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PLT ION CYCLOTRON RANGE OF FREQUENCIES HEATING PROGRAM

By

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PLT ION CYCLOTRON RANGE OF FREQUENCIES HEATING PROGRAM

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ABSTRACT- Measurements of energetic ions, impurity influx, recycling, and Bernstein waves generated in the plasma core are described for ICRF heating in PLT. Such measurements are being used for several launchers in order to optimize rf power deposition and discharge conditions. Preparations are underway to extend operation to higher rf power levels (~ 5 MW) for the best attainable PLT conditions to permit more reactor-relevant extrapolations.

I. Introduction

The PLT research program is directed toward two main objectives: first to evaluate rf heating and current drive methods of potential benefit to larger fusion devices and reactors, and second, to extend PLT operation to plasma conditions as close as possible to those contemplated for these larger devices in order to permit relevant extrapolations of performance. In support of the first objective, the program emphasis is placed on wave physics (coupling, penetration, absorption) and heating and current drive effects (efficiency, particle energy distributions, confinement and transport, stability, and edge conditions). To achieve the second objective there is a continuing effort to maximize power input through source and launcher system development, to optimize the power deposition profile, and to control the plasma edge conditions including provision for high thermal loading on limiters and launchers.

In this paper we describe the status of our evaluations of minority ion fundamental and majority ion second harmonic cyclotron heating regimes studied on PLT, and the preparations being made for higher power experiments (up to ~ 5 MW) under the best PLT discharge conditions attainable.

II. Status of ICRF Heating Evaluations

Very promising heating results obtained on PLT in both the minority ion fundamental and majority ion second harmonic ICRF heating regimes have been reported previously for rf powers up to ~ 3 MW.[1-4] Notably, deuterium ion temperatures of T_d ~ 3 keV have been attained in both the ^{3}He minority regime at an electron density of $\bar{n}_e$ ~ 3 × 10^{13} cm^{-3} and in the H minority regime in conjunction with deuterium neutral beam heating at $\bar{n}_e$ ~ 6 × 10^{13} cm^{-3}. Hydrogen average ion energies up to $\langle E_H \rangle$ ~ 4 keV have been achieved in the second harmonic regime at $\bar{n}_e$ ~ 4 × 10^{13} cm^{-3}. These results when combined with theoretical projections support the scientific feasibility of utilizing the combined minority-second harmonic regime (minority ^{3}He - second harmonic T; minority H-second harmonic D) for heating a reactor to ignition. This combined scenario leads to non-Maxwellian heating of the fuel ions from a cold start-up condition and provides for greater reactivity.

In order to enhance our confidence in the scaling of these results to the reactor regime, we are investigating the details of the plasma effects occurring during the rf heating, the physics of the waves launched into the plasma, and the appropriateness of the modelling used in the extrapolations. Particular emphasis is being placed on studies of energetic ions, impurity influx, and recycling, during ICRF heating for wave excitation with several couplers. Concurrently, we are preparing the launcher and source systems for higher power operation under the best possible PLT discharge conditions.

II.a Energetic Ions

Since heating for both the minority and second harmonic regimes occurs via energetic ion "tail" production, it is imperative that these energetic ions be well confined to obtain maximum heating efficiency and to avoid deleterious effects on the plasma equilibrium and stability. It has been shown earlier that the plasma current in PLT must be maintained at values above ~ 300 kA to prevent a precipitous drop in ion heating efficiency and the simultaneous influx of impurities from the plasma edge[5,6] concomitant with the predicted loss of energetic ions from the plasma core. More recent investigations of the energetic ions have been made at elevated plasma currents with direct charge exchange and particle bolometer probe measurements in an attempt to determine their contribution to energy losses and surface material erosion.

During H minority heating in a deuterium plasma, a horizontally-scanning charge exchange analyzer is being used to observe counter-going or co-going energetic ions.[7] As expected, the energetic hydrogen flux for counter-going ions is observed to increase toward the near-perpendicular viewing angle. However, it is discovered that for co-going ions, the maximum flux occurs between the perpendicular and parallel sightlines. This maximum in flux is interpreted as corresponding to banana trapped ions whose banana tips lie in the resonance layer, with $V_\perp > V_\parallel$. These ions are detected at the edge of the plasma where the neutral density is high and $V_\parallel$ is comparable to $V_\perp$ as indicated in Fig. 1. Analysis of the phase space ion distributions using a bounce-averaged Fokker-Planck code, which includes a modified Kennel-Engelmann quasilinear operator, is now underway.[8] Preliminary calculated results for the energetic ion distribution have anisotropies qualitatively similar to those observed experimentally and show that banana trapped ions are lost near the plasma boundary.

The emphasis of recent probe work on PLT has been on the use of a rotating calorimeter[9] to determine fast ion losses directly in the plasma edge. This probe consists of a pair of tantalum calorimeter elements fitted with thermocouples which are mounted behind diametrically opposed apertures in a rotating cylindrical graphite housing. At any particular angle of an aperture relative to the magnetic field direction, the probe admits ions of large gyroradius which have a certain range of $V_\perp/V_\parallel$ values. As reported earlier,[4] during H minority heating of a deuterium plasma a large flux is observed at ~ 50° to the outside midplane magnetic field direction which is attributable to particles having $V_\perp/V_\parallel \sim 1.2 - 1.3$ and energies of ≈ 100 keV. Recently, studies have been made using two identical probes, one located in the outside midplane as before, and the other located at the top of the plasma (120° away toroidally) in order to obtain the poloidal dependence of the fast ion losses. No signal has as yet been detected on the top probe even with the probe located ~ 0.8 cm inside the top limiter radius. This result suggests that the ion losses at the surface are dominated by banana trapped ions (supporting the interpretation of the charge exchange measurements).

If the energetic ion losses were poloidally and toroidally symmetric, the observed probe signal would represent ~ 15% of the rf power input. However, the poloidal asymmetry of the flux suggests that the power lost by escaping fast ions is much less than this level (although charge-exchange losses could still be significant). Nevertheless, the loss of these ions on limiters is a major concern with regard to localized heating and material sputtering. A recent analysis of a graphite probe cap (Fig. 2) used for these studies[10] indicates that there may be a synergistic carbon erosion effect between the fast ions and the bulk plasma. The heavily eroded, blackened zone seen in Fig. 2, which is at 50°-60° from the aperture, has been caused by the impact of fast ions. This erosion is much larger than the level expected for either thermal plasma or fast ion bombardment separately. It appears that a small flux of fast ions increases the sputtering rate of the D^+ bulk plasma ions by a factor of ~ 30 to ~ 50. Similar effects for graphite have been reported for surface experiments.[11] It is not known at present whether such a synergism is the result of a special carbon-hydrogen chemistry or whether a similar effect may occur for metals. In any event, it is clear that the flux of energetic ions impinging on the graphite limiters in PLT must be minimized if acceptable levels of carbon impurity are to be maintained during high power rf heating experiments.

Fast ion losses in the case of ^{3}He minority heating of deuterium have not been detected with the bolometer probes in either the midplane or top locations. It is clear from 14.7 MeV proton spectra that very energetic ^{3}He ions (up to 200 keV) are present in the plasma core.[4] Thus, the diffusion of these ions to the surface or the production of trapped ions in the outer region of the plasma is tentatively thought to be much reduced over that for the case of H minority heating. This result if confirmed could lead to less carbon erosion for intensely ICRF heated discharges in the ^{3}He regime.

II.b Centerfed Quarter-Turn Launcher

It is possible that the energetic ion losses observed in the H minority heating case are enhanced by the rf fields produced at the top and bottom of the plasma in the vicinity of the resonance layer by the ends of the half-turn coils employed above. Centerfed quarter-turn coils (Fig. 3) have been installed to better simulate launcher geometries desired for future devices and to remove the launcher elements from the vicinity of the resonance zone. It has been observed that the coupling and heating efficiencies for this launcher are similar to the half-turn launcher case as expected.[12,13] However, ray-tracing theory indicates that this coupler should focus the rf fields toward the plasma core and reduce considerably the surface fields.[14] Initial studies have not shown a clear difference in the charge exchange signals for the half-turn and quarter-turn launchers. However, these signals are extremely sensitive to plasma conditions, especially to plasma density and neutral density profiles, and therefore the experimental uncertainty is large. Future experiments at higher power will be made with additional diagnostics to investigate possible improvements with centerfed couplers.

