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SPOKE WAVENUMBERS AND MODE TRANSITIONS IN THE NASA LEWIS BUMPY TORUS

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The NASA Lewis Bumpy Torus consists of 12 superconducting magnets arranged in a toroidal array with anode rings placed in the midplanes between adjacent coils. The anode rings are operated at high positive potentials with respect to the grounded coils and tank walls to form a modified Penning discharge in the toroidal magnetic field. Under certain conditions of anode current, neutral gas pressure and magnetic field, two voltage modes exist. Electron and ion spokes[1] are observed and their wavenumbers, k_{φ}, k_{θ}, k_r, are measured using capacitive probes as a function of wave frequency and discharge parameters. Preliminary results indicate that the sense of minor azimuthal rotation, k_{θ}, of these spokes changes on a mode transition with the rotation being consistent with an outward pointing electric field in the lower voltage mode and with an inward pointing electric field in the higher voltage mode. The major azimuthal wavenumber, k_{φ}, is found to be zero in the two cases.

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[1] J. R. Roth, Phys. Fluids 16, 231-236 (1973);
G. A. Gerdin, NASA TM X-71567 (May 1974).

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INTRODUCTION

Waveforms of fluctuations of plasma potential, resulting from rotating electron and ion charge concentrations, have been observed in the Lewis bumpy torus[1]. Since these fluctuations are thought[2, 3] to be spoke rotations in the direction of the ExB drift, measuring the direction of spoke rotation should determine the direction of the electric fields over much of the plasma surface. Since inward pointing electric fields should enhance confinement of the hot ions in this device[3], knowledge of the direction of the spoke rotation could give valuable information on the mechanism of plasma confinement and radial transport. A Langmuir probe was inserted into the plasma to measure the floating potential of the plasma, hence the direction of the electric field could be checked another way.

PLASMA DEVICE AND RADIO FREQUENCY EQUIPMENT

The Lewis Bumpy Torus consists of a toroidal array of twelve superconducting coils (ref. 4), see figure 1. The major diameter of the torus is 1.5 meters. The maximum magnetic field is 3.0 tesla in the coil throats and 1.2 tesla in the midplane between two coils. A 17.8 cm diameter anode ring is placed in each midplane concentric with the minor axis of the torus. In the results reported here, these rings were operated at a voltage of up to 35 kilovolts above the grounded coils and tank. A diagram of the current-voltage characteristic of the plasma at magnetic field maximum of 2.4 tesla with the pressure of deuterium as a parameter is shown in figure 2. At con-

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stant pressure above $2.65 \cdot 10^{-5}$ torr, the current increases as the anode voltage, V_A, to the third power until a transition voltage is reached where the current falls suddenly, the current then increases as $V_A^{3/2}$ above about 10kV and at a steeper slope between the transition voltage and 10 kilovolts. The portion of the I-V curve before the transition is called the "high pressure mode" or HPM; and the portion after the transition is the "low pressure mode" or LPM.

The radio frequency equipment used in the measurements reported here consisted of a number of capacitive probes placed in three different configurations around the torus, to make measurements of k_θ, k_φ, and k_r, where θ, φ, and r are the minor azimuthal coordinate, the major azimuthal coordinate, and the minor radial coordinate of the torus, respectively (see fig. 3). The spatial relationships of these probes to the plasma in each configuration are shown in figure 4(a), (b), and (c). The positions of these probes in terms of the coordinate system of figure 3 are given in table I, where the midplane of sector number 3 is taken as $\varphi = 0$. These capacitive probes measure fluctuations in plasma potential. Their outputs are amplified by cathode followers and are connected to the vertical amplifiers of a dual beam oscilloscope for relative phase information. The frequency response of this system was found to be flat from 1kHz to 1MHz with usable phase information obtainable to 10 MHz. The decision to use capacitive probes was based on earlier studies by Roth and Krawczonek (ref. 5), which indicated that considerably less sheath noise was generated around capacitive probes compared with floating Langmuir probes at frequencies up to 10 MHz. Other diagnostic equipment was used to check the direction of the electric and magnetic fields. The direction of the magnetic field was determined by a rotating coil gaussmeter, and the direction of the electric field was indicated by the use of a floating Langmuir probe (fig. 5). Spectroscopically determined electron density and temperature profiles measured by Richardson (ref. 6), were used to be sure electron temperature effects did not change the direction of the electric field indicated by the floating probe measurements.

