ICRF Heating and Flow Generation in DT Plasmas

J. R. Wilson

Princeton Plasma Physics Laboratory

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1996-97 RF Research Focused on Possible Profile Control Techniques

- Attempt to control transport barriers directly
  - Use direct ion Bernstein wave (IBW) heating (ala PBX-M)
- Current profile control
  - Explore mode conversion CD in DT plasmas:
  - Eliminate competition from ^{7}Li ions (present in TFTR from machine conditioning techniques) which was believed to plague earlier experiments

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Principal Results of these Experiments are:

- Successful IBW wave coupling was found to be sensitive to poloidal phasing.
- Elimination of ^{7}Li ions resulted in efficient mode conversion heating in DT plasmas.
- Localized poloidal flows were observed with both direct IBW and mode conversion heating.

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Direct IBW Heating Experiments

- Past experiments on other devices have found heating and wave coupling to be difficult

- Two Coupling Regimes Explored
  – Electron plasma wave (EPW)
  – Cold electrostatic ion cyclotron wave (CESICW)

- Two Antenna Phasings Explored
  – Four straps phased (0,0,0,0) or $(0,0,\pi,\pi)$

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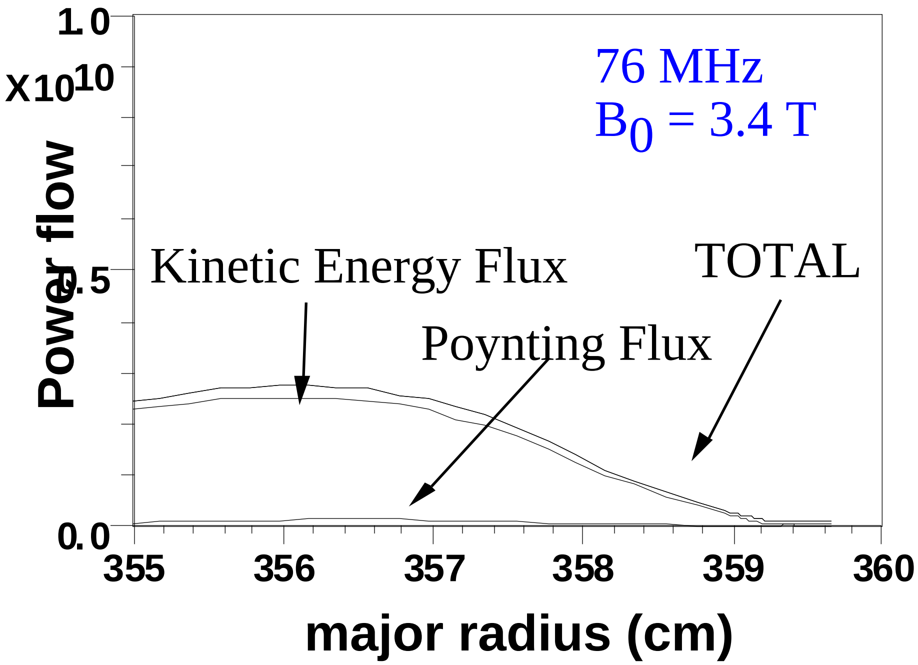
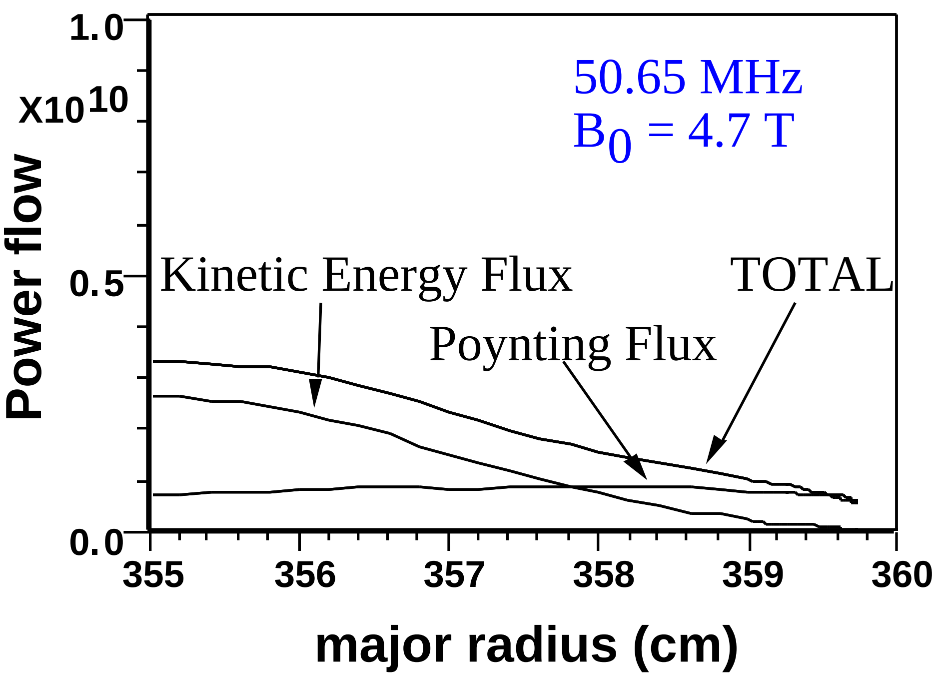
Two IBW Launch Scenarios Attempted

