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Review on Resonance Cone Fields

Toshiro Ohnuma

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan.

Permanent Address:

Department of Electrical Engineering,
Tohoku University, Sendai 980, Japan

Preface

Controlled thermonuclear powers have been expected as future energy for human being. To achieve this object, additional heatings of plasmas by injection of rf-power or neutral beams have been required. The plasma rf= heating is of great importance as they make possible rapid heating of the ion or electron plasma components. For such heating, we must investigate penetration of the electromagnetic waves into inhomogeneous high density plasmas. Ray trajectories, namely, energy flow of electromagnetic waves, should be investigated in details to know the penetration and an effective heating of plasmas.

Among rf-heating of plasmas, lower hybrid resonance heating by using lower hybrif waves have been paid much attention for the effectiveness. On the otherhand, resonance cone fields have been studied independently of the lower hybrid heating. The cone field has been used for measurement of plasma parameters, because the cone angle is determined directly by the electron plasma and electron cyclotron frequencies, etc.. According to the development of study on resonance cone fields and lower hybrid heatings, lower hybrid waves are easily understood to be related to resonance cone fields. Therefore, investigations on resonance cone fields becomes also important for an accomplishment of lower hybrid heating of plasmas.

In this paper, the author will review both the resonance cone fields and lower hybrid heating together. One can know the relation between them. Furthermore, one can understand lower hybrid heating more deeply by knowing fundamentals of resonance cone fields. Many investigations on these problems have been performed experimentally (1-46) and theoretically (47-118). However, much efforts should be paied to accomplish effective rf-heating of plasmas in controlled thermonuclear system. On the experimental data of resonance cones in this report, several unpublished data will be shown which the author had observed in his stay at SSD, ESA.

Contents of this report are as follows:

I. Experiments on resonance cones

I-1. Resonance cones in uniform magnetoplasmas

Fisher and Gould (1) observed high frequency resonance cone fields for the first time. This experimental observation has initiated much later work. They observed also a fine structure inside the cones which resulted from an interference between a fast electromagnetic wave and a slow plasma wave. They proposed the use of measurements of the resonance cones and structure as a diagnostic tool to determine the plasma density and electron temperature in a magnetoplasma, because the cone angle θ_c is given by

$$\sin^2 \theta_c = \frac{f^2 (f_p^2 + f_c^2 - f^2)}{f_p^2 \, f_c^2},$$

where f_p and f_c are the electron plasma and cyclotron frequencies, respectively. After their work, more extended experimental data have been measured by Gonfalone (2), Burrell(3), and Ohnuma (4) et al.. As an example of the experimental data, figure 1 shows the typical spatial variation of the resonance cone and fine structures radiated from a point source in a uniform magnetoplasma. The data were obtained in ESA machine by this author. Main peaks and fine structures indicate resonance cone fields and the electron thermal mode, respectively.

This kind of resonance effect has been used by rocket experiments in space for measurements of plasma parameters (5)(6). Gonfalone and Beghin (7) have detected an interference between a slow electrostatic wave (the electron Bernstein wave) and the cold plasma field, by measuring the potential around a point-source probe. Boswell (8) and Stenzel (9) measured the far-field resonance cone in comparison with whistler mode propagations.

I-2. Transient resoance cones

Simonutti (10) observed that the linear response of a cold anisotropic plasma to a point source under impulse excitation displayed a frequency spectrum having maxima at the two frequencies determined by the resonance cone condition and at the upper hybrid frequency. By applying a temporal wave packet of f_o ($f_{ci}, f_{pi} < f_o < f_{ce}, f_{pe}$) to a finite probe, Bellan (11) showed also to excite an electrstatic field consisting of a short-duration resonance cone and a wave=like disturbance which follows aftreward. This latter disturbance, which is related to the lower frequency mode of the delta-function induced transients discussed by Simonutti, persists long after the resonance cone.

I-3. Resonance cones in nonuniform magnetoplasmas

I-3-1. Ray trajectory, reflection and ducting of resonance cone

Ohnuma et al (12)(13)(14) have measured bending, reflection and ducting of resonance cones in detail. It would be fruitful to explain those by using raw data. Figure 2 indicates typical spatial trajectory of resonance cone fields radiated from a point source in an inhomogeneous magnetoplasma. Solid curves are the theoretical cone trajectories which were obtained from the fact that cone-trajectory is determined by the local parameters in a cold magnetoplasma. The experimental ray trajectory is clearly explained by the local theory. This kind of data have been observed with respect to lower hybrid heating by Briggs and Parker as will be discussed later.

Figure 3 shows a reflection and ducting of resonance cone fields in a magnetized plasma column. Unlike the case of lower hybrid heating, rf-source is located inside the plasma column. Experimental and theoretical trajectories of cone fields are found to be multi-reflected and be finally trapped in the plasma column. The theoretical curve is obtained by the local theory. The reflection of cone fields occurs at the electron plasma frequency layer. These multi= reflected cone fields are also confirmed to construct the so-called Trivelpiece= Gould mode. Reflections from conducting and insulating plates which make an arbitrary angle to the magnetic field are also observed. Tanaka et al (26) observed a reflection ot lower hybrid waves which will be discussed later. The theoretical ducting of cone fields is investigated in detail by Sanuki et al (57).

I-3-2. Thermal modes associated with resonance cones.

Typical data of propagating thermal modes in an inhomogeneous magneto-plasma are shown in Figs. 4 and 5. The density profile and the position of the rf-source are indicated in Fig. 5. In Fig. 4, inhomogeneous effects of thermal modes and cone fields are clearly observed. In Fig. 5, trajectories of the resonance cone and the thermal modes show pathe of enegy flow of cone fields and wave fronts of the thermal modes, respectively. Theoretical cone trajectories in an inhomogeneous plasma are indicated by solid curves. The dotted lines are theoretical wave fronts of thermal modes, which are obtained with an assumed uniform plasma for simplicity. These theoretical curves are in near accord with the experimental results. The author will describe this interpretation of thermal modes by wave fronts in more detail. These wave fronts are obtained from the ray velocity surface of the thermal mode. Figure 6 shows typical ray velocity, group velocity and phase velocity surfaces of the thermal mode in the same frequency range. The understandable termination of these velocities are given in Ref. 54. In Fig. 7, wave fronts of the thermal mode radiated from a point source are drawn for two different plasma densities. Figure 5 indicates that wave fronts from the ray velocity surface are in near accord with thermal modes associated with resonance cones, that is, the thermal mode can be interpreted as an obliquely propagating electron plasma mode, the frequency of which is below the electron plasma frequency.

I-3-3. Reflection of thermal modes

Reflections of the thermal mode from near theelectron plasma frequency layer and an insulating plate have been observed by Ohnuma and Lembege (4)(13). These reflections will be shown in detail because these are not known well. Figures 8 and 9 show raw data of reflected thermal modes. Figure 8 indicates reflected thermal modes from an insulating plate which is located perpendicular to the magnetic field. In Figs. 9 and 10, reflections of the thermal mode from near the electron plasma frequency layer are shown. The thermal mode is observed to penetrate and be reflected in the density lower than the electron plasma frequency. With these reflections, reflection and refraction of cone fields are also observed.

In figure 11, typical data of reflection, refraction and ducting of the thermal mode and resonance cone fields in an inhomogeneous magnetoplasma are shown. The position of reflection and refraction of cone fields is in accord with the electron plasma frequency layer.

I-4. Nonlinear effects of resonance cones

Boswell and Giles (15) reported the decay of a right-hand polarized wave (whistler resonance cone) in the presence of a spatial gradient of pump amplitude. They showed that the low-frequency ion wave can be trapped in the vicinity of the gradient. Furthermore, they (16) observed the parametrical decay of a Bernstein wave into another Bernstein wave and a whistler mode.

To study nonlinear interactions free of boundary effects, Stenzel and Gekelman (17) used a circular line source of radius R in a plane $\perp \vec{B}_o$ driven with an rf signal at $f < f_c \simeq f_p$ which excites two resoance cones with focal points at Z $= \pm R\cot\theta_c$ (θ_c is the cone angle). At large applied rf signals, $\epsilon_\theta E_{rf}^2/nkT_e > 0.2$, a stron depression, ion acoustic turbulence and corresponding random rf field distribution. They (18) investigated this experiment in details to observe fast ion bursts ($(1/2)mv_i^2 \simeq 35eV \gtrsim 100kT_i$), large amplitude ion acoustic waves and ion heating ($\Delta T_i/T_i > 100$) when rf burst of intensity $\epsilon_o E_{rf}^2/nkT_e \lesssim 0(1)$ is applied. This ion bursts are qualitatively explained by an acceleration of ions by space charge fields.

In Figs. 12 and 13, spatial behavior of resonance cone fields radiated from a ring source which are observed by Ohnuma is shown when small or large rf-powers are applied to the ring source. Trajectories of cone fields for both power application are shown clearly. For an application of high power rf-fields, the focal point of the cone fields approaches to the launcher. That is, the focal position is Z= 8-9cm for low-power case and Z= 6-7cm for high power case. This effect is in accord with recent theoretical considerations by Wang and Kuehl (62) who considered effects of nonlinear ponderomotive force.

I-5. Beam-generated resonance cones

Boswell (19) presented experimental results which show that a mono-chromatic low energy (50-150V) electron beam propagating into a collisionless plasma produces broad band whistler (resonance cone) mode noise by the process of parametric decay of a beam produced Bernstein wave. It is proposed that this is the dominant process responsible for the generation of the VLF hiss and the so-called VLF saucers. Figure 14 shows amplitude-frequency-"time" (radial distance) plot of low frequency waves ($<f_c$) which are observed outside the beam implying that energy is radiated away into the far field. The display shows the characteristic "V" of broad band whistler mode radiation. The edge of the V are in good agreement with the whistler group velocity resonance cone defined by $\theta = \sin^{-1} f/f_c$.

Stenzel (20) observed unstable whistler wave propagation along the resonance cone in a large beam-plasma system. A large uniform electron beam is injected along a magnetic field into a dense background plasma. The beam is found to drive oblique whistler waves ($f < f_c < f_p$) unstable which are in resonance with the beam ($\omega/k_{\parallel} \approx V_b$) and propagate nearly along the resonance cone angle ($\cos\theta = k_{\parallel}/k = f/f_c$). Beam-radiated plasma modes are also described in Ref. 21.

II. Experiments on lower hybrid waves

II-1. Linear lower hybrid waves

Galaktinov et al (22) have done experiments on linear-mode conversion effect emphasized for lower hybrid heating. Lower hybrid waves have been the subject of propagations from the edge of plasma to the lower hybrid layer, because of their potenital for heating fusion reactors. Hooke and Bernabei (23) observed oscillations electrostatically driven by a parallel plate source near the lower hybrid resonance frequency. The index of refraction of these waves was measured directly and was seen to peak at a critical density as the wave propagated radially inward. Briggs and Parker (24) investigated transport of energy from localized coupling structures to the lower hybrid resonace layer in an inhomogeneous plasma. Colestock and Getty (25) described experimental rf-potential launched electrostatically by coaxial half-cylinders near the lower hybrid frequency. Bellan and Porkolab (26) studied in details lower hybrid waves excited by a multiple ring slow-wave source, having $2\pi/k_{\parallel}$=23cm. The typical experimental data of the lower hybrid waves are shown in Fig. 15. The measurements of the dependence of wavelength on frequency were in good agreement with the cold plasma dispersion relation. Measured values of the wave damping were shown in good agreement with Landau damping by the combination of the main body of the electron distribution and an approximately 30% high enegy electron tail.

Bernabei et al (27) studied the coupling and propagation of electron plasma waves excited by waveguide arrays. The efficient coupling to plasma waves could be obtained under appropriate conditions. Furthermore, Bernabei and Hooke et al (28, 29) investigated penetration of slow waves into a dense plasma using a phased waveguide array as a slow-wave structure. The data demonstrated wave penetration to plasma interior only if the accessibilty criterion was satisfied. Reflection coefficient as low as 4% were observed.

II-2. Reflection of lower hybrid waves

Tanaka et al (30) observed reflection of lower hybrid waves. Typical trajectories of launched and reflected lower hybrid waves are shown in Fig. 16. Phase reversal was demonstrated on reflection at a metal.

II-3. Lower hybrid and ion acoustic waves radiated from a point source

Ohnuma et al (31) observed lower hybrid and ion acoustic waves radiated from a point source near the lower hybrid frequency. Those lower hybrid and ion acoustic waves have almost cylindrical and spherical wave fronts, respectively. Instead of the experimental result, numerically obtained potential radiated from a point source is shown in Fig. 17 near the lower hybrid frequency. The structure indicates the interference of the radiated field of cylindrical lower hybrid and spherical ion acoustic waves, that is, the structure shows co-existence of lower hybrid and ion acoustic waves near the lower hybrid frequency.

II -4. Interaction of lower hybrid waves with fluctuations

The parametric decay of a finite-extent cold-electron plasma wave (slow wave) was studied experimentally by Wong et al (32). They found that the decay waves propagated along pump wave rather than in the $\vec{E}_o x \vec{B}$ direction using a frequency of $f_o \gtrsim 10 f_{pi}$. Belan et al (33) measured effect of density fluctuations on lower hybrid resonance cone propagation. The measurements showed that coherent, azimuthal density fluctuations focused lower hybrid resonace cone azimuthally, and modulate the radia location of the resonance cones. The data were expained by a theory on wave refraction. The typical result is shown in Fig. 18. Furthermore, they (34) presented the enhancement of low frequency oscillations (collisional drift wave) by lower hybrid waves at electric fields lower than the thresholds of other parametric decay processes.

