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ABSTRACT

Experimental observations have been made during steady-state operation of the NASA Lewis Bumpy Torus experiment at input powers up to 150 kilowatts in deuterium and helium gas. A steady-state ion heating method utilizes a Modified Penning discharge operated in a bumpy torus confinement geometry. The bumpy torus plasma is acted upon by a combination of strong electric and magnetic fields. In a deuterium plasma, electron temperatures from 14 to 140 electron volts and ion kinetic temperatures from 160 to 1785 electron volts were observed. At least two distinct operating regimes exist, each of which is associated with a characteristic range of background gas pressure and electron temperature. Experimental data show that the average ion residence time (ionization time) in the plasma is virtually independent of the magnetic field strength. DC current-voltage curves were taken of the plasma in the "standard" configuration in which all 12 anode rings were at high voltage, and other symmetric configurations in which the toroidal plasma was generated by applying positive potentials to 6, 3, and a single anode ring.

INTRODUCTION

The plasma in the NASA Lewis Bumpy Torus facility is generated by a modified Penning discharge operated in conjunction with the bumpy torus magnetic field geometry. This results in a <u>combination</u> of electric <u>and</u> magnetic fields acting on the plasma which are responsible for heating the ions to high kinetic temperatures. The electric fields are applied to the plasma in such a way that they may also have a beneficial effect on stability and confinement. The entire experiment, including the confining magnetic field and the high positive potentials which are responsible for heating the plasma, are operated in the steady state.

The basic geometry of the magnetic field is shown schematically in figure 1. The superconducting NASA Lewis Bumpy Torus magnet facility consists of 12 coils spaced in a symmetric toroidal array 1.52 meters in major diameter (refs. 1, 2). The inner bores of the coils are 19 centimeters in diameter. Each of the 12 superconducting coils can generate 3 T on its axis, and the ratio of minimum to maximum field on the magnetic axis is $2\frac{1}{2}$:1. A photograph of the superconducting magnet facility with the lid removed from the vacuum tank is shown in figure 2. This toroidal array of 12 superconducting coils is located in a vacuum tank $2\frac{1}{2}$ meters in diameter. A photograph of the bumpy torus plasma is shown in figure 3. The vertical element in the center is a midplane electrode ring 19 cm in inside diameter which is maintained at high DC potentials up to 50 kilovolts. The plasma follows the magnetic field lines and necks down into the throats of the two adjacent magnetic field coils. Visible to the left of center in the background is the anode ring and the plasma at the opposite diameter of the toroidal array. The ions and electrons are heated by ExB drift in the strong crossed electric and magnetic fields which exist between the midplane electrode ring and the plasma; and also between the plasma and the grounded coils and walls of the vacuum tank. The plasma tends to float at a high positive potential, when a positive voltage is applied to the circular midplane electrode.

The plasma can be operated in the steady state at power input levels up to 60 kilowatts, and power levels as high as 150 kilowatts have been maintained for periods of approximately 30 seconds. The power inputs have been limited only by heating of uncooled sheet metal surrounding the plasma. In deuterium gas, ion kinetic temperatures have ranged from 160 to 1785 eV, and electron temperatures have ranged from 14 to 140 eV. The DC input power is preferentially dumped into the ion population by the Penning discharge (refs. 3 to 6). Estimated number densities on the axis of a helium plasma were as high as $10^{11}/cm^3$ at an average ion residence time (ionization time) of 0.5 milliseconds.

An equivalent circuit of the bumpy torus plasma is illustrated on figure 4. The plasma is confined on magnetic field lines which close on themselves around the torus and is surrounded by a circular midplane electrode between the coils at 12 or fewer of the magnetic field midplanes. When the midplane electrode is operated as an anode and positive potentials are applied, electrons must flow from the plasma to the anode ring, while ions must flow from the plasma to the grounded magnet dewars. The anode sheath between the anode ring and the plasma has an effective resistance R_a, and the cathode between the plasma and the grounded dewars has an equivalent resistance of R_c. The potential assumed by the plasma depends on the relative value of these two equivalent resistances. This is determined in turn by the relative mobility of ions and electrons across the cathode and anode sheaths, respectively, as well as the sheath geometry and other plasma properties.

It was originally anticipated that the ions would be the most mobile species in the strong magnetic fields applied, and that R_c would be considerably less than the resistance of the anode sheath R_a. In fact, this proved not to be the case. The processes which occur in the two sheaths are such that the value of R_c is significantly greater than the value of the anode sheath resistance, and as a result the plasma tends to assume a positive potential close to that of the circular anode rings in the midplane. With the midplane electrode operated as an anode, the electric fields in the anode sheath point radially inward and point radially outward between the plasma and the grounded superconducting magnet dewars. This situation is reversed when the midplane electrode is operated with a negative potential.

