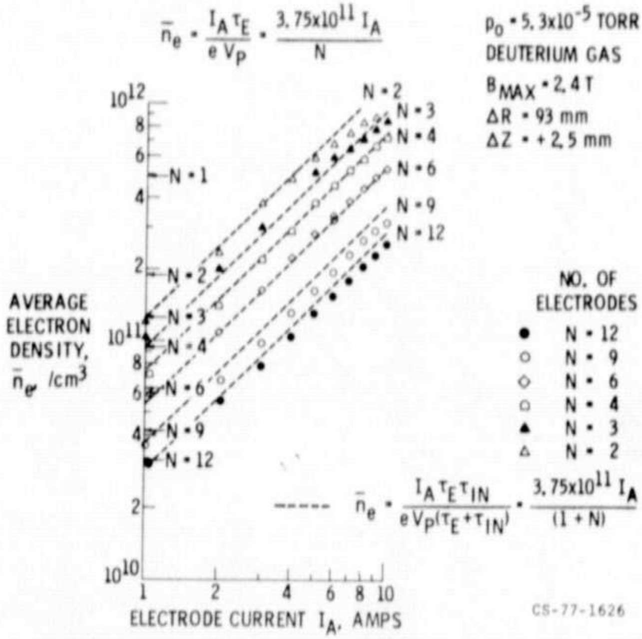

Figure 6.

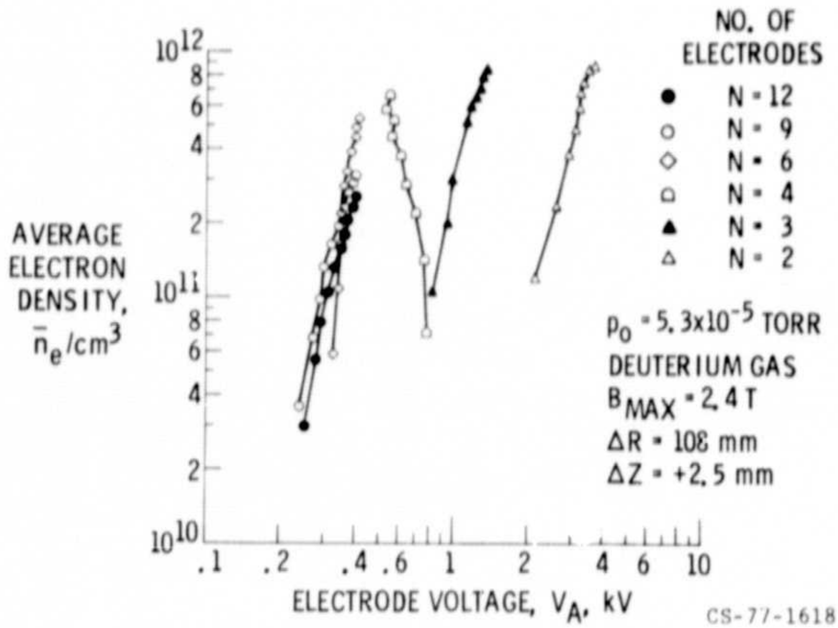

Figure 7.

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