Electron Plasma Wave Launch



Cold Electrostatic Ion Cyclotron Wave Launch



- EPW launch consistent with localized ion heating on LFS (desired for CH mode), but very sensitive to edge density profile.
- CESICW launch is less sensitive to the edge density profile and has greater power flux at the edge.

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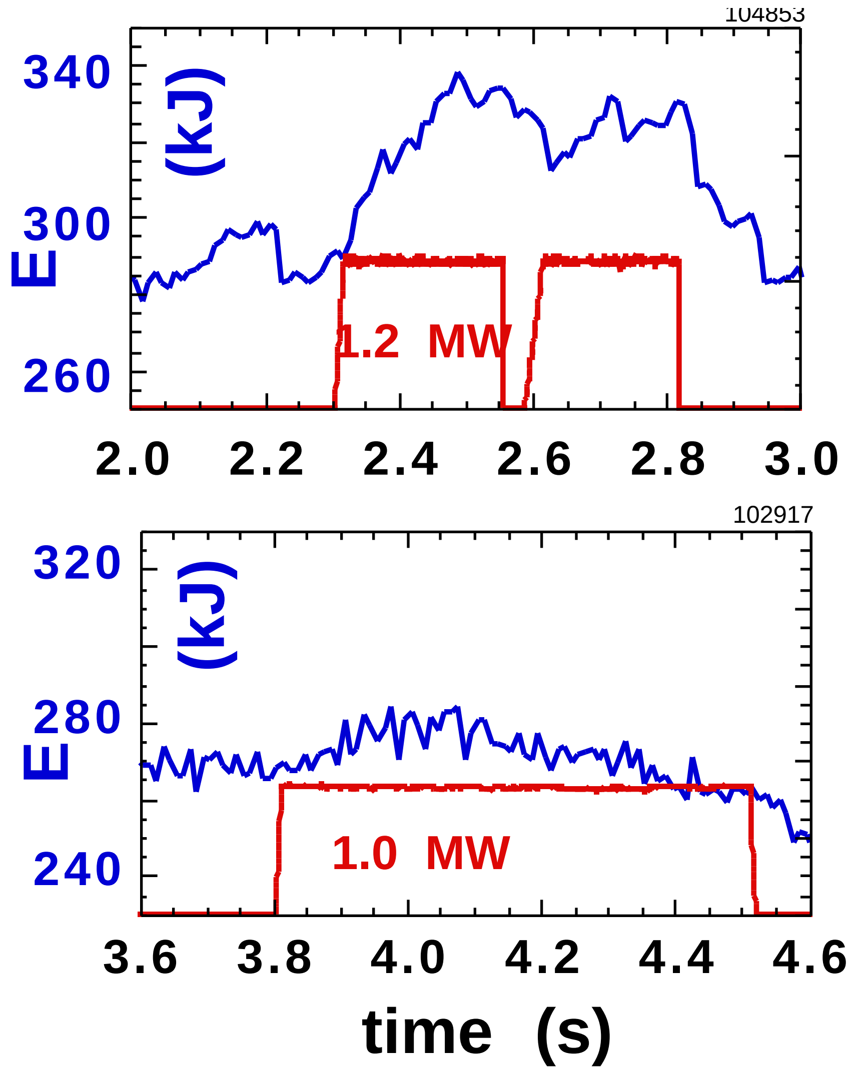
Coupling Improved with 0/0/π/π Phasing



