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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4-SMR 393/53

SPRING COLLEGE ON PLASMA PHYSICS

15 May - 9 June 1989

RADIO FREQUENCY HEATING IN TOKAMAKS (III)

RF Current Drive

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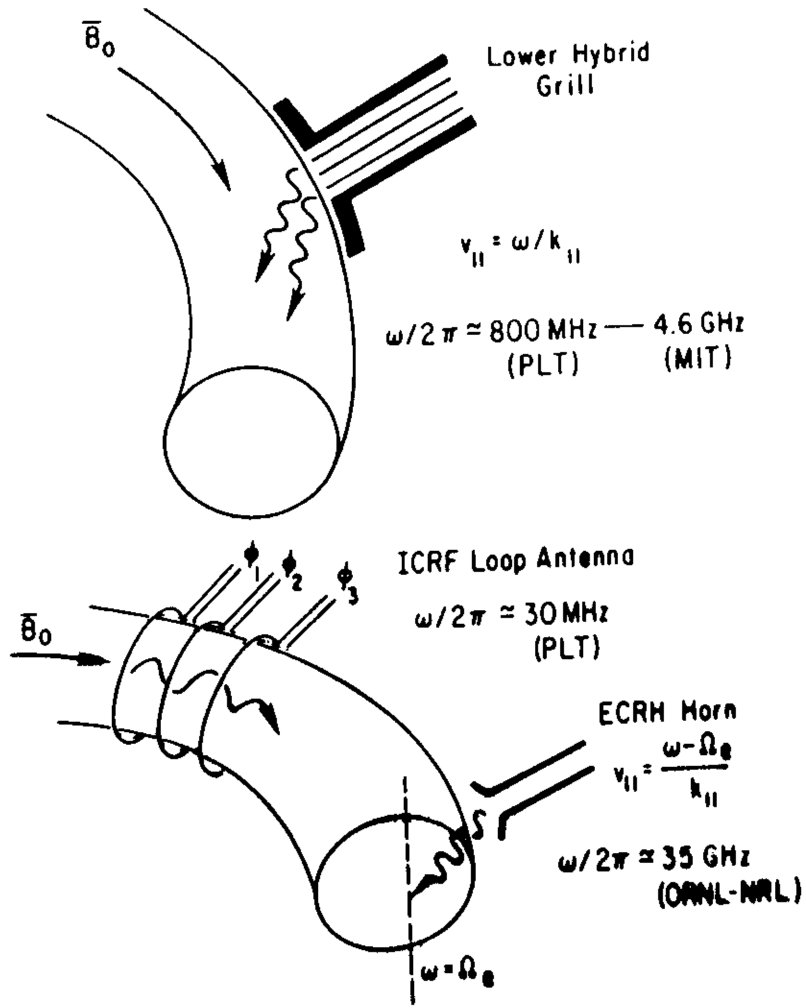
RF Current Drive

- Lower Hybrid Waves - Landau damping
- Electron Cyclotron Waves - Asymmetric Heating
- ICRH Minority Ion Current Drive

#84T0258

RF METHODS OF CURRENT DRIVE



Lower Hybrid Waves

L-H frequency $\omega_{LH} \approx \frac{\omega_{ci}}{\sqrt{(1+\omega_{pe}^2/\omega_{ce}^2)}}$

Experiments range from $0.8\,GHz \rightarrow 8\,GHz$

Slow wave launched $E = E_\parallel$

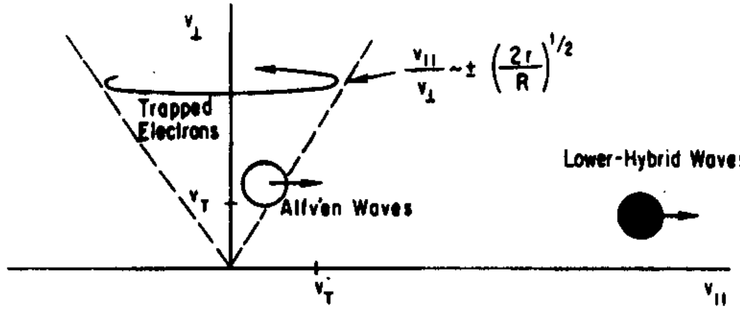
Absorption by Landau damping on electrons

with $v_\parallel = v_{phase}$

Resonance condition

$$\omega - k_\parallel v_\parallel = 0$$

LOWER HYBRID CURRENT DRIVE



- current is driven by // acceleration of superthermal electrons with LH waves
- efficiency is a balance between
  - collisions which tend to drive the electrons to thermal equilibrium
  - injected waves which produce the required assymetry
- incremental energy input ΔE produces incremental current Δj

  $\Delta j = \Delta E \frac{q}{[illegible]}$ (ν collision frequency).

  $P_{RF} = \nu \Delta E$

  $j/P_{RF} = \frac{q}{m v_\parallel \nu}$ for $v_\parallel \gg v_t$ $\nu \sim$ [illegible]

  $j/P_{RF} \sim \frac{v_\parallel^2}{m}$ $I_{MA}/P_{MW} \sim \frac{1}{n}$ [illegible]

- damping of LH waves when [illegible] ([illegible])
- interest to use the lowest possible $N_{//}$ waves limitation by accessibility conditions

$$N_\parallel = \frac{c k_\parallel}{\omega}$$

Fokker-Planck Calculations

L-H wave essentially electrostatic — $\tilde{E} = \tilde{E}_{\parallel}$

Damping produces diffusion in $v_{\parallel}$

Electron F-P eqn

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial v_{\parallel}}\left[D\,\delta\left(\frac{\omega}{k_{\parallel}} - v_{\parallel}\right)\frac{\partial f}{\partial v_{\parallel}}\right] + C_{ei} + C_{ee}$$

(C_{ei}: e-i collisions; C_{ee}: e-e collisions)

Analytic sol possible if C_{ee} neglected

$$\left(\frac{J}{P_d}\right)_n = \frac{1.33}{Z}\frac{v_e}{v_{phase}} \quad \text{as } v_{phase} \to 0$$

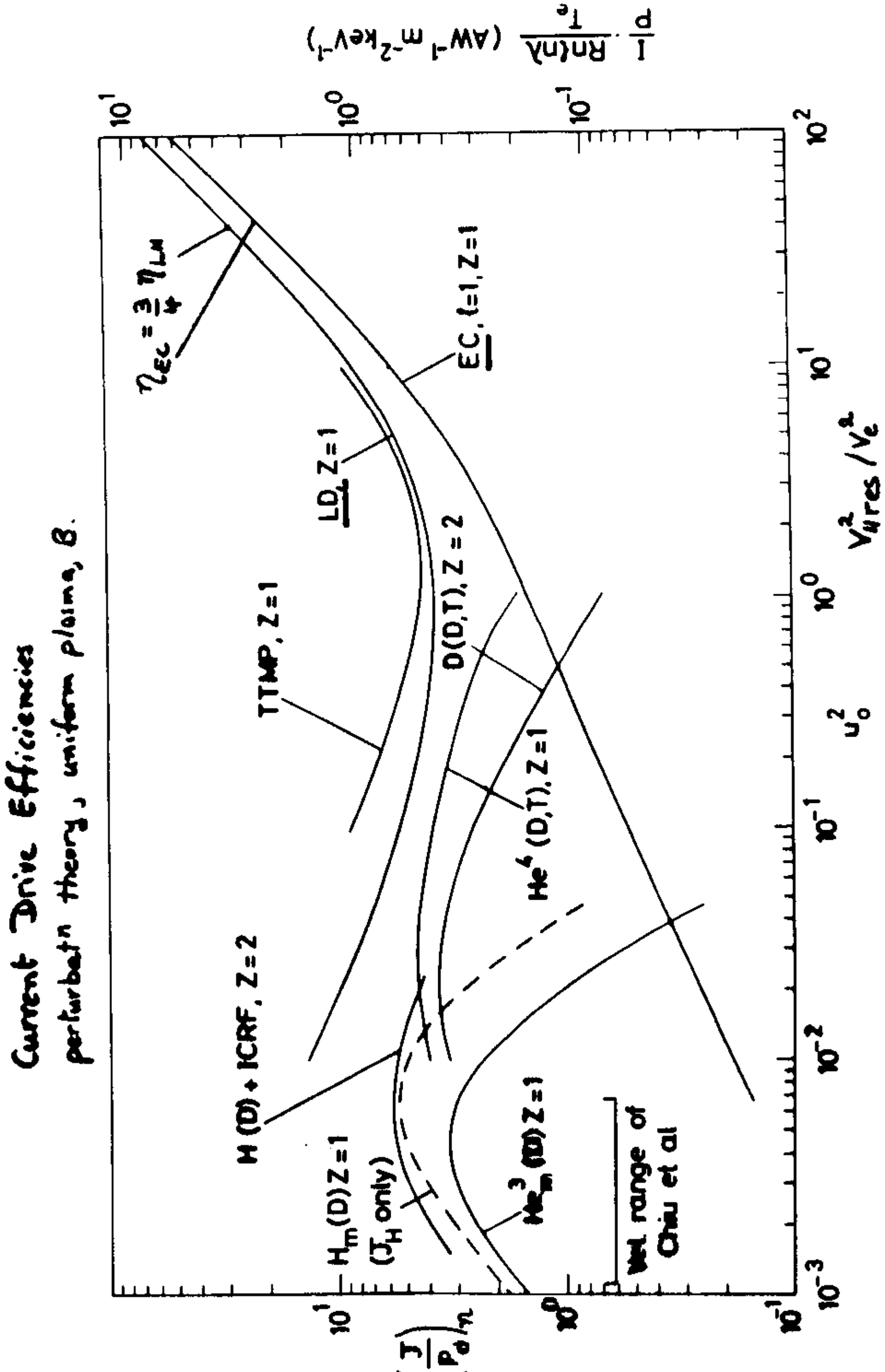
$$\left(\frac{J}{P_d}\right)_n = \frac{4}{Z}\left(\frac{v_{phase}}{v_e}\right)^2 \quad \text{as } v_{phase} \to \infty$$

Cordey et al Plasma Phys. 24 (1982) 73

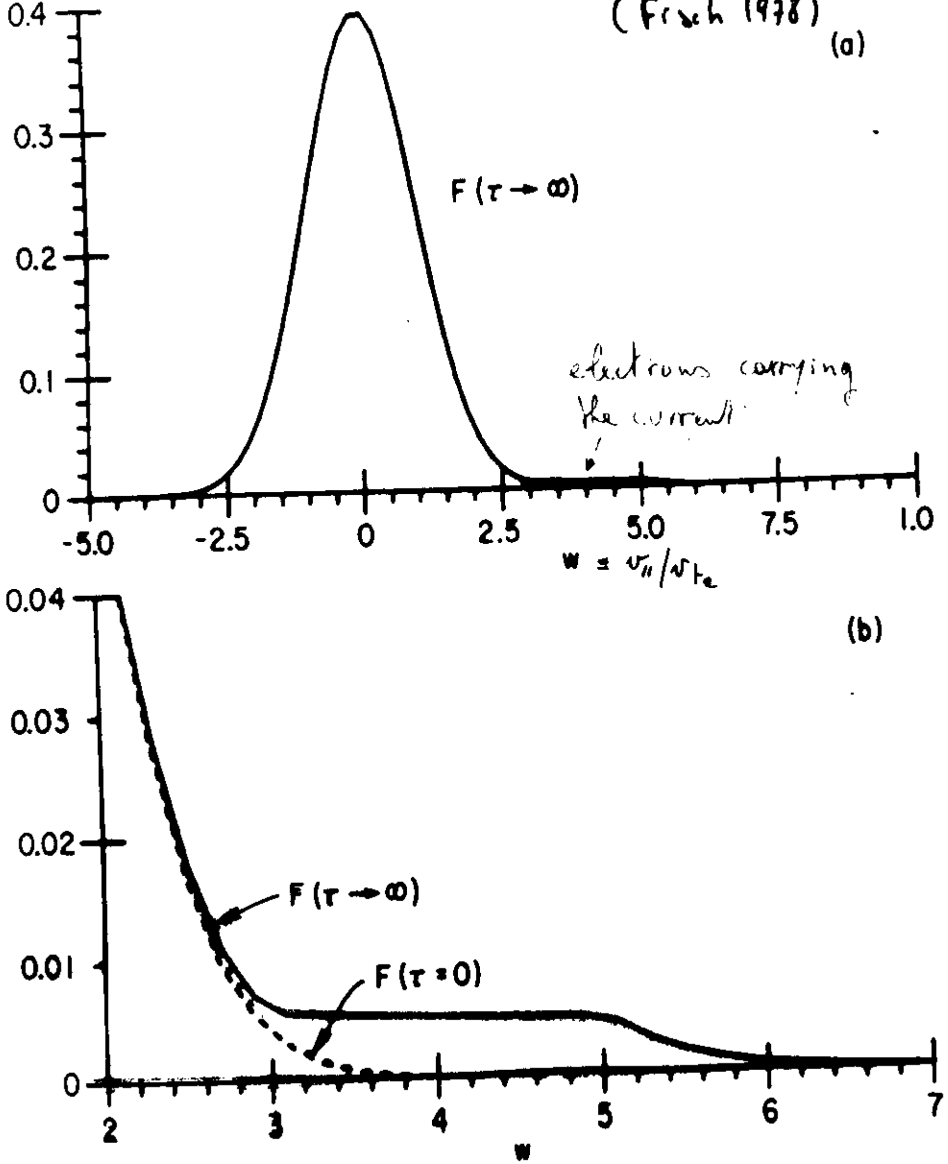
$J_n = J/n e v_e \qquad P_{dn} = P_d / n m_e v_e^2 \nu_0$

