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## AUTUMN COLLEGE ON PLASMA PHYSICS

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# Absorption Physics of High-Frequency Fast Magnetosonic Waves

**J. MENARD**

Princeton University
Plasma Physics Laboratory
Princeton, U.S.A.

# Absorption Physics of High-Frequency Fast Magnetosonic Waves

Presented by J. Menard

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ICTP
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PPPL
PRINCETON PLASMA PHYSICS LABORATORY

# Fast Wave Review (cold plasma)

Assume $\mathbf{E}=\mathbf{E}_0\, e^{i(\mathbf{k}\bullet\mathbf{r}-\omega t)}$, define $\mathbf{n} = c\mathbf{k}/\omega$, $\Rightarrow$ wave eqn. is $\mathbf{n}\times\mathbf{n}\times\mathbf{E}+\mathbf{K}\bullet\mathbf{E}=0$

$\mathbf{K}=1+\Sigma\chi_s \qquad \chi_s=i\sigma_s/\omega\varepsilon_0 \qquad \mathbf{J}_s= \sigma_s \bullet\mathbf{E}$

where $\sigma_s$ is determined from the linearized equations of motion in a strong magnetic field $B_z$

$$\mathbf{K} = \begin{bmatrix} S & iD & 0 \\ -iD & S & 0 \\ 0 & 0 & P \end{bmatrix}$$

S: Vacuum + $\perp$ polarization current

D: $\mathbf{E}\times\mathbf{B}$ drift induced current

P: Vacuum + $\|$ polarization current

Solve for $n_\perp^2 = n_\perp^2(n_\|,\mathbf{r}) \Rightarrow n_\perp^2 = \dfrac{(n_\|^2-R)\,(n_\|^2-L)}{(S-n_\|^2)}$ L,S < 0 near edge $\Rightarrow$

$S=(R+L)/2 \quad D=(R-L)/2$

wave is evanescent until $R > n_\|^2$, then $\omega^2 \approx k_\perp^2\, v_A^2(1+c^2k_\|^2/\omega^2_{pi})$

$v_A \approx c\Omega_i/\omega_{pi}$

# Motivation for Studying High-Frequency (High-Harmonic) Fast Waves

- Fast waves with frequencies near the ion cyclotron fundamental are routinely used to resonantly heat ions in present fusion experiments.
- Auxiliary current drive and current profile control are important for improving several fusion concepts (Tokamak, ST, RFP)
  - Fast waves well above the cyclotron fundamental can:
    - preferentially heat electrons
    - drive toroidal current
- In particular, next-generation spherical tokamaks will require strong auxiliary heating and current drive to test stability limits and confinement trends
- Wave inverse damping length $1/L_{damp} \propto \beta_e / v_A \propto \boxed{(\omega_{pe}/\Omega_e)^3 T_e}$ for fixed $\omega/k_{\parallel} v_{Te}$
  - Standard tokamaks have $\omega_{pe}/\Omega_e \approx 1$
  - Spherical tokamaks have $\omega_{pe}/\Omega_e > 5 \Rightarrow$ very strong damping, off-axis CD
- High-harmonic $\Rightarrow \omega = 15\text{-}30 \times \Omega_{ci}$
  - Weaker ion damping per ion-cyclotron harmonic resonance
  - Weaker IBW mode conversion per resonance
  - Natural fit to present low-field ST experiments (NSTX will use TFTR hardware)

# Dielectric Tensor Elements

Working in the limit $\Omega_i < \omega \ll | \Omega_e |$ and neglecting ion and electron finite Larmor radius (FLR) effects, the lowest order dielectric tensor elements are:

$$K_{xxc} = 1 + \frac{\omega_{pe}^2}{\Omega_e^2} - \sum_i \frac{\omega_{pi}^2}{\omega^2 - \Omega_i^2} \tag{1}$$

$$K_{xyc} = -\frac{\omega_{pe}^2}{\Omega_e \omega} + \sum_i \frac{\Omega_i}{\omega} \frac{\omega_{pi}^2}{\omega^2 - \Omega_i^2} \tag{2}$$

$$K_{yyc} = K_{xxc} + n_\perp^2 \delta_m \tag{3}$$

$$K_{xzc} = -n_\perp n_\| \delta \tag{4}$$

$$K_{yz} = n_\perp \delta_X K_{zze} \tag{5}$$

$$K_{zz} \approx K_{zze} = -\frac{\omega_{pe}^2}{k_\|^2 V_{Te}^2} Z_0'(\frac{\omega}{k_\| V_{Te}}) \tag{6}$$

$$\delta_m = \frac{\omega_{pe}^2}{\Omega_e^2} \frac{V_{Te}^2}{c^2} \frac{\omega}{k_\| V_{Te}} Z_0(\frac{\omega}{k_\| V_{Te}}) \tag{7}$$

$$\delta = \sum_s (\frac{V_T}{c})^2 \frac{\omega^2 \omega_p^2}{(\omega^2 - \Omega^2)^2} \tag{8}$$

$$\delta_X = (\frac{V_T}{c})^2 \frac{\omega}{2\Omega_e} n_\| \tag{9}$$

Here $\delta_m$ is the magnetic pumping (MP) term, $\delta$ is small, $\delta_x$ represents the cross (X) terms from $K_{yz}$ and $K_{zy}$, $K_{zze}$ gives the electron Landau damping (ELD), and "c" and "e" indicate cold and (thermal) electron, respectively. Cyclotron frequencies carry the sign of the particle species charge.

# Wave Dispersion Relation

The dispersion relation is obtained from the determinant equation:

$$\det \begin{bmatrix} K_{xxc} - n_{\|}{}^2 & -iK_{xyc} & n_\perp n_\| (1-\delta) \\ iK_{xyc} & K_{xxc} - n_\|^2 - n_\perp^2 (1-\delta_m) & i n_\perp \delta_x K_{zze} \\ n_\perp n_\| (1-\delta) & -i n_\perp \delta_x K_{zze} & K_{zz} - n_\perp{}^2 \end{bmatrix} = 0 \qquad (10)$$

The resulting dispersion relation, g=0, is quadratic in $n_\perp^2$:

$$\mathrm{g}(\mathrm{n}_{\perp \mathrm{r}}, \mathrm{n}_{\perp \mathrm{i}}, \mathrm{n}_{\| \mathrm{r}}) \equiv \mathrm{a}\mathrm{n}_\perp^4 + \mathrm{b}\mathrm{n}_\perp^2 + \mathrm{c} = 0 \qquad (11)$$

The coefficients in the quadratic equation are:

$$a = [\eta - n_\|^2 (1-\delta)^2](1-\delta_m) \qquad (12)$$

$$b = -K_{xyc}^2 - 2K_{xyc} n_\| \delta_x (1-\delta) K_{zze} + \eta^2 - \eta[n_\|^2 (1-\delta)^2 + K_{zze}(1-\delta_m) + \delta_x^2 K_{zze}^2] \qquad (13)$$

$$c = [K_{xyc}^2 - \eta^2] K_{zze} \qquad (14)$$

$$\eta = n_\|^2 - K_{xxc} \qquad (15)$$

# Treatment of Complex Roots

Keeping $g$ stationary along the power flow (ray) trajectory $\Rightarrow$

$$\frac{d\vec{r}}{dt} = -\frac{\partial g/\partial \vec{k}}{\partial g/\partial \omega} \qquad \frac{d\vec{k}}{dt} = +\frac{\partial g/\partial \vec{r}}{\partial g/\partial \omega} \qquad \frac{d\omega}{dt} = -\frac{\partial g/\partial t}{\partial g/\partial \omega}$$

Problem: Power flow velocity (usually taken to be $d\vec{r}/dt$) should be real-valued, but g is generally complex when damping is strong.

Partial solution: expand $k_\perp$ about $k_{\perp r}$ to derive real-valued dispersion relation:

$$G(\vec{r}, t, k_{\perp r}, k_{\|}, \omega) = g_r + g_i \frac{\partial g_i/\partial k_{\perp r}}{\partial g_r/\partial k_{\perp r}} = 0$$

Interestingly, finding the root of this dispersion relation is equivalent to minimizing the modulus of $g$, i.e solving $\frac{\partial}{\partial k_{\perp r}} |g(\vec{r}, t, k_{\perp r}, k_{\|})|^2 = 0$.

This methodology also yields the imaginary part of $k_\perp = k_{\perp i} = \frac{-g_i}{\partial g_r/\partial k_{\perp r}}$

# Ray Tracing Equations

The ray-tracing equations in cylindrical coordinates become:

$$\frac{1}{c}\frac{dR}{dt} = \left[\frac{v_{g\perp}}{c}\left(\frac{k_R - k_{||}\frac{B_R}{B}}{k_{\perp r}}\right) + \frac{v_{g||}}{c}\frac{B_R}{B}\right]$$

$$\frac{1}{c}\frac{Rd\phi}{dt} = \left[\frac{v_{g\perp}}{c}\left(\frac{k_\phi - k_{||}\frac{B_\phi}{B}}{k_{\perp r}}\right) + \frac{v_{g||}}{c}\frac{B_\phi}{B}\right]$$

$$\frac{1}{c}\frac{dZ}{dt} = \left[\frac{v_{g\perp}}{c}\left(\frac{k_Z - k_{||}\frac{B_Z}{B}}{k_{\perp r}}\right) + \frac{v_{g||}}{c}\frac{B_Z}{B}\right]$$

where

$$v_{g\perp} = -\frac{\partial G/\partial k_{\perp r}}{\partial G/\partial \omega} \qquad v_{g||} = -\frac{\partial G/\partial k_{||}}{\partial G/\partial \omega} \qquad k_\phi = \frac{n_\phi}{R}$$

# Current drive efficiency $\eta_{CD}$

For good review, see J. Wright, Ph.D. Thesis, Princeton (1998)

$\partial f_e/\partial t = C_{collision}(f_e) + C_{wave}(f_e) = 0$ in steady state $\Rightarrow$
$C_{collision}(f_e) = -C_{wave}(f_e) = -\,\partial/\partial\mathbf{v} \bullet \mathbf{D}_{ql} \bullet \partial f_e/\partial\mathbf{v} = \partial/\partial\mathbf{v} \bullet \boldsymbol{\Gamma}_{ql}$

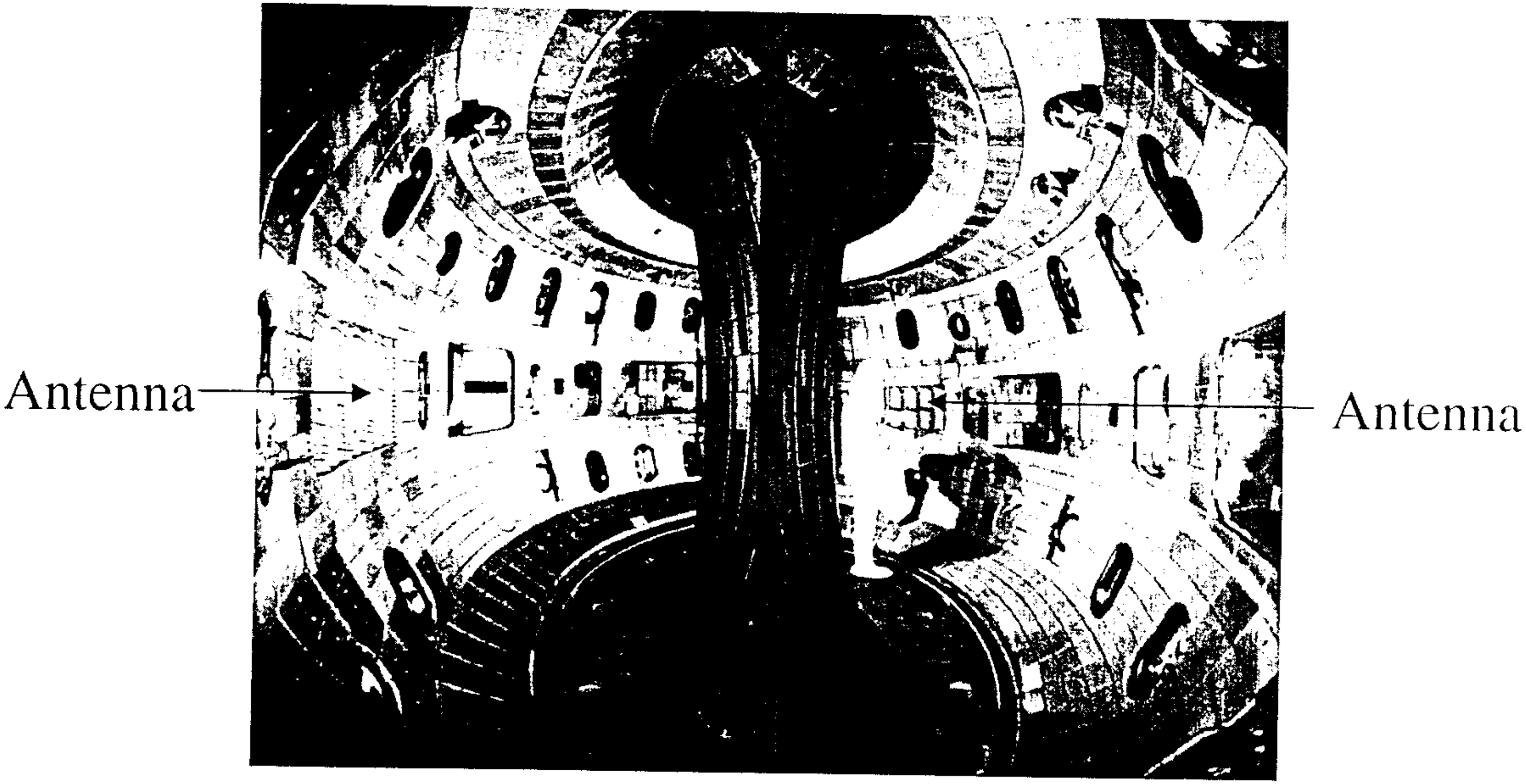
Linearize $C_{collision}$ and generate Green's function $g(v,v') \Rightarrow$
formal solution $f_e(v) = \int d^3v'\ g(v,v')\ \partial/\partial\mathbf{v'} \bullet \Gamma_{ql}(v')$