II-5. Lower hybrid waves in nonuniform magnetic fields

Ohnuma et al (35) observed that lower hybrid cone radiated from a point source went along magnetic field lines. Figure 19(A), (B) indicates raw data of resonance cone field radiated from a point source in a converging magnetic field. Cone signals near the lower hybrid frequency of Fig. 19(A) are those of the lower hybrid cone. One can say the data of Fig. 19(B) as spatial variation of resonance cone field in the nonuniform magnetic field. Figure 20 is the spatial trajectory of the cone potential in the nonuniform magnetic field. The measurements show that the trajectory of the lower hybrid cone is on the magnetic field line. As indicated in this experiment, the point-radiated lower hybrid cone belongs to the so-called resonance cone.

Javal et al (36) reported cone fields in toroidal inhomogeneous plasmas and confirmed under the combined influence of toroidicity, strong inhomogeneity and energy depletion by ionization and heating up to close to the lower hybrid density.

II-6. Lower hybrid heating in Tokamak devices

Several experimental data on lower hybrid heating in tokamak devices have been reported (37 -43, etc.). Alikaev et al (37) studied the microwave absorption with $f_{ce} > f \gtrsim (f_{ce} f_{ci})^{1/2}$ and $f_{pe} > f \gtrsim f_{pi}$ in the TM-3 tokamak. Significant microwave absorption was observed over the entire range of the plasma. The absorption was accomplished by ion heating, additional displacement of the plasma, and the appearence of hard X rays. Porkolab et al (39) observed parametric instabilities and the ion heating correlated with the presence of the parametric spectra, during lower-hybrid, radio-frequency heating of the Princeton University adiabatic toroidal compressor tokamak (ATC). Lallia et al (40) presented the loer hybrid heating in WEGA tokamak with emphasis on the ion measurements by charge exchange analysis. The application of rf power resulted in a hot ion tail which could absorb much of the rf-power because of the short life time. An increase of 20-30% of the bulk ion temperature had been observed during the rf-pulse.

Fujii et al (41) obtained rf-coupling efficiency around 90% to the power level of 140KW using an array of four waveguides in JFT-2 tokamak. Effective ion heating ($\Delta T_i/T_i \approx$ 50-60% by CX and 25-30% by spectroscopy) had been obtained on the application of 135KW when the turning point was near the plasma center. Schuss et al (42) reported the results of injectig 90 kW of microwave power near the lower hybrid frequency into the Alcator-A tokamak through a two-waveguide array. The observed plasma heating was in disagreement with that expected from linear waveguide-plasma coupling theory. They infered the nonlinear formulation of a high-k wave power spectrum at the plasma edge.

In JFT-2 tokamak, Imai et al (43) identified decay spectra during the lower hybrid heating as the parametric decay into the cold lower-hybrid waves and the ion cyclotron waves at the plasma surface. The decay instabilities absorbed some fraction of the rf-power, hence they affected the plasma heating. However, they did not prevent the penetration of the lower hybrid wave to the plasma center. In addition to these experiments, lower-hybrid heating experiments have been performed in other machines, namely, Petula, FT-1, Doublet IIA devices et al. As an example of the experimental data, Figs. 21 and 22 indicate the experimental set-up and typical data of ion heating for lower hybrid heating in JFT-2 tokamak. The data show that the bulk ion heating by the rf-power is associated with a production of high energy ion tails.

In summary, a good coupling of rf-power to the plasma had been obtained, and the bulk heating of electrons and ions had been observed. However, much efforts should be paied to these heating experiments for controlled fusion power.

III. Experiments on low frequency resonance cones

Experimental observations of low frequency resonance cone near the ion cyclotron frequency have been reported by Ohnuma et al (44, 46) and Bellan (45). Figure 23 shows the typical potential pattern of the low frequency resonance cone radiated from a point source.

IV. Theory on resonance cones

Kuehl (47) investigated electromagnetic radiation from an electric dipole in a cold anisotropic plasma and found that for some operating frequency, the fields should become singular on a conical surface, the so-called resonance cone. The nature of the singularity in the fields is such that it yields an infinite amount of power flow from the dipole. This was called the "infinity catastrophe". Many papers have been published after his work. Singh and Gould (48) studied the effects of electron temperature on the radiation fields of a short electric dipole in a uniaxial plasma, and solved the infinity catastrophe by an description of the plasma medium including the electron thermal motion. A characteristic interference structure was noted in the angular distribution of the field.
In reference 49, the interference structure near the resonance cone of an oscillating point charge in a warm magnetized plasma was investigated, using the quasistatic approximation. Depending on the frequency and the plasma parameters, the interference structure appeared inside, outside, or both sides of the resonance cone. Furthermore, Kuehl (50) investigated the electric field and potential at and close to the resonance cone and showed the interference

structure of the potential of the point charge is the largest. From the multipole expansion of an arbitrary charge distribution, high-order multipole contributions were shown to be small it the characteristic source dimension was small compared with spatial separation between two successive interference maxima. The potential created by an alternating point charge in a warm magnetoplasma was also studied by Chasseriaux (51). An approximate expression for the dispersion relation for $f < f_{pe}, f_{ce}$ enabled to obtain an analytical result for the potential, which remained finite on the resonance cone.

IV-2. Drift effects on resonance cones

In a drifting warm magnetoplasma, Singh (52) studied the group velocity resonance cone by calculating potential of a point charge. The down stream interference pattern was appreciably modified for $V_d/V_t/\tan\theta_c$, where V_t was the electron thermal velocity. The upstream interference pattern was appreciably modified even for small drifts. Storey and Thiel (53) investigated thermal and field-aligned-drift effects near the lower oblique resonance. Group velocity surface from a point source in a plasma stream had also been described in Ref. 54.

IV-3. Resonance cone fields in bounded magnetoplasmas

IV-3-1. Ray trajectory, reflection and ducting of resonance cone fields

Leuterer and Derfler (55) investigated gap excitation of plasma waves in a bounded inhomogeneous cold plasma. The electromagnetic fields excited by an azimuthally symmetric gap in a plasma filled waveguide were described as a superposition of radial eigenmodes. This resulted in a radially confined energy flow along the resonance cone. The effect of a finite gap width and of a radial inhomogeneity of plasma was reported. Sanuki et al (56) calculated resonance cone trajectories in an inhomogeneous magnetoplasma, in which thermal effects were included by using kinetic theory. The typical reflected and ducted resonance cone fields are shown in Fig. 24. The reflection of the field is from the layer of the electron plasma frequency layer.

IV-3-2. Reflection and refraction of thermal modes associated with resonance cone

Grabbe (57) obtained the resonance cone structure in a warm bounded slab magnetoplasma in the electrostatic approximation for small electron and ion temperatures and a large magnetic field. It was found that the conducting boundaries acted as perfect mirrors as in the cold plasma case; the cone reflected off the boundaries without any distortion of shape. The thermal effects produced the appearence of an interference structure inside each cone as in unbounded plasma theory. Furthermore, he discussed the effect of a finite source on the warm plasma resonance cones in a bounded plasma. Graphs of the potential produced by a Gaussian source were presented for parameters which illustrated the individual resonance cones and their interference.

Watanabe et al (59) investigated in detail behavior of thermal modes in an inhomogeneous magnetoplasma by using a kinetic equation. Figure 25 indicates the theoretical ray trajectory of the cone field and wave fronts of thermal modes which were radiated from a point source in an inhomogeneous magnetized plasma.

Solid and dotted lines except cone trajectory indicate equipotential lines of the thermal mode, and the solid lines have phase difference of half wavelength to the nearest dotted lines. Inhomogeneous effects on wave fronts of the thermal mode are shown clearly in the figure. Figure 26 (A)(B) show bending and reflection of resonance cone field and wave fronts of thermal modes with reflections. The reflection of resonance cone is at the electron plasma frequency layer as expected. The reflection of the thermal mode is found to occur in the lower density region than the electron plasma frequency, namely, the thermal mode passes through the f_{pe}-layer. "Ray" in the figure indicate the ray trajectory of the thermal mode for an initially given $k_{\parallel}$, and only wave signals radiated on the lefthand side from a point source are indicated in the figure.

IV-4. Nonlinear effects on resonance cones

Kuehl (60) studied nonlinear ponderomotive force effects on plasma resonance cone effects. The nonlinear equation was derived governing the field on two= dimensional resonance cones and was found to reduce to the modified Kortweg-de Vries equation only if the electric field was real. Reiman (61) described the effects of two- and three dimensional geometry for parametric decay of a finite width pump in an inhomogeneous medium. The analysis in three dimension focused on the geometry appropriate to decay in a lower hybrid resonance cone.

Levine, Greene and Gould (62) evaluate exactly and asymptotically the potential for an oscillating ring source immersed in cold, magnetized, collisionless plasma in the resonance cone regime, giving insight into the gross spatial behavior of the focusing resonance cones. Thermal effects were considered numerically, revealing an interesting interference structure in potential as well as a density depression near the focus of the cone due to the ponderomotive force. Figure 27(A)(B) indicates the numerical magnitude of the complex potential for a part of the inner resonance cone, displaying the interference structure due to thermal effects and the first-order density depression due to the ponderomotive force. Wang and Kuehl (63) also presented the theory of nonlinear plasma resonance cone due to a circular ring exciter. By assuming the nonlinearity due to the ponderomotive force, they showed that the resonance cone trajectory was modified by the nonlinearities in a direction opposite to that caused by thermal effects, especially near and after the focus, and that the peak electric field on the cones and at the focus was enhanced due to nonlinearity. The location of the focal point was found to be shifted toward the exciter due to nonlinearities in contrast to the shift to thermal effects which was away from the exciter. This effect was observed by Ohnuma as shown in Sec. I-4.

V. Theory on lower hybrid waves

V-1. Excitation, propagation and linear mode conversion of lower hybrid waves in inhomogeneous plasmas

Stix (64) studied initially linear mode conversion of fast electromagnetic waves into a slow electrostatic mode (or vice versa) in an inhomogeneous plasma. Piliya and Fedorov (65) considered the wave equation for an inhomogeneous magnetoplasma, taking account of weak spatial dispersion under the assumption that there was a resonant point within the plasma. Pesic (66) investigated the interaction of extraordinary waves with an inhomogeneous anisotropic plasma column at the lower hybrid frequency within the framework of the cold plasma theory. The plasma column exhibits a series of geometric resonances in the medium frequency range and a main absorption resonance in the high frequency range. The influence of temperature and nonlinear effects on the wave absorption efficiency in the lower hybrid range were presented.

Golant and Piliya (67) presented the theory of linear transformation of electromagnetic waves into plasma waves and gave several numerical results. Golant (68) discussed penetration of electromagnetic waves into a magnetized plasma for frequencies near the lower hybrid frequency. The electromagnetic waves were transformed into slow, highly damped plasma waves. Conditions for wave penetration into homogeneous and inhomogeneous mangetic fields were analyzed and the coupling efficiency was discussed. The accessibility condition was obtained as $n_{\parallel} > 1 + (f_{pe}/f_{ce})^2$. Glagolev (69) solved the problem of electromagnetic wave propagation and absorption in weakly inhomogeneous plasma layer in the geometrical optics approximation. The conditions for a transformation of electromagnetic wave into plasma wave had been calculated in the hydrodynamic approximation.

Pesic (70) investigated damping of quasi-longitudinal plasma oscillations in the lower hybrid frequency range, by using complete dispersion equation. The results indicated that the wave energy was preferentially given to the ion perpendicular motion while an efficient energy transfer to the electrons required a large electron velocity spread along the field lines. Puri and Tutter (71) extended to the slow-wave case and studied coupling slow wave energy to the lower hybrid resonance, and found the following recommendation; (1) if $f_{pe}/f_{ce} \lesssim 0.4$, efficient coupling is possible by launching TEM-like waves on the plasma column, (2) if $f_{pe}/f_{ce} \gtrsim 0.4$ and if the transverse machine dimensions exceed the radio frequency vacuum wavelength, it is possible to couple TM waves using passive slow-wave structures inside the machine walls, (3) if $f_{pe}/f_{ce} \gtrsim 0.4$, but for smaller machine dimensions, recourse must be taken to transverse electric slow-wave coupling with current-carrying coils of appropriate periodicity.

Simonutti (72) emphasized the effects of finite temperature and inhomogeneity of the plasma. The two-fluid theory predicted that a mode-conversion to an ion acoustic wave took place near the lower hybrid resonance layer. The Vlasov theory, in addition, predicted that this might be followed by a second mode conversion at a lower density.

Bellan and Porkolab (73) calculated the propagation of electrostatic plasma waves and the subsequent conversion into hot plasma waves at the lower hybrid frequency for realistic density profile and finite rf-sources in a slab geometry. A finite length slow wave source having a potentialdistribution $\phi \sim \cos k_0 x$ was found to generate spatial oscillations having a well-defined wavelength as shown in Fig. 28. These oscillations are confirmed to regions bounded by conical curves originating at the ends of the source. The axial distance of rf energy propagation to the lower hybrid layer was found to be greater than the radial distance of propagation by a factor of the order $(m_i/m_e)^{1/2}$. The conversion at the lower hybrid layer of the electrostatic cold plasma waves excited by a finite source into propagating hot plasma waves was calculated. It was shown that collisional damping at the lower hybrid layer might predominate over mode conversion even for relatively low collision frequencies. Kuehl and Ko (74) considered the field near the resonance cone for frequencies near the lower hybrid frequency. By including higher-order thermal terms, the proper non-singular fields near the resonance cones due to a localized rf source at the plasma boundary were derived. Colestock and Getty (75) solved numerically the boundary-value problem for the electrostatic potential in a cold, inhomogenous plasma as a superposition of the radial eigenmodes excited by a finite-length source. Galushko et al (76) investigated the distribution of oscillatory fields excited by a source in magnetoplasma and the absorption of high-frequency energy. The effect of plasma inhomogeneity, thermal motion of particles, finite size of source, and other factors, on th structure of source field was considered.