PLASMA CONFINEMENT IN THE BUMPY TORUS

The operating regime of the plasma was mapped out on a series of current voltage curves shown in figures 5, 6, and 7. On figure 5 are shown the current voltage curves for deuterium gas at a maximum magnetic field of 2.4 T and eight different background pressures of deuterium gas. The anode currents ranged from 1 mA to 4 A, and the voltages ranged from $1\frac{1}{2}$ kV to 50 kV of positive potential on the anode ring. The plasma operation is characterized by at least three distinct regimes of operation. A so-called "high pressure mode" at the higher neutral gas pressures is described by the curves in the upper left of figure 5. The "low pressure mode" is represented by the curves in the lower right of figure 5. The low pressure mode data is further separated by a change in slope at approximately 10 kV, which appears to be associated with a transition from m = -1 to an m = -2 mode in the ion spoke rotation (ref. 8). In the high pressure mode, the current is approximately proportional to the cube of the anode voltage until a critical current and voltage are reached at which the discharge spontaneously changes from one mode to another. Current-voltage curves were taken at lower magnetic fields. Data for 1.43 T are shown in figure 6 and for 0.48 T in figure 7. The current-voltage curves at the lower magnetic fields are similar to that at 2.4 T, except that the originally sharp transition from the high to the low pressure mode becomes washed out as the magnetic field decreases, and at 0.48 T the mode structure is virtually nonexistant.

The surprising feature about the current-voltage curves shown in figures 5, 6, and 7 is that they are very little displaced as the magnetic field varies over a factor of 5. If the processes in the anode or cathode sheath were controlled by classical diffusion, one might expect the current at a fixed anode voltage to vary inversely as the square of the magnetic field; and if Bohm diffusion were operating, one might expect the current to vary inversely as the magnetic field. In fact, the currents are virtually independent of magnetic field over about a factor of 5 variation in the magnetic field strength. This result indicates that in the bumpy torus plasma, the radial transport processes which determine the anode current are relatively independent of magnetic field.

The same point can be made from spectroscopic data in deuterium gas shown in figure 8. The average ion residence time or ionization time is the time required to reproduce the ions in this steady-state discharge and is calculated from the electron temperature and the neutral number density. Plotted in figure 8 is the average ion residence time as a function of magnetic field over more than a factor of 10 variation in the latter quantity. Shown are data for two pressures at each magnetic field strength; one in the low pressure mode of operation and one in the high pressure mode of operation. The average ion residence time is independent of magnetic field strength in the low pressure mode and is very weakly dependent, if at all, on the magnetic field strength in the high pressure mode. One might expect a factor of 100 or a factor of ten variation in the average ion residence time if classical or Bohm diffusion processes were important in the discharge.

OPERATING REGIMES OF THE BUMPY TORUS PLASMA

An attempt was made to determine the physical processes and parameters which characterize the operating regimes of the bumpy torus plasma. In figure 9 are shown the current-voltage curves for helium gas. Comparison of this current-voltage curve with that for deuterium in figure 5 shows that there is relatively little qualitative or quantitative difference in the operating regimes of these two gases. Both of them display a high and a low pressure mode, and the current-voltage curves have the same characteristic slopes in analogous regions of the current-voltage diagram. The similarity of the current-voltage curves for these two gases suggests that the high and low pressure modes of operation do not occur because of metastable production or as a result of processes associated with a diatomic or monatomic molecular structure.

It was thought possible that charge-exchange processes might play a role in determining the operating regime in which the plasma found itself. In figure 10 is shown a plot of experimentally measured ion temperature versus electron temperature in deuterium gas. This plane is divided by a curved line which is obtained by setting the charge-exchange time of D^+ on D_2 equal to the ion residence time in the plasma. In deuterium gas, all of the data were taken in the region in which the charge-exchange time was longer than the average ion residence time. The deuterium ions have a higher probability of being lost from the plasma than they have of undergoing a charge exchange. Figure 11 shows similar data plotted for helium gas. In helium, the data lie in the region in which the average ion residence time is longer than the charge-exchange time. In helium gas, a helium ion will charge exchange on the average long before it is lost to the walls. The fact that in helium charge-exchange processes dominate, while in deuterium they do not also tends to rule out charge exchange as a cause of the similar high and low pressure mode behavior observed in the two plasmas.

Two of the parameters which seem to characterize the high and low pressure modes of operation were the background neutral gas pressure and the electron temperature. On figure 12 are shown data for the two modes of operation in deuterium gas plotted with gas pressure as a function of electron temperature. The high pressure mode of operation existed only above a pressure of approximately 2.5×10^{-5} torr of deuterium, and the two modes of operation appeared to be separated by an electron temperature of approximately 35 eV. The high pressure mode of operation dominates below an electron temperature of 35 eV, and the low pressure mode dominates above that temperature. The low pressure mode, however, could occur at almost any pressure at which data were taken. Similar data are shown on figure 13 for helium gas. The high and low pressure modes of operation are distinguished by an electron temperature of about 35 eV and, in the case of the high pressure mode, by a minimum pressure below which that mode is not observed.

