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ABSTRACT

A phased program of plasma heating at the electron cyclotron frequency is proposed for the Oak Ridge tokamaks ISX and ORMAK Upgrade. The past history of the program of electron cyclotron heating (ECH) at ORNL on mirrors and in the ELMO Bumpy Torus has shown demonstratd success. Future technological developments in the production of high power high frequency microwave tubes look promising at this time. The physics of wave propagation and particle heating are fairly well understood and indicate the viability of this technique. Studies on breakdown and on runaway electron reduction will provide useful information for larger machines. Recent experiments in the USSR on small tokamaks have shown that ECH is a viable heating technique. Providing that the microwave tubes become available, the engineering considerations suggest that the technique is practical and workable, based on present day technology.

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1. INTRODUCTION

This study concerns the application of high frequency microwave radiation to plasma heating near the electron cyclotron frequency in the Oak Ridge tokamaks. Successful plasma heating by microwave power has been demonstrated in numerous experiments. Predicted future technological developments suggest that a vigorous program in plasma heating should lead to promising results. We propose here a phased program tied

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to high power millimeter microwave tube development, leading to interesting new regimes in the auxiliary heating of tokamaks, particularly ISX and ORMAK Upgrade. Section 2 discusses the advantages of this technique. Sections 3 and 4 briefly consider the physics of propagation, heating, and breakdown. Section 5 is a brief summary of the USSR electron cyclotron heating results in tokamaks. Some considerations on technology and engineering are discussed in Section 6, and the last section gives a summary.

2. THE PRESENT STATUS OF MICROWAVE HEATING

Since 1960, a vigorous program of plasma heating with microwaves at the electron cyclotron frequency has been carried on at ORNL.[1-5] Other laboratories have also made significant contributions.[6-8] Until 1974, the U.S. effort was almost entirely devoted to mirror machines. Solutions were obtained for the technological problems of waveguide coupling, microwave leakage from evacuated microwave cavities, and optimized plasma production.[9] Industrial involvement was encouraged through the support of high frequency tube development.

The present microwave heating effort on EBT indicates the advanced level to which this program has risen.[10] These new developments can also be implemented on the Oak Ridge tokamaks ISX and ORMAK Upgrade. Prospects for utilizing this technology on larger machines such as the Technological Toroidal Assembly (TTAP) and the Experimental Power Reactor (EPR) look encouraging in the light of recent developments in high frequency microwave technology.

The successes in the program of microwave heating on the tokamaks in the USSR[11-13] have indicated the viability of this technique in heating the main body of the plasma. The experiments to date confirm only adequate heating of electrons, but extrapolations to higher density devices would indicate that energy transfer from electrons to ions can also be achieved.

One of the particular advantages of this kind of heating is the simplicity of the coupling. Simple waveguides bolted to the wall of the plasma chamber usually sufficed. Occasionally, horns have proved useful. The waveguides have been used to launch ordinary (E // B), extraordinary (E ⊥ B), and circularly polarized radiation.

As mentioned, the present experiments on small tokamaks have demonstrated only electron heating. In EBT, at typically much lower densities, the electron-ion energy transfer maintains the ions at roughly half the electron temperature. As the density rises and as this technique is applied to larger devices, the electron-ion energy transfer rate is expected to improve.

This approach to plasma heating has been at a disadvantage because of the unavailability of microwave power. With the recent successes in the USSR in gyrotron development,[14] and the current proposed U.S. effort, this particular disadvantage may disappear. It is predicted that efficiencies of power production will be about 30% to 40%.

3. THE PHYSICS OF PROPAGATION, AND HEATING WITH MICROWAVES

The heating of plasmas in mirror machines at or near the electron cyclotron resonance (ECR) has been successful in a number of laboratories. The theoretical aspects of this process have been explored for mirror machines by a number of authors,[15-20] and some experimental confirmation has been obtained in support of their work.[8]

There have been a few ECH experiments in tokamaks, but very little theory for toroidal machines. The tokamak experiments performed to date are described briefly in Section V. The heating of the body of the plasma observed has been generally successful, with some runaway production.

3.1 PROPAGATION AND ACCESSIBILITY

A large body of literature has been produced on the propagation of waves in magnetized plasmas. In the last 15 years of experience with ECH in mirrors and multipole machines, there is very little evidence that the accessibility conditions are relevant for heating.

Efficient heating of electrons is well established even in cases where the waves must have propagated through evanescent regions. On the other hand, it must be noted that as a general rule plasma densities achieved by ECH have a limiting density defined approximately by $\omega_{pe} \lesssim \omega_{ce}$. As discussed in Section 5, some evidence has been obtained in the USSR that these accessibility conditions are important in ECH in tokamaks.

The present section contains a brief review of the theoretical propagation and accessibility considerations for ISX and ORMAK Upgrade are included.

The Clemmow-Mullaly-Allis diagram[34] for cold electron plasma is shown in Fig. 1. The solid horizontal line at $\omega_{ce}^2/\omega^2 = 1$ represents cyclotron resonance; the line marked UH represents the upper hybrid resonance $\omega_{pe}^2 + \omega_{ce}^2 = \omega^2$; and the line marked cutoff between regions 1 and 4 represents the cutoff boundary for the extraordinary wave and is defined by

$$\omega_1 = + \frac{\omega_{ce}}{2} + \sqrt{\left(\frac{\omega_{ce}}{2}\right)^2 + \omega_{pe}^2} \quad , \tag{1}$$

i.e., $n^2 = 0$. The solid arrow shows the proposed path of radiation incident from the inside of a tokamak, where the magnetic field is large and $\omega_{ce} > \omega$.

(a) In regions 1 and 2 all polarizations may propagate freely, so that both the ordinary and extraordinary wave may reach cyclotron resonance. The ordinary wave propagates in the entire region $\omega_{pe}^2 < \omega^2$.

(b) In region 3 the extraordinary wave energy propagates along resonance cones.[22] The energy flux is concentrated along a cone aligned with the magnetic field, with opening angle

$$\theta = \tan^{-1} (-S/P)^{\frac{1}{2}}, \tag{2}$$

where

$$S = 1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} \tag{3}$$

is the perpendicular dielectric function, and

$$P = 1 - \frac{\omega_{pe}^2}{\omega^2} \qquad (4)$$

is the parallel dielectric function. The electrostatic approximation is valid, and the dispersion relation is

$$n^2 S + n_{11}^2 P = 0, \qquad (5)$$

with $\vec{n} = c\vec{k}/\omega$. The group velocity $\vec{V}_g = \frac{\partial\omega}{\partial\vec{k}}$ is perpendicular to the phase velocity. The phase velocity of the wave becomes perpendicular to the magnetic field as the upper hybrid resonance is approached, so the group velocity and energy flux approach the resonant surface tangentially. The electric fields can become quite large near upper hybrid resonance and nonlinear processes may be important. One expects any wave energy that has not been absorbed at cyclotron resonance to be dissipated here.