ν_0 – coll freq. $= 4\pi \ln\lambda \, n e^4 / v_e^3 m_e^2$

$$\frac{I\,(\text{amps})}{P\,(\text{watts})} = 0.122\,\frac{T_e\,(\text{keV})}{R(\text{m})\, n_e(10^{20}\text{m}^{-3}) \ln\lambda} \cdot \left(\frac{J}{P_d}\right)_n$$



1. dimensional model (Frisch 1978)



- Current Drive is a balance between effects due to injected waves which tend to produce the asymmetry necessary for current drive and effects due to collisions which tend to drive the electrons to thermal equilibrium

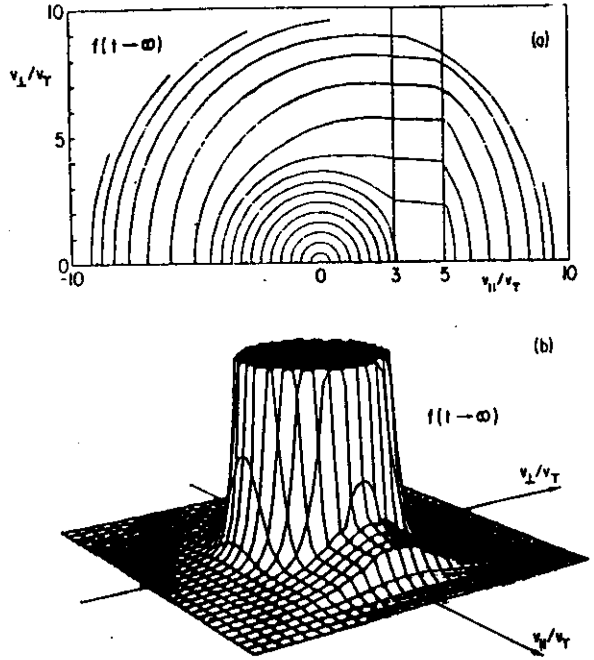
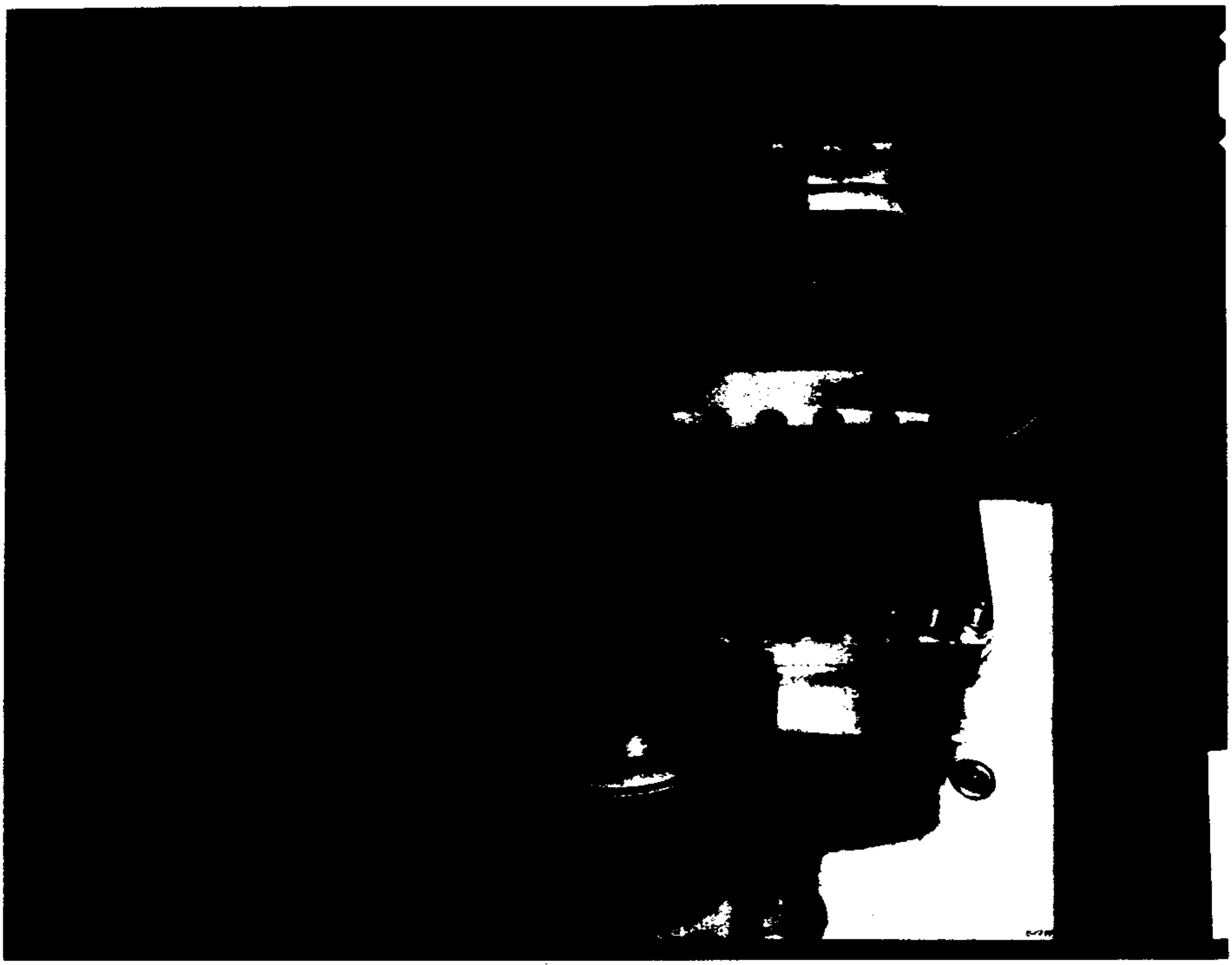
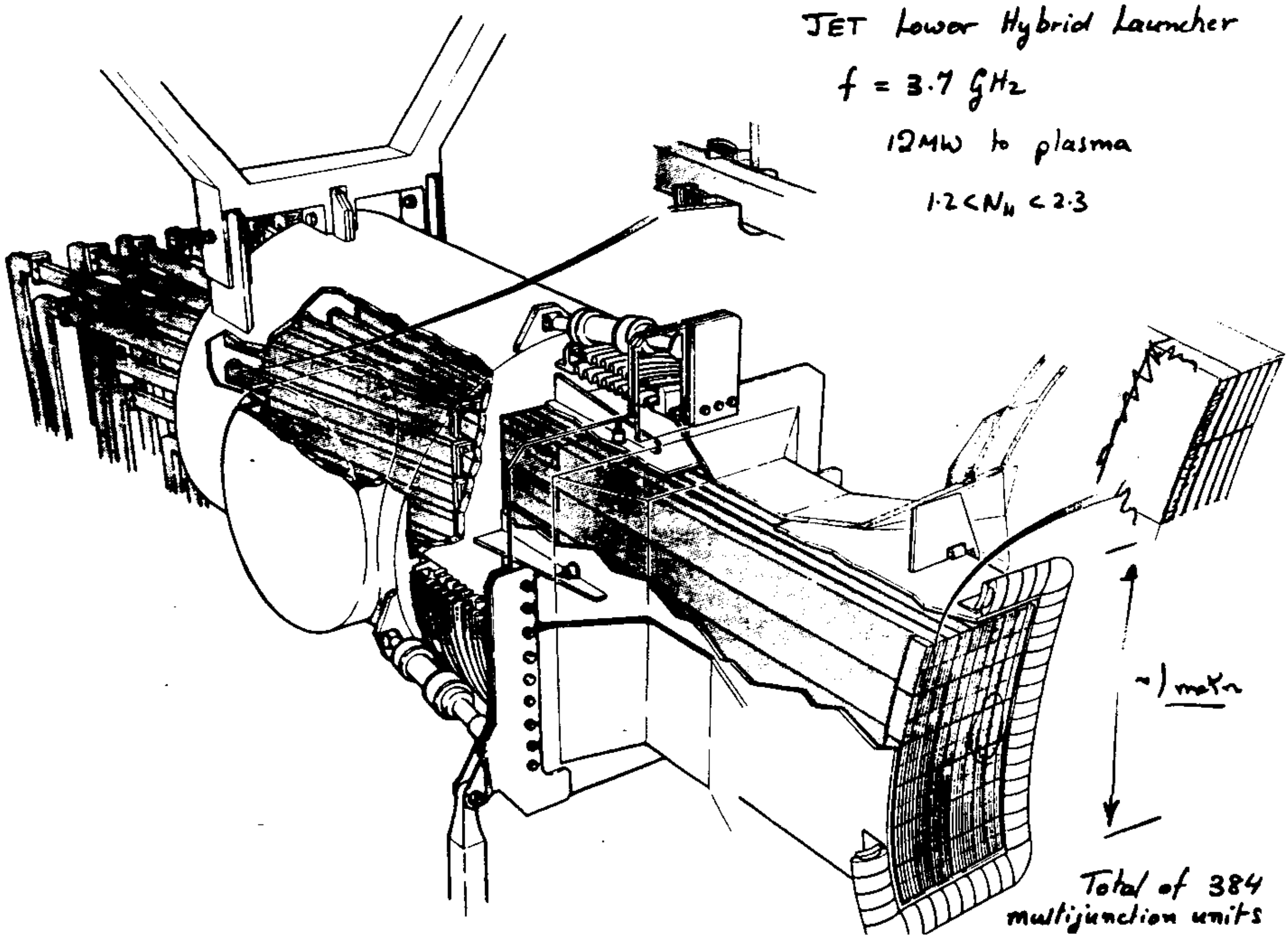


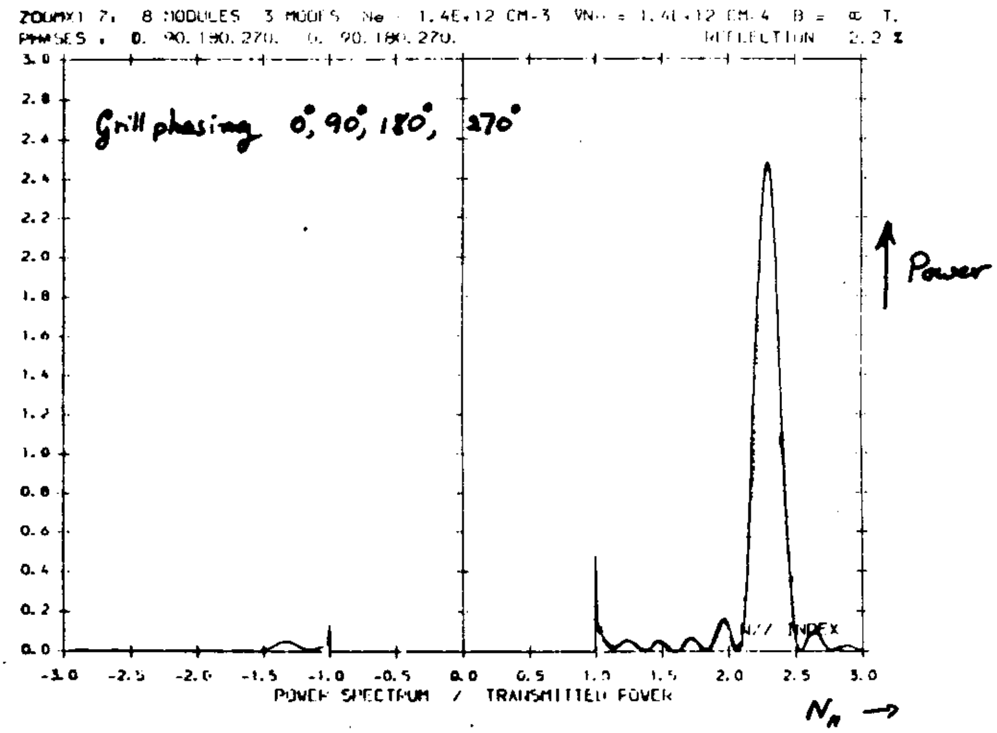
FIG. 5. (a) Contours of steady-state electron velocity distribution f when lower-hybrid waves are injected with parallel-phase velocities between 3 and 5 times thermal velocity v_T. (b) Surface of f, truncated at low speeds (Karney and Fisch, 1979).

