INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4-SMR 393/52

SPRING COLLEGE ON PLASMA PHYSICS

15 May - 9 June 1989

RADIO FREQUENCY HEATING IN TOKAMAKS

Electron Cyclotrin Resonance Heating

D. F. Start

Jet Joint Undertaking
Oxfordshire
Abingdon OX14 3EA
U. K.

MAIN BUILDING STRADA COSTIERA, 11 TEL. 22401 TELEFAX 224163 TELEX 460392 ADRIATICO GUEST HOUSE VIA GRIGNANO, 9 TEL. 224241 TELEFAX 224531 TELEX 460449

Electron Cyclotron Resonance Heating

$2\pi f = eB/\gamma m_e$ $\gamma = (1 - v^2/c^2)^{-1/2}$ - relativistic mass correction

Ex $B = 2T$ $f = 56$ GHz, $\lambda_{\text{free space}} = 5.4$ mm

Experiments $28\,\text{GHz} < f < 80\,\text{GHz}$

Dispersion Relation - Appleton-Hartree

$$N^2 = 1 - \frac{2\alpha\omega^2(1-\alpha)}{2\omega^2(1-\alpha) - \omega_c^2\sin^2\theta \pm \omega_c\Delta}$$

ω = wave freq

ω_c = cycl. freq.

θ angle between $\underline{k}$ & $\underline{B}$

$\Delta^2 = \omega_c^2\sin^4\theta + 4\omega_c^2(1-\alpha)^2\cos^2\theta$

$\alpha = \omega_p^2/\omega^2$

ω_p = plasma freq (rad s^{-1}) $= 5.6\times10^4\, n_e^{1/2}$ (cm^{-3})

2 Modes [O, X]	$\theta = \pi/2$	$\theta = 0$
+ve sign Ordinary [O] mode	$E_{\parallel}$ to B	LH polarisat^n
-ve sign Extraordinary [X] mode	$E_{\perp}$ to B	RH polarisat^n

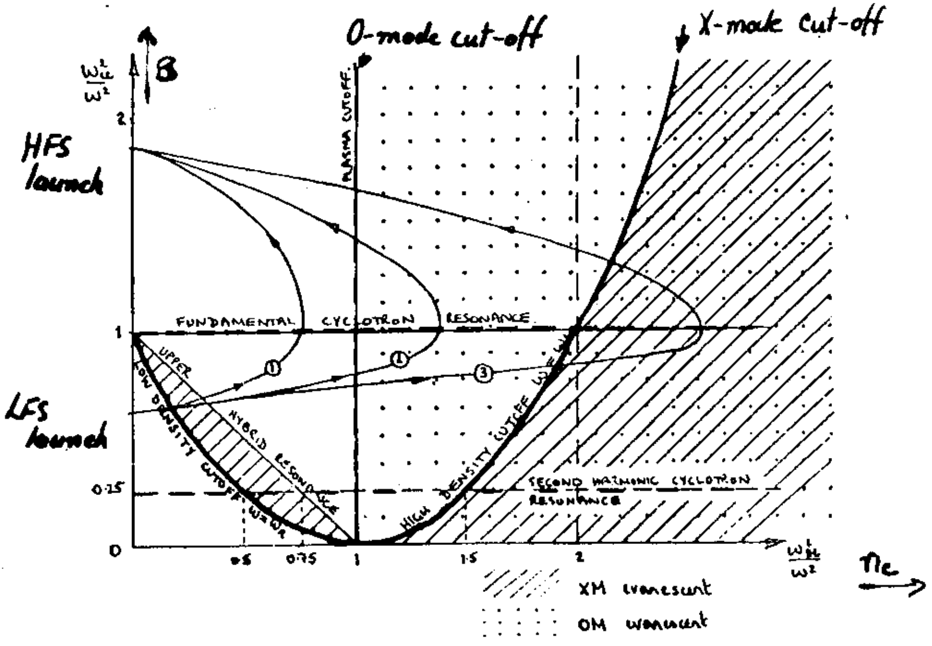
Cut-offs when $N \to 0$

O mode $\omega = \omega_p$

X mode $\omega_{R,L} = \left(\omega_p^2 + \frac{\omega_c^2}{4}\right)^{\frac{1}{2}} \pm \frac{\omega_c}{2}$

Plasma resonance when $N \to \infty$

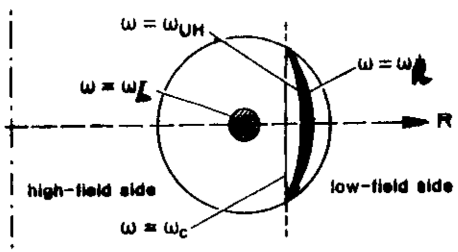
Upper hybrid resonance $\omega_{UH}^2 = \omega_c^2 + \omega_p^2$



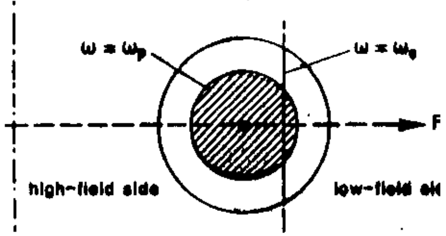
Cut-offs limit values of $(\omega_p/\omega_{ce})^2$

		O-mode	X-mode
und.	$\omega = \omega_{ce}$	1	2 (HFS)
nd Harm	$\omega = 2\omega_{ce}$	4	2