RESULTS

IDENTIFICATION OF THE SPOKE

The waveforms studied were identified as spokes in the following way. The waveforms were either cusped in the positive or negative potential direction indicating a grouping of ions or electrons, respectively. The high voltages applied between the grounded magnets and the anode rings should create strong electric fields perpendicular to the plasma surface and, hence, a rapid plasma rotation in the ExB direction which, in a torus, should be in the direction of the minor azimuth.

The direction of spoke propagation was determined by the capacitive probes in each of three configurations shown in figure 4. The configuration with all the probes outside the plasma boundary, (fig. 4(a)), was used over a wide range of conditions to determine k_θ and k_φ. The other two configurations were used to see if the interior of the plasma rotated with respect to the exterior, and hence was a measure of k_r. Under all but the low pressure, high voltage conditions, an ion spoke could be identified, which had $k_\varphi = 0$, that is the entire ion spoke rotated around the minor azimuth in phase. This ion spoke rotated in the azimuthal direction corresponding to outward pointing electric fields, (see fig. 6). Additional results using probes placed inside the plasma, indicated that the interior of the plasma rotated in phase with the exterior. The interior probes could only be used at anode voltages below 8kV, so these latter results can only be extrapolated to the higher voltage conditions.

Since the phase coherence around the torus of the ion spoke indicated outward pointing electric fields in the bulk of the plasma, a check of these was made by inserting a floating Langmuir probe at various radial positions (see fig. 6) for 0.7 sec and letting the probe reach equilibrium. The results are shown in figure 7.

The floating potentials measured inside the plasma are much higher than either the ion or electron temperatures measured under these conditions, which are about 100eV and 500eV, respectively. This means the plasma potential is much higher than ground, and, hence, the electric field is pointing outward over much of the surface of the plasma torus to the grounded tank walls and magnet dewars. Thus, the floating Langmuir probe measurements corroborate the hypothesis that these "spokes" propagate in ExB direction.

ELECTRIC FIELD STRUCTURE IN THE BUMPY TORUS

Having shown the spoke moves in the ExB direction under the conditions where the Langmuir probe was inserted (see fig. 7), the direction of the electric field can now be determined from the direction of spoke propagation under conditions where Langmuir probe is not used. The results of the k_θ, k_φ, measurements, (see fig. 4), over a wide range of operating conditions are shown in table II for magnetic field maximum of 2.4 tesla and 1.42 tesla, respectively. The number in parenthesis refers to the m and ℓ wavenumber where $\Phi(r, t) = \Phi(r)e^{i\omega t}e^{im\theta - i\ell\varphi}$, and $m > 0$ corresponds to inward pointing electric fields and and $m < 0$ corresponds to outward pointing electric fields and $\Phi(r, t)$ is the plasma potential. The magnitude of m refers to the number of "cusps" co-rotating.

Under all conditions but low pressure ($p_t \leq 5.3\times10^{-6}$ torr) deuterium, and high voltage ($V_A > 10$kV), an ion spoke could be identified. In all cases it rotates in a direction corresponding to an outward pointing electric field. The phase coherence around the torus means that the local phase velocity in each sector is the same. Otherwise the ion spoke would be incoherent between sectors. Since the local phase velocity of the fluctuations is the same in all sectors, the electric field, E, must point in the same direction in all sectors. Whether E points outward over the entire sector or just in some dominant region sampled by the capacitive probes is not known, but probes placed in the toroidal midplane near the throat and magnetic midplane of one sector (see fig. 3) gave no phase shift indicating the region of outward E is quite extensive. It is also hard to see how this spoke could remain in phase around the torus if there is any break in this ExB rotation around the torus. This coherence may imply that the magnitude of E somehow changes by a factor of 2.4 along the φ direction to compensate the changes in magnetic field. In summary, at two different magnetic fields under most operating conditions, (V_A up to +35 kV and $5.3\cdot 10^{-6}$ torr $\leq p_t \leq 5.3\cdot 10^{-5}$ torr) the electric fields in this device point outward with a positive potential on the anode rings.