Rev. Mod. Phys., Vol. 59, No. 1, January 1987




JET Lower Hybrid Launcher
f = 3.7 GHz
12MW to plasma
1.2<N∥<2.3
~1 metre
Total of 384
multijunction units

Calculated Launched Wave $N_{\parallel}$ Spectrum – JET Launcher



Lower Hybrid Current Drive in PLT

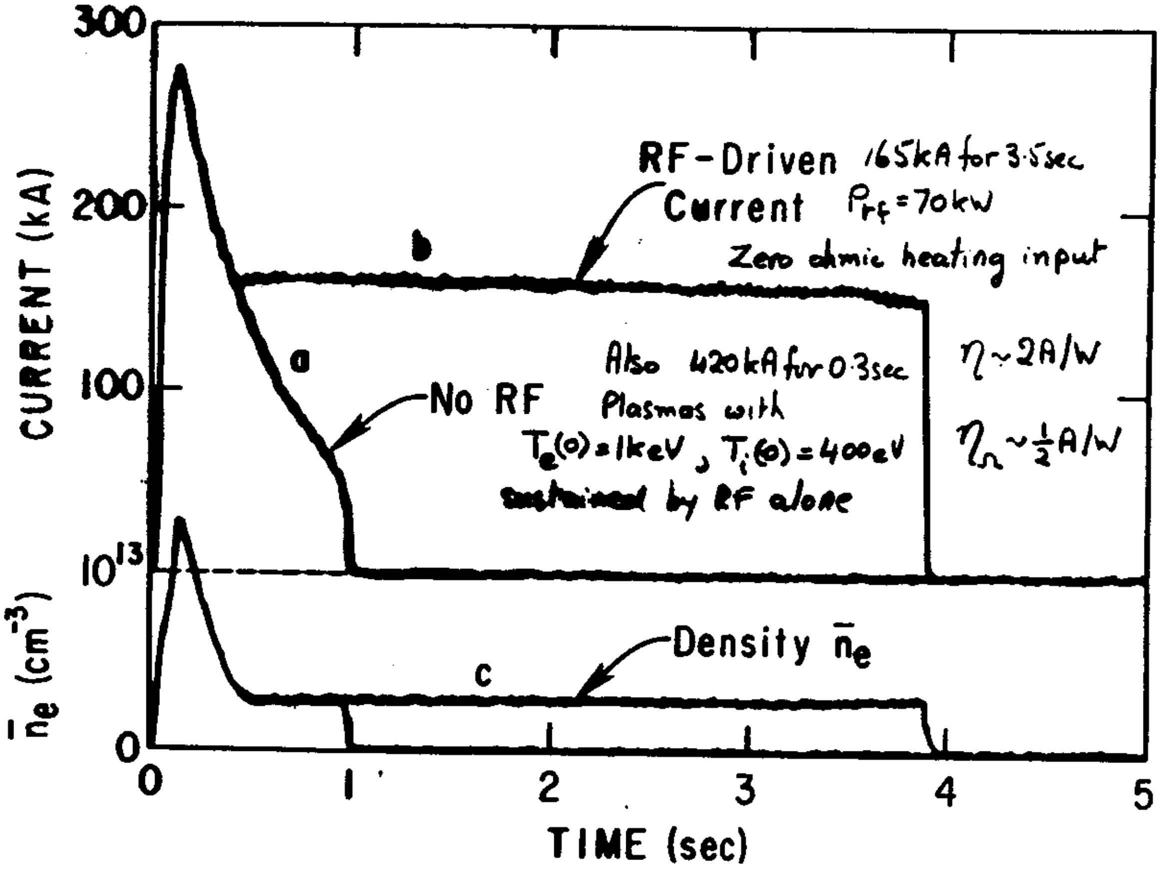


Fig. 1

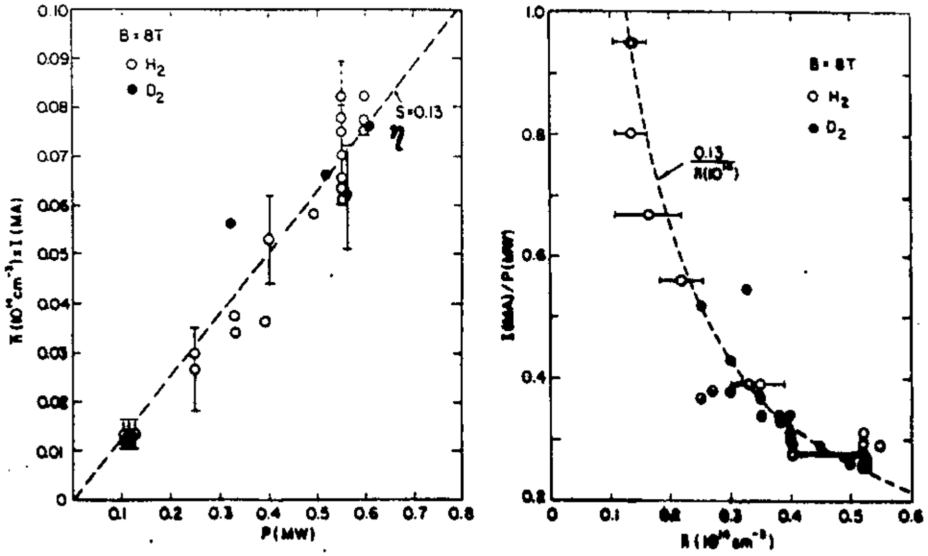
Scaling Experiments

$$\frac{I}{P} \sim \frac{v_p^2}{nR}$$

Define efficiency $\eta = n_e R I / P \quad \propto v_p^2$

For given $N_{\parallel}$ spectrum expect η = const for good accessibility

Alcator C, Lloyd et al IAEA Tech Committee on Non Inductive C-D Culham 1983 p250



$f = 4.6$ GHz, $P \leq 650$ kW

(a) (b)

FIGURE 4

Present Status

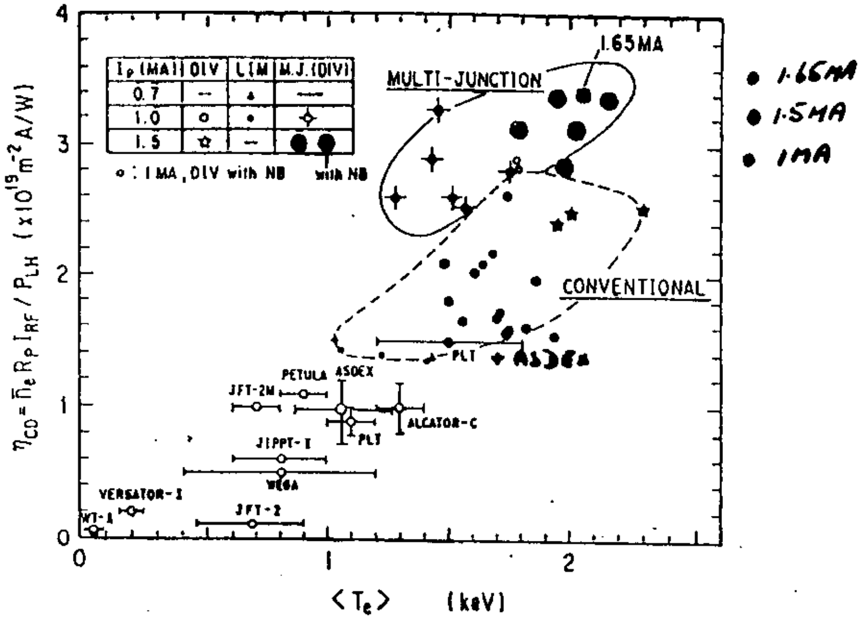


Fig.5 ηCD vs. <T_e>

LOWER HYBRID CURRENT DRIVE IN PLT

Hard X-rays from discharge centre

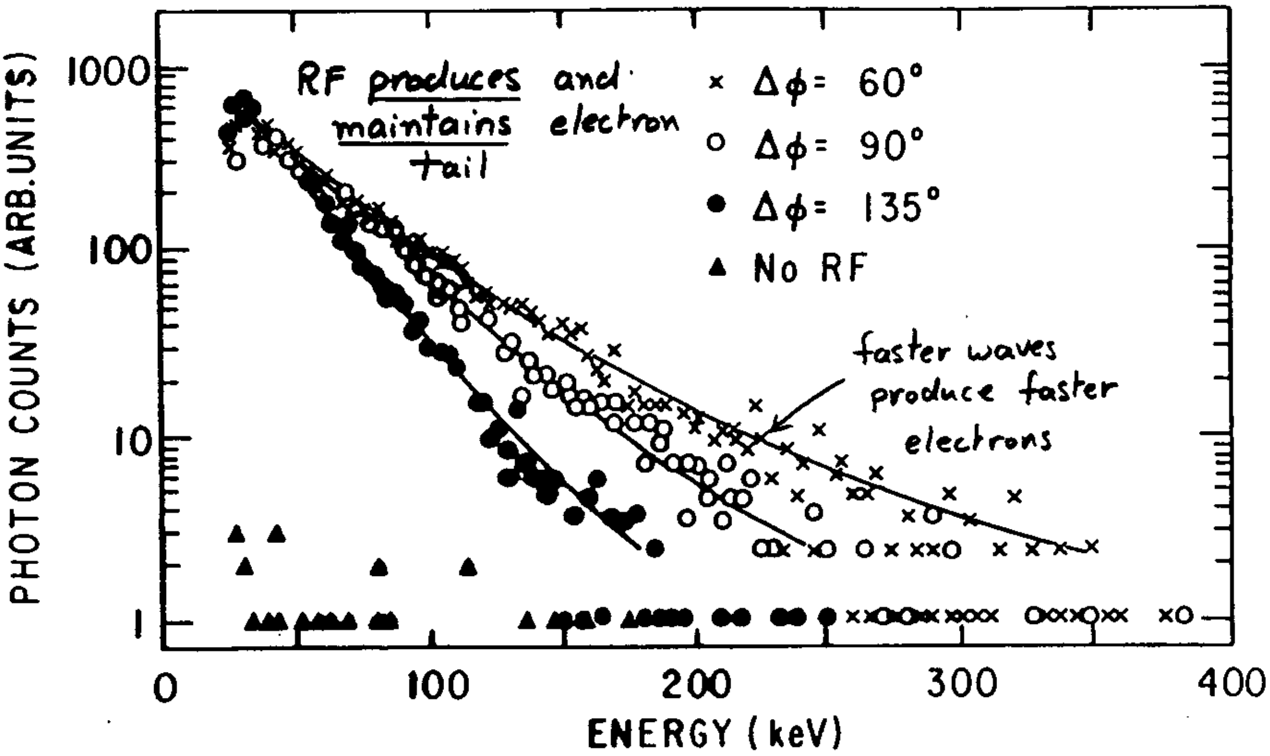
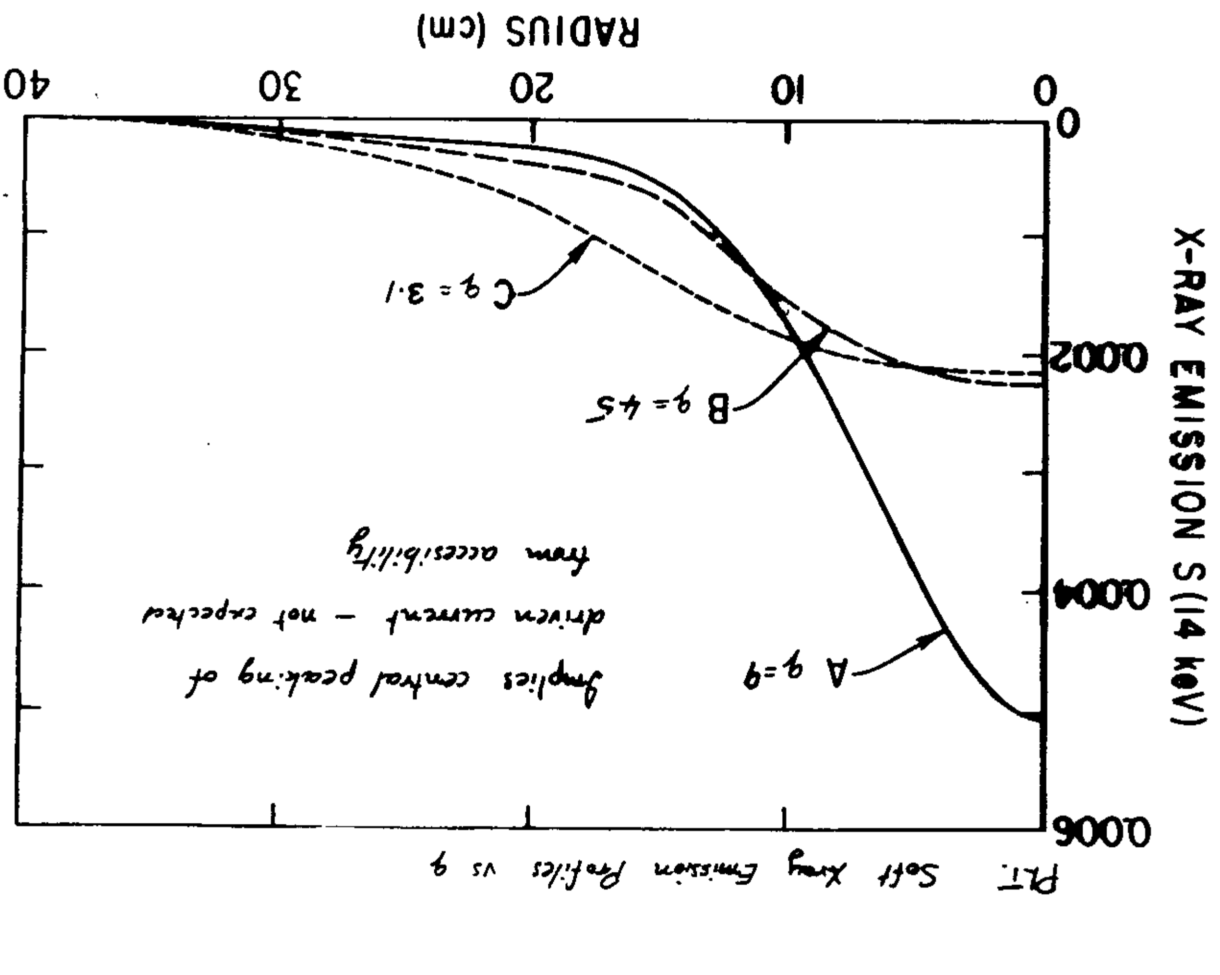
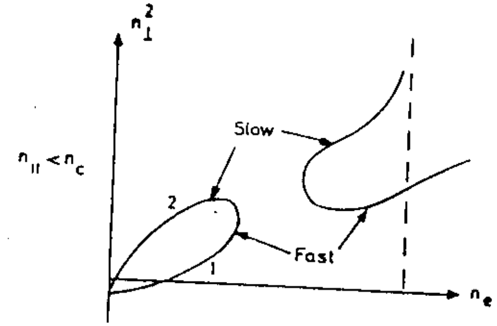


