Physics and Applications of Electron Cyclotron Heating and Current Drive

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GENERAL ATOMICS

Why Electron Cyclotron Waves?

- **Effective source of highly localized and controlled heating and current drive**
  - electron heating
  - current profile control and sustainment in tokamaks
  - control of MHD activity
- **Coupling is EASY because the wave propagates in vacuum**
  - launchers far from the plasma
  - insensitive to plasma edge conditions
  - no impurity generation
- **Power density can be very high (10^9 W/m^2) => small antennas**
- **EC technology (gyrotron, transmission) is well developed**
- **Theory is well validated by experiment**

What are Electron Cyclotron Waves?

- **Electromagnetic waves with frequency near the electron cyclotron frequency or its low harmonics h:**

$$\omega = h\,\Omega_e = h\frac{eB}{m}, \quad f = 28\,h\,B_{Tesla}\ \mathrm{GHz}, \quad h = 1,2,3,\ldots$$

- **Useful concepts**
  - $n_{\parallel}$ = parallel index of refraction $= c/v_{\parallel}$
  - θ = angle between wavevector $\vec{k}$ and magnetic field $\vec{B}$
  - $\omega_p = n_e e^2/\varepsilon_0 m$ = plasma frequency

Cold Plasma Dispersion Relation Describes EC Waves Fairly Well for Most Conditions

$$D(\omega,\vec{k},\vec{r}) = \tan^2\theta + \frac{P(n^2 - R)(n^2 - L)}{(Sn^2 - RL)(n^2 - P)} = 0$$

Chapter 1, Stix' book

where $P = 1 - (\omega_p/\omega)^2$,

$$R = (P - \Omega_e/\omega)/(1 - \Omega_e/\omega),$$

$$L = (P + \Omega_e/\omega)/(1 + \Omega_e/\omega),$$

$$S = (R + L)/2$$

Propagation is where $n^2 > 0$

Cutoff is where $n^2 = 0$

Resonance is where n^2 is extremely large

Absorption is not described in the cold plasma model

There are two normal modes in a magnetized plasma

$$D(\omega,\vec{k},\vec{r}) = \tan^2\theta + \frac{P(n^2-R)(n^2-L)}{(Sn^2-RL)(n^2-P)} = 0$$

- **For θ = π/2 (perpendicular propagation) there are two solutions:**
  - $n^2 = P$ ("**ordinary mode" = O-mode**)
  - $n^2 = RL/S$ ("**extraordinary mode" = X-mode**)
- **For θ=0 (parallel propagation) these two solutions become**
  - $n^2 = L$ (O-mode; left-hand circularly polarized)
  - $n^2 = R$ (X-mode; right-hand circularly polarized)
- **These two waves are the complete set of normal modes**
- **Consider phase and group velocities (eg, O-mode):**

$$v_{phase} \equiv \frac{\omega}{k} \equiv \frac{c}{n} = \frac{c}{\sqrt{1-\omega_{pe}^2/\omega^2}} > c, \qquad v_{group} \equiv \frac{\partial\omega}{\partial k} = c\sqrt{1-\omega_{pe}^2/\omega^2} < c$$

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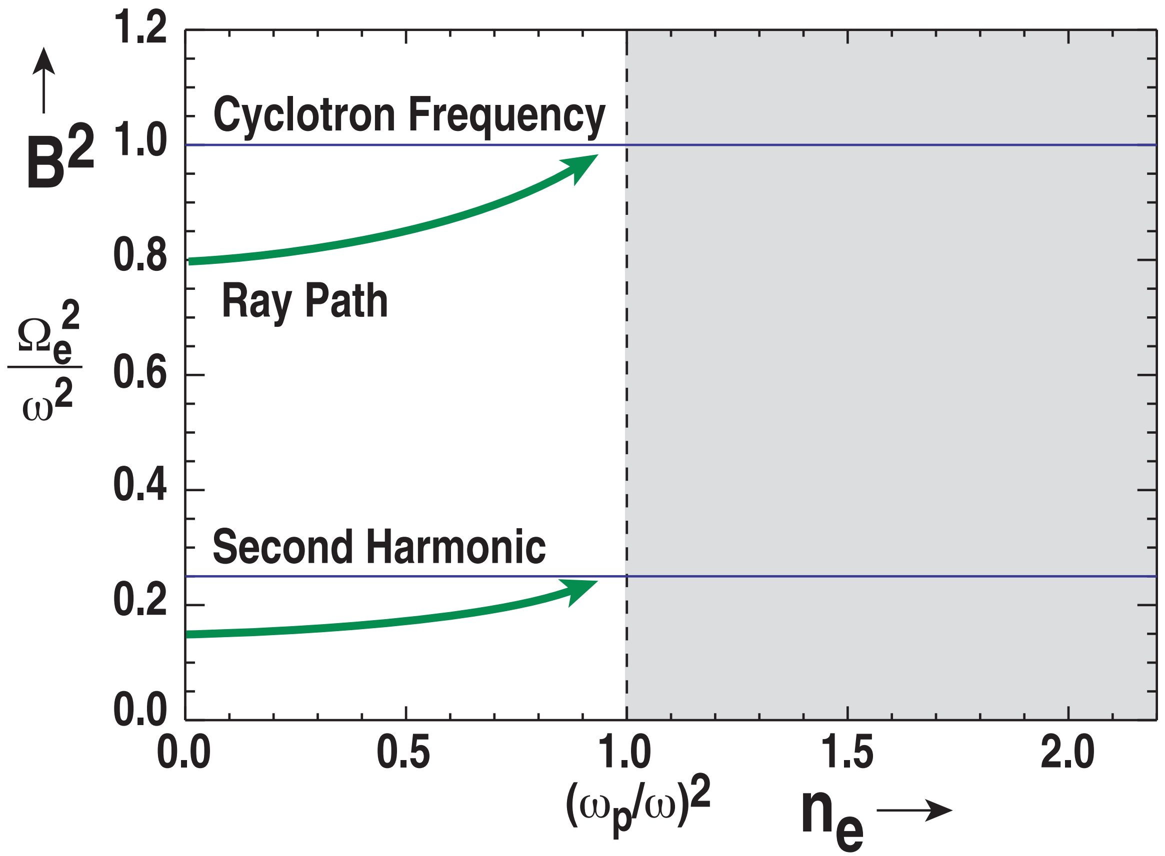
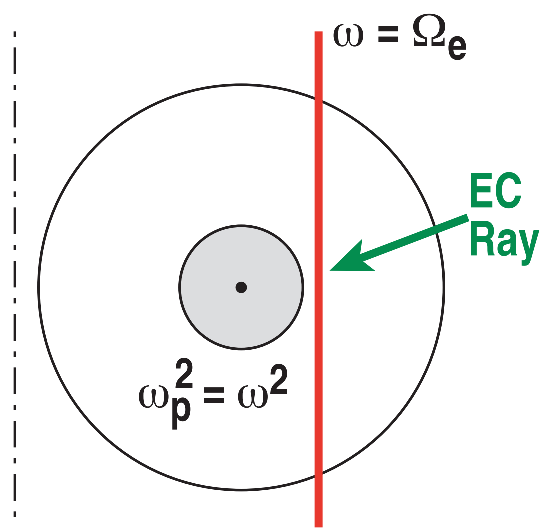
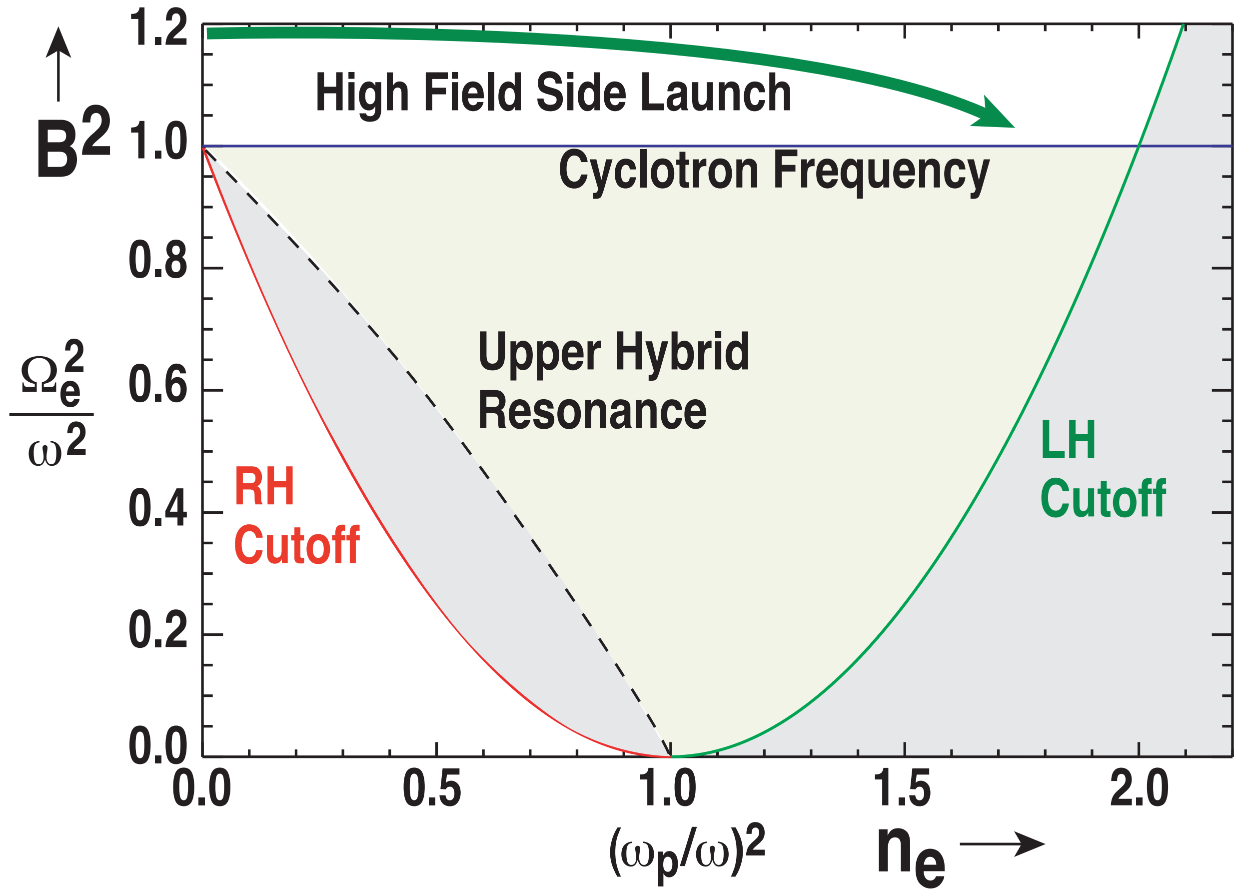
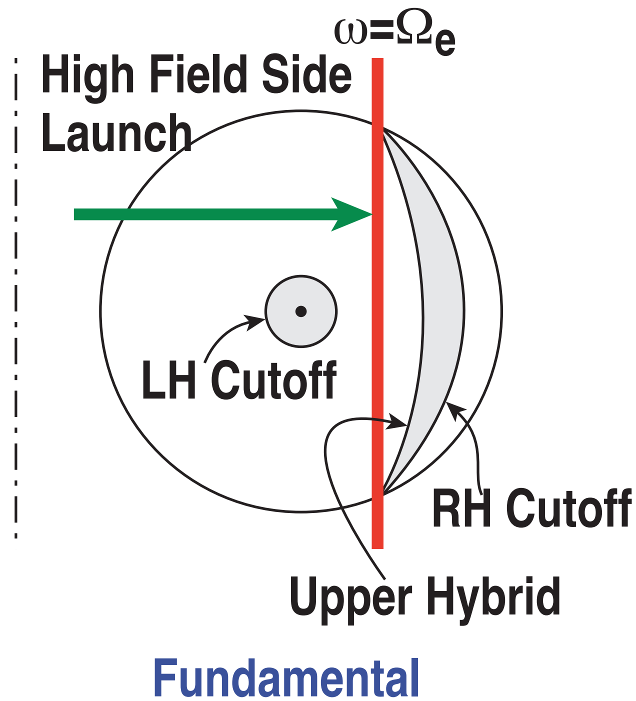
O-mode is Limited by $\omega_p^2 < \omega^2$