EFFECT OF THE NUMBER OF ANODE RINGS ON PLASMA CHARACTERISTICS

The toroidal plasma was generated by applying a positive potential to all 12 anode rings, then only to the 6 even-numbered anode rings, and then to 3 anode rings located 120° apart, and finally to a single anode ring. The anode rings not used were retracted from the discharge volume. The current-voltage curves for these cases in deuterium gas are shown in figures 14(a) and (b) for a single pressure in each mode and with the number of anode rings as a parameter. In general, the anode current tends to increase as the number of anode rings decreases until the case of a single anode ring is reached. Figures 15(a) and (b) show similar data for helium gas, and the same general trend applies.

It was found through spectroscopic measurements that the average particle residence time and number density both tended to increase as the number of anode rings decreased from 12 down to 3. These results are being reported by Richardson (ref. 7). In figure 16 is shown the relative electron number density on the axis as a function of the number of anode rings in the high and low power mode of operation. As the number of anode rings is reduced from 12 to 3, the number density increases by approximately an order of magnitude in the high pressure mode, and by a factor of three in the low pressure mode. The density resulting from operation with a single anode ring depended on the particular anode ring to which the voltage was applied. This may result from problems of alignment of the anode rings with respect to the magnetic axis.

CONCLUSIONS

It has been found that the containment of the plasma in the NASA Lewis Bumpy Torus is virtually independent of magnetic field when a positive potential is applied to the midplane anode rings. The average particle residence times and the current-voltage curves which characterize the plasma operating regimes are relatively insensitive to magnetic field strength over a factor of at least 5.

The NASA Lewis Bumpy Torus plasma operates in a high and low pressure mode of operation. These modes of operation do not appear to be significantly affected by the type of gas used, and the mode transitions do not appear to be influenced by charge-exchange processes, metastable ion formation, or processes depending on whether the gas is monatomic or diatomic. The parameters which characterize the modes of operation are electron temperature, with lower electron temperatures characterizing the high pressure mode, and higher electron temperatures characterizing the low pressure mode; and background neutral gas pressure, the high pressure mode of operation not being observed below a certain threshold of pressure.

The reduction of the number of anode rings used to generate the plasma seems to have a beneficial effect on the plasma number density and average ion residence time. Further investigation is required to optimize the alignment of the anode rings and the number of anode rings which maximize the plasma density and containment time for various operating conditions.

FIGURE CAPTIONS

1. Schematic drawing of the bumpy torus magnetic confinement geometry.

2. Photograph of the superconducting NASA Lewis Bumpy Torus magnet facility with lid removed from the vacuum tank.

3. Photograph of the bumpy torus plasma taken on the equatorial plane of the torus.

4. Equivalent circuit of the bumpy torus plasma.

5. Current-voltage curves of the bumpy torus plasma in deuterium gas with $B_{max} = 2.4$ T.

6. Current-voltage curves of the bumpy torus plasma in deuterium gas with $B_{max} = 1.43$ T.

7. Current-voltage curves of the bumpy torus plasma in deuterium gas with $B_{max} = 0.48$ T.

8. Average ion residence time as a function of magnetic field for high and low pressure regimes of operation.

9. Current-voltage curves of the bumpy torus plasma in helium gas with B_{max} = 2.4 T.

10. Ion and electron temperatures of the bumpy torus plasma in deuterium gas for B_{max} = 2.4 T.

11. Ion and electron temperatures of the bumpy torus plasma in helium gas for B_{max} = 2.4 T.

12. Electron temperature and neutral number density of the bumpy torus plasma for high and low pressure regimes of operation in deuterium gas.

13. Electron temperature and neutral number density of the bumpy torus plasma for high and low pressure regimes of operation in helium gas.

14. Current-voltage curves of the bumpy torus plasma as a function of number of anode rings for deuterium gas a) high pressure regime, and b) low pressure regime.

15. Current-voltage curves of the bumpy torus plasma as a function of number of anode rings for helium gas a) high pressure regime, and b) low pressure regime.

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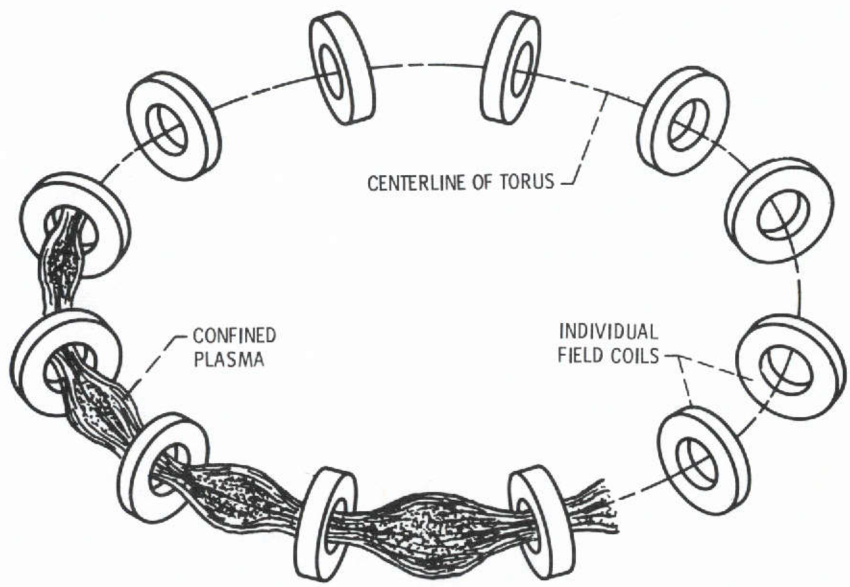

Figure 1. - Schematic drawing of the bumpy torus magnetic confinement geometry.