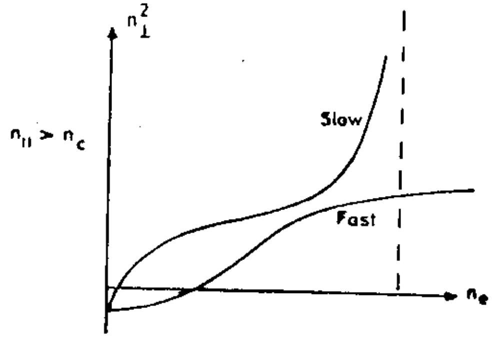
Fig. 4

Fig. 3



Accessibility Criteria





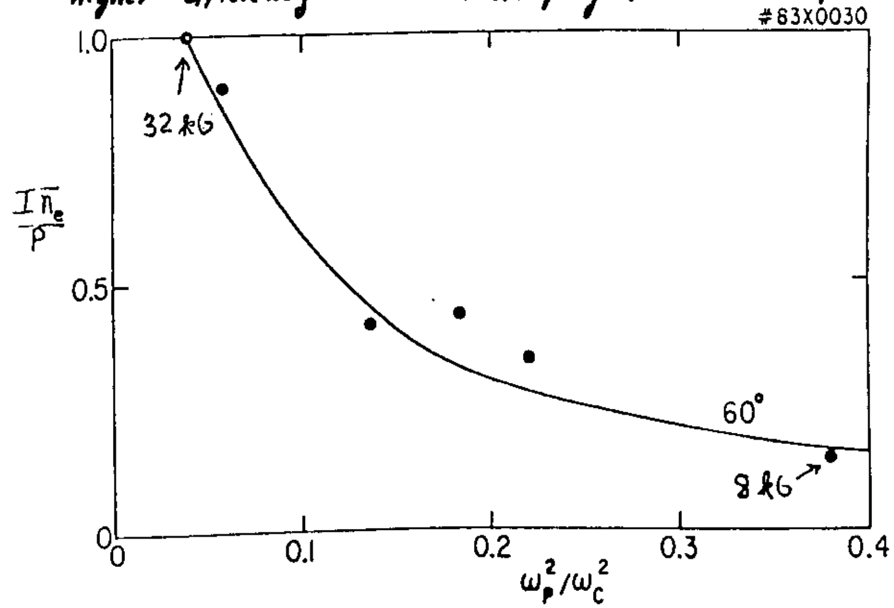
$$N_\parallel > N_{\parallel acc} = \frac{\omega_{pe}}{\omega_{ce}} + \sqrt{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2}} \qquad \text{Golant}$$

$\therefore$ low $N_\parallel$ gain access to plasma centre

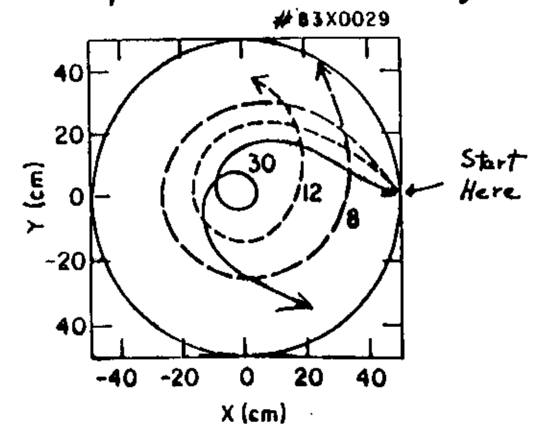
at high B

& low n_e

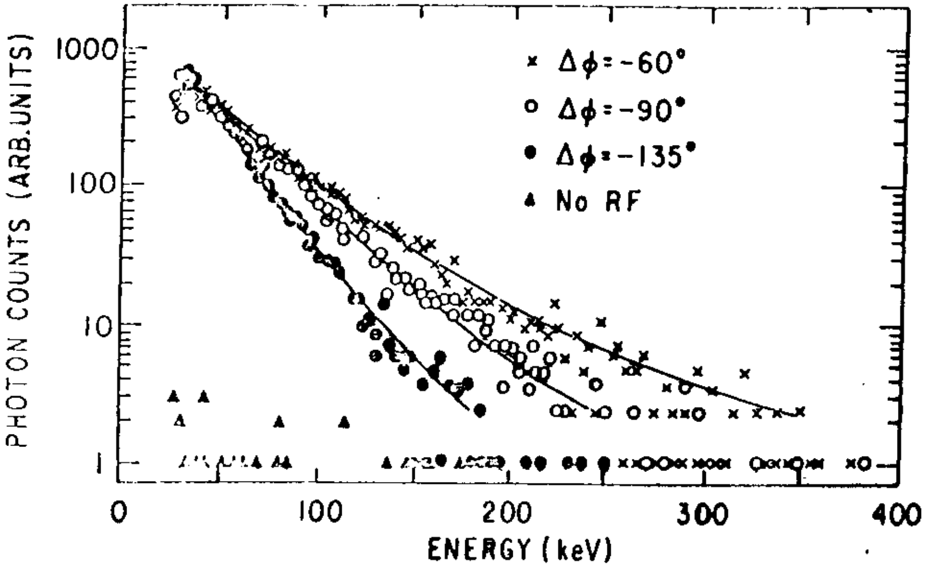
Evidence of improved accessibility giving higher efficiency – central damping of low $N_\parallel$ components.



However, even when acc. criteria fulfilled, 'whispering gallery' modes can be problematic in toroidal geometry.



Spectral Gap Problem

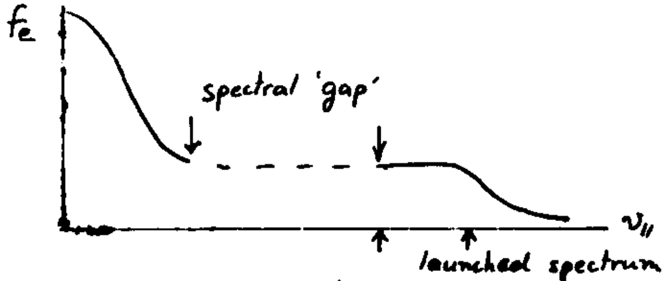


1. For $N_\parallel \simeq 2$, wave drives 50keV electrons
2. Observed J/P_d agrees with Fisch theory
3. However J and P much larger than given by own non-perturbation FP theory
4. Many more electrons in resonance than theory predicts
5. What mechanism pushes electrons from bulk distribution (T~1keV) to tail?

"THE GAP PROBLEM"

- Theoretical values for I/P in quite a good agreement with experimental values (within a factor of 2)

- But large discrepancy between theoretical and experimental values of the HF current



- Possible explanations:

  scattering of LH waves by low frequency fluctuations + magnetic shear effects

  non-linear broadening via ray focussing

  anomalous Doppler electron excitation of waves(Parail-Pogutse fast elelectron instability)

  non-linear effects due to parametric instabilities

  N// broadening due to magnetic field ripple

  multiple reflections of the wave trajectories which enhance N// via toroidal effects

  (to be noted that only 10% of the launched power is dissipated in such processes)

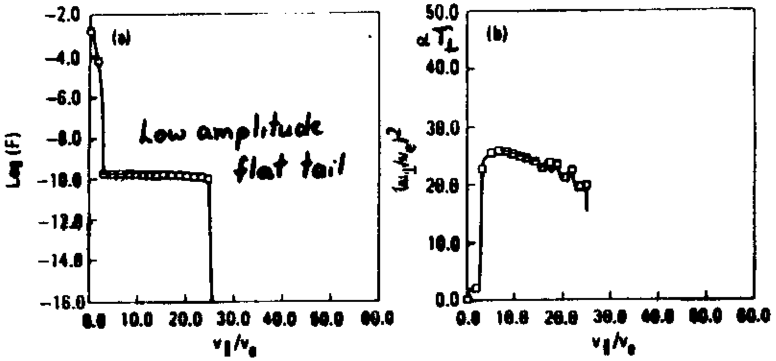
- The latest effect is used in :

  the Bonoli code (Fokker-Planck absorption)

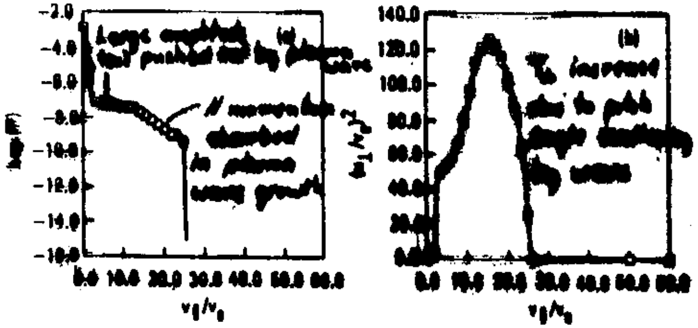
  global propagation (Moreau ,Samain)

2-D F-P calculations. LH waves + plasma waves destabilised by tail $T_{\parallel}/T_{\perp}$ anisotropy via anomalous Doppler resonance $\omega + \Omega_{ce} = k_{\parallel} v_{\parallel}$

1) No plasma waves



2) Plasma waves on - absorb little energy but large // momentum by pitch angle scattering



Relaxation behaviour

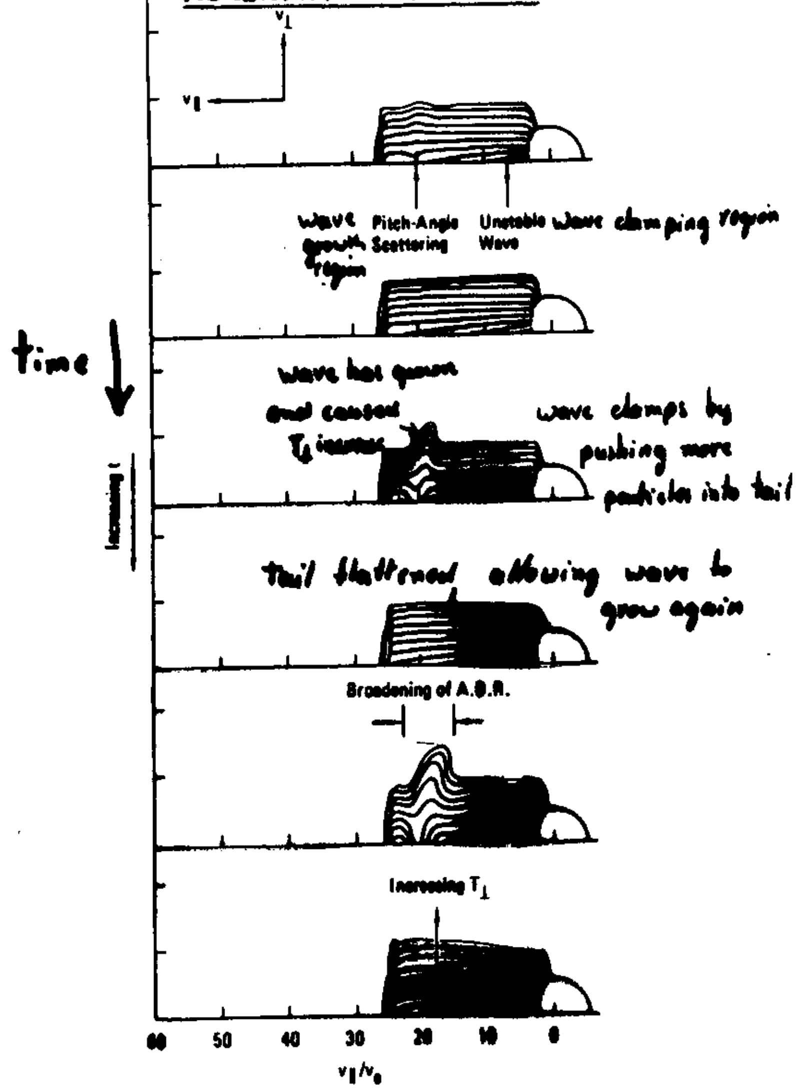


Fig. 4. Behavior of electron distribution during turbulent phase.