X - mode



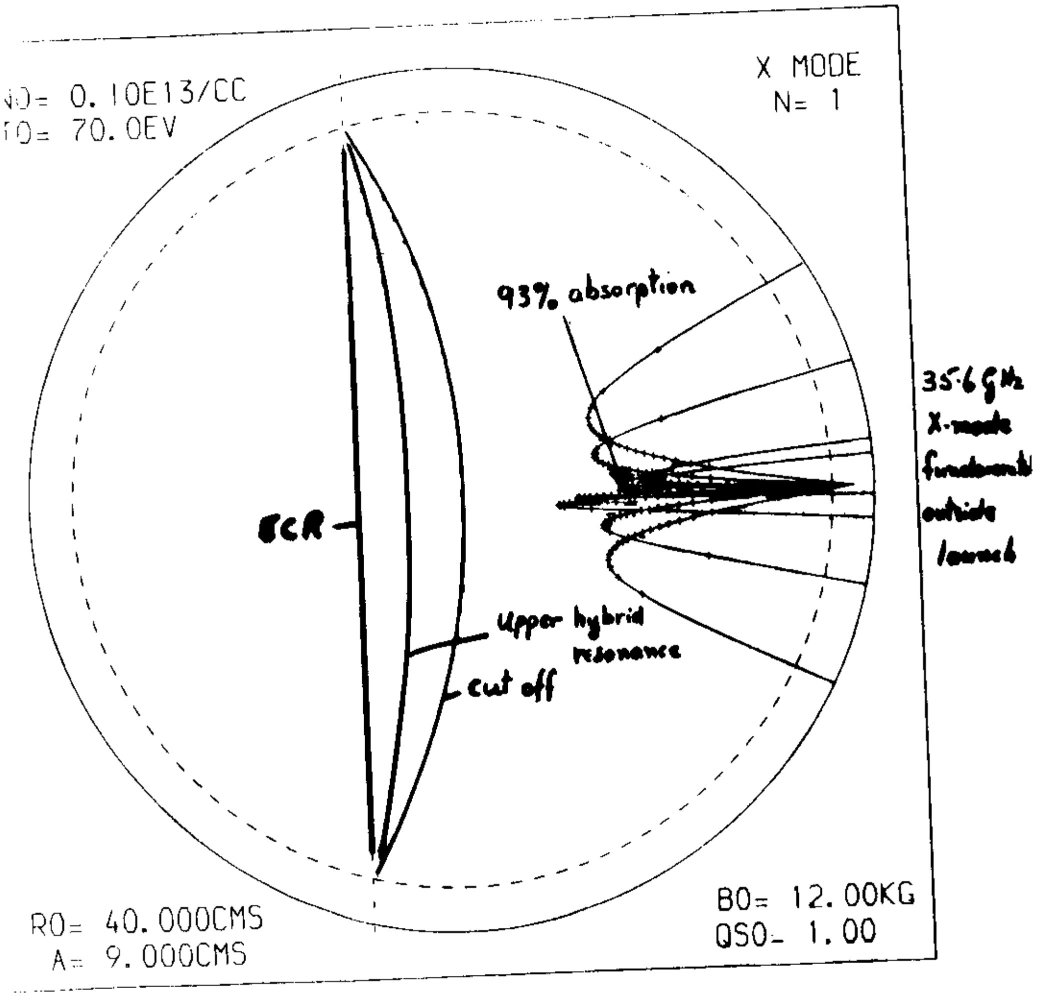
O - mode



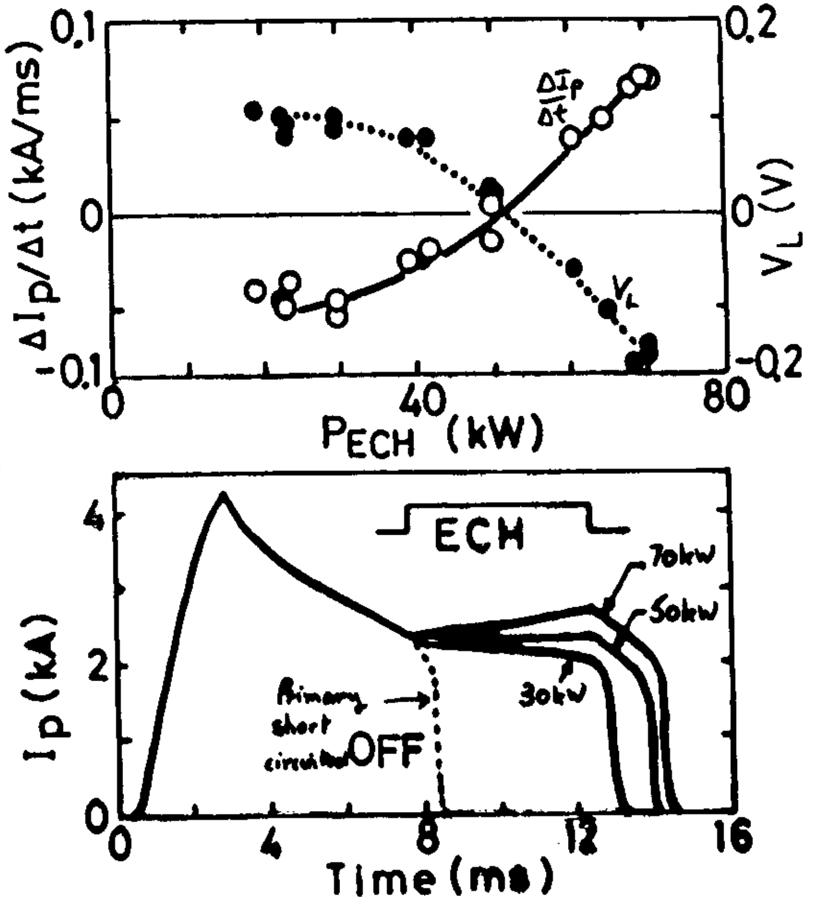
W1-4

X-mode fundamental, 35.6 GHz outside launch

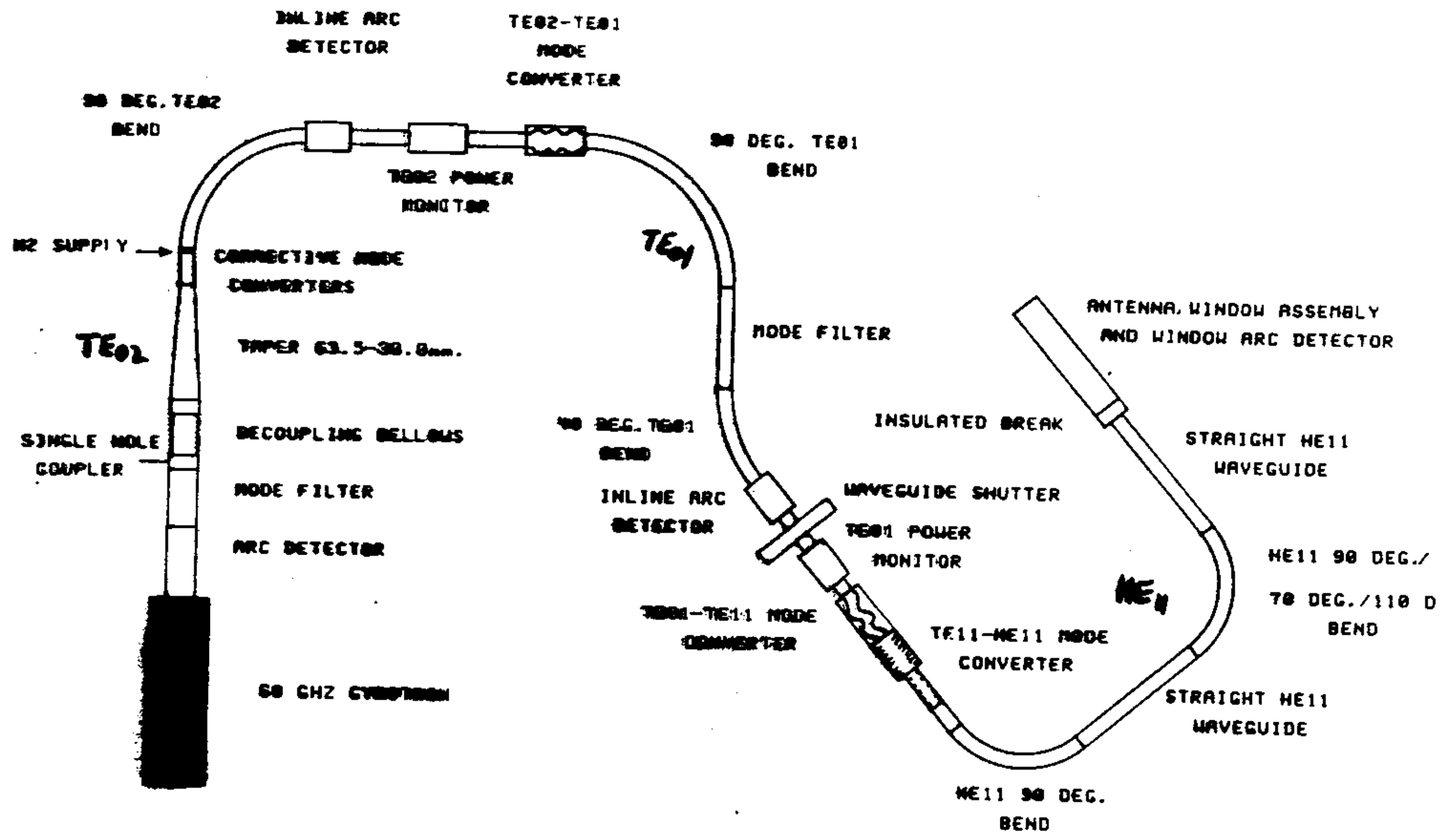
co, ctr + ⊥r into slideaway OH plasma $T_e = 70\,eV$ $n_e = 2\times10^{12}\,cm^{-3}$



Co-injection



⊥r + ctr injection reduce V_L but do not produce reversal

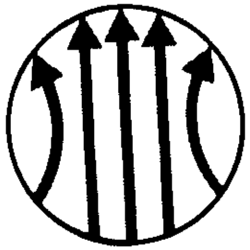


SCHEMATIC OF COMPASS CIRCULAR VESSEL E.C.R.H SYSTEM

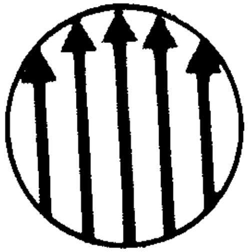
N.AINSWORTH 27-5-88

Output from gyrotron, TE_{02}, i.e. Transverse Electric circular field in a 2-ring pattern.

After conversion to TE_{01}, i.e. circular 1-ring pattern



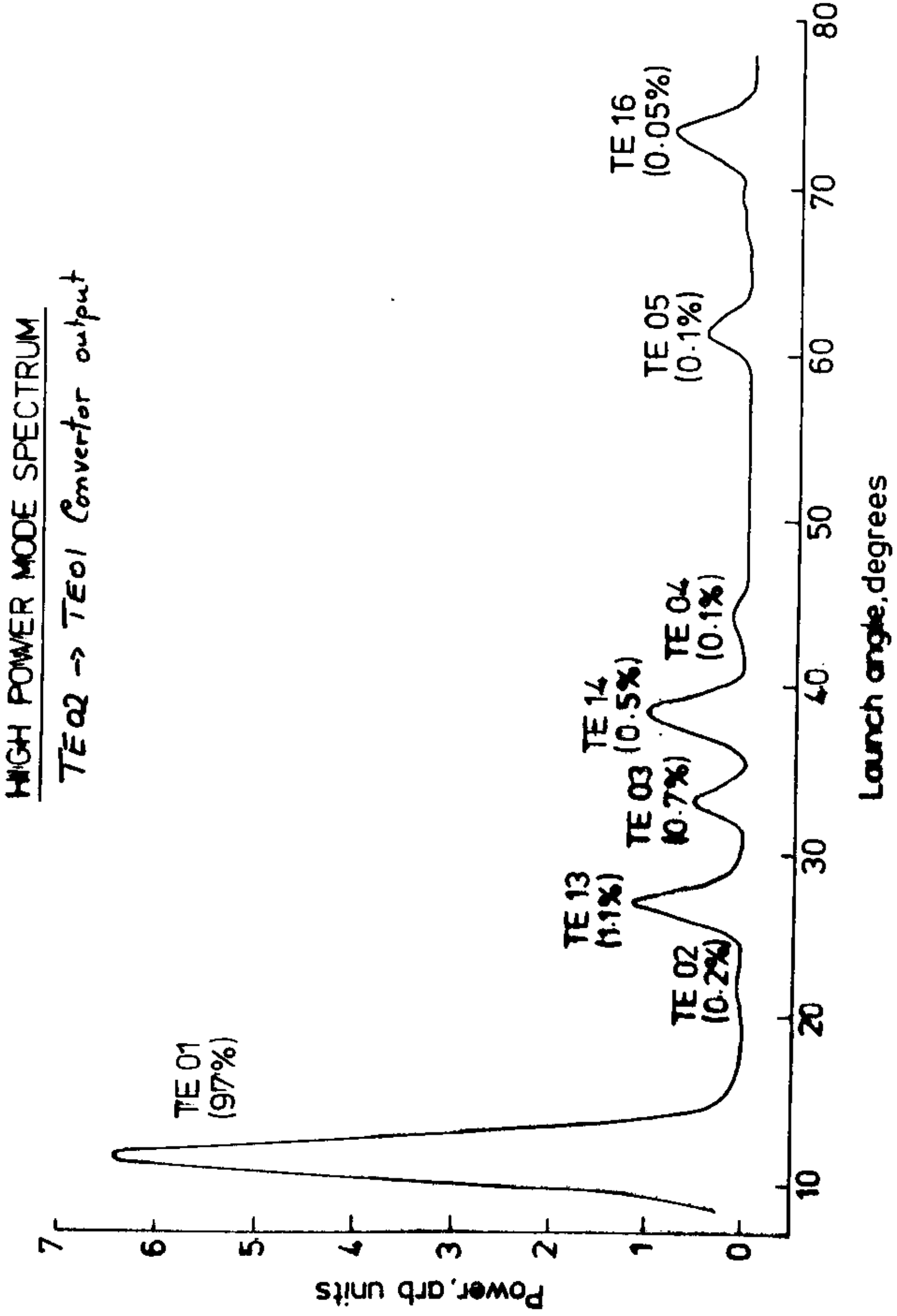
After conversion to TE_{11}, i.e. nearl parallel field pattern