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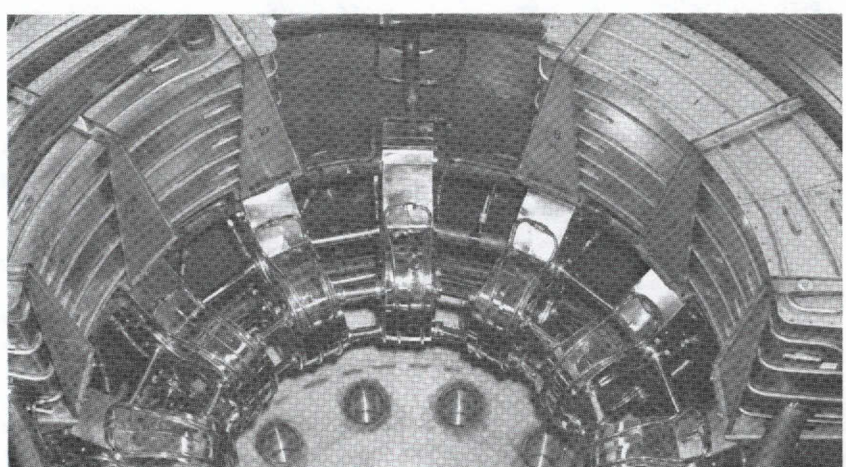

Figure 2. - Photograph of the NASA Lewis bumpy torus magnet facility with lid removed from vacuum tank.

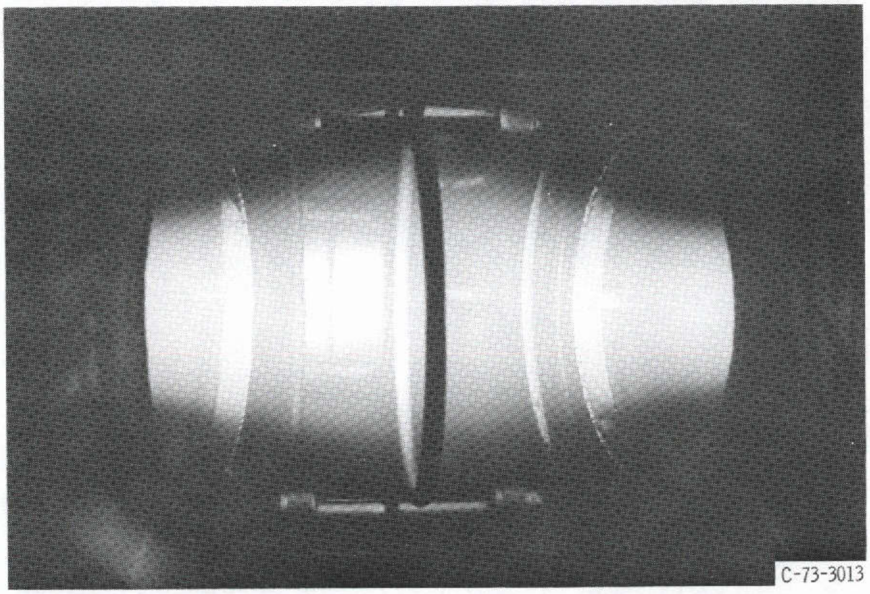

Figure 3. - Photograph of the bumpy torus plasma taken on the equatorial plane of the torus. The plasma at the opposite diameter of the torus is visible to the left of the anode ring in the foreground.

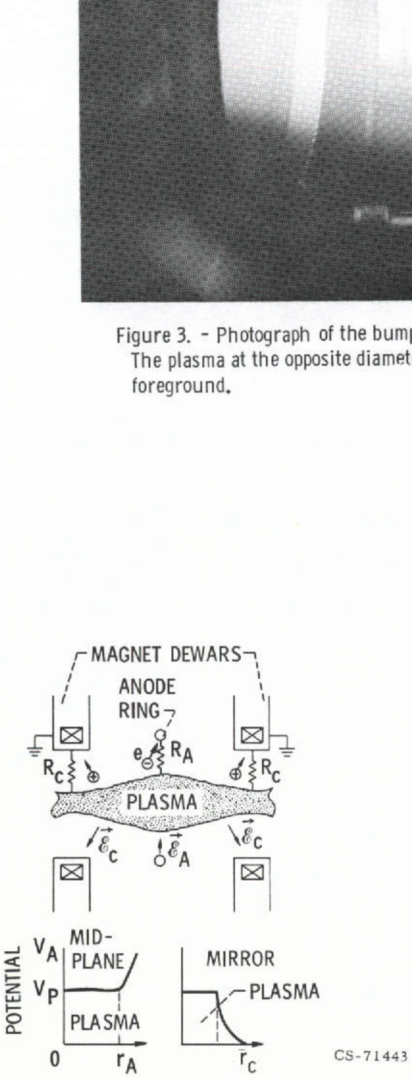

Figure 4. - Equivalent circuit of bumpy torus plasma.

