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RESEARCH REPORT

IPPCZ 285 November 1988

POD VODÁRENSKOU VĚŽÍ 4, 180 69 PRAGUE 8
CZECHOSLOVAKIA

ELECTRON CYCLOTRON EMISSION AND ABSORBTION EXPERIMENT ON THE CASTOR TOKAMAK

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ABSTRACT

Electron cyclotron radiation and absorbtion measurements on the CASTOR tokamak are reported. Emission spectra are obtained with fast-scanning Fourier spectrometer and InSb detectors, working in the spectral range 30 - 300 GHz and receiving two-orthogonal polarization components simultaneously. When the plasma loop voltage is high, runaway electrons give rise to intense broad-band emission. Runaway particles can be removed by increasing the plasma density. The electron temperature profile was deduced from thermal emission and absorbtion around second cyclotron harmonics. From non-thermal emission second and third harmonics the energy and number of non-thermal particles could be calculated. During the lower-hybrid-current-drive (LHCD) experiments, presence of 60 keV electrons with density of 1.10^{16} m^{-3} was deduced from emission spectra.

1. INTRODUCTION

In recent years cyclotron plasma radiation in closed magnetic devices is widely used for determination of electron temperature. The exact correlation between intensity of cyclotron radiation for second harmonics and electron temperature holds when the following factors are satisfied:

a) Plasma should be optically thick ($\tau > 1$) at the used harmonics. The optical thickness of extraordinary mode at the second harmonics is equal /1, 2, 3/:

$$\tau^{e}_{\ell=2} = \frac{\pi\,\omega^{2}_{pe}}{\omega_{ce}\,c}\left(\frac{T_e}{mc^2}\right) f(q)\,\frac{B}{dB/dR}, \qquad (1)$$

where c is light velocity, m electron mass, $q = \omega^2_{pe}/\omega^2_{ce}$, ω_{pe} is electron plasma frequency, ω_{ce} is electron cyclotron frequency, and $f(q) = 1 + q/6$ at $q < 1$. B is toroidal magnetic field in teslas and R major radius in metres. For tokamak $B/(dB/dR) \approx R$ and approximately $\tau^{e}_{\ell=2} \approx 3{,}7.n_e T_e\,R/B$, where $\bar{n}_e$ is density in 10^{19} m^{-3} and T_e is electron temperature in keV.

b) The non-thermal (or runaway) level of radiation is not to high, because it prevents sometimes to determine exactly T_e and results in spreaded spectrum and overlapped harmonics.

2. EXPERIMENTAL SET-UP

To study the spectrum of electron cyclotron radiation in the CASTOR tokamak we have used fast-scanning Fourier spectrometer (FSFS) /4/. The distinguishing feature of the device is a possibility to measure simultaneously of orthogonal components of radiation and a short time (< 2 ms) of interferogramm performance by means of 4 enters of an axisymmetric screw rotating mirrors. The spectral range is about 30 - 300 GHz with spectral resolution ~ 3 GHz and amplitude of scanning mirrors 4.6 cm. Receiver is a n-InSb helium cooled detector; its sensitivity being less than 20 eV.

The FSFS is arranged at low-field side of the torus in the equatorial plane and recieves radiation by antenna with narrow diagramm $\sim 3^0$ what gives radiation spot in the plasma center to be equal ~ 2 cm. The radiation, emerging at an angle 90^0 to the toroidal magnetic field, passed through wedged crystal quartz window (the wedge angle is 3^0 and the effective aperture of the window is 25 mm). Next, the radiation is transported over a path length 1 m to the FSFS through a oversized copper waveguide with diameter of 24 mm.

In the absorbtion experiment the microwave power from generator (1 kHz modulation) is emitted by antenna placed in the vacuum chamber from high field size in the equatorial plane. Then it is received by horn, passes through polarization filter (extra ordinary mode) and is detected by InSb detector.