$\chi = \int d^3v\ qv_{\|}\, g(v,v')$ $\quad$ $\varepsilon = \int d^3v\ mv^2/2\ \ g(v,v')$
$J_{\|} = \int d^3v\ qv_{\|}\, f_e$ $\quad$ $P = \int d^3v\ mv^2/2\ f_e$
$\eta_{CD} = J_{\|}/P = \int d^3v\ \ \Gamma_{ql} \bullet \partial\chi/\partial\mathbf{v}\ \mathbf{/} \int d^3v\ \ \Gamma_{ql} \bullet \partial\varepsilon/\partial\mathbf{v}$ (after $\int$ by parts)

$\mathbf{D}_{ql} = D_0\delta(\omega - k_{\|}v_{\|})\,\mathbf{e}_{\|}\mathbf{e}_{\|}(2-x^2)^2 \quad x = v_{\perp}/(T_e/m_e)^{0.5}$ for near-Maxwellian
and Fast Wave dispersion relation (Ehst and Karney, Nucl. Fusion **31**, 1991)

$\eta_{FW} \propto T_e/(n_e \ln\Lambda) * f(Z_i,\varepsilon,\ldots.)$
where f is a function of ion charge, particle trapping, ...

# Most high frequency fast wave experiments have been performed in DIII-D using frequencies $\omega_{RF}/\Omega_D \approx 4\text{-}7$




The following DIII-D data is reproduced from the review article:
**Recent progress in ICRF physics**, by M. Porkolab, et al.
Plasma Phys. Control. Fusion **40** (1998) A35-A52

# Measured central driven current density is generally in good agreement with theory

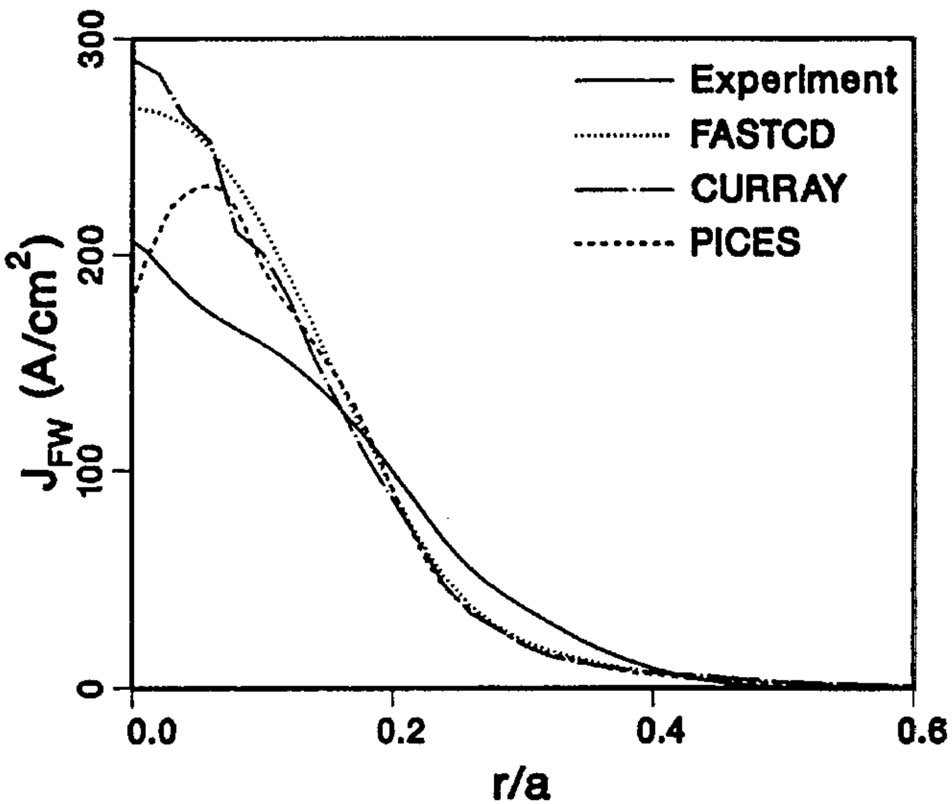



**Figure 10.** Radial profile of the non-inductive current density driven by FWs in DIII-D together with theoretical profiles ($B_T = 2.1$ T, $\bar{n} = 2.1 \times 10^{19}$ m$^{-3}$, $P_{fw} = 2.1$ MW).

Plasma Phys. Control. Fusion **40** (1998) A35-A52

# Current drive efficiency scales linearly with $T_e$

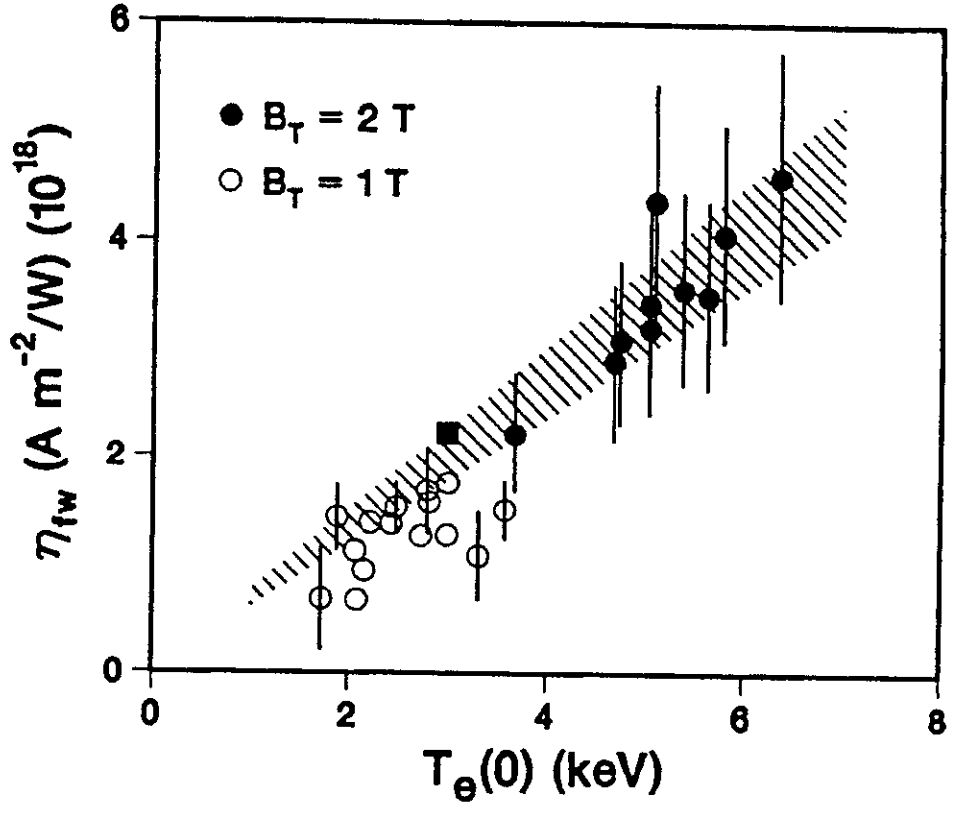



**Figure 11.** Experimental FWCD efficiency as a function of central electron temperature in DIII-D. The shaded band indicates the predictions from the CURRAY ray tracing code. The solid square represents data from Tore Supra [28].

Plasma Phys. Control. Fusion **40** (1998) A35-A52

# Fast ion stored energy increases near resonances

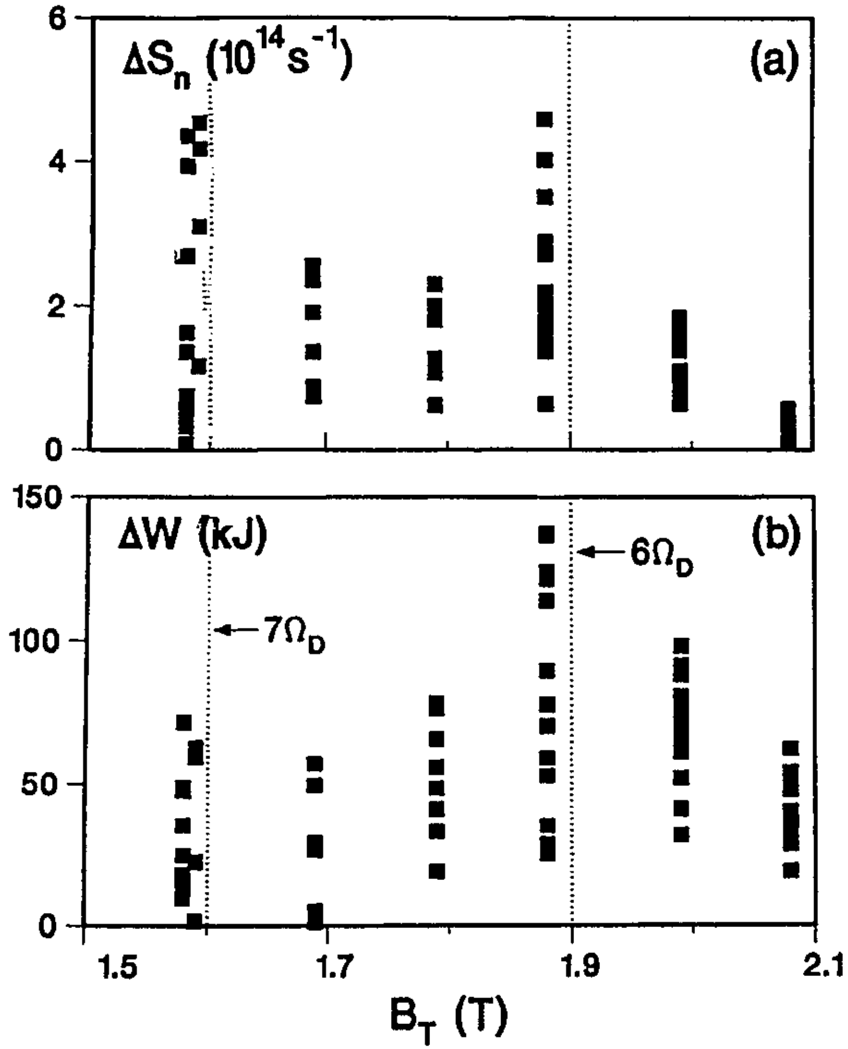



**Figure 12.** Toroidal magnetic field dependence of the (*a*) anomalous neutron rate and (*b*) anomalous fast-ion stored energy ($P_{NI} \approx 3.7$ MW, $P_{fw} \simeq 2.3$ MW).