II.c Impurity Influx

Clearly, it is necessary to minimize high Z impurity influx during ICRF heating in order to minimize radiation energy loss from the plasma core and thereby achieve maximum heating efficiency for stable discharge conditions. As stated earlier, we have found that it is necessary to maintain the plasma current above ~ 300 kA to inhibit serious metal impurity buildup in the plasma core. This requirement is especially important when metal limiters are employed. We have documented saturation of the iron impurity influx at acceptable levels while employing iron limiters and using a low field launcher for rf powers up to ~ 500 kW.[15] This is in marked contrast to the ever increasing metal influx observed on TFR at low values of plasma current for both metal and carbon limiters.[16]

Upon installation of carbon limiters on PLT (1980), the metal impurity levels have dropped substantially for all modes of operation (OH, RF, NB). Radiated power is now found to be dominately at the plasma edge and caused by C and O impurities as illustrated for a typical ^{3}He minority case in Fig. 4. For second harmonic heating, the steady-state radiation levels increase linearly as a function of power, as indicated by the bolometer array and spectroscopic scans in Fig. 5. Total radiated power is found to be ~ 30-35% of the rf power level (a similar result is obtained for minority heating) and the radiated power due to high Z impurities in the plasma core is found to be $\lesssim$ 10% of the rf power.[17]

Even though high Z impurities are not playing a dominant role in the central energy balance in PLT, it is desirable to understand their origin to ensure that they do not impede heating at higher rf powers on PLT and that they can be minimized in larger fusion devices. A series of experiments have been performed using different Faraday shield materials on the half-turn coils and comparing impurity levels between launching with half-turn coils and quarter-turn coils.[13,17] It is clear that the metal surfaces closest to the plasma contribute the most metal impurities (Faraday shield material as opposed to materials on the wall), but that both the shield and wall related impurity levels in the plasma core increase to a higher level during the heating pulse apparently independent of the type of coupler used. This result would be expected for a higher plasma thermal content but also could indicate a change in the metal impurity source rate (recycling condition) or in the impurity transport or in both. A change in the source rate has been documented as the principal cause of the disparity of impurity influx levels at the center of PLT observed between co- and counter-beam injection.[18]

It is more likely that low Z impurities will prove to be the most difficult to control as rf power and especially rf energy throughput to the plasma are increased substantially above the present levels. Carbon limiters must absorb most of the energy. Also, it is possible that the fast ions impinging on the limiter could increase sputtering of the limiter surfaces as discussed earlier for the bolometer probe. If low Z_{eff} operation is to be obtained for intensely heated rf discharges, considerable attention will have to be given to controlling the rf energy deposition at the plasma periphery and especially on the limiter.

II.d Recycling

In addition to an increase in impurities during ICRF heating, there is a density increase which is due primarily to an increase in the deuterium ion density. This result indicates an increase in particle confinement and/or in the source of particles at the plasma periphery. Studies are ongoing to separate out the relative importance of these effects.

There is an increase in the charge-exchange outflux, Γ, during the ICRF heating pulse as measured with a low energy neutral detector (LENS) for discharge with plasma current > 300 kA.[19] With Γ given by the integrated neutral flux between 25 eV and 1 keV, we obtain the two curves of Fig. 6 for top-bottom limiters located first around the torus from the LENS system and then at the same port. It is observed that the OH level of Γ depends strongly on the limiter location as expected, but that the ΔΓ due to the application of ICRF power is essentially independent of the limiter location. Thus, ΔΓ is apparently uniform toroidally (the poloidal uniformity has not been explored). The increase in Γ is measured to be linearly dependent on ICRF power, $\Delta\Gamma \sim 10^{15}\ \mathrm{cm}^{-2}\mathrm{s}\ \mathrm{MW}^{-1}$. The spectrum of the outflux, dΓ/dE, increases more at low (50 eV) and high (10 keV) energies than at energies in between. The increase at higher energy is due mainly to plasma heating, whereas that at lower energy is due to increased recycling and a cooling of the plasma edge. The cause of this increase in recycling is interpreted to be an increase in the deuterium ion flux to the wall which increases the neutral density at the plasma edge and hence the charge exchange rate.

It is noteworthy that ΔΓ is increased significantly for plasma currents below ~ 300 kA as shown in Fig. 7. This current threshold effect parallels that for the ion heating and for the impurity influx discussed earlier and suggests that fast ion losses may trigger the increase in recycling.

II.e Wave Studies

To extend our understanding of the properties of the waves excited in the plasma we continue to investigate the fast wave coupling and damping properties via coil loading measurements, magnetic probe measurements, and comparison of eigenmode properties (when observable) to theoretical predictions.[20] In addition, we have begun to make direct microwave scattering measurements of the ion Bernstein waves inside the plasma. Such measurements should lead to a much more quantitative prescription of the fate of the rf wave energy delivered to the plasma and assist in determining the degree of control which can be exercised over the rf power deposition in the plasma cross section.

Observations of the mode conversion of the fast magnetosonic waves into ion Bernstein waves at the ion hybrid layer have been reported earlier for the TFR[21] and Micrator[27] tokamaks. With a 2 mm heterodyne microwave scattering system, we have clearly identified the same phenomenon in PLT during ICRF heating of a two component plasma. The scattering geometry has been set to detect fluctuations of the electron density having their wavevector along the minor radius at a fixed location in the equatorial plane, 10 centimeters from the plasma center on the high field side. The spatial resolution in the equatorial plane is ≈ 3 cm giving a wavenumber resolution of $\Delta k \approx \pm 1\ \mathrm{cm}^{-1}$. The spatial resolution perpendicular to the equatorial plane is dependent on the scattering angle; for a detected wavenumber of 6 cm^{-1}, it is ≈ 10 cm. Thus, relatively well-localized measurements for relatively well-selected k values are possible.

The identification of the detected density fluctuations as ion Bernstein waves driven by the launched fast waves is based on the dependence of their amplitude on the minority concentration and toroidal magnetic field, and on the direction of their phase velocity. The time evolution of density fluctuations measured during an rf pulse for $k \approx 11\ \mathrm{cm}^{-1}$ is shown in Fig. 8a. These data have been obtained with an outside antenna in the ^{3}He minority regime for which the ^{3}He concentration varies from 20% (of n_e) to 5% from the beginning to the end of the rf pulse. Density fluctuations are observed only during the time interval when the minority concentration has the value necessary to localize the ion Bernstein waves with $k \approx 11\ \mathrm{cm}^{-1}$ in the region of observation. Figure 9 demonstrates that at the time of maximum amplitude, the theoretical dispersion curve crosses the detection region.

The density fluctuation amplitude dependence on magnetic field for constant minority concentration is shown in Fig. 10 for $k \approx 4.5\ \mathrm{cm}^{-1}$. Again fluctuations are observed only in that narrow range of toroidal field values for which the dispersion curve crosses the detection region.

Ion Bernstein waves are backward waves and since their group velocity must be toward the high field side of the plasma due to the nature of their generation (Fig. 9), their phase velocity must be directed toward the low field side. A comparison of density fluctuations is made in Fig. 1 for the phase velocity directed toward the (a) low field side versus (b) the high field side. Obviously, the detected waves have the phase velocity direction of Bernstein waves.

In the case of second harmonic heating of a hydrogen plasma it has been found that the antenna loading does not generally exhibit high Q eigenmodes as originally expected.[1] An extensive experimental investigation and theoretical analysis[20] has revealed that (1) fast mode overlap and dispersion properties account for some of the smoothing of the loading, and (2) ion Bernstein wave generation must be included in the theory to provide an adequate enhancement of the wave damping to give the fast mode Q values measured. Recently, ion Bernstein waves have been observed in the second harmonic regime in PLT as shown in Fig. 11. Here the density fluctuations are plotted versus the ratio of the rf frequency (90 MHz) to the second harmonic frequency at the detection region for $k \approx 7.5\ \mathrm{cm}^{-1}$. Again, the fluctuations are observed only when the Bernstein branch of the dispersion curve crosses the detection region.

III. High Power ICRF Heating Under Optimum PLT Conditions

Preparations are underway to provide for routine high power ICRF operation in PLT. Emphasis is being placed on providing the highest source power possible, delivering that power to the desired waves in the plasma via improved antenna system designs, and developing machine hardware capable of handling large energy throughput while providing for acceptable plasma equilibrium conditions (impurity levels, confinement, stability, etc.).