3. EXPERIMENTAL RESULTS

a) OH regimes

All discharges studied here (Fig. 1 - 3) are runaway dominated.

Firstly, we will analyse the shot in fig. 1. The ECE spectrum develops from thermal (with hollow) at 3 ms to non-thermal

at 5.7 ms. In the last spectrum, it is seen the non-absorbed $2\omega_{ce}$ peak. If the suprathermal electron distribution function is $f(E) = A\, n_{Run} \exp(-E/E_0)/E_0$, with constant pitch-angle θ for all electrons, the energy E_0 is equal to /1/:

$$E_0 = mc^2 \frac{1 - x^2/\ell^2}{2x^3/\ell^2} \approx 100 \text{ keV},$$

where $x = \omega_{peak}/\omega_{ce} = 44.6/28$, $\ell = 2$. ω_{peak} is frequency corresponding to the peak.

If E_0 is known the ratios of specific intensities of the peaks of the harmonics (I_ℓ) can be used to find θ:

$$\frac{I_\ell}{I_{\ell+1}} = f_\ell(\theta, \frac{mc^2}{E_0}),$$

where f_ℓ is function defined in /1/. For $I_2/I_3 = 1.9$, in our case, we obtain $\theta = 60^0$. To find constant A we take $n_{Run} = \int_{E_1}^{E_2} f(E)dE$ from $E_1 = 5$ keV (runaway energy) to $E_2 = 140$ keV (from f~~u~~an-like instability criterion /5/). We find A = 1.4. Finally, we can determine absolute value of I_2. Its ratio to the thermal spectrum is $I_2/I_{th} = 4.3$, where the amplitude of I_{th} is known:

$$I_{2th} = 4\omega^2 kTe/8\pi^3 c^2 = 4.57 \times 10^{-13} \text{ W/m}^2.$$

(Electron temperature is taken from shot in fig. 3, decribed bellow.) By a knowledge of I_2 we can estimate density of runaway electrons, n_{Run} from relation /1/:

$$I_\ell = \frac{\Delta r}{1 - r} f_\ell\ (x, E_0, \theta, n_{Run}, A), \qquad (2)$$

where f_ℓ is function defined in /1/, Δr = 5 cm is diameter of suprathermal electron beam, an r = 0.95 is wall reflection coefficient. From (2) we find $n_{Run} \approx 2.9 \times 10^{15}$ m^{-3}. The current associated with runaway electrons should be

$$I_{Run} = n_{Run} . e . v(E) . \pi (\frac{\Delta r}{2})^2 = 35 \text{ A},$$

where e is electron charge and v runaway electron velocity.

In fig. 2, the above analysis only for third harmonics ($\ell = 3$) is possible. We obtain $x = \omega_3/\omega_{ce}$ = 74/28 and E_o = 30 keV. Note, that the thermal spectrum at 3 ms is non-hollow.

The evolution of soft-x-ray signal in fig. 3 shows that the electron temperature is nearly constant. It is also seen from electron cyclotron absorption (ECA). The refraction in absorbtion signal was cross-checked at 1.5 ms for non-resonant frequency. The bias on ECA signal is due to the EC-emission. Absolute value of Te(0) = 280 eV was determined from (1) for density profile $n_e(r) = n_e(0)\ (1 - r^2/a^2)$, where a is limiter radius, a = 85 mm. The error bars in fig. 3c are the scatterings of 3 - 4 discharges. A good agreement with ECE profile is obtained.

For comparison, temperature from Spitzer conductivity is:

$$T_e = 100(\frac{I_p}{U})^{0.66} \approx 261 \text{ eV}, \qquad [\text{kA,V}]$$

for Z_{eff}= 4 and $T_e(r) = T_e(0) \left[1 - (\frac{r}{a})^2\right]^2$.