Plasma Phys. Control. Fusion **40** (1998) A35-A52

# Ion absorption can significantly reduce effective current drive efficiency

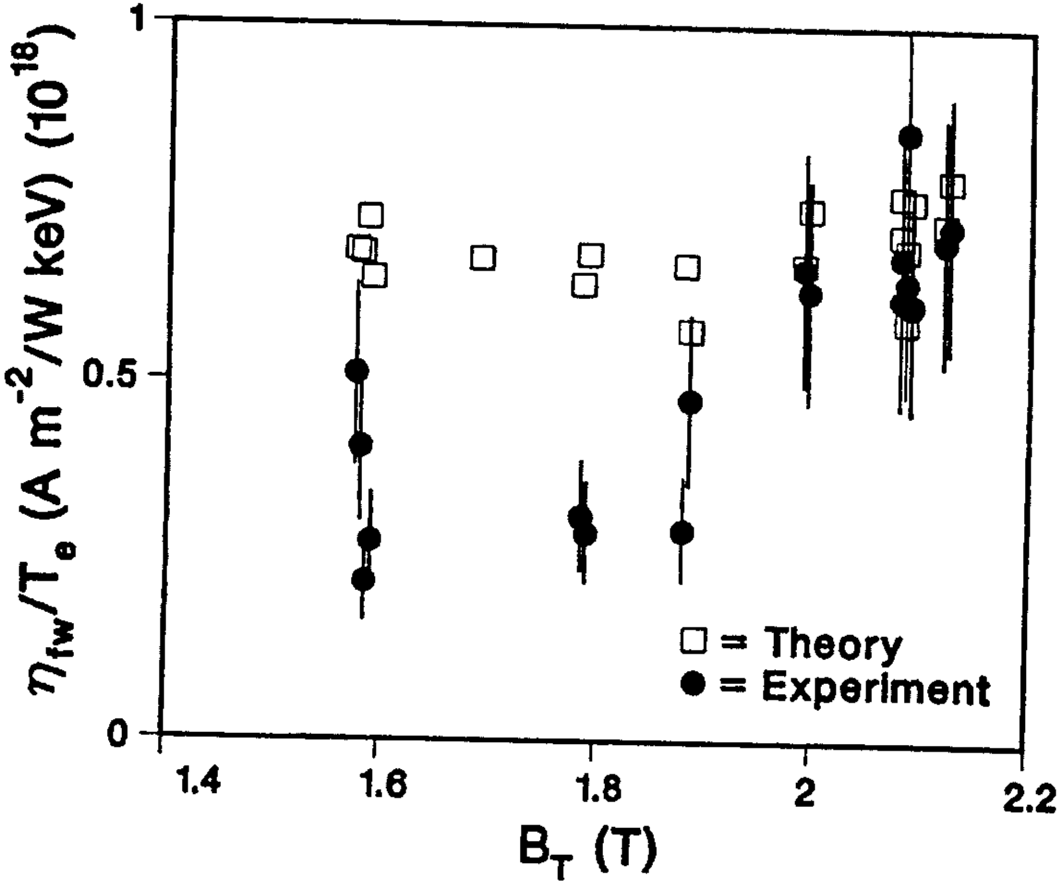



**Figure 13.** Toroidal magnetic field dependence of the FWCD efficiency normalized to the central electron temperature.

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# High edge density (H-mode) can lead to anomalous edge wave absorption ⇒ reduced FWCD

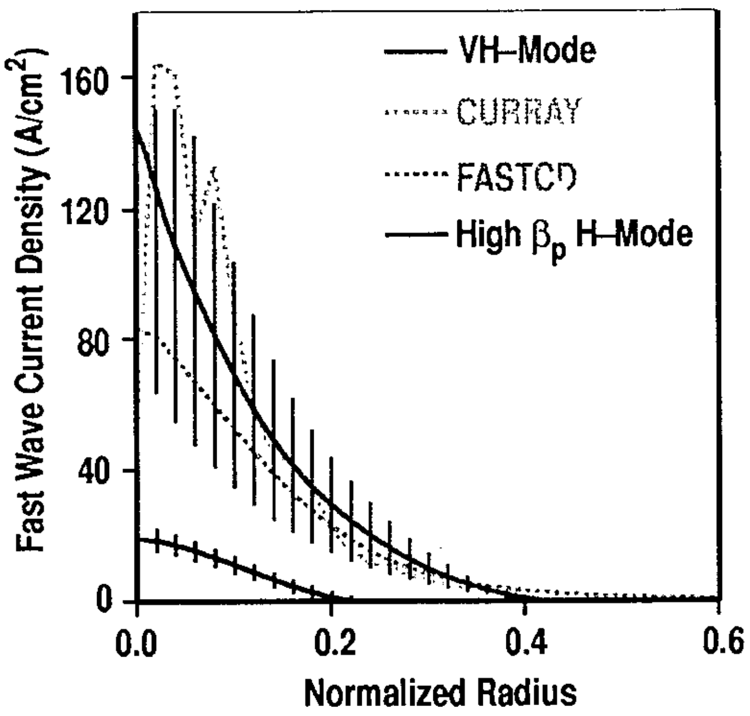



*Fig. 1. Radial profile of experimental and theoretical FWCD.*

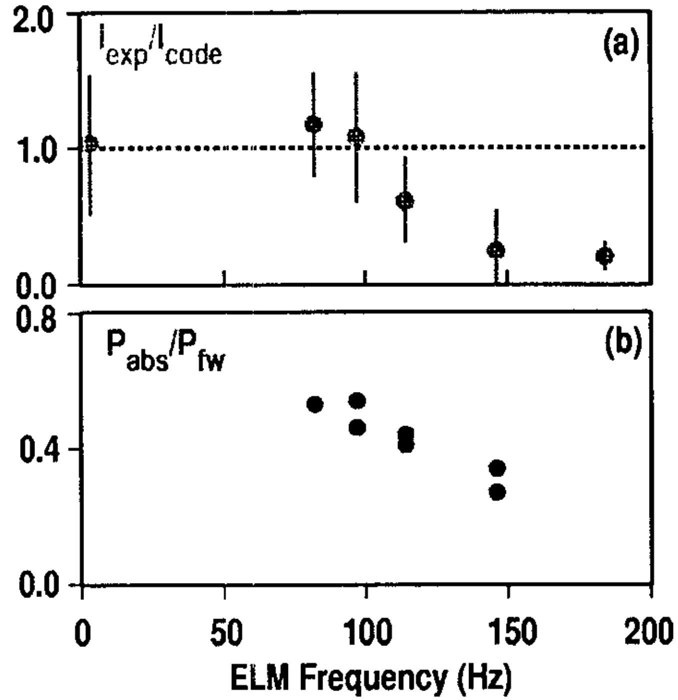



*Fig. 2. Dependence on ELM frequency of (a) experimental FWCD, normalized to the theoretical value, and (b) fraction of FWCD power absorbed by electrons.*

Data reproduced from:

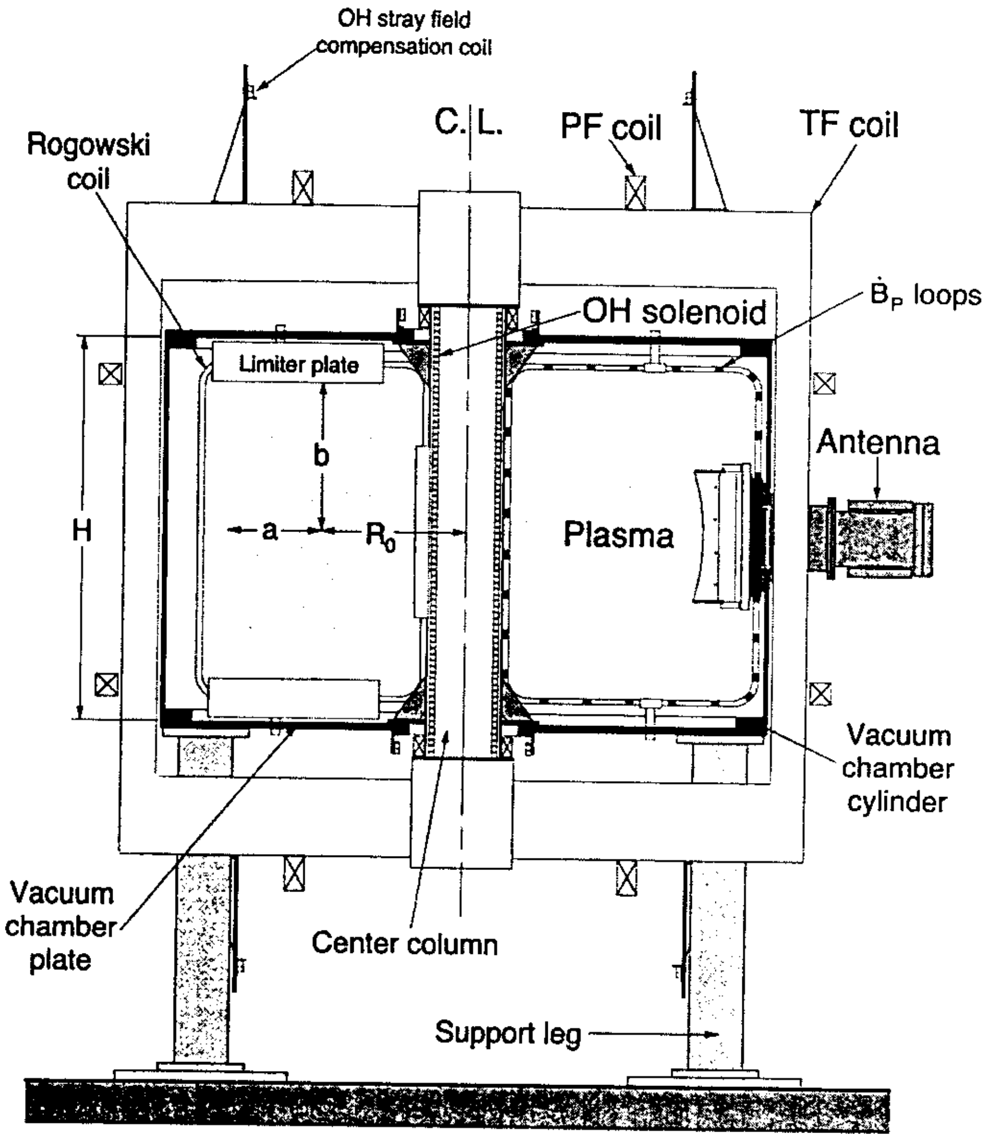

**DIII–D TECHNICAL BULLETIN**

Number 6 June 10, 1999 A23064

**Fast Wave Current Drive in H–Mode Plasmas**

**C.C. Petty, GA**

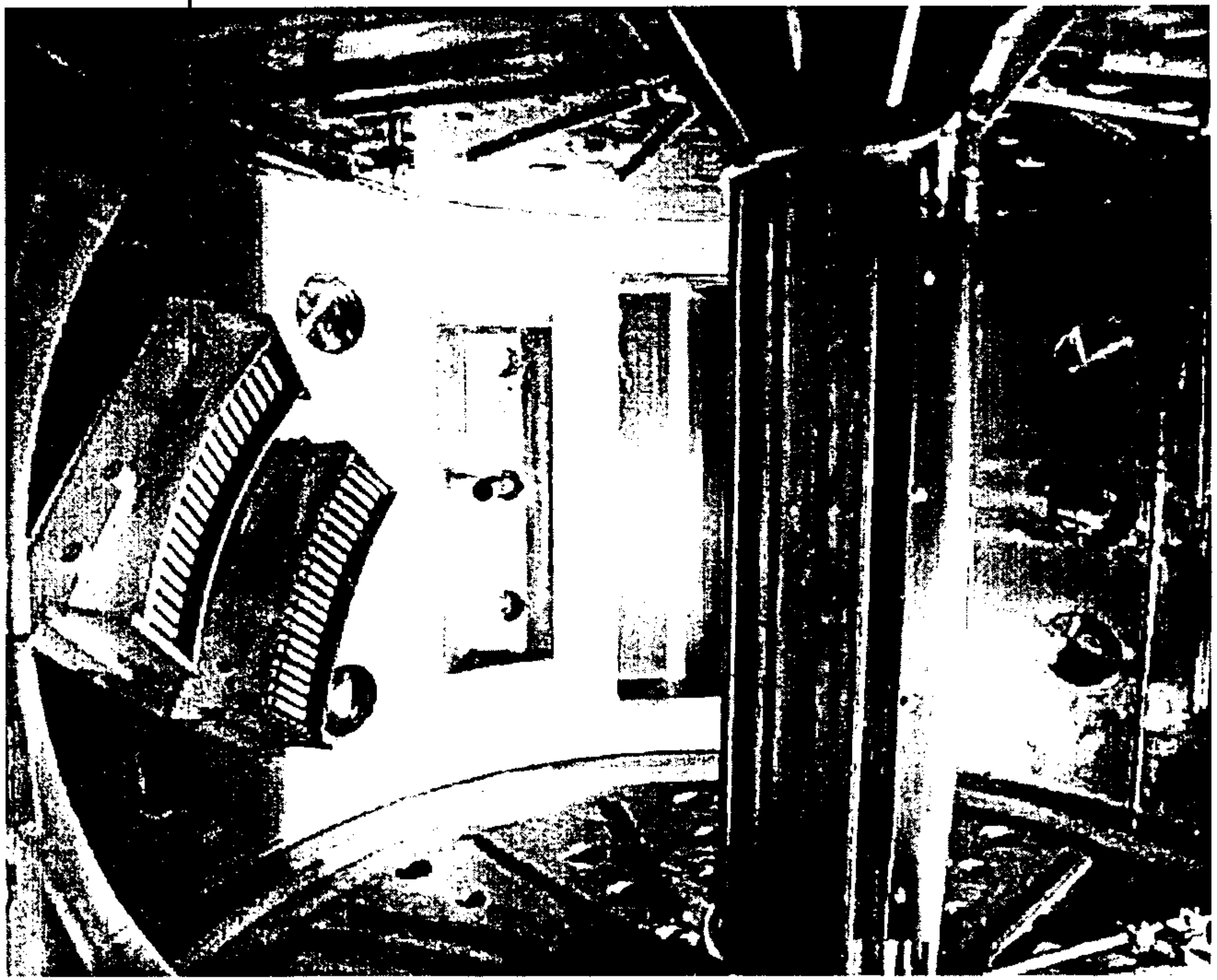
# The CDX-U device at PPPL has studied high-frequency fast wave heating in a spherical tokamak geometry