(c) The extraordinary wave is cut off in region 4. In Fig. 2a, the cross section of a tokamak with a parabolic density profile is shown. The maximum density is such that $\omega_{pe} < \omega_{ce}$ everywhere. One sees that the cutoff region for the extraordinary wave can be quite broad, so according to these theoretical considerations it may not be advisable to launch a wave from the outside. The port on the top inside of the vacuum tank (top left port in Fig. 2a) is available for launching. Waves propagating from this port would follow approximately the arrow in Fig. 1 and would not be subject to the cutoff at ω_1.

(d) Most tokamaks operate at densities where $\omega_{pe}^2 < \omega_{ce}^2$. However, if the density in the center is large enough, the wave passes from (Fig. 1) region 2 and enters region 5, where the extraordinary wave becomes left circularly polarized and no longer heats cold electrons. The right circularly polarized wave cannot propagate perpendicular to the field lines. However, resonance cones also occur in this region, and the energy can propagate to the cyclotron resonance.

(e) Only the left circularly polarized wave can propagate in (Fig. 1) region 6, so the right circularly polarized wave is absorbed at cyclotron resonance.

(f) No waves can propagate in (Fig. 1) region 7, according to the cold plasma theory. In region 8 the right circularly polarized wave can propagate and reach the cyclotron resonance.

To further clarify these points, Figs. 2a, 2b, and 2c illustrate the regions of propagation and evanescence for the ISX tokamak with the electron cyclotron resonance located at the center of the chamber. Projected on the cross section are the cutoffs, resonances, and evanescent regions for (a) low density plasma, (b) moderate density plasma, and (c) high density plasma, for the use of the propagation of extraordinary wave. Note that the electron cyclotron and upper hybrid resonances are always accessible from the high field side, but only in the high density case is the plasma center shielded by the cutoff at

$$\omega_2 = \frac{-\omega_{ce}}{2} + \sqrt{\left(\frac{\omega_{ce}}{2}\right)^2 + \omega_{pe}^2} \ . \qquad (6)$$

As already noted, propagation to the resonances from the low field side may be difficult. It is necessary to penetrate through the evanescent region, unless the wave will bounce around the region between the wall and the first cutoff. Of course, for some cases the evanescent region is so narrow that tunneling through it will allow access to the resonances.

If the ordinary wave propagation is used, there is no upper hybrid or cyclotron resonance and only a cutoff at ω_{pe}. This cutoff is also illustrated on Figs. 2b and 2c by a dotted line. In the cold plasma theory, collisional damping of this wave is possible and the hot plasma theory should give cyclotron damping.

For a very low density plasma, the upper hybrid layer is near the cyclotron resonance layer. Heating by either mechanism would provide body heating and the two would probably not be distinguishable. For cases in Fig. 2a and 2b, low to moderate density plasmas, the ECH and

Upper Hybrid Heating (UHH) layers are widely separated, and the evanescent region may be thick enough to inhibit propagation from the weak field side. The ordinary wave could not propagate into the region bounded by the dotted line $\omega_{rf} = \omega_{pe}$ in Fig. 2b. Heating at the cyclotron layer would provide body heating, whereas UHH would provide surface heating. Finally, in Fig. 2c we observe that for a very high density plasma the center is shielded by the ω_2 cutoff. For an incident extraordinary wave, the plasma could only have surface heating. For example, this condition of Fig. 2c would require a peak density of ~ 2.7×10^{13} in ISX for the expected plasma parameters (B = 9.3 kG and f = 26 GHz), and this density may not be achievable. For ORMAK Upgrade (B = 40 kG and f = 120 GHz), this would require a peak density of 5.7×10^{14}, which again may not be achievable.

Moving the cyclotron resonance to the inside or the outside will produce similar plots. These resonance positions will result largely in surface heating. Hogan[23] has shown that large changes in the current channel can result from surface heating. By excluding the electron cyclotron resonance region from the machine for low field operation, the upper hybrid can be isolated. This would present the possibility of a pure UHH experiment. By careful adjustment of the field, the second harmonic resonance zone could be placed in the machine. Recent calculations for the proposed Russian T-20 tokamak by Dnestrovskii et al.[24] suggest that the ordinary wave can be completely absorbed in one pass through the machine, if launched at an angle of ~ 60° to the field. The extraordinary wave is damped too heavily in the outer regions to heat the interior. The wave would be launched in that direction which would minimize runaway production.

3.2 LINEAR HEATING RATES AT CYCLOTRON RESONANCE

In principle, electrons may be efficiently heated by microwaves at cyclotron resonance or at the upper hybrid resonance. The mechanisms are not necessarily distinguishable in experiments. Near the upper hybrid resonance the microwave fields become large and many linear or non-linear processes can occur. The exact heating mechanism is thought to be mode conversion to hot plasma mode at the same frequency.[21] Landau damping of the more energetic electrons is also possible.

From the inside edge of the torus, the incident radiation first passes through the cyclotron resonant surface. The heating rates calculated[17,20] for ECH in a mirror geometry are easily extended to a tokamak with a toroidal field B(R), given by

$$B(R) = B(0)\,\frac{R_0}{R}, \qquad (7)$$

where

B(0) = field on the minor axis

R_0 = major radius

R = radius.

The perpendicular heating rate at cyclotron resonance is

$$\frac{dW_\perp}{dt} = \frac{\omega_{pe}^2}{4\omega}\,RA\,|Ex - iEy|^2, \qquad (8)$$

where the right side of the equation is to be evaluated at resonance. The area at the resonance irradiated is A, and $W_\perp$ and W_{11} are the total perpendicular and parallel energy in the irradiated volume. This energy is gained by the electrons as they drift across resonant surfaces. In a tokamak this crossing is provided primarily by the rotational transform. The time required for an electron to circulate around the machine is on the order of a microsecond, so one expects the entire plasma to be heated.

The parallel heating is due to three effects. One is a finite cyclotron radius effect with a rate

$$\frac{dW_{11}}{dt} = \frac{\omega_{pe}^2}{16\omega}\,RA\,|E_z|^2 \left\langle \frac{v_\perp^2}{c^2} \right\rangle \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right). \qquad (9)$$

Another effect is the parallel heating that always accompanies perpendicular heating in a non-uniform field, due to the $\mu\nabla_{11}B$ force which couples the perpendicular and parallel motion. A final heating effect results from the parallel electric field driving harmonics of the bounce motion (in a mirror) or harmonics of the resonant zone crossing frequency motion (in a toroidal machine).

For incident radiation exactly perpendicular to the magnetic field, the heating rate of Eq. 8 vanishes. For the extraordinary mode, one has the perpendicular index of refraction

$$n^2 = \frac{(\omega^2 - \omega_{pe}^2)^2 - \omega^2\omega_{ce}^2}{\omega^2(\omega^2 - \omega_{pe}^2 - \omega_{ce}^2)}, \tag{10}$$

with fields

$$\frac{E_y}{E_x} = i\,\frac{\omega_{pe}^2 + \omega_{ce}^2 - \omega^2}{\omega_{pe}^2} \cdot \frac{\omega}{\omega_{ce}}. \tag{11}$$

At cyclotron resonance one finds $E_y = iE_x$, so that the combination responsible for electron heating, $E^- = E_x - iE_y$, is zero. However, the radiation pattern of a waveguide source is wide enough to result in appreciable energy propagation at oblique angles, and if necessary the aperture may be oriented obliquely with the magnetic field. The resonance also has a finite spatial width, which may be derived from the spatial damping factor.