Temperature from energy balance /6/ can be estimated to:

$$T_e(0) = 88 \left[\frac{I_p\sqrt{Z_{eff}}}{\Delta(P_{OH}/P_{Rad})}\right]^{4/5} \approx 270 \text{ eV}, \ [\text{kA}]$$

where ohmic heating power P_{OH} = 33,6 kW and radiated power P_{RAD}=20 kW.

b) LHCD/OH - plasmas

Fig. 4 and 5 show ohmic discharges with lower-hybrid-current-drive. Feedback position system is switched off. Effect of absorbtion of energy is evident from radial displacement Δ_R and enhancement of integral ECE signal. The amplitude of ECE signal is 6 times higher for LHCD/OH plasma comparing with OH discharge. It is caused by appearence of fast electrons. At t = 4.6 ms for $\ell = 2$ we find $x = \omega_{peak}/\omega_{ce}$ = 50/29 and E_o = 52 keV. For ℓ= 3, $x = \omega_{peak}/\omega_{ce}$ = 68/29 and E_o = 70 keV. From I_2/I_3 = 1.4 we find $\theta \geq 60^o$. If we take Te = 280 eV, energy interval E_1 = 5 keV, E_2 = 140 keV and $I_2/I_{2\,th}$ = 10 we obtain for density of runaway electrons (Δr = 5 cm, r = 0.95) r_{Run}= 1.1×10^{16} m^{-3}. Corresponding number of electrons is

$$N_{Run} = 2\pi R_o \pi (\frac{\Delta r}{2})^2\ n_{Run} = 7.4 \times 10^{13} \text{ m}^{-3},$$

where R_o = 0.4 m is tokamak major radius.

For comparison, the current driven by LH-waves, derived from loop voltage drop ΔU, is equal to

$$I_p . \frac{\Delta U}{U} \approx 11.6 \text{ kA} \ \frac{0.8\text{V}}{2.6\text{V}} = 3.5 \text{ kA}.$$

Corresponding number of electrons is:

$$N_{Run} = \frac{I_{Run} 2\pi R_o}{ec} = 1.9 \times 10^{14} \text{ m}^{-3}.$$

In fig. 5, electron density is higher, and thus smaller current is driven:

$$I_p \frac{\Delta U}{U} = 1.1 \text{ kA.}$$

The amplitude of non-thermal ECE spectrum is 3 times smaller than in fig. 4. Assumming the same E_0 and θ we obtain smaller I_{Run} which is consistent with LH-current.

4. CONCLUSIONS

From the thermal ECE spectrum, at the beginning of OH-discharge, electron temperature profile was measured. From ECA Te(r) profile in absolute units Te(0) = 280 eV was determined and good agrement was obtained.

From non-thermal ECE spectra, in the end of OH-regimes, energy number and pitch-angle of runaway electrons was determined. During LHCD/OH - regimes, the amplitude of non-thermal ECE - spectra was proportional to the LH - current. In this regime energy of fast electrons was determined to 60 keV and their total number to 7.4×10^{13}.

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Figure captions

Fig. 1 (a) Temporal evolution of plasma current (I_p), line averaged electron density ($\bar{n}_e$) and loop voltage (U) during ohmic discharge with high population of runaway electrons. (b) dynamics of ECE spectra. (c) the spectrum at 3 ms in enhanced scale.

Fig. 2 The same as in fig. 1 but with less population of runaway electrons.

Fig. 3 (a) Temporal evolution of plasma parameters in absorbtion experiments (I_p as in fig. 1) (b) P_{RAD} bolometrically measured radiated power, SXR - soft x-ray emission, HXR - hard x-ray emission (c) transmitted power with resonant frequency f = 56 GHz and with frequency f = 61 GHz (d) measured electron temperature profile at t = 5 ms. Solid line: ECE - profile at 3 ms from fig. 2 with $T_e(0)$ = 280 eV.