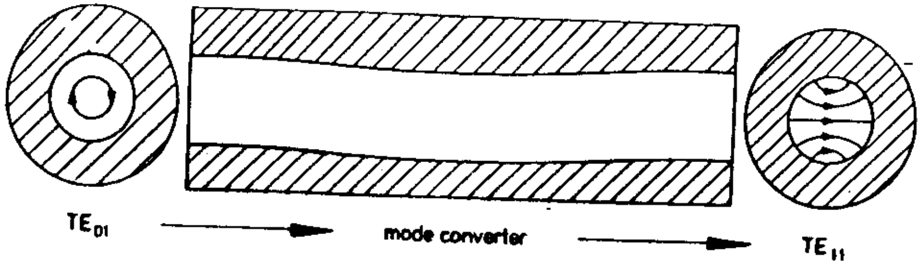


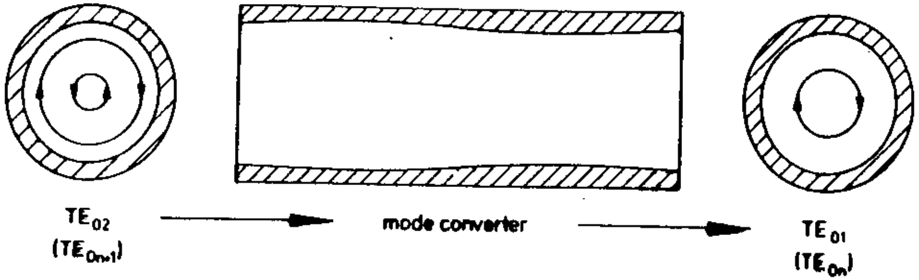
After conversion to linearly polarised HE_{11} (Hybrid) mode.

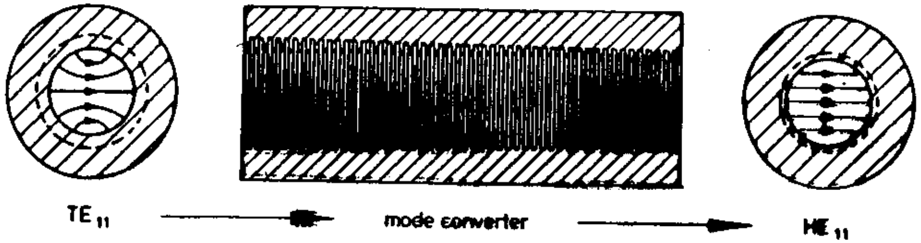
HIGH POWER MODE SPECTRUM

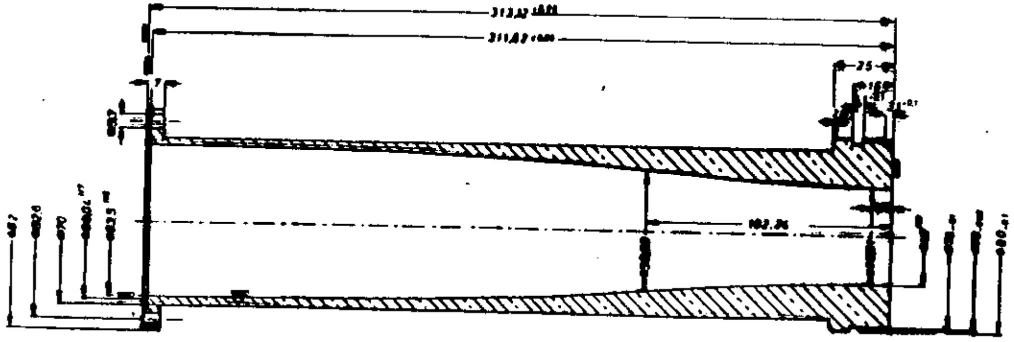
TE02 -> TE01 Convertor output







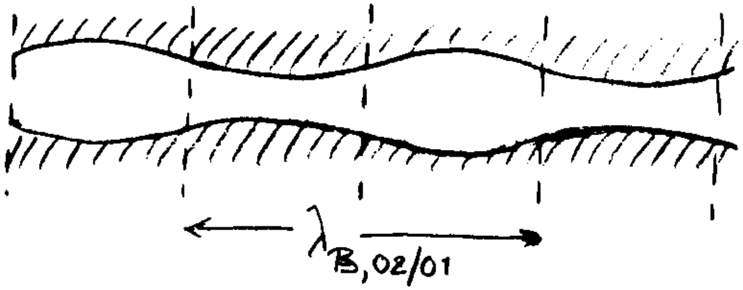


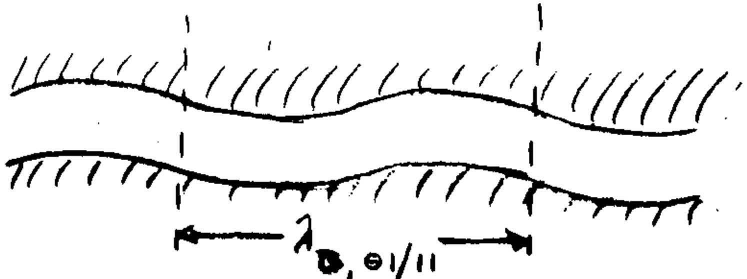


CROSS-SECTIONAL VIEW OF AN OPTIMUM TAPER ($TE_{01} \leftrightarrow TE_{02}$ COUPLING)

28 GHz / 60 GHz | mode converters

$TE_{02} \rightarrow TE_{01}$ ($l = 6 \lambda_{B,02/01}$)



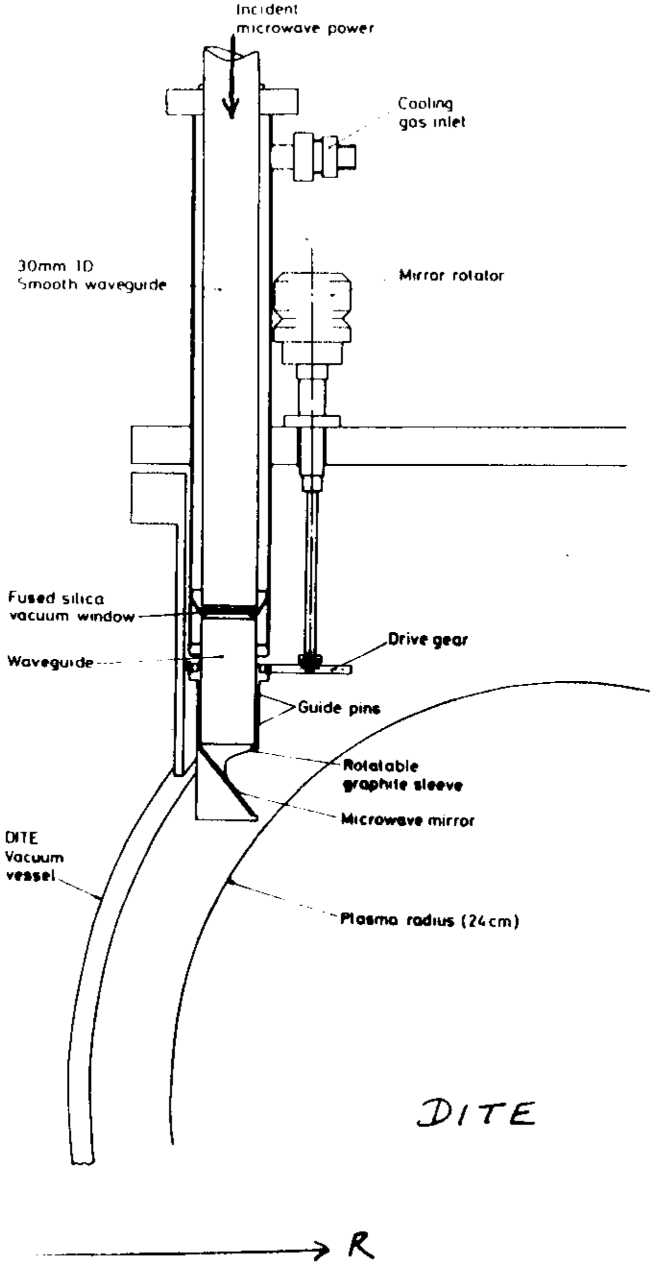


$TE_{01} \rightarrow TE_{11}$ ($l = 10 \lambda_{B,01/11}$)

Overall lengths (for 60 GHz)

$6 \lambda_B (02/01) = 0 \cdot 59$ m

$10 \lambda_B (01/11) = 3 \cdot 11$ m



Results

- High Te plasmas
- Peaked Te profiles
- Power deposition profiles
- Evidence for electron trapping
- Effect on MHD activity – sawteeth
  - m=2
- Central density pump-out
- Relativistic effects – downshifted freq.