At the lower pressures ($p_t \leq 1.1 \times 10^{-5}$ torr D_2) an electron spoke was observed in the vàcinity of the anode ring. In all cases it rotated in the direction corresponding to an inward pointing electric field. This spoke was found to be incoherent between sectors of the torus and, in fact, to have different frequencies in different sectors, but no twisting of the wave was observed in an individual sector. Also when observed by capacitive probes positioned along a minor radius, (see fig. 4(b)) an electron spoke was seen at the probe closest to the anode ring and not at the inner or outer probe, indicating that the electron spoke is very localized. The higher frequencies of these electron spokes indicate the electric fields involved are on the order of 10kV/cm. (The electric field may be estimated for an electron spoke, since the electrons should remain within the sheath due to their small orbit.)

These experimental results indicate the region of inward pointing electric fields in the toroidal plasma is a small region near the anode ring. The incoherence and different frequencies of the electron spokes between sectors of the torus indicates this spoke is a property of the bump itself and, hence, these inward fields cannot extend even as far as the mirror throats. This incoherence of electron spokes between sectors was found to hold at pressures less than or equal to 1.1×10^{-5} torr D_2 and at magnetic fields maximum of 2.4 tesla. The position of the spoke, as measured by radial probes, (fig. 4), indicate that the extent of these inward electric fields from the anode ring is small radially, less than 6.4 cm, whereas the counter rotating ion spoke was clearly observed on both the inner and outer probes, but hard to observe at the anode ring when this electron spoke was present. As the pressure is increased, the region where the electric field points inward probably decreases in proportion to the ion Debye length, and these spokes no longer exist in the region observed by the probes. Thus the plasma appeared to have outward pointing electric fields except for a small region near the anode ring. (A sketch of the deduced E field arrangement in the Bumpy Torus is shown in figure 8.)

The fact that electron spokes occur in regions of inward pointing electric fields and ion spokes in regions of outward pointing electric fields is explainable as follows: for a plasma with the anodes and cathodes on the outside of the torus, an increase in negative charge density, that is an electron spoke, at the edge of the plasma will cause a local increase in the electric field in an inward pointing electric field region (see fig. 9(a)). The same will be true for the ions in an outward field region, (see fig. 9(b)). Hence, the experimental result of ion spokes corresponding to outward electric fields and electron spokes in inward pointing electric fields is consistent with this model of spoke formation.

The effect of the plasma mode transitions on the spoke are limited to a few empirical observations. On the transition from the high pressure mode to the low pressure mode, and the amplitude of the wave increases dramatically. An order of magnitude in amplitude is not uncommon. The results of the radial measurements for the high pressure mode, (see fig. 4), indicated an ion spoke rotating on the plasma edge in phase with an electron spoke corotating near the plasma center (see fig. 10). These spokes corotated in the direction of outward pointing fields and indicated a migration of particles in the direction of the force of the electric field on the individual particle species. In the low pressure mode, all waveforms were those of a co-rotating ion spoke as if the plasma sheath extended deeply into the center of the torus.

Finally, the point where the slope of the I-V curve changes in the low pressure mode was found to correspond to a transition from an $m = -1$ ion spoke to an $m = -2$ ion spoke (see table II), so there appears to be a cause and effect relationship, although its nature is not clear at this time.

CONCLUSION

The result of this research, that the electric fields point outward over most of the toroidal plasma surface of the Bumpy Torus, demonstrates that valuable information about the plasma can be obtained from a study of plasma potential fluctuations with capacitive probes. The direction of the electric field should have a significant effect on particle containment[3]. These data are the first information obtained on the direction of the electric field in this device.

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2. J. R. Roth, Phys. Fluids, 16, 231 (1973).

3. J. R. Roth, IEEE Trans. Plasma Sci., PS-1, 34 (1973).

4. J. R. Roth, A. D. Holmes, T. A. Keller, and W. M. Krawczonek, Proc. 1972 Applied Superconductivity Conf., (IEEE, New York), 361 (1972).