- 0/0/π/π phasing
- 0/0/0/0 phasing

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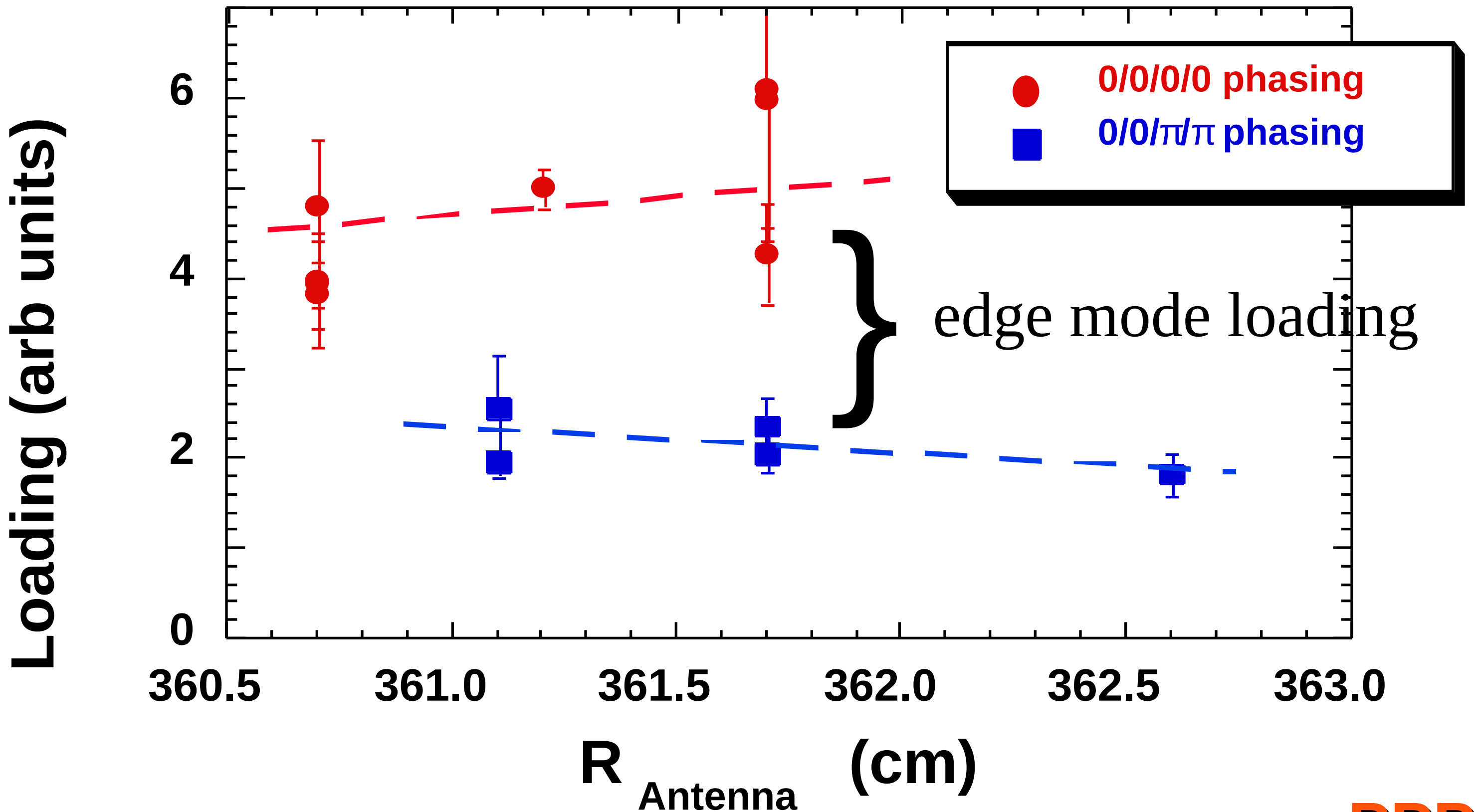
Loading Affected by Poloidal Phasing