The damping is proportional to

$$\Lambda \sim \exp\left[-\frac{m}{2T}\frac{(\omega - \omega_c)^2}{k_{11}^2}\right]. \tag{12}$$

By expanding the cyclotron frequency about the resonance position, one finds

$$\omega_c \cong \omega + \frac{x d\omega_c}{dx} = \omega - \frac{x\omega}{R}, \tag{13}$$

where x is the distance from resonance. So

$$\Lambda \sim \exp\left[-\frac{x^2}{2\Delta^2}\right], \tag{14}$$

with

$$\Delta^2 = \frac{T}{mc^2} R^2 n_{11}{}^2 . \tag{15}$$

For T = 250 eV, R = 80 cm, and $n_{11} = 1$, one finds $\Delta = 1.8$ cm.

The heating rate depends on the angle of propagation and may be calculated from the radiation pattern by ray tracing techniques. The basic rate of Eq. 8 is very large, and rough estimates show complete absorption of the extraordinary mode, except for a narrow cone near perpendicular incidence.

As an example, with a volume of 10^6 cm^3, a density of $n = 5 \times 10^{12}$ cm^{-3}, and 100 kW of power, one finds dW/dt = 120 eV/msec. For parallel heating, one has

$$\frac{1}{S_x A}\frac{dW_{11}}{dt} = \pi^2 \frac{\omega_{pe}^2}{\omega^2} \frac{R}{\lambda} \sqrt{1 - \frac{\omega_{pe}^2}{\omega^2}} \left\langle \frac{V_\perp^2}{c^2} \right\rangle . \tag{16}$$

For a 250 eV plasma with R = 80, $\lambda = 1$ cm, and $\omega_{pe}^2 = \omega^2/2$, 5% of the ordinary wave is absorbed in one pass. The wave is probably depolarized by reflection from cavity walls, and most of it goes into perpendicular energy. For 100 kW of power, initially unpolarized, one expects $dW_{11}/dt = 5$ eV/msec. The rate of energy exchange between the perpendicular and parallel components is rapid for typical tokamak parameters. Hence it is expected that isotropization of the electron energy will occur quickly.

4. PRE-IONIZATION EFFECTS ON BREAKDOWN, RUNAWAY PRODUCTION, AND PLASMA STARTUP

4.1 INTRODUCTION

In a tokamak, gas breakdown generally results from the induced electric field. The principle heating mechanism is the induced plasma current. The establishment of the full value of this current may entail runaway production, increased volt-second requirements on the transformer until ionization is complete, and large resistive losses which result in intense wall bombardment. The auxiliary method of pre-ionization by microwaves at the electron cyclotron frequency may alleviate some of these problems.

4.2 GAS DISCHARGE PARAMETERS

The ISX machine will have the values R = 92 cm, a = 25 cm, and B_T = 9 kG for the breakdown experiment, and an estimated filling pressure of ~ 4 x 10^{-4} torr. The available breakdown voltage is 50 V, hence E = 6.9 x 10^{-2} V/cm and E/p $\simeq$ 170 V/cm torr. This is very close to the value for ORMAK. The number of ionizations per centimeter torr electron is α/p. For hydrogen gas, an analytical fit[25] to the data in the region 20 < E/p < 1000 is given by

$$\alpha/p = 5.4 \exp(-139/(E/p)) \text{ ions/cm torr electron.} \qquad (17)$$

Efficient ionization requires E/p $\gtrsim$ 100, since α/p drops rapidly below E/p = 100. The drift velocity of an ensemble of electrons in a gas is approximated[26] by

$$V_D = 3.5 \times 10^5 \; E/p \text{ cm/sec}, \qquad (18)$$

where this drift velocity is superimposed on the higher random velocities. The electron temperature in electron volts is approximately[26] given by

$$T_e = 0.1\ (E/p) \qquad E/p < 100$$
$$T_e = 10 \qquad E/p > 100 \tag{19}$$

4.3 RUNAWAY PREVENTION

Runaway electrons result from free-fall in the toroidal electric field. The runaway flux depends on conditions of density and temperature which are only imprecisely known. Theoretical estimates can be made in the presence of plasma or neutral gas.

The critical field[27] in a very weakly ionized plasma (neutral gas) is given by

$$E_{cn} = 4\pi e^3\ n_o (Z/2.72)\bar{\varepsilon} \simeq 7 \times 10^{-15}\ n_o\ \mathrm{V/cm}, \tag{20}$$

where n_o is the neutral gas density. Hence, the critical field can be given by $E_{cn}/p = 248$. Operating a tokamak at $E/p > 100$ gives a high probability of a significant runaway production; in fact, even values of E/p an order of magnitude lower can lead to runaways.

The critical field in a plasma[27] is given by

$$E_{ci} = \frac{4\pi^2 n_e e}{T_e}\ \ell n\ \frac{mv_e^2\ D}{e^2} \simeq$$
$$2.6 \times 10^{-13}\ \frac{n_e}{T_e}\ \ell n\ \frac{4 \times 10^9 (T_e)^{1/2}\ mv_e^2}{n_e^{1/2}}, \tag{21}$$

where v_c is the critical velocity for runaways, and T_e and mv_c^2 are in electron volts. The logarithmic term has a value of ~ 10 for typical conditions, and it is relatively insensitive to parameters. For $E/p \simeq 100$, $T_e \simeq 10$ eV, so that

$$E_{ci}/p \simeq 9.2 \times 10^3\ (n_e/n_o). \tag{22}$$

To avoid runaways, we require $E_{ci}/p \gg E/p \approx 100$, which implies that $n_e/n_o \gg 10^{-2}$. For a typical filling pressure of 4×10^{-4} torr, this would require $n_e \gg 1.4 \times 10^{11}$.

It should be noted that in the absence of a movable or magnetic limiter it will probably be necessary to pre-ionize the entire volume to prevent runaways, since an electric field is induced over the entire plasma volume until the current builds up. Electrons in the un-ionized region can run away if $E/p \simeq E_{cn}/p$.

Alikaev[28] has found that runaways can be enhanced by microwave heating if the cyclotron resonance is not present. The ability to control the runaways by this technique may be of some significance.

4.4 PLASMA BUILDUP RATE

In the absence of losses, or for low losses, the density buildup equation is

$$\frac{d}{dt} n_e = \nu n_e = \alpha v_D n_e, \tag{23}$$

where ν ($= \alpha v_D$) is the ionization rate. If E/p is constant, then the solution is

$$n_e = n_{e\,o} \exp (\alpha v_D t). \tag{24}$$

Defining $\eta = n_e$ final$/n_{e\,o}$, then the buildup time, τ, is

$$\tau = \ln \eta/\alpha v_D. \tag{25}$$

Devices like ISX and ORMAK Upgrade are expected to have large values of E/p and p, which result in large values of α and rapid ionization rates. We take as examples $\eta = 10^2$ for good pre-ionization, and $\eta = 10^{12}$ for no pre-ionization. The following table shows the machine parameters, breakdown electric field, typical values of E/p, and buildup time for these values of η. We have assumed $p = 4.4 \times 10^{-4}$ torr for both machines.