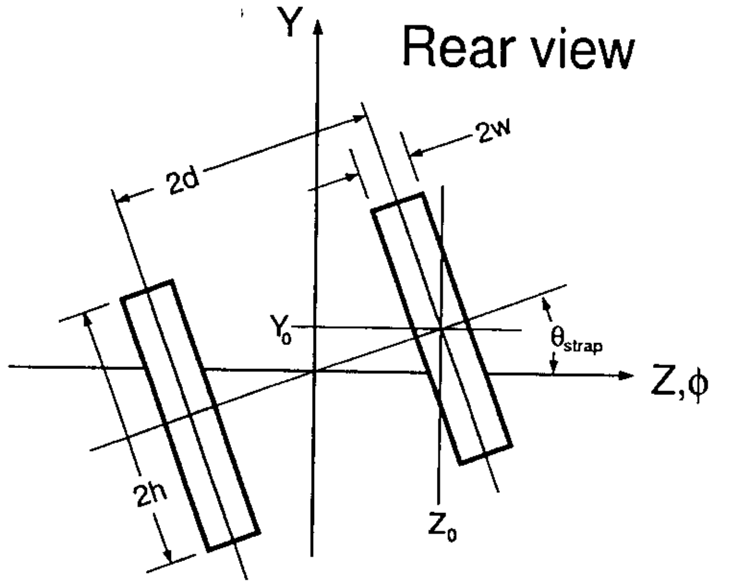

## Question:

Does the large poloidal field in an ST complicate coupling to the fast wave?

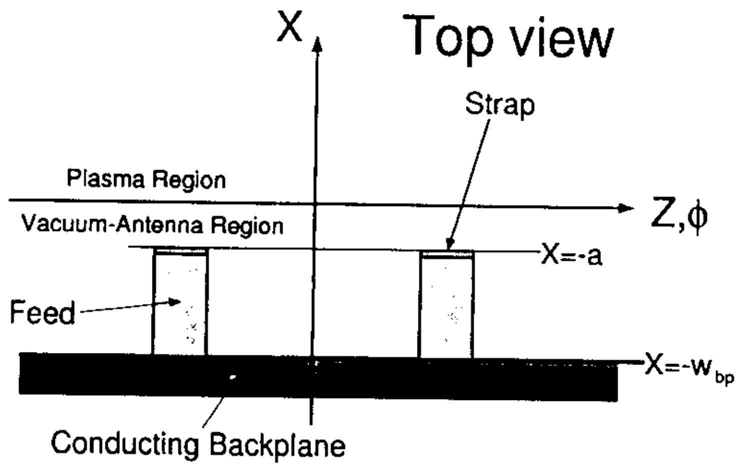
The rotatable fast wave antenna inside CDX-U is used to study FW coupling and heating physics



# Simplest possible model for computing fast wave radiation resistance (excitation efficiency)




Antenna Model




## Wave equations for fast wave fields in sheared-cylindrical plasma:

$$E_\perp = \rho \hat{E}_\perp \qquad 0 = \frac{d^2}{dx^2}\hat{E}_\perp + \Phi_{FW}\hat{E}_\perp$$

$$\rho = \sqrt{\frac{\Sigma}{x\sigma}} \qquad \Phi_{FW} = -\Sigma + \frac{D^2}{\sigma}$$

$$\Sigma = n_\perp^2 + n_\parallel^2 - S \qquad \sigma = \Sigma - n_\perp^2$$

$$n_\perp = \alpha_f n_y - \beta_f n_z \qquad n_\parallel = \alpha_f n_z + \beta_f n_y$$

$$\alpha_f = \cos\theta_f \qquad \beta_f = \sin\theta_f$$

$$cB_\perp = -\frac{\omega_0}{\omega} n_\parallel E_x \qquad cB_\parallel = \frac{\omega_0}{\omega}\left[n_\perp E_x + i\frac{d}{dx}E_\perp\right]$$

$$E_x = \frac{-i}{\Sigma}\left[n_\perp \frac{d}{dx}E_\perp + DE_\perp\right] \qquad cB_x = \frac{\omega_0}{\omega} n_\parallel E_\perp$$

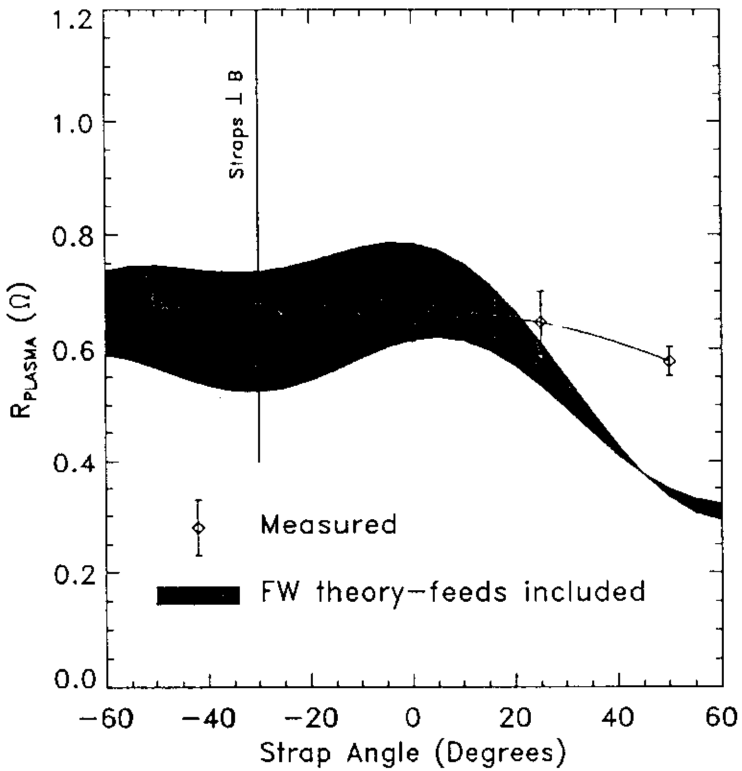
$$E_y = \alpha_f E_\perp + \beta_f E_\parallel \qquad E_\phi = \alpha_f E_\parallel - \beta_f E_\perp$$

$$cB_y = \alpha_f cB_\perp + \beta_f cB_\parallel \qquad cB_\phi = \alpha_f cB_\parallel - \beta_f cB_\perp$$

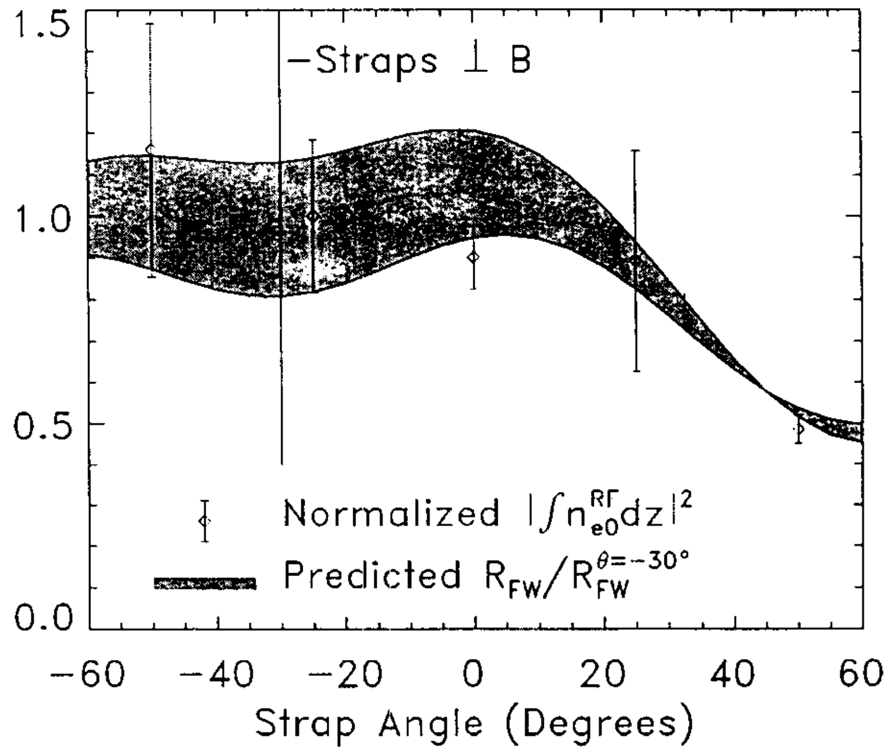
$$n_z = \frac{n}{x} \qquad E_\parallel = \frac{n_\parallel\left[ix\frac{d}{dx}\left(\frac{E_x}{x}\right) - n_\perp E_\perp\right]}{P - n_\perp^2}$$

# The simple CDX-U antenna can be treated accurately with an analytic model

Measured radiation resistance agrees with model for non-parallel straps




Core wave energy density drops when straps become parallel to B




Phys. Plasma, Vol. 6, No. 5, May 1999

# In CDX-U, a peaked heating profile is predicted, but a broad heating profile is typically measured

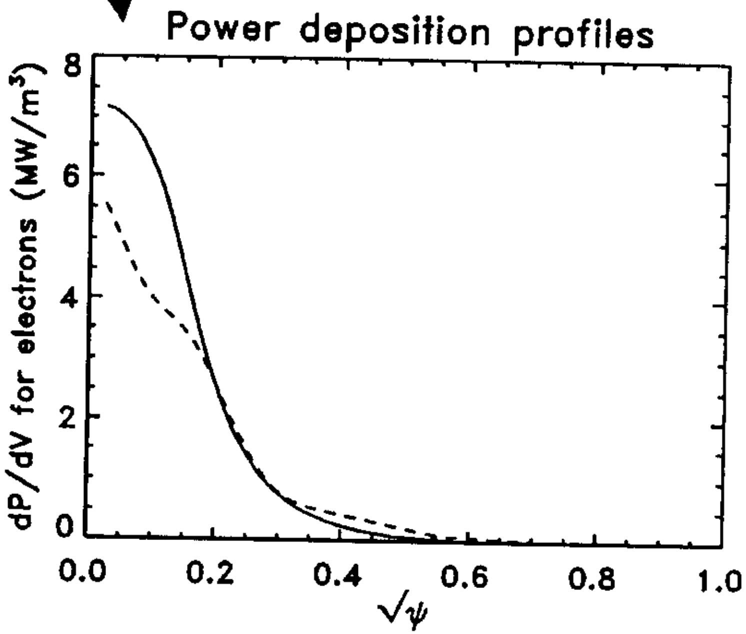
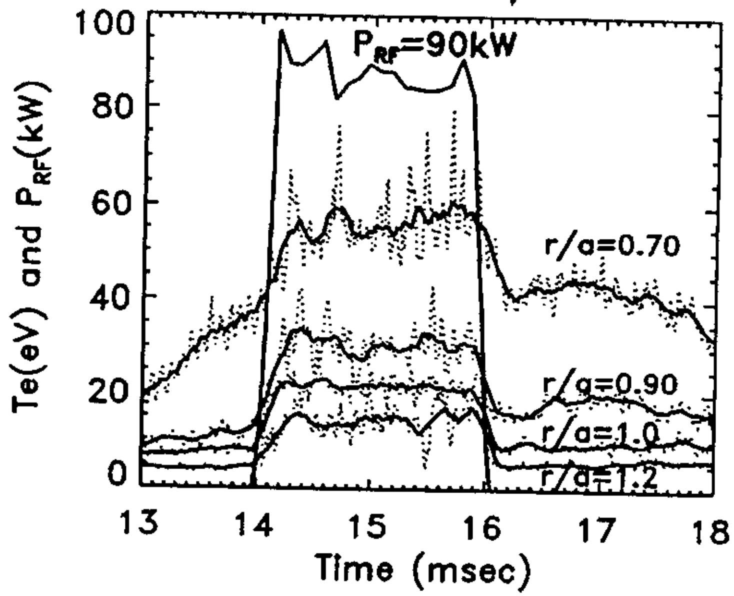



FIG. 6. Predicted power deposition profiles for electron heating in CDX-U computed using hot-electron ray tracing (solid line) and the TORIC full-wave code (dashed line) for an rf input power of 100 kW.