Since the ion heating efficiency is highest for the ^{3}He minority regime, we are converting all three of the existing rf sources to 30 MHz so that we can explore this regime at a power level up to ~ 5 MW at a relatively high toroidal field of ~ 30 kG. Baldur code projections based on the model employed to simulate earlier heating results[3] suggest that we should obtain $T_d \gtrsim 5$ keV for $\bar{n}_e \sim 4 \times 10^{13}$ cm^{-3} at this elevated power level. Of course, such a projection presupposes that we will be able to maintain the ion energy confinement at approximately the level for the lower power experiments. This frequency selection also permits high power exploration of the minority hydrogen regime at ~ 20 kG and of the second harmonic hydrogen regime at ~ 10 kG. Thus, the β transition from minority H to second harmonic D may be attainable at 20 kG and relatively high β conditions can be explored in both regimes (an additional 1.5 MW of NB power is also available).

Additional preparations for delivering ~ 5 MW of rf power to the PLT plasma include the development of high voltage rf feedthroughs, studies of various launcher designs in PLT - $1/2$ turn low field, $1/4$ turn low field, $1/2$ turn high field fast wave couplers, and low field electrostatic wave couplers -

for optimizing rf power deposition, conceptual studies of Faraday/thermal shield designs for high energy operation, and implementation of a rotating pumped (or gaseous) limiter on PLT for edge (and possibly confinement) control. A cone-type feedthrough[6] has been tested to stand off voltages in excess of 100 kV and in recent operation on PLT has sustained ~ 600 kW operation (limited by source power) without exhibiting breakdown. We expect this feedthrough to permit each coil on PLT to operate at $P_{rf} > 1$ MW. The rotating pumped limiter shown in Fig. 12 has been operated on a test stand to temperatures of ~ 600°C and is now functional on PLT. The rotational feature of this limiter should approximately double its energy handling capability and could ameliorate the erosion due to fast ion bombardment.

Other discharge control techniques will be explored as well. In particular, electron cyclotron heating and pellet injection may provide improvements in power deposition and in controlling surface heating and recycling. Also, additional rf relevant diagnostics will be added to better document the heating characteristics. Notable among these is neutral beam assisted charge-exchange spectroscopy which permits measurement of the fully stripped minority ^{3}He, C,O, etc., bulk properties in the core of the plasma.[23]

The study of second harmonic hydrogen heating is being extended to the better PLT confinement regime at higher toroidal field. Presently, experiments are underway at ~ 300 kW with a 90 MHz source (~ 30 kG), and in the near future construction of a 1.5 MW, 80 MHz source (~ 27 kG) will be completed. These sources will permit direct comparison of second harmonic heating with minority ^{3}He heating for similar discharge conditions.

IV. Discussion

Efficient wave coupling and heating have been established for both the minority and second harmonic regimes for powers up to ~ 3 MW. In these studies, the energy content of the ions increases linearly with the rf power level, whereas the global energy confinement (including electron energy) decreases with power in a manner qualitatively similar to that for neutral beam heating.[4] Identification of effects which could produce this result are under investigation. In particular, fast ion losses not taken into account in the energy balance are described in this paper. However, present data suggest the direct energy loss by escaping fast ions is not significant. Thus, we are concentrating our efforts on better understanding the response of the total plasma equilibrium to the ICRF heating, especially with regard to impurity influx and recycling as outlined in this paper, and, ultimately, confinement. In this endeavor, we are also concentrating our rf power at frequencies (5 MW, 30 MHz; 1.5 MW, 80 MHz) which are compatible with higher field PLT operation and consequently with better confinement generally.

Studies of impurity generation and transport during ICRF heating on PLT lead us to conclude that the metal impurities come primarily from the Faraday shields and to a lesser extent from the vessel wall. However, the level of metal impurities is not of primary concern in PLT since $\lesssim$ 10% of the rf power is radiated by them under normal operating conditions. Instead, the level of carbon impurities coming from the limiter is the major concern for high power heating on PLT. It is very important that the limiter be maintained below ablation temperature and that local erosion due to fast ion bombardment be minimized if reasonably low Z_{eff} discharge conditions are to be maintained.

Enhanced recycling effects during ICRF heating on PLT appear to be localized at the wall and to result from a higher, colder neutral density population being produced near the wall. It is suspected that this condition results from the increased inflow of charge-exchange neutrals from the bulk plasma. However, the recycling is strikingly enhanced at low plasma current (< 300 kA) as is metal impurity influx into the plasma. These results could suggest that a sufficient loss of fast ions serves as a catalyst to produce a global change in the discharge equilibrium, e.g., by changing the plasma potential as has been observed recently for co- versus counter-neutral beam operation on ISX-B.[24] In any event, the enhanced recycling is a major contribution to the increase in deuterium density during the ICRF heating pulse and could be responsible as well for the low level of wall impurities entering the plasma.

Finally, we are attempting to optimize rf power deposition, and, consequently, heating efficiency and energy confinement, through launcher optimization. Tests with various couplers and wave measurements such as described in this paper are being used to determine the control that it is possible to achieve with antenna selection over the rf fields generated in the plasma. These measurements are also vital for extrapolating the ICRF heating results for intensely heated PLT discharges to future devices.

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FIGURE CAPTIONS

Fig. 1 Fast neutral flux versus $V_{\parallel}/V$ derived from the detector tangency radius at three energies during ICRF heating (I_p = 450 kA, B_{ϕ} = 29 kG, f = 42 MHz).

Fig. 2 Two views of graphite probe cap eroded at fast ion impact location.

Fig. 3 Centerfed quarter-turn coils.

Fig. 4 Total radiated power and abel inverted profiles during ^{3}He minority heating ($P_{rf} \sim 700$ kW, rf at 400 to 600 msec).

Fig. 5 Total radiated power and brightness of several impurity lines versus rf power during second harmonic heating ($\bar{n}_e = 3.8 \times 10^{14}$, B_{ϕ} = 14 kG).

Fig. 6 Neutral flux in the energy range 25-1000 eV during ohmic and ICRF heating phases of the discharge. The upper curve gives the flux with the top-bottom limiters at the detection port while the lower curve gives the flux measured with these top-bottom limiters removed.

Fig. 7 Change in the neutral flux during ICRF heating versus plasma current at P_{rf} = 520 kW.

Fig. 8 Microwave scattering signal for $k \cong 11$ cm^{-1} during ICRF heating pulse in a D-^{3}He plasma with $n_{^3He}/n_e$ varying from 20% to 5%.

a. phase propagation towards the low magnetic field side.

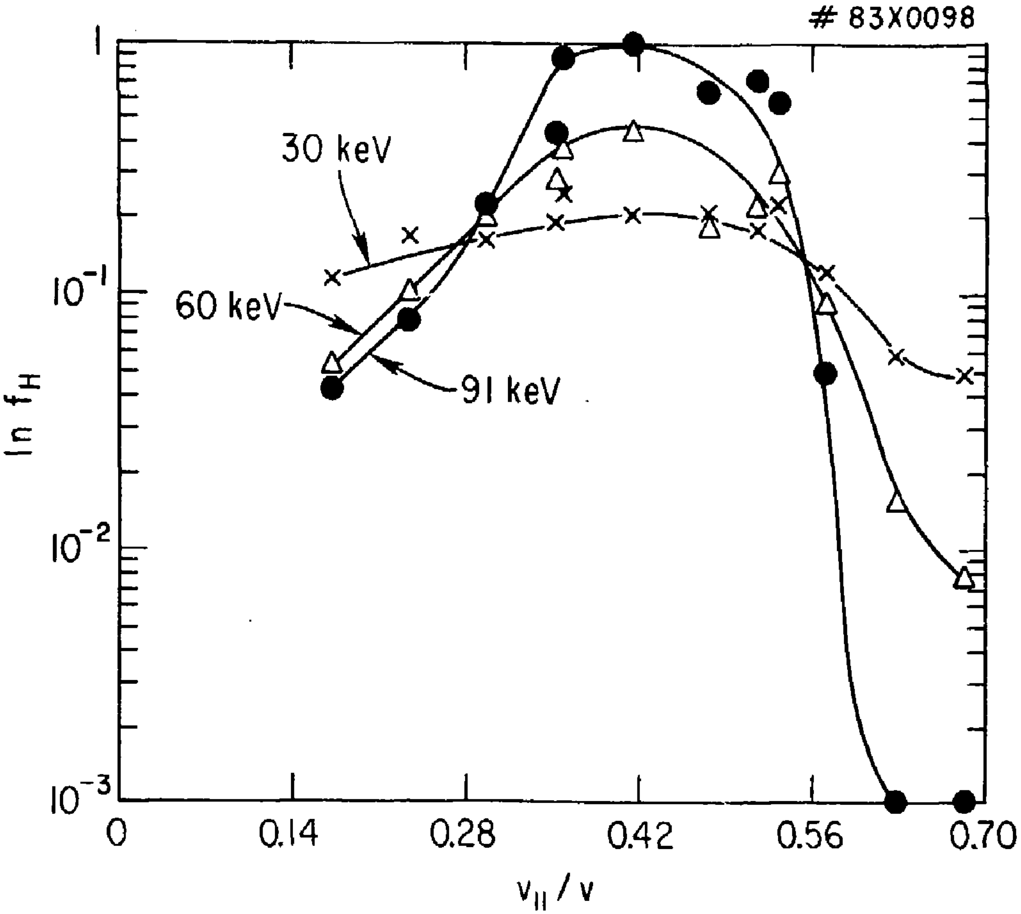
b. phase propagation toward the high magnetic field side.