	R_o (cm)	a (cm)	Loop voltage (V)	E (V/cm)	E/p (V/cm torr)	$\eta = 10^2$ τ (sec)	$\eta = 10^{12}$ τ (sec)
ISX	92	25	50	8.6×10^{-2}	195	5.8×10^{-5}	3.5×10^{-4}
ORMAK Upgrade	92	30	66	11.4×10^{-2}	259	3.7×10^{-5}	2.2×10^{-4}

A calculation of the savings in transformer volt seconds shows no significant effect for either machine under high pre-ionization. Similar calculations for a large machine such as an EPR, with a lower E field, show a savings of ~ 10% of the available volt seconds, which is significant.

Pre-ionization is still important to reduce the probability of runaways. For no pre-ionization, $E_{cn}/p = 248$ and the applied electric field is near the critical field for ISX and above the critical field for ORMAK Upgrade.

4.5 RATE EQUATIONS

The density and temperature rate equations for low or no losses are

$$\frac{dn_e}{dt} = n_e n_o (\sigma v)_i$$

$$\frac{d}{dt}\left(\frac{3n_e T_e}{2}\right) = -E_i n_e n_o (\sigma v)_i + P_\mu , \qquad (26)$$

where $(\sigma v)_i$ is the ionization rate of H_2 by electrons, E_i is the energy required to produce an electron-ion pair (~ 93 eV) at low electron temperatures, and P_μ is the absorbed microwave power per unit volume. The solutions to these equations, for constant $(\sigma v)_i$ and n_o, are

$$n_e = n_{e\,o} \exp\,(tn_o(\sigma v)_i) = n_{e\,o} \exp\,(t/\tau_b)$$

(27)

$$\frac{dT_e}{dt} = -n_o(\sigma v)_i(T_e + \frac{2}{3}E_i) + \frac{\frac{2}{3}P_\mu}{n_{e\,o} \exp\,(tn_o(\sigma v)_i)}.$$

Initially, the second term in the T_e equation dominates due to low density, and T_e increases rapidly to a maximum value, due to relativistic detuning of the resonance. Eventually, $\frac{dT_e}{dt} = 0$, and then

$$P_\mu \text{ (initial)} = \frac{3}{2}n_{e\,o} \exp\,(tn_o(\sigma v)_i)\cdot n_o(\sigma v)_i(T_e + \frac{2}{3}E_i)\ . \quad (28)$$

If the temperature saturation model is applicable, we can deduce the qualitative behavior of the system by an approximate analytic solution of the rate equations. As the density rises, eventually the full power will become available. In the early states, T_e is typically between 100 eV and 1 keV, so that $(\sigma v)_i$ is roughly constant. Thus, the characteristic density level at which the exponential buildup changes to a slower buildup is

$$n_{eb} \simeq \frac{2}{3}\,\tau_b P_\mu/(T_e + \frac{2}{3}E_i). \quad (29)$$

At this level, T_e begins to drop, and below 100 eV the $(\sigma v)_i$ rate drops rapidly. If the temperature change is slow compared to the density change, then

$$\frac{d}{dt}\,n_e = P_\mu/(E_i + \frac{3}{2}T_e). \quad (30)$$

If the pre-ionization time, τ_p, is several times τ_b, then the final density at the end of the pre-ionization is approximately

$$n_{ep} = P_\mu \tau_p/(E_i + \frac{3}{2}T_e), \quad (31)$$

and the required microwave power may be calculated from the desired density.

4.6 APPLICATION TO ISX AND ORMAK UPGRADE

The single particle drift time is given by

$$\tau_D = \frac{a\ RB}{2 \times 10^8\ T_e} . \tag{32}$$

For ISX, with $T_e \simeq 100$ eV, and $t_D \simeq 1.0$ msec, a high pre-ionization level of $n_e/n_o \simeq 0.1$ would require $n_e \simeq 1.6 \times 10^{12}$. Setting τ_p and τ_D would require $P_\mu = 3.89 \times 10^{17}$ eV/cm^3 sec, or a total power of 71 kW for breakdown.

For ORMAK Upgrade, with the same T_e, and $\tau_D = 5.4$ msec, the same pre-ionization level would require $P_\mu = 7.2 \times 10^{16}$ eV/cm^3 sec, or a total power of ~ 19 kW for breakdown.

Part of the experimental program would be to explore the validity of these calculations. The available microwave power should be much larger than these predicted levels so that a wide parameter space may be explored.

5. EXPERIMENTS ON ECH IN TOKAMAKS IN THE USSR

There have been two laboratories in the USSR where significant experiments have been performed on ECH in tokamaks. As early as 1971, both Alikaev at the Kurchatov Institute and Golant at the Ioffe Institute had reported high power microwave experiments.

Golant[12] used a microwave source of 80 kW at 9 GHz on the Tuman-2 tokamak for fundamental ECH studies in low (~ 5 kG) magnetic fields. Pulse lengths were between 100 and 300 μsec. Also, 100 μsec pulses of ~ 30 kW at 34 GHz were used for second harmonic ECH. At 9 GHz, the heating was concluded to be due to wave conversion at the upper hybrid frequency. The presence of a cyclotron resonance region was necessary for heating, and the heating efficiency was correlated with the position of the evanescent region and the magnitude of the conversion efficiency.[21] A heating efficiency of 60% could be obtained under optimum conditions.

For second harmonic heating, the energy change in the plasma could not be measured directly but could be inferred from the change in plasma current. The heating efficiency was estimated to be 5-10% based on this, and it was attributed to larger attentuation in the evanescent region and lower conversion efficiency.

Alikaev[29] used ~ 40 kW of power at ~ 30 GHz for 500 μsec in TM-3 tokamak. In a cold plasma, he found no heating at the second harmonic, but heating both in the presence and absence of a fundamental cyclotron resonance. This was attributed to the upper hybrid resonance and collisional heating. In a hot plasma ($T_e \geq 200$ eV), absorption at the second harmonic was observed. The efficiency of heating at the fundamental was given as 20-30%.

In 1972[30] Alikaev et al. reported further measurements with the 30 GHz microwave source on TM-3. An increase of the energy containment time, τ_E, with electron temperature, T_e, was observed. Also, damping of oscillations during the microwave pulse, a decrease in the high energy (> 10 keV), X-ray intensity, a shift of the plasma column outward, and an increase in the loop voltage were observed. Some of these effects could be attributed to bulk heating.

In 1973 Golant[12] et al. reported experiments in the FT-1 tokamak. They used sources supplying 50 kW at 30 GHz and 12 kW at 22 GHz, both with pulse times of 200 μsec. Fundamental cyclotron heating was observed at 22 GHz with an absorption efficiency of 30%. Because of the low temperature, some absorption could be attributed to collisions. The efficiency of absorption could be qualitatively related to the thickness of the evanescent regions and the location of the upper hybrid surface.