5. J. R. Roth and W. M. Krawczonek, Ref. of Scien. Instru., 42, (1972).

6. R. W. Richardson, NASA TM X-71569, (1974).

TABLE I. - PROBE CONFIGURATION IN

TORIODAL COORDINATES

[R = 75 cm; φ = 0 in midplane sector no. 3]

Probe	r(cm)	θ	φ
A	14±0.6	$45^\circ \pm 3^\circ$	$0 \pm 1^\circ$
B	14±0.6	$0^\circ \pm 3^\circ$	$0 \pm 1^\circ$
C	14±0.6	$315^\circ \pm 3^\circ$	$0 \pm 1^\circ$
D	40±2	$0^\circ \pm 3^\circ$	$210^\circ \pm 1^\circ$
E	14±0.6	$270^\circ \pm 3^\circ$	$88^\circ \pm 1^\circ$
F	15±0.6	$0^\circ \pm 3^\circ$	$30^\circ \pm 1^\circ$
G	10±0.6	$0^\circ \pm 4^\circ$	$22^\circ \pm 1^\circ$
H	8.9±0.6	$0^\circ \pm 4^\circ$	$30^\circ \pm 1^\circ$
I	2.5±0.6	$0^\circ \pm 13^\circ$	$30^\circ \pm 1^\circ$
J	6.4±0.6	$90^\circ \pm 6^\circ$	$30^\circ \pm 1^\circ$
K	6.4±0.6	$0^\circ \pm 6^\circ$	$30^\circ \pm 1^\circ$
L	6.4±0.6	$270^\circ \pm 6^\circ$	$30^\circ \pm 1^\circ$

TABLE II. - MEASURED SPOKE PARAMETERS

UNDER VARIOUS CONDITIONS

Conditions				Ion spoke+		Electron spoke*	
p_t, 10^{-6} torr	B, t	V_A, kV	Mode	ω, kHz	m	ω, MHz	m
26.5	1.42	2.5	LPM	40	-1	---	--
↓	↓	4.6	↓	74	-1	---	--
↓	↓	7.2	↓	220	-2	---	--
↓	↓	8.2	↓	220	-2	---	--
↓	↓	11.4	↓	250	-2	---	--
58	1.42	2.2	HPM	111	-2	---	--
↓	↓	4.5	HPM	200	-2	---	--
↓	↓	6.1	LPM	66	-1	---	--
↓	↓	7.7	LPM	36	-1	---	--
↓	↓	21.3	LPM	74	-2	---	--
5.3	2.4	2.0	LPM	10	-1	.50	+1
↓	↓	4.9	↓	25	-1	.67	+1
↓	↓	10.0	↓	50	-1	---	--
↓	↓	20.0	↓	---	--	2.0	+1
↓	↓	24.9	↓	---	--	3.6	+1
↓	↓	29.9	↓	---	--	2.5	+1
↓	↓	34.9	↓	---	--	2.0	+1
9.5	2.4	2.7	LPM	26	-1	---	--
9.5	↓	5.0	↓	40	-1	---	--
9.5	↓	8.5	↓	50	-1	---	--
9.5	↓	9.9	↓	--	-2	---	--
9.8	↓	14.9	↓	270	-2	---	--
10.1	↓	19.9	↓	330	-2	2.9	+1
10.1	↓	25.0	↓	330	-2	2.5	+1

+All ion spokes had $\ell = 0$.

*Electron spoke localized to regions near anode ring and is incoherent bump to bump. Therefore ℓ could not be defined.

TABLE II. - Continued. MEASURED SPOKE PARAMETERS UNDER VARIOUS CONDITIONS

Conditions				Ion spoke[+]		Electron spoke[*]	
p_t, 10^{-6} torr	B, t	V_A, kV	Mode	ω, kHz	m	ω, MHz	m
10.3	2.4	29.9	LPM	330	-2	2.9	+1
10.3	↓	35.0	↓	---	--	2.6	+1
14.5	↓	3.0	↓	23	-1	---	--
14.8	↓	6.1	↓	53	-1	---	--
14.8	↓	9.2	↓	67	-1	---	--
14.8	↓	12.0	↓	400	-2	---	--
15.1	↓	16.0	↓	370	↓	---	--
15.9	↓	20.0	↓	400	↓	---	--
15.6	↓	22.9	↓	370	↓	---	--
16.2	↓	26.7	↓	400	↓	---	--
28	2.4	1.9	HPM	22	-1	---	--
↓	↓	4.1	HPM	116	↓	---	--
↓	↓	6.3	LPM	50	↓	---	--
↓	↓	8.0	↓	71	↓	---	--
↓	↓	9.9	↓	385	-2	---	--
↓	↓	15.0	↓	385	↓	---	--
↓	↓	20.0	↓	400	↓	---	--
↓	↓	25.0	↓	400	↓	---	--
34.5	2.4	1.9	HPM	59	-1	---	--
↓	↓	4.1	HPM	238	↓	---	--
↓	↓	5.9	LPM	71	↓	---	--
↓	↓	8.3	LPM	95	↓	---	--
↓	↓	11.2	LPM	370	-2	---	--
↓	↓	14.3	LPM	435	-2	---	--

[+]All ion spokes had $\ell = 0$.