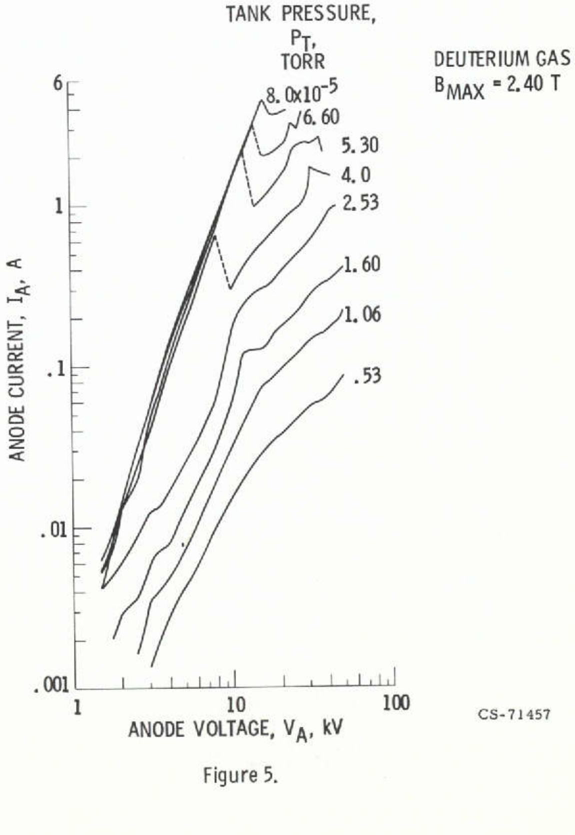

Figure 5.

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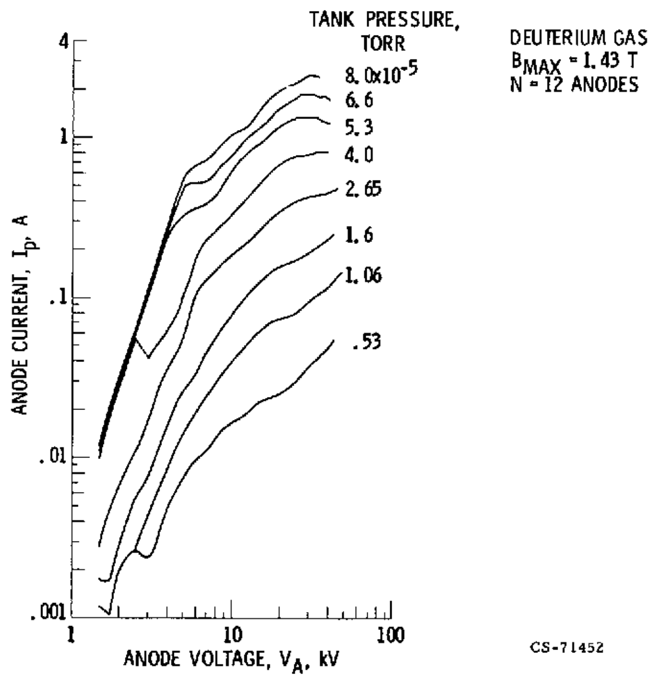

Figure 6.

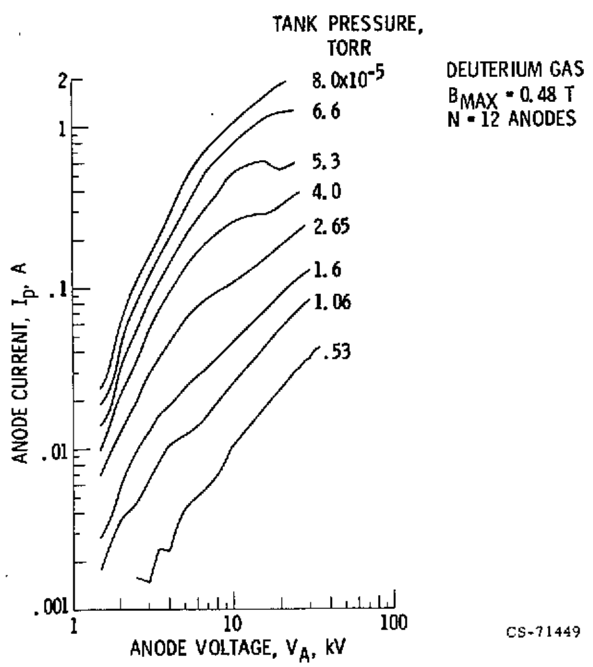

Figure 7.