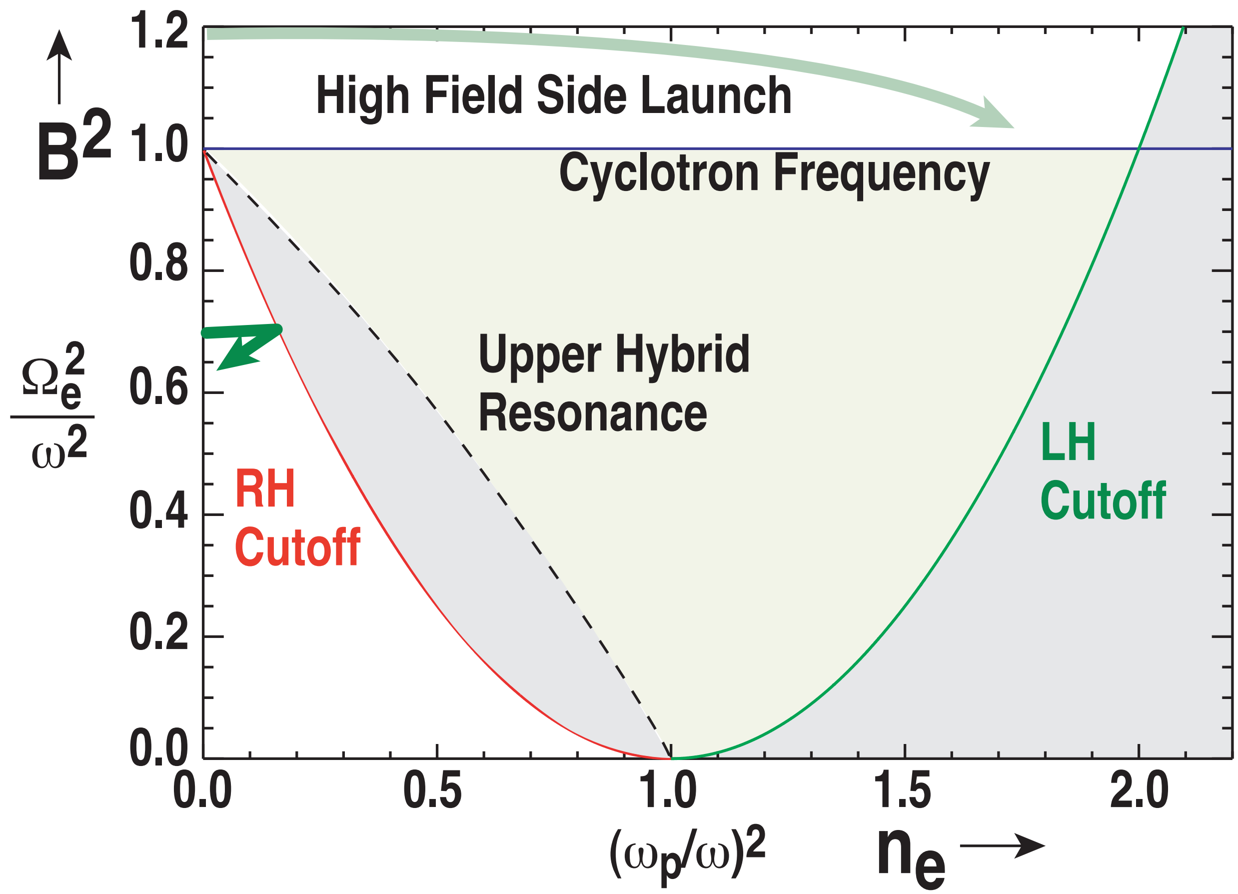


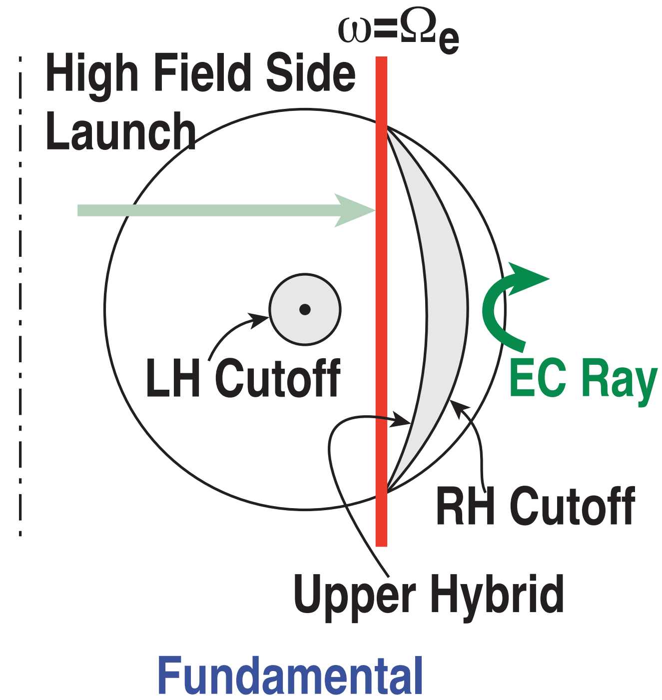
X-mode is Limited by LH and RH Cutoffs



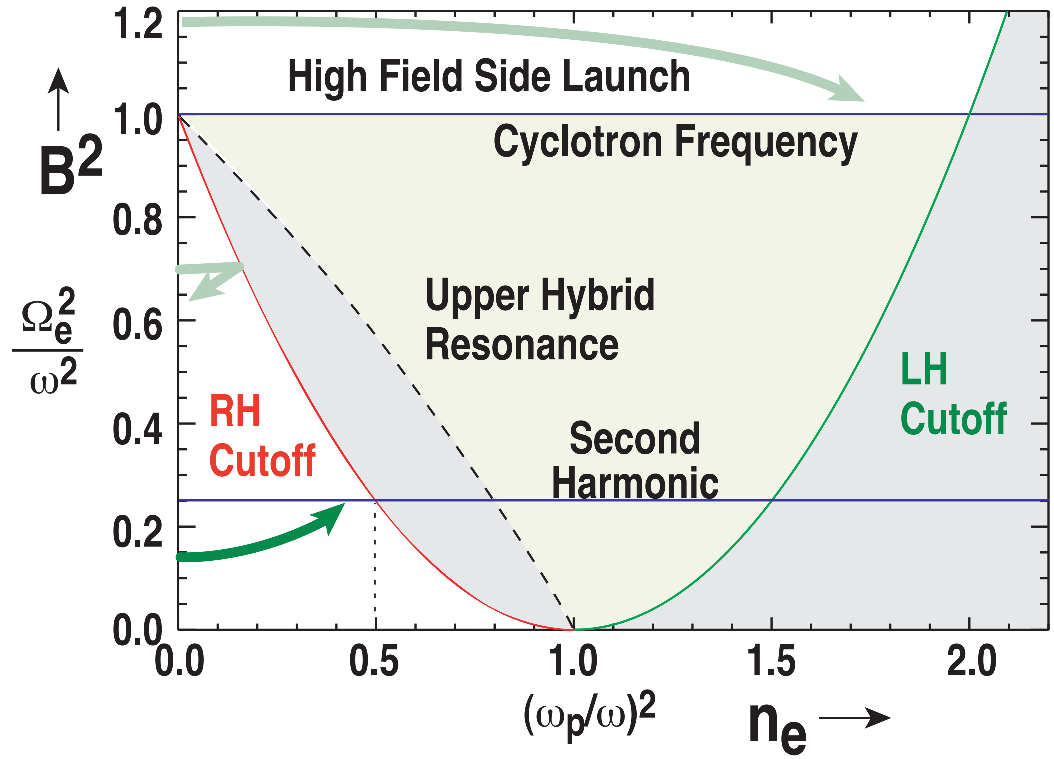


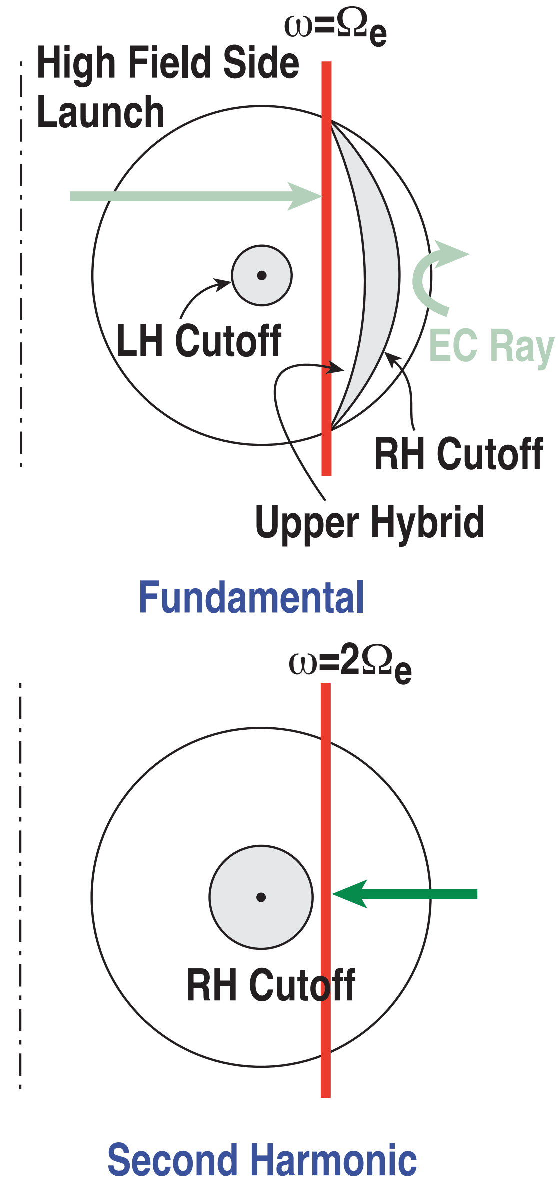
X-mode is Limited by LH and RH Cutoffs





Second Harmonic X-mode Limited by RH Cutoff



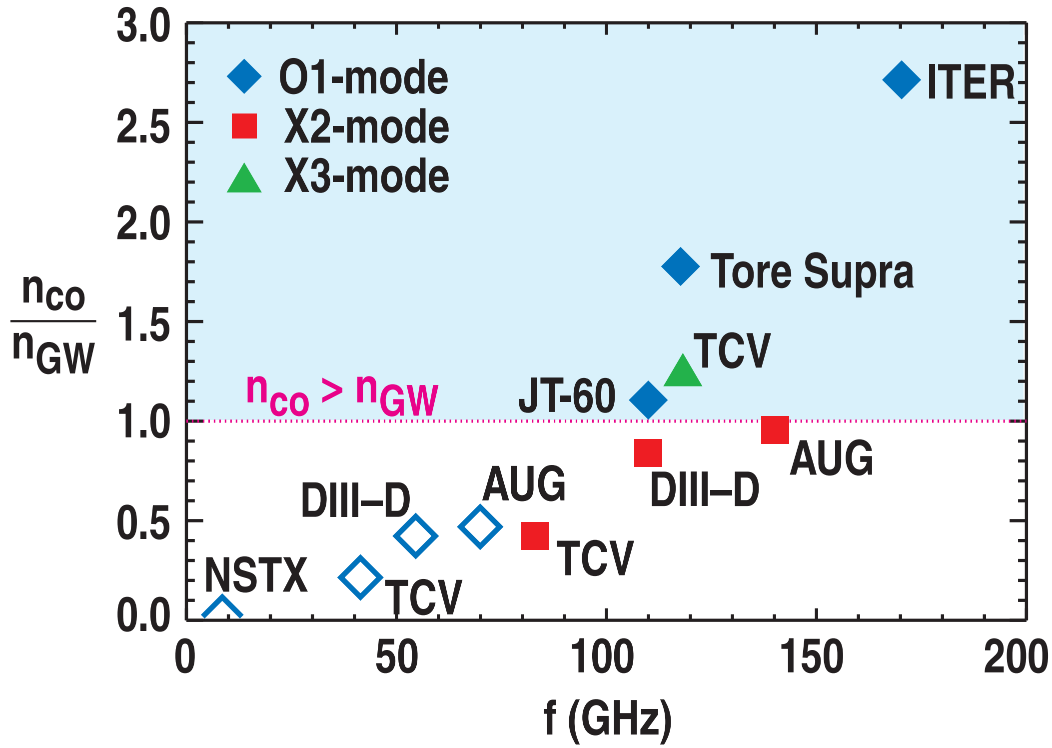


Density Cutoffs May Limit Operational Space

Mode	O1	X1	X2	O2	X3
Frequency	Ω_e	Ω_e	$2\Omega_e$	$2\Omega_e$	$3\Omega_e$
Density	n_{O1}	$2n_{O1}$	$2n_{O1}$	$4n_{O1}$	$6n_{O1}$

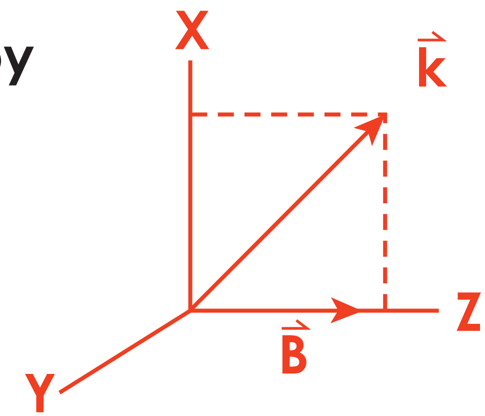
$$n_{O1} = \frac{B_T^2}{10.3} \times 10^{20}\ m^{-3}$$

- Tokamaks limited by $n_{GW} = (I_{MA}/\pi a_m^2) \times 10^{20}\ m^{-3}$
- O1-mode not a limit for ITER
- In order to apply ECH over full density range the harmonics can be used
- For low field devices the electron Bernstein mode may be used



Propagating Modes are Distinguished by Polarization

- **Polarization in the Stix coordinate system is given by**

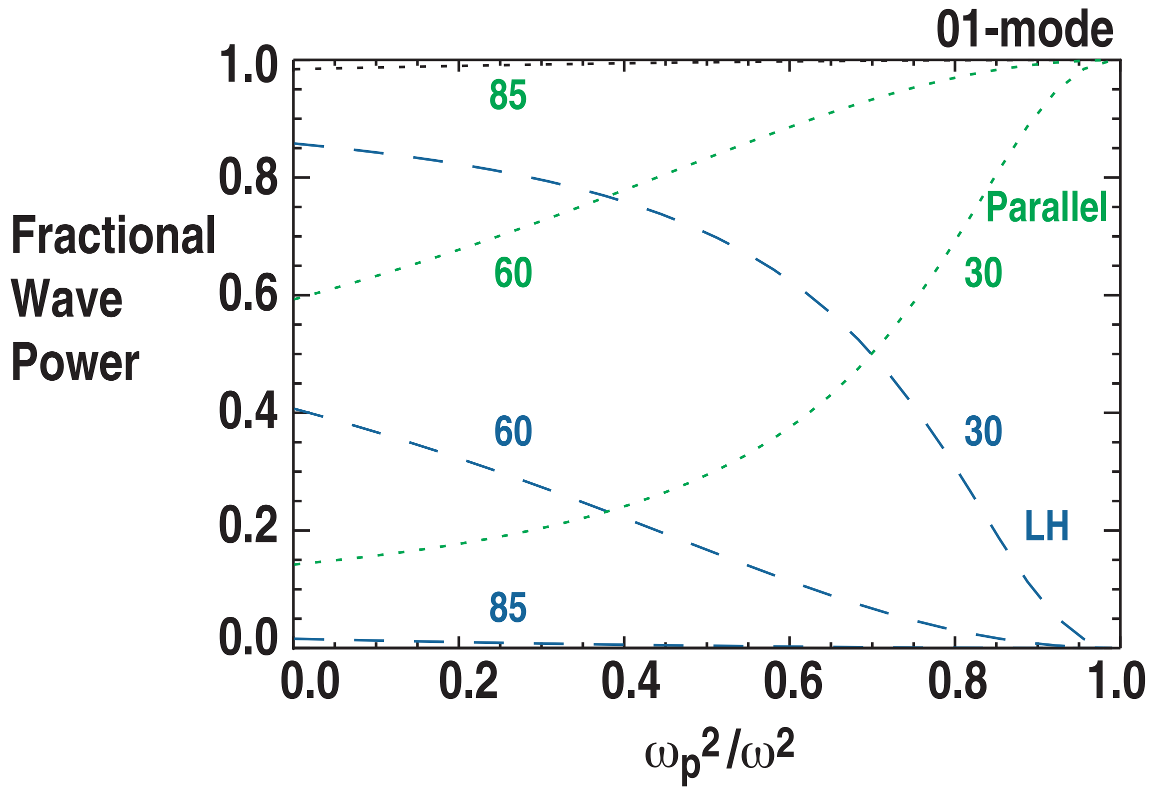


$$\frac{iE_y}{E_x} = \frac{R-L}{2(S-n_{O,X}{}^2)} \qquad \frac{E_z}{E_x} = \frac{-n_{O,X}{}^2 \cos\theta \sin\theta}{P-n_{O,X}{}^2 \sin^2\theta}$$

- **The RHS is real, so E_y and E_x are $\pi/2$ out of phase**
  - polarization is elliptical in plane perpendicular to B
  - the ellipticity is right-handed for $iE_y/E_x < 0$
    - Note: electrons gyrate right-handedly about B

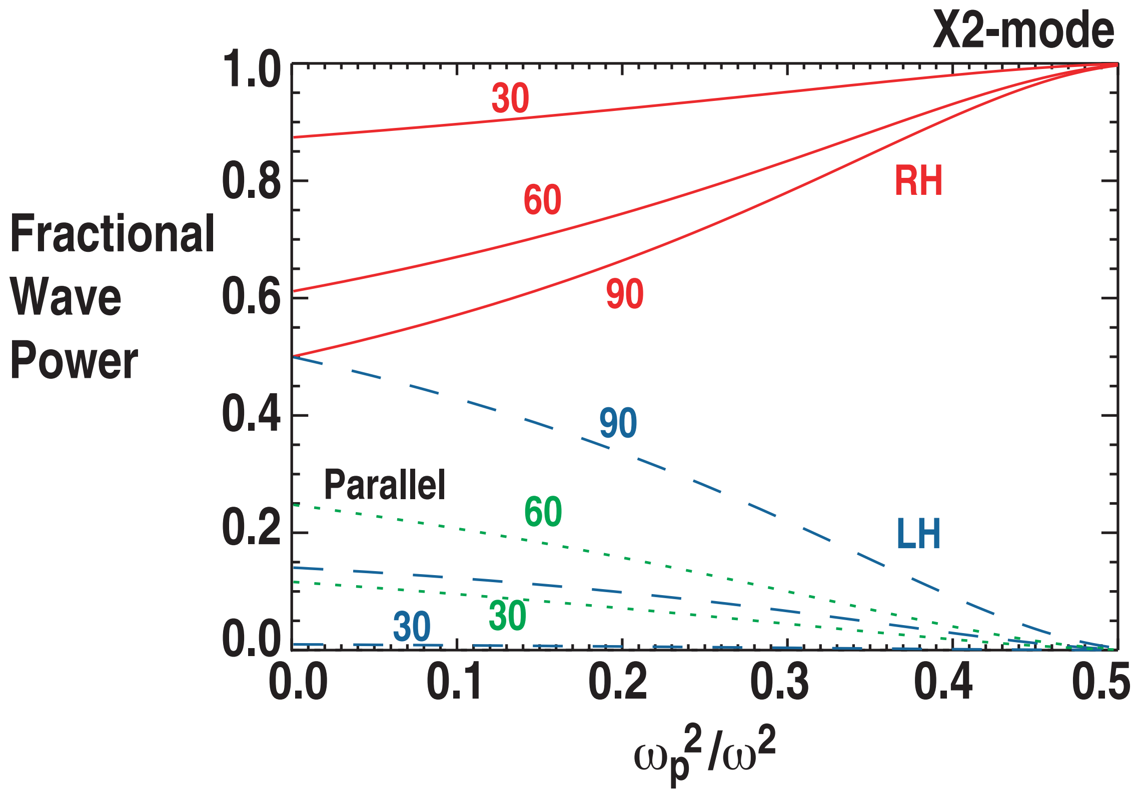
- **Concept: polarization is maintained as mode propagates**
  - this is what we mean by “mode purity”
  - may not be completely true in systems with strong magnetic shear, like stellarators

O1-mode Polarization has No Right-hand Component to Electric Field Polarization



- At launch point (zero density) wave may have LH component
- As wave approaches the cutoff, it becomes purely longitudinal
- Lack of RH component to wave electric field has consequences for absorption

X2-mode has Strong RH Polarization



- At launch point (zero density), RH, LH, and paralled components
- RH component grows as cutoff is approached

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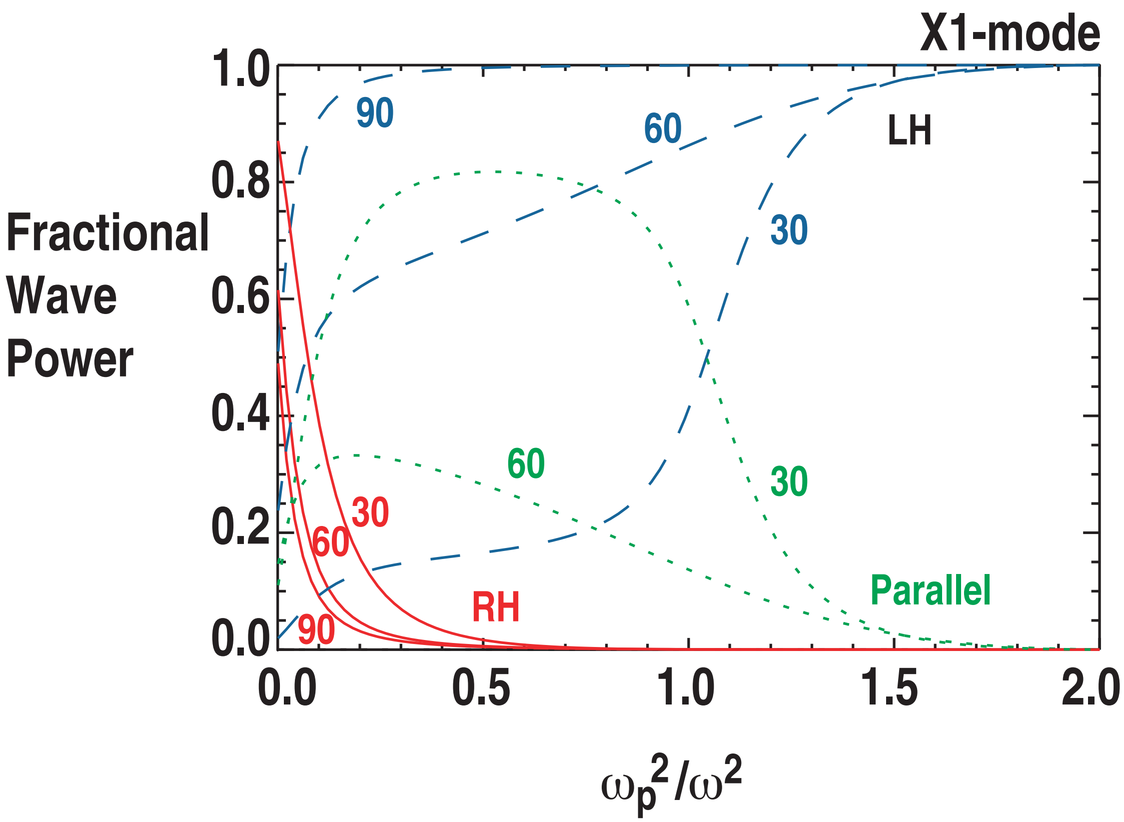
X1-mode is RH Polarized at Zero Density



- RH component at zero density is very good for preionization
- RH and parallel component vanishe near the cutoff, reducing its utility at high density

Wave/particle Interaction is Key to Heating

- Wave/particle resonance is NOT a dispersion relation resonance
- Wave/particle resonance condition is

$$\omega = h\frac{\Omega_e}{\gamma} + k_{\parallel}v_{\parallel}, \text{ where } \gamma = \left(1 - v_{\perp}^2/c^2 - v_{\parallel}^2/c^2\right)^{-1/2}$$

- The γ factor gives the relativistic shift and the $k_{||}v_{||}$ term gives the Doppler shift
- In velocity space ($v_{||}$, $v_{\perp}$), the relativistic Doppler-shifted resonance is an ellipse
  - even at $T_e <<< mc^2$ the relativistic effects are crucial to understanding the wave/particle interaction
- Resonance exists only for some values of $v_{||}$

Wave Power Can be Absorbed by Resonant Electrons

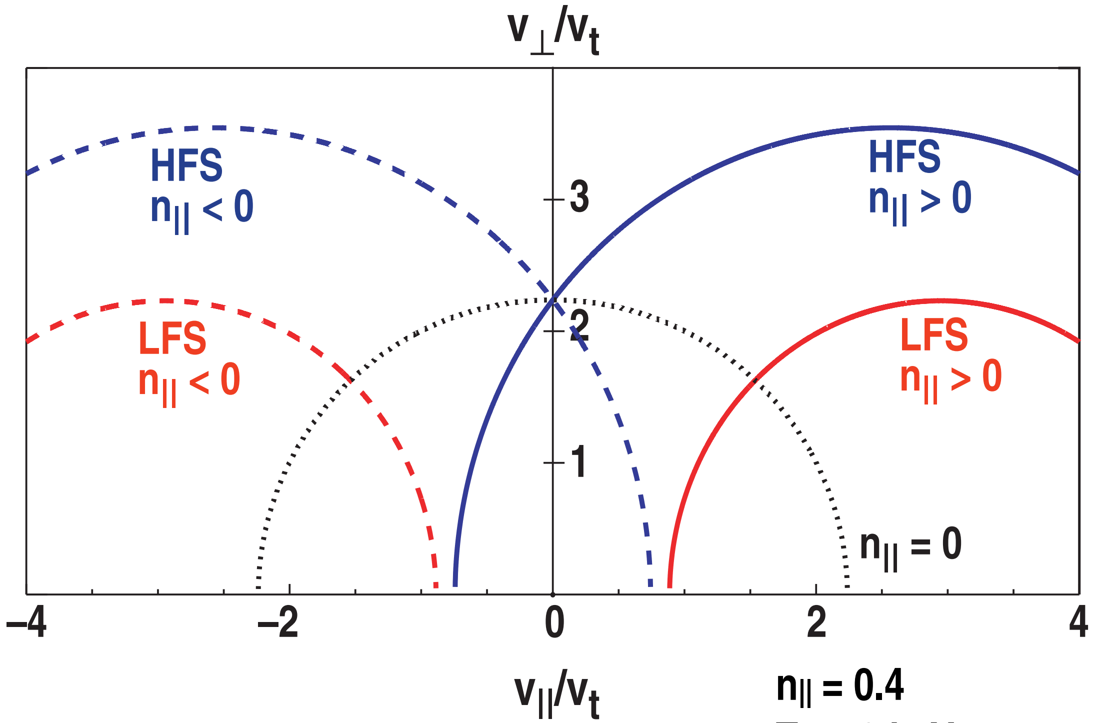
$$\omega = \frac{h\Omega_{eo}}{\gamma} - k_{||} v_{||}$$

Doppler shift (the $k_{||} v_{||}$ term)

Relativistic shift (the γ term)

$$\gamma \equiv [1 - v_{||}^2/c^2 - v_{\perp}^2/c^2]^{-1/2}$$

Resonance is an ellipse in velocity space



$n_{||} = 0.4$
$T_e = 8$ keV
$B_{max}/B_{min} = 1.35$

Low field side launch

High field side launch

- <u>Relativistic effects</u> must be included even for moderate T_e

Location of Resonance Relative to Trapped Region Affects Wave/Particle Interaction