[*]Electron spoke localized to regions near anode ring and is incoherent bump to bump. Therefore ℓ could not be defined.

TABLE II. - Continued. MEASURED SPOKE PARAMETERS

UNDER VARIOUS CONDITIONS

Conditions				Ion spoke+		Electron	
p_t, 10^{-6} torr	B, t	V_A, kV	Mode	ω, kHz	m	ω, MHz	m
34.5	2.4	17.2	LPM	500	-2	---	--
34.5	2.4	21.2	LPM	500	-2	---	--
45	2.4	2.9	HPM	90	-1	---	--
↓	↓	5.9	HPM	45	-1	---	--
↓	↓	8.4	HPM	167	-2	---	--
↓	↓	10.2	LPM	370	↓	---	--
↓	↓	13.0	LPM	500	↓	---	--
↓	↓	17.0	LPM	500	↓	---	--
↓	↓	20.0	LPM	500	↓	---	--
53	2.4	4.9	HPM	37	-1	---	--
53	↓	8.0	HPM	220	-2	---	--
53	↓	10.9	HPM	220	-2	---	--
58	↓	16.1	LPM	420	-2	---	--
64	↓	18.0	LPM	620	-2	---	--

+All ion spokes had $\ell = 0$.

*Electron spoke localized to regions near anode ring and is incoherent bump to bump. Therefore ℓ could not be defined.

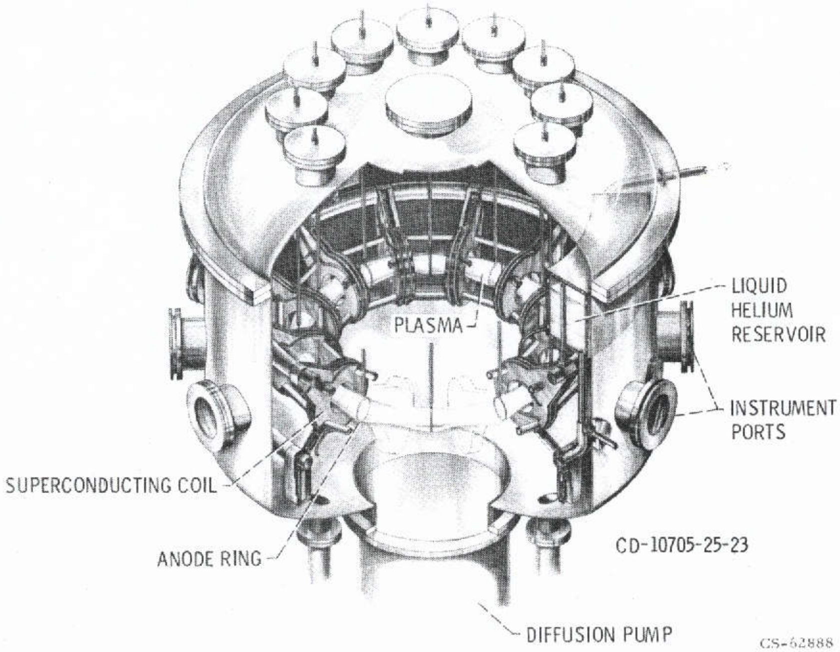

Figure 1. - Isometric, cutaway drawing of the NASA Lewis Bumpy Torus magnet facility.