Phys. Plasma, Vol. 6, No. 5, May 1999

# Spectroscopy data shows strong core heating for some discharges (input power may be marginal)

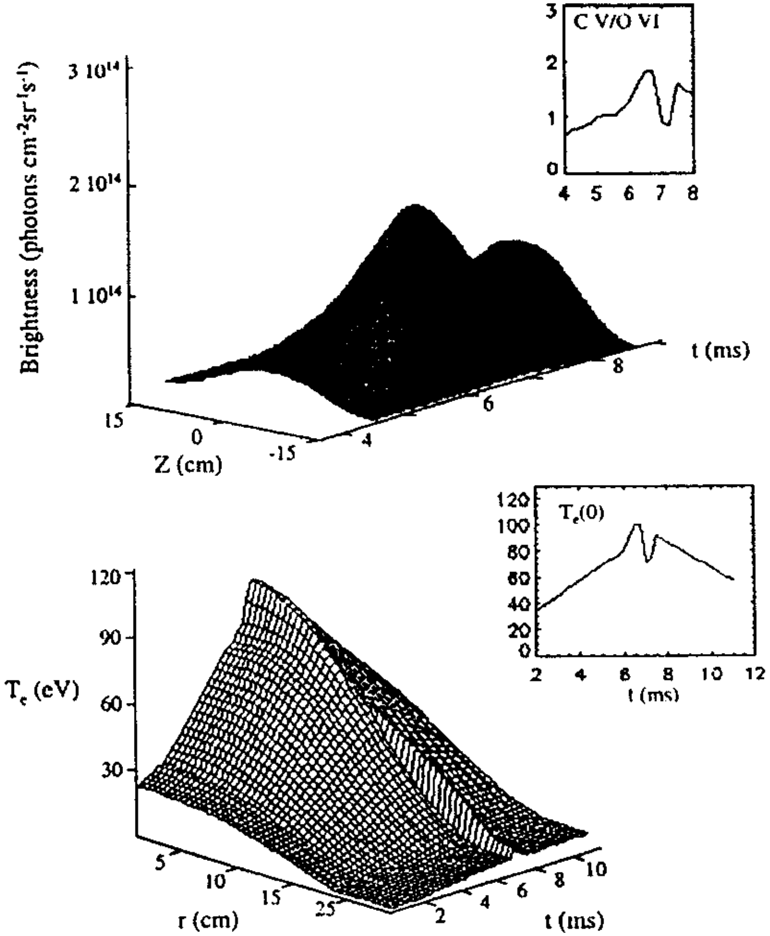



**Figure 4.** Computed spectroscopic signals and the temperature distribution for the ohmic discharge.

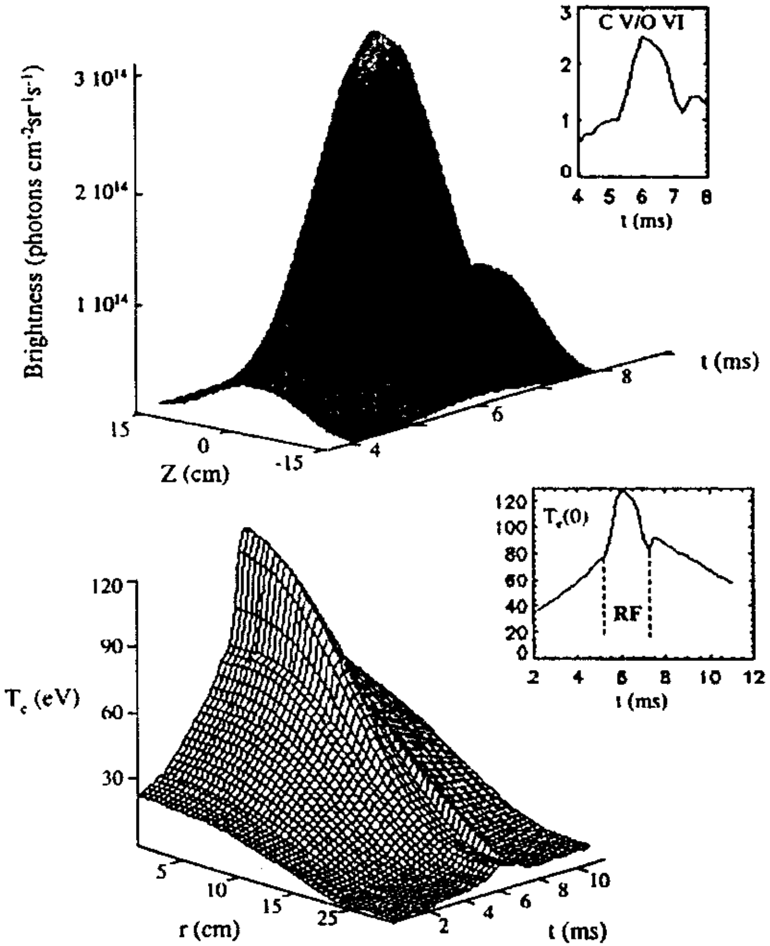
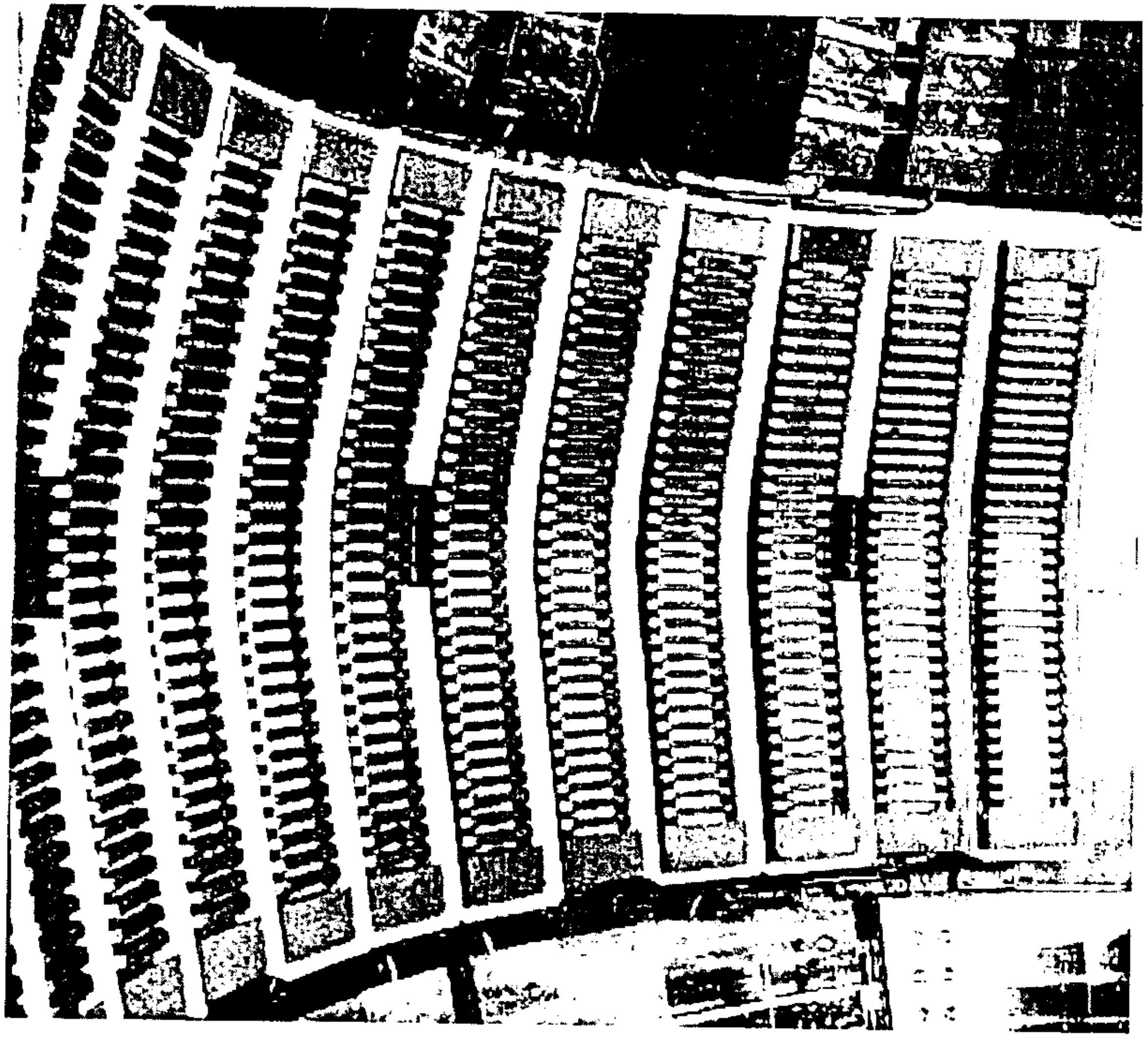



**Figure 5.** Computed signals and the estimated temperature evolution for the RF discharge.

Plasma Phys. Control. Fusion **41** (1999) 867-879

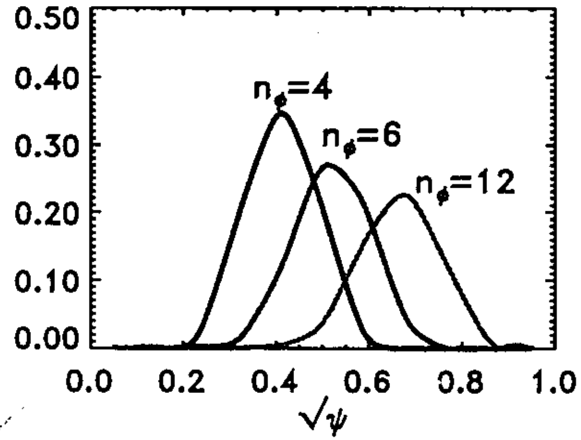
# 12 Strap HHFW Antenna Inside NSTX

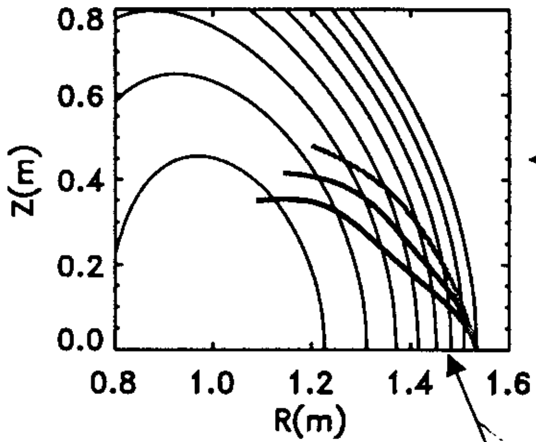


# 2D equilibrium effects are important in HHFW modeling

## Large $B_P$ in ST causes large poloidally directed wave power flow

(Strong $n_{||}$ upshift further enhances damping)

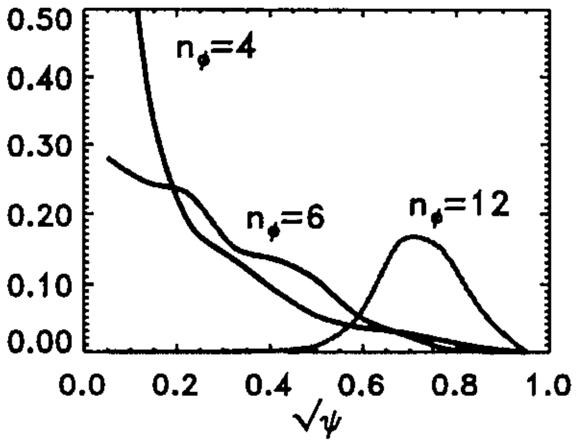


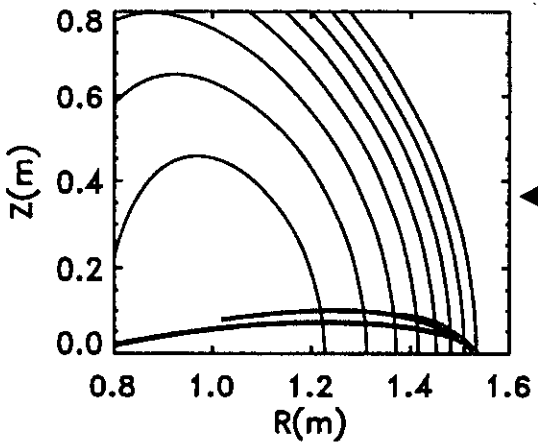




Cold ion ray tracing at β=30% in NSTX

$$\frac{1}{c}\frac{dZ}{dt} = \left[\frac{v_{g\perp}}{c}\left(\frac{k_Z - k_{||}\frac{B_Z}{B}}{k_{\perp r}}\right) + \frac{v_{g||}}{c}\frac{B_Z}{B}\right]$$

Power deposition profiles




Same, but $B_P$ reduced 90%

# Ion-Cyclotron Damping Modeling Issues:

- For B = 0.3 Tesla and $k_\perp = 200\ m^{-1}$, $k_\perp \rho_D = 1$ at $T_D = 55eV$
- At $T_D = 1500eV$, $\lambda_D \equiv \frac{(k_\perp \rho_D)^2}{2} \approx 14 \Rightarrow$ codes which expand in small $\lambda_D$ should be used with some caution
- And, resonances are at high harmonic number (15-20)

One plausible solution:

Satisfy full hot plasma dispersion relation along cold-ion ray trajectories using cold-ion $n_{||} \Rightarrow$ exact $\vec{E}$ polarization and damping (within WKB approximation) but approximate deposition profiles.