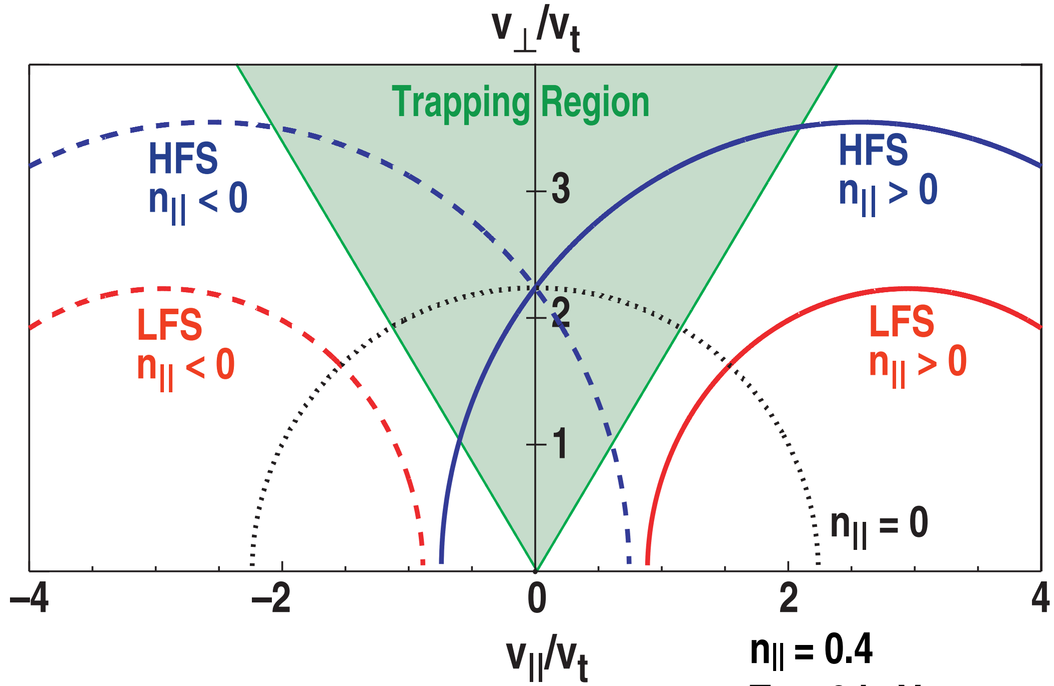
$$\omega = \frac{h\Omega_{eo}}{\gamma} - k_{\|} v_{\|}$$

Doppler shift

Relativistic shift

$$\gamma \equiv [1 - v_{\|}^2/c^2 - v_{\perp}^2/c^2]^{-1/2}$$

Resonance is an ellipse in velocity space



$n_{\|} = 0.4$
$T_e = 8$ keV
$B_{max}/B_{min} = 1.35$

Low field side launch

High field side launch

- **Launch side has major effect on interaction with trapped electrons**
  - HFS launch not suitable for current drive due to trapping of electrons in magnetic well

Electrons on the Resonance can Absorb Power from the Wave Fields

- **Start with the nonrelativistic equation of motion**

$$m\,d\vec{v}/dt = e(\overrightarrow{E_\omega} + \vec{v} \times \overrightarrow{B_0})$$

- **Define the RH vectors** $v_- = v_x - iv_y$ **and** $E_- = E_x - iE_y$**, then**

$$\dot{v}_- + i\Omega_e v_- = -(e/m)E_- \exp[-i(k_\perp \rho \sin\Omega_e t - \ell\Omega_e t)]$$

- **Apply the mathematical identity**

$$\exp[i\xi \sin\varphi] = \sum_{p=-\infty}^{\infty} \exp(ip\varphi) J_p(\xi)$$

- **Then the equation of motion becomes**

$$\dot{v}_- + i\Omega_e v_- = -\frac{eE_-}{m}\sum_p J_p(k_\perp \rho)\exp[i(p-\ell)\Omega_e t]$$

and the term with $p - \ell = 1$ **has net time-averaged acceleration**

Quasilinear rf Diffusion Model is Used to Calculate Wave Absorption

- **Premises:**
  - use unperturbed electron orbits to find effects of wave fields
  - when electrons re-enter the EC beam the gyrophase is uncorrelated with its previous entry
- **Averaging over an ensemble of electrons gives the Timofeev rf diffusion in velocity space, to lowest order in the Bessel function**

$$G_\ell = \left| v_\perp E_- J_{\ell-1}(k_\perp \rho) + v_\parallel E_\parallel J_\ell (k_\perp \rho) \right|^2$$

  - a relativistic analog of this equation is used to calculate the effect of waves on the electon distribution function using Fokker-Planck codes

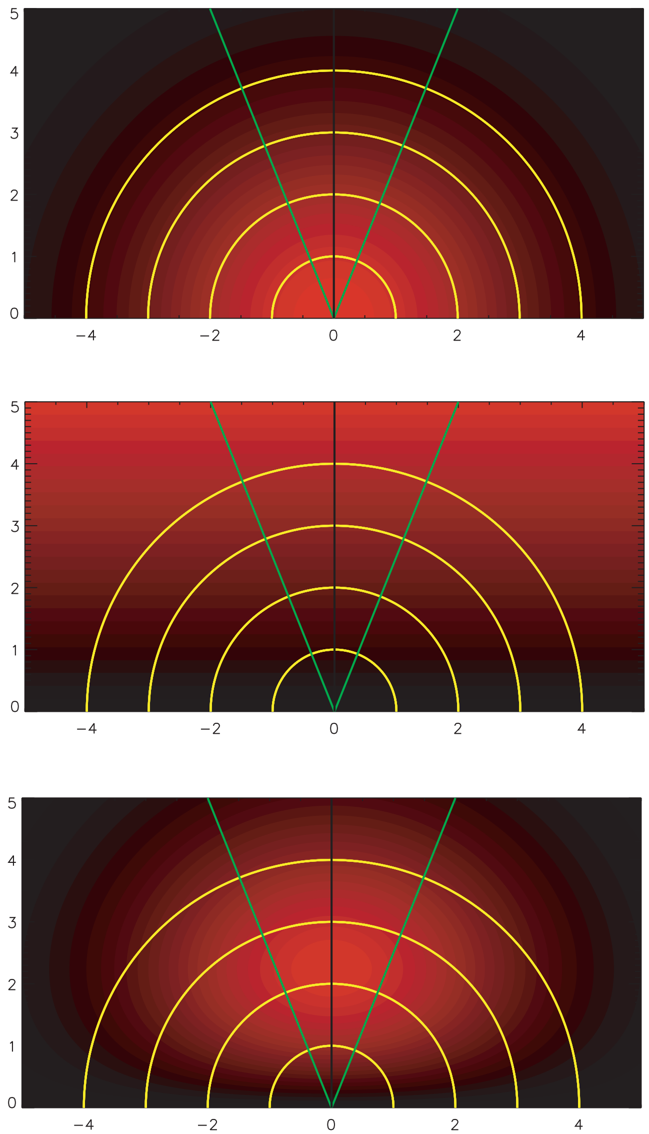
This Simple Treatment of Wave Interactions Shows Some Key Features of the EC Wave/particle Interaction

$$G_\ell = \left| v_\perp E_- J_{\ell-1}(k_\perp \rho) + v_\parallel E_\parallel J_\ell(k_\perp \rho) \right|^2$$

- **Note that** $k_\perp \rho = n_\perp \ell v_t / c = n_\perp \ell \sqrt{T_e / mc^2}$ **is always small for fusion plasmas, and the Bessel function can be expanded for small argument as** $J_{\ell-1}(k_\perp \rho) \propto (k_\perp \rho)^{\ell-1}$

- **Some consequences:**
  – For cold plasmas, then, only the fundamental $(\ell = 1)$ heats
  – Heating depends on the right hand component E_- and more weakly (ie, one order higher in Bessel function) on $E_\parallel$
  – As the harmonic number is increased the interaction strength decreases by the small factor T_e / mc^2

EC Wave Absorption is a Finite Larmor Radius Effect



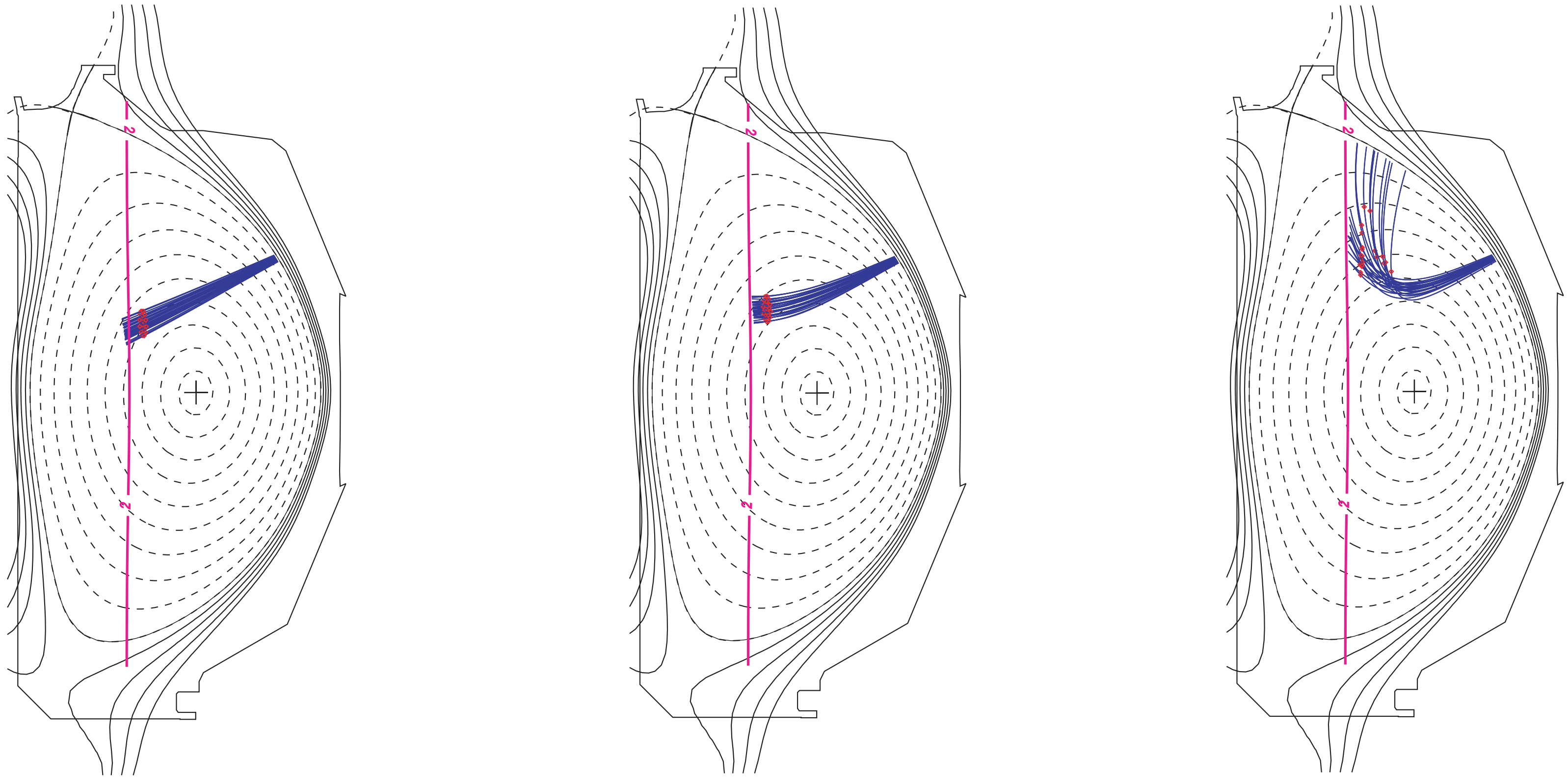
- **Distribution function is concertrated near V=0**
- **Larmor radius increases with $V_\perp$**
- **Shaded area shows the location where power can be absorbed**

Computational Tools are Used to Evaluate Wave Propagation and Absorption

- **Ray equations of motion:** $\frac{d\vec{r}}{dt} = -\frac{\partial D / \partial \vec{k}}{\partial D / \partial \omega}, \qquad \frac{d\vec{k}}{dt} = \frac{\partial D / \partial \vec{r}}{\partial D / \partial \omega}$
- **Ray-tracing codes (TORAY, GENRAY, etc) use an array of non -interacting rays to simulate a Gaussian distribution in the far-field**
  - misses effects of diffraction and interference
  - in many cases of interest this model is satisfactory
- **Gaussian beam codes (GRAY, TORBEAM, etc) keep effects of diffraction, astigmatism, and interference**
  - when the beam focus lies inside the plasma this model is needed
- **Both approaches calculate the absorption as the rays or beam propagate, using linear warm plasma absorption models**
  - this provides radial profiles of the wave heating and current drive

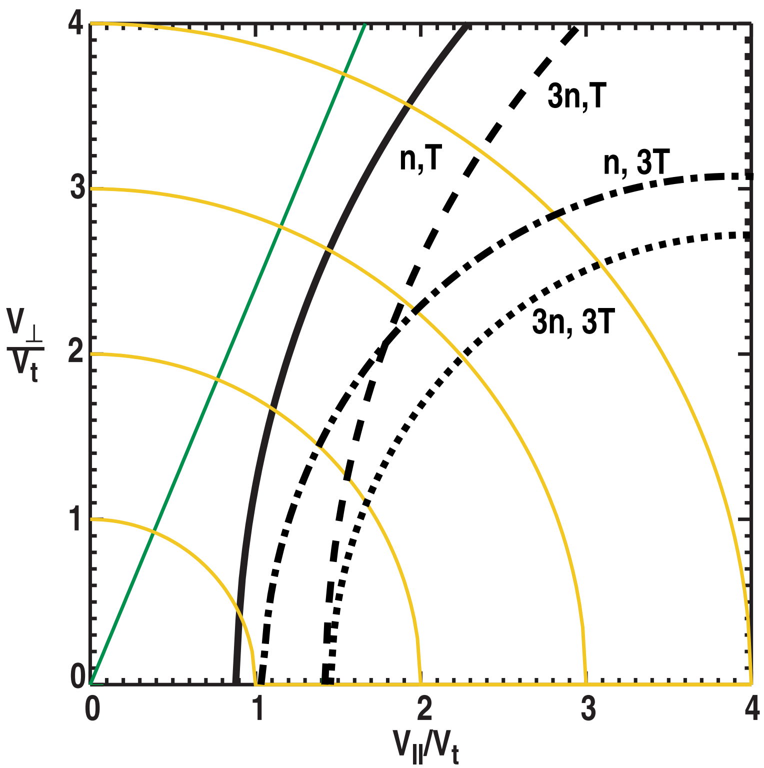
Ray Tracing Provides Heating and Current Drive Profiles in Realistic Geometries

- **TORAY-GA calculations for DIII-D; B_T = 1.7 T, T_e (0) = 5 keV, f_{EC} = 110 GHz**



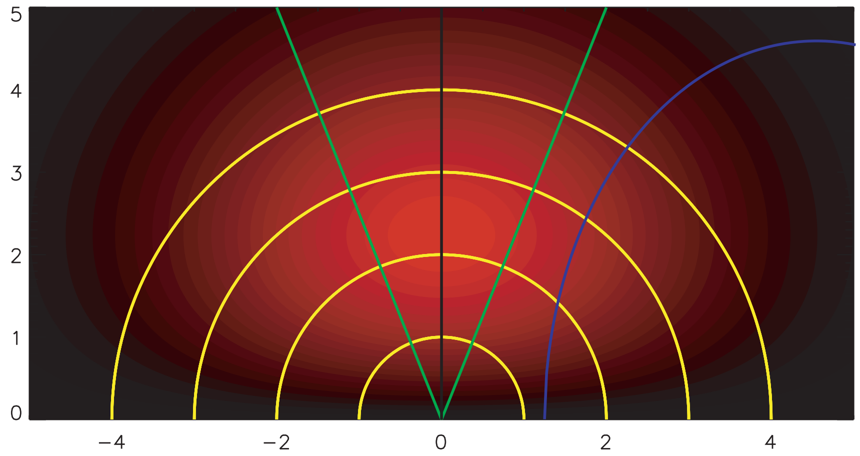
n_e (0) = 3 × 10^{19} m^{-3} | 8 × 10^{19} m^{-3} | 11 × 10^{19} m^{-3}

With Ray-tracing, the Effects of Changing the Kinetic Profiles can be Seen in the Resonance Curves



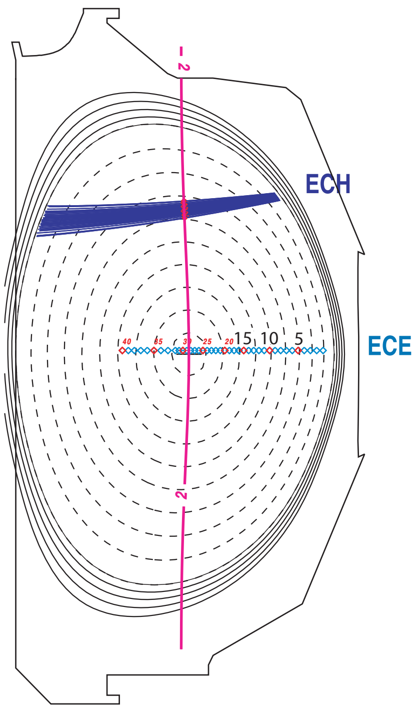
- Resonance curves are made at the spatial location of maximum absorption
- Raising density shifts the curve to the right, while raising T_e causes the resonance to curve more strongly

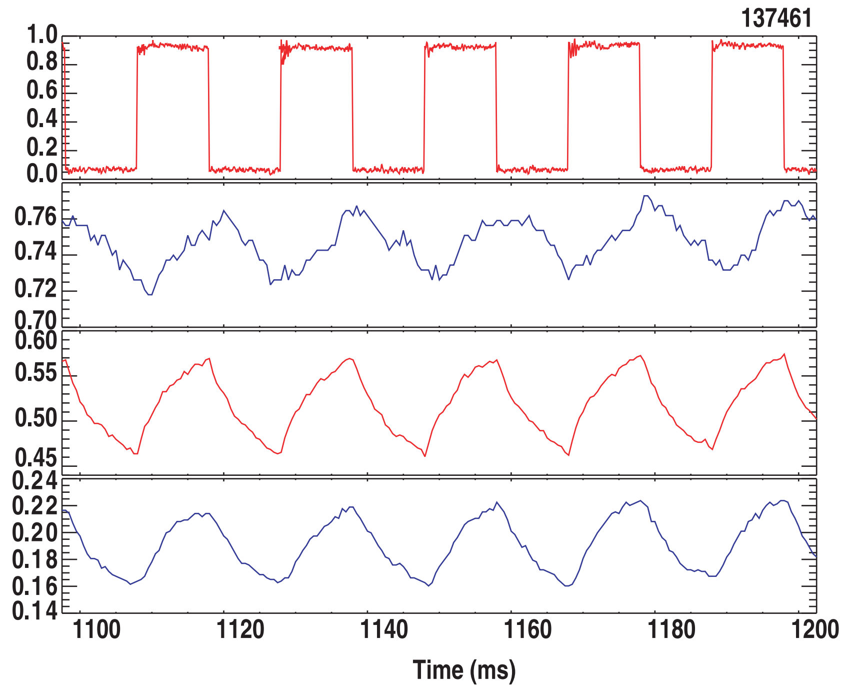
Where on the Resonance Curve do the Electrons Actually Absorb Power?