Baranov and Shcherbinin (77) analyzed the excitation of slow waves in a plasma in the linear approximation. An array of waveguides was oriented in a manner to excite an E wave having a singularity at the lower hybrid resonance. The reflection coefficients and the spectra of the power absorbed by the plasma were found as functions of the number and size of the waveguides, the plasma parameters, and the impedance of the chamber walls. With a large number of waveguides the spectrum of the waves capable of penetrating into the interior of the plasma turned out to be independent of the wall impedance. Brambilla (78) studied the coupling efficiency of a phased multi waveguide structure (the "Grill") designed to launch high frequency waves at the lower hybrid resonance to heat toroidal plasmas, which satisfied the accessibility condition. It was found that the reflection coefficient could be made acceptably low and was not sensitively dependent on the plasma parameters. It was concluded that it was possible to design a Grill capable to launch lower hybrid waves at the power level required for the ignition of a reactor plasma.

Weytzner and Bachelor (79) presented possibility for an ordinary mode electromagnetic wave, incident on an inhomogeneous plasma slab for a particular angle of incidence, to be totally converted into an extraordinary mode. They concluded that for plasma parameters characteristics of modern tokamaks, significant mode conversion occured only for waves incident within a very narrow cone ($\delta\theta \sim 1^{\circ}$) about the critical angle. Grabbe (80) applied macroscopic and microscopic forms of the energy conservation theorem for quasi-static waves to determine the approximate power flux density and rate of energy absorption along the resonance cones near the lower hybrid resonance, both for the incoming cone and the outgoing converted ion thermal cone. It was found that for the incoming cone excited by a point gap source, there was almost as much power flux and absorption along each of the first few secondary peaks as along the main peak, so that the channel along which most of the energy flow and absorption occured extended the width of several peaks of the cone. On the outgoing cone, the power flow and absorption was more concentrated on the main peaks than the incoming cone. Nonlinear ponderomotive force effects were found to be more important for this cone that the incoming cone unless substantial absorption ocuured in the mode conversion region.

Puri (81) investigated lower-hybrid wave absorption in the presence of simultaneous density and magnetic field gradients. It was shown that the WKB requirements were satisfied in almost the entire region from the antenna up to and including the ion-cylotron-harmonic resonance. Expressions for the electric field and the energy density in the WKB approximation were derived. Both the collisionless and collisional damping became significant near the resonance, and the wave attenuation due to the two processes was estimated. The effect of impurities, although negligible near the plasma edge, became important following wave conversions and a significant fraction of the wave energy might end up heating the impurity ions in the plasma interior. Tang, Fu and Farshori (82) studied the case under the influence of a nonuniform magnetic field. When the gradients of plasma density and magnetic field were in the same direction, it was found that the presence of the ion cyclotron harmonic resonance in the vicinity of the first turning point resulted in a new second turning point and a new branch for the hot plasma wave. On the otherhand, if the gradients of plasma density and magnetic field were inopposite directions, the second turning points disappear and there was no mode conversion between the warm plasma wave and the hot plasma wave.

V-2. Parametric processes of lower hybrid waves

Parametric instabilities near the lower hybrid frequency have been investigated theoretically by many authors. Porkolab (83) derived and analyzed the dispersion relation parametric instabilities near the lower hybrid frequency. It was found that for propagating angle $\cos^2\theta(m_i/m_e) \lesssim 1$ resonant decay into ion acoustic (ion-cyclotron) waves did not occur; rather, decay into nonresonant quasi-ion modes and lower-hybrid waves occured. Chen and Berger (84) studied numerically the nonlinear evolution and saturation of parametrically excited lower-hybrid waves and found that nonlinear electron and ion Landau damping provided effective saturation mechanisms only for pump powers close to the threshold value. Furthermore, they (85) obtained analytic solutions for the envelope structures of two nonlinearly coupled lower hybrid waves propagating along their respective cone trajectories. The coupling occured through induced scattering by particles. The results indicated anomalous spatial pump depletion.

Tripathi, Grebogi and Liu (86) formulated a unified theory of parametric instabilities in the lower hybrid frequency region using the drift kinetic equation for electrons and the Vlasov equation for unmagnetized ions. Nonlinear scattering rates by electrons and ions (i.e. nonlinear Landau damping) were evaluated. It was seen that the dominant channel of decay was through ion acoustic and lower hybrid waves when $T_e/2T_i > 4$ and through lowr hybrid waves and lower hybrid quasi-modes when $T_e/2T_i < 4$. Watson and Bers (87) presented a new formulation of the nonlinear coupling of coherent waves described by the Vlasov equation. This was used to derive the parametric growth rate for the down conversion from a lower hybrid pump wave to ion Bernstein waves. It was found that the maximum growth rate for this interaction was larger than that for any othe resonant interaction.

Berger et al (88) studied the case of nonuniform pump waves. Electrostatic lower hybrid "pump" waves launched in well-defined resonance cones gave rise to parametric instabilities driven by electron ExB velocities. The finite size of the cone region determined the threshold for convective quasi-mode decay instabilities and absolute instabilities. Parametric instabilities driven by ExB velocities occured for threshold fields significantly below the threshold for filamentation instabilities driven by ponderomotive forces. Applications to tokamak heating showed that nonlinear effects set in when a certain power-per= wave launching port was exceeded. For sufficently high powers, these instabilities will occur in the low-density edge region of a tokamak. Porkolab (89) presented the linear theory of parametric instabilities relevant to radiofrequency heating near the lower-hybrid frequency of tokamak-type plasmas by including all orders of the ion Larmor radius. As the pump wave propagated from the edge of the plasma toward its interior, the transition from resonant decay to decay into quasi-modes was demonstrated. The effects of inhomogeneities upon the threshold for parametric decay, such as density gradients, finite pump width, and magnetic shear, were obtained.

Sinha and Goswami (90) showed a magnetosonic wave to damp in the presence of a lower hybrid microturbulence which in turn effectively heated the plasma ions. Sperling and Harvey (91) studied the harmonic oscillating two-stream instability in lower-hybrid heating. Shukla and Mamedow (92) presented the three-wave interaction process between a large amplitude propagating lower hybrid wave and two electromagnetic waves in a plasma. It was shown that a finite wavenumbe lower-hybrid pump could decay into a whistler and a kinetic Alfven wave. Tripathi, Liu and Gregobogi (93) studied effects of ion nonlinearity. They showed that the contribution of ions was important only for decay into a Bernstein wave of short perpendicular wavelength ($\omega \gg k_{\parallel} v_e, k_{\perp} \rho_i \gg 1$). A comparative study of various channels of decay revearled that the oscillating two= stream instability and nonlinear Landau damping by electrons were the predominant channels in the high density region.

V-3. Nonlinear phenomena of lower hybrid waves

Morales and Lee(94) showed the nonlinear distorsion of the propagation cones of lower hybrid waves to be governed by the modified Kortweg-de Vries equation. It was predicted that filamented cones should be formed when large= amplitude lower-hybrid waves were excited in a plasma. Kuehl (95) considered nonlinear ponderomotive force on mode-converted lower hybrid waves. The nonlinear distortion of these waves was shown to be governed by the cubic nonlinear Schrodinger equation. The threshold condition for self-focusing and filamentation was derived. Morales (96) considered the mode-conversion process in the lower-hybrid heating scheme at the edge of the plasma, where the frequency of the external radiation was comparable to the local value of the electron plasma frequency. I was confirmed that a backward wave was excited at the edge and that it leaded to a net energy flow directed toward the interior of the plasma. For small external power, the flow was chracterized by the propagation of a leading-edge pulse whose arrival at a given spatial location marked the onset of the steady state. At large external power levels, the self consistent modification of the density profile by the ponderomotive force was found to quench the mode= conversionprocess, thus causing a significant reduction in the amount of rf energy that can be coupled from the external source to the interior of the plasma.

Sanuki and Ogino (97) also investigated the nonlinear lower hybrid waves. They emphasized the results of finite temperature, inhomogeneity of the plasma and density depression due to the ponderomotive force and showed that the waves were localized in a spatial wave packet that propagated into the plasma center along the conical trajectory . Pereira et al (98) investigated the instability of a planar lower hybrid soliton to transverse long wavelength numerically. They showed that in the nonlinear regime the soliton broke up into bunches which moved apart and spread the energy throughout the plasma.

Sen et al (99) studied self-modulation effects in three dimensions including the nonlinear effect arising from the ExB motion of electrons. They derived an enhancement in the threshold value for the formation of solitons and found that the third dimension introduced additional dispersive effects which rendered the solitons unstable to these perturbations. Karney, Sen and Chu (100) studied numerically the complex modified Kortweg-de Vries equation which governed the two-dimensional steady-state distribution of lower hybrid waves. Two types of solitary waves (not solitons) could arise: one is a constant phase pulse, whereas the other was an envelope solitary wave. The occurence of the constant phase pulses pointed to the possiblity of internal reflections due to scattering of ponderomotive density fluctuations. With typical fields for lower hybrid heating of a tokamak, it was found that large reflections could occur close to the edge of the plasma.

Decyk, Dawson and Morales (101) presented a computer simulation of the launching of lower hybrid waves by several kinds of external sources. When the oscillating frequency did not match a bounded plasma resonance, one could observe resonance cones, energy absorption at the plasma surface, ion cyclotron modulation of the source, and energetic ions, depending on the parameters chosen. The excitation of a bounded plasma resonance was also considered. The nonlinear evolution of the resonance showed that wave-particle interaction and poderomotive force effects played an important role. In figure 29, numerical electrostatic potential associated with lower hybrid rasonance cones excited by a point source (A) and the electron density profile at peak density depression (B) are shown.

Sperling and Chu (102) examined nonlinear instabilities driven by waves with frequenccies comparable to the lower hybrid frequency using particle simulation techniques. Bothe the oscillating two-stream and ion-cyclotron instabilities were discussed. It was found that ion-cyclotron damping could be a more effective mechanism for driving instabilities in a hot tokamak than electron Landau damping. Abe, Itatani and Momota (103) observed the increase in the ion and electron kinetic energies in the case of the large amplitude by using a particle simulation model. Ion perpendicular energy distributions were observed to have the components of the high energy tail. These phenomena were explained in terms of the mechanism of trapping and stochastic acceleration of a charged particle in the monochromatic and nearly perpendicular propagating wave with a frequency near cyclotron harmonic. A strong increase in the parallel kinetic energy of the electron was observed near the plasma surface. This was mainly due to the trapped electrons.

Leclert et al (104) studied the two-dimensional self-modulation effects due to ponderomotive force for lower hybrid waves under the assumption that the field was electrostatic and had a narrow k spectrum. For a locally linear temperature profile and a broad class of density profiles, exact nonlinear solutions (solitons) were obtained by the inverse scattering method. Chan and Chiu (105) considered the problem of steady state nonlinear wave-coupling at the lower hybrid frequency. A nonlinear equation for the electric field in the low-density region at the plasma surface was derived self-consistently. Analytical and numerical solutions for different plasma models showed a decrease in coupling efficiency with increasing power level. Ott (106) formulated a wave kinetic equation for lower hybrid scattering by low frequency density fluctuations. Implications for heating of tokamak plasmas were discussed. Kuehl (107) derived the differential equation for mode-converted lower-hybrid waves including the effect of the nonlinear ExB motion of electrons.

V-4. Ray trajectory of lower hybrid waves in toroidal systems

Nishitani, Fukushima, Terumichi and Tanaka (108) studied propagation of the cold lower hybrid waves in a cylindrical tokamak plasmas. The trajectory of wave energy flow was spiral and arrived at the lower hybrid resonance layer along the poloidal field. It traveled along the toroidal direction and its distance to the resonance layer was equal to $(m_i/m_e)^{1/2}a$, where a was the radius of the plasma column. Ohkubo, Ohasa and Matsuura (109) compared the ray trajectories of electrostatic wave to the lower hybrid resonance on the meridian plane of torus. The ray starting from the vicinity of the plasma surface rotated spirally around the magnetic axis. The ray reaching the layer S=0, where the perpendicular dielectric constant vanishes, was reflected along the second characteristic curve towards another point on the layer S=0. After being reflected successively, rays finally converge on the node point of the layer S=0 on the equatorial plane. In the absence of the layer S=0 the rays finallys reflected between the cutoff layers near the center and surface of plasma. Momota et (110) also considered the effect of toroidicity. Maekawa et al (111, 112) studied wave trajectories propagating obliquely to the magnetic field in toroidal plasmas, and showed that the ordinary wave at the appropriate incident angle was mode converted to the extraordinary wave at the first turning point and further converted to the electron Bernstein waves while passing a loop or a folded curve near the second turning point and was cyclotron-damped away, resulting inlocal electron heating, before arriving at the cyclotron resonance layer.