BCRH

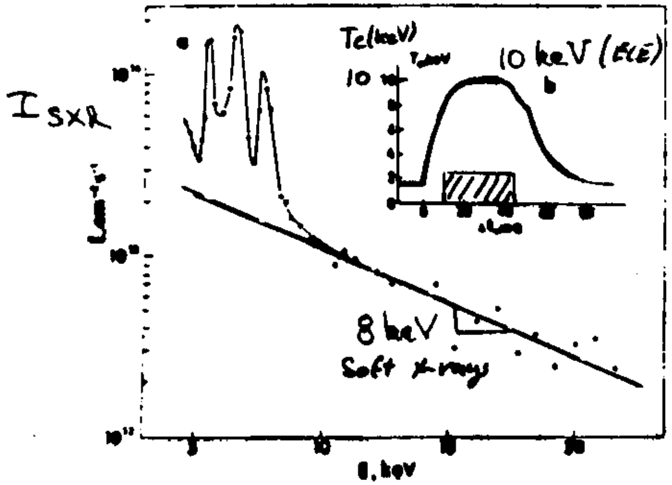
High T_e Plasmas

- Temperatures as high as 10 keV obtained with 4 MW in T-10
- High temperatures, 5 keV, also attained in DIII–D
- These cases show that high temperature, low density discharges with ECH can still be thermal
- These discharges are excellent targets for electron cyclotron current drive studies

---

T-10

Central heating (± 6 cm); $P_{ABS} \sim 2$ MW
Nearly 10 W/cm^3 !



$\bar{n}_e = 1.5 \times 10^{19}$ M
$\tau_E^{OH} = 50$ ms
$\tau_E^{ECH} = 7$ ms
$\tau_E^{KG} = 8$ ms

Outside L.
O-mode

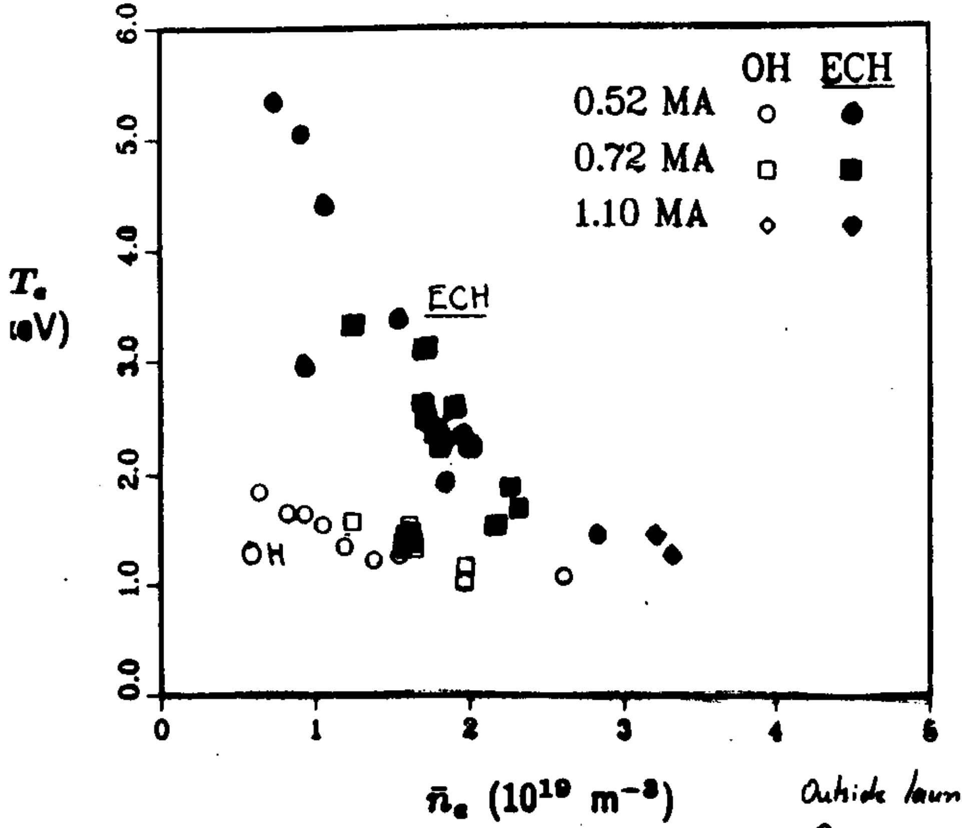
Fig. 5 a) X-ray spectrum detected for the time interval shown in Fig. 5b. 10 gyrotrons. I_p = 210 kA, B_t = 2.82T, $\bar{n}_e$ = $1.5 \cdot 10^{13}$ cm^{-3}, before carbonization. The dashed line is the simulation for $T_e(0)$ = 8 keV and a typical $T_e(r)$.
b) temporrl behaviour of $T_e(0)$ recorded by ECE. Labelled by arrows is the interval over which the spectrum was recorded.

Difference between 8 keV from SXR PHA and 10 keV from ECE can be understood from Fokker-Planck calculations (R. Harvey)
(Quasi-perpendicular launch)

DIII-D

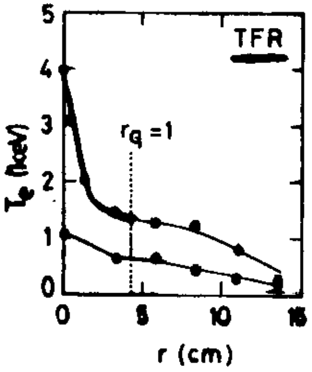
GENERAL ATOMICS

CENTRAL ELECTRON TEMPERATURE AS A FUNCTION OF DENSITY

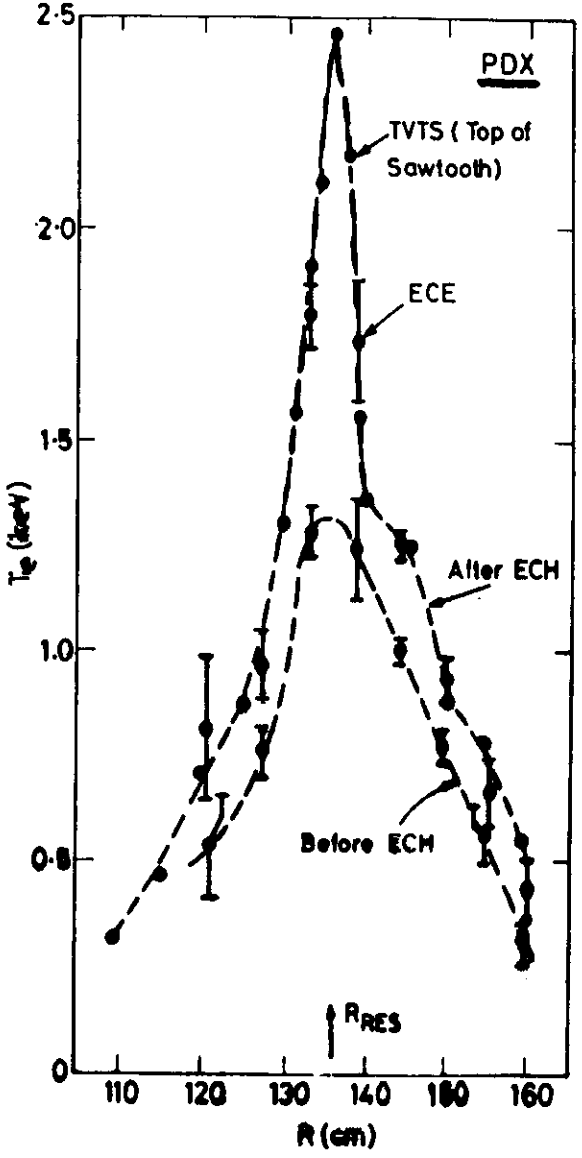


Outside launch
O-MODE
$B_T = 2.15$ T

Resonance on axis

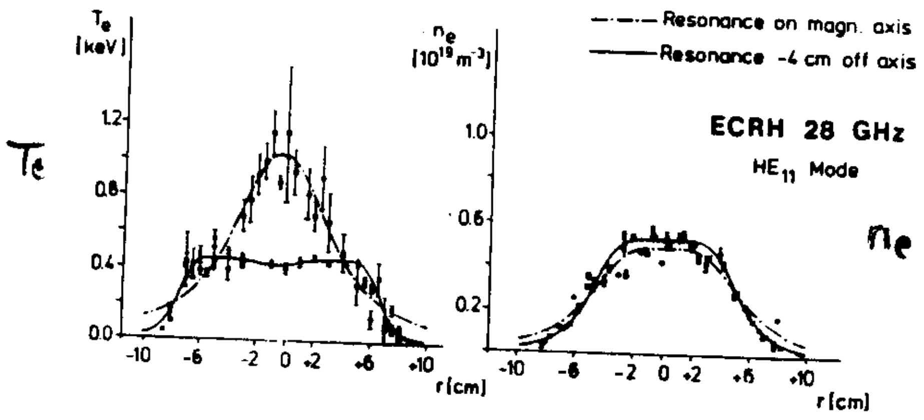


$\bar{n}_e = 0.8 \times 10^{19}$ m^{-3}



P = 75 kw $I_p = 0.26$ MA
$n_e(0) = 1.2 \times 10^{19}$ m^{-3}

STELLARATOR ECRH plasma



Erckmann et al. (1985)