## Motivation:

Non-negligible ion damping $\Rightarrow$

- Reduced current drive
- Ion tail formation
- Possible fast ion losses

# Dielectric Tensor Elements for Hot Plasma

$$
\begin{aligned}
K_{xx} &= 1+\frac{\omega_{\rm pe}^2}{\omega_{\rm ce}^2} \\
&\quad +\sum_s \frac{\omega_{\rm ps}^2}{\omega^2}\sum_n \xi_{0,s} Z(\xi_{n,s})\, n^2\,\frac{W_n(\lambda_s)}{\lambda_s} \\
K_{xy} &= -K_{yx} \\
&= i\frac{\omega_{\rm pe}^2}{\omega\omega_{\rm ce}} + i\sum_s \frac{\omega_{\rm ps}^2}{\omega^2}\sum_n \xi_{0,s} Z(\xi_{n,s})\, n\, W_n'(\lambda_s) \\
K_{yy} &= K_{xx} - 2\,\lambda_e \frac{\omega_{\rm pe}^2}{\omega^2}\xi_{0,e} Z(\xi_{0,e}) W_0'(\lambda_e) \\
&\quad -2\sum_s \lambda_s \frac{\omega_{\rm ps}^2}{\omega^2}\sum_n \xi_{0,s} Z(\xi_{n,s}) W_n'(\lambda_s) \\
K_{zz} &= 1+\frac{\omega_{\rm pe}^2}{\omega^2}\, 2\,\xi_{0,e}^2\,\left(1+\xi_{0,e}Z(\xi_{0,e})\right) - \sum_s \frac{\omega_{\rm ps}^2}{\omega^2} \\
K_{yz} &= -K_{zy} \\
&= +i\frac{k_\perp}{k_\parallel}\frac{\omega_{\rm pe}^2}{\omega^2}\frac{\omega}{\omega_{\rm ce}}\left(1+\xi_{0,e}Z(\xi_{0,e})\right) \\
&\quad -i\frac{k_\perp}{k_\parallel}\sum_s \frac{\omega_{\rm ps}^2}{\omega^2}\frac{\omega}{\omega_{cs}}\sum_n \left(1+\xi_{n,s}Z(\xi_{n,s})\right) W_n'(\lambda_s) \\
K_{xz} &= K_{zx} \\
&= \frac{k_\perp}{k_\parallel}\sum_s \frac{\omega_{\rm ps}^2}{\omega^2}\frac{\omega}{\omega_{cs}}\sum_n \left(1+\xi_{n,s}Z(\xi_{n,s})\right)\, n\,\frac{W_n(\lambda_s)}{\lambda_s}
\end{aligned}
$$

- Complex $k_\perp \Rightarrow$ need complex Bessel functions
- Need 50-100 harmonics in sum
- Need complex root-finder capable of distinguishing between FW and ion-Bernstein branches near resonances at low $n_\parallel$

# Wave Power Absorption in WKB Approximation

Vlasov equation $\Rightarrow$

Time average

$$\left\langle \frac{\partial}{\partial t}\int \frac{m_s v^2}{2} f_{2s}\, d^3v \right\rangle + \left\langle \nabla \bullet \int \frac{m_s v^2}{2} \vec{v}\, f_{2s}\, d^3v \right\rangle = \left\langle \vec{E}_1 \bullet \vec{J}_{1s} \right\rangle$$

(The equivalence of these terms is **assumed**)

$$\frac{\partial}{\partial t} W_{ps} \quad + \quad -2k_{\perp i} \bullet T_{\perp s} = \frac{1}{2}\omega\varepsilon_0 \vec{E}^* \bullet \overleftrightarrow{\varepsilon}_{As} \bullet \vec{E}$$

Field amplitude

$$\frac{\partial P_s}{\partial V} = \frac{1}{2}\omega\varepsilon_0 \left[ \vec{E}^* \bullet \overleftrightarrow{\varepsilon}_{As} \bullet \vec{E} - n_{\perp i} \vec{E}^* \bullet \frac{\partial \overleftrightarrow{\varepsilon}_{Hs}}{\partial n_{\perp r}} \bullet \vec{E} \right]$$

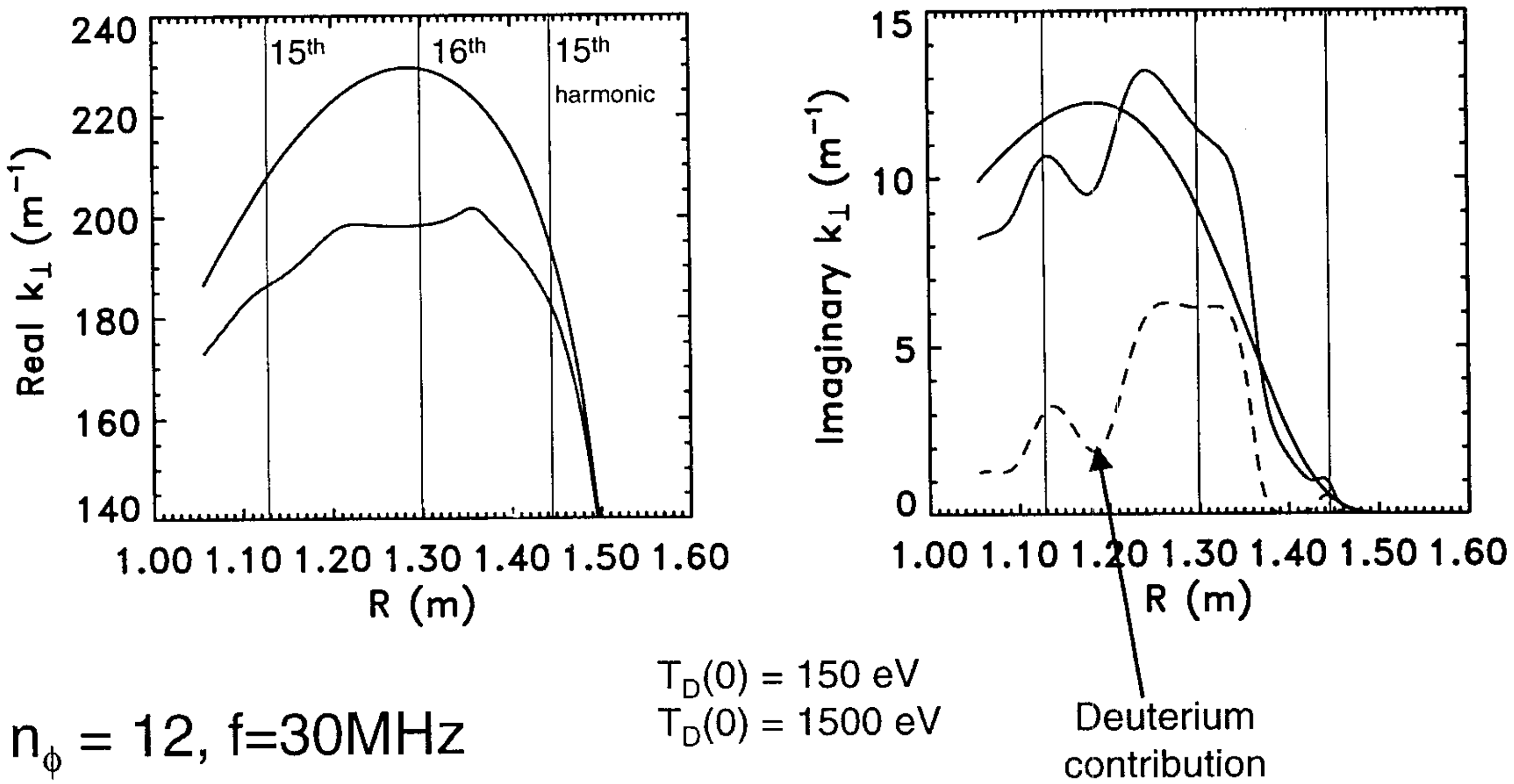
Volumetric power absorption for species s

Full hot plasma $\overleftrightarrow{\varepsilon}$ and $\vec{E}$ evaluated with complex $\vec{k}$