Fig. 9 WKB kinetic dispersion curve with $n_{\parallel} = 10$, $T_i(o) = 750$ eV, $n_e(o) = 3 \times 10^{13}$ cm^{-3}, $n_{^3He}/n_e$ = 15%.

Fig. 10 Microwave scattering amplitude for $k \cong 4.5$ cm^{-1} in D-^{3}He plasma ($n_{^3He}/n_e$ = 8%) during ICRF heating versus the central B_{ϕ}.

Fig. 11 Microwave scattering amplitude for $k \cong 7.5$ cm^{-1} in H plasma during second harmonic heating versus the applied frequency normalized by the local ion cyclotron frequency ($f = 90$ MHz, $P_{rf} \sim 100$ kW, $\bar{n}_e = 2 \times 10^{13}$ cm^{-3}).

Fig. 12 Rotating pumped limiter on PLT.


83X0098
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10^{-1}
10^{-2}
10^{-3}
ln f_H
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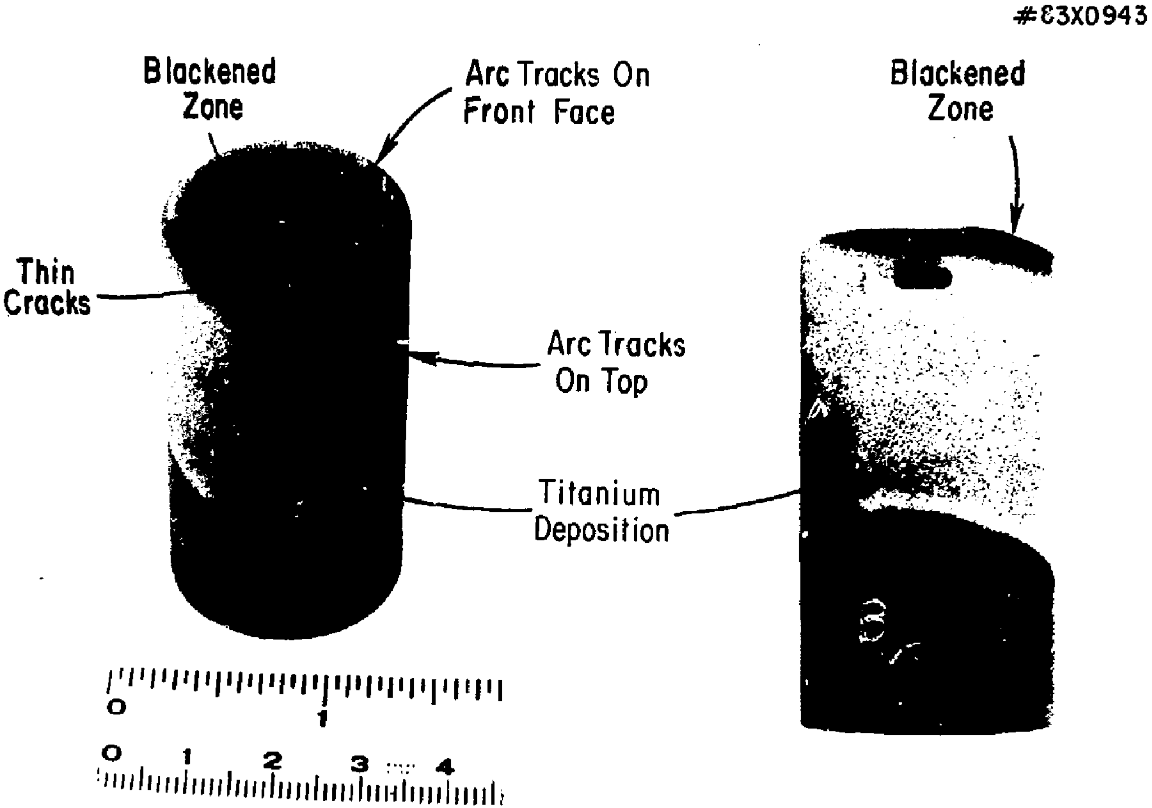
$v_{\parallel}/v$
30 keV
60 keV
91 keV

Fig. 1


#83X0943
Blackened Zone
Arc Tracks On Front Face
Thin Cracks
Arc Tracks On Top
Titanium Deposition
Blackened Zone
0
1
0 1 2 3 4

(a)

(b)