Fig. 4 (a) Plasma parameters in LHCD/OH and OH-discharges for density $\bar{n}_e = 4\times10^{18}\ m^{-3}$. (b) total intensity $I_{ECE} = \int I_{ECE}(\omega)d\omega$ (c) radial plasma displacement. (d) ECE - spectra.

Fig. 5 The same as fig. 4 but for density $\bar{n}_e = 8\times10^{18}\ m^{-3}$.

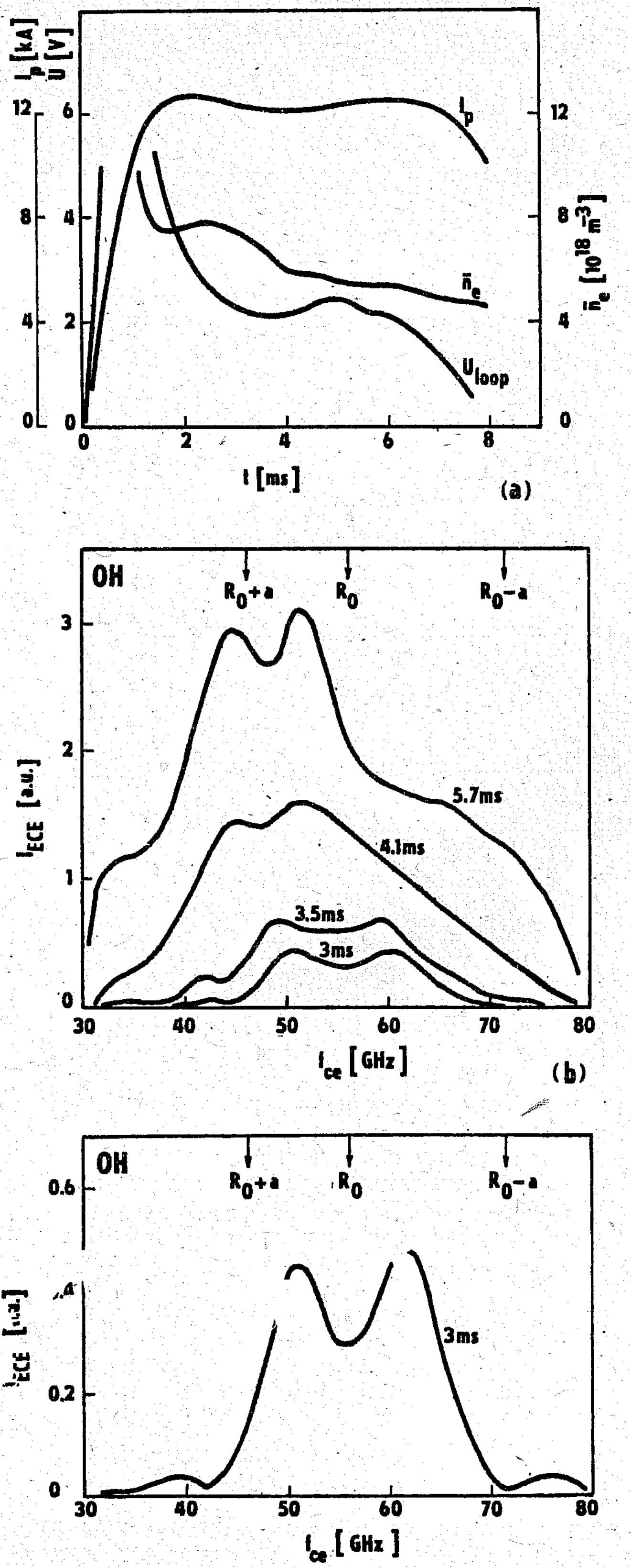

Fig. 1

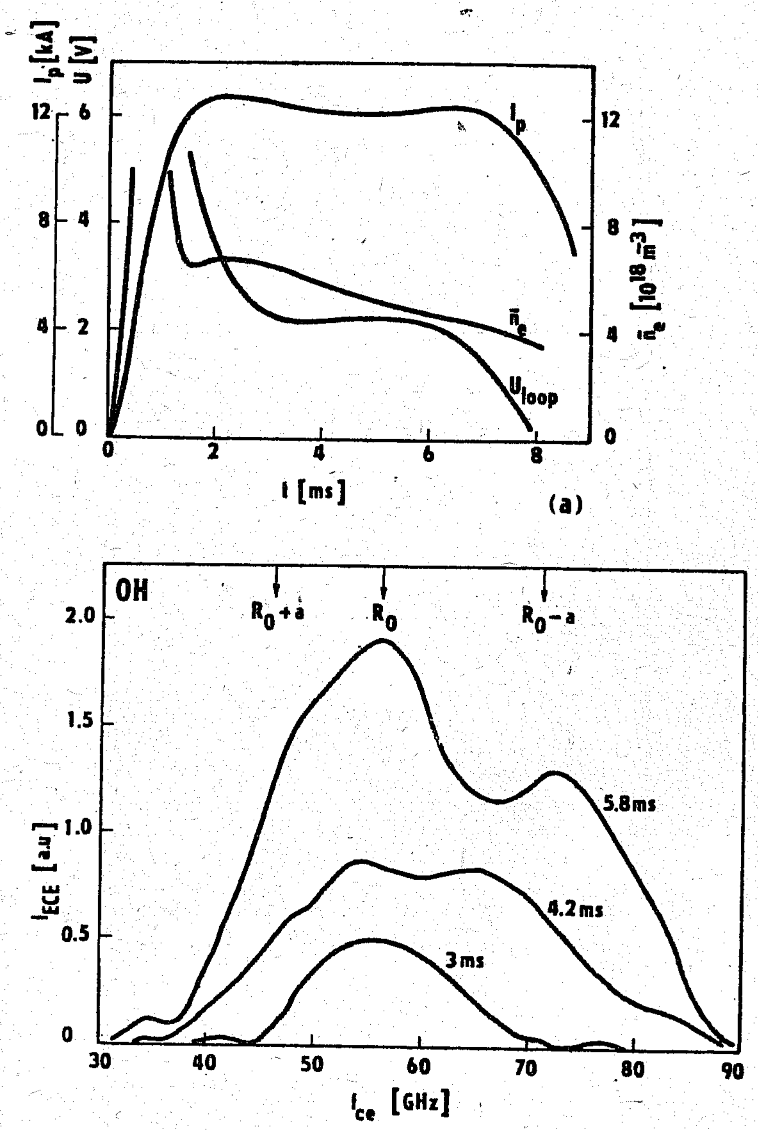
I_p [kA]
U [V]
12
6
8
4
4
2
0
0
12
8
4
0
$\bar{n}_e$ [10^{18} m^{-3}]
I_p
$\bar{n}_e$
U_{loop}
0
2
4
6
8
t [ms]
(a)
OH
R_0+a
R_0
R_0-a
2.0
1.5
1.0
0.5
0
I_{ECE} [a.u]
5.8ms
4.2ms
3ms
30
40
50
60
70
80
90
f_{ce} [GHz]
(b)