Effects of second harmonic absorption at 30 GHz could be observed over a very narrow region of thickness of ~ 4 mm, and the efficiency of the absorption was not high.[31]

The absorption process at 22 GHz was attributed to linear wave transformation of the microwave energy at the upper hybrid surface. The plasma waves arising from this transformation were believed to be absorbed between the upper hybrid and cyclotron resonance surfaces.

In 1974 Alikaev[13] et al. reported further measurements on the TM-3 tokamak using 30 GHz with up to 70 kW of power and a pulse length of 1 msec. Runaway electrons were observed by the bremsstrahlung radiation and by millimeter microwave radiation, when the magnetic field on axis was higher than the resonant field by 30%; i.e., when the resonant zone was displaced to the outside. The X-ray measurements suggest that electrons with longitudinal energy of ~ 20 keV did not acquire more than 10% of the plasma energy gain measured diamagnetically. The number of runaway electrons could be minimized by operating at high density. Also, applying the microwave power early did not increase the runaway population.

With the magnetic field adjusted for electron cyclotron resonance on the axis, the number of runaways was also decreased. Operating with the resonance on axis, the measurements suggest that only 25% of the bulk of the electrons are heated. In any case, no ion temperature increase was observed.

In 1975 Alikaev[28] et al. reported further measurements on the TM-3 tokamak. This time, laser scattering was used to measure the central electron temperature. Measurements with the resonant field on axis resulted in a bulk heating of the electrons, but experiments at the second harmonic caused some runaway production. Also, heating at the second harmonic resulted in a $\beta_p \simeq 2.2$. The lifetime of the runaway was estimated at 2 msec for 10 keV electrons and 9 msec for 60 keV electrons.

Recent unpublished results on TM-3[32] have indicated no heating of the main body of the plasma when only the upper hybrid resonance exists and there is no electron cyclotron resonance. The measurements also suggest that the electron thermal conductivity decreases as the electron temperature increases under ECH, so that the energy confinement time increases with T_e.

All of the above experiments in the USSR have been made with the microwave feed on the outside of the torus. Hence, there is the possibility that the evanescent region on the low field side of the torus could interfere with extraordinary wave propagation. Since in many of the experiments the guide was circular, the actual wave launched could be a combination of ordinary, and extraordinary right- and left-hand circularly polarized radiation. In the latest experiments of Ref. 32, a horn was used, primarily to launch the ordinary wave. In the later experiments, particularly at Kurchatov, gyrotrons were used to supply the microwave power. There is no evidence in the published literature that any kind of matching device other than a simple horn has been used.

6. ENGINEERING CONSIDERATIONS

We are considering application of ECH to two machines at Oak Ridge. The first is ISX, which will be operating in 1977. Its minor radius (a) is 25 cm; its major radius (R) is 92 cm, and the maximum toroidal magnetic field on axis (B) is approximately 18 kG. Since we are considering using the first gyroklystron to be developed here, we would anticipate operating ISX at 9-10 kG, appropriate for ECH at 25-28 GHz. This would allow a maximum plasma current of ~ 70 kA for $q(a) \simeq 5$.

The next machine that is planned is ORMAK Upgrade. In this case, $a = 30$ cm, $R \simeq 90$ cm, and $B \simeq 43$ kG. The microwave development plan anticipates acquisition of 120 GHz/100-200 kW tubes in the late 1970's. These would be ideally suited for use on ORMAK Upgrade with the frequency appropriate for resonance on axis. Here the plasma current should be ~ 400 kA for typical q values.

Because in ISX the field will necessarily be low, and hence the plasma current is limited, the ohmic heating dissipation is expected to be ~ 200 kW. Hence, one or two gyroklystron tubes at ~ 200 kW each would provide an adequate test of the principle of ECH on a current generation tokamak. It would be an experiment on a well-diagnosed tokamak, that would lead to an extrapolation of the results to a first line device like ORMAK Upgrade. There are some particular advantages of doing the experiment on ISX: ISX is designed to be a flexible experiment. If the waveguides are in the wrong place, or the microwave leakage is too great, or some other difficulty occurs, it can be easily corrected.

In ORMAK Upgrade the ohmic heating dissipation should be on the order of 1 MW, so that a number of the anticipated 120 GHz tubes would be required in order to make the auxiliary heating comparable to the ohmic heating. Neutral beams supplying ~ 2 MW of auxiliary heating are planned for ORMAK Upgrade. An ECH experiment at this same power level would provide an important comparison between these two heating techniques.

Aside from these rather simple power and frequency considerations, the following subjects must be carefully considered in any detailed engineering study:

(a) high voltage power supply; power control and overload protection
(b) magnet supply
(c) waveguide type, orientation and modeing
(d) window location
(e) tube location; field perturbation
(f) vacuum tank construction

We are considering the potential problems anticipated for ISX with some care, because they are better known at the present. When possible, we also consider the problems to be anticipated for ORMAK Upgrade.

6.1 HIGH VOLTAGE POWER SUPPLY: POWER CONTROL AND OVERLOAD CONTROL

For the gyroklystron for EBT, a dc power supply with an output of ≥ 100 kV and ≥ 10 A is anticipated. This would be in the general vicinity of EBT, probably on the mezzanine of building 9201-2. Spark gaps for removal of electron beam power within 10 μsec of a fault would be required for the normal dc operation of the tubes on EBT.

It is possible that this supply could be used for ISX. Since we expect pulsed operation with pulse lengths of 10-100 msec, the power supply cable inductance would need to be considered. If the power supply is located between EBT and the anticipated location of ISX, then the cable may be short enough so that this may not be a consideration. This supply would probably be required to have a slow regulation (milliseconds to seconds) of ~ ½%. This could be accomplished by an inductrol or saturation transformer. In addition to this main beam supply, a gun anode supply operation ~ 50 kV, 0.1 A is also required. The regulation required for this supply may be somewhat more restrictive than for the main beam supply. This supply is expected to be tied to the cathode and float at the ~ 100 kV level. It is required to control the transverse energy of the beam. Short line lengths for this supply are required and it may not be possible to utilize EBT's supply. This portion of the supply may be a non-trivial part of the total required unit.

There is the possibility that for the pulsed operation typical of a tokamak, the entire supply could be replaced by a pulse-forming line or a capacitor bank and modulator tube. Again, the required regulation would be ~ ½%. The gun anode voltage could be supplied by a divider network from the main supply. For operation on ISX the microwave drive power would be pulsed inside of the high voltage pulse.

6.2 MAGNET POWER SUPPLY

Well-regulated supplies are required to maintain output frequency and stability. A regulation of 0.02% may be required for a 10 kW supply providing ~ 500 A at ~ 20 V.