Fig. 2

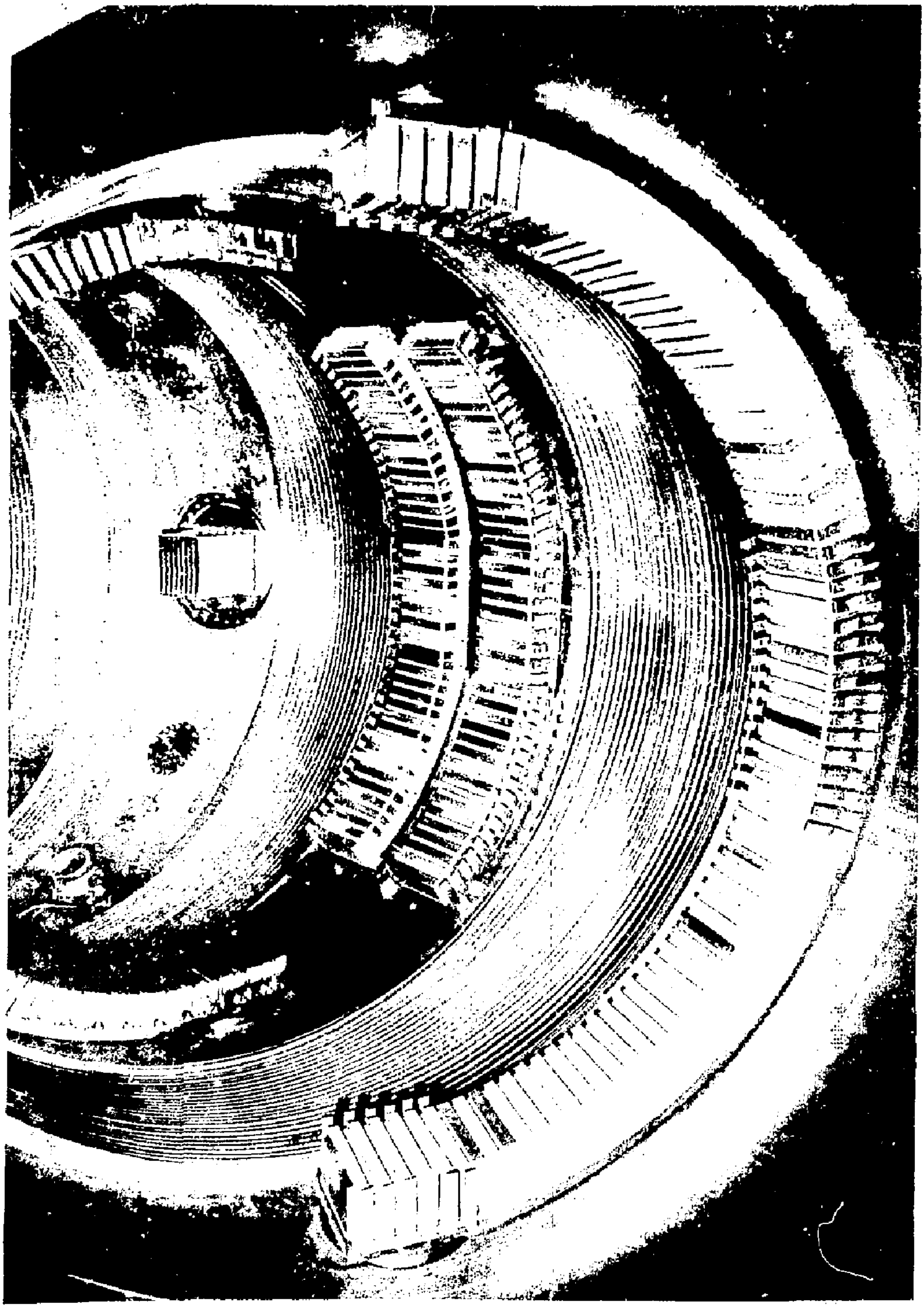
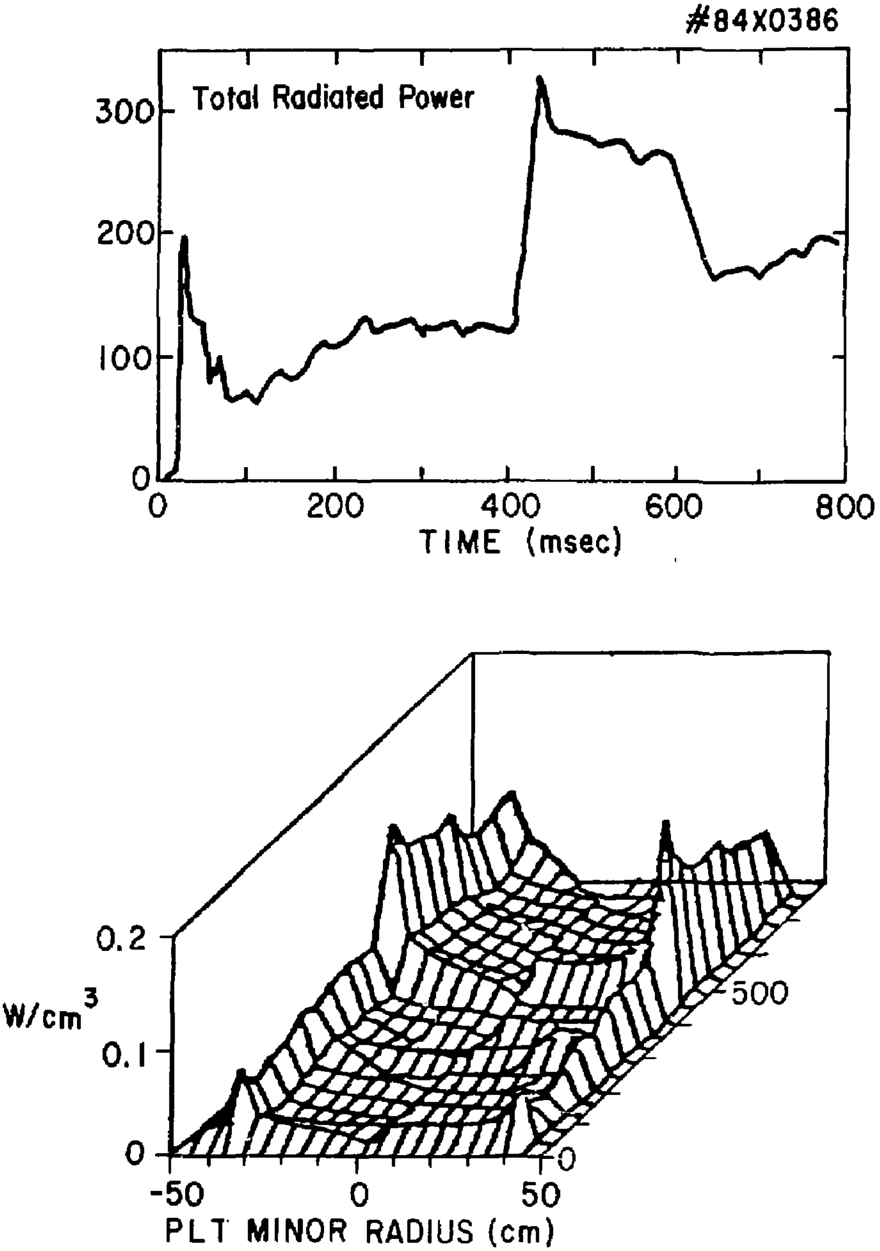


Fig. 3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200
100
0
0
200
400
600
800
TIME (msec)
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W/cm^3
0.1
0
-50
0
50
PLT MINOR RADIUS (cm)
500
0

Fig. 4

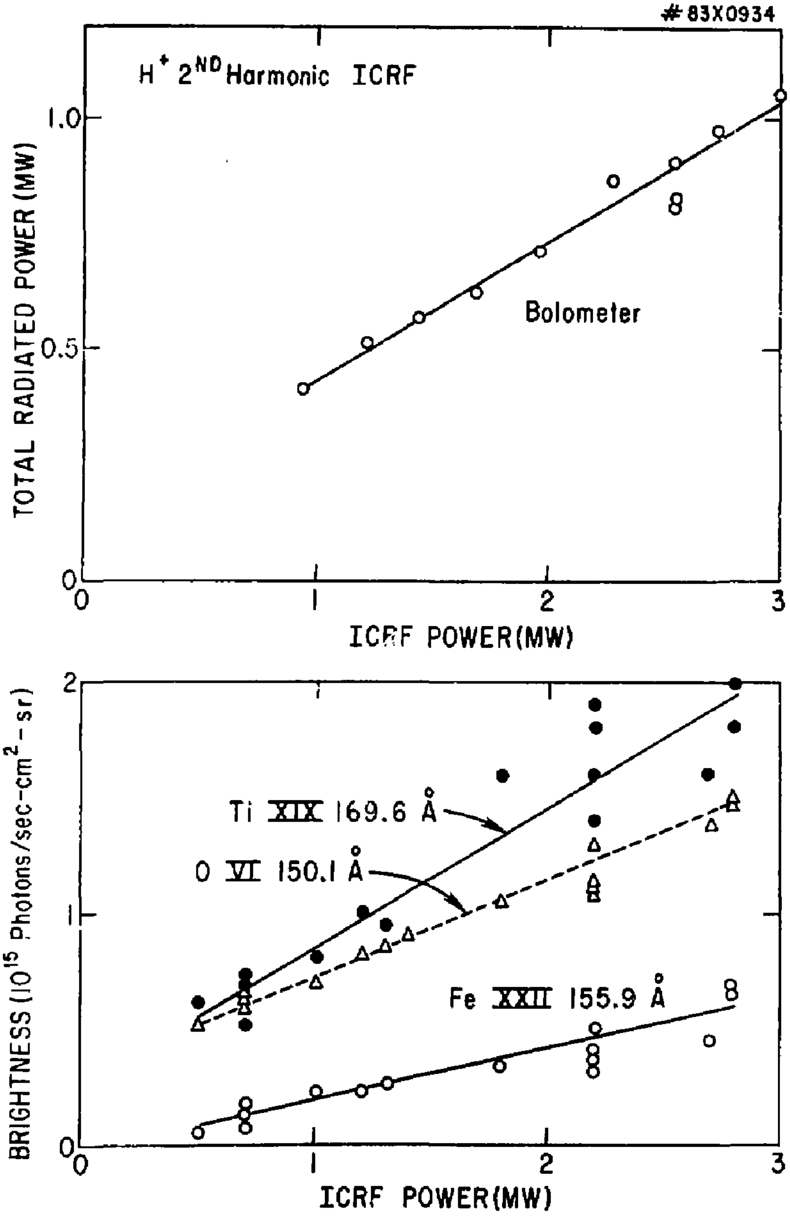

#83X0934
H⁺ 2ND Harmonic ICRF
TOTAL RADIATED POWER (MW)
1.0
0.5
0
Bolometer
0
1
2
3
ICRF POWER(MW)
BRIGHTNESS (10^15 Photons/sec-cm^2-sr)
2
1
0
Ti XIX 169.6 Å
O VI 150.1 Å
Fe XXII 155.9 Å
0
1
2
3
ICRF POWER(MW)