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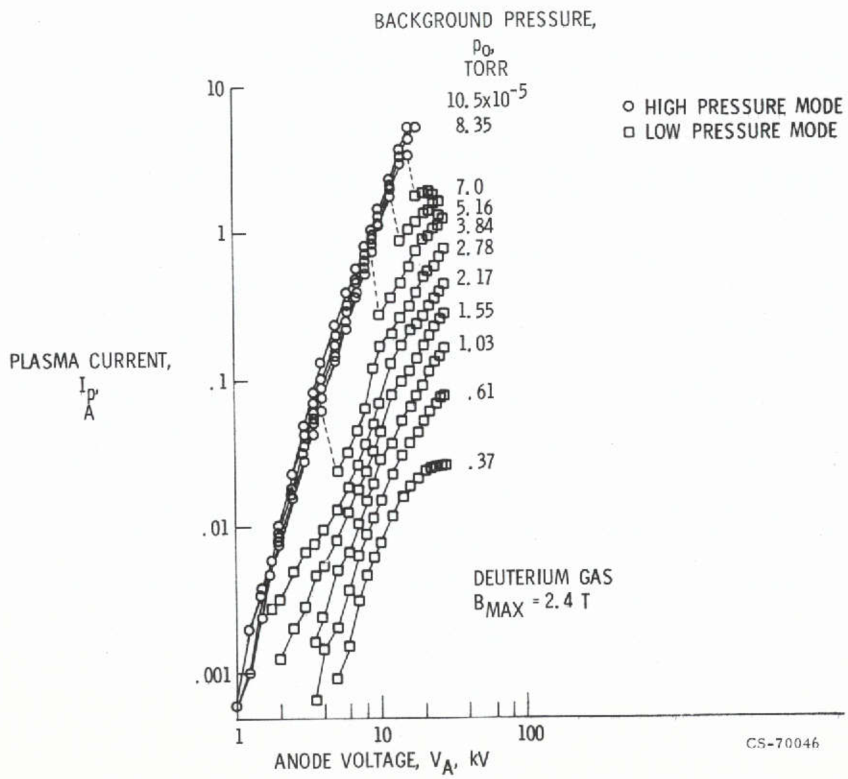


Figure 2. - Current voltage characteristic for the Lewis Bumpy Torus with a maximum magnetic field of 2.4 tesla.

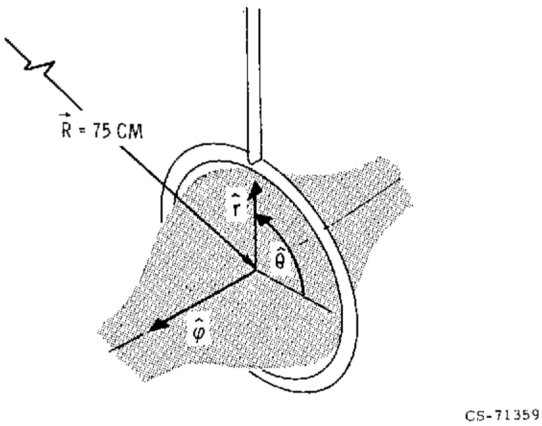
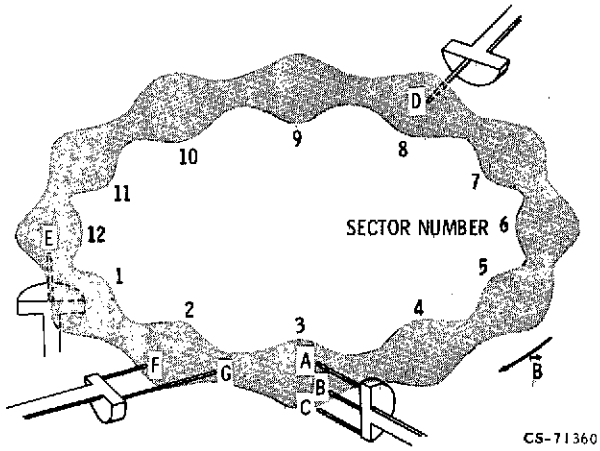
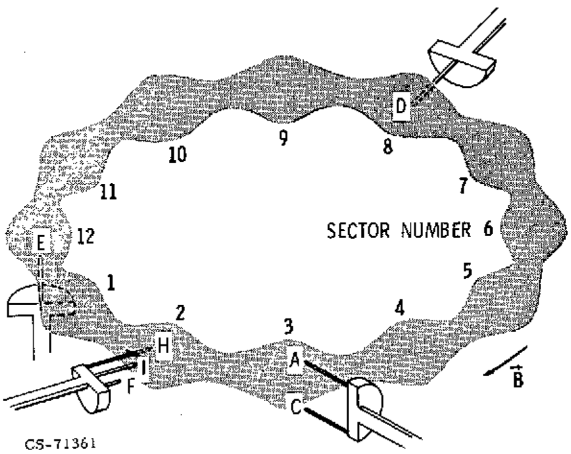


Figure 3. - Coordinate system for the Bumpy Torus.