6.3 TUBE LOCATION

Because of the high frequency losses in the waveguides, the microwave tube should be mounted as close as possible to the tokamak. Because of the considerations of mode conversion in the waveguides, the waveguides may be required to be run straight to the machine wall. The tube itself for ISX will require a solenoid with a field of ~ 10 kG in the interaction region. In the case of ISX, any single external field should not be allowed to produce more than a 100 G perturbation on the minor axis. For the worst case, this restricts the tube to being more than ~ 1.1 m from the minor axis or ~ 75 cm from the vacuum wall. With iron shielding of the solenoid, it may be possible to reduce this distance; however, this shielding may have to be taken into account in the tube design.

For ORMAK Upgrade, the solenoid on the gyroklystron would produce a field of ~ 40 kG. This may present a more serious field perturbation. Also, the external field from the air core transformer may seriously perturb the gyroklystron.

6.4 WAVEGUIDES: LOCATION, LENGTH, TYPE, MODE CONTROL, ORIENTATION

For the initial experiments, the simplest waveguide location would be on the outside of the tokamak vessel. Because of the conditions on accessibility mentioned in Section 3, it may be advisable to introduce the power from the high field side. Based on past experience, for ISX the first location would allow launching from the outside from a gyroklystron at a major radius of ~ 2 m. The second location, as suggested by the accessibility requirements above, would probably be from the top inside of the machine. Figure 2 shows the relevant ports on ISX that have already been planned. In either case, launching tangentially along the field is not possible, but angles with respect to the field $\geq 50^o$ for the outside ports would be reasonable. Angles between 20^o and 30^o are possible with special techniques.

The waveguide type would be chosen for minimum attenuation. The waveguides recommended for high power transmission with least attenuation are the circular guides carrying the $TE_{0\ell}$ modes. For these modes, the attenuation decreases as the frequency increases. Inevitable nonuniformities, the fact that the guides can carry a number of lower order modes if they can carry the $TE_{0\ell}$ mode, and the fact that irregularities can cause mode conversion to the unwanted modes make the waveguide design a very serious matter. It is anticipated that the recommended guide will be circular and will be designed for the TE_{01} mode. There is some possibility of bends produced by 45^{o} reflectors on waveguides operating in quasi-optical modes. These considerations, plus the desire to minimize the guide length, will put more restrictions on the location of the microwave tubes.

For ORMAK Upgrade, guides carrying the TE_{02} mode may be desirable, and the problem of unwanted modes becomes more severe.

6.5 WINDOW LOCATION

The windows for these frequencies are anticipated to be BeO or Al_2O_3. If the microwave feed is to be from the outside of the torus, there will never be a resonant region in the waveguide and the exact location of the window will not be important. A resonance in an evacuated guide can result in a waveguide arc, which can propagate back to the source and destroy the windows and the tube.

For the microwave feed on the top, the guide can pass through a possibly resonant region between the top of the tank and the toroidal field coil. Hence, the window should be located close to the vacuum tank and well inside the rectangular field coil. It may be necessary to monitor the toroidal field at the place where the evacuated guide enters the vacuum tank and interlock the field sensor to the microwave drive.

6.6 VACUUM TANK CONSTRUCTION

Microwave power will be present at high energy density levels inside the vacuum tank. Small holes will allow propagation to the outside; thus, their size and number must be carefully controlled to avoid (1) diagnostic interference, (2) interference with the control of the machine, and (3) hazard to people.

In EBT, laser scattering is performed in the plasma by observing the scattered light through a ~ 50% transparent perforated copper grid.[33] If higher transmission is required and the microwave loss is not excessive, it may be possible to view the plasma through a window containing flowing demineralized water.

There may be some considerations concerning the use of organic materials in certain critical places. However, as ISX is expected to be baked, these are not expected to be a problem. The use of rubber O-rings must be restricted to places where metal-to-metal contact can be made before the O-ring vacuum seal.

Vacuum pump ports will be covered with metal screening to avoid the loss of microwave power.

7. SUMMARY

The preceding sections have endeavored to show that promising regimes of auxiliary heating can be obtained by ECH in tokamaks. Our specific near-term goals for ISX are: bulk heating, profile heating, breakdown studies to control runaways and the initial current channel, and discharge cleaning.

A longer-term goal would be a major bulk or profile heating experiment on ORMAK Upgrade. Breakdown studies would rate high on a priority list if sufficient power was not available for bulk heating.

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FIGURE LIST

Caption

Fig. 1. ORNL-DWG 76-3598

Clemmow-Mullaly-Allis diagram for a cold electron plasma.

Fig. 2a. ORNL-DWG 76-3599

Cross section of ISX with a low density plasma and cyclotron resonance in the plasma center. The plasma density maximum is such that $\omega_{pe} < \omega_{ce}$.

Fig. 2b. ORNL-DWG 76-3597

Same as Figure 2a, but with a higher density plasma, such that $\omega_{pe} > \omega_{ce}$.

Fig. 2c. ORNL-DWG 76-3596

Same as Figures 2a and 2b, but with much higher density plasma, such that $\omega_{rf} < \omega_2$.

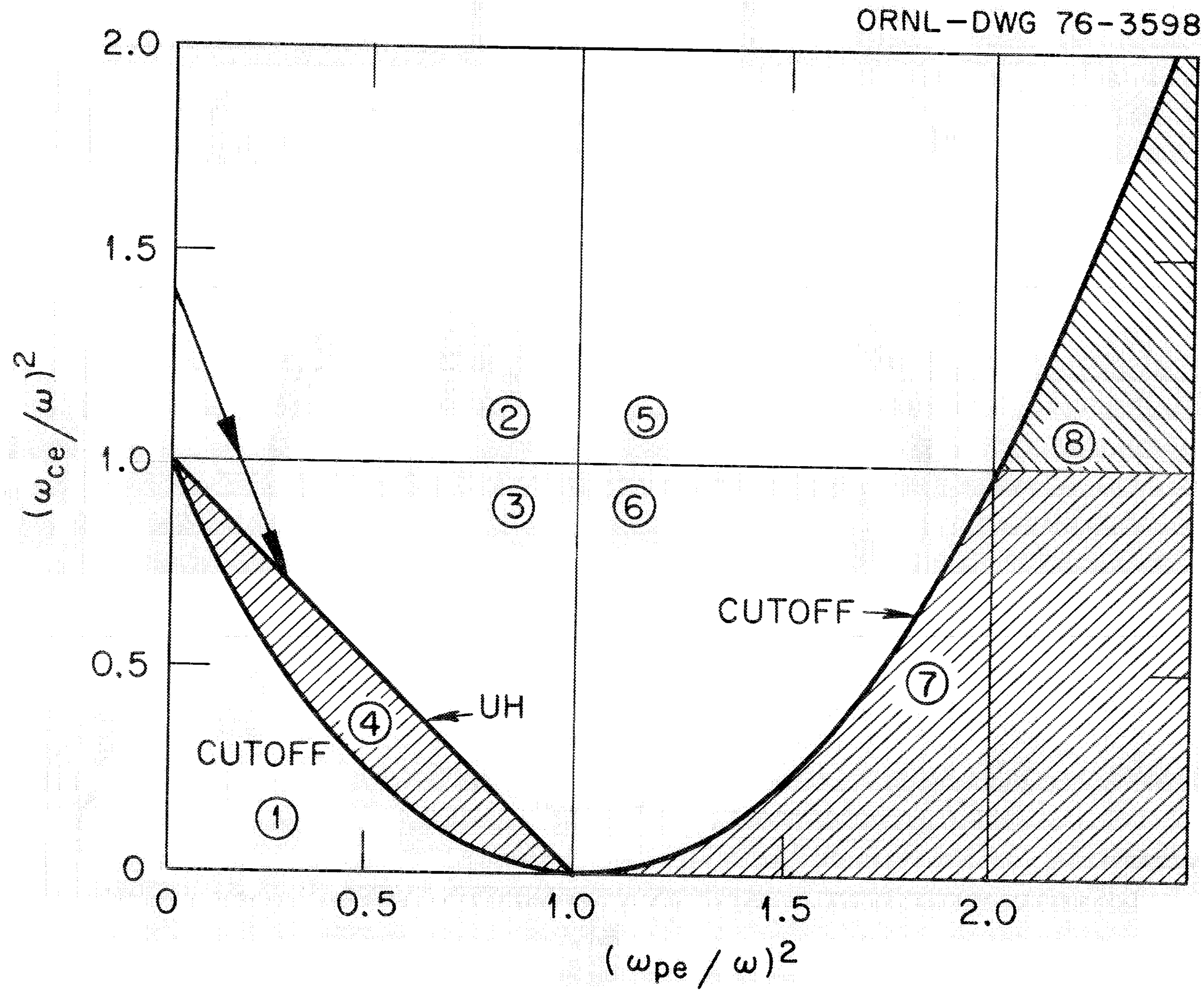
ORNL-DWG 76-3598
2.0
1.5
1.0
0.5
0
$(\omega_{ce}/\omega)^2$
0
0.5
1.0
1.5
2.0
$(\omega_{pe}/\omega)^2$
1
2
3
4
5
6
7
8
CUTOFF
UH
CUTOFF