Fig. 5

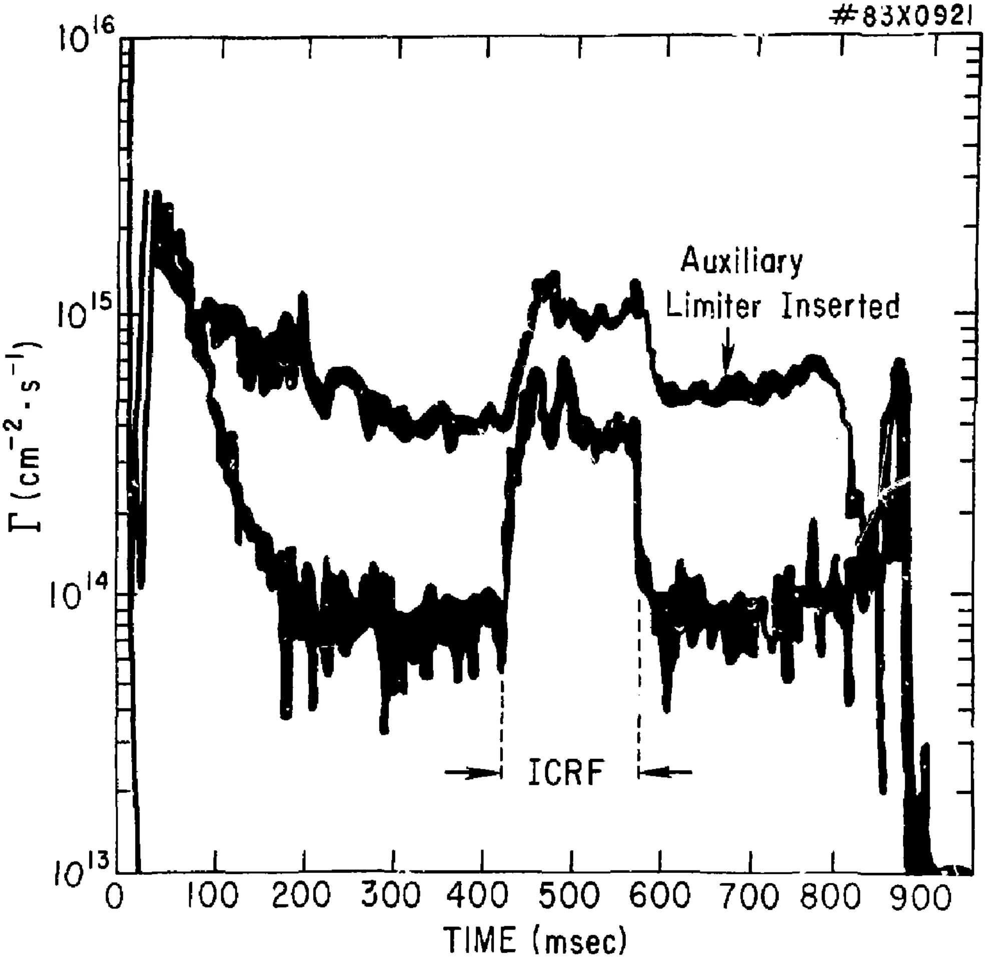
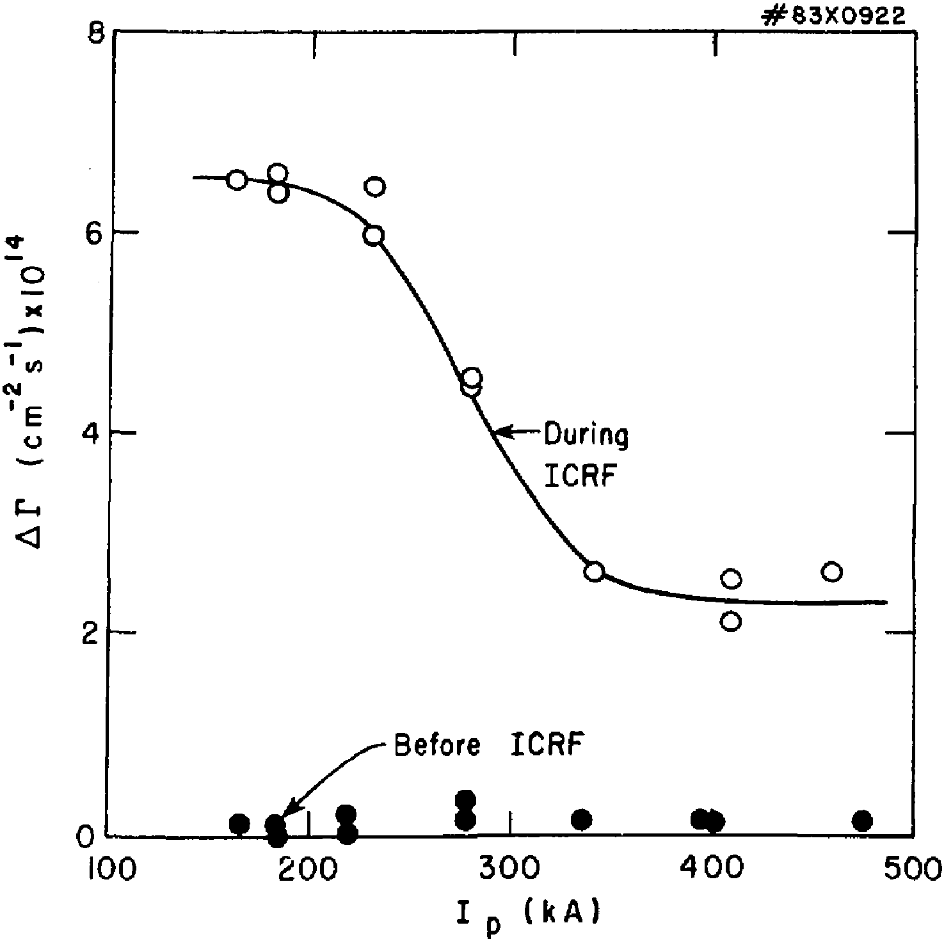

#83X0921
10^{16}
10^{15}
10^{14}
10^{13}
$\Gamma\,(cm^{-2}\cdot s^{-1})$
Auxiliary
Limiter Inserted
ICRF
0
100
200
300
400
500
600
700
800
900
TIME (msec)

Fig. 6



#83X0922
$\Delta\Gamma$ $(cm^{-2}s^{-1})\times10^{14}$
0
2
4
6
8
100
200
300
400
500
I_p (kA)
During ICRF
Before ICRF