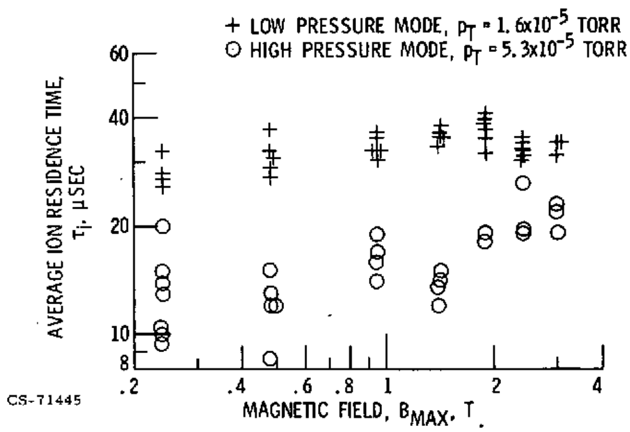

Figure 8.

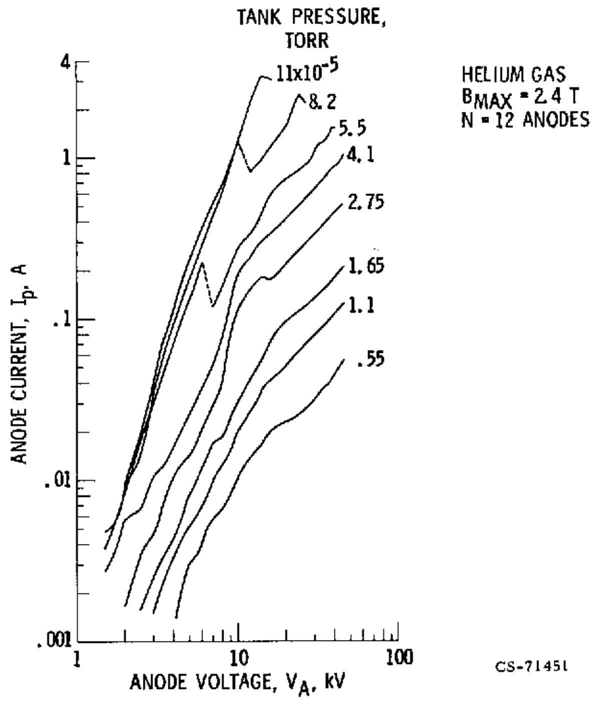

Figure 9.

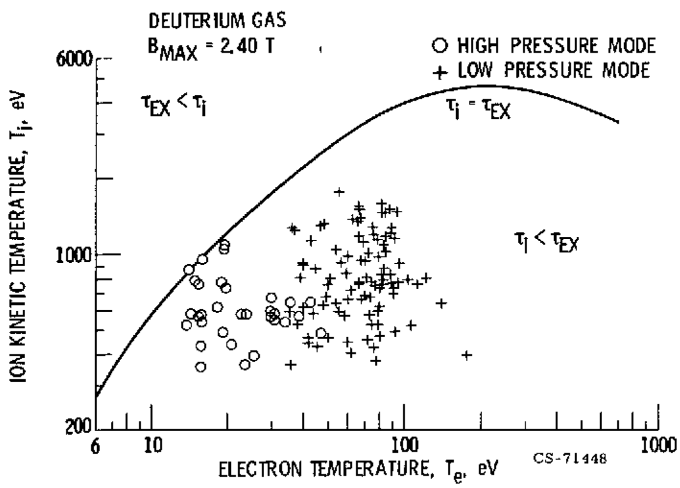

Figure 10.

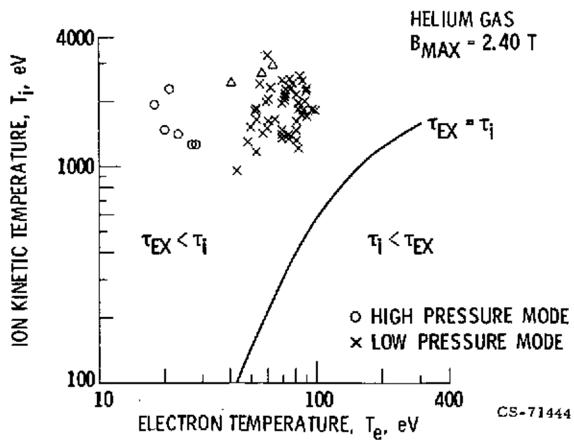

Figure 11.