# Effect of $T_D$ on wave-number

Finite ion temperature reduces $k_{\perp r}$

Average magnitude of $k_{\perp i}$ similar, but split between species

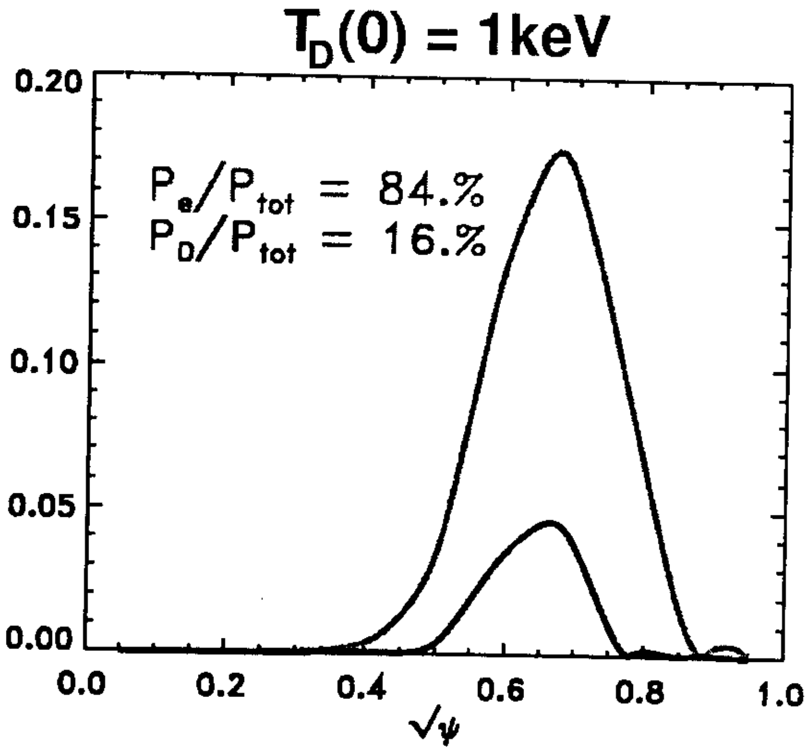


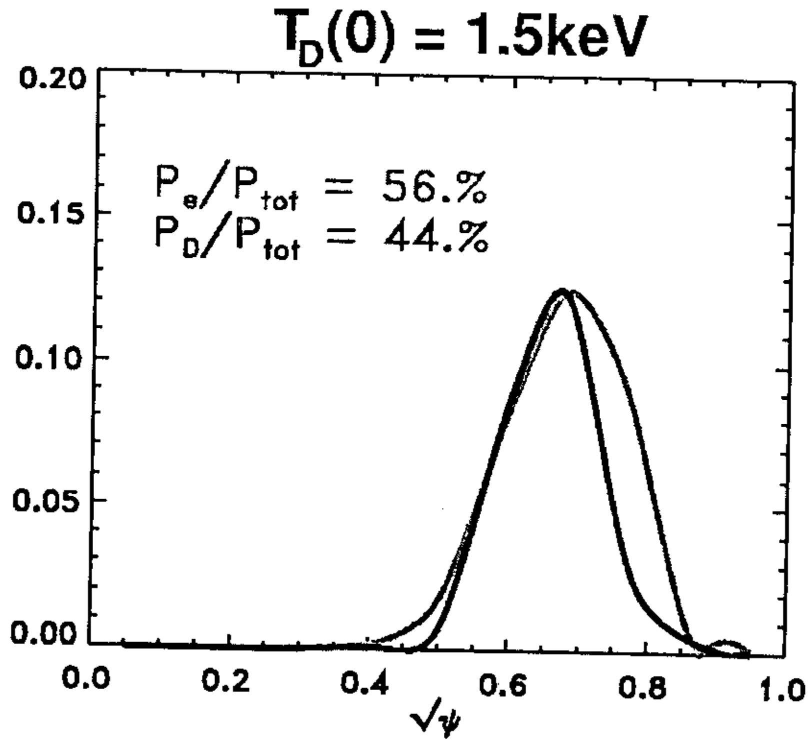

$n_\phi = 12$, f=30MHz

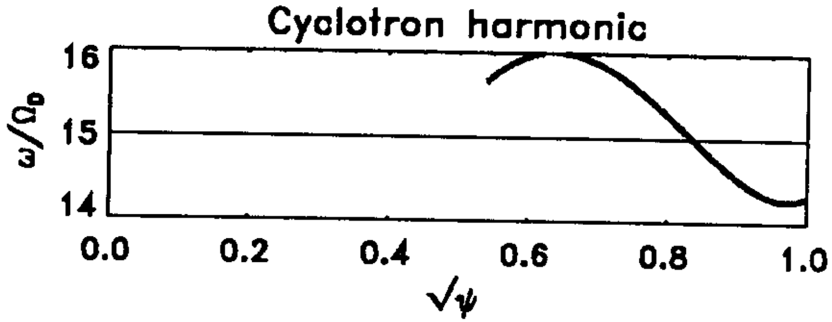
$T_D(0) = 150$ eV
$T_D(0) = 1500$ eV

$T_e(0) = 1500$ eV

# Bulk ion absorption competes with electron damping for temperatures above 1keV



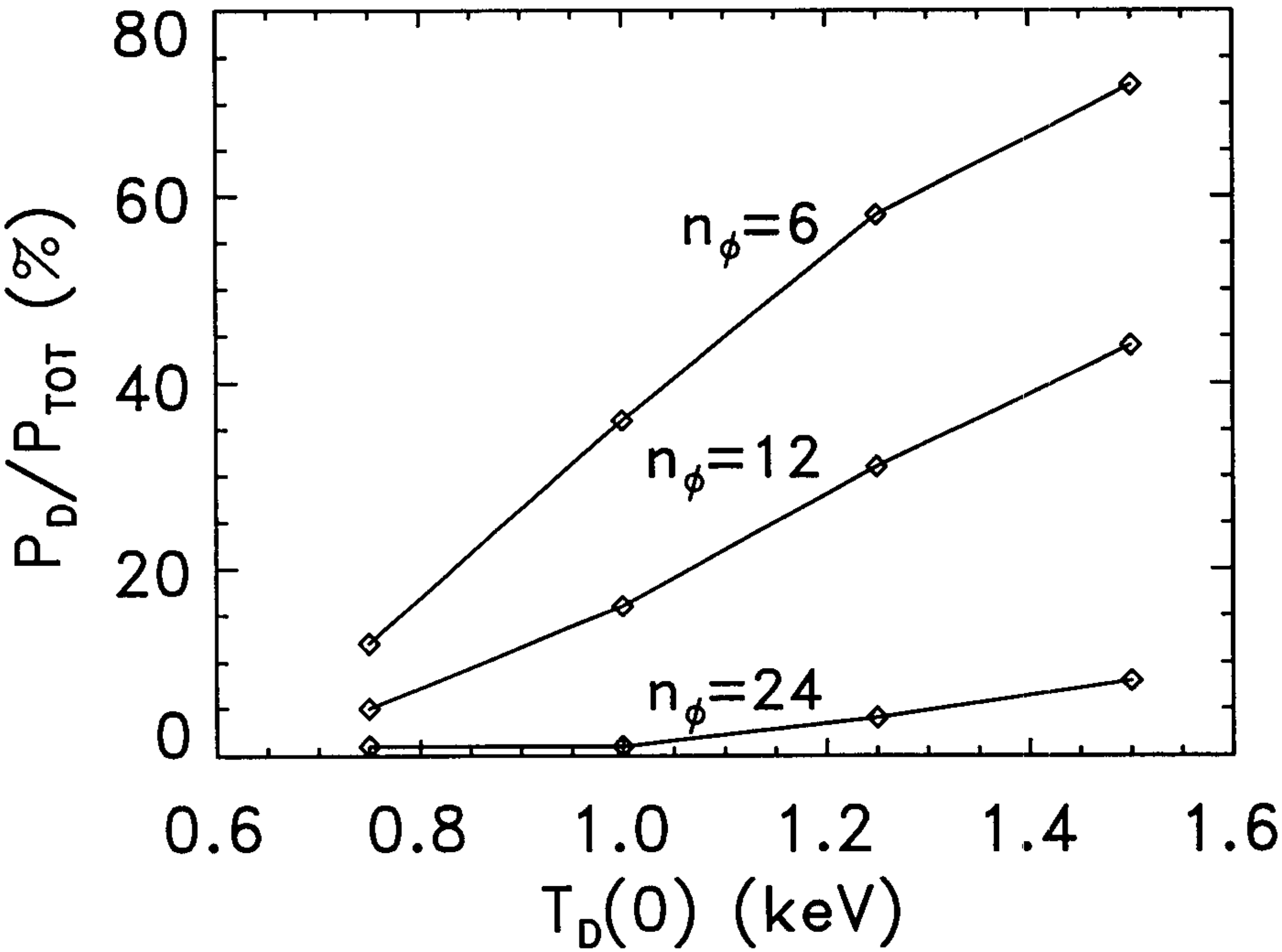




$n_\phi$ = 12 (90° phasing) for both cases

$T_e(0)$ = 1.5keV

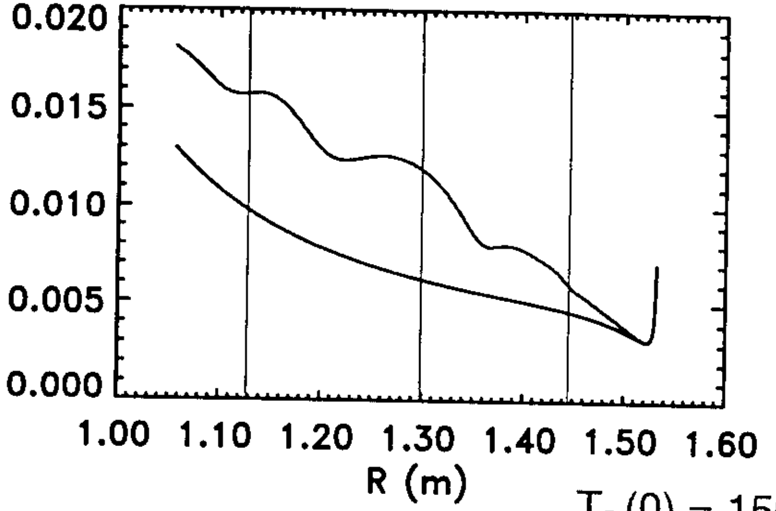
# Deuterium ion absorption shows strong launched toroidal mode number ($n_\phi$) dependence




Lower phase velocity broadens and weakens the ion resonances

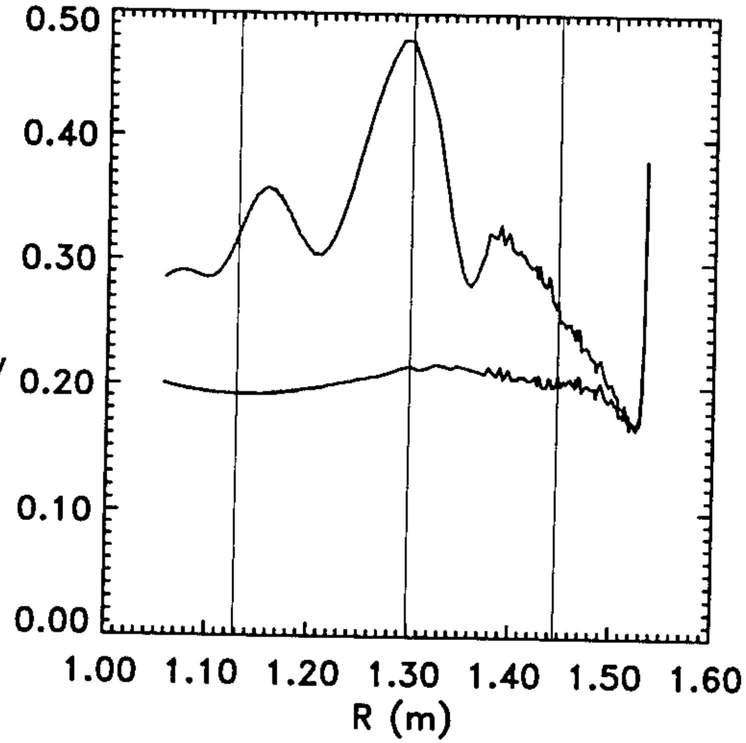
# Use of hot electron - cold ion ray trajectory may be inaccurate at high ion temperature