VERSATOR II LH Current Drive

Anisotropy-driven instability suppressed by ECRH

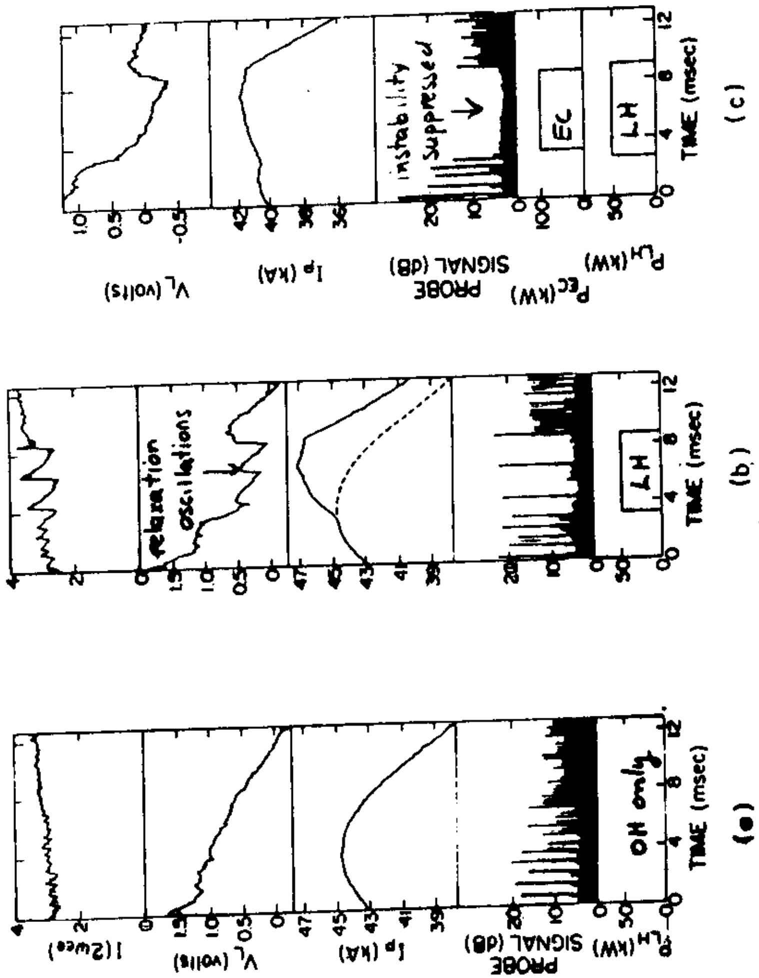


FIG. 5 $2\omega_{ce}$ emission $I(2\omega_{ce})$, V_L, I_p, and RF probe signal at f = 500 MHz at $\bar{n} = 3 \times 10^{12}$ without RF (a), with LHCD power (b) and LHCD and ECRH added (c).

MHD EFFECTS

Supression of sawteeth with partial replacement of the plasma current
depends upon density (ASDEX)

Effective in all experiments (up to a given density)
substantial increase and peaking of Te (PLT,ASDEX,JT-60)

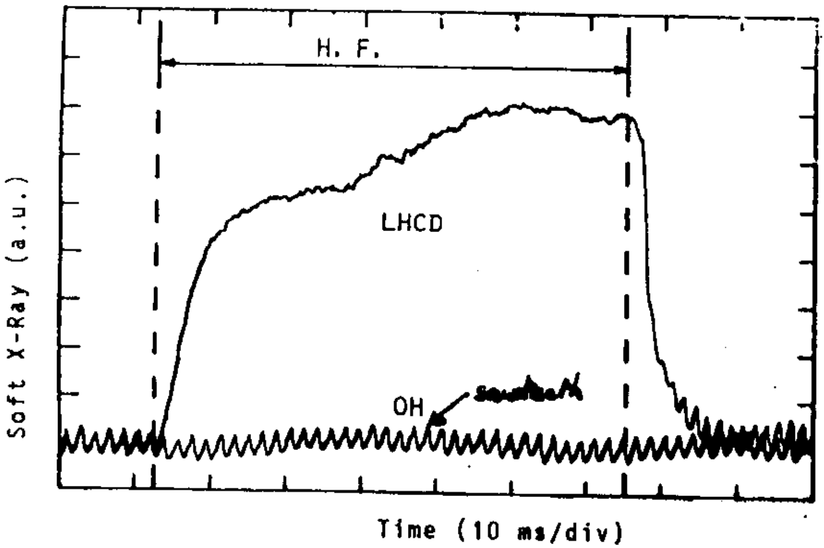
Effective in LHCD + ICRH (PLT)
LHCD + NBI (ASDEX,JT-60)
(no accumulation of impurities)

WHY ?

Current broadening leading to an increase of q(o) above unity

Control of the m=1 mode by fast electrons (change of resistivity,local current)

Sawtooth Stabilization by LHCD on Petula

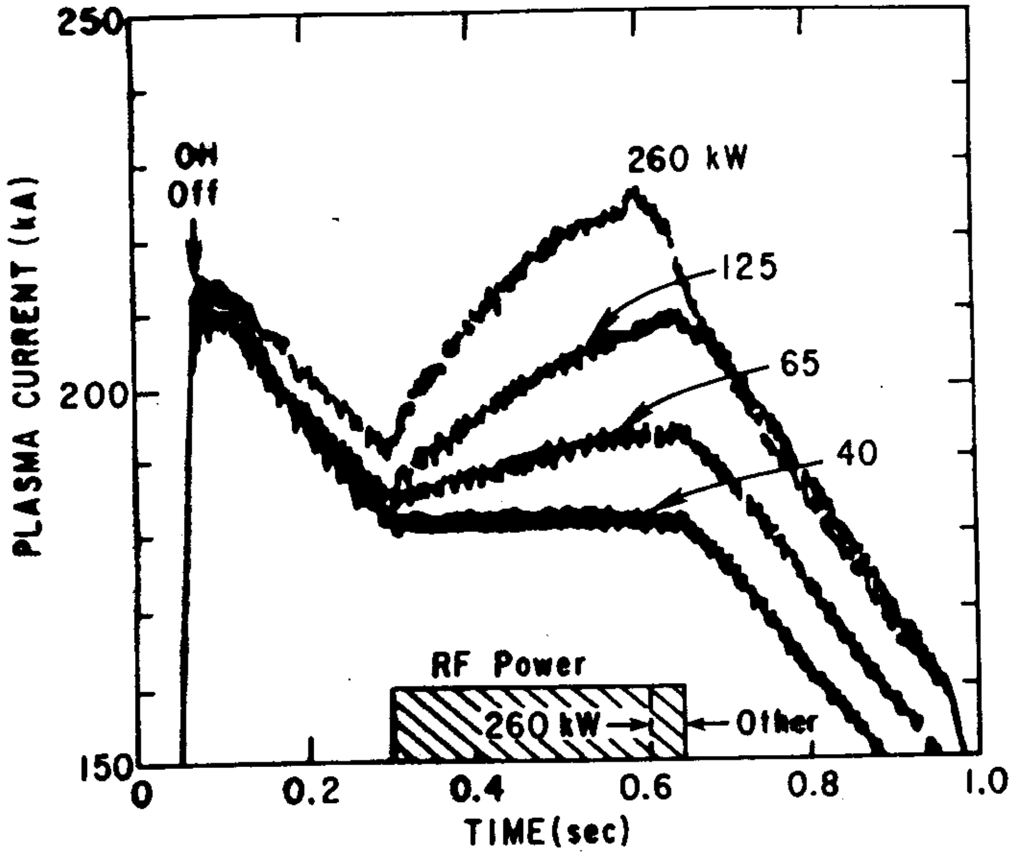


$\frac{\Delta V}{V} \sim 30\text{-}50\%$

- Observation of q(o) above 1 during LHCD
  (ASDEX at low density)
- Current broadening is observed in JT-60 at high N//
  but effective stabilisation is obtained at low N//
- m=1 mode stabilised but m=2 mode triggered
  depends upon
  time duration of LHCD pulse (ASDEX)
  density (PETULA)
- Stabilisation of sawteeth but the m=1 mode still present. Depends upon
  power (PLT)
  density (PETULA)

Both stabilising effects can occur depending upon the accessibility of the fast electrons to the m=1 island

Current Ramp-up on PLT by LHCD



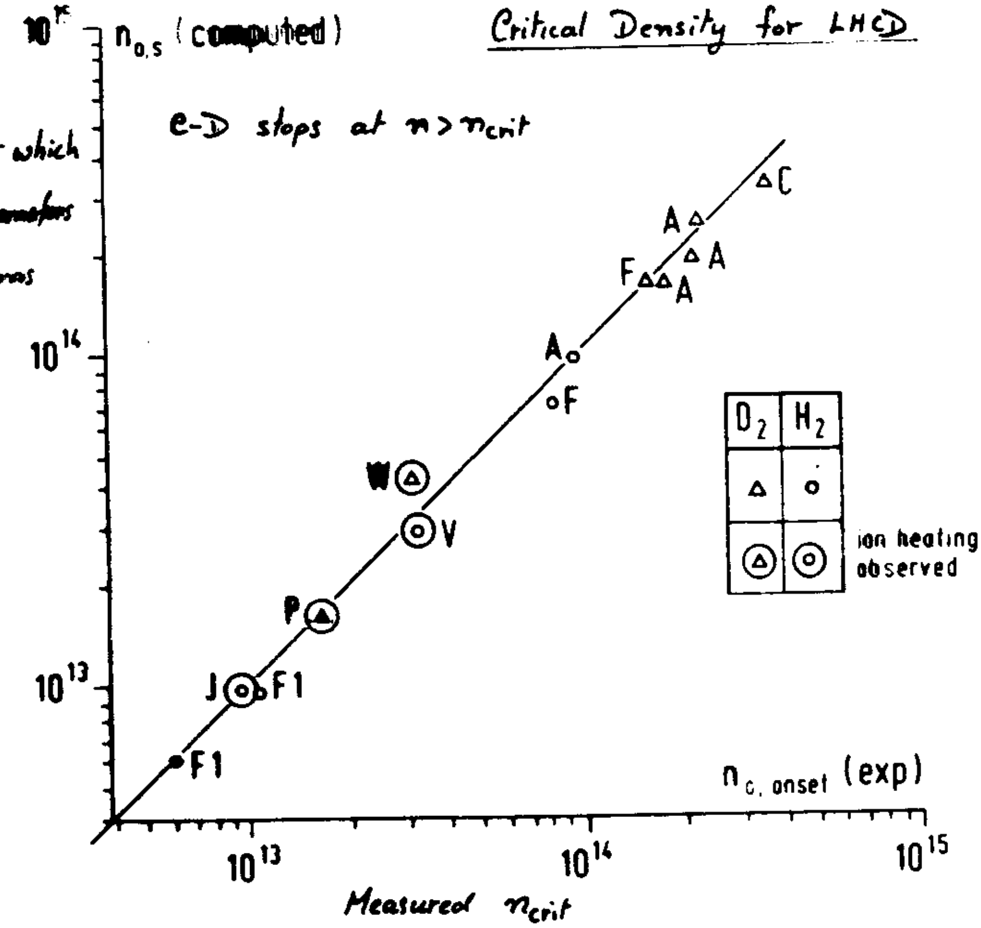
4.5

If transformer used to keep $I_p = const$
LH pulse recharges transformer

Critical Density for LHCD

FIG. 2

Density at which damping transfers from electrons to ions

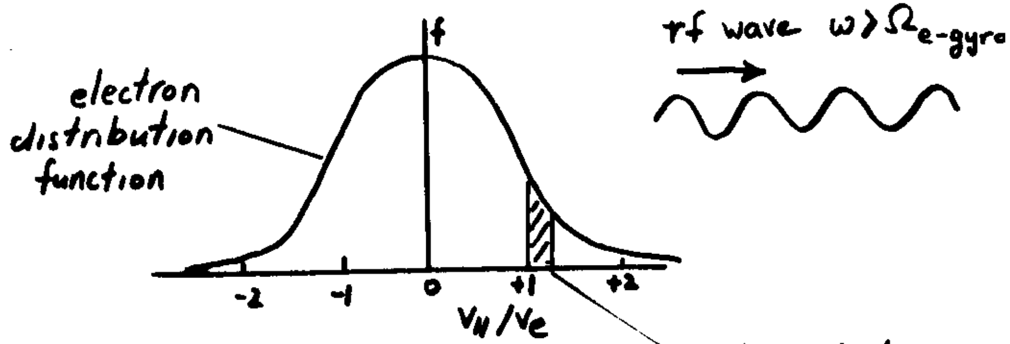


$n_{crit} \propto f^2$

Current Drive by Electron Cyclotron Waves

Asymmetric heating of electrons using travelling EC waves

$\perp$r energy increase – no net momentum input



these electrons see Doppler shifted rf frequency

$\omega_D = \omega - k_\parallel v_\parallel = \Omega_{e\text{-gyro}}$

1) Electrons moving to right see $\omega_D = \Omega_{e\text{-gyro}}$ and gain $E_\perp$

2) $\therefore$ Collisions with ions less frequent than for electrons moving to left

3) Electron distribution gains net parallel momentum to right, ions gain momentum to left – No net momentum transfered by cyclotron wave

4) Resonance condition $\omega - \Omega_{e\text{-gyro}}(r) = k_\parallel v_\parallel$ implies current reversal on opposite sides of resonance in the inhomogeneous field of a tokamak. Need strong absorption to prevent cance[llation]

Fokker-Planck Theory

electron eqn

$$\frac{\partial f}{\partial t} = \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left[D v_\perp^{2l-1}\,\delta\!\left(\frac{\omega - l\Omega}{k} - v_\parallel\right)\frac{\partial f}{\partial v_\perp}\right] + C_{ei} + C_{ee}$$