Wersinger et al (113) also investigated radially trapped lower hybrid decay waves bouncing back and forth in the low density region of plasma as a result of both magnetic shear and density gradient. It was shown that weak toroidicity caused some of these waves to follow ergodic ray trajectories and hence to be detrapped and to reach their lower hybrid resonance. Furthermore, Ott et al (114) showed in tokamak parameters that cold lower hybrid waves were reflected in the lower hybrid surface than encountering a resonance. For high temperatures, however, mode conversion occured before the wave could bounce. Figure 30 indicates those ray trajectories in the r-θ plane.

V-5. Lower hybrid heating of tokamaks

On this subject, many reports have been performed as shown in the references of Sec. V-2 - V-4. Only a few papers will be presented here. Harvey and Rawis (115) showed that the incorporation of a quasilinear-collisional wave damping of lower hybrid electron heating into trans port code revealed favorable prospects for heating tokamak plasmas to ignition. For a particular test reactor design, 30MW of lower hybrid power used in conjunction with a programmed plasma density startup sufficed to initiate a self-sustained thermonuclear burn. Chan et al (116) examined the characteristics of electron heating when high power RF near the lower hybrid frequency was applied to a tokamak plasma.

VI. Theory on low frequency resonance cone

Kuehl (117) showed that the potential of an oscillallating point charge for frequencies below the ion cyclotron frequency contained the low frequency resonance cone which was due to the electrostatic ion wave. Burrell (118) used asymptotic analysis of the electrostatic Green's function to show the existence of the low frequency resonance cone in addition to the cold plasma resonance cone for frequencies below the lower hybrid frequency. These cones existed for frequencies $0 \lesssim f \lesssim \min.(f_{pi}, f_{ci})$ and $\max.(f_{pi}, f_{ci}) < f \lesssim f_{LH}$. The interference structure associated with this cone was quite sentive to the ion temperature and could be the basis of an ion temperature diagnostic technique for plasmas.

Summary

In this report, the author surveyed historically many works on resonance cone fields and lower hybrid waves. In some part, he felt difficult to explain them independently, because that fundamental physics of resonance cone fields and lower hybrid waves are the same. In many cases, lower hybrid waves have been investigated with a problem of accessibility and with the fixed parallel wave number. On the other-hand, studies of resonance cone fields have been performed with many non-fixed wave number radiated from sources.

As shown in this report, one could have much knowledge about resonance cone fields and lower hybrid waves. However, one should pay much efforts on these problems to achieve future controlled thermonuclear power.

Appendix On the nonlinear resonance cone fields

In addition to such a change of the ray trajectories as Figs. 12 and 13, other experimental data will be presented in this appendix. Figure 31(A) shows a variation of field patterns of resonance cones radiated from a monopole type source when an applied power to the exciter is varied. The position of the resonance cone field is found to go outside with an increase of the applied power. This effect is quantative agreement with the amplitude-dependency of the cone location, which Wang et al (63) derived in case of a ring source. Figure 31 (B) indicates a relation of amplitude of the resonance cone fields to the corresponding electron density when high power rf field to the source is applied. Density depressions due to the ponderomotive force of resonance cone fields are obtained together with a density depression due to near-fields of the exciter which is produced along the magnetic field line in this experiment.

Appendix-II Further investigations

After this report was written, following interested results are reported. Wilson and Wong (Phys. Rev. Lett. vol. 43, p. 1392, 1977) investigated the modification of the trajectory of a focused resonance cone as a result of the ponderomotive force. The results are essentially similar to the author's experimental data of Appendix-I. Motley, Hooke and Anania (PPPL-1567) found formation of thermal eddies during RF heating of plasma. Moderate power (~1kW) excitation of lower hybrid waves was found to increase the reflectivity of the phased waveguide exciter and the increased reflection was driven by thermal eddies associated with asymmetrical electron heating in the plasma surface. Surko et al (Phys. Rev. Lett. vol. 43, p. 1016, 1979) studied spatial distributions of driven lower hybrid wave fluctuations in the Alcator tokamak with use of CO_2-laser scattering. They found that the waves are not localized in resonance cones and that the wave amplitudes are nearly independent of the relative phase of the electric fields at the exciting waveguides for incident microwave power densities from 0.4 to 4.5 kW/cm^2.

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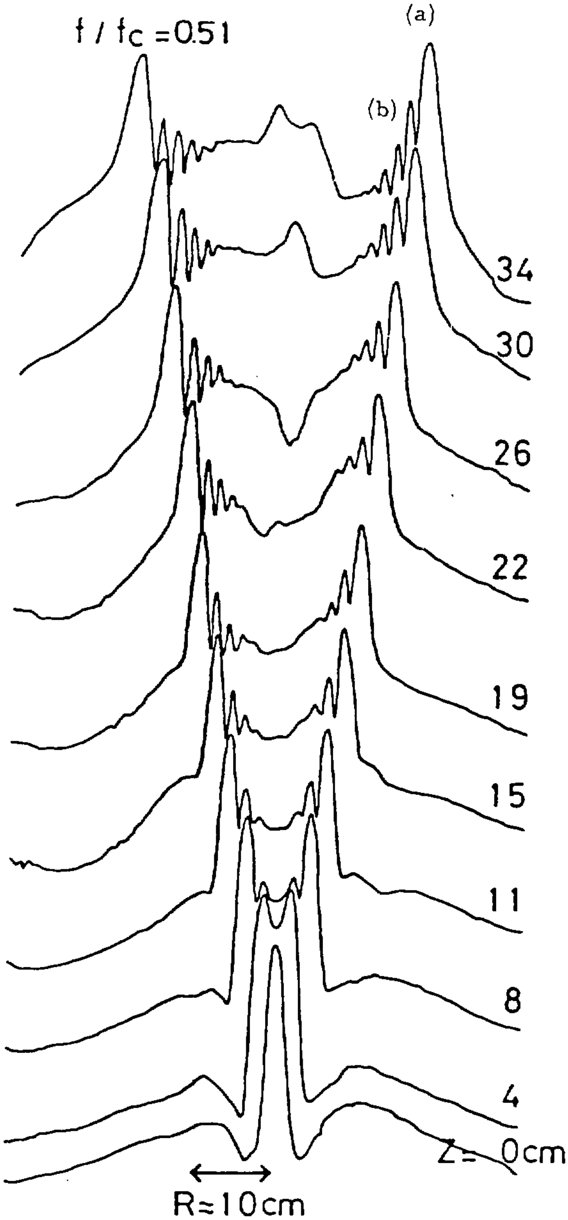


Fig. 1. Spatial variation of resonance cone fields (a) and thermal modes (b) radiated from a homogeneous plasma. The magnetic field is applied to Z-direction. $f_p/f_c \approx 1.5$, $f_c \approx 197$MHz

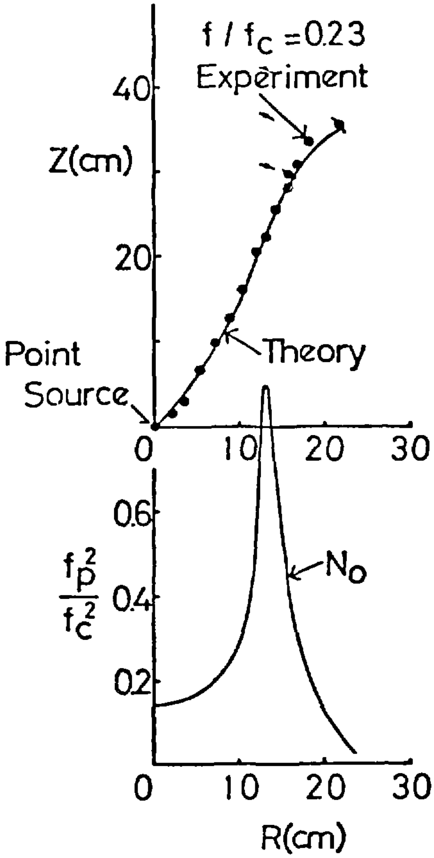


Fig. 2. Experimental and theoretical resonance cone trajectory in an inhomogeneous magnetopiasma. Bottom figure is the density profile.

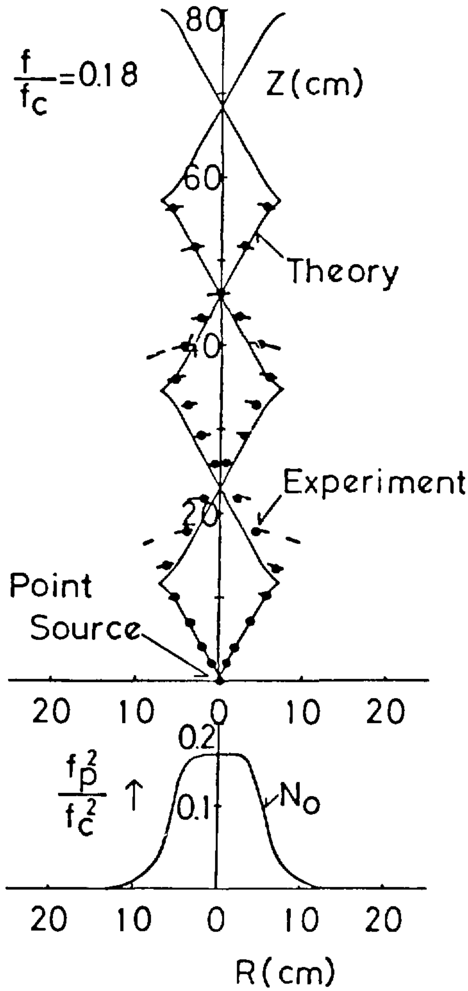


Fig. 3. Experimental and theoretical trajectories of resonance cone fields radiated from a point source in a magnetized plasma column where reflections occur at the electron plasma frequency layer. Bottom figure is the corresponding density profile.

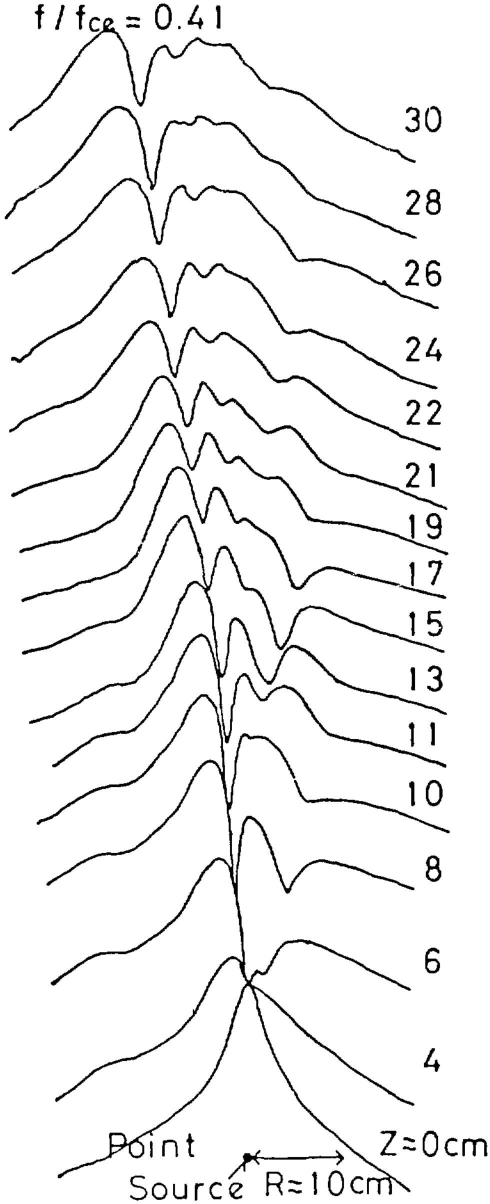


Fig. 4. Raw data of resonance cones (a) and thermal modes (b) in an inhomogeneous magnetoplasma. The density profile and the location of a source is the same as Fig. 5.

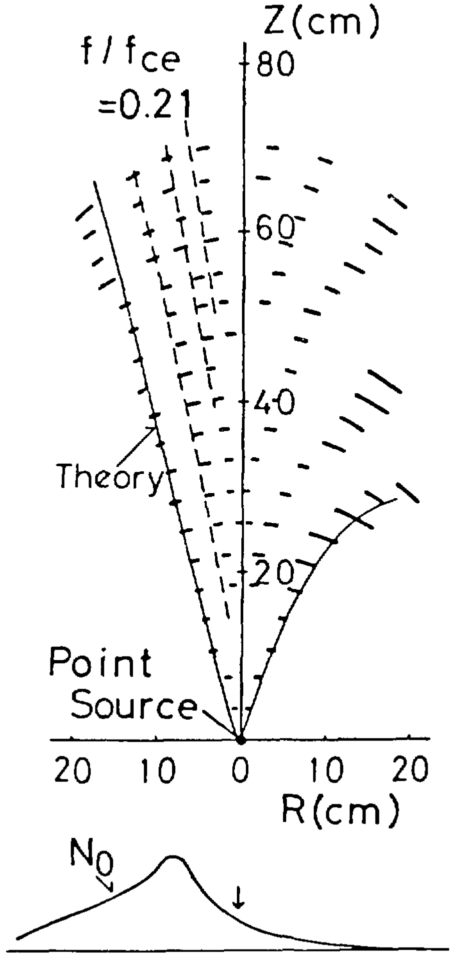


Fig. 5. Trajectories of resoance cones (a) and thermal modes (b) in an inhomogeneous plasma. Solid lines are the theoretical resonance cone trajectories. Dashed lines are theoretical wave fronts obtained from ray velocity surface of oblique electron mode. $f_{pe}/f_{ce} \approx 1$ at the point source.