Fig. 7

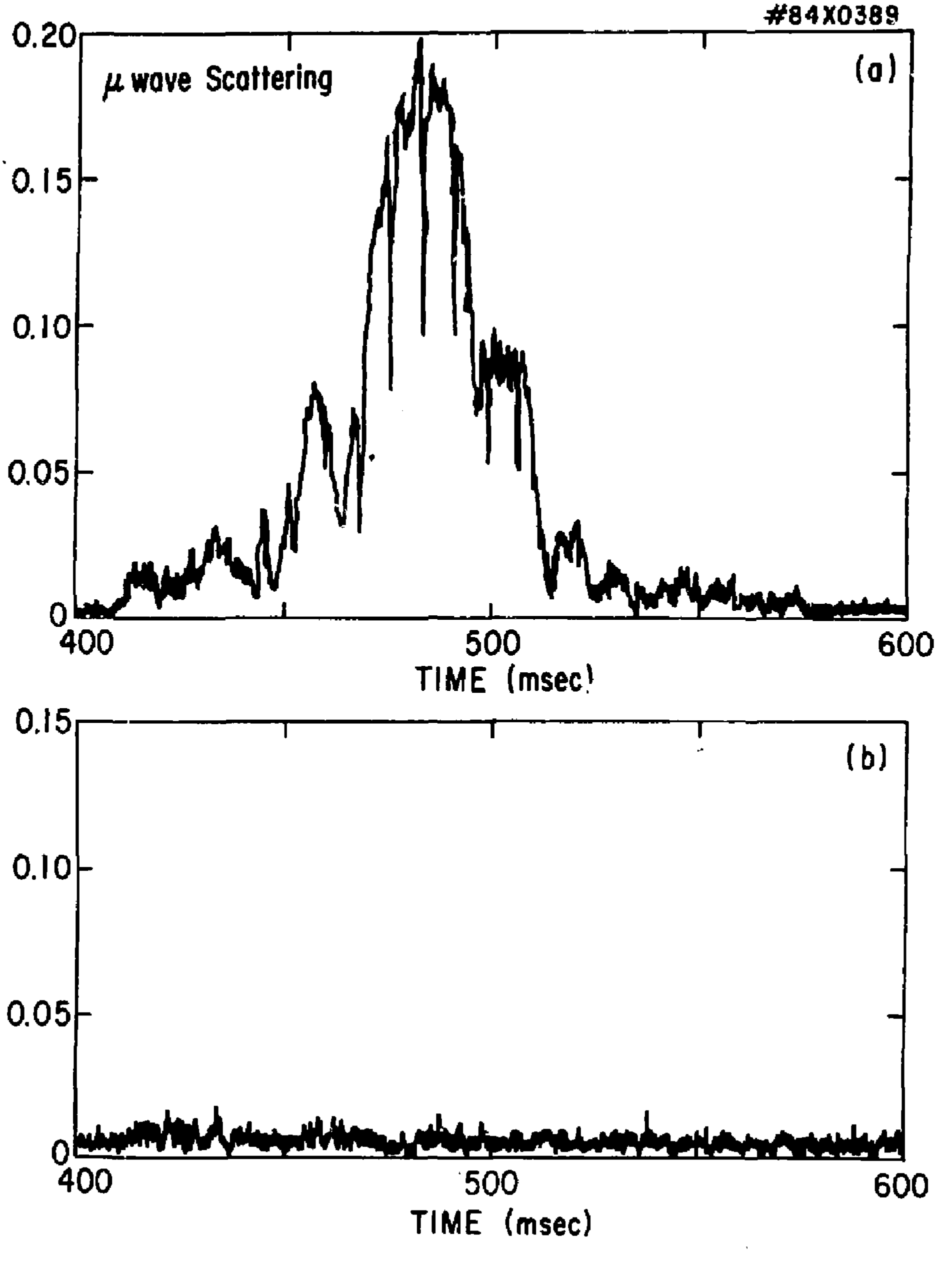

#84X0389
μ wave Scattering
(a)
0.20
0.15
0.10
0.05
0
400
500
600
TIME (msec)
(b)
0.15
0.10
0.05
0
400
500
600
TIME (msec)

Fig. 8

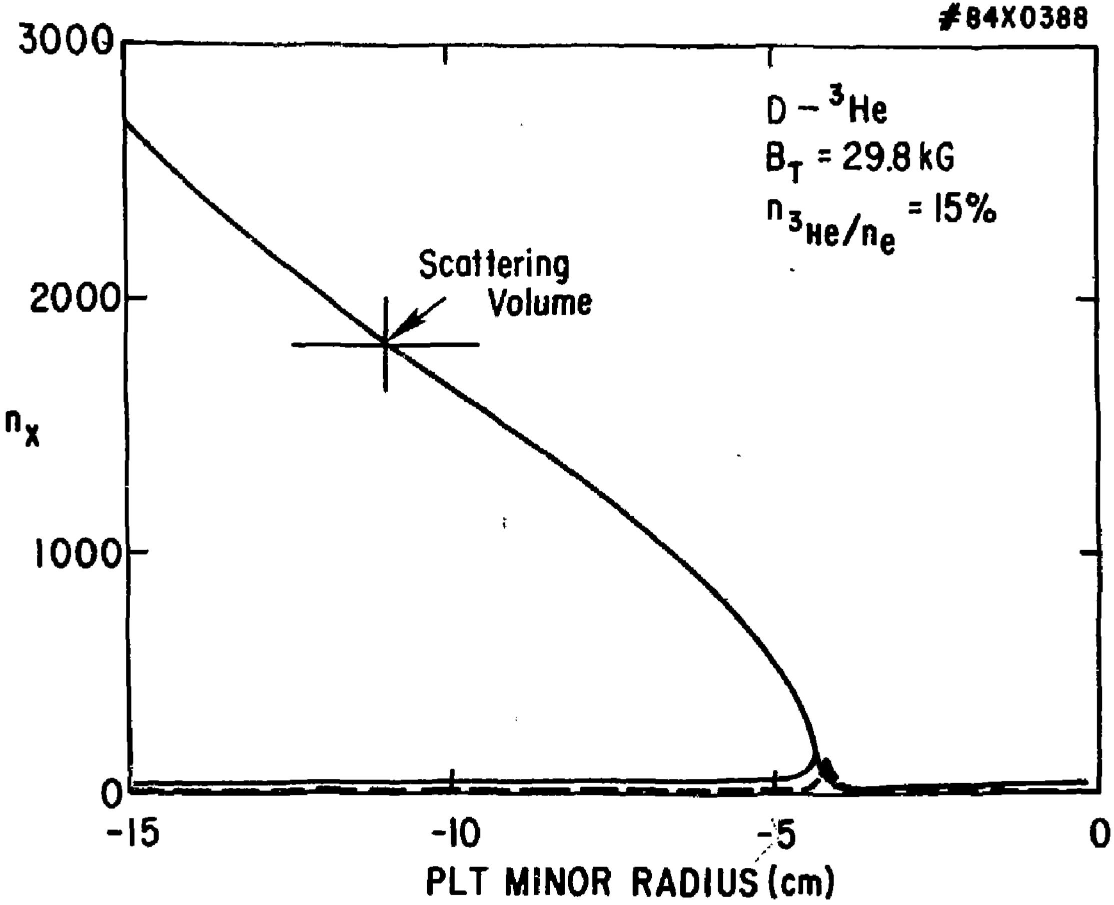

#84X0388
D – ^{3}He
B_T = 29.8 kG
$n_{^3He}/n_e$ = 15%
Scattering Volume
n_x
3000
2000
1000
0
-15
-10
-5
0
PLT MINOR RADIUS (cm)

Fig. 9

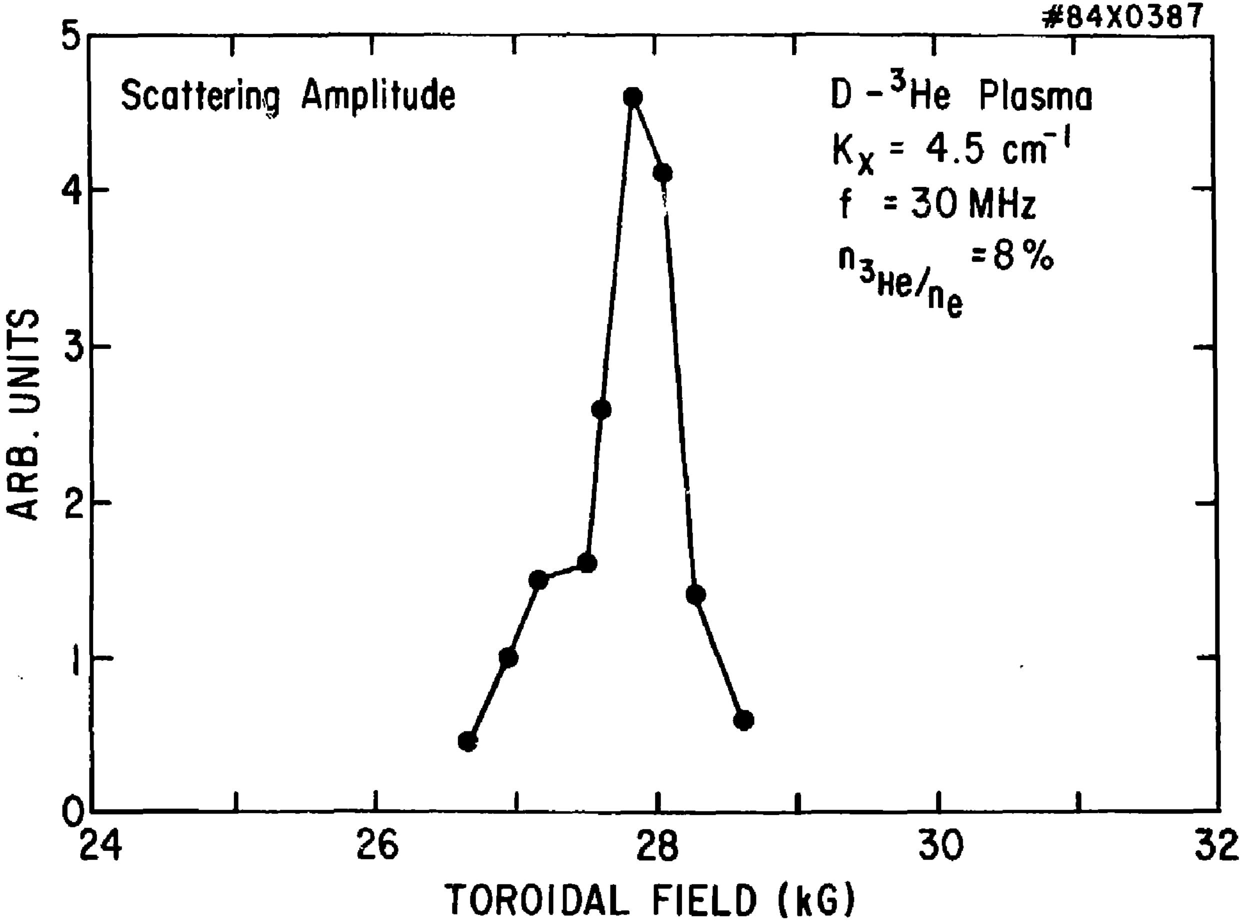

#84X0387
Scattering Amplitude
D - ^{3}He Plasma
K_X = 4.5 cm^{-1}
f = 30 MHz
$n_{^3He}/n_e$ = 8 %
ARB. UNITS
0
1
2
3
4
5
24
26
28
30
32
TOROIDAL FIELD (kG)