- **Typically, absorption is by electrons with $v_{\perp}/v_t$ ~2 and $v_{||}/v_t$ ~2**

EC Propagation and Absorption can be Measured for Comparison with Theory



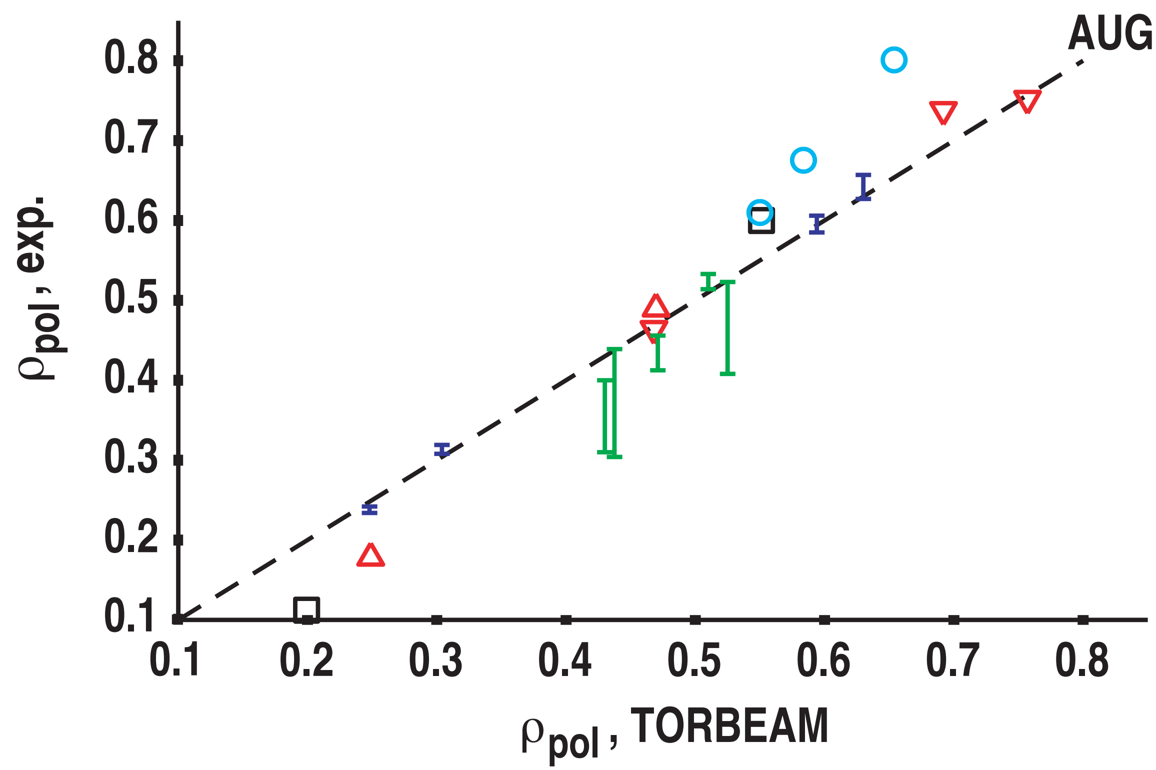


P_{ECH} (MW)

ECE 10 (keV)
ρ = 0.5
ECE 6 (keV)
ρ = 0.64
ECE 2 (keV)
ρ = 0.83

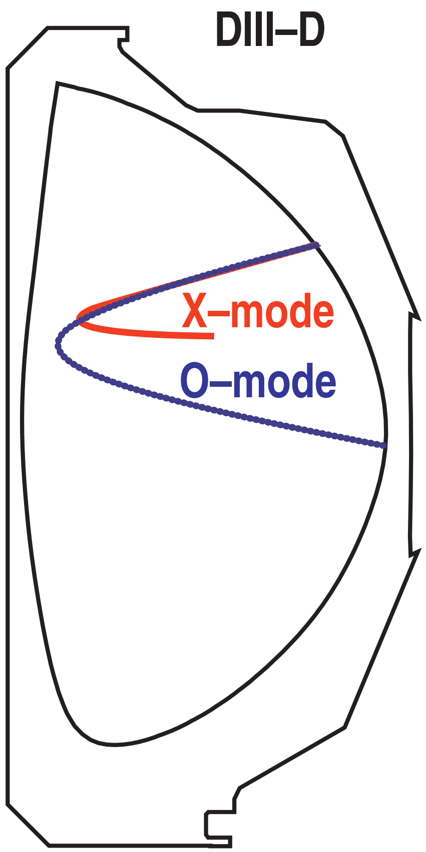
- Amplitude and phase delay of ECE signals indicates location of power deposition
- Fourier analysis needed for clearest interpretation

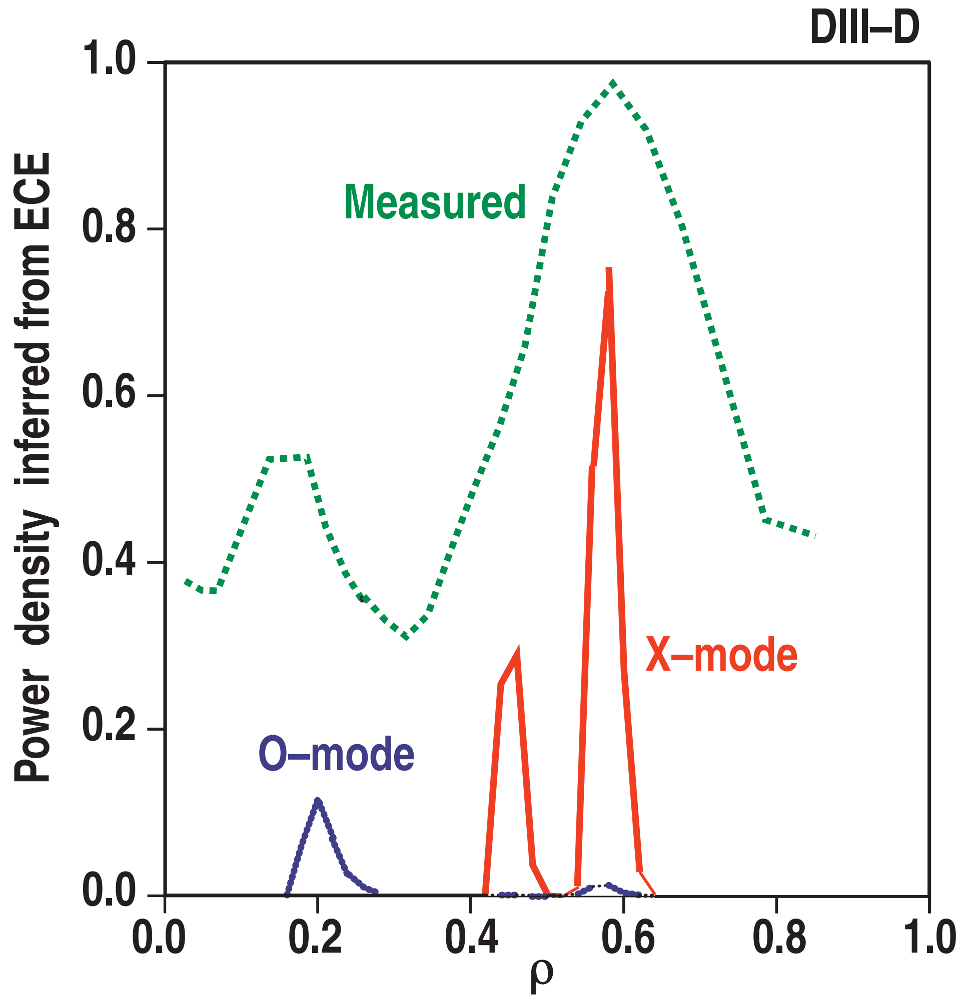
Measured Location of ECH Agrees with Theory



- **Heating location determined from radial profile of ECE response to modulated ECH**

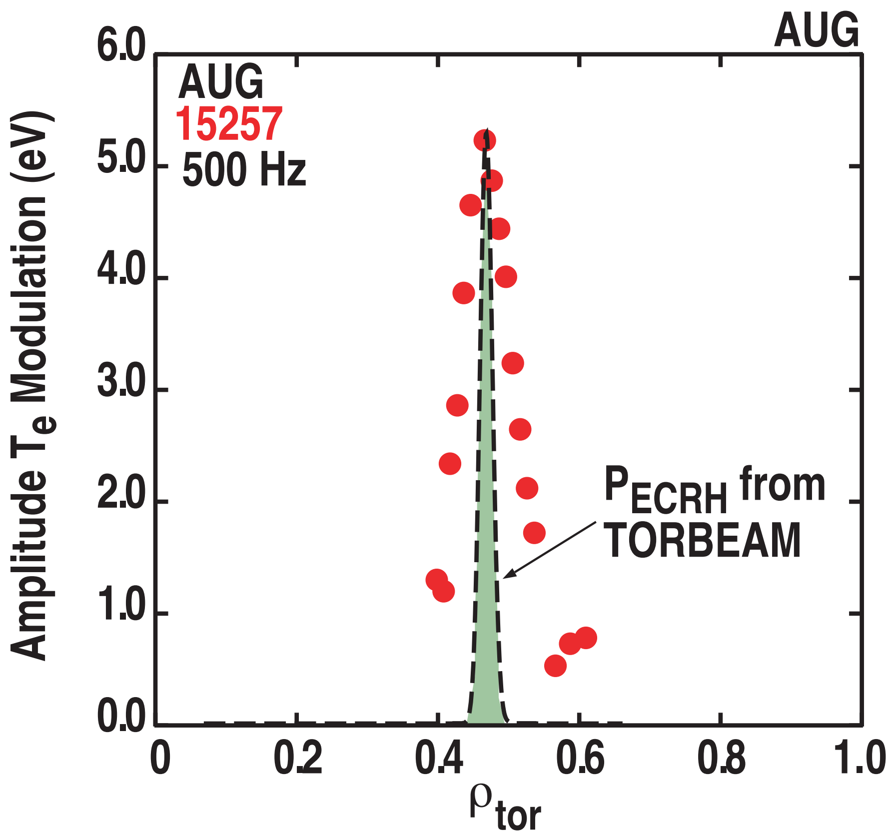
Measured Location of ECH Depends on Mode





- This process is used to optimize mode purity through adjustment of the launched polarization

Theoretical and Experimental Profiles of ECH can be Extremely Narrow

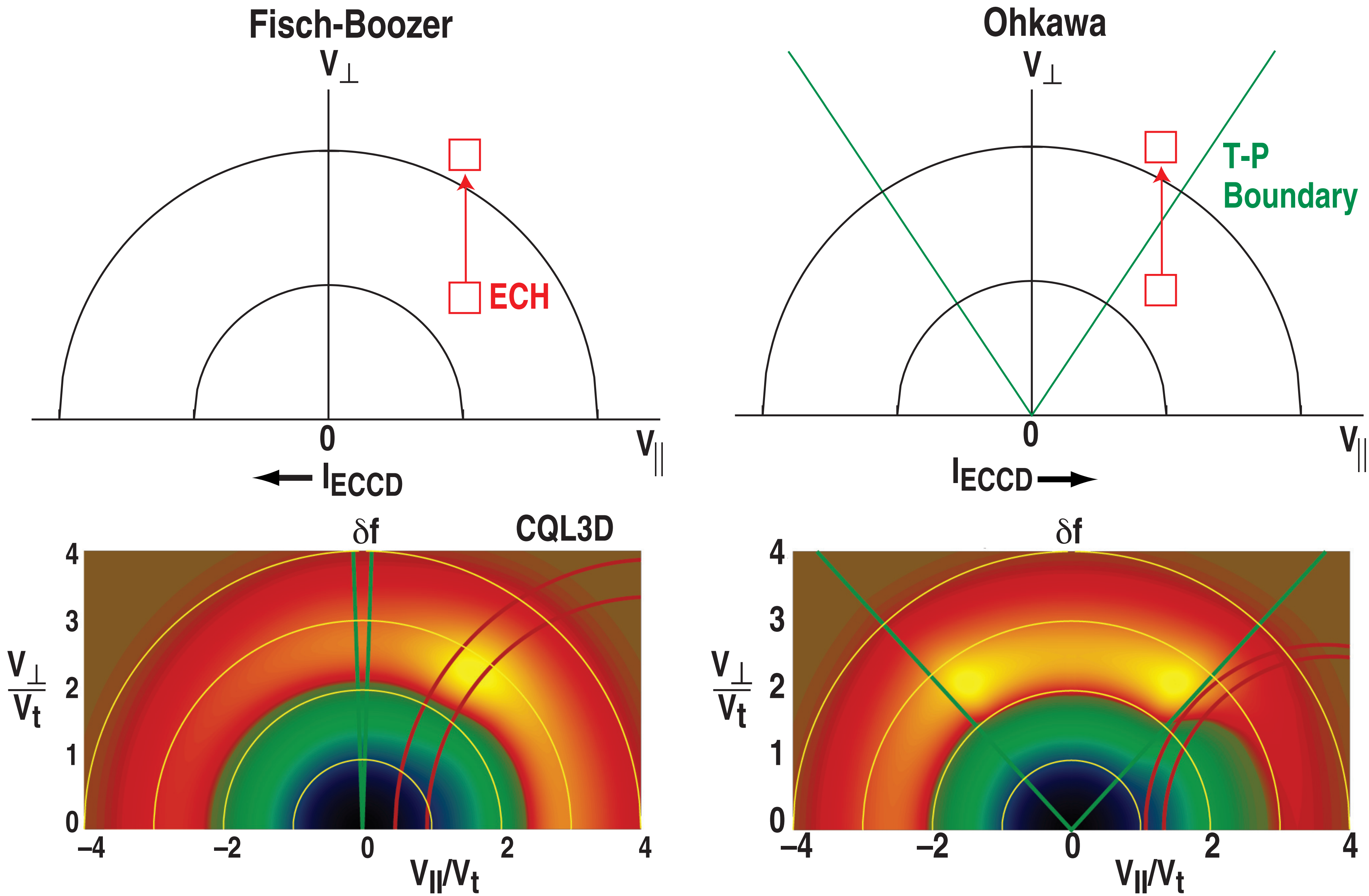


- **ECH response to modulated ECH clearly identifies the radial location of the absorption**
- **Response profile is very narrow**
  - Some of the broadening is due to transport

Narrow and Robustly Controllable EC Power Profiles Motivate Electron Cyclotron Current Drive

- **Localized and controllable off-axis current drive has important applications**
  - Current profile control for optimization of tokamak performance
  - Stabilization of MHD modes
  - Tuning the shear profile in stellarators
- **Electron cyclotron current drive has unique features which address these applications due to strong control over where the power is deposited**
- **A key physics issue is effect of trapping of electrons in the magnetic well**

Electron Cyclotron Current Drive in Toroidal Systems is Driven by Two Competing Effects



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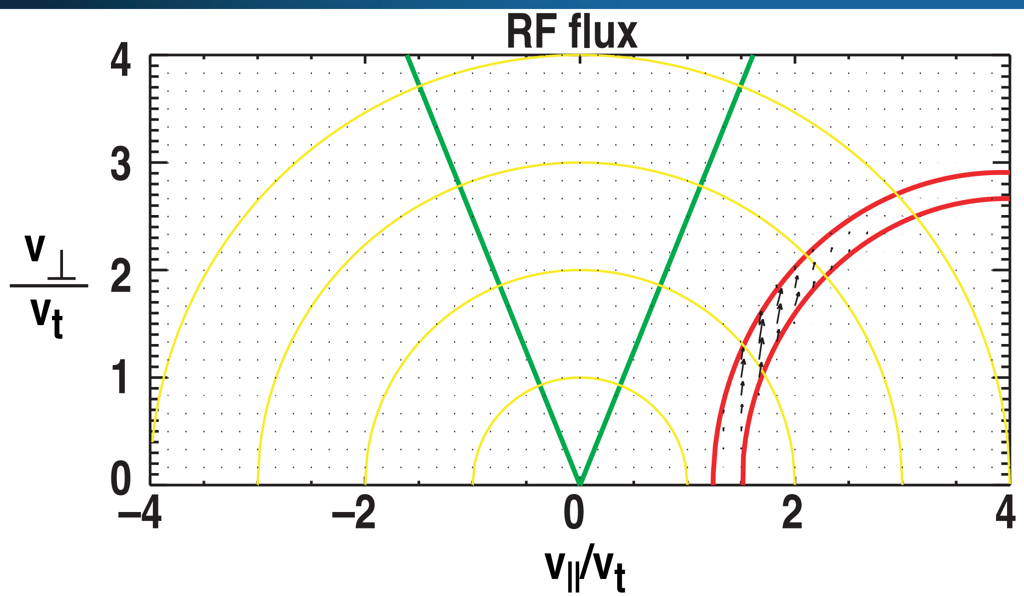
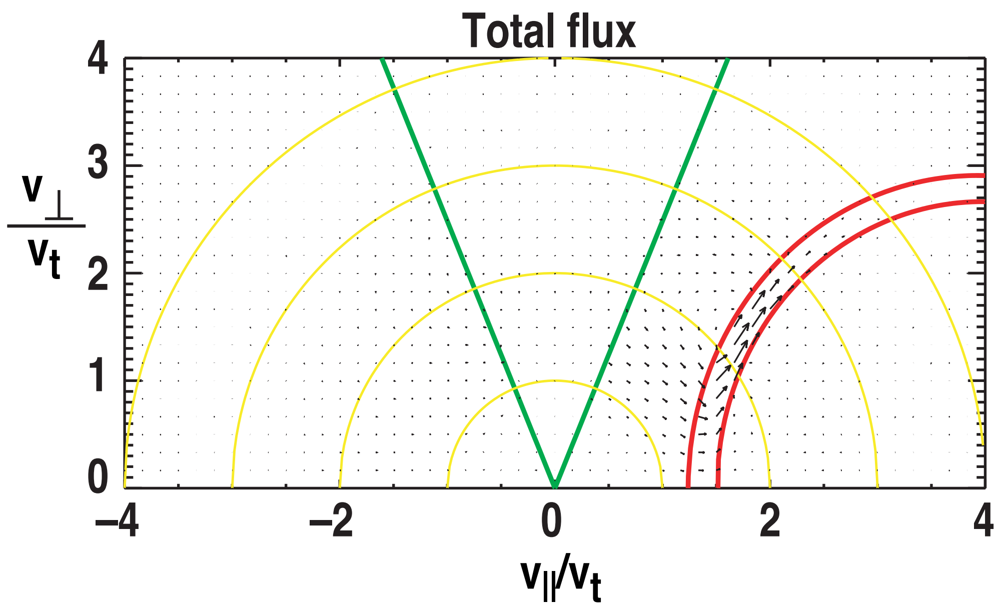
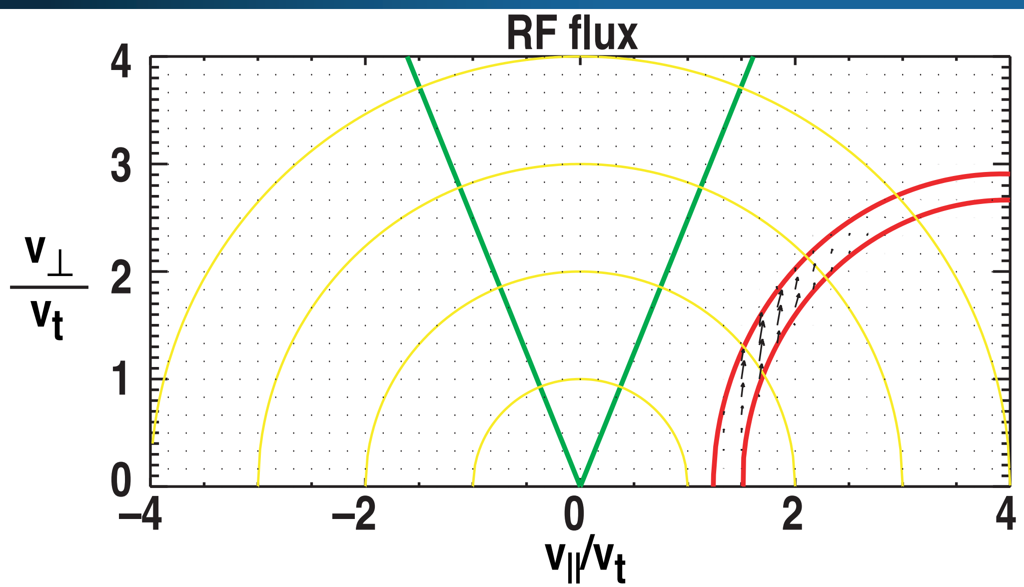
Fokker-Planck Code Shows Where Interaction Takes Place



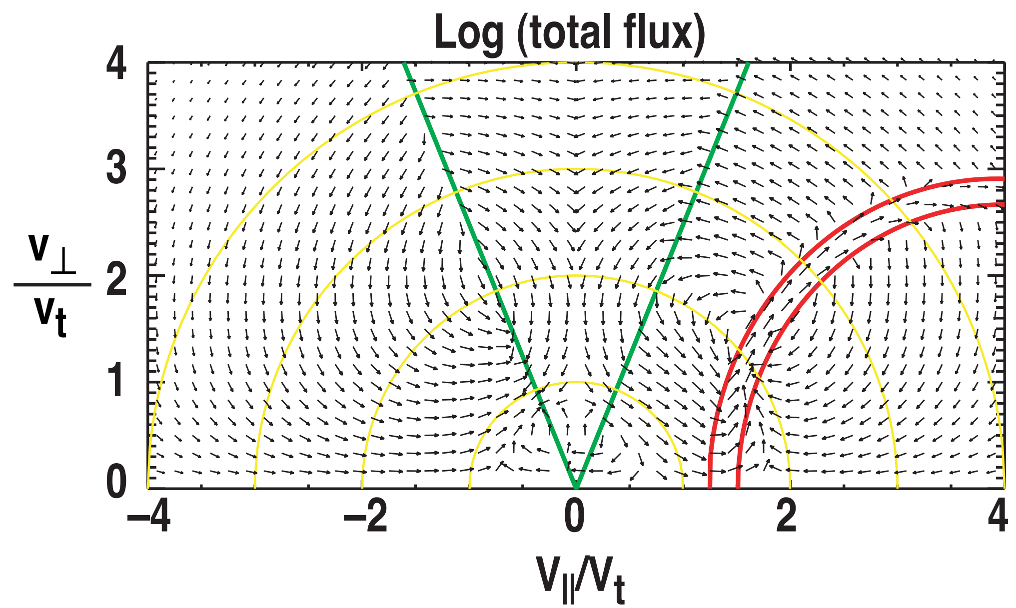


- EC drives velocity-space flux near resonance, with $v_{\perp} > 0$
- Total flux includes collisional relaxation
- Flux is well-aligned for effective current drive

Vortices Link the Interaction Region with the Trapping Region



- EC drives velocity-space flux near resonance, with $v_\perp > 0$



- Flow patterns show that even when the resonance is far from the trapped region there still is interaction with trapped electrons

ECCD can be Calculated by Linear or Quasilinear Codes

Linear code (TORAY–GA, TORBEAM, GRAY, . . .) use model by R. Cohen, Phys. Fluids 1987, Improved by Y.R. Lin-Liu

- Fast; accurate in many situations

Quasilinear Fokker-Planck codes (CQL3D, . . .)