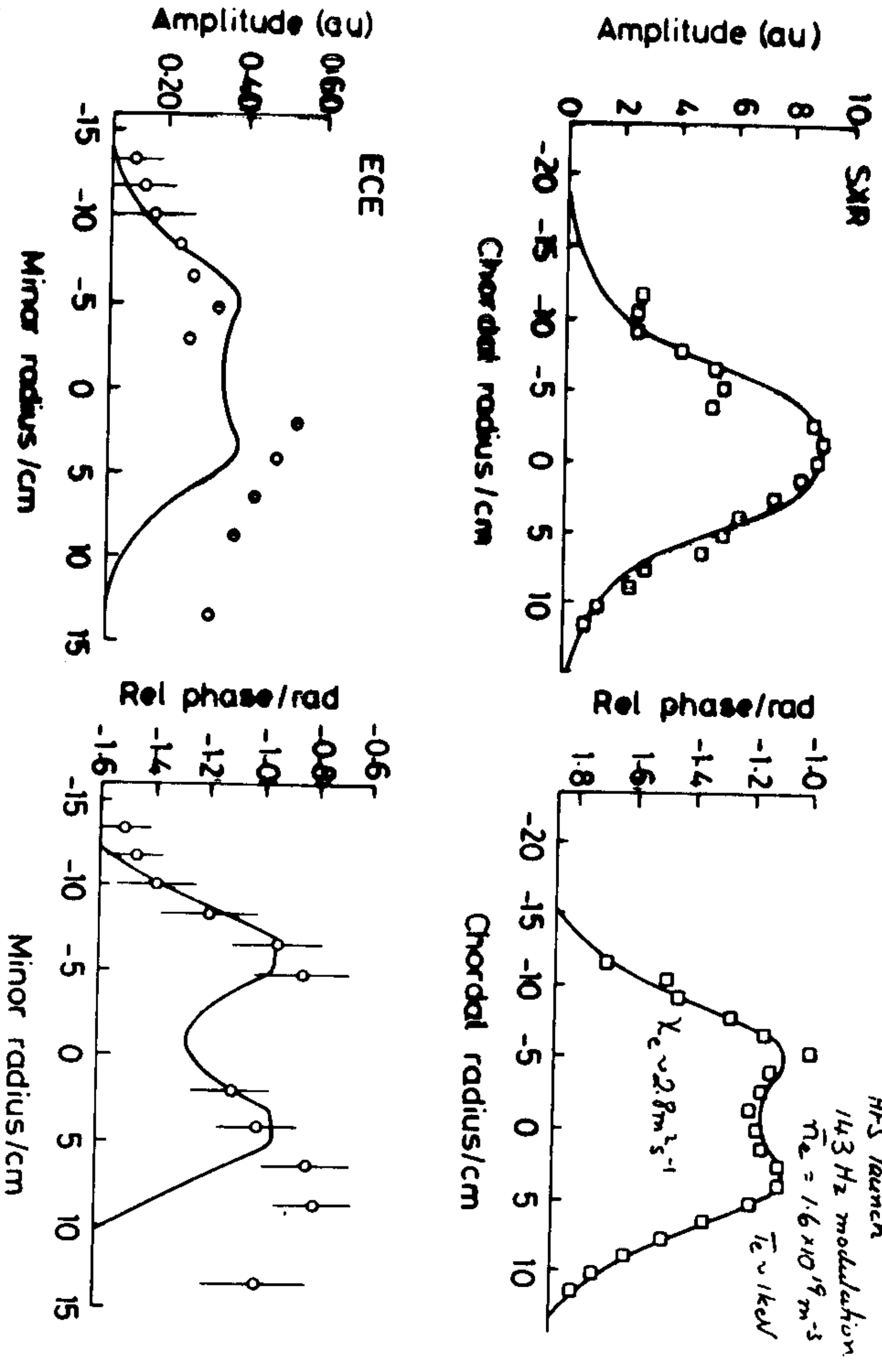
$P_{RF} \approx 170$ kW $\rightarrow 190$ kW

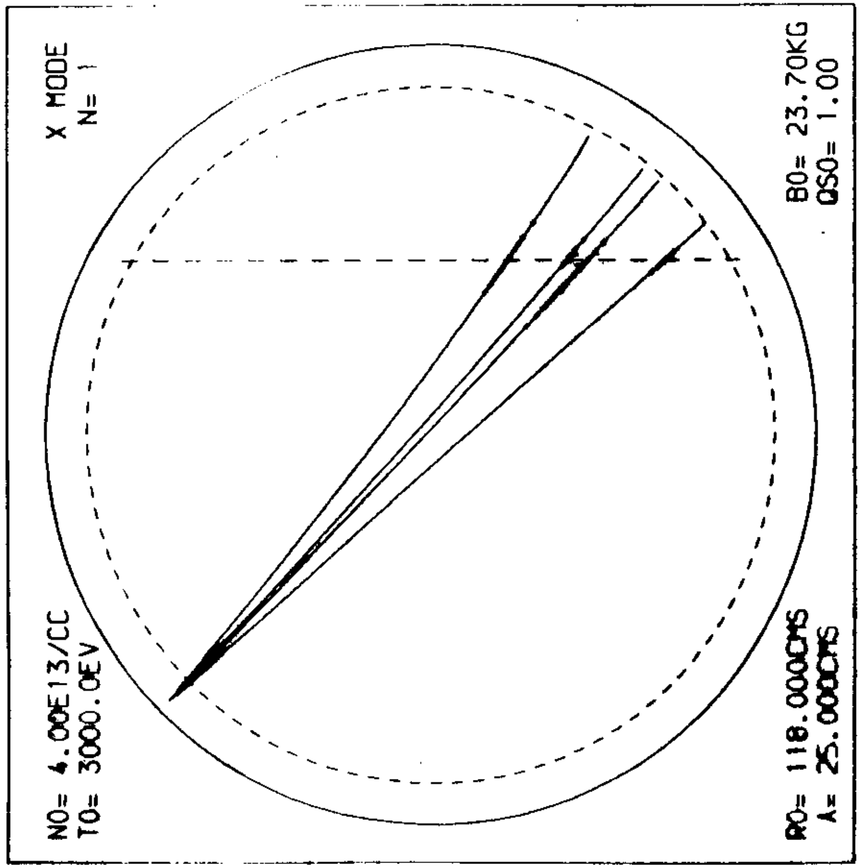
Change of resonance position
→ change of power deposition
→ change of plasma profiles

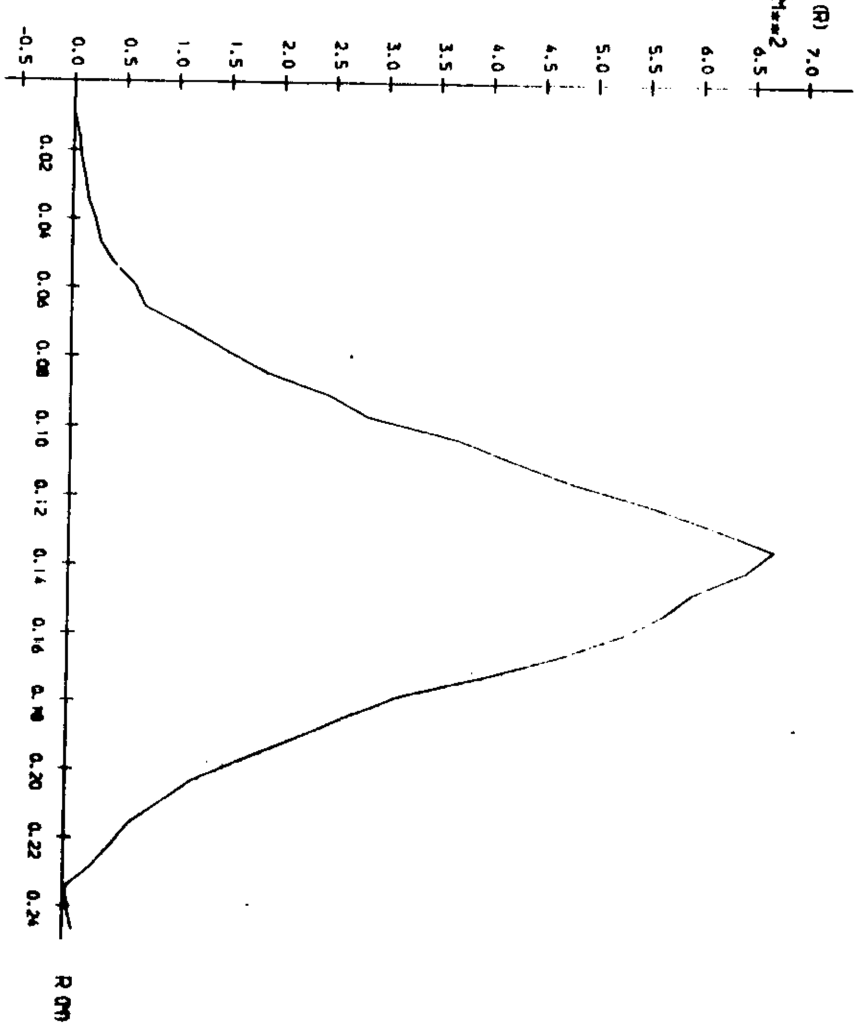
No "profile consistency"