Fig. 10

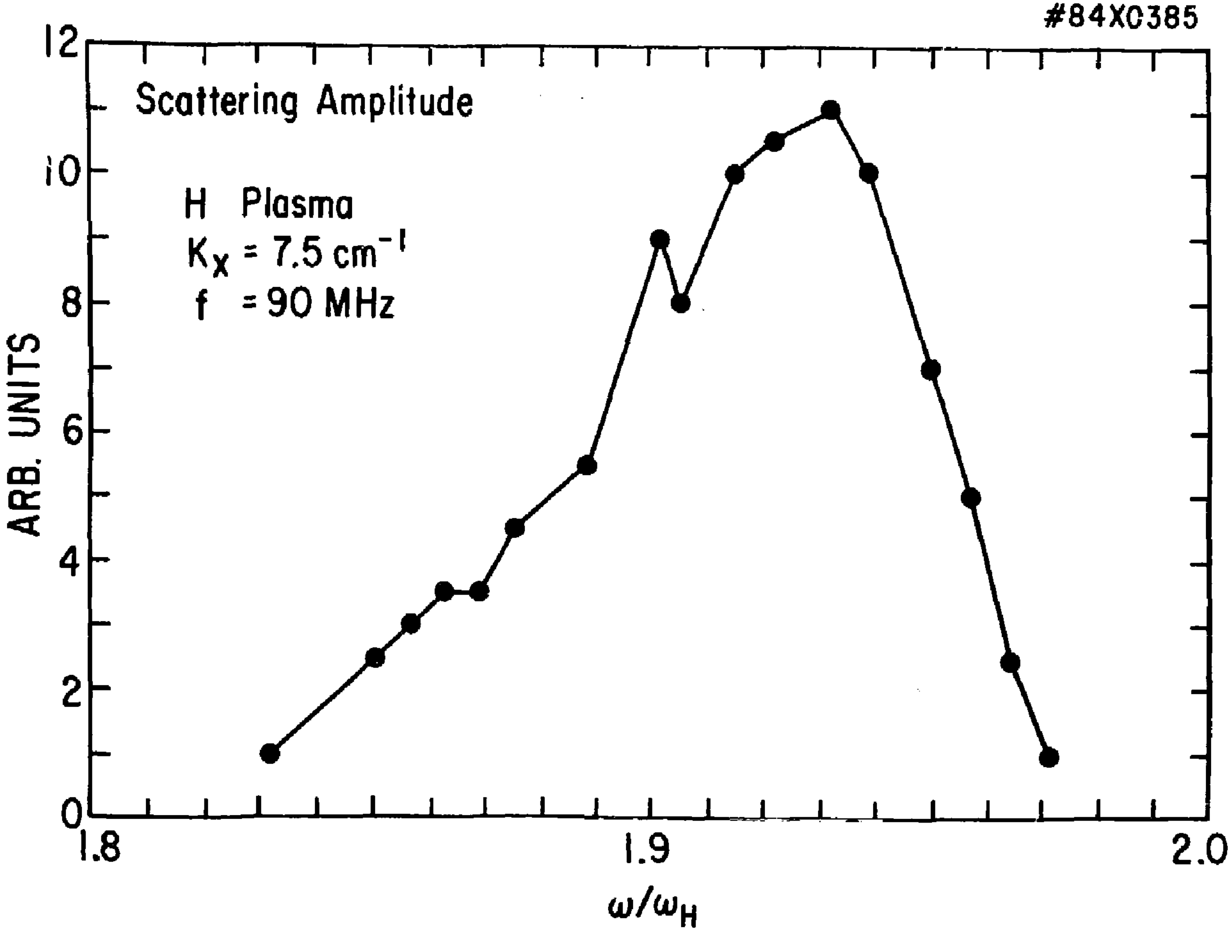

#84X0385
Scattering Amplitude
H Plasma
$K_X = 7.5\ \mathrm{cm}^{-1}$
f = 90 MHz
ARB. UNITS
0
2
4
6
8
10
12
1.8
1.9
2.0
ω/ω_H

Fig. 11

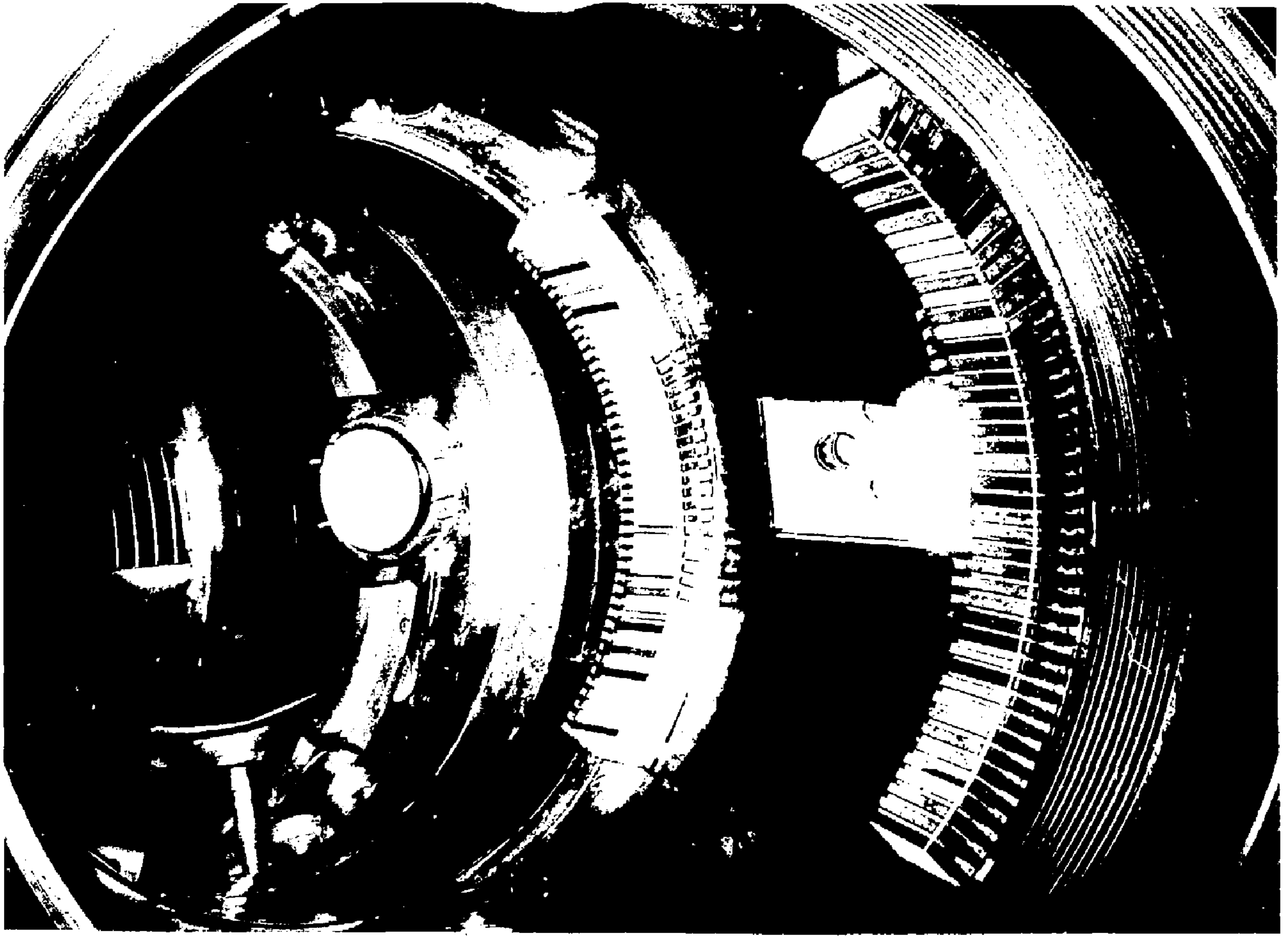


Fig. 12

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