Better Core Heating with Lower Loading - indicates edge modes



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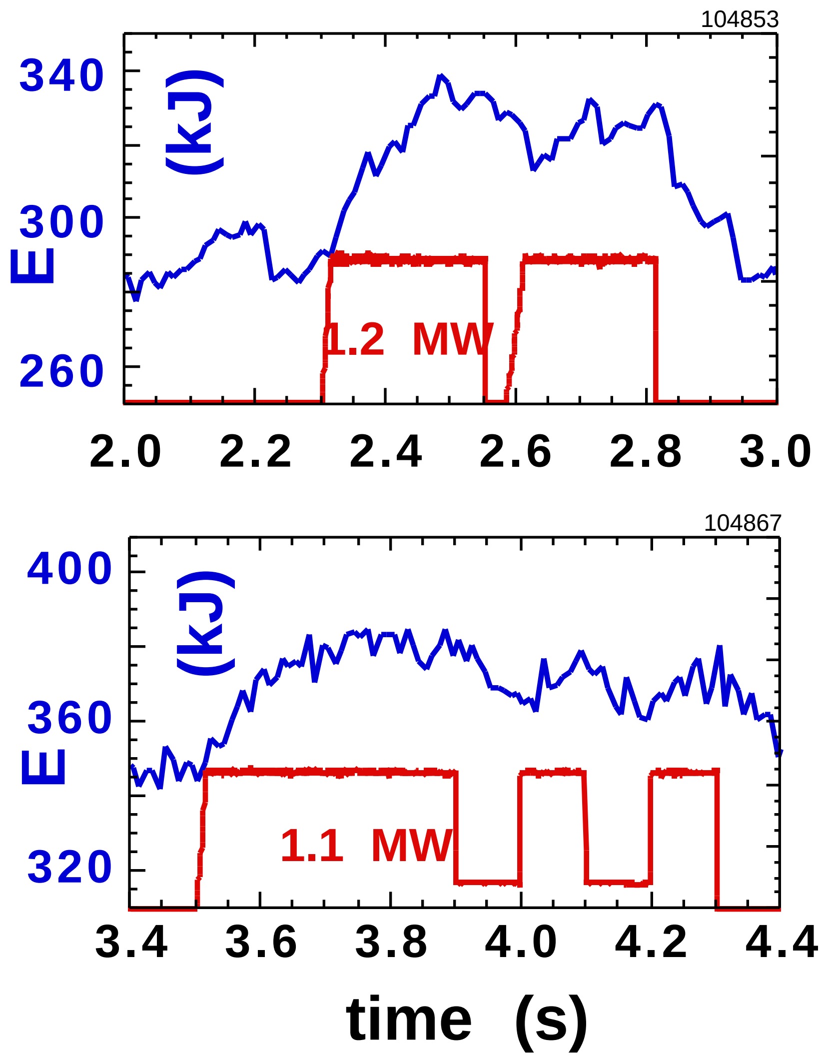
Similiar Coupling with EPW and CESICW



- **EPW launch**
  - > **0/0/π/π**
  - > **50.65 MHz**
  - > **B_0=2.4 T**
- **CESICW launch**
  - > **0/0/π/π**
  - > **50.65 MHz**
  - > **B_0=4.7 T**