- Slow; accurate to higher power densities
- Superior momentum-conserving model for collisions
- Nonthermal effects on conductivity included
- Quasilinear: energy gain of electron is calculated using unperturbed orbits

Efficiency for current drive:

$$\zeta = \frac{e^3}{\varepsilon_o^2} \frac{n_e I_{ec} R}{T_e P_{ec}}$$

– Dimensionless
– Includes expected dependences on n_e and T_e

ECCD can be Measured Two Ways

- **ECCD can be determined from measurement of the loop voltage at the plasma edge**
  - In stellarators the total toroidal current is easily measured (Wendelstein 7AS)
  - In tokamaks the loop voltage drops more than expected from conductivity increase
  - Fully noninductive operation in TCV validated

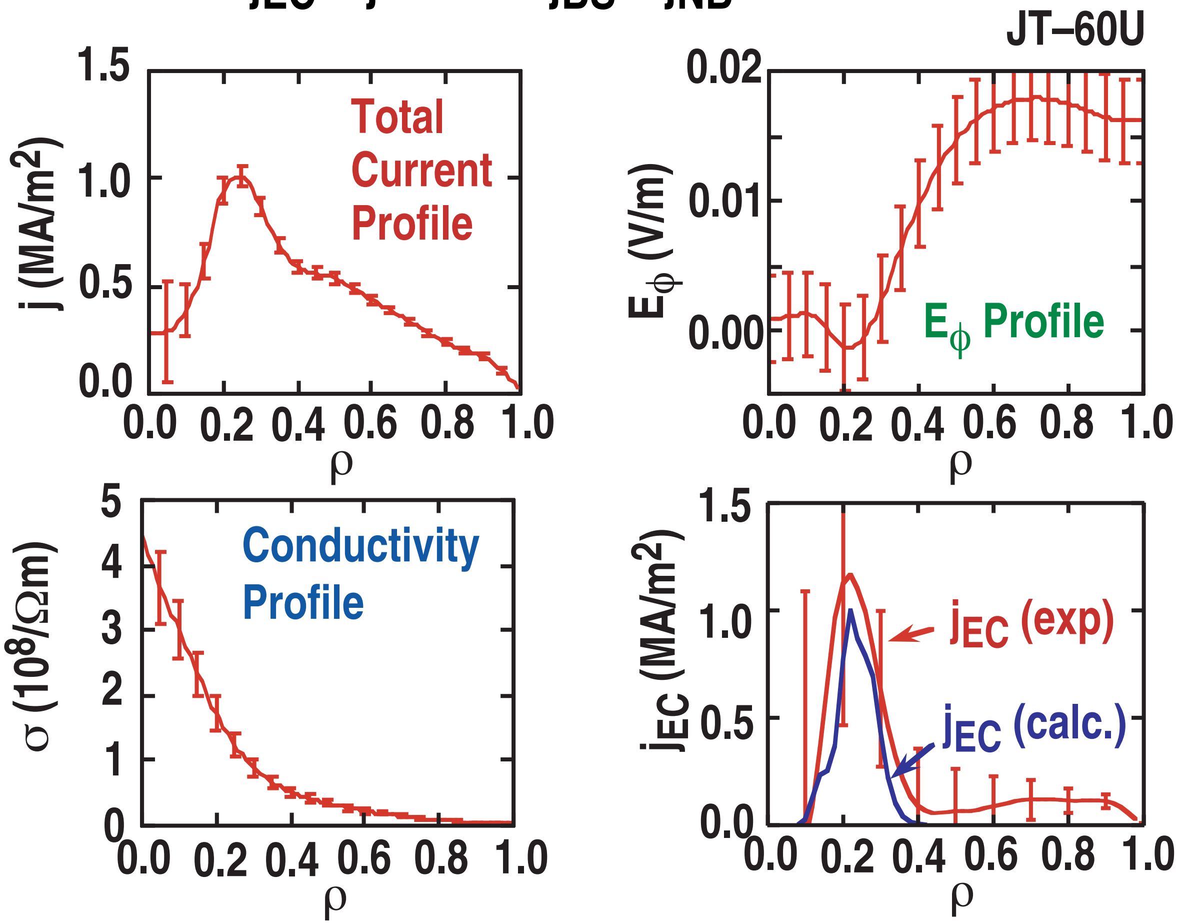
- **ECCD <u>profile</u> can be determined from measurements of the internal magnetic field**
  - Requires MHD-quiescent plasma, with flux diffusion consistent with neoclassical resistivity

ECCD Profile can be Determined from Measurements of Internal Magnetic Field

Method 1: use field measurements to constrain equilibrium reconstruction (C. Forest)

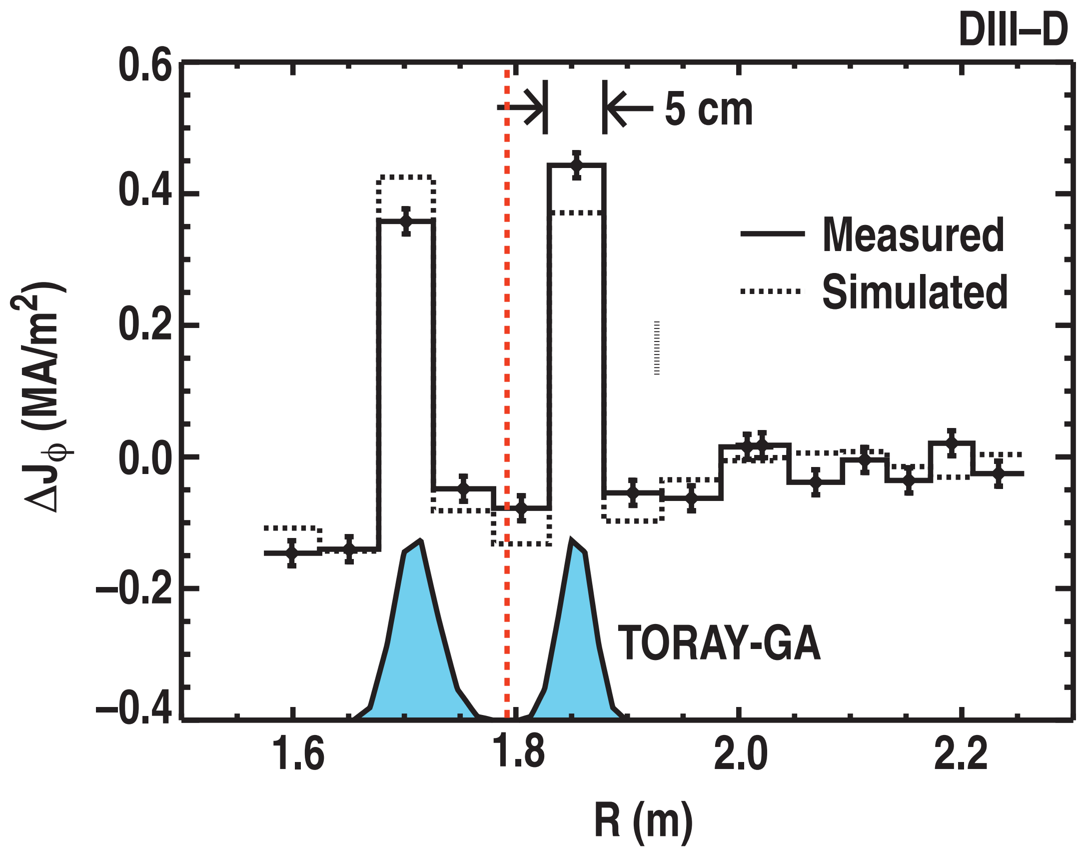
Equilibrium → $j(\rho)$, $\psi(\rho)$; $d\psi/dt$ → $E(\rho)$

$j_{EC} = j - \sigma E - j_{BS} - j_{NB}$



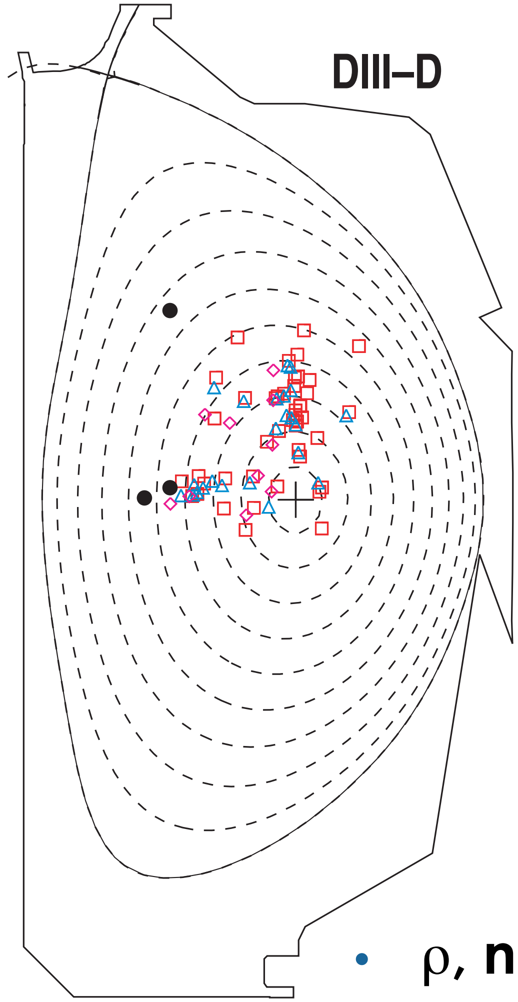
ECCD Profile can be Determined from Measurements of Internal Magnetic Field

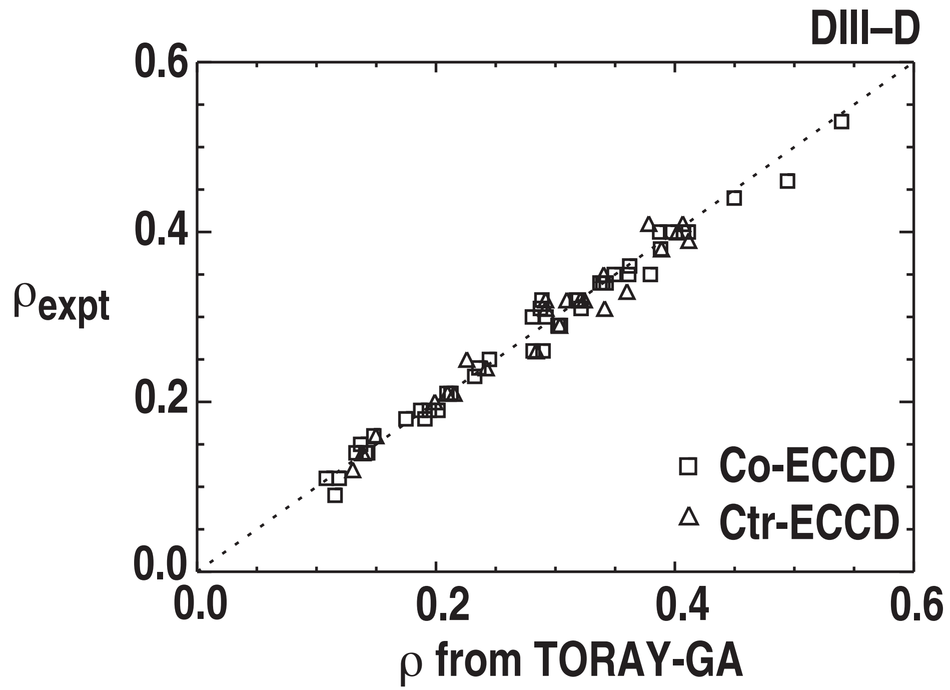
Method 2: compare measured magnetic field with that calculated from simulations to find best fit (C.C. Petty)



- **ECCD profile width can be than resolution limit of motional Stark effect diagnostic**

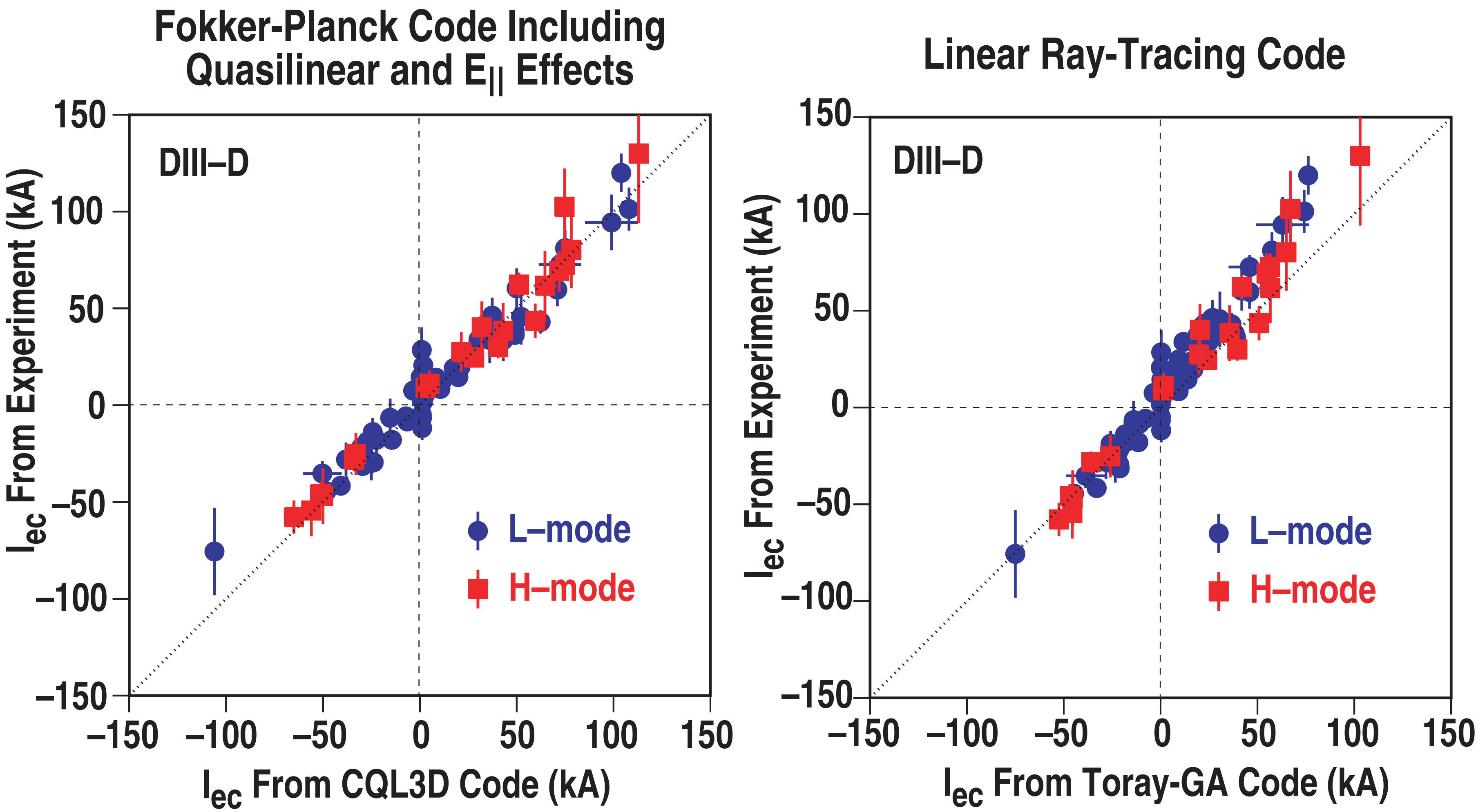
Measured Location of ECCD Agrees with Theory