ECRH Modulation Experiments on DITE

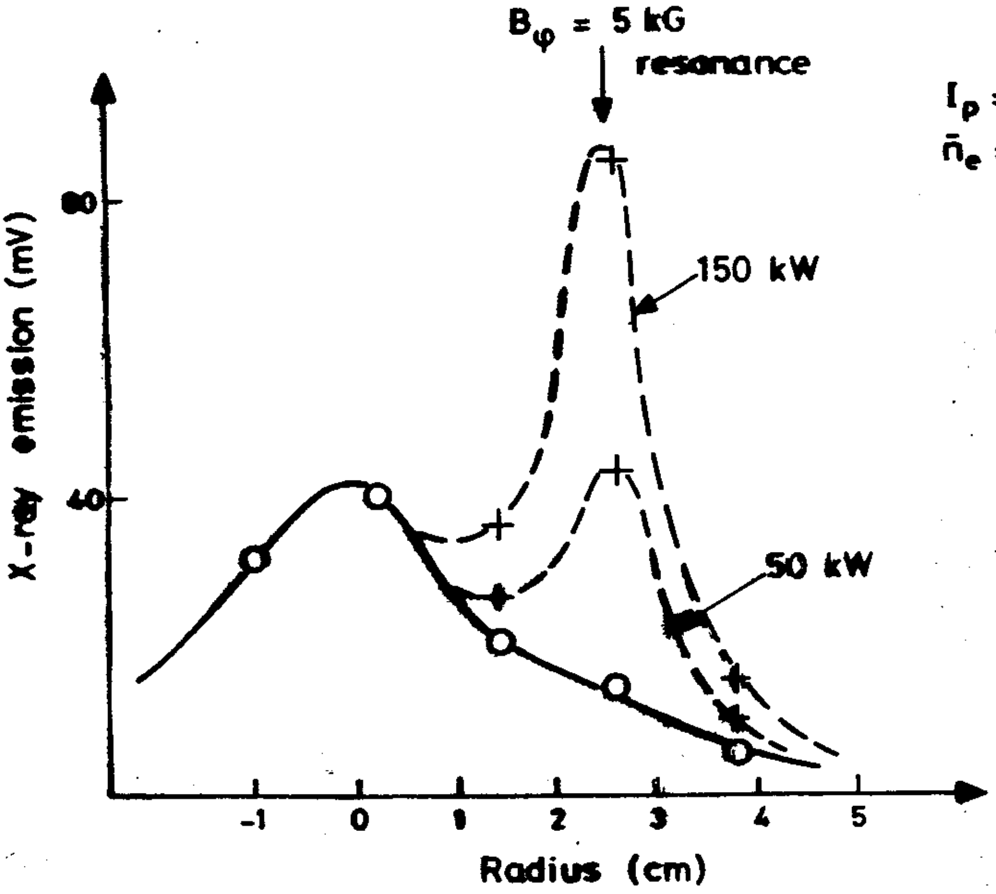
60 GHz X-mode t.rad.
HFS launch
14.3 Hz modulation
$\bar{n}_e = 1.6 \times 10^{19}$ m^{-3}
$\bar{T}_e \sim 1$ keV




X MODE
N= 1
BO= 23.70KG
QSO= 1.00
NO= 4.00E13/CC
TO= 3000.0EV
RO= 118.000CMS
A= 25.000CMS


P(R)
/M**2
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
R (m)

Evidence for Energetic Trapped Electrons - ToscA

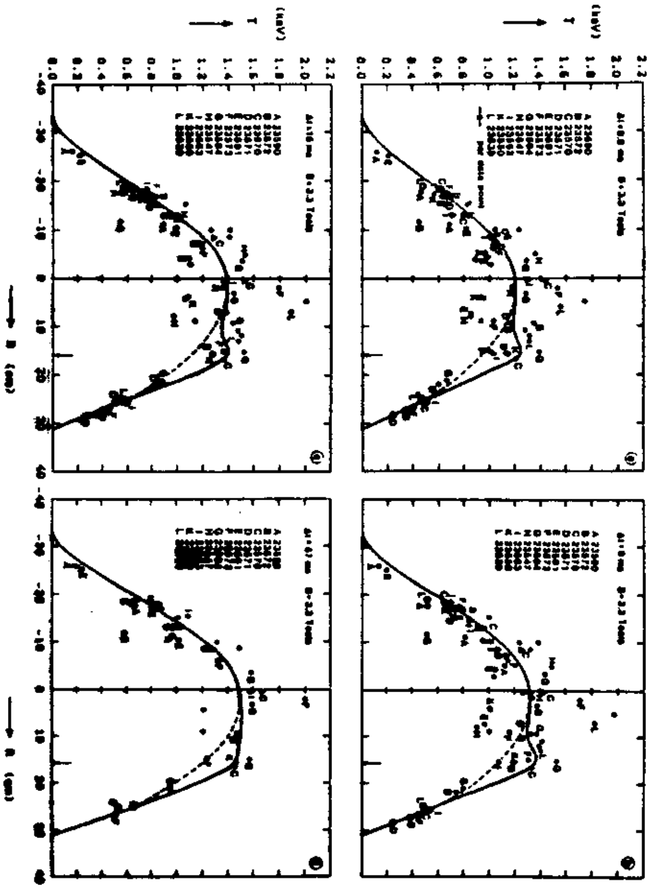


I_p = 8 kA
$\bar{n}_e = 5 \times 10^{12}\,cm^{-3}$

Soft x-ray emission profile during ECRH
(TOSCA results)

T10

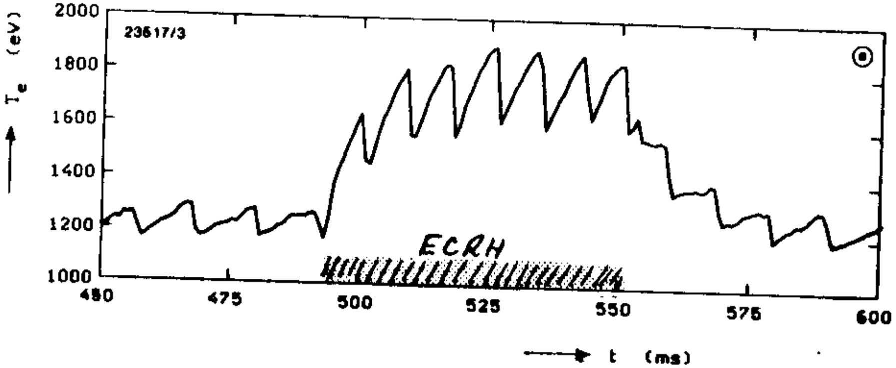
ECE



ECRH: Sawtooth Response

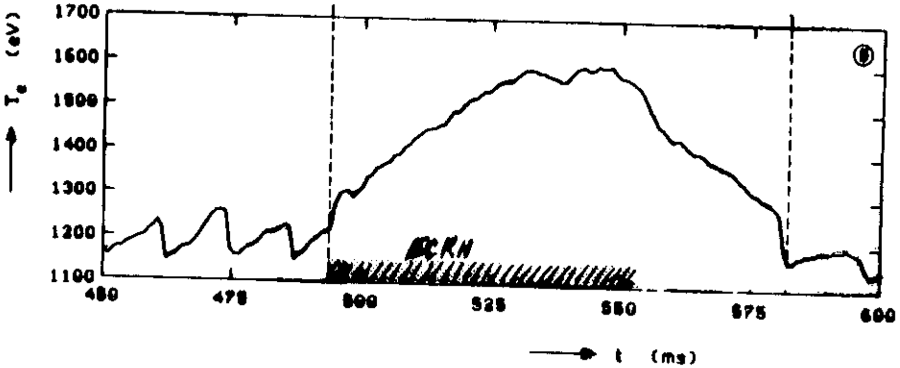
T10 $R = 1.48$ m $a = 0.34$ m $f = 84$ GHz, 500kW
$\theta = 90°$ O mode 70% X mode 30%

On axis $B = 3.0$ T $I_p = 0.44$ MA $\bar{n}_e = 4.5\times10^{19}\,m^{-3}$



(From ace)

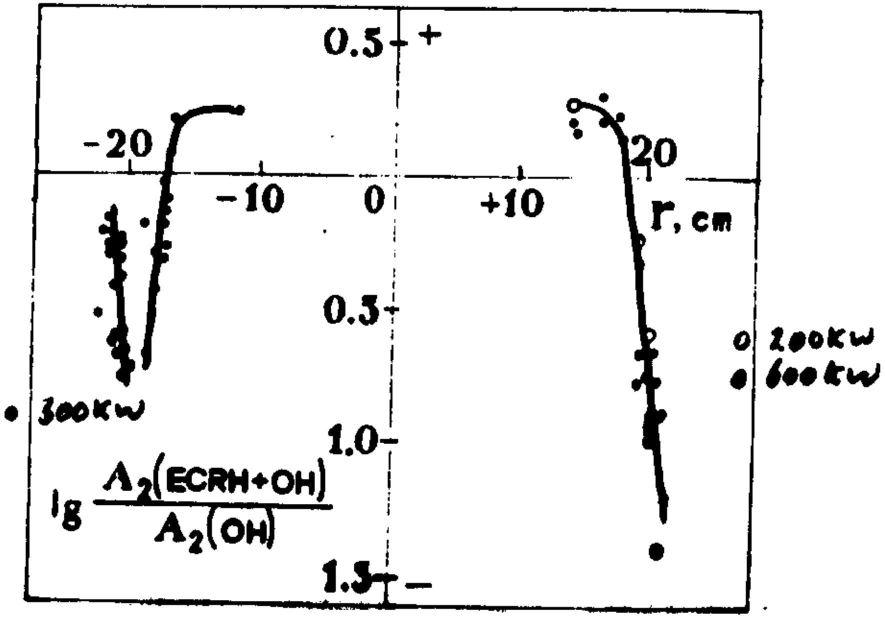
Off axis (+16cm) $B = 3.3$ T $I_p = 0.35$ MA $\bar{n}_e = 4.2\times10^{19}\,m^{-3}$



(From ace)