Neglect C_{ee}

$$\left(\frac{J}{P_d}\right)_n = \frac{3}{Z}\left(\frac{v_{phase}}{v_e}\right)^2 \qquad v_{phase} \to \infty$$

cf LHCD $$\left(\frac{J}{P_d}\right)_n = \frac{4}{Z}\left(\frac{v_{phase}}{v_e}\right)^2 \qquad v_{phase} \to \infty$$

$$\eta_{LHCD} = \frac{4}{3}\,\eta_{ECCD}$$

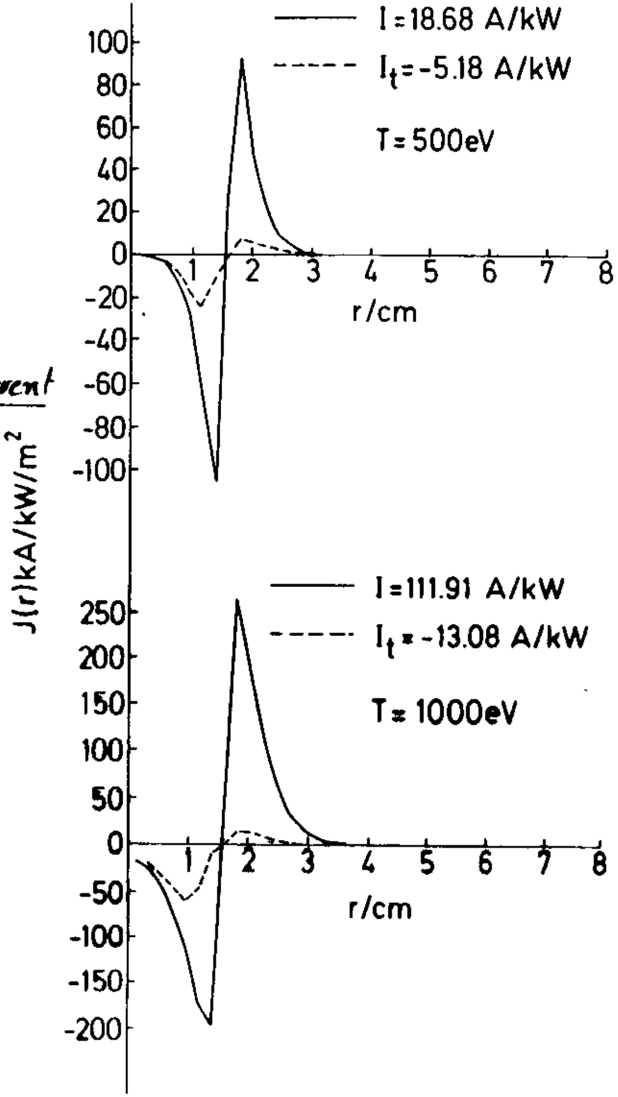
LHCD efficiency largely due to heating effect + only 25% due to momentum input

Fig. 8

Ray tracing + Fokker Planck calculation of current density profiles.

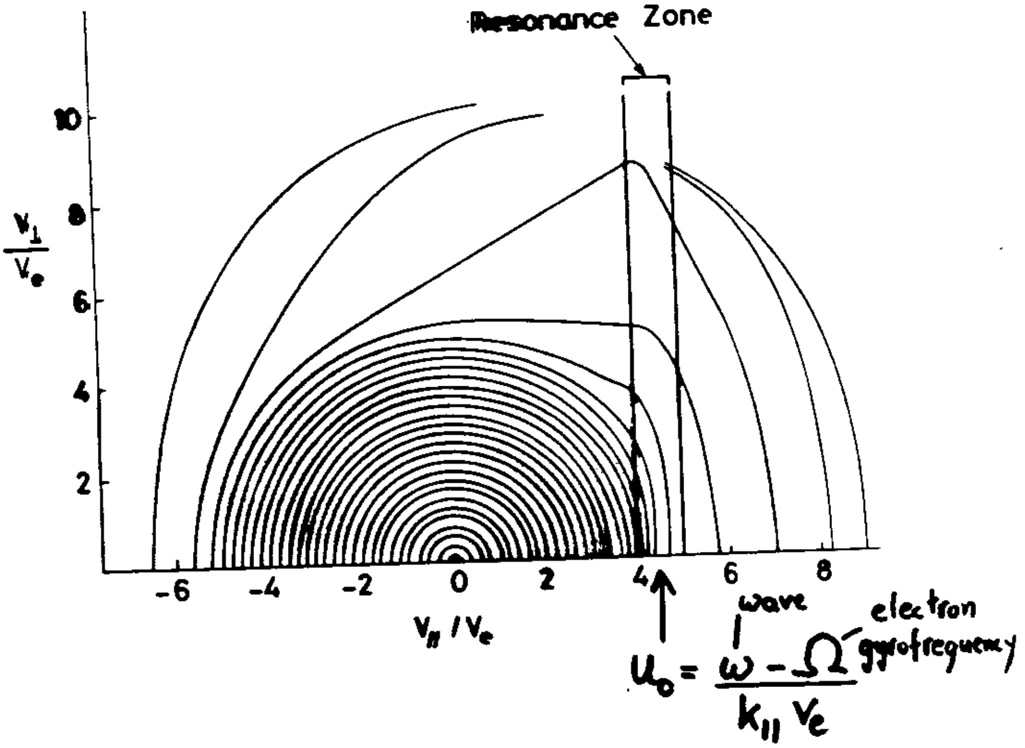
TOSCA Tokamak

$2\omega_{ce}$

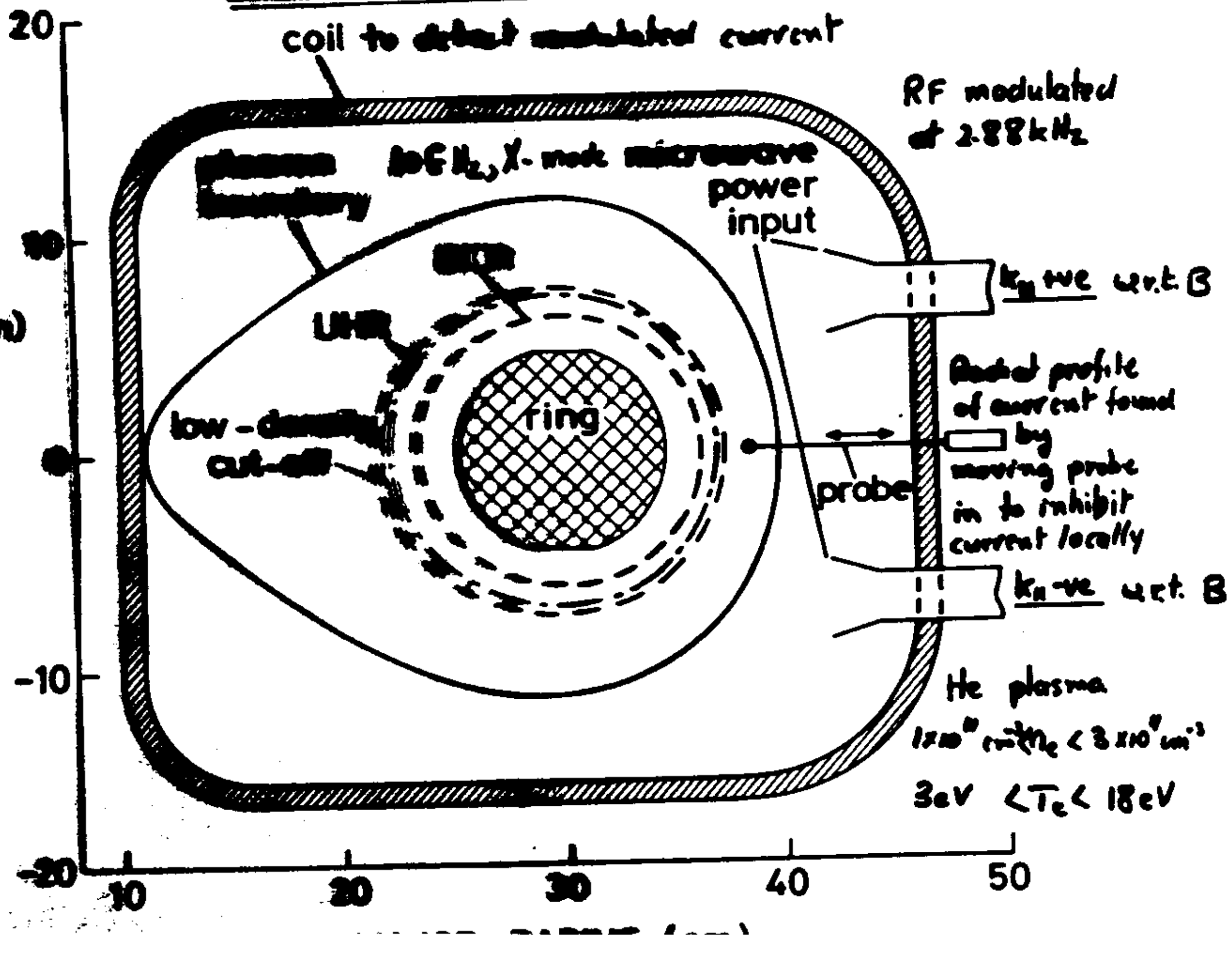


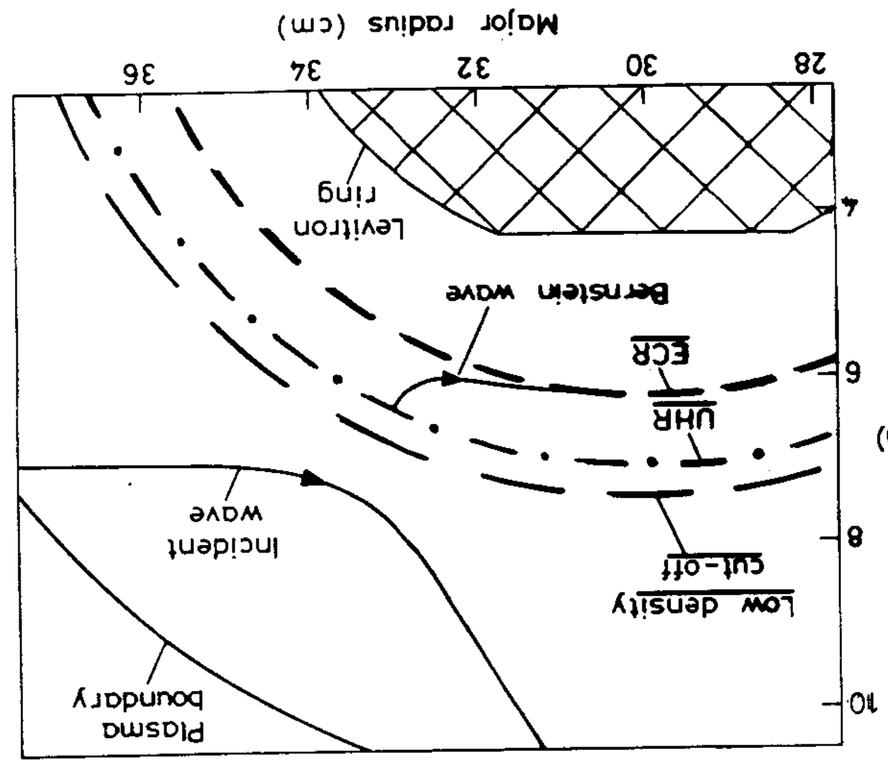
Asymmetric ECRH

Electron distribution function contours

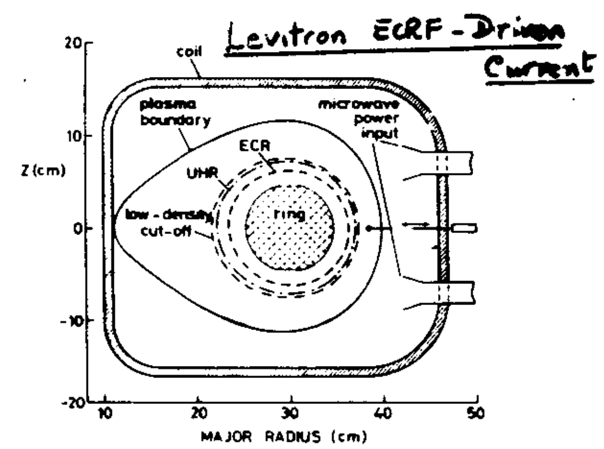


ECCD Experiment



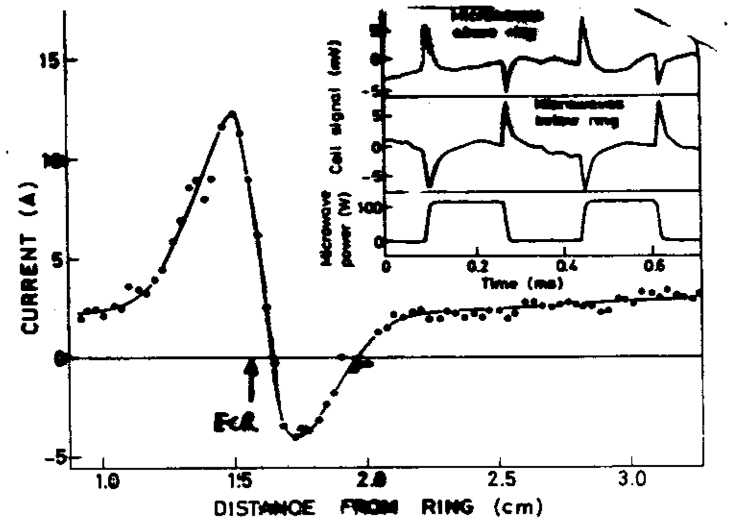


Plasma boundary
Incident wave
Levitron ring
Bernstein wave
ECR
UHR
Low density cut-off
Z (cm)
Major radius (cm)