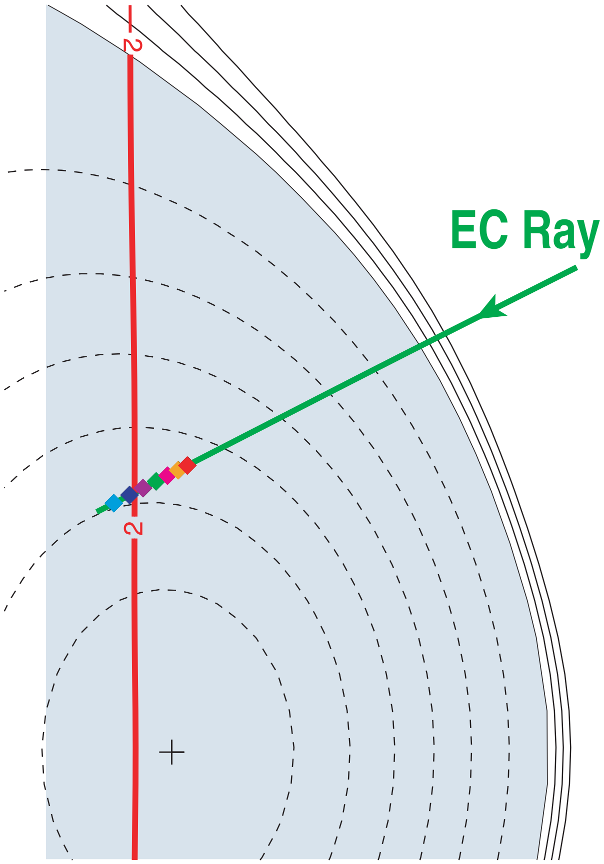


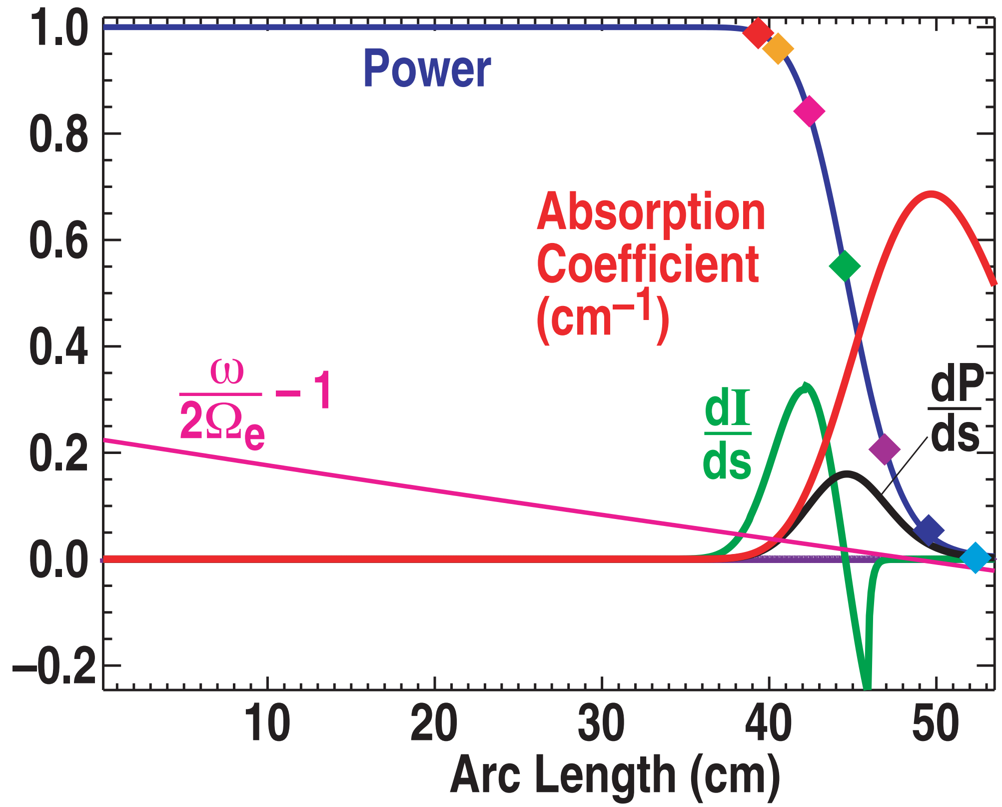
- ρ, $n_{||}$, location along a flux surface varied systematically
- ECCD measured using motional Stark effect diagnostic

Measured ECCD Agrees with Theory



Ray Tracing Shows Relationship of Absorption and Current Generation





$n_e = 1.2\times10^{19}\ m^{-3}$

$T_e = 1.4$ keV

$n_{||} = 0.38$

$\beta_e = 0.2\%$

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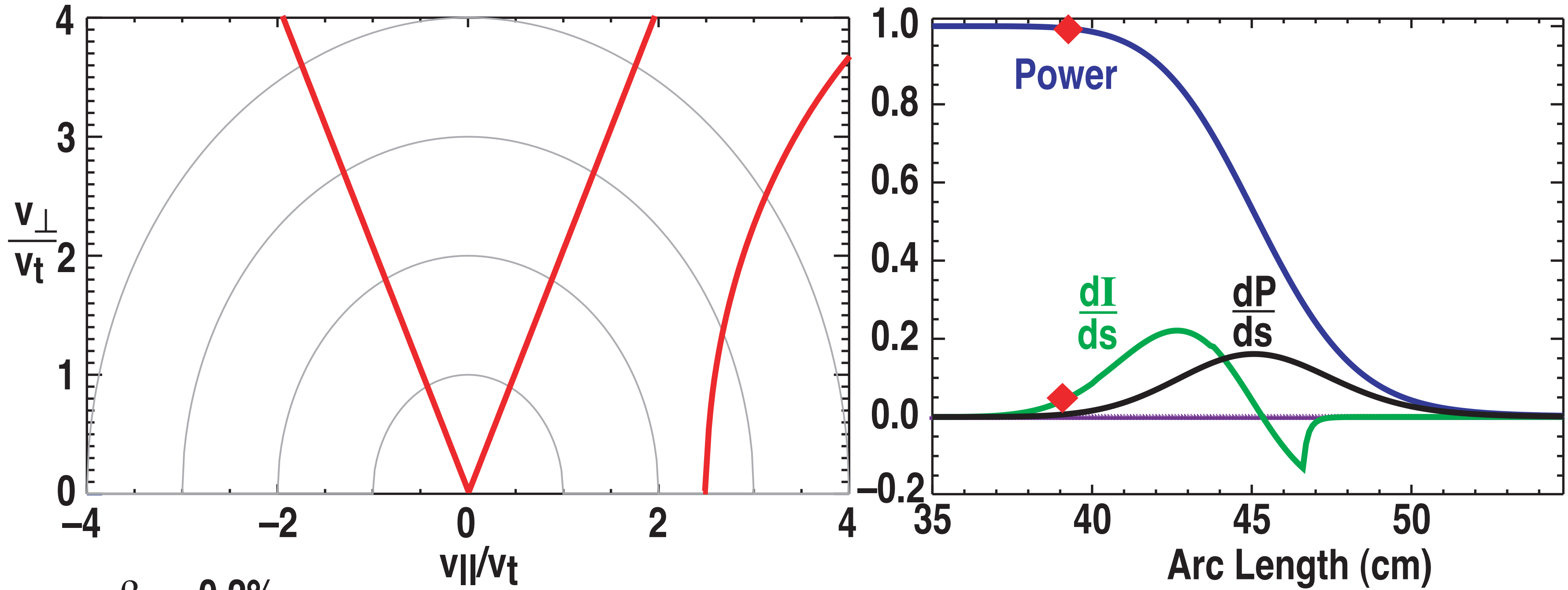
For Weak Absorption (Low β_e) There can be Large Cancellation of FB Current by Ohkawa Current



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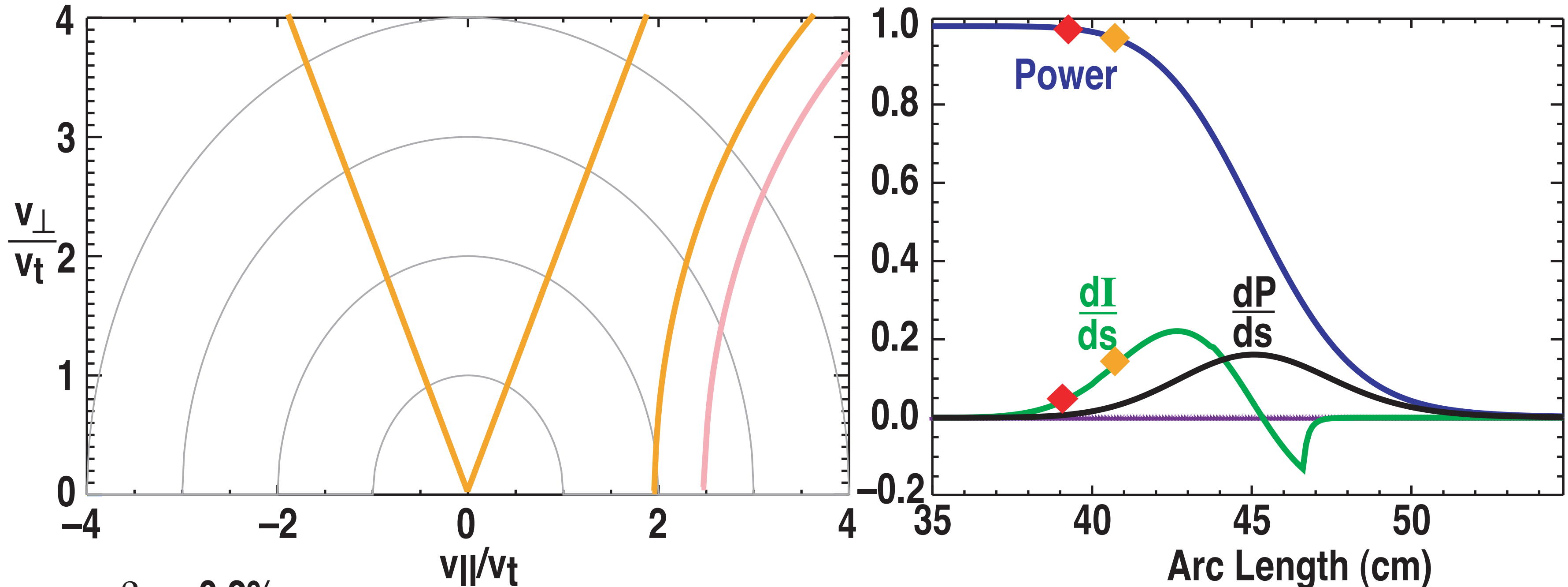

β_e = 0.2%
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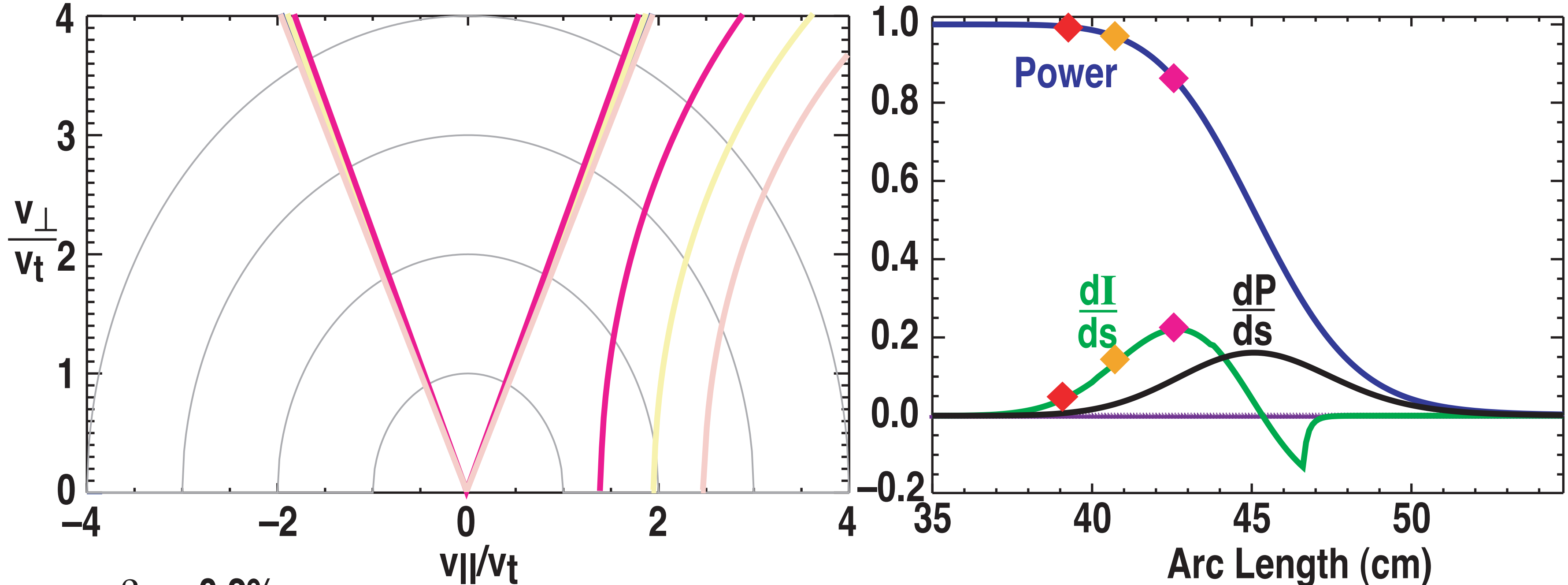

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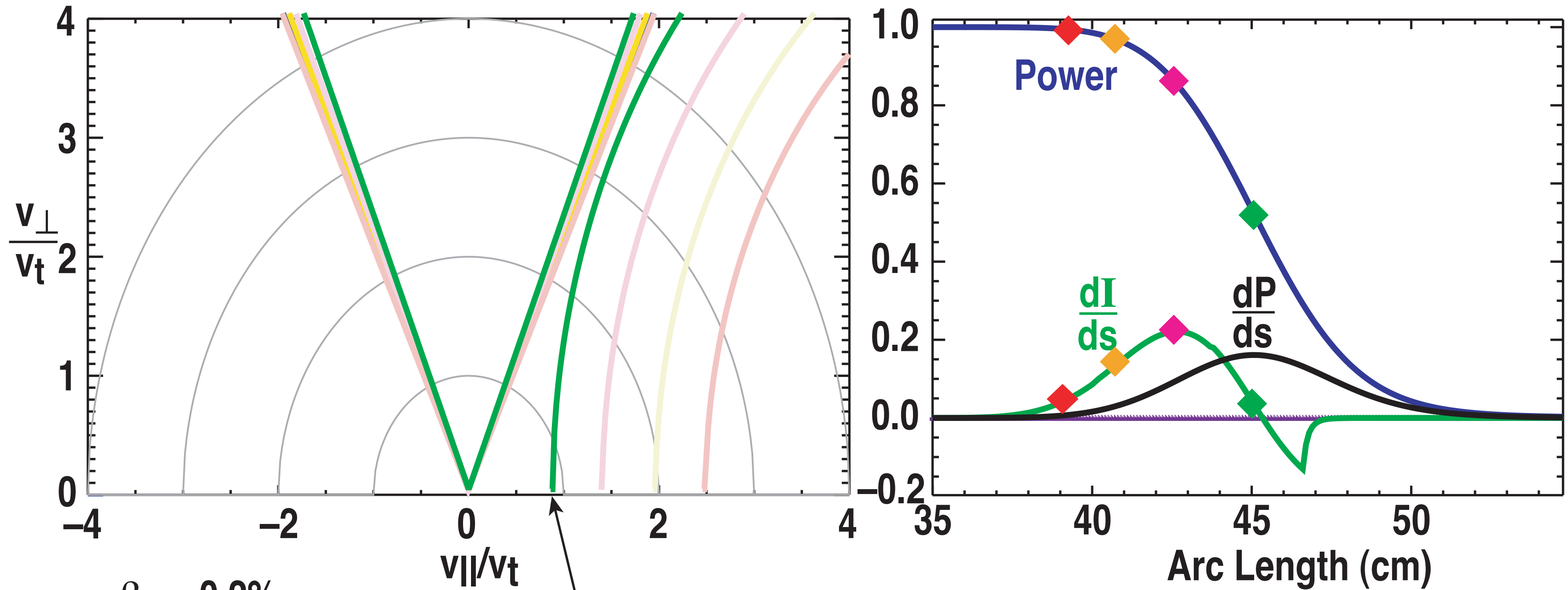
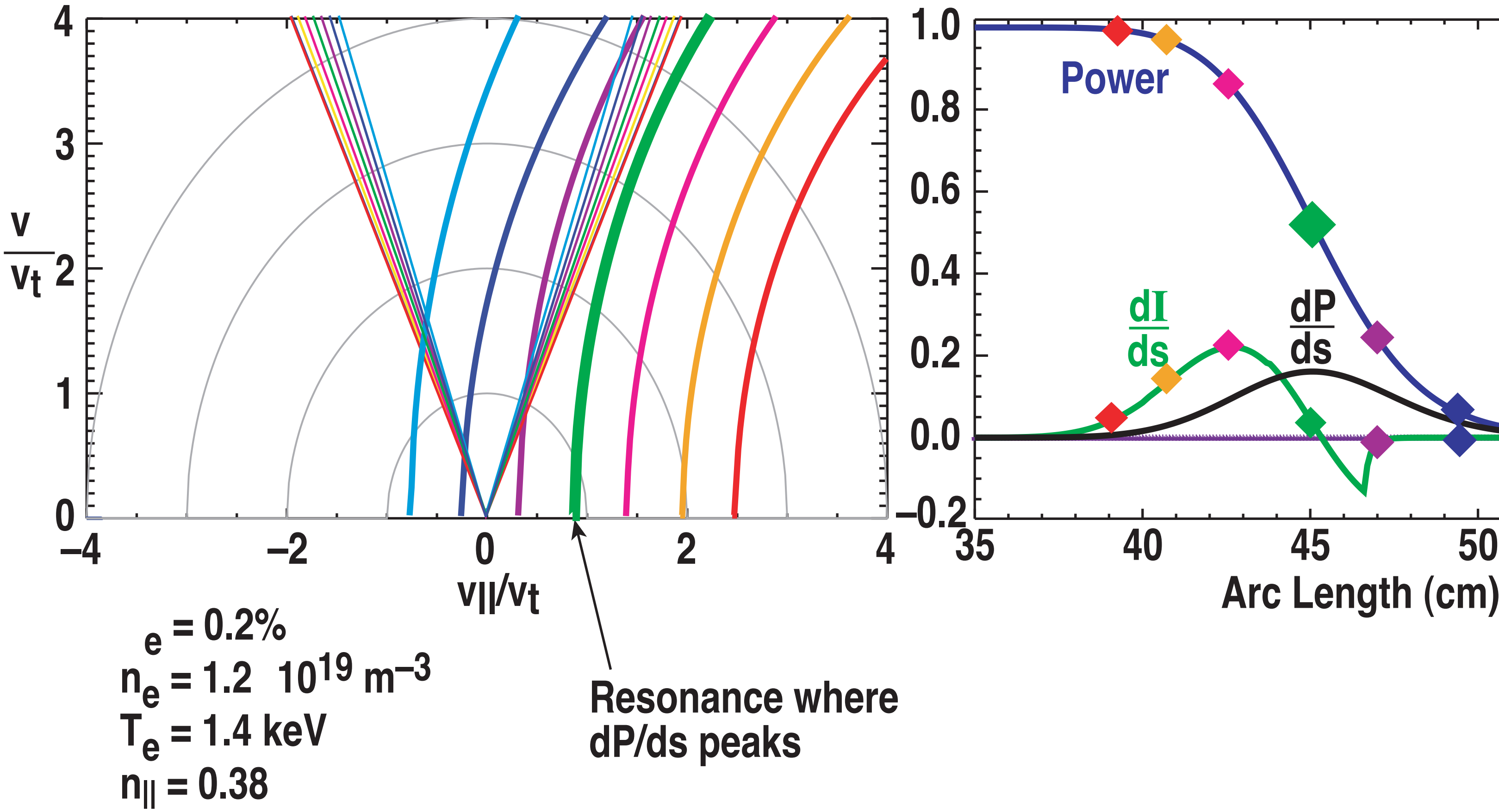