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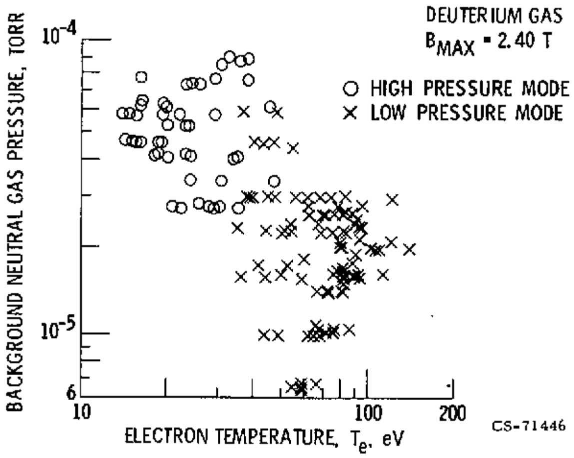


Figure 12.

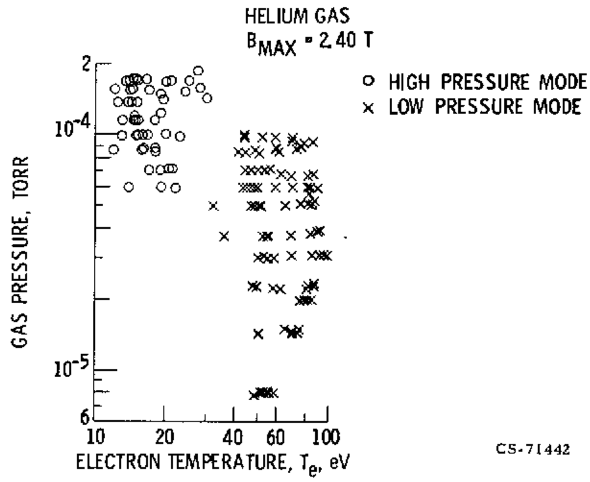


Figure 13.

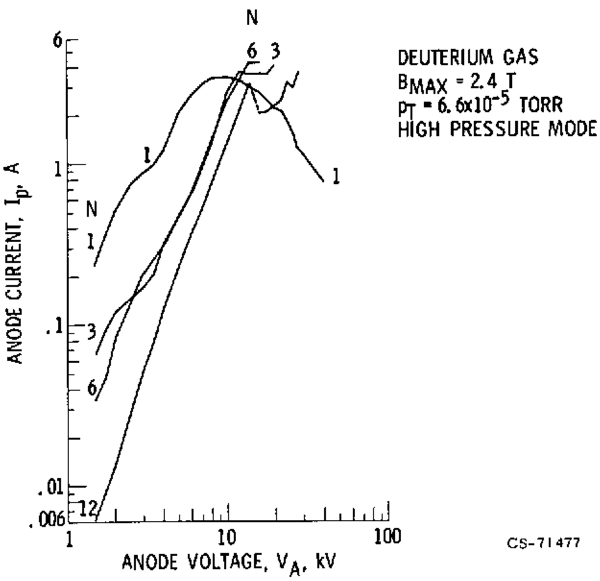


Figure 14(a). - High pressure mode.

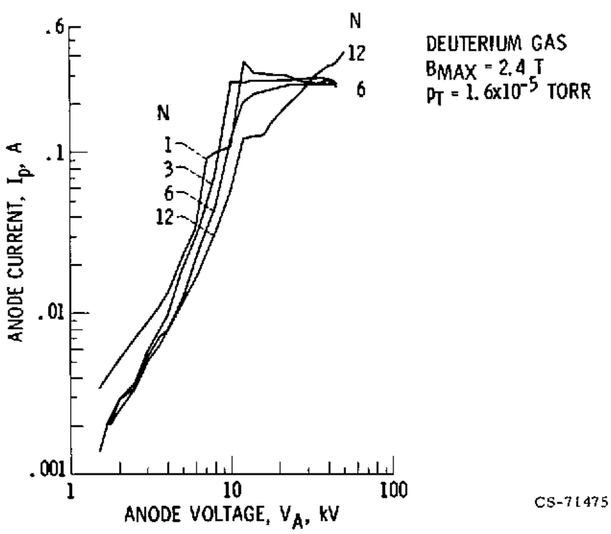
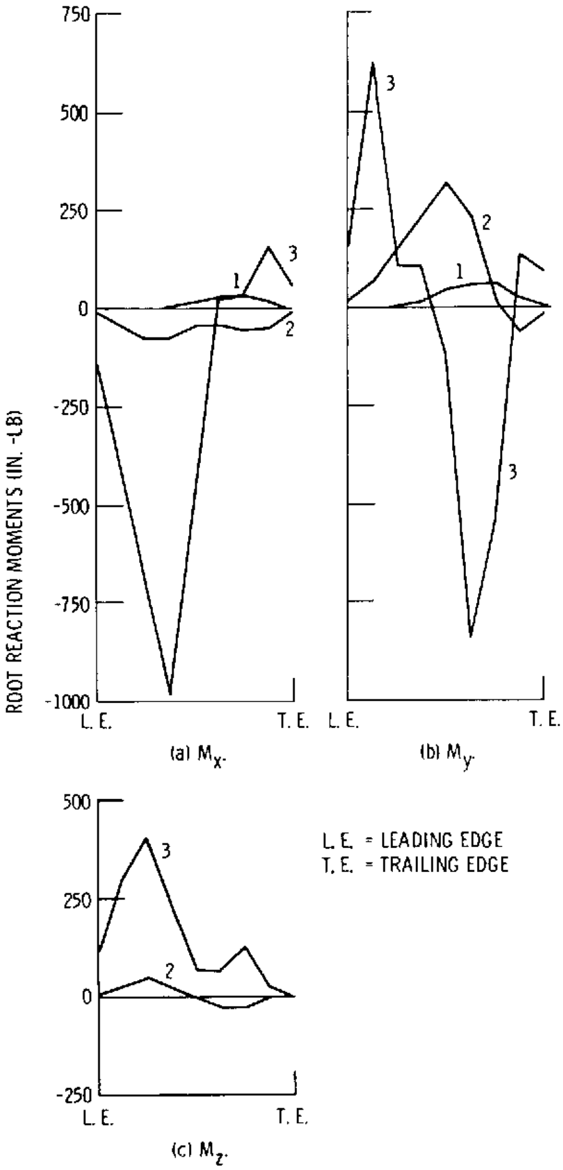