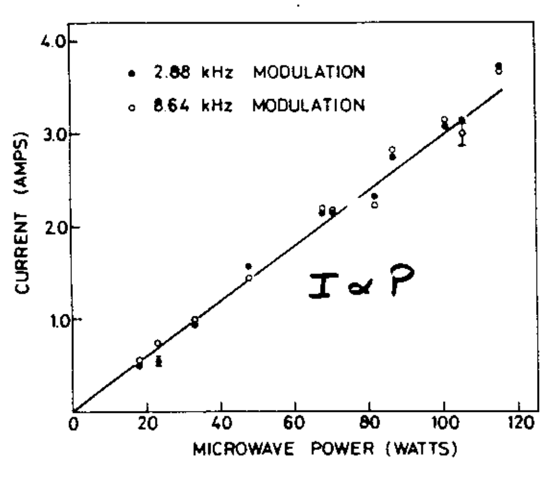
Levitron ECRF-Driven Current
coil
plasma boundary
microwave power input
ECR
UHR
low-density cut-off
ring
Z (cm)
MAJOR RADIUS (cm)

Fig. 1

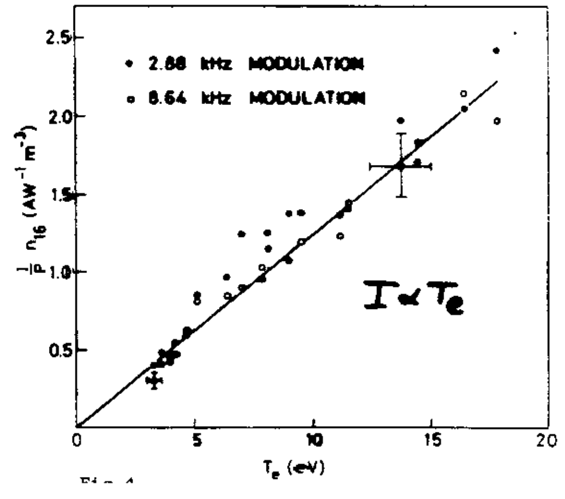


CURRENT (A)
ECR
DISTANCE FROM RING (cm)
Cell signal (mV)
Microwave power (W)
Time (ms)

Fig.2



2.88 kHz MODULATION
8.64 kHz MODULATION
CURRENT (AMPS)
MICROWAVE POWER (WATTS)
I ∝ P



2.88 kHz MODULATION
8.64 kHz MODULATION
$\frac{1}{P}$ n_{16} ($AW^{-1} m^{-3}$)
T_e (eV)
I ∝ T_e

Budden analysis for cut-off / resonance pair

Power absorbed from Bernstein wave

$$P_a = \eta(1-\eta) P_{injected}$$

$$\eta = \exp\left(-\pi \sqrt{\Omega^2 X L} / c^2\right),$$

X = distance from cut-off to UHR

$L = \omega_p^{-2} \frac{d}{dr}(\omega_p^2 + \Omega^2)$

Present case

$T_e = 7.5\,eV$, $n_e = 3\times10^{11}\,cm^{-3}$

$X = 0.35\,cm$ $\quad$ $L = 0.5\,mm$

$P_a/P_{inj} \sim 10\%$

Predicted $I/P \sim 0.05\,A/W$ for $v_{res}/v_e = 1$

Experiment $I/P \sim 0.03\,A/W$

TOSCA Tokamak

$R = 30\,cm$

$f = 28\,GHz$

$2\omega_{ce}$ outside launch

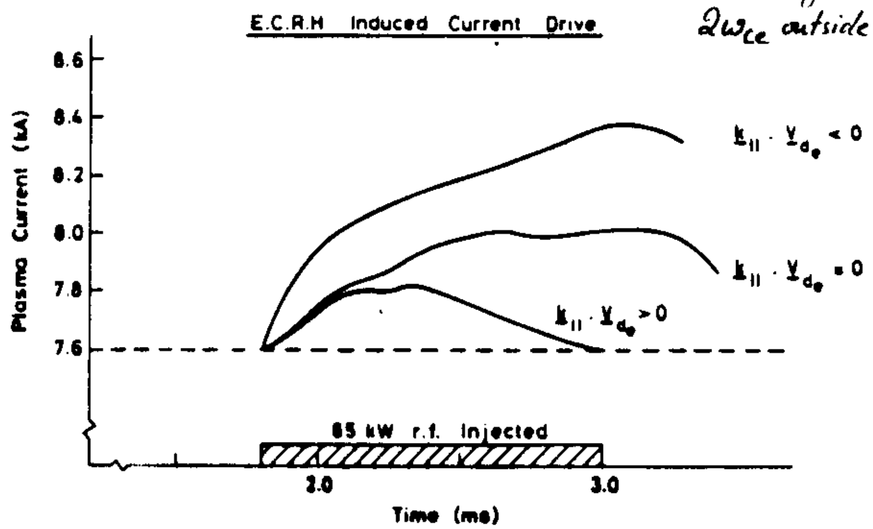


Fig.5

Dependence on resonance position

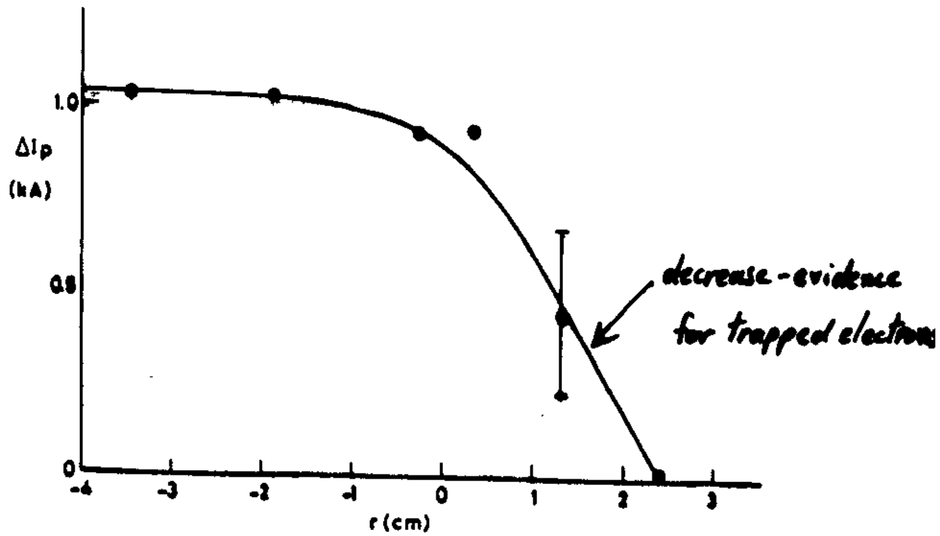
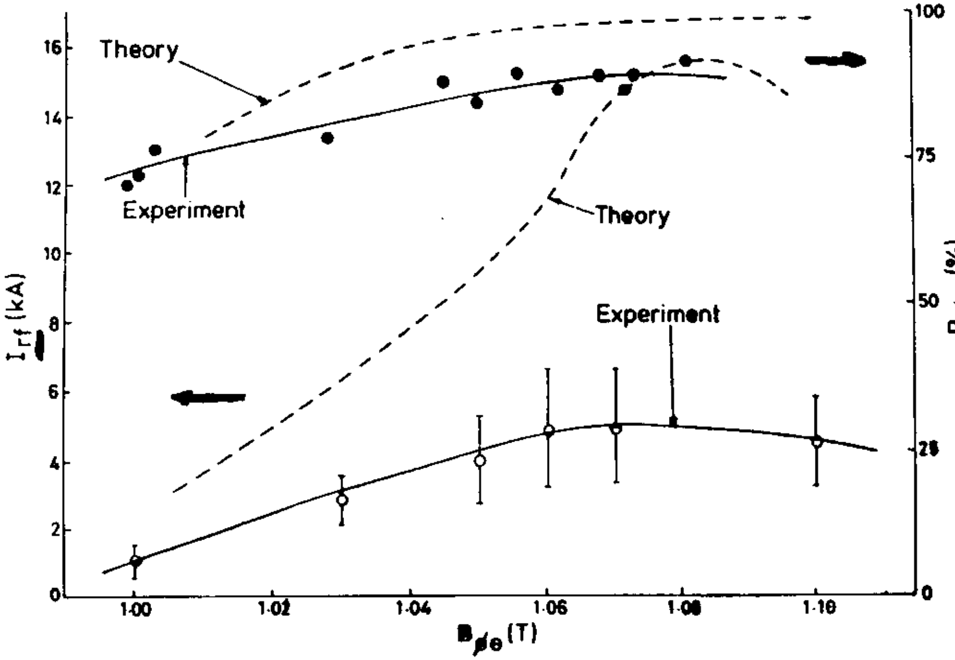


Fig.6

Resonance position

CLEO



Theory based on ray tracing and current drive model including trapping effects and weakly relativistic resonance condition.

Start et al. (1984)

Asymmetric Heating of Minority Ions

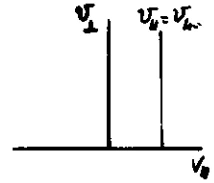
+ collisions with majority ions and electrons

Rest frame of majority ions

$$J = J_m + J_e$$

NJ Fisch — Analytic theory – uniform B

– $v_{\parallel res} = \delta(v_\parallel - v_{\parallel o})$



Current Drive efficiency

$$\left(\frac{J}{P_d}\right)_{norm} = 3\,\frac{\left(1-\frac{Z_i}{Z_m}\right)}{\left(1+\frac{M_m}{M_i}\right)}\,\frac{v_{\parallel res}^2}{\left(1+Y v_{\parallel res}^3\right)^2}$$

Max when $v_{\parallel res} = (2Y)^{-1/3}$ – switch-over from collisions with majority ions to collisions with electrons as $v_{\parallel res}\uparrow$

$J = 0$ if $Z_m = Z_i$ (eg H^+_{min}, D^+_{maj}) $\rightarrow$ $J_e = -J_m$

Tokamak B — electron trapping allows net J.

Example

$n_e = 3\times10^{19}\,m^{-3}$
$T_e = 5\,keV$
$R = 2.96\,m$
(H)D scheme

$$\left(\frac{J}{P_d}\right)_{max} = 55, \quad \frac{I}{P} = 0.25\,A/W \quad (J_H \text{ only})$$

Electron trapping $\quad J_t = J\left(1 - 1.46\,A(Z_i)\,\varepsilon^{1/2}\right)$

$A = 1.7 \quad Z_i = 1$
$\;\;= 1.4 \quad Z_i = 2$

$\varepsilon = r/R = 0.1 \quad (r = 0.3\,m,\ JET)$
$Z_i = 1$

$I/P = 0.19\,A/W$

Features not treated by simple theory

- Resonance broadening
- Minority ion trapping
- Directivity of travelling wave

Resonance broadening

$$\omega - \Omega_{cz}(R) = k_{\parallel} v_{res}$$

Spread in $v_{\parallel res}$ due to $\Delta\Omega$ – flux surface averaging, Ω variation along B

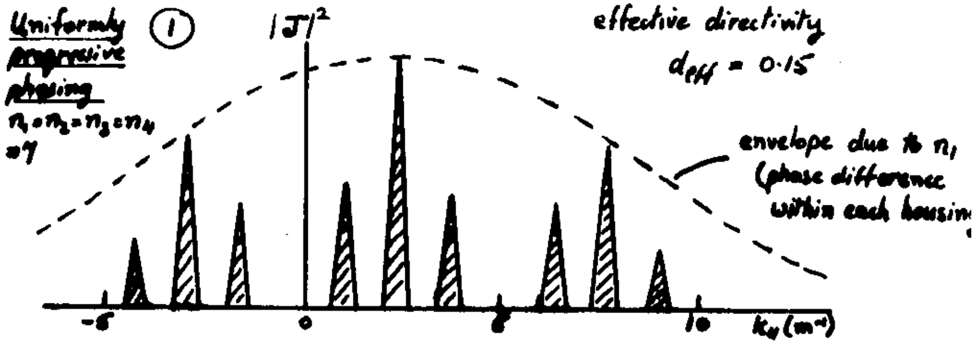
$\Delta k_{\parallel} \sim \frac{1}{W_{beam}}$ (small for phased array)

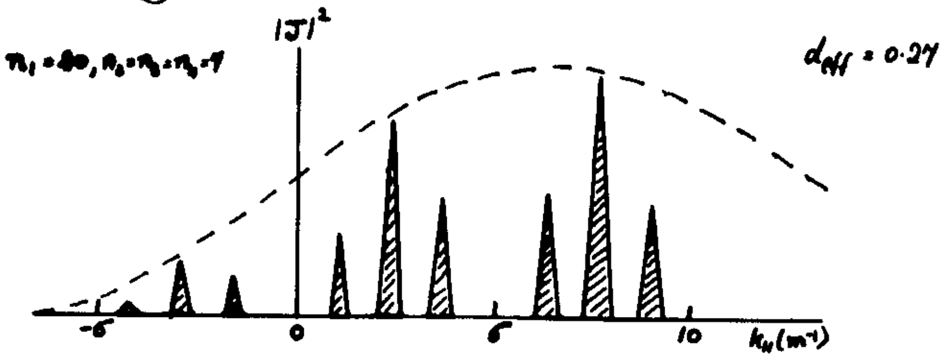
Antenna Array 8 housings, 2 antennae / housing