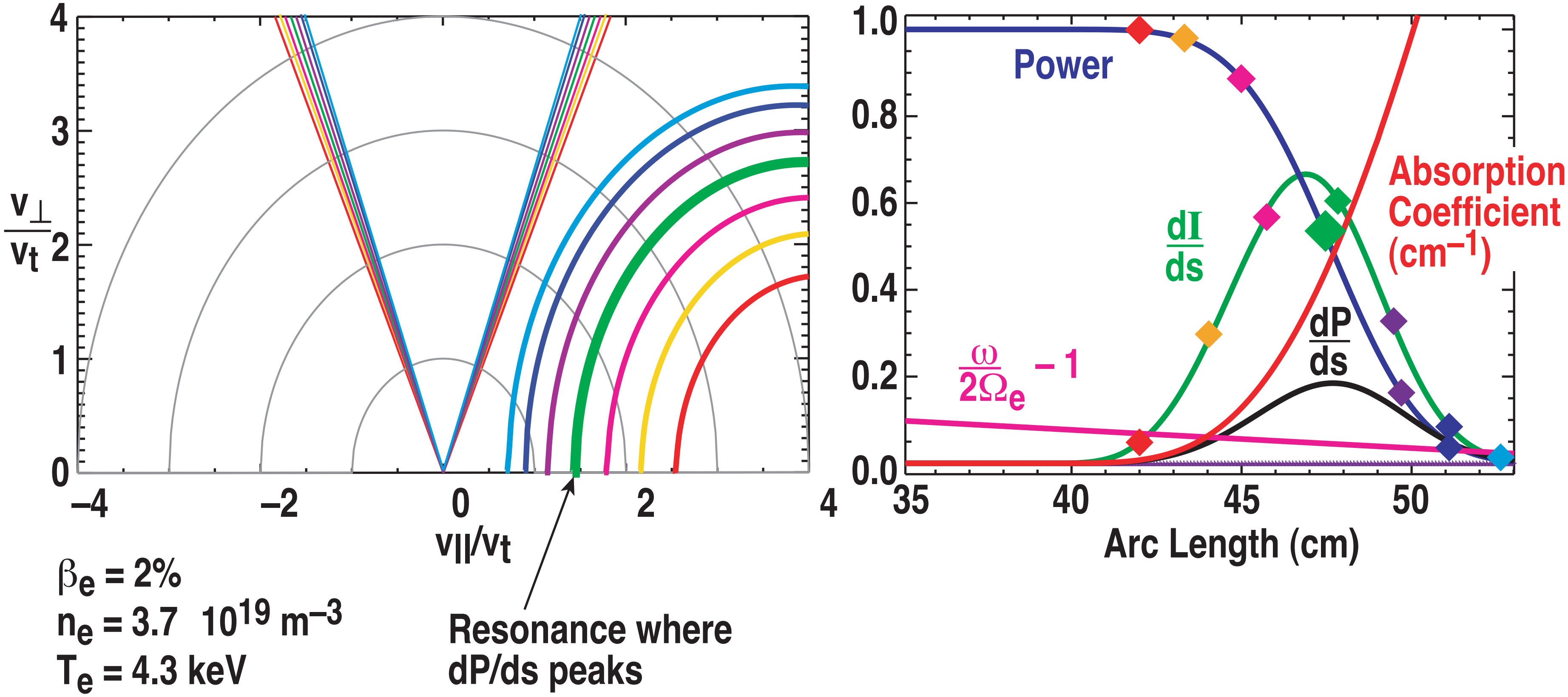
$\beta_e = 0.2\%$
$n_e = 1.2 \quad 10^{19}\ m^{-3}$
$T_e = 1.4$ keV
$n_{||} = 0.38$

Resonance where dP/ds peaks

For Weak Absorption (Low β_e) There can be Large Cancellation of FB Current by Ohkawa Current



For Stronger Absorption (Higher β_e) the Reduction of ECCD by Ohkawa Current is Much Smaller



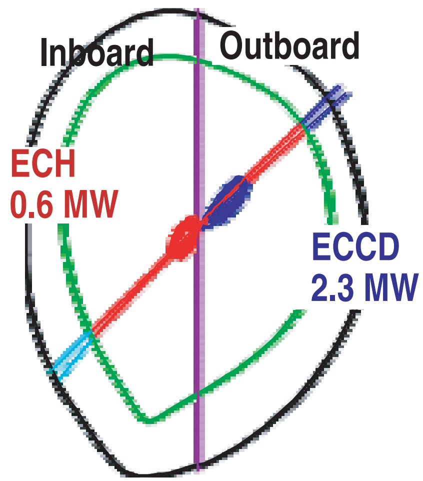
$\beta_e = 2\%$
$n_e = 3.7 \ 10^{19} \ m^{-3}$
$T_e = 4.3$ keV
$n_{||} = 0.38$

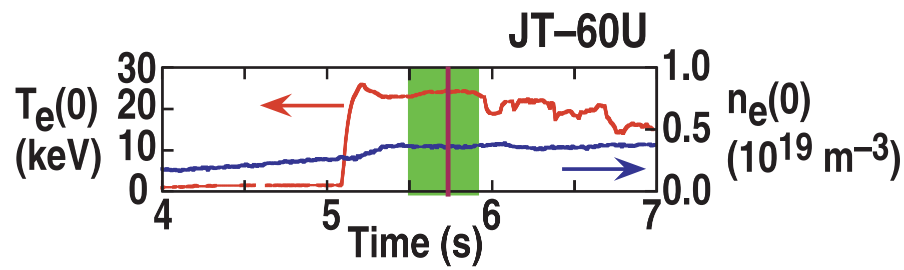
ECCD Theory Provides Solid Basis for Projection to Applications

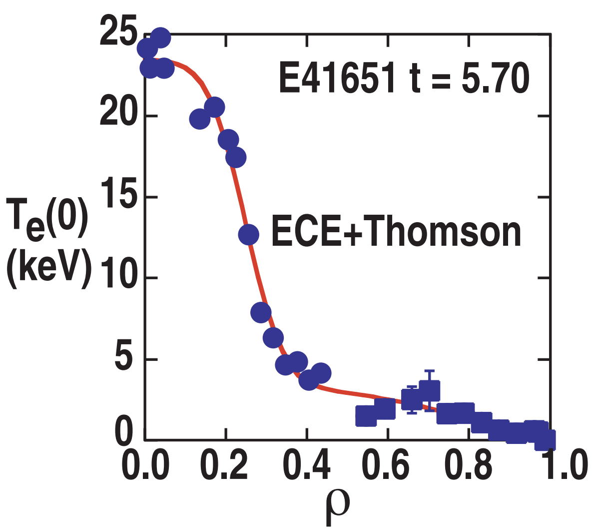
- **Theory is encapsulated in practical computer modeling codes**
- **Theoretical predictions are well supported by experiments**
- **Now we know how to use ECCD for useful applications**
  - Off-axis current drive for optimization of current profile
  - Support of transport barriers to improve confinement
  - Stabiliation of neoclassical tearing modes to raise beta limit
  - On-axis current drive to sustain current

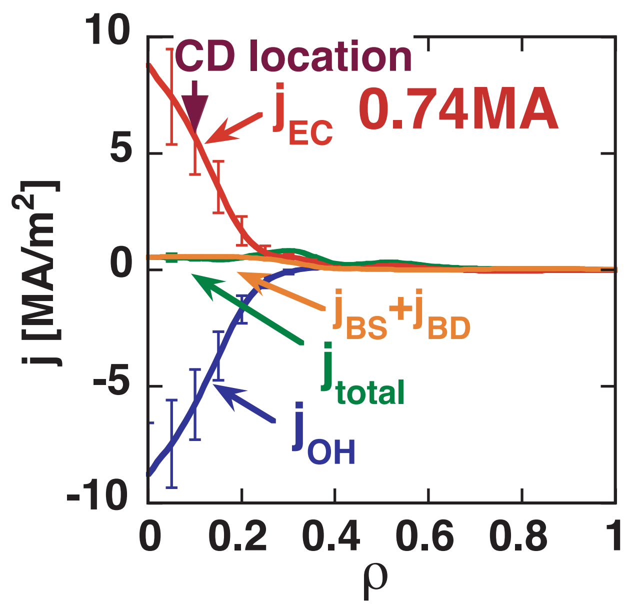
Central ECCD can Support Current

- **ECCD on JT–60U uses ITER mode (O1–mode) at ITER temperature**

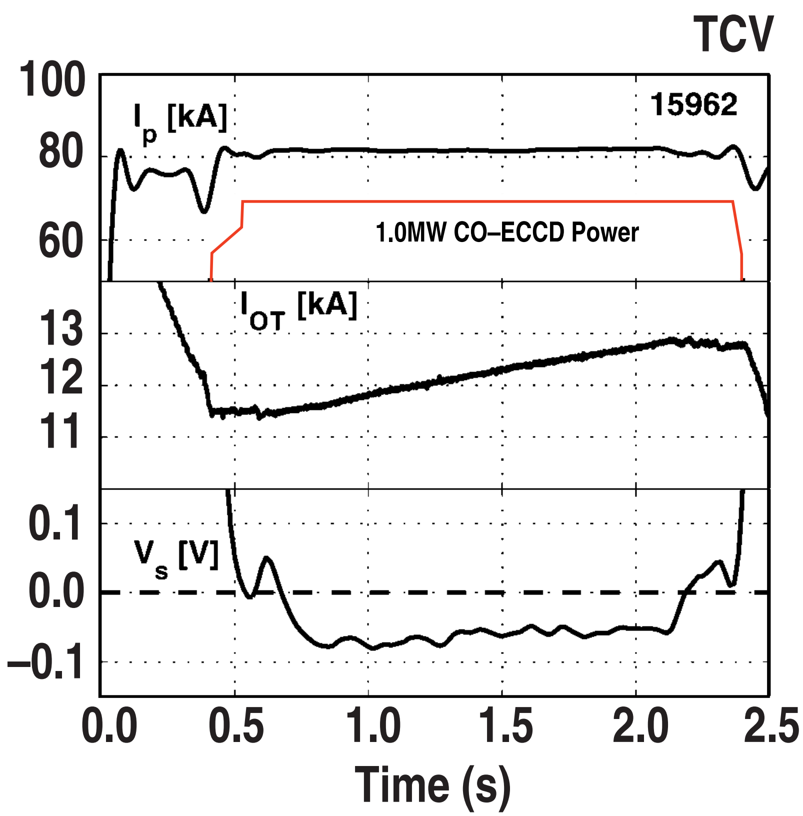






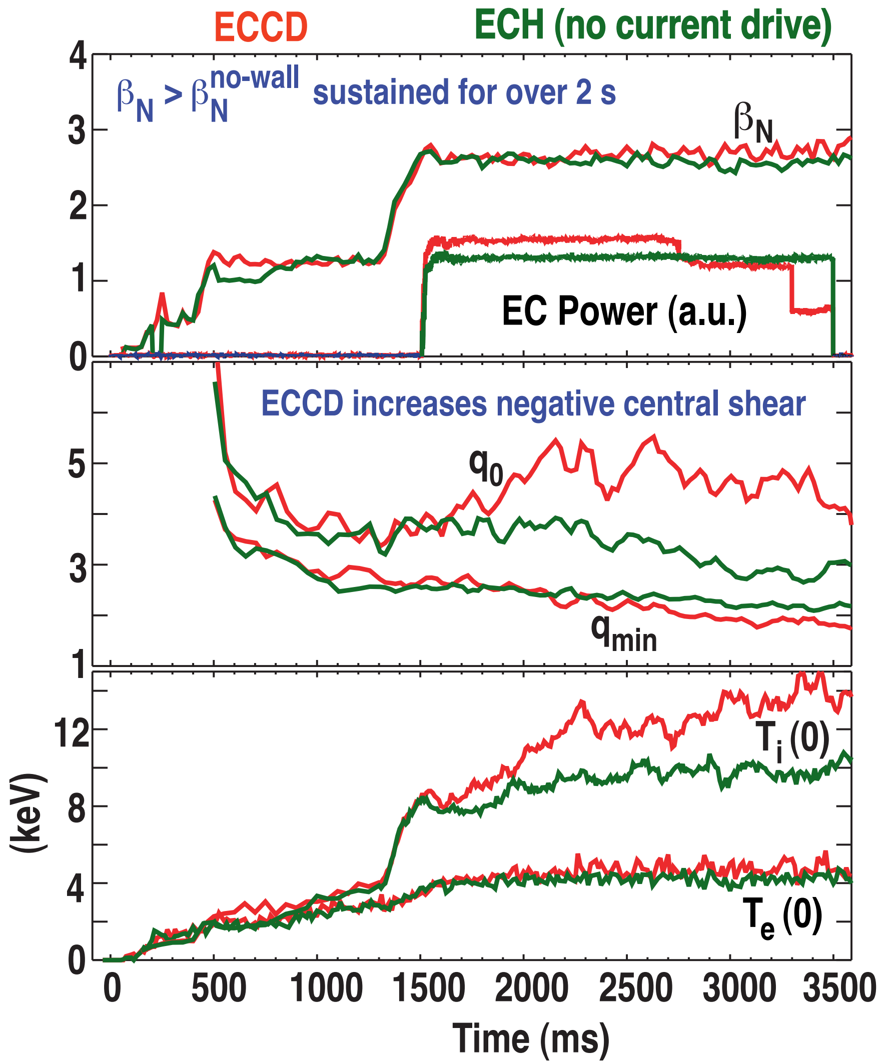


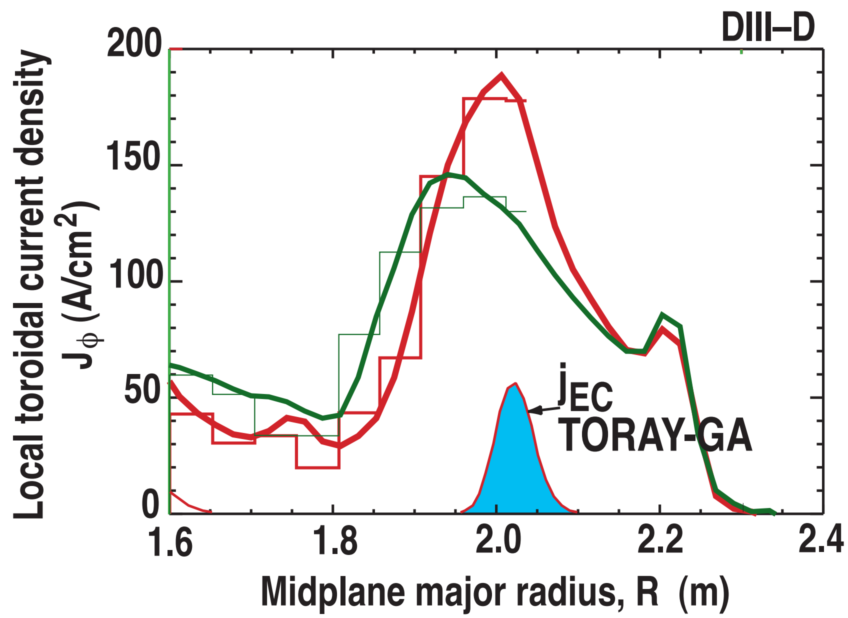
Full Noninductive Current is Sustained in TCV Using ECCD



- 80 kA discharge sustained for 10 current relaxation times, limited by EC source duration
- Surface voltage is negative leading to recharging of the Ohmic heating transformer
- Central currents up to 210 kA can be obtained transiently
- Measured ECCD is five times smaller than theory (CQL3D Fokker-Planck)

The Ability to Modify the Current Density Profile in a High β Plasma Has Been Demonstrated

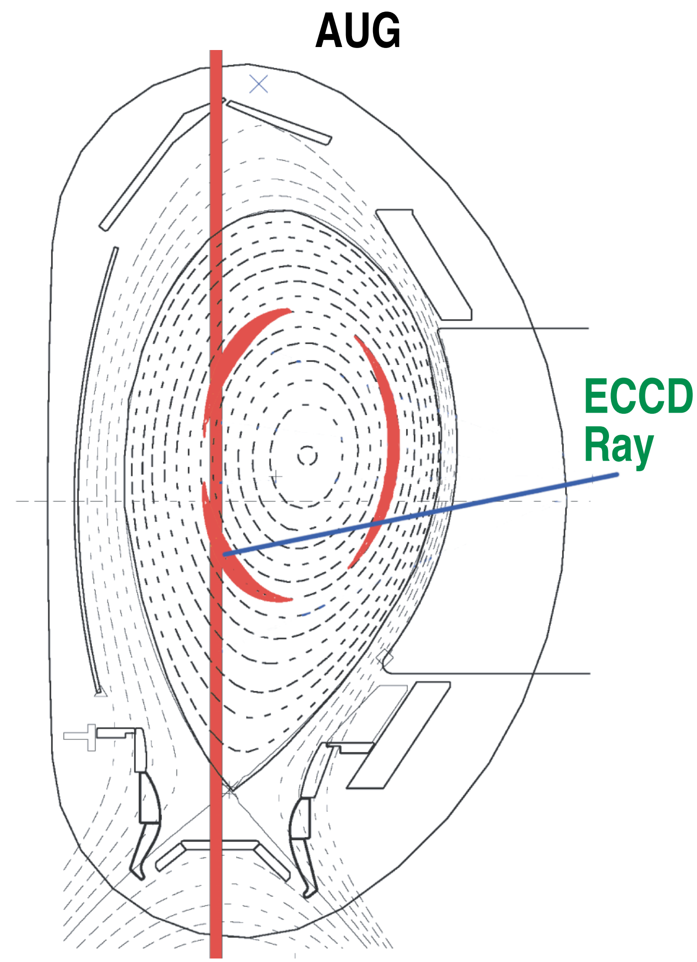




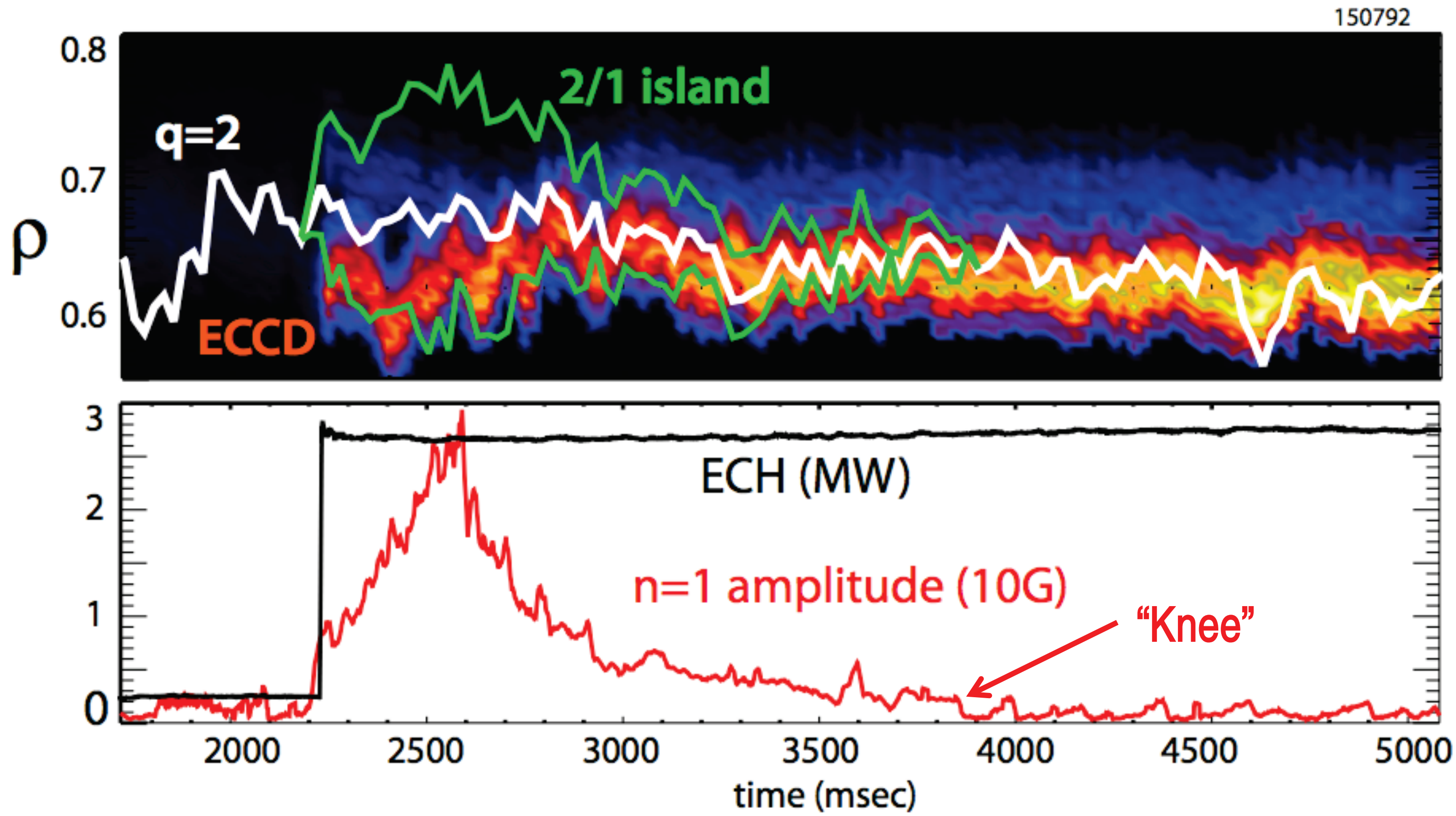
- Off-axis co-ECCD increases negative central shear
- Increased negative central shear leads to increased core confinement
- f_{NI} > 85% with nearly stationary profiles