Fig. 2

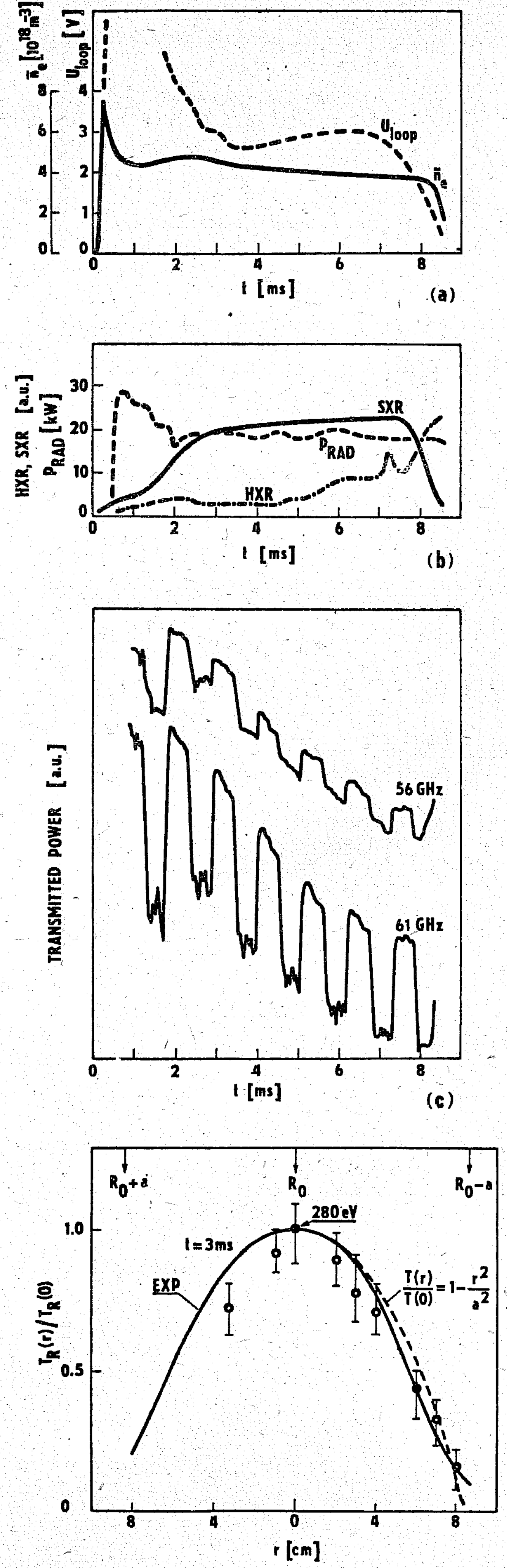
$\bar{n}_e$ [10^{18} m^{-3}]
U_{loop} [V]
8
6
4
2
0
4
3
2
1
0
U_{loop}
$\bar{n}_e$
0
2
4
6
8
t [ms]
(a)
HXR, SXR [a.u.]
P_{RAD} [kW]
30
20
10
0
SXR
P_{RAD}
HXR
0
2
4
6
8
t [ms]
(b)
TRANSMITTED POWER [a.u.]
56 GHz
61 GHz
0
2
4
6
8
t [ms]
(c)
R_0+a
R_0
R_0-a
1.0
0.5
0
$T_R(r)/T_R(0)$
280eV
t=3ms
EXP
$\frac{T(r)}{T(0)}=1-\frac{r^2}{a^2}$
8
4
0
4
8
r [cm]
(d)