Fig. 1

ORNL-DWG 76-3599

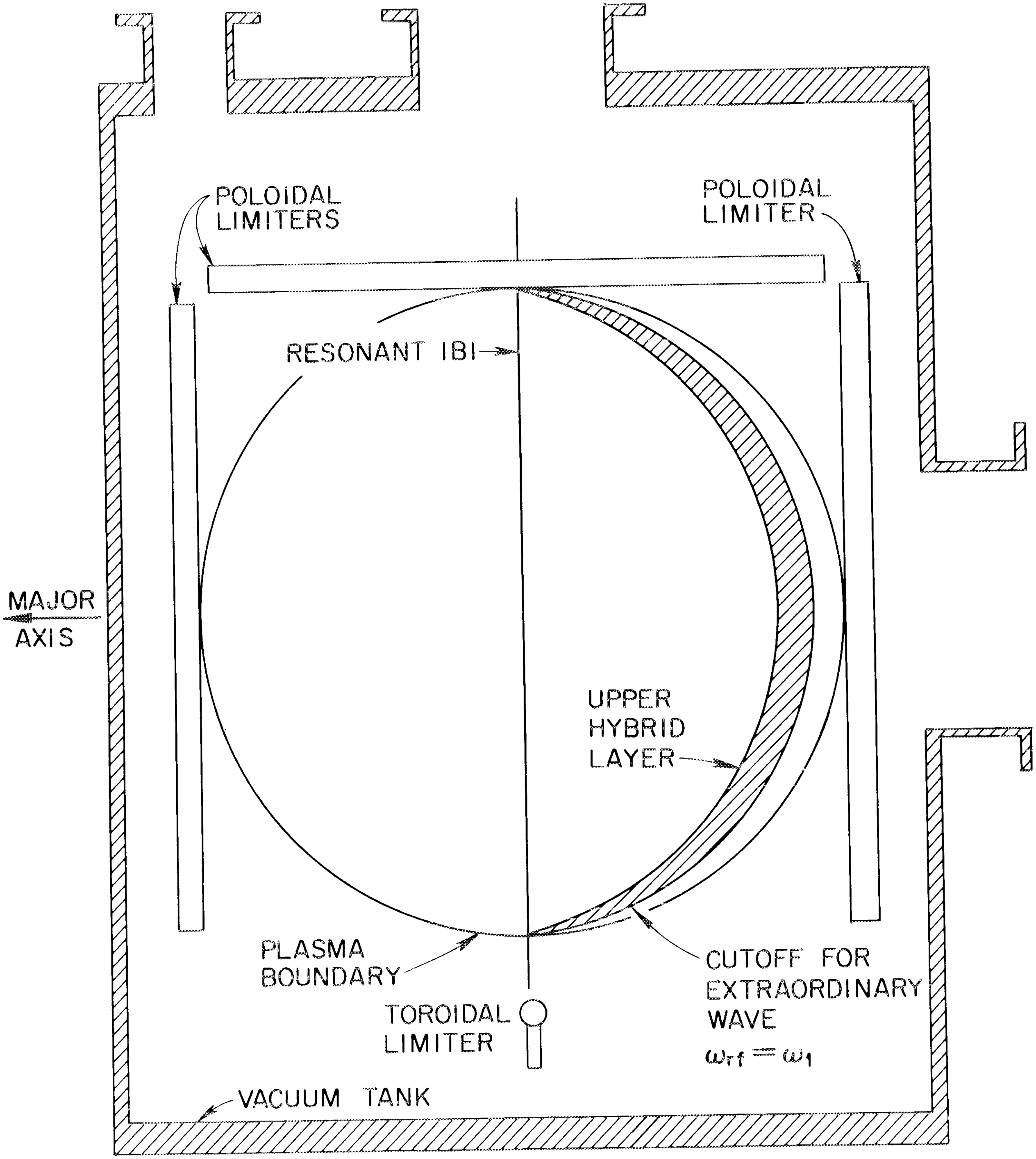

Fig. 2a

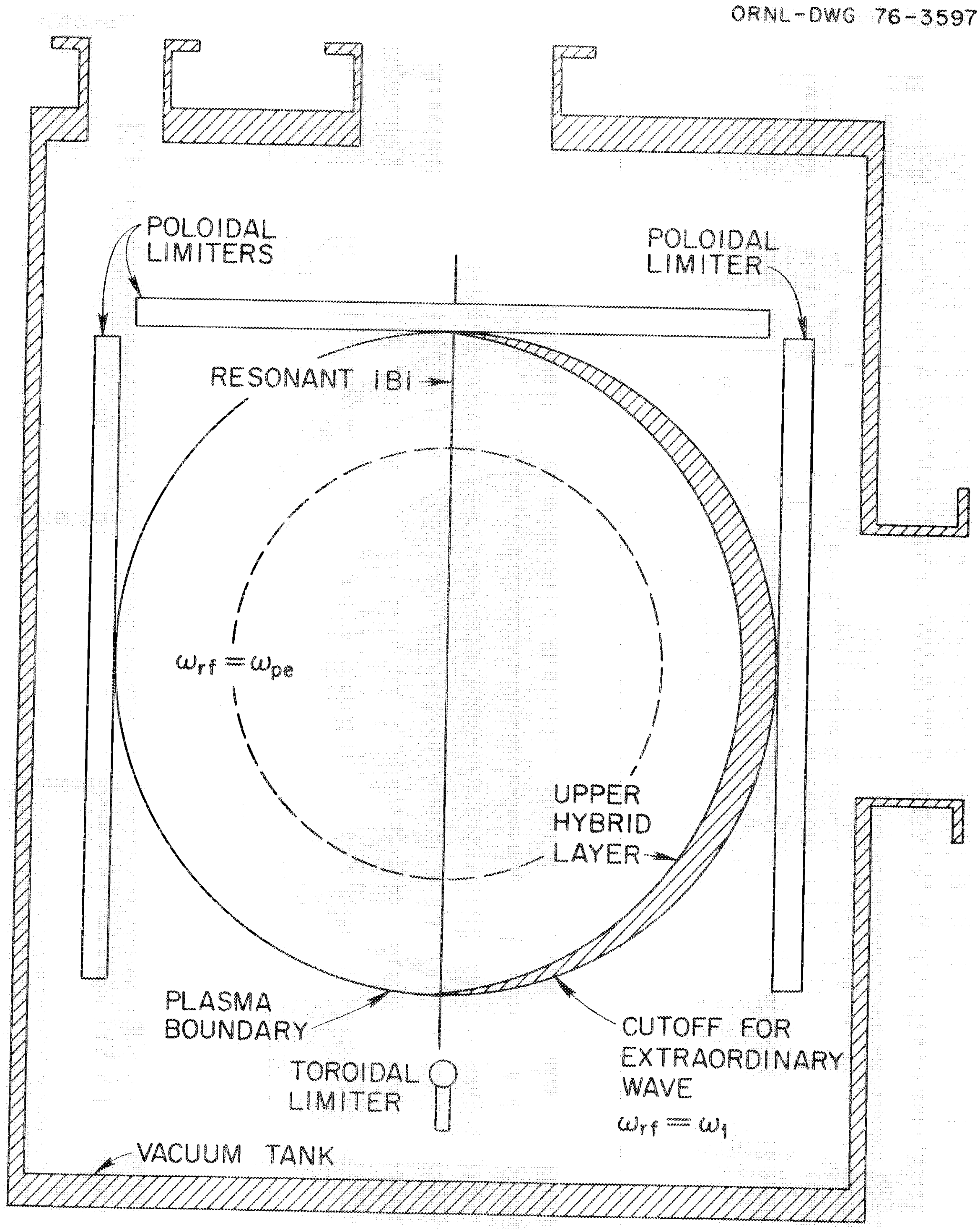
ORNL-DWG 76-3597
POLOIDAL LIMITERS
POLOIDAL LIMITER
RESONANT |B|
$\omega_{rf} = \omega_{pe}$
UPPER HYBRID LAYER