Pinpoint Localization of EC Power Supports Stabilization of MHD Modes

- **Stabilization of neoclassical tearing modes uses ECCD inside magnetic islands**
  - Leads to higher operation
  - Avoids plasma disruptions (2/1 modes)
- **Accurate placement of ECCD is required to hit island**
  - Real time feedback schemes developed
- **Interaction of wave with instability allows measurement of mode onset conditions and growth rates for comparison to theory**

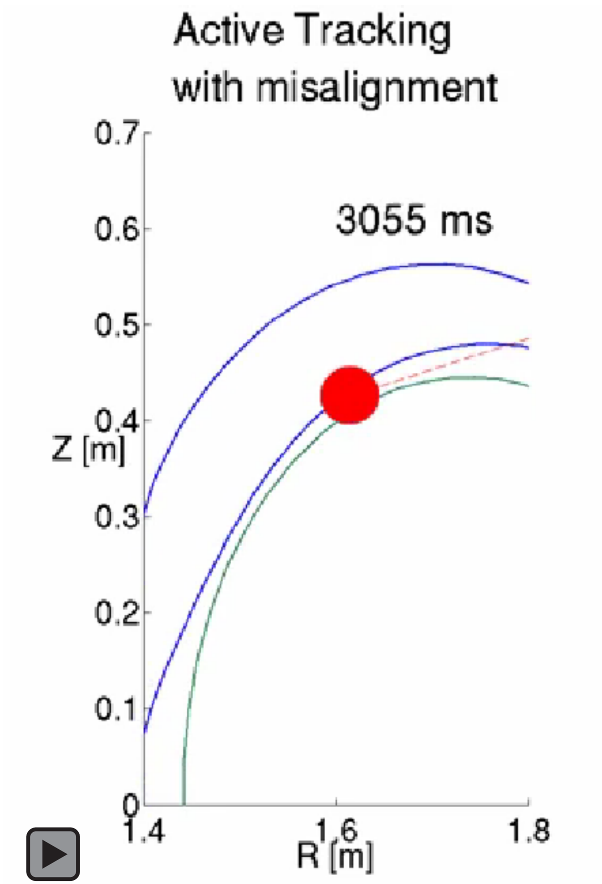


Successful 2/1 NTM Catch and Subdue Demonstrated

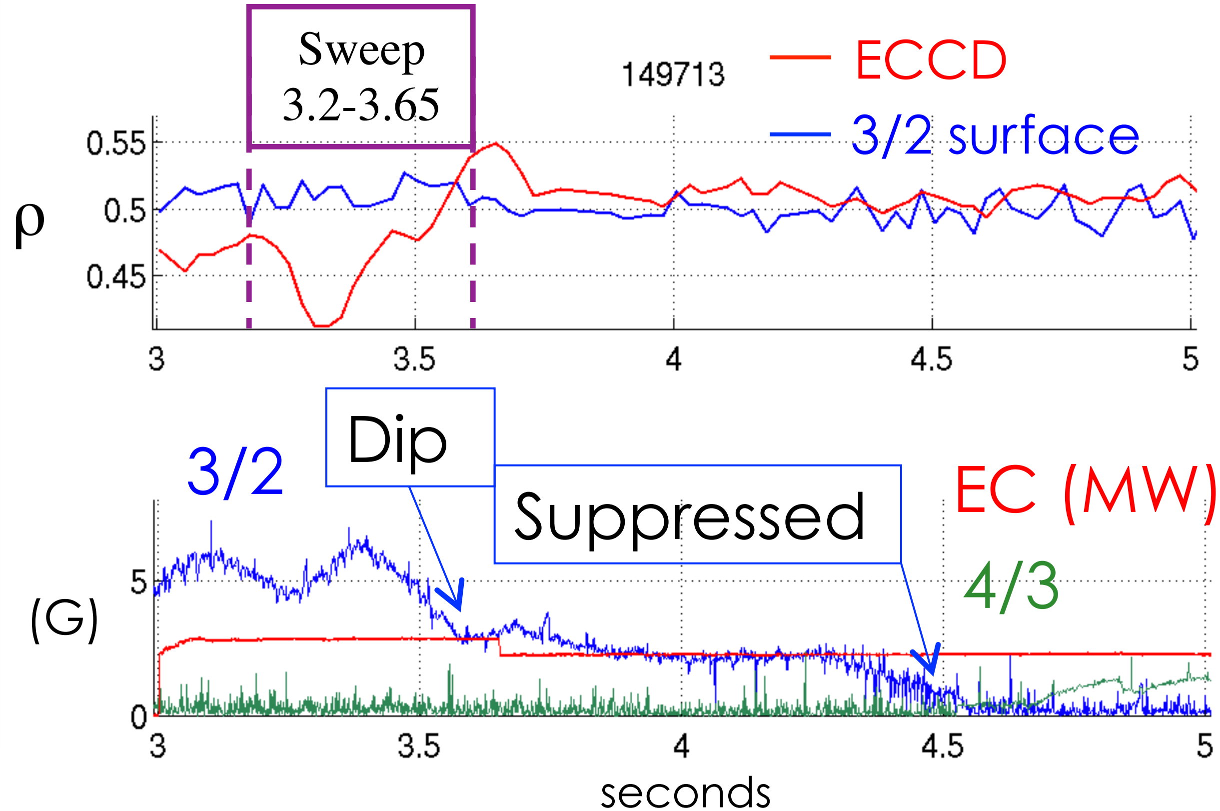


- Peak mode amplitude is reduced; without ECCD, mode reaches ~40 G and locks with loss of H-mode
- The mode is eventually brought to full suppression

When NTM Grows Despite ECCD, Tuning Alignment With The Target Lock Algorithm Can Achieve Suppression



- Decision to sweep ECCD at 3.2 seconds
- Upward sweep 3.25–3.65 seconds
- Best suppression found slightly before dip
- Correction applied at 3.65 seconds



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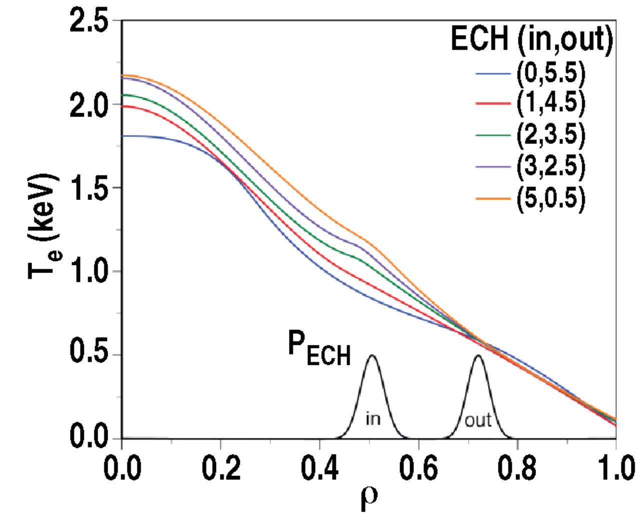
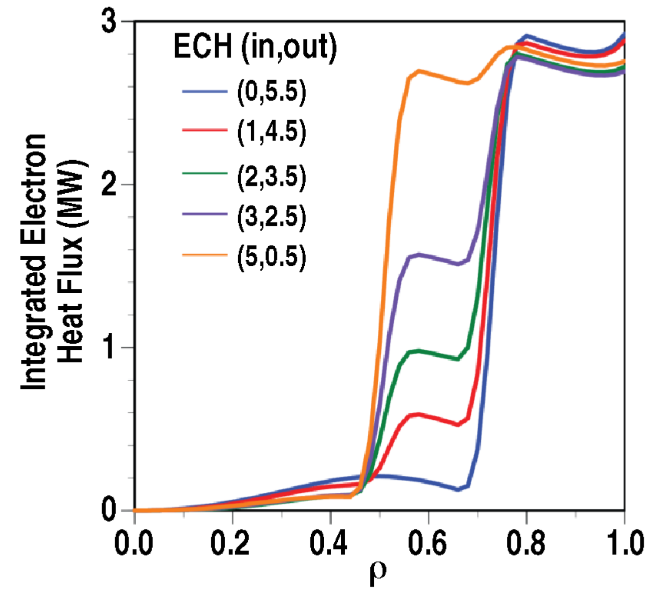
AS Welander/APS/DPP/October 2012

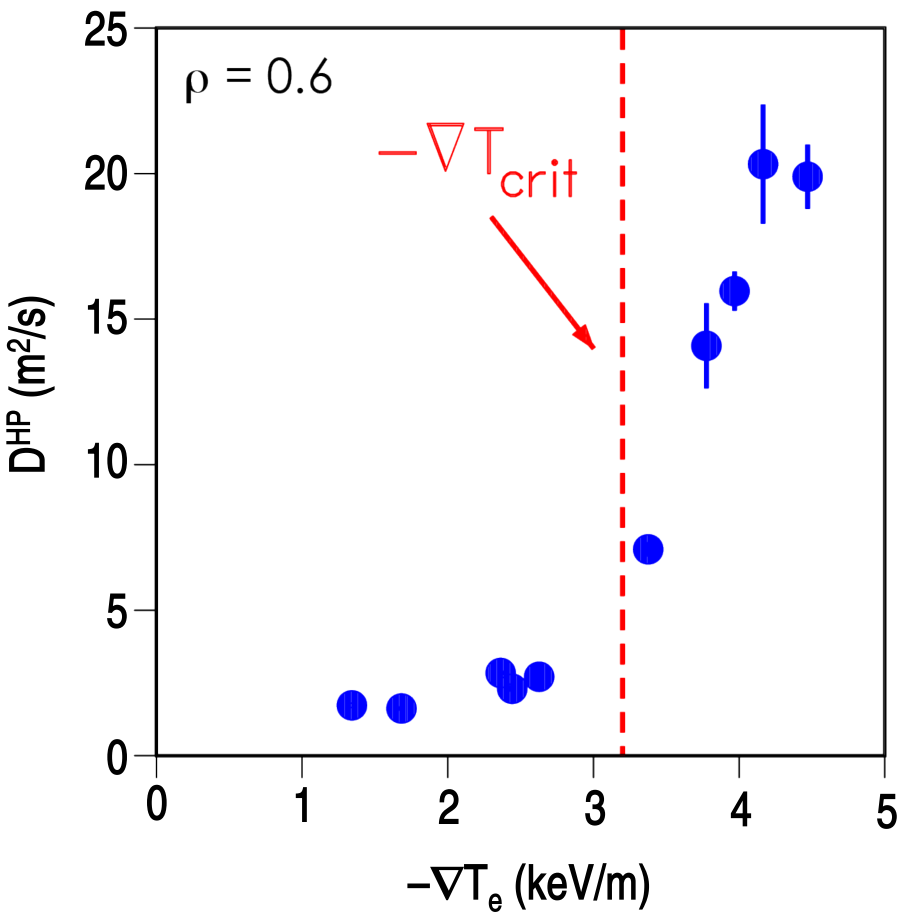
Fundamental Behavior of Drift Wave Turbulent Transport is Tested Using Heat Pulse Propagation

- **Carefully constructed experiment directly probes diffusive transport to test key predicted behaviors:**
  - Instability threshold in ∇T_e
  - Electron transport stiffness
- **Off-axis ECH varies electron heat flux to scan ∇T_e over large range**
  - Moved one gyrotron from outside to inside on shot-to-shot basis
- **Modulated one gyrotron (outside) for measurement of heat pulse propagation**





The "Heat Pulse" Diffusivity at ρ = 0.6 Rapidly Increases for $-\nabla T_e > 3.2$ keV/m — Critical Gradient Threshold?



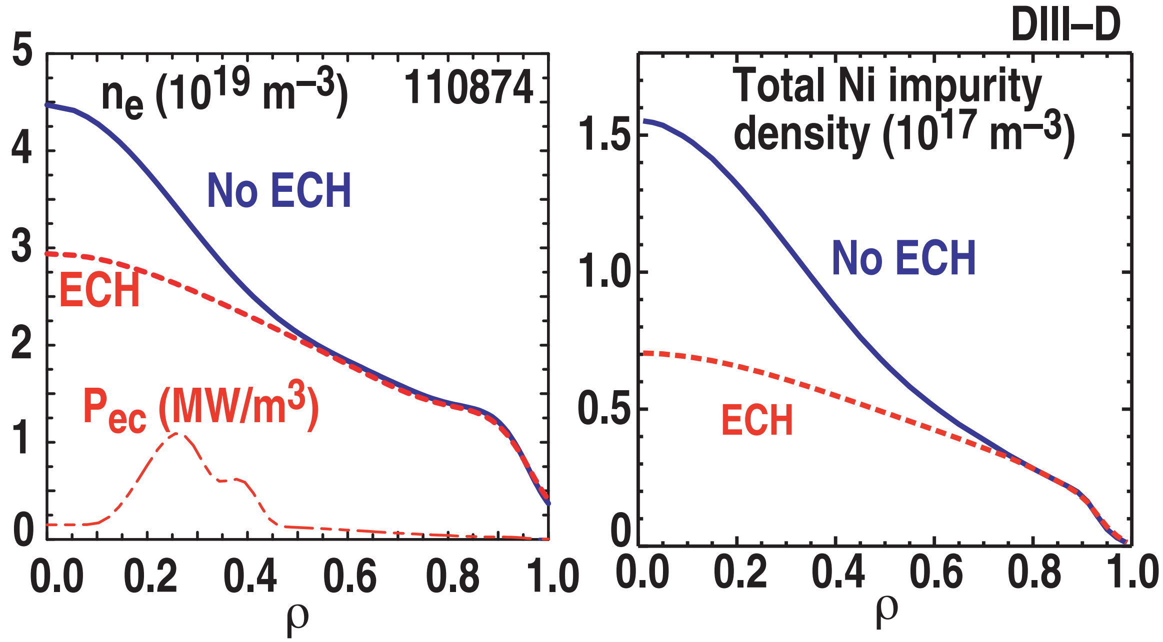
- **Key analysis step is to determine the "power balance" diffusivity by numerical integration of the measured "heat pulse" diffusivity:**

$$D^{\mathrm{PB}} = \frac{1}{\nabla T_e} \int_0^{\nabla T_e} D^{\mathrm{HP}} d(\nabla T_e)$$

- **This yields the purely diffusive portion of the equilibrium heat flux**

ECH May Affect Density Profile

- **Rearrangement or loss of density when ECH is applied has been seen in tokamaks since 1976 (T–10) but is not understood**
  - Not a universal effect
  - Related to transport (T_e/T_i?)
  - Physics understanding is a key need



- **"Density pumpout" can be used as a control tool in experiments**
  - Reduce density peaking to increase β limit
  - Reduce Z_{eff}

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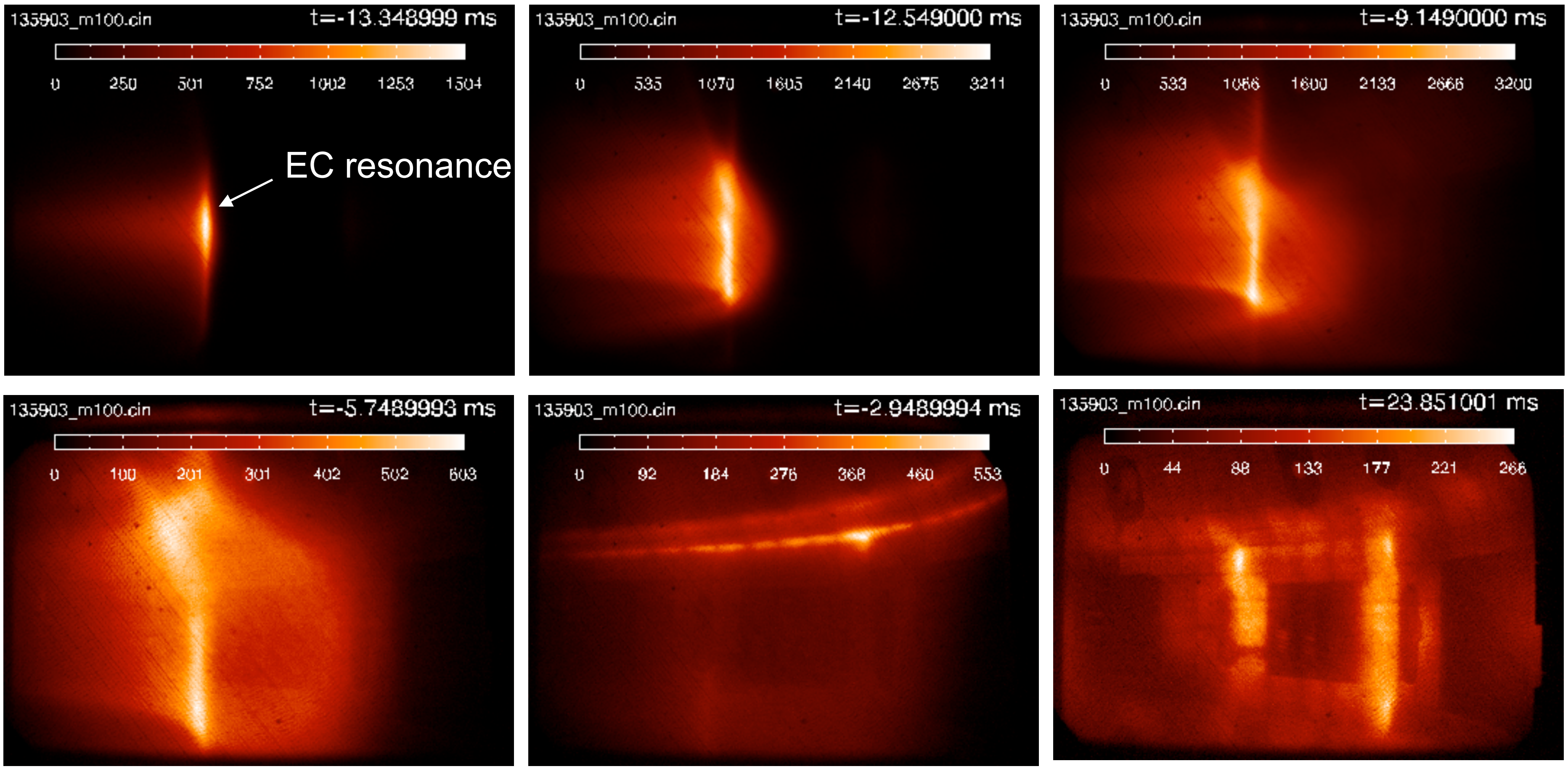
Fast camera tangential view of startup with EC assist

135903, D alpha filter, 5000 fps, 195 μs exposure

J. Yu, UCSD



Practical requirements for an ECH system

- **Power source—gyrotrons**
  - superconducting magnets
  - power supplies
- **Transmission of power to the tokamak**
  - waveguide or quasioptical
- **Match incident polarization to desired mode**
- **Model wave propagation, absorption, and current drive**
  - linear; eg, TORAY or GENRAY
  - quasilinear; eg, CQL3D
- **Set launch angles to accomplish physics goals**
- **Integrate ECH into tokamak control system**

References

- **Huge body of literature in theory and experiment**

- **Review papers:**

  - M. Bornatici, et al., Nucl. Fusion **23**, 1153-1257 (1983)
  - N.J. Fisch, Rev. Mod. Physics **59**, 175 (1987)
  - V. Erckmann and U. Gasparino, Plasma Phys. Control. Fusion **36**, 1869-1962 (1994)
  - T.C. Luce, IEEE Trans. Plasma Sci. **30**, 734-754 (2002)
  - R. Prater, Phys. Plasmas **11**, 2349-2376 (2004)

Conclusions

- **ECH and ECCH have a solid theory base**

- **The theory has been validated against experiment in considerable detail for parameters representative of today's tokamaks and stellarators**

- **Much of the physics can be understood from the cold plasma dispersion relation, but absorption and current drive require kinetic description**
  - The Fokker-Planck description is an excellent predictor of performance, and it also provides insight into the physics

- **Coupling to the plasma is not an issue**

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