Figure 14(b). - Low pressure mode.



LOAD CONDITION: 1. THERMAL; 2. PRESSURE; 3. CENTRIFUGAL; 4. COMBINED (NOT PLOTTED)

Figure 15. - Root reaction moments vs. blade span for various load conditions. (x, y, z airfoil coordinates, fig. 1).

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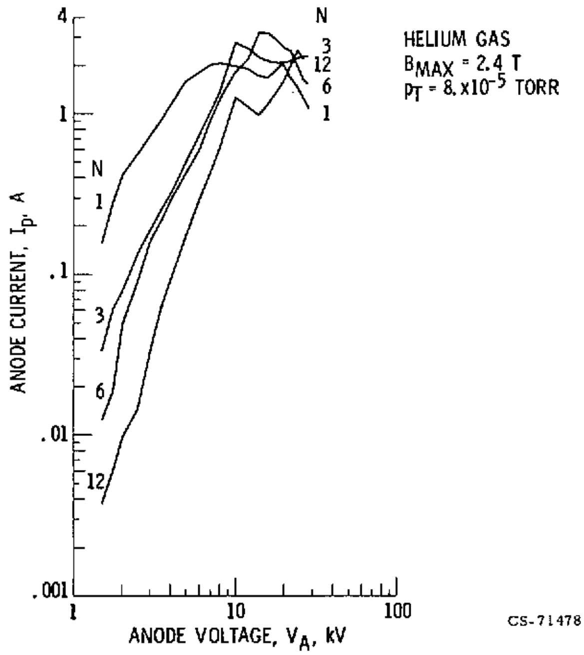

Figure 15(a). - High pressure mode.

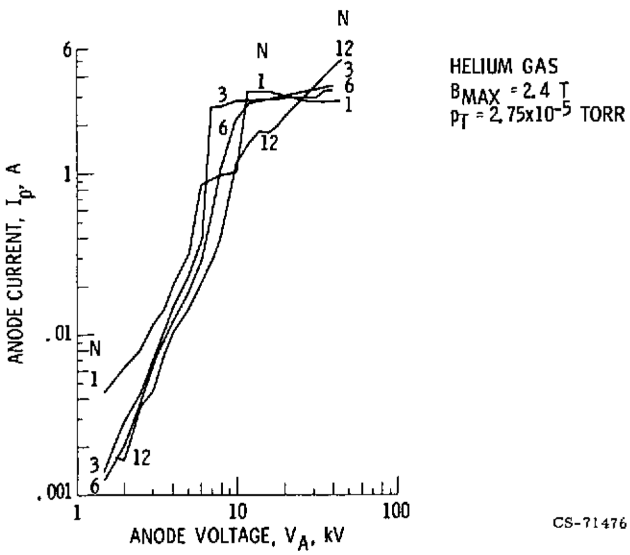

Figure 15(b). - Low pressure mode.

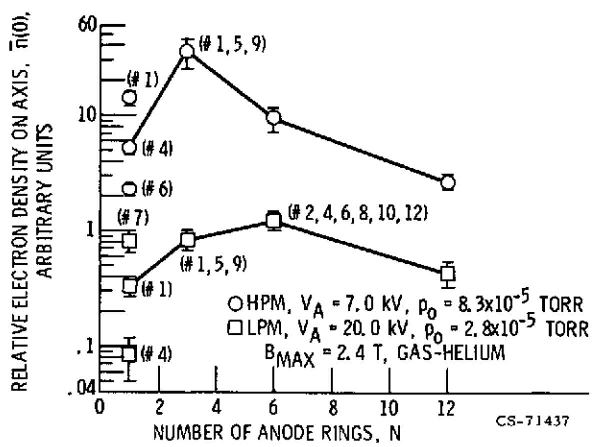

Figure 16. - Electron density on axis as function of number of anode rings.