Fig. 3

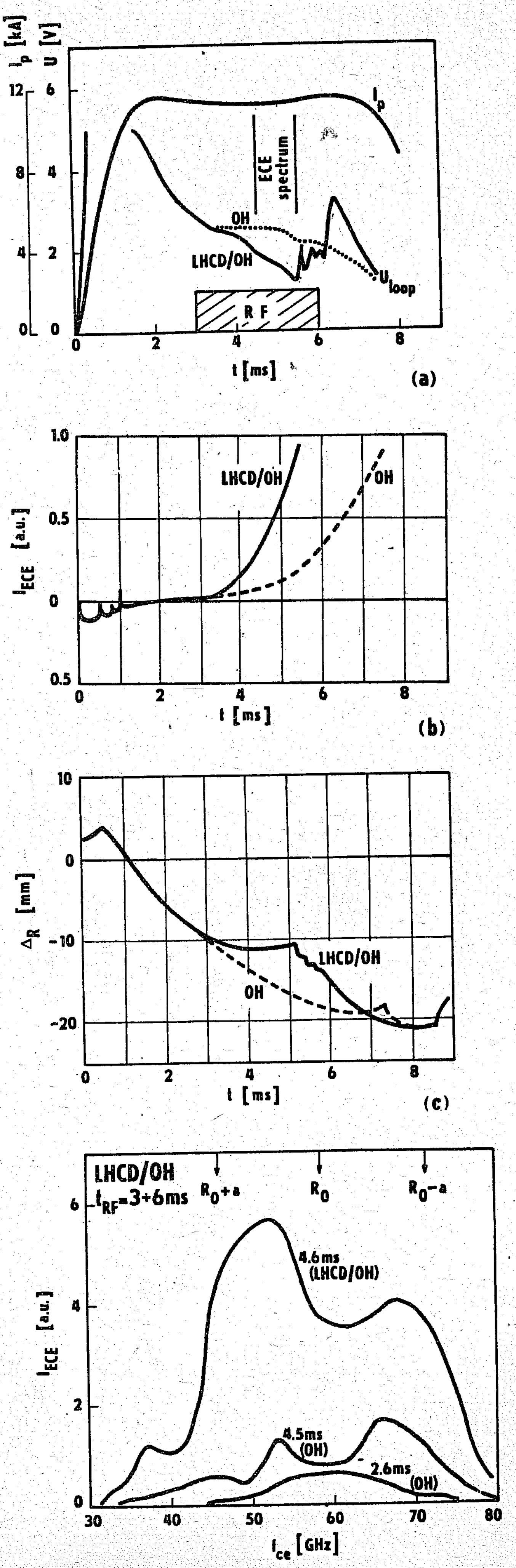

Fig. 4

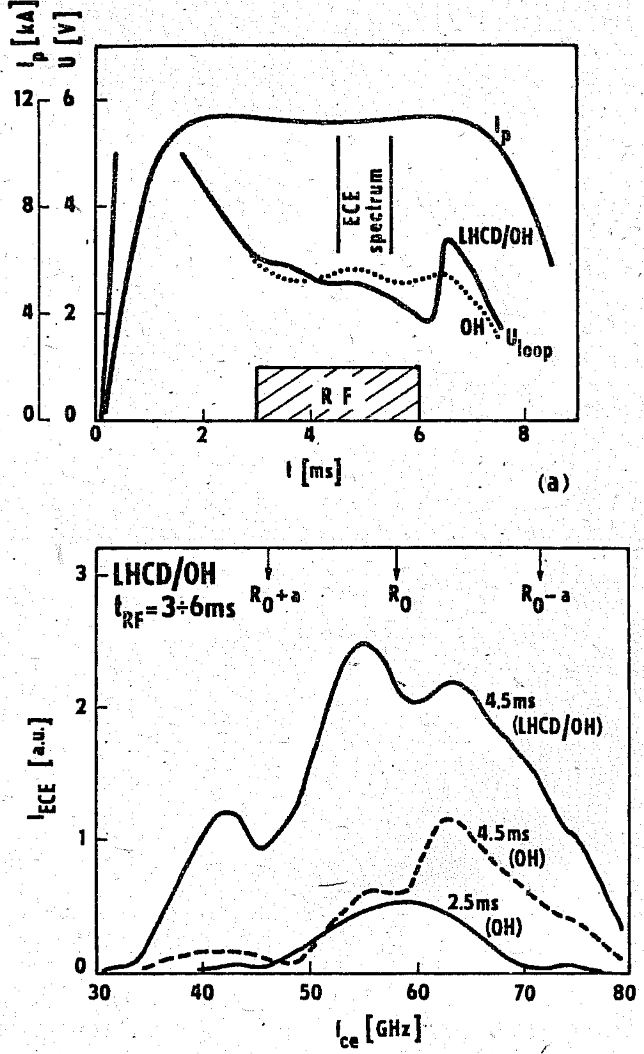

Fig. 5

TZ 56