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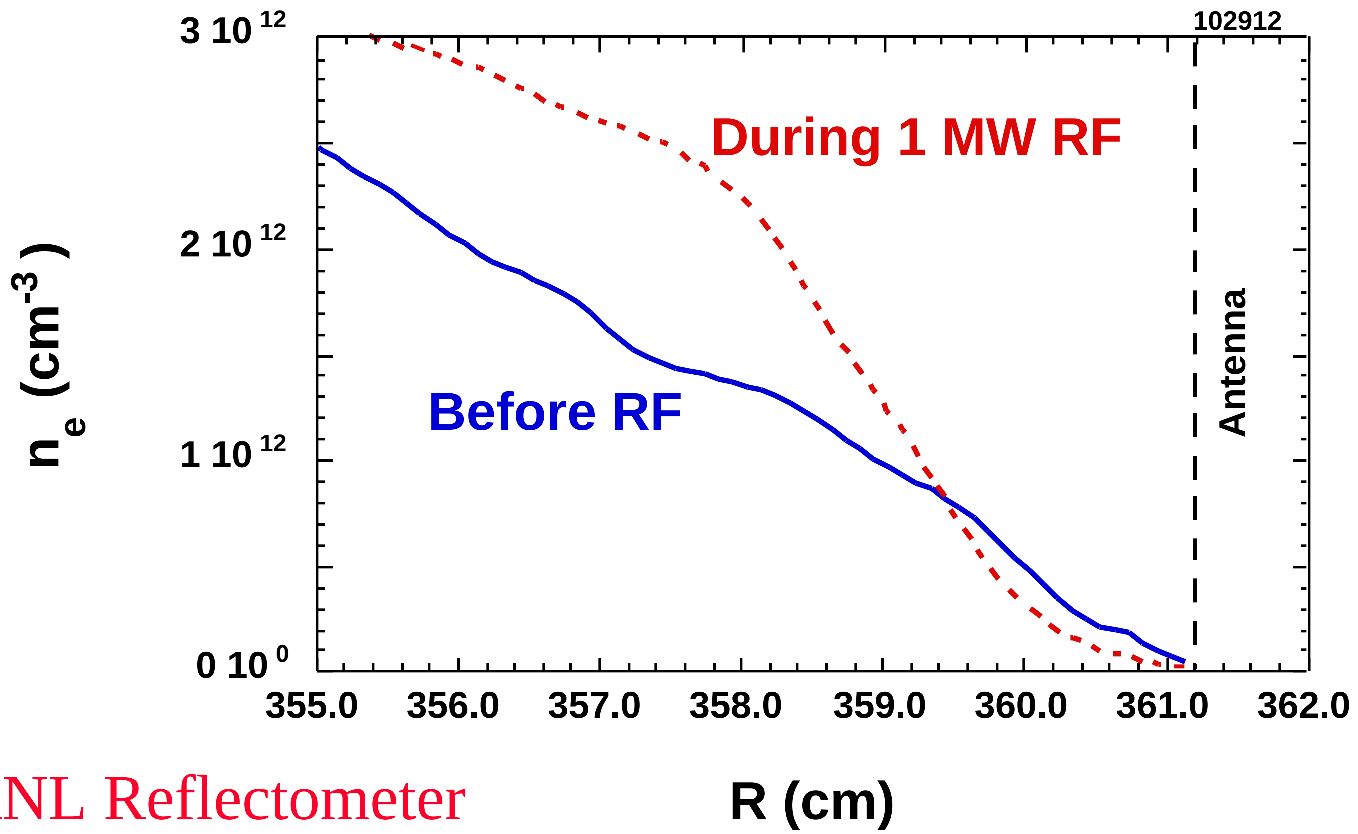
Measured Edge Density Profile Consistent with Theory for Good Coupling

- **Edge density modification consistent with Ponderomotive force.**
- **Independent of phasing**