$P_\perp + T_\perp$



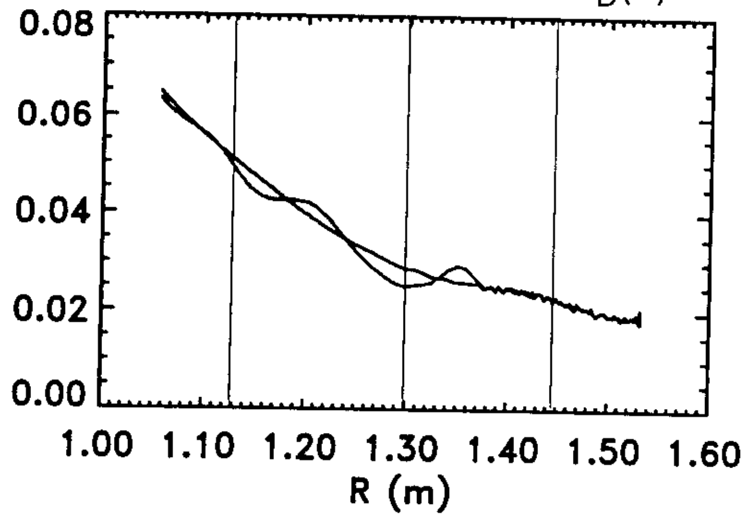

**Ion perpendicular kinetic flux changes energy propagation direction**

$(P_\perp + T_\perp)/(P_{||} + T_{||})$




$T_D(0)$ = 150 eV
$T_D(0)$ = 1500 eV

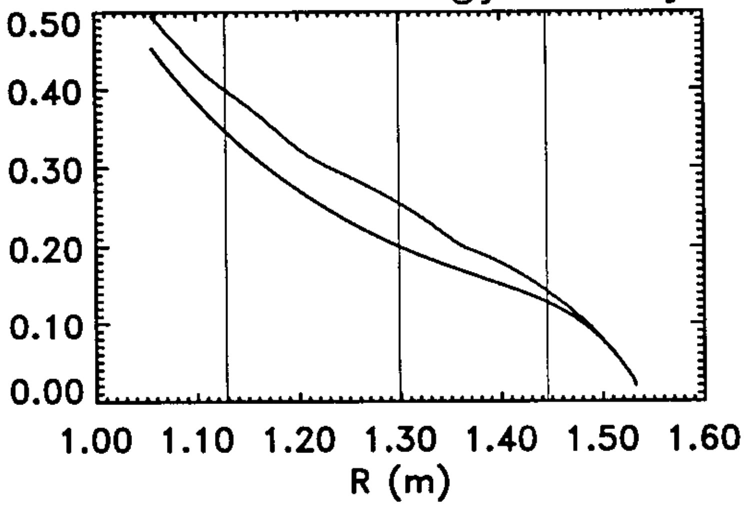
$P_{||} + T_{||}$



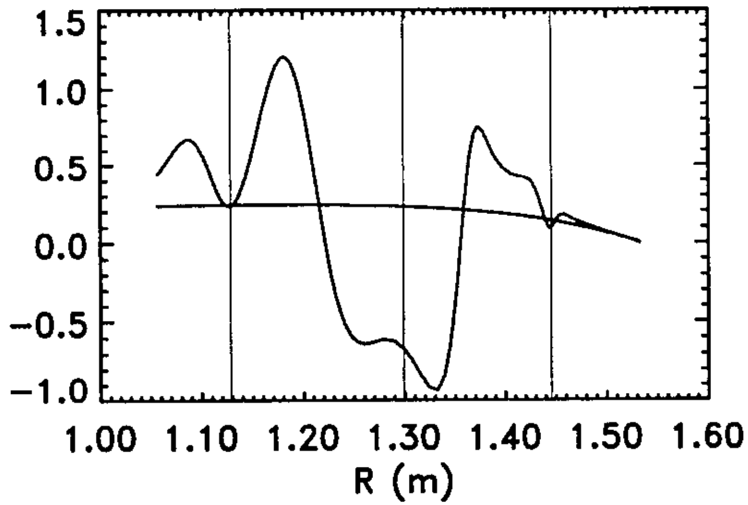

$n_\phi = 12$, f=30MHz
Fluxes normalized to $|\vec{E}| = 1$V/m

# Standard "definition" of perturbed plasma kinetic energy density can become negative with hot ions

Wave-field energy density



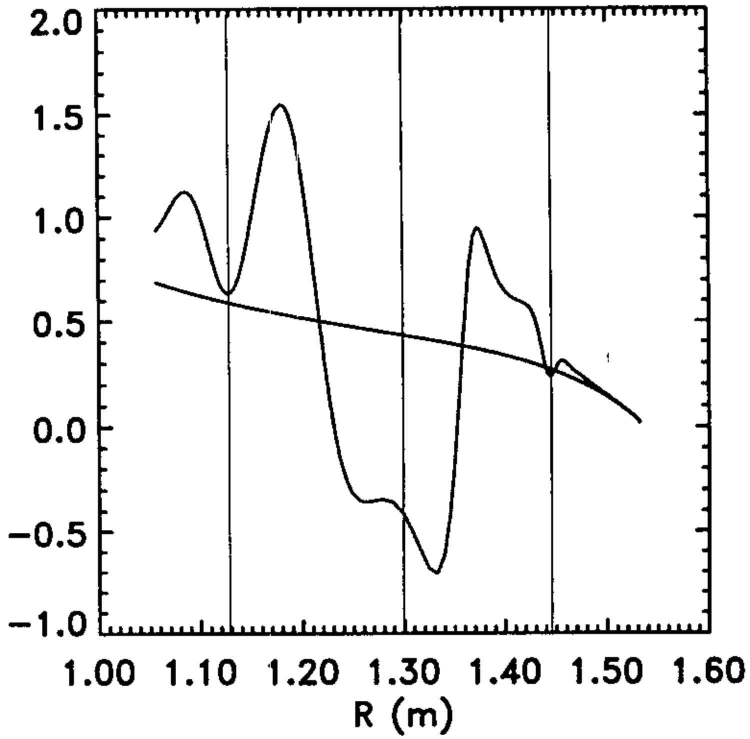

Plasma kinetic energy density




Equation for perturbed plasma kinetic energy density (which can become negative):

$$W_{ps} = \frac{1}{4}\,\varepsilon_0\,\vec{E}^{*}\bullet\frac{\partial}{\partial\omega}(\omega\overleftrightarrow{\chi}_{Hs})\bullet\vec{E}$$

Total energy density




$T_D(0)$ = 150 eV
$T_D(0)$ = 1500 eV

$n_\phi$ = 12, f=30MHz

Fluxes normalized to $|\vec{E}|$ = 10kV/m

Negative energy density near cyclotron harmonics $\Rightarrow$ oscillatory group velocity $\Rightarrow$

**Hot ion ray tracing on a strongly complex dispersion relation is ill-posed**

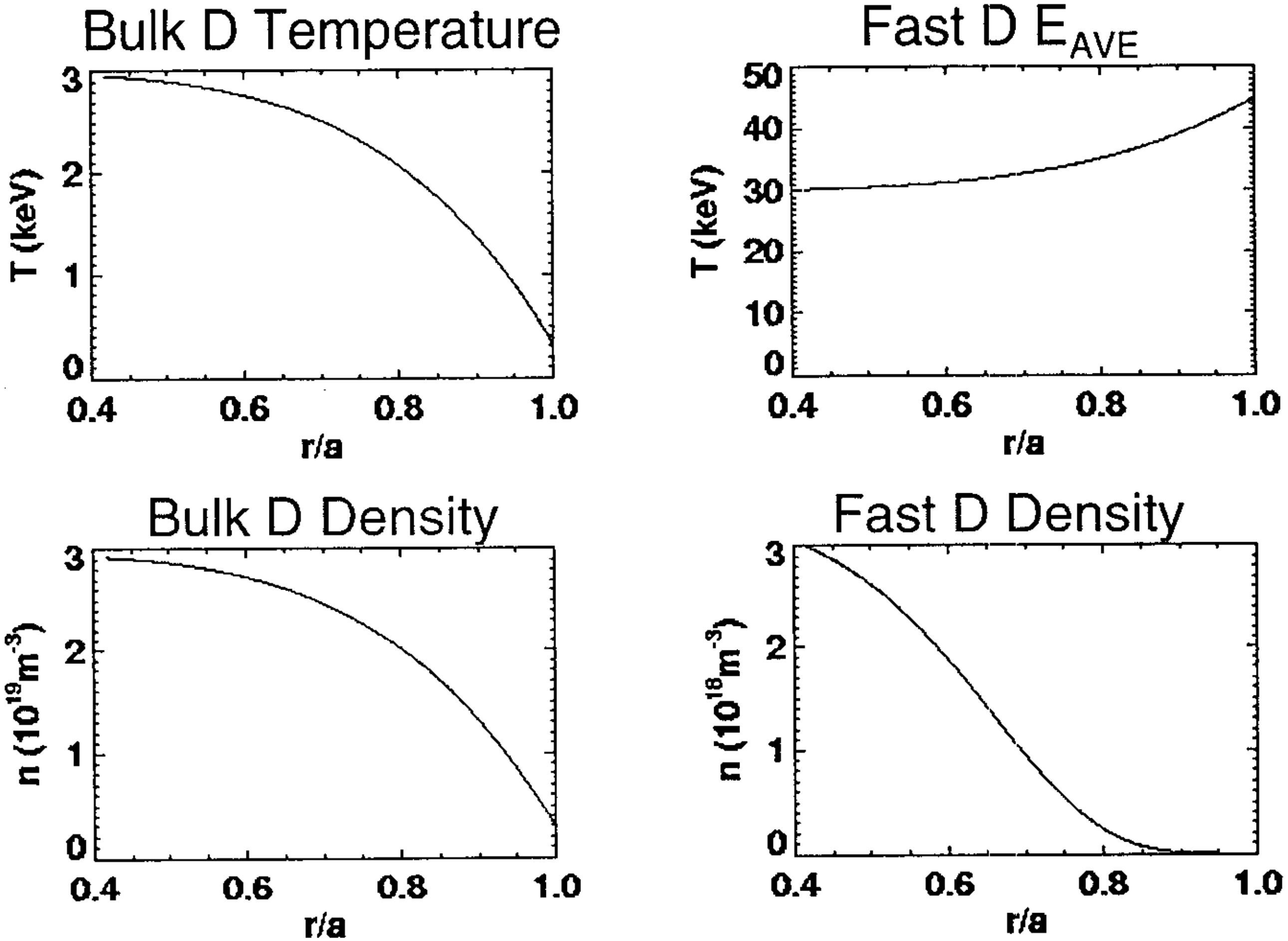
Possible solution: re-normalize power flux $\Rightarrow$

Ray-trace using
$$\frac{\left\langle \vec{P} \right\rangle + \sum_s \left\langle \int \frac{m_s v^2}{2} \vec{v}\, f_{2s}\, d^3v \right\rangle}{\left\langle W_{\text{field}} \right\rangle + \sum_s \left\langle \int \frac{m_s v^2}{2} f_{2s}\, d^3v \right\rangle}$$
as group velocity

In other words, compute the power flow velocity explicitly from the RF perturbed distribution function, fields, and Poynting flux

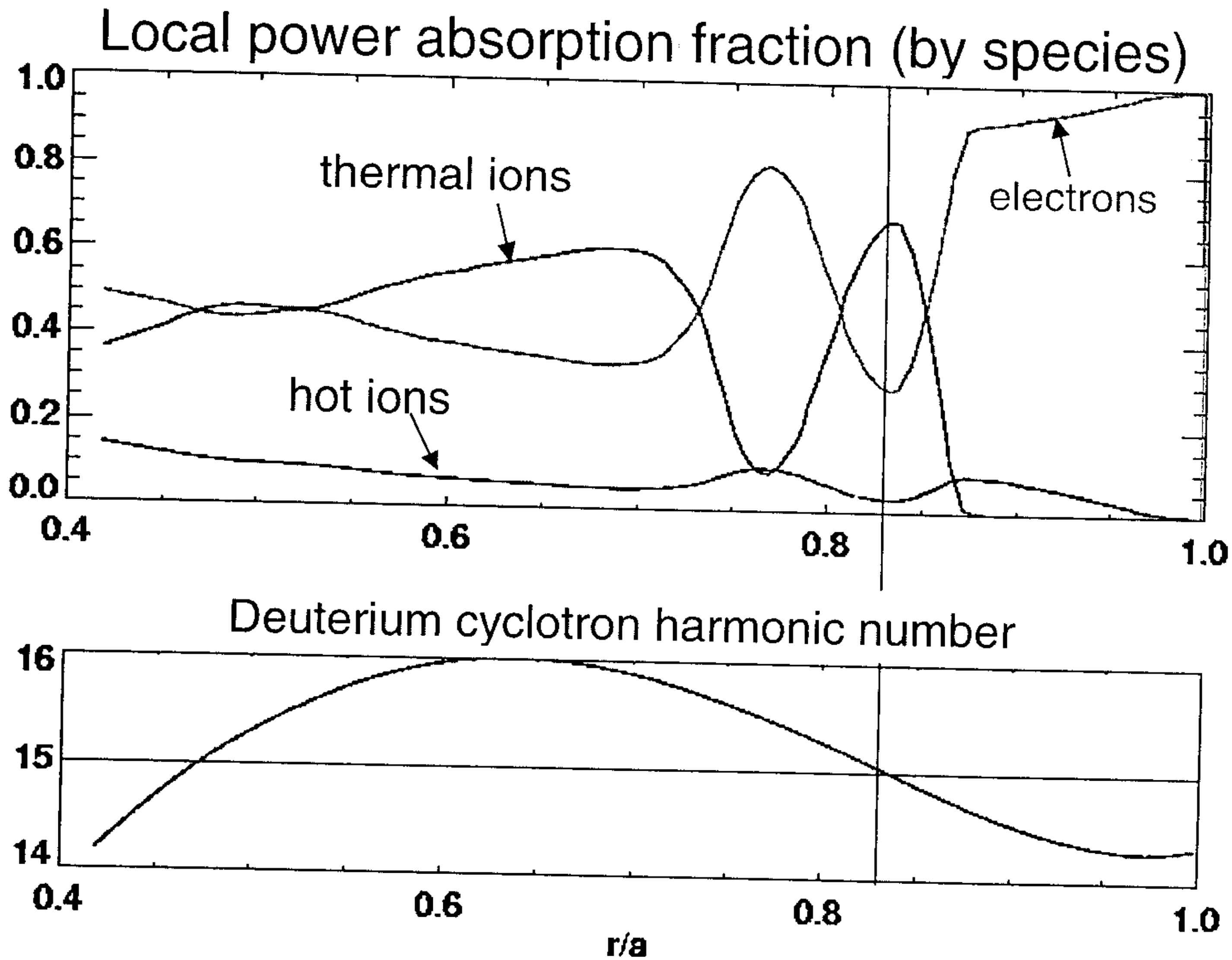
# What about interactions with beam ions?

Treat NBI fast ions as hot thermal species using approximate profiles from β=40% TRANSP run




$T_e(0)$ = 2.5keV, $E_{BEAM}$=80keV, $P_{BEAM}$=5MW

# NBI ions absorb < 5% of incident HHFW power




$T_e(0) = 2.5\text{keV}$, $n_\phi = 12$, $P_D/P_{TOT} \approx 50\%$

# Summary

• DIII-D has shown that high frequency fast waves can be used to heat electrons and drive current on-axis in accordance with theory.

• CDX-U has shown efficient fast wave coupling in an ST.

• Controllable <u>off-axis</u> power deposition and current drive is predicted for high-harmonic fast waves in NSTX.

• At high ion $\beta$, ion absorption becomes competitive with electron absorption, and should be strongly dependent on launched toroidal mode number.

# Summary (continued)

- Cold ion ray trajectories are potentially inaccurate because of the large ion kinetic flux at high ion $\beta$.

- Ray-tracing theory with hot thermal ions breaks down at high ion $\beta$ is not (necessarily) because of mode conversion to IBW waves, but because of problems in computing the perturbed particle kinetic energy density from the dispersion relation near cyclotron harmonics.
- Re-normalization of the total power flux may remove this difficulty.

- Unlike DIII-D, absorption on NBI generated fast ions in an ST is predicted to be small $\Leftrightarrow$ fast ion $\beta$ is small and wave phase velocity too slow to damp on fast ions.