Current spectrum

$$|J(n)|^2 = \frac{I}{N}\cos^2\frac{\pi}{84}(n-n_1)\cos^2\frac{\pi}{16}(n-n_2)\cos^2\frac{\pi}{4}(n-n_3)\cos^2\frac{\pi}{2}(n-n_4) \times \frac{\sin^2(nW/R)}{(nW/R)^2}$$

$n = k_{\parallel}R$, $2W$ = antenna width





$$(J/P)_{net} = \sum_i d(k_{\parallel i})\,\frac{J}{P}(k_{\parallel i}); \quad \left(\frac{J}{P}\right)_{net\,②} \approx 1.8\left(\frac{J}{P}\right)_{net\,①} \quad \text{Fig 6}$$

H_{min} in D

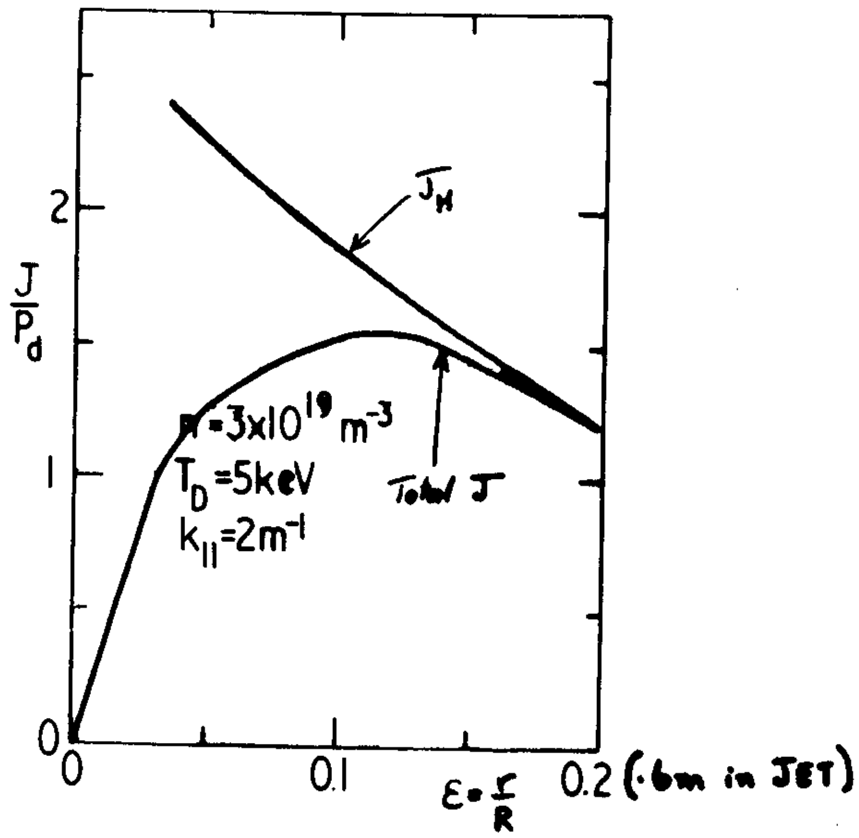
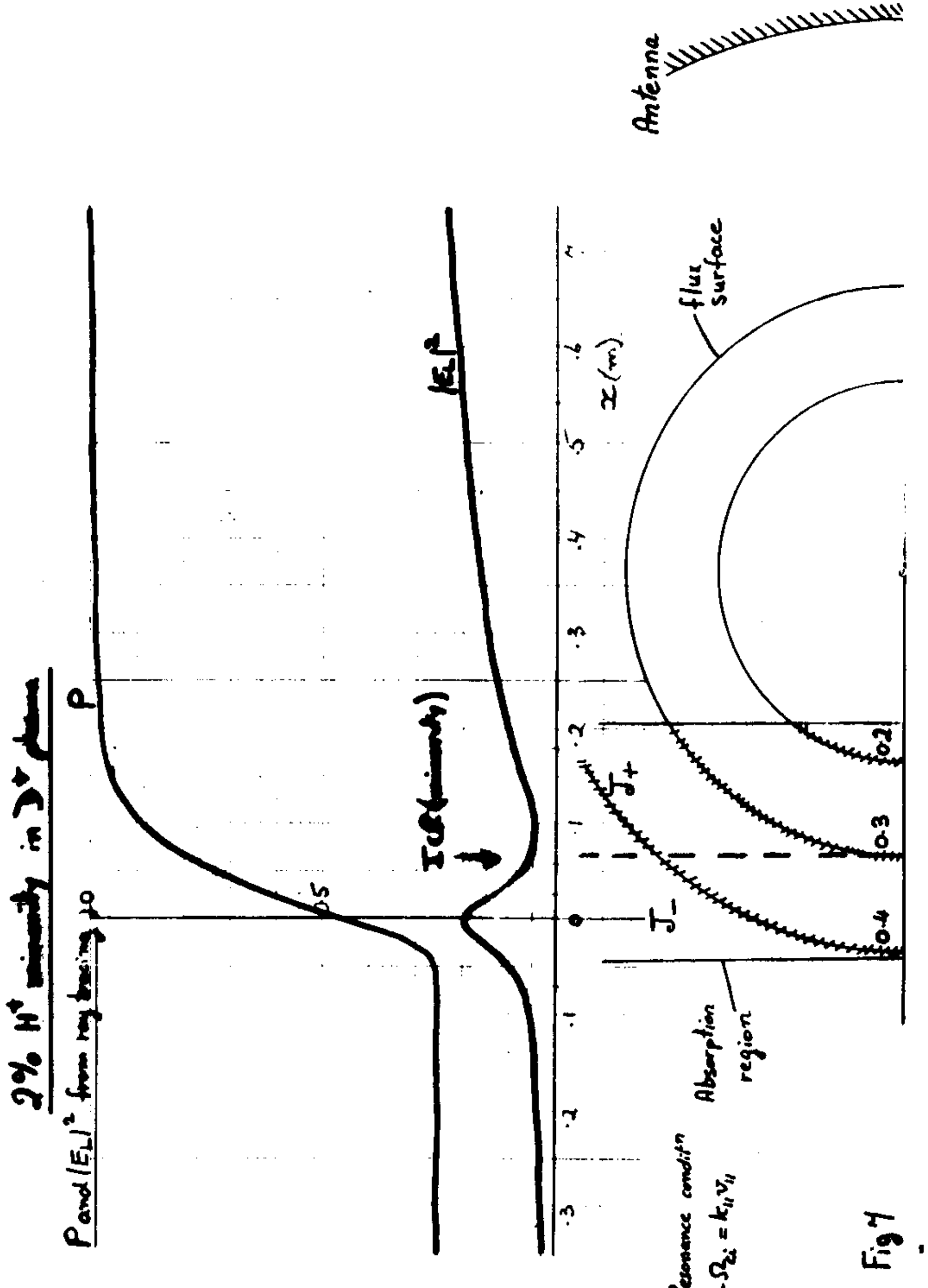


Fig 3



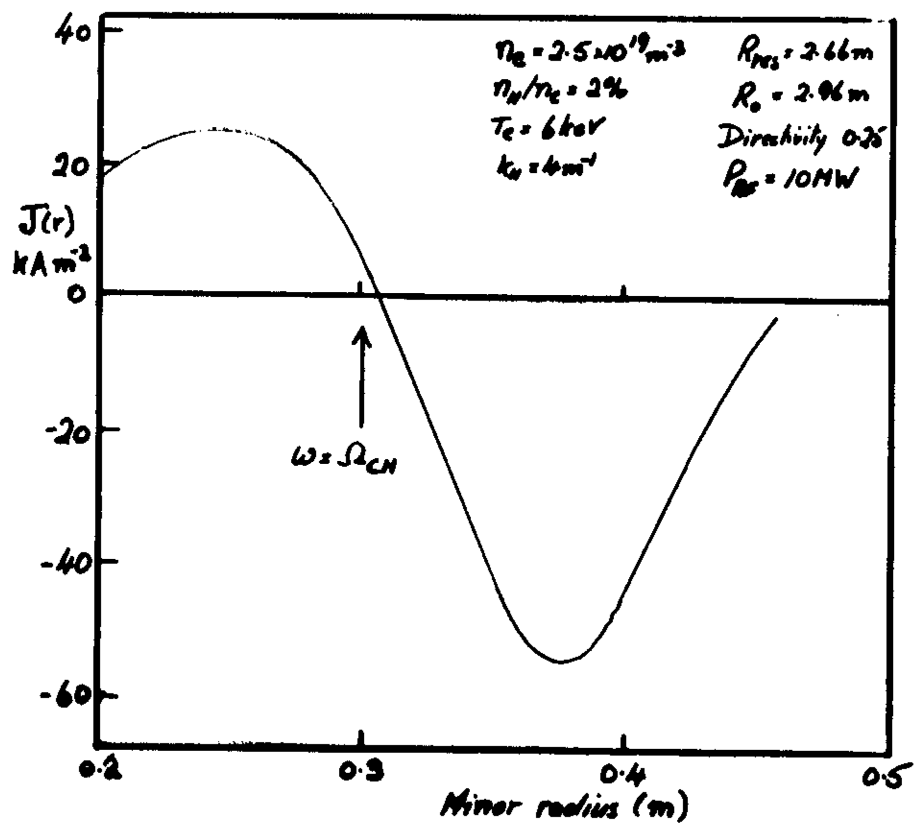


Fig 9 Current density profile produced by asymmetric minority heating current drive scheme

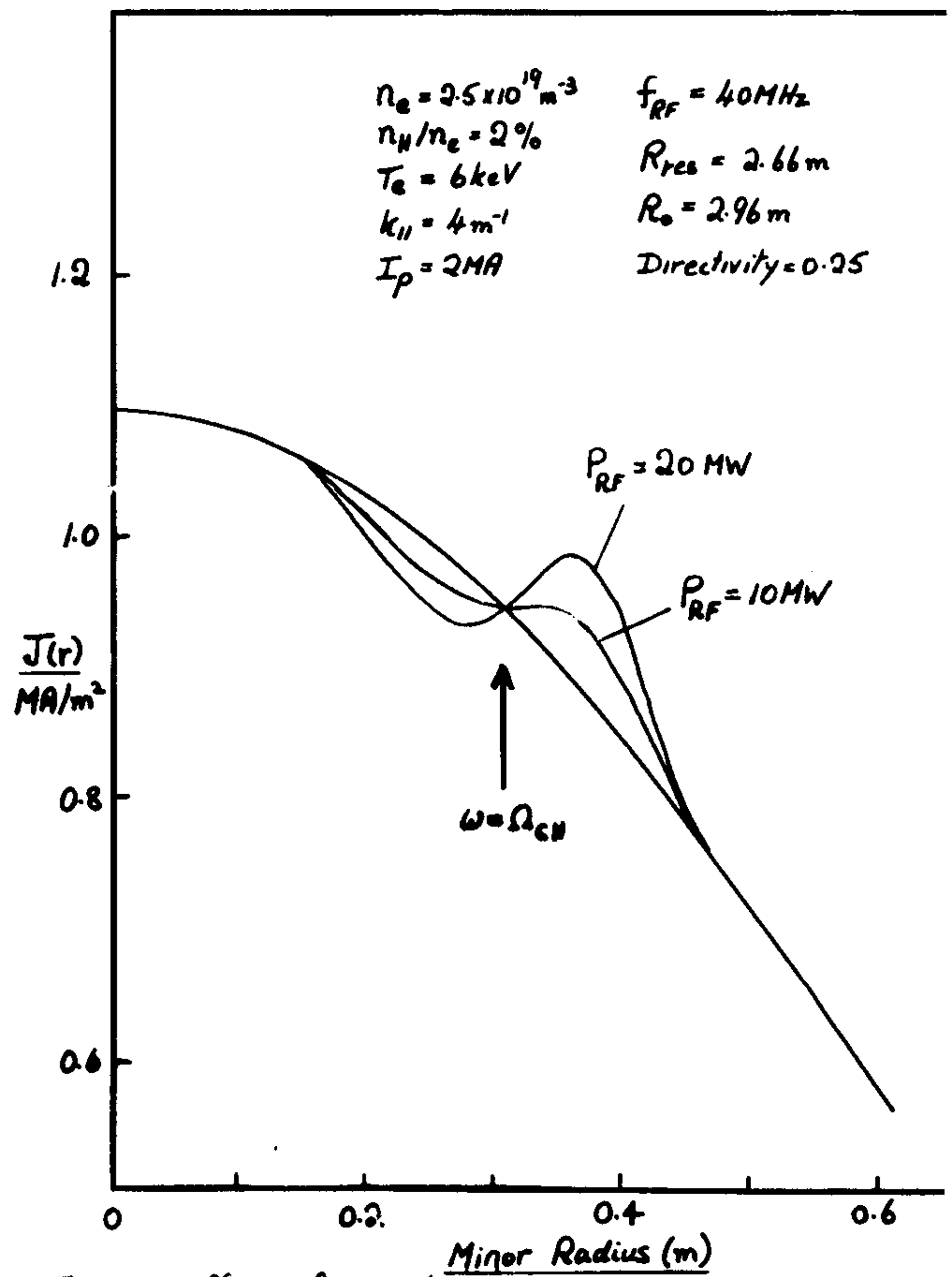


Fig 10 Effect of current drive