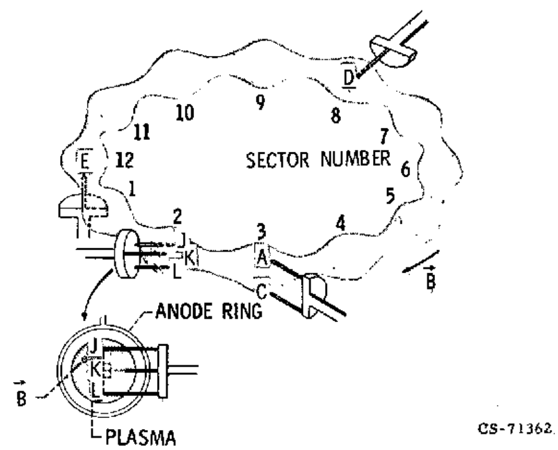
(a) TO MEASURE k_θ, k_φ.

Figure 4. - Capacitive probe configuration.



(b) TO MEASURE k_r AND k_θ, k_φ (FIRST CONFIGURATION).

Figure 4. - Continued.



(c) TO MEASURE k_r AND k_θ, k_φ (SECOND CONFIGURATION).

Figure 4. - Concluded.

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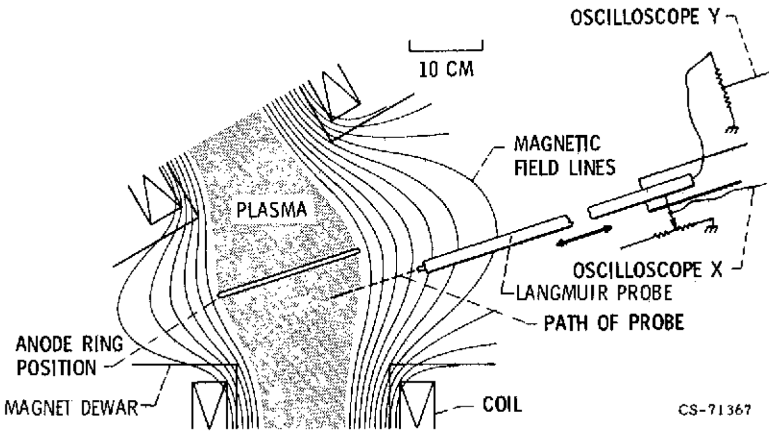


Figure 5. - Region of plasma sampled by Langmuir probe.

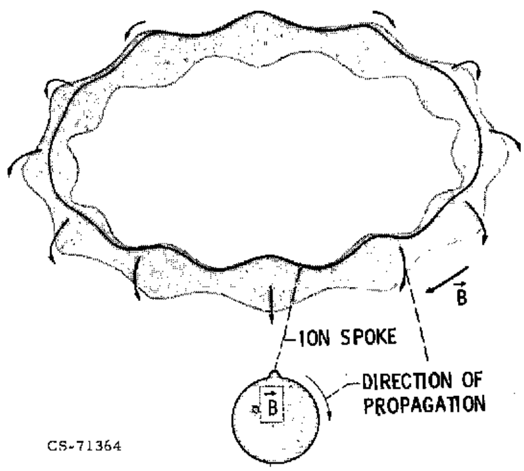


Figure 6. - Propagation of ion spoke on surface of the Bumpy Torus. It is coherent and in phase in all sectors and propagates in a direction of outward pointing electric fields.