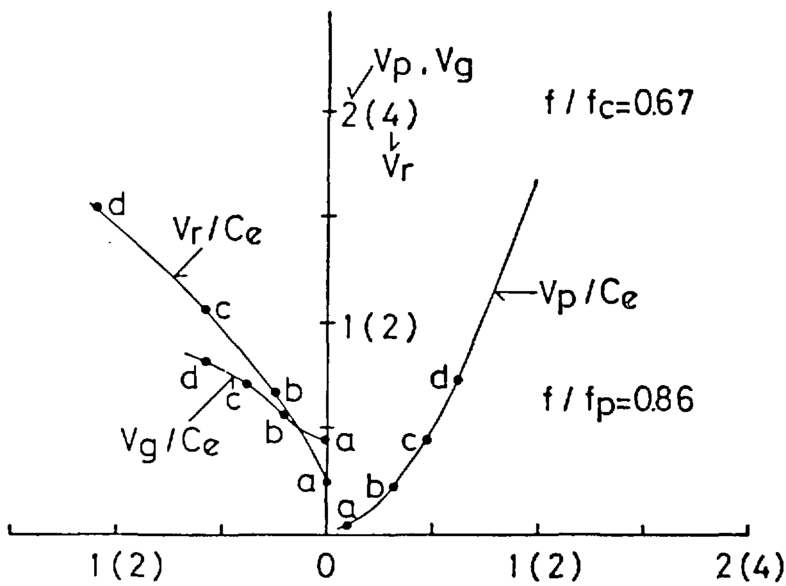


Fig. 6. Theoretical ray velocity (V_r), group velocity (V_g), and phase velocity (V_p) surfaces of the thermal mode (the oblique electron mode). C_e: the electron thermal velocity.

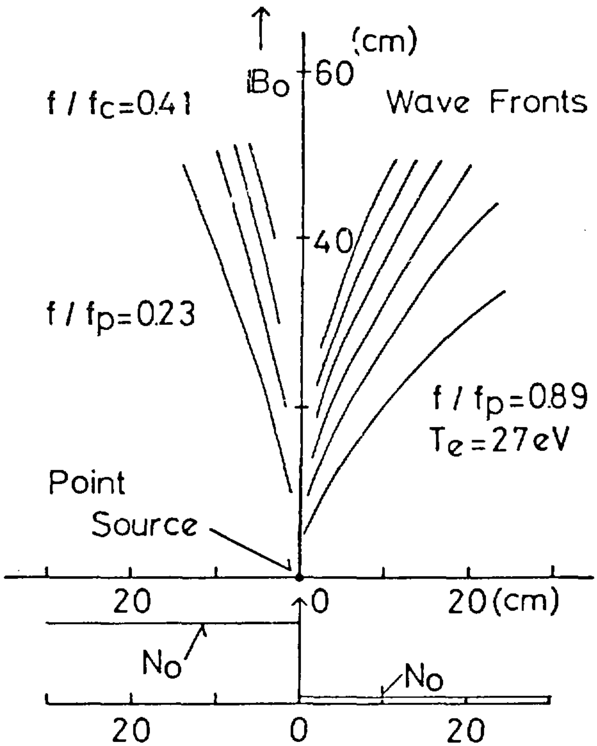


Fig. 7. Theoretical wave fronts of the thermal mode which are obtained from such a ray velocity surface as Fig. 6. Two cases of plasma density are indicated.

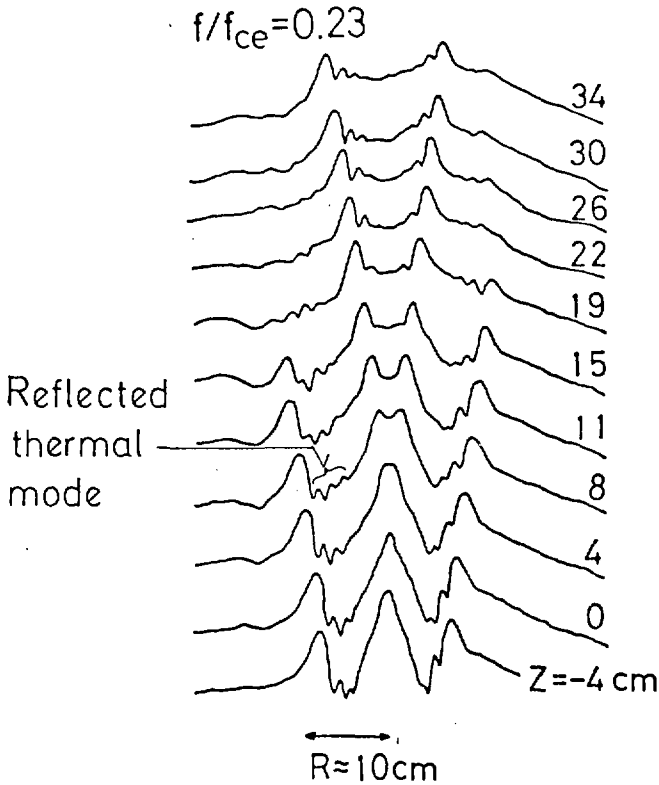


Fig. 8. Reflected thermal modes from an insulator disk which is placed perpendicular to magnetic field at Z= - 20cm.

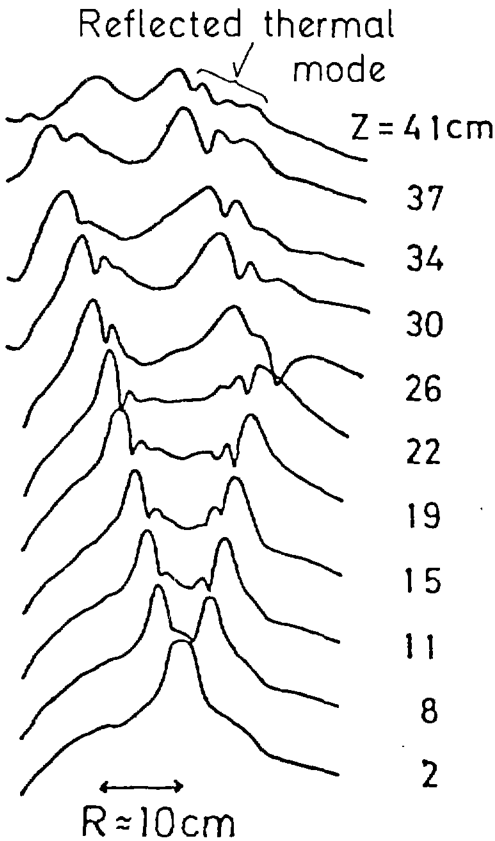


Fig. 9. Reflected thermal modes from the layer near the electron plasma frequency in an inhomogeneous magnetoplasma column.

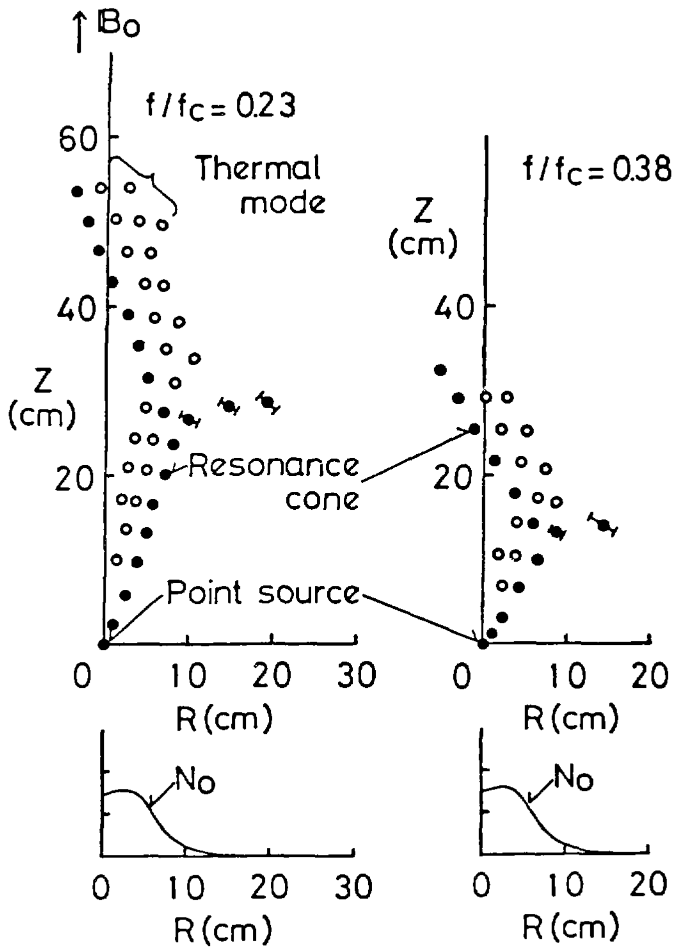


Fig. 10. Reflection of thermal modes associated with reflection and refraction c resonance cone fields in an inhomogeneous plasma. The electron plasma frequency layer is at the point where the cone fields are reflected and refracted.

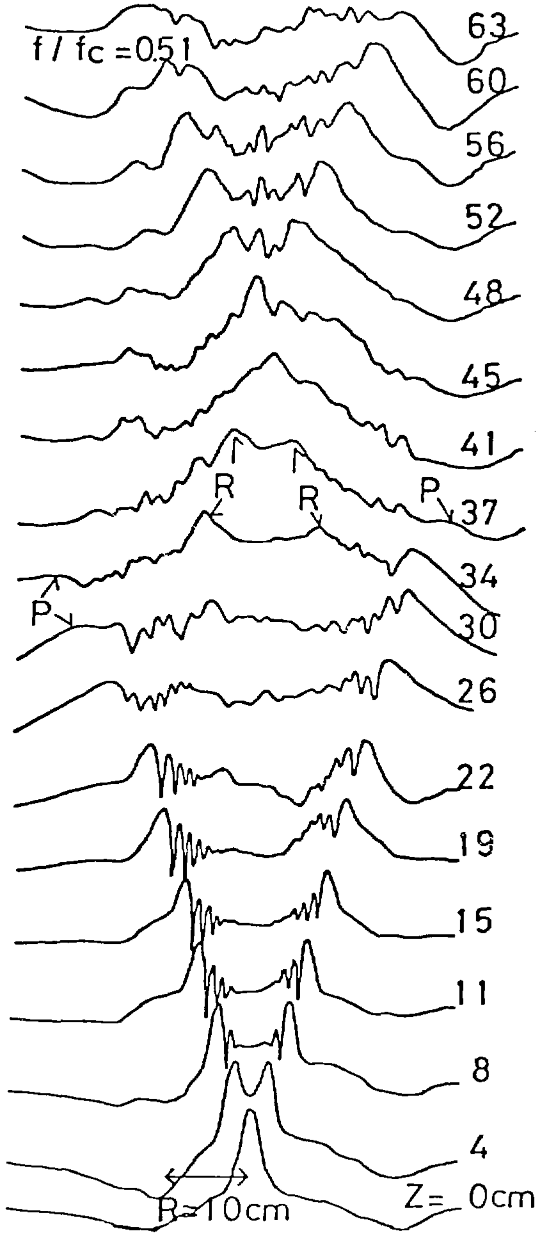


Fig. 11. Ducted resonance cone fields and thermal modes in an inhomogeneous magnetoplasma column. "R" and "P" are refleted and refracted cone fields at the electron plasma frequency layer.

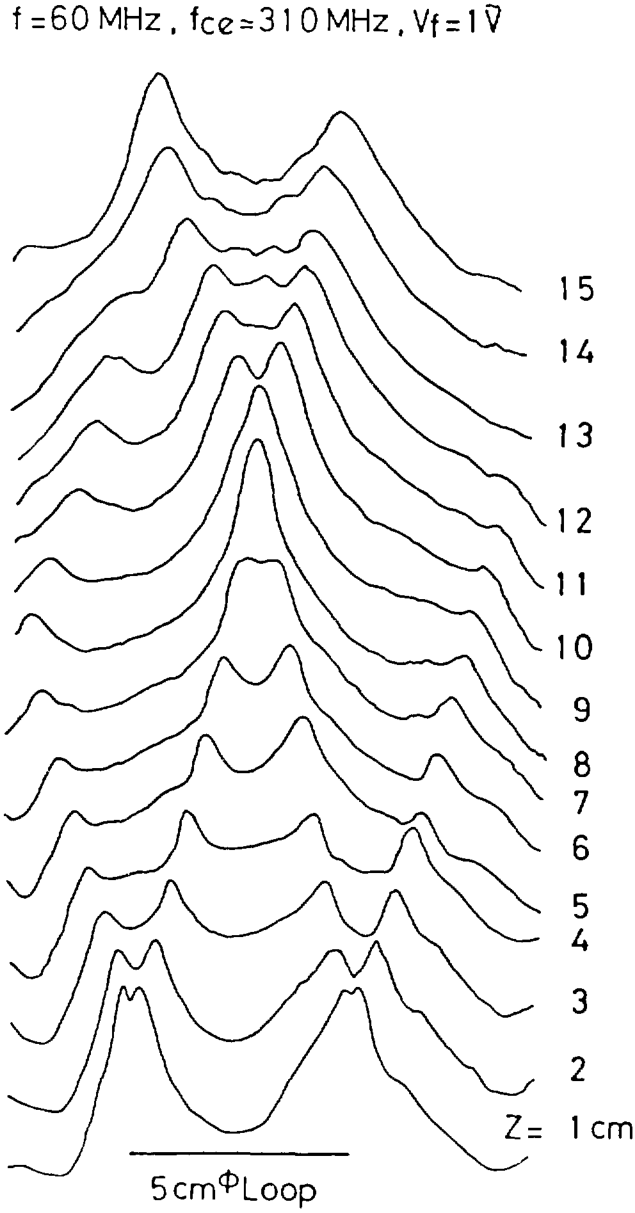


Fig. 12. Resonance cone fields radiated from a ring source with a small oscillating amplitude.