T10 Alikaev and Razumova (1985) Varenna

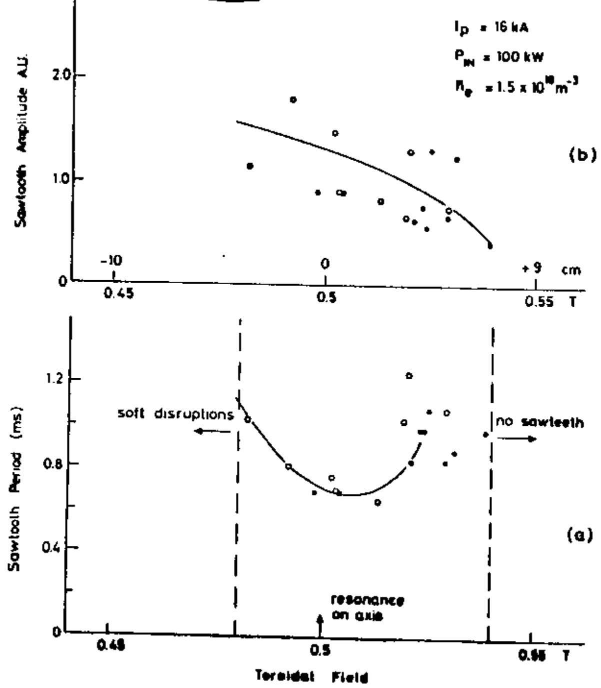
Suppression of m=2 mode

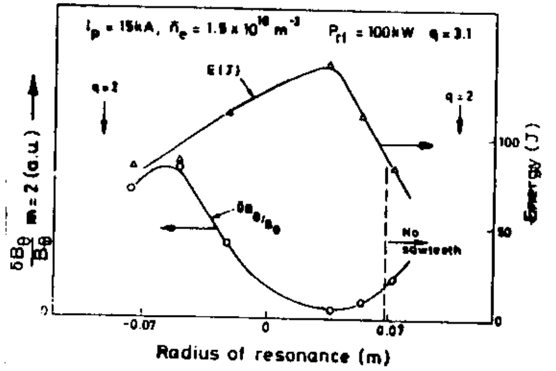


location of resonance

$P_{abs.} \approx 0.75\, P_{aux.}$

CLEO



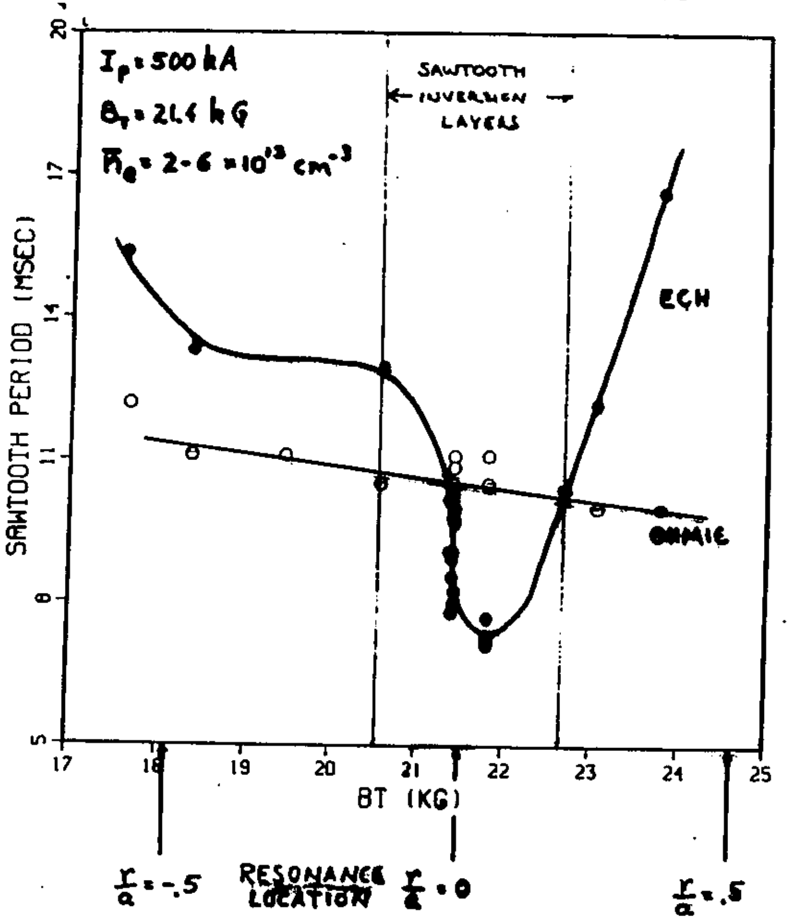


28 GHz 2ωce $n_e < n_c$

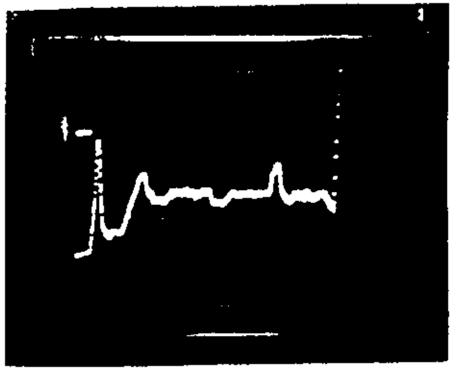
$q_a \sim 3$

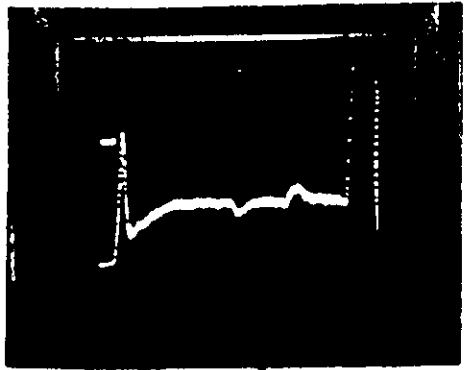
DIII

SAWTOOTH PERIOD VERSUS TOROIDAL FIELD FOR ECH AND OHMIC DISCHARGES

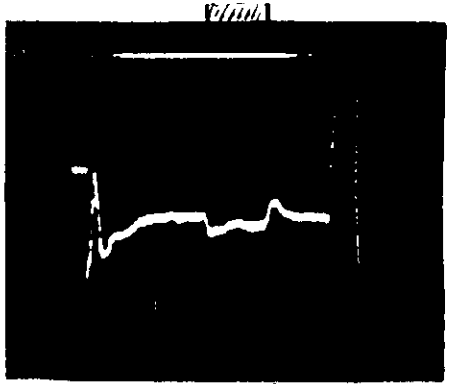


CLEO 28 GHz ω_{ce} $n_{c.o.} = 5.10^{12}\ cm^{-3}$ 15KH

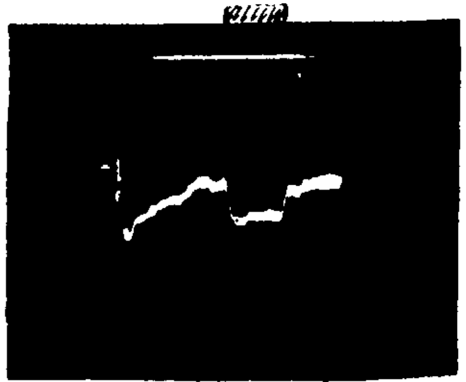




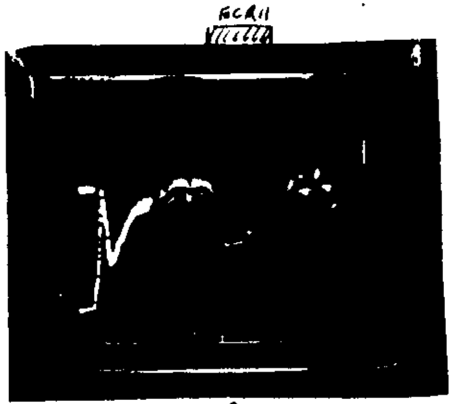
$1\cdot9 \times 10^{12}\ cm^{-3}$



$2\cdot4 \times 10^{12}\ cm^{-3}$

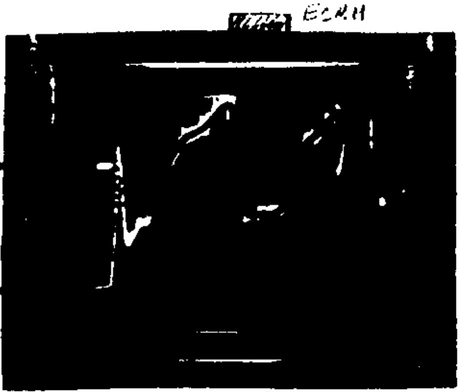


$3\cdot4 \times 10^{12}\ cm^{-3}$



$\bar{n}_e = 4. \times 10^{12}\ cm^{-3}$ before ECRH

1fringe 4.10^{12}



$5\cdot9 \times 10^{12}\ cm^{-3}$

T10

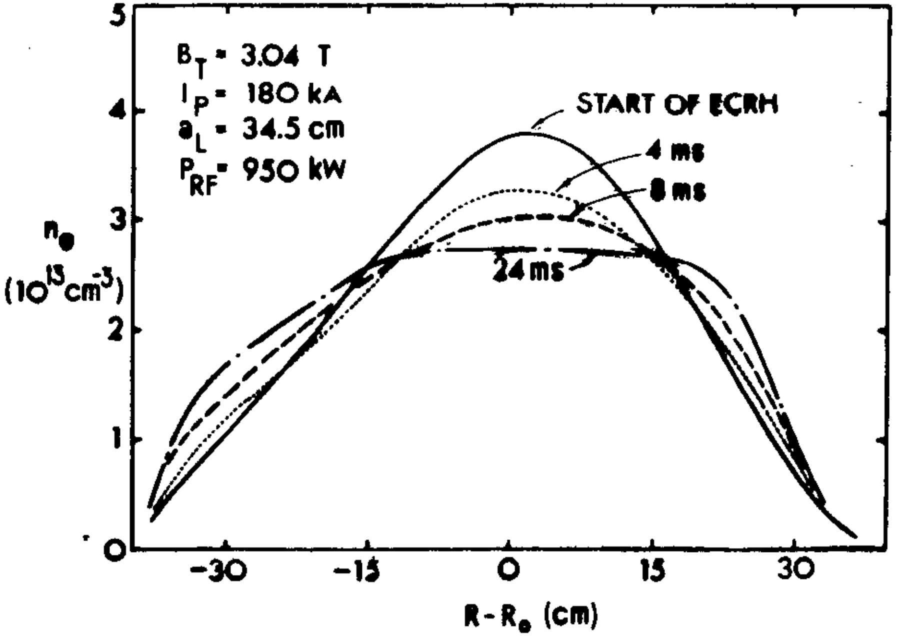


FIG. 10

Relativistic Effects

- **Relativistic form of EC resonance condition**

  - mass increase with increasing energy

$$\omega - \Omega\left(1 - v^2/c^2\right)^{1/2} = k_\parallel v_\parallel \qquad \Omega = eB/m_0$$