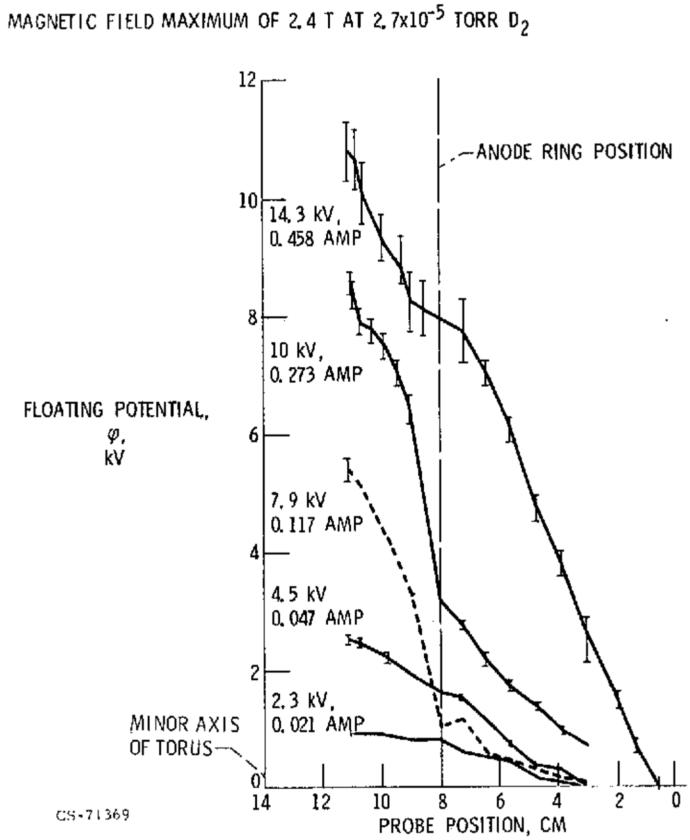


Figure 7. - Floating potential versus probe position along a radius 4.3 cm from the magnetic midplane of sector 8 at a magnetic field.

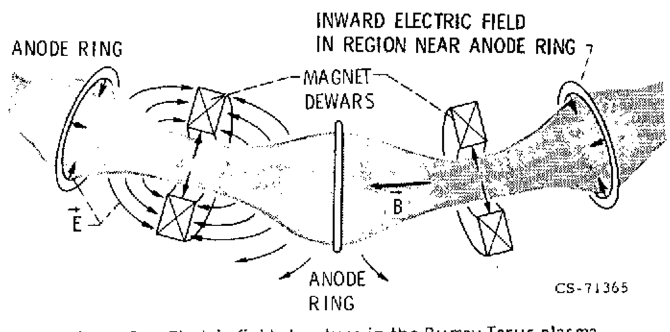
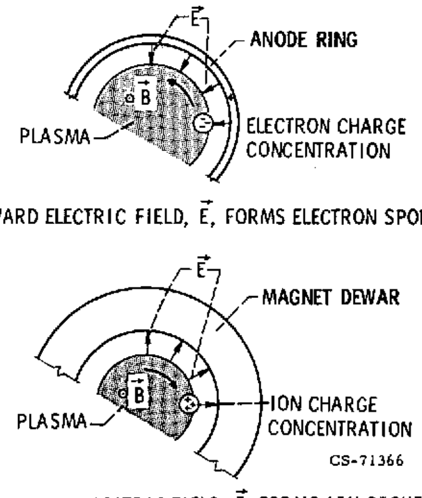


Figure 8. - Electric field structure in the Bumpy Torus plasma. Inward electric field, $\vec{E}$, near anode rings; outward $\vec{E}$ elsewhere.



(a) INWARD ELECTRIC FIELD, $\vec{E}$, FORMS ELECTRON SPOKE.

(b) OUTWARD ELECTRIC FIELD, $\vec{E}$, FORMS ION SPOKE.

Figure 9. - Model of spoke formation.

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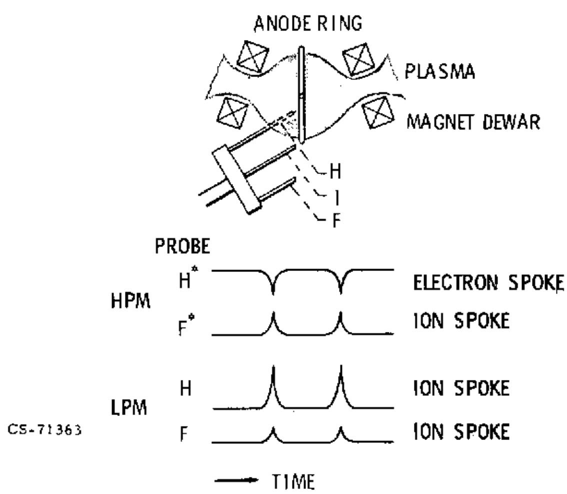

*THE COORDINATE POSITIONS OF PROBES H AND F ARE GIVEN IN TABLE I.

Figure 10. - Difference in spoke structure between the high pressure mode, HPM, and the low pressure mode LPM.