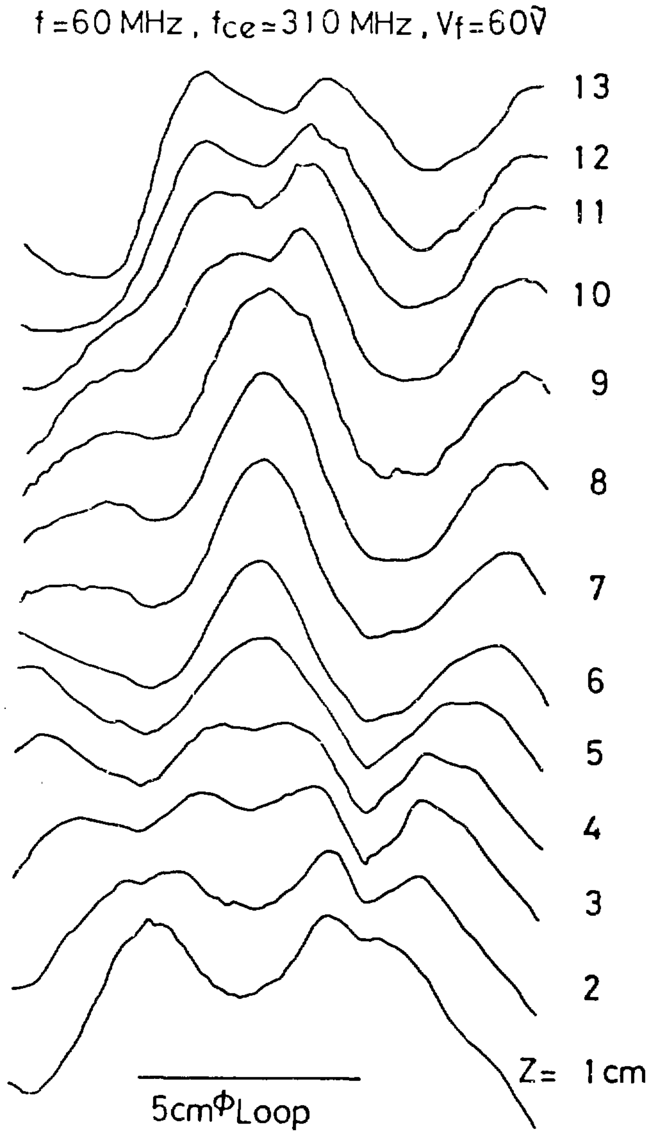


Fig. 13. Resonance cone fields radiated from a ring source with a large oscillating amplitude.

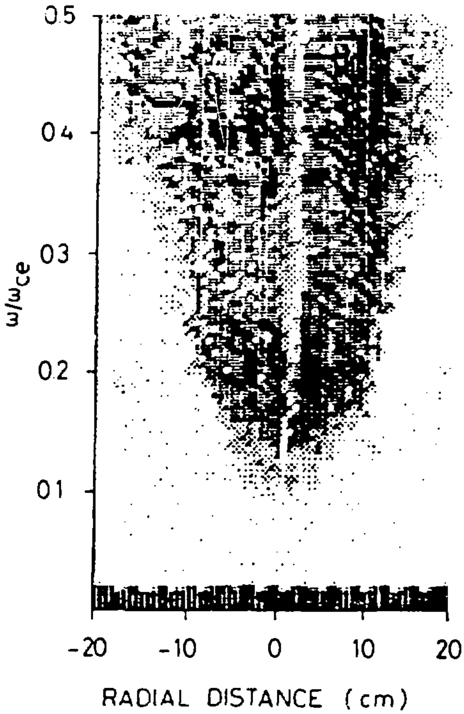


Fig. 14. Amplitude-frequency-"time" plot of low frequency waves ($< f_{ce}$) which are radiated from the electron beam (Ref. 19).

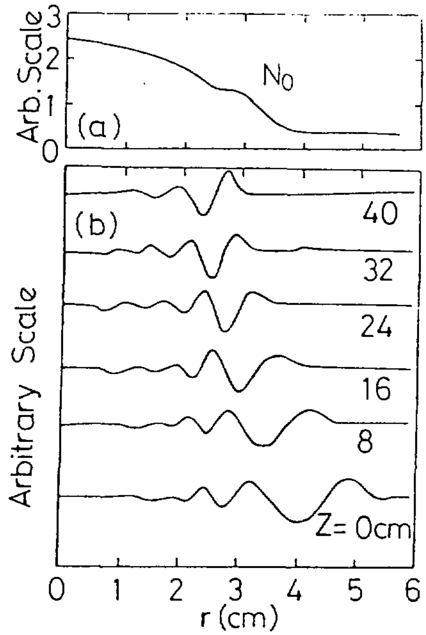


Fig. 15. Interferometer signal of radial lower hybrid wave field for a sequence of axial positions (b) and density profile (a). He gas. B=1.3kG, f=20MHz. (Ref. 26)

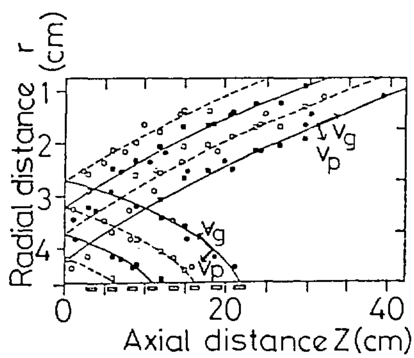


Fig. 16. Lower hybrid waves launched by the modofied Millman circuit. Experimental plots for the contours of constant phase, where ●,■ are for peaks and o, □ for troughs (Ref. 30).

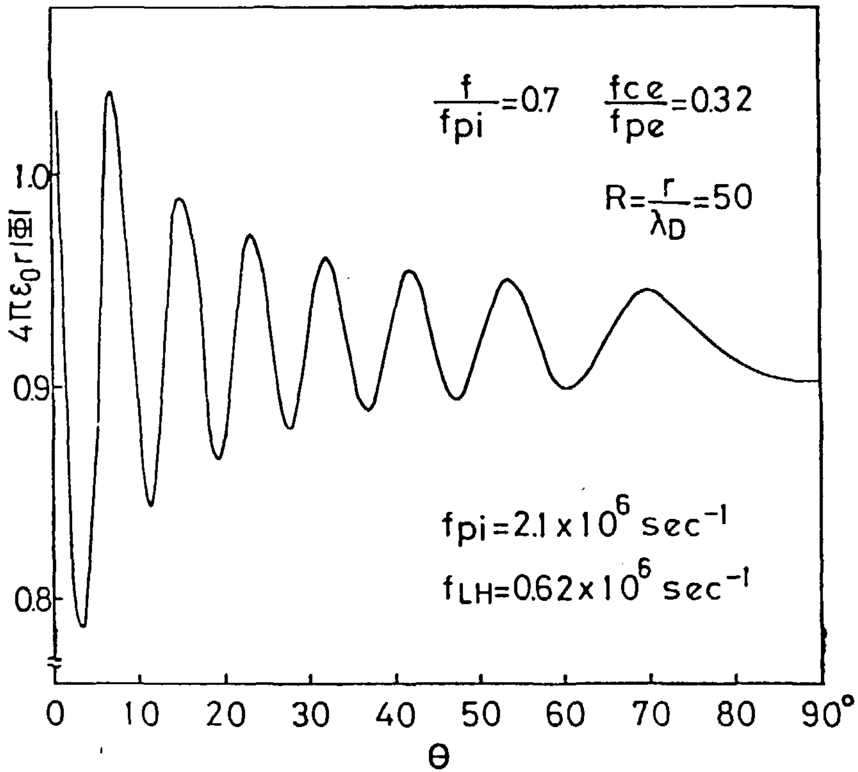


Fig. 17. Potential amplitude radiated from a point source near the lower hybrid frequency, i.e. an interference pattern between lower hybrid and ion acoustic waves.

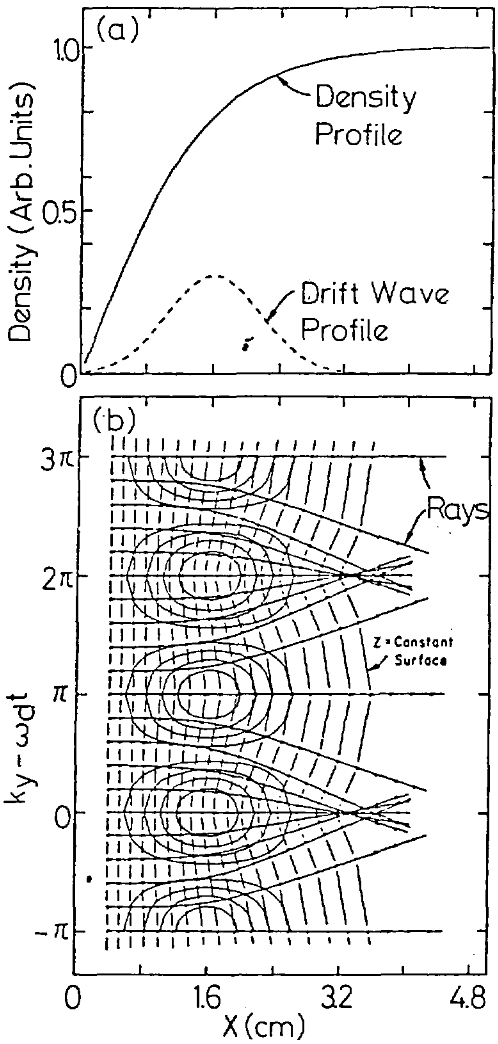


Fig. 18. (a) Density and drift-wave profiles (b) Ray refraction of resonance cone fields due to drift waves. Concentric ellipses are constant drift-wave amplitude contours (Ref. 33).

(A)

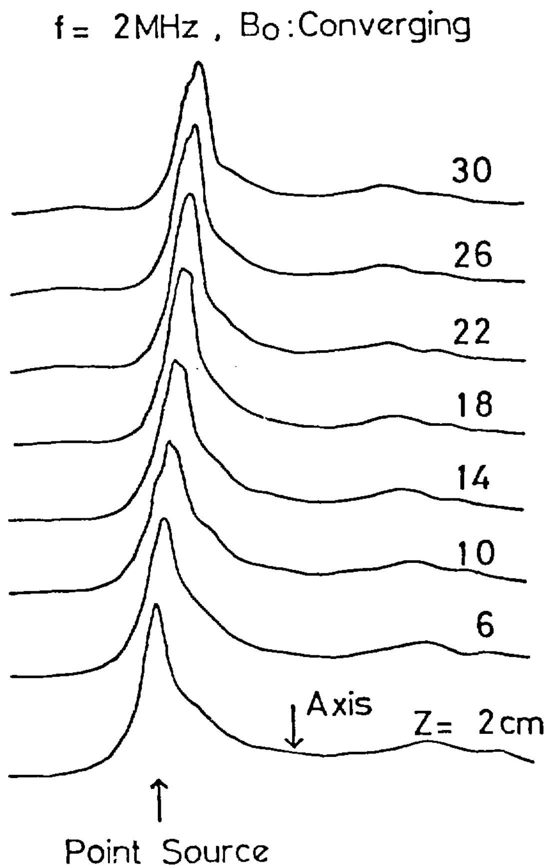
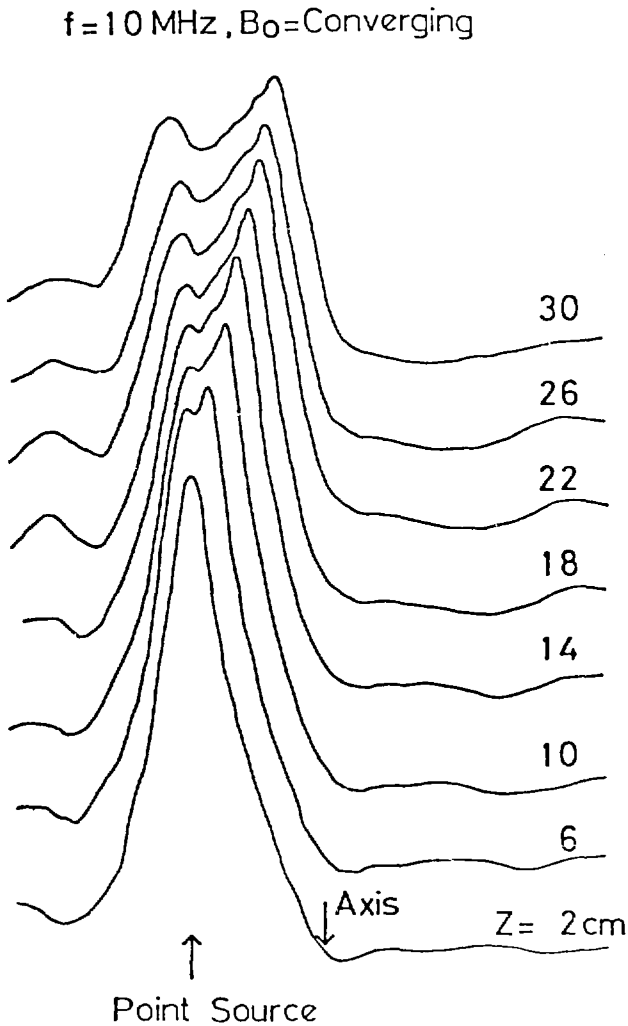


Fig. 19. (A) Lower hybrid cone radiated from a point source in a converging magnetic field. (B) Resonance cone fields radiated from a point source in a converging magnetic field. Point source is located at Z=0cm. The axis means the magnetic axis of the converging field.