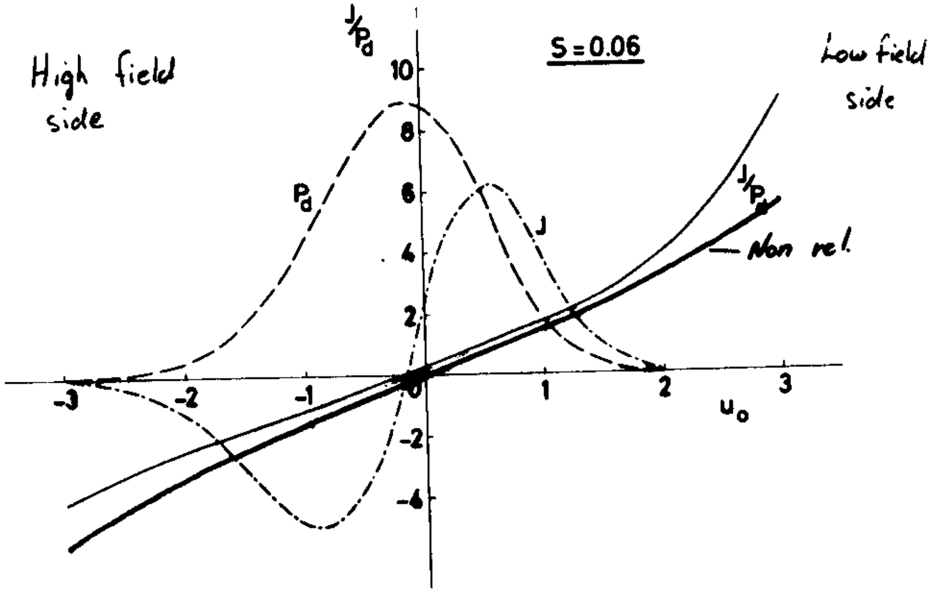
relativistic mass increase
down-shifts gyrofreq.

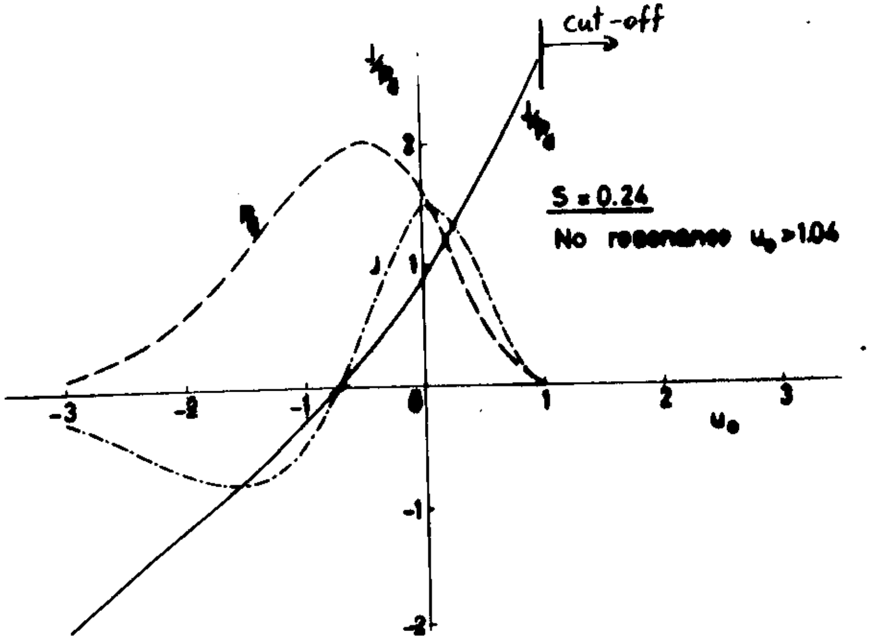
Doppler
shift

$\omega < \Omega$ (high field side resonance)
electrons with +ve or −ve values of $v_\parallel$ can resonate

$\omega > \Omega$ (low field side resonance)
only electrons with $v_\parallel$ same sign as $k_\parallel$ can resonate
+ these electrons have larger $|v_\parallel|$ than in non-rel. case

Effect of relativistic resonance condition on power deposition and current drive

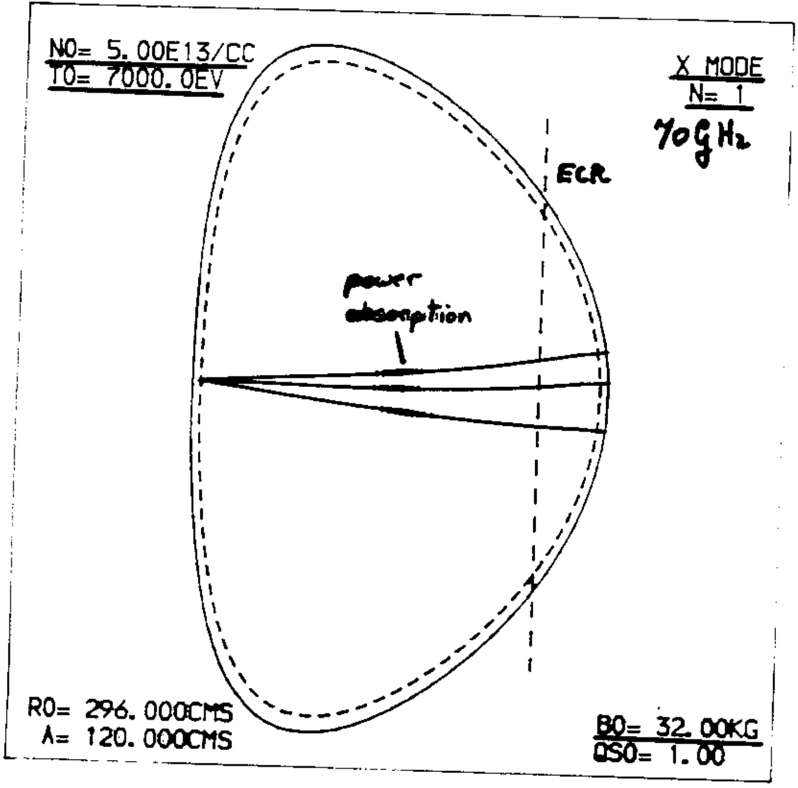


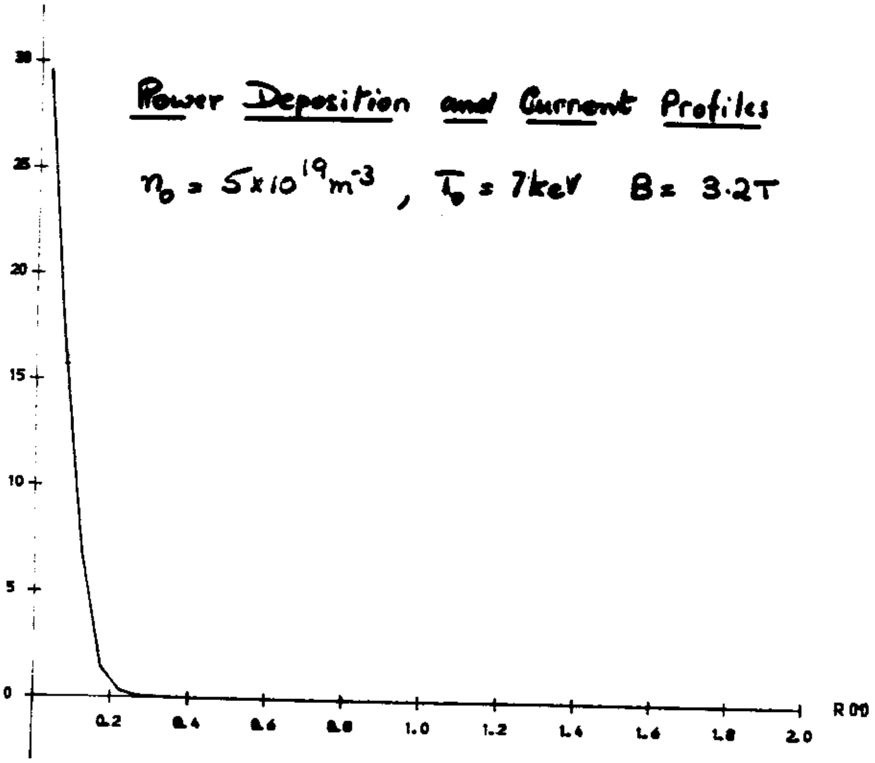


$$\omega - \Omega\left(1 - v^2/c^2\right)^{1/2} = k_\parallel v_\parallel \Rightarrow \underbrace{\frac{\omega - \Omega}{k_\parallel v_e}}_{''} + \underbrace{\frac{\Omega v_e}{2 k_\parallel c^2}}_{''} \cdot \frac{v}{v_e^2} = \frac{v_\parallel}{v_e}$$

$T_e = T_0(1-\psi) \approx T_0(1-r^2/a^2)$ & n_e similarly.

Launch angle 50° to $\vec{B}_\phi$





Power Deposition and Current Profiles

$n_0 = 5\times10^{19}\,m^{-3}$, $T_0 = 7keV$ $B = 3.2T$

Evidence for down-shifted resonance (DITE)