PLASMA BOUNDARY
CUTOFF FOR EXTRAORDINARY WAVE
$\omega_{rf} = \omega_1$
TOROIDAL LIMITER
VACUUM TANK

Fig. 2b

ORNL-DWG 76-3596

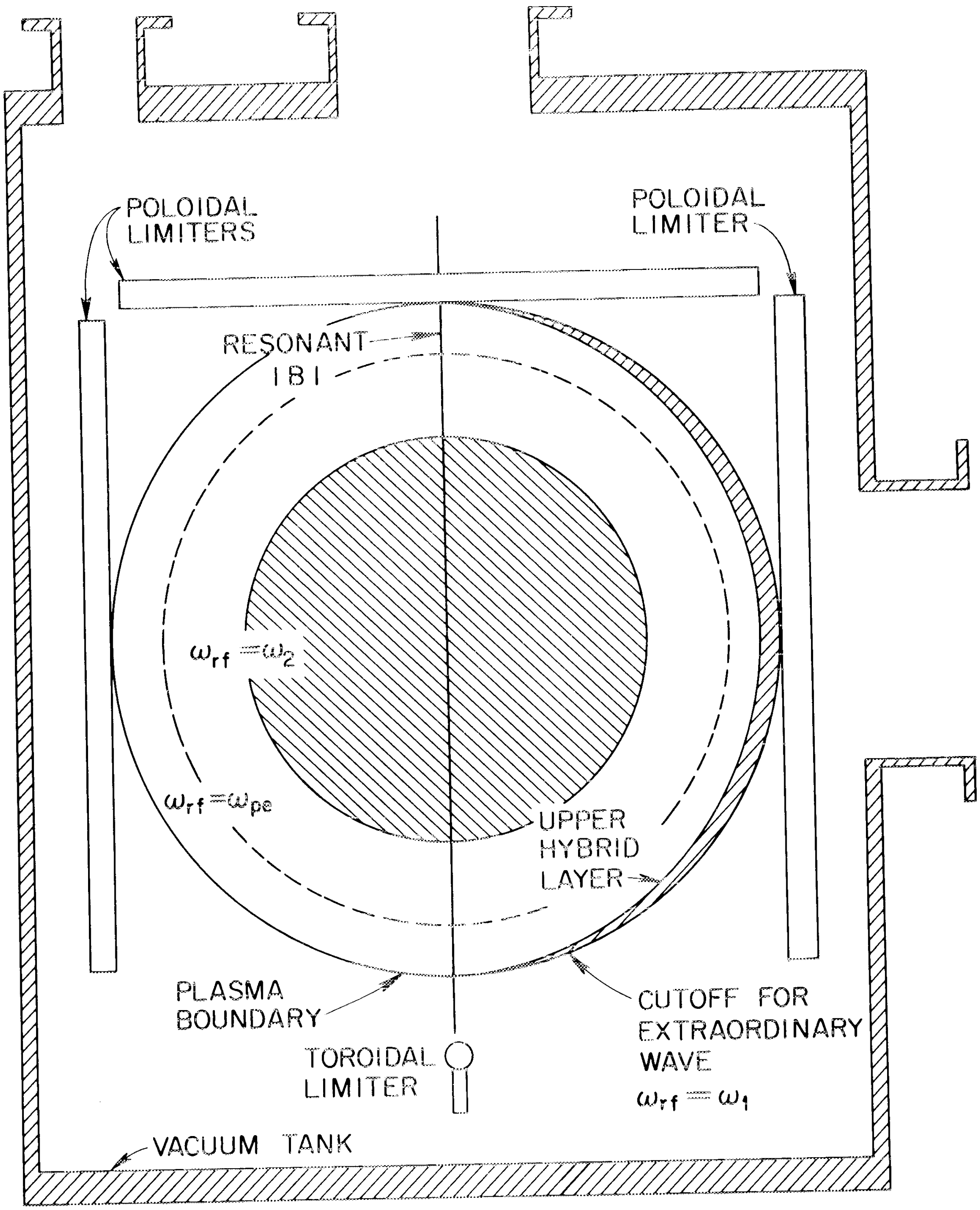

Fig. 2c

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