(B)



f=10 MHz, Bo=Converging
30
26
22
18
14
10
6
Axis
Z= 2cm
Point Source

Fig. 19(B)

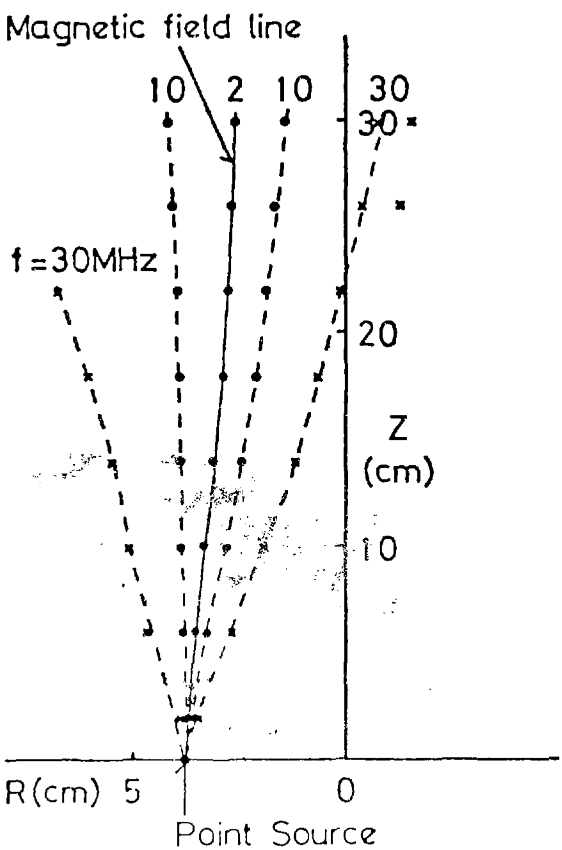


Fig. 20. Experimental trajectories of resonance cone fields radiated from a point source in a converging magnetic field. Solid line is the magnetic field line which passes through the point source.

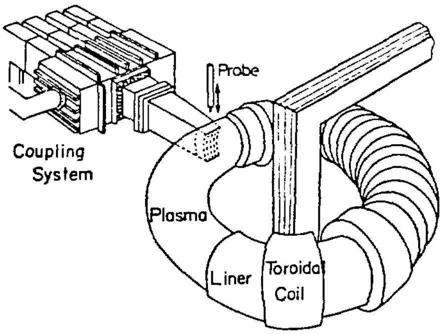


Fig. 21. Schematics of a waveguide coupling system of the JFT-2 tokamak for lower hybrid heating (Ref. 43)

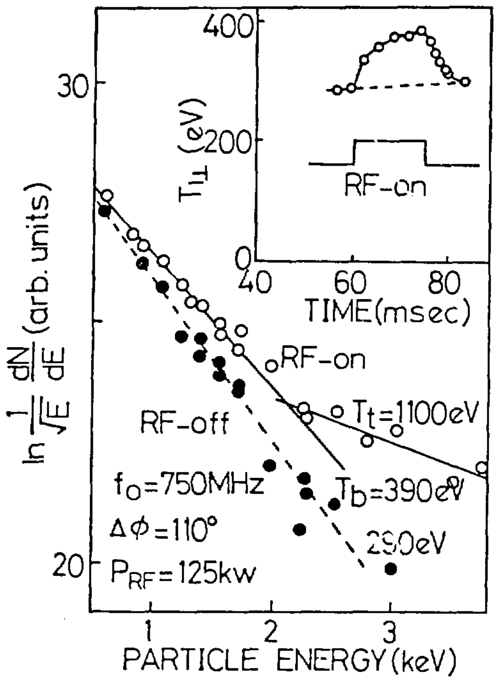


Fig. 22. Increase of ion temperature and a change of ion distribution function during lower hybrid rf heating in JFT-2 tokamak (Ref. 41)

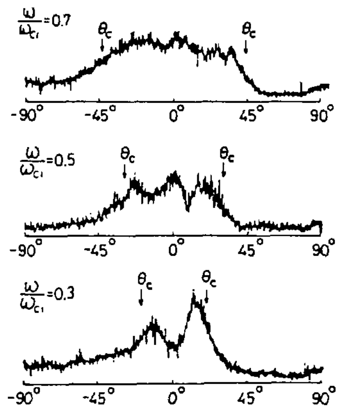


Fig. 23. Typical patterns of low frequency resonance cone fields near the ion cyclotron frequency. "θ_c" indicates the angle of low frequency resonance cone.

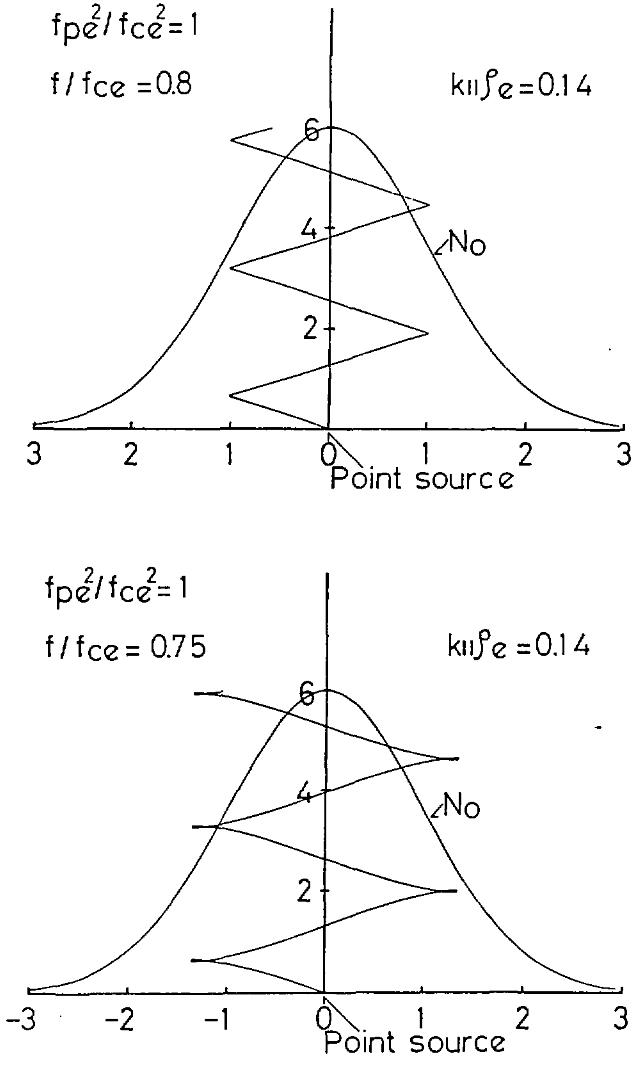


Fig. 24. Theoretical ray trajectories of localized rf fields in an inhomogeneous magnetoplasma column, in which thermal effects are included (Ref. 56).

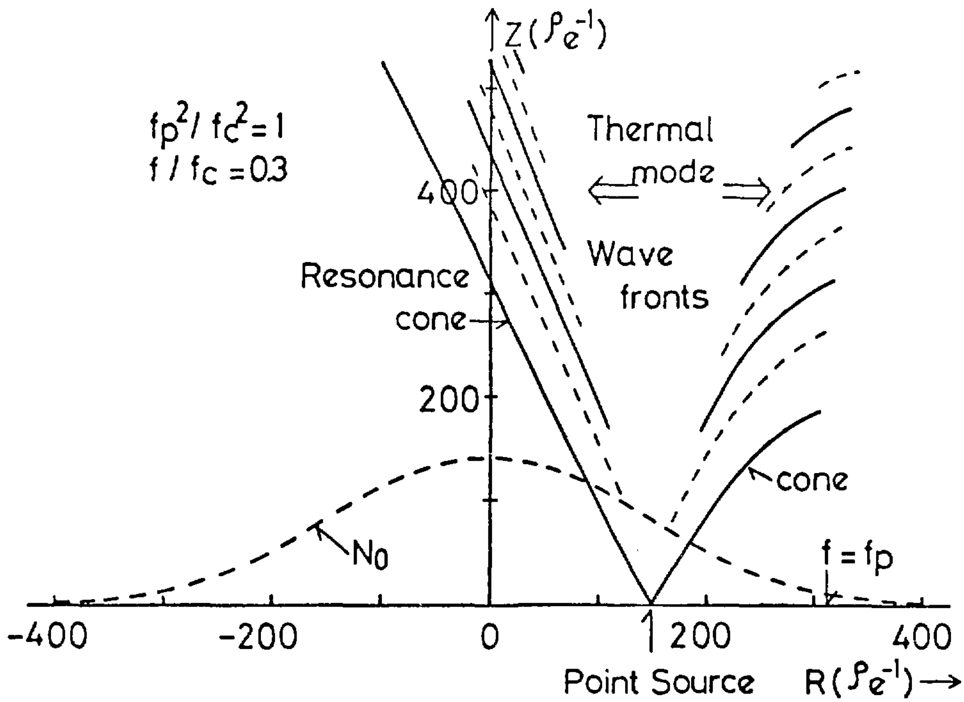


Fig. 25. Theoretical resonance cone fields and wave fronts of thermal modes radiated from a point source in an inhomogeneous plasma, which are derived from a kinetic theory (Ref. 59).

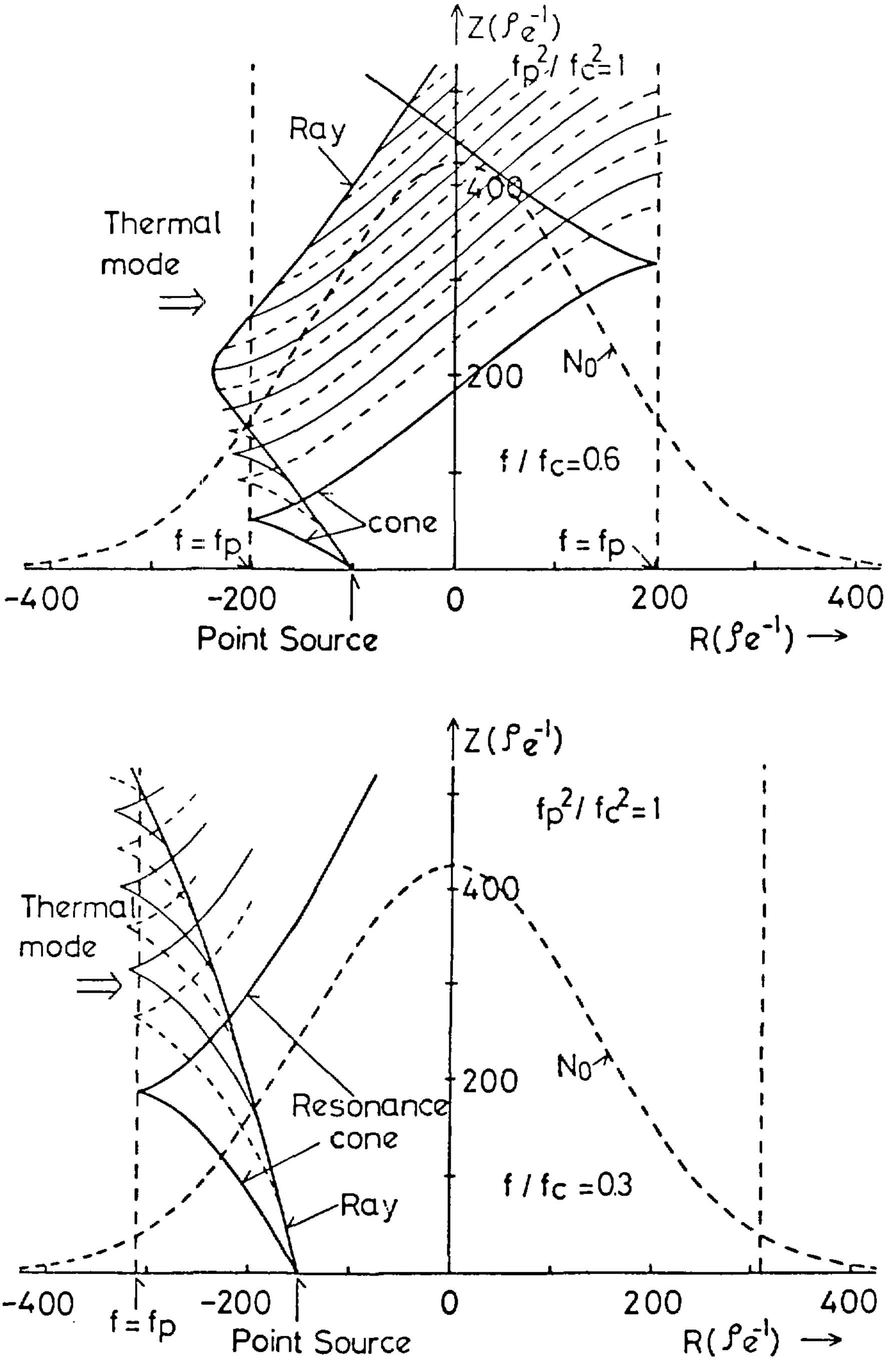


Fig. 26. Reflection of thermal modes and resonance cone fields in an inhomogeneous magnetoplasma from a kinetic theory (Ref. 59). "Ray" means a ray trajectory of the thermal mode for a fixed parallel wave number.

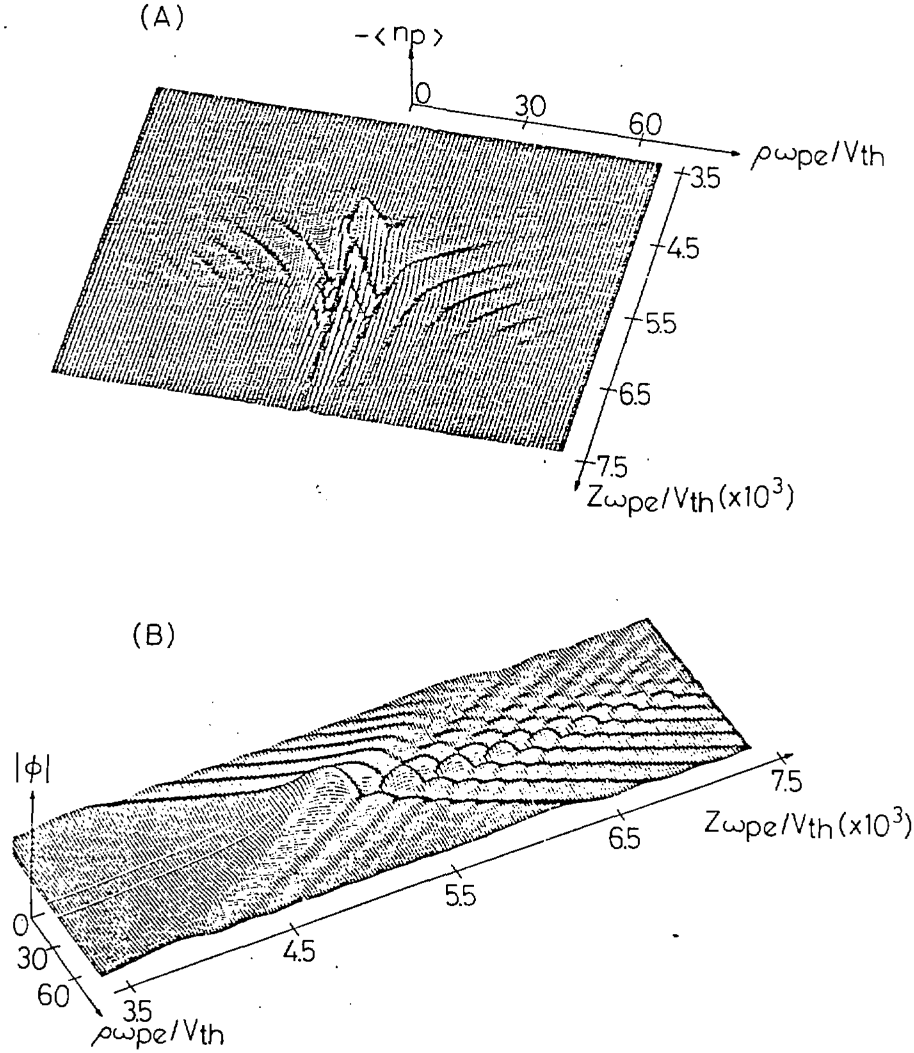


Fig. 27. Magnitude of the complex potential radiated from a ring source, displaying the interference structure due to thermal effects. $f/f_{pe}=0.02$, $\rho_o\omega_{pe}/v_{th}=270$ (B), the first-order density depression due to the poderomotive force for $f/f_{pe}=0.02$ (A) (Ref. 62)

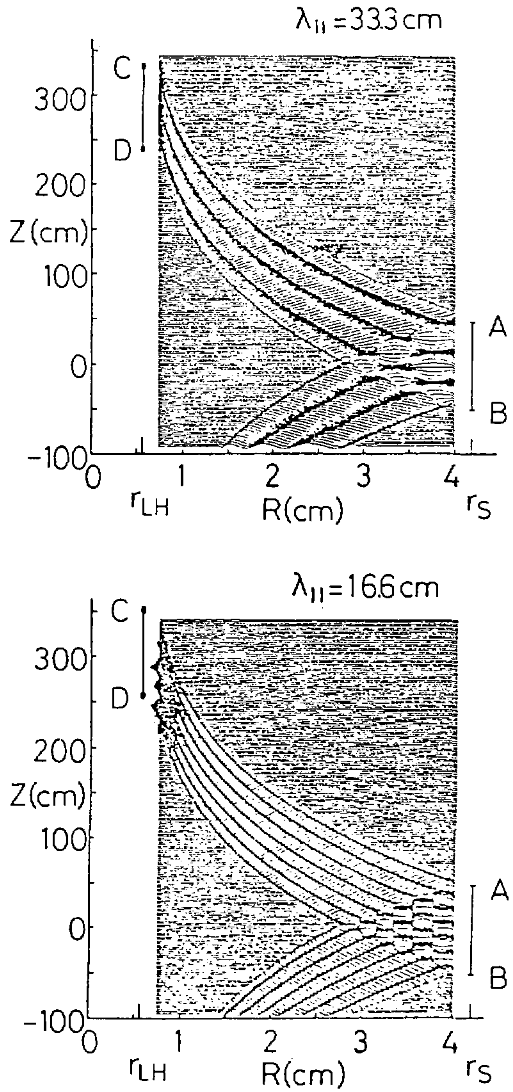


Fig. 28. Patterns of electric field generated by a 100cm long slow wave structure located along line AB. f=50MHz, B=2kG, He gas. Two cases of $\lambda_{\parallel}$ are shown (Ref. 72).

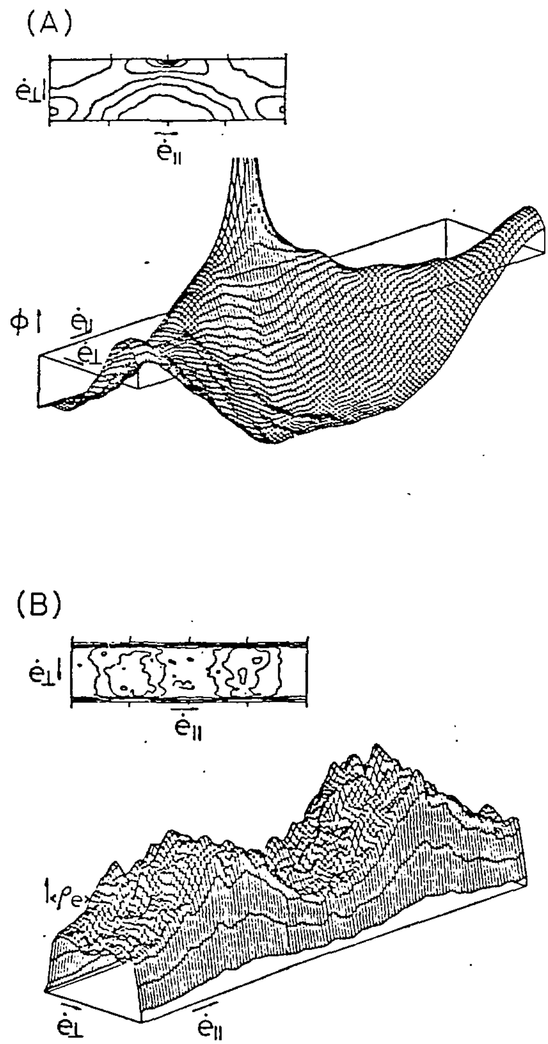


Fig. 29. Numerical electrostatic potential associated with lower hybrid resonance cone excited point source, $f/f_{pe}=0.35, f_{ce}/f_{pe}=1$ (A), Typical density profile at peak density depression averaged over one oscillation period (B), (Ref.101).

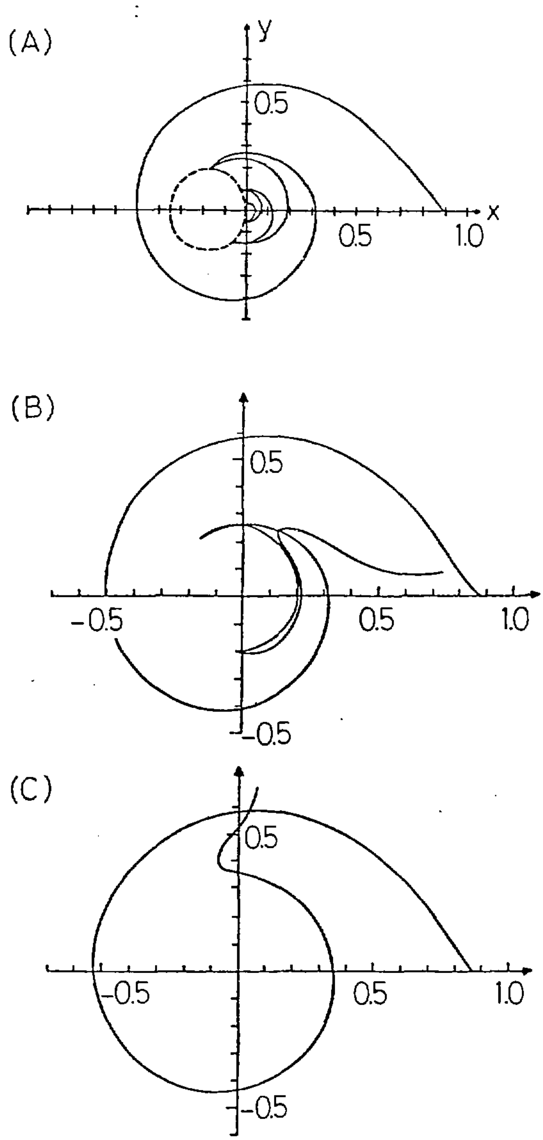


Fig. 30. Ray trajectories in r-θ plane in toroidal plasmas. The ray makes successive bounces off the lower hybrid surface (A). Thermal effects come into play after the first few bounces, and the wave mode-converted to a hot plasma wave (B: $T_e=T_i=100eV$, C: $T_e=T_i=1keV$), (Ref. 114).

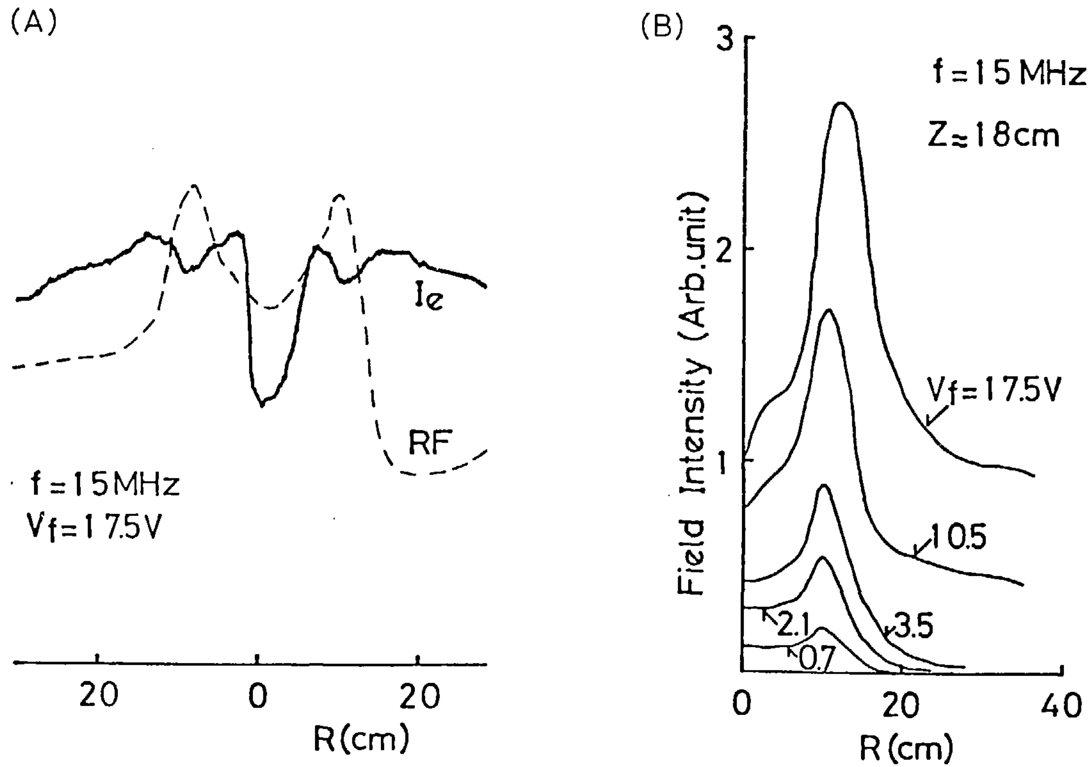


Fig. 31. (A) Resonance cone fields radiated from a point source when an applied power is varied. (B) Electron density profile and the corresponding amplitude of resonance cone rf fields under an application of high power fields.