ORNL Reflectometer

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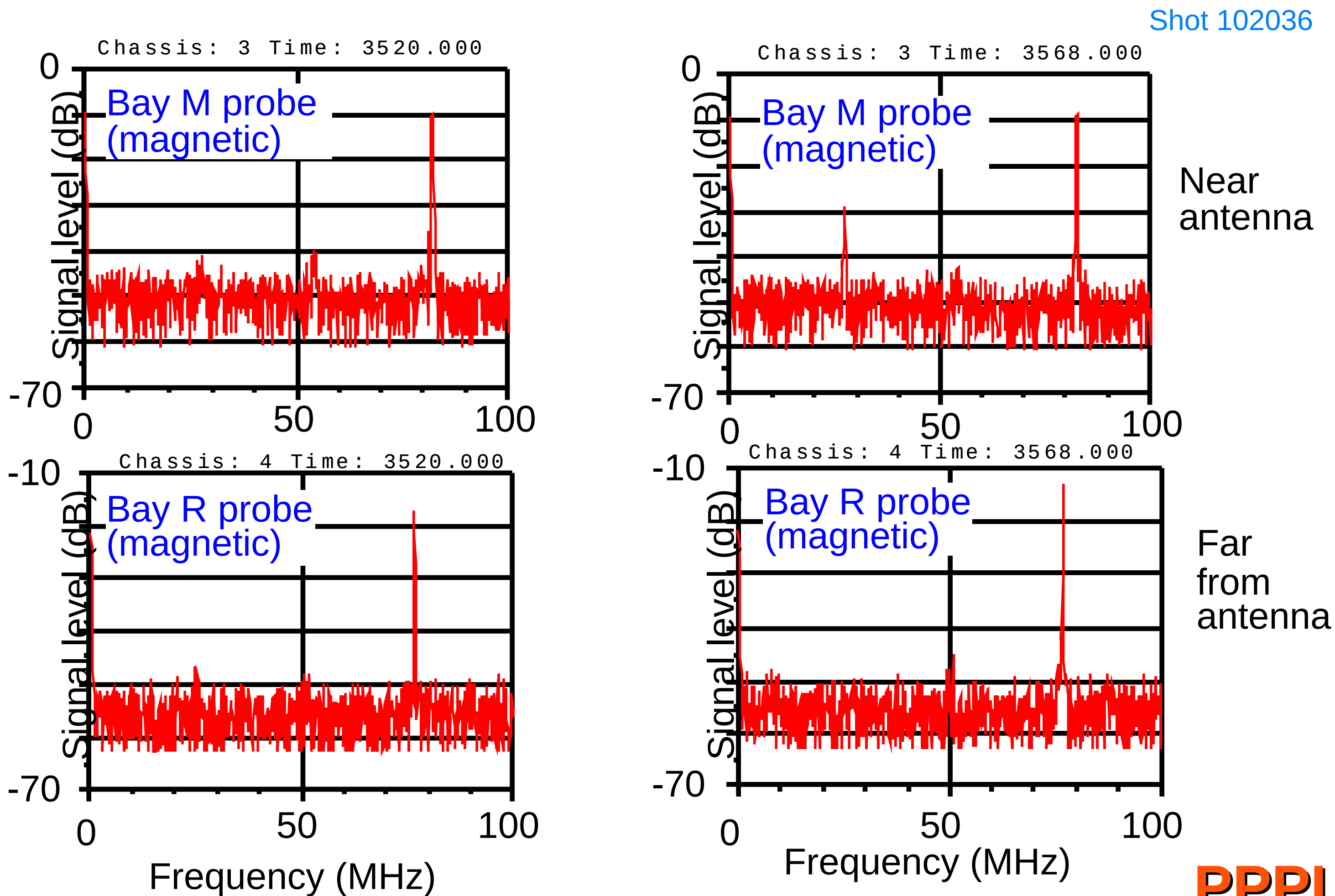
RF probes indicate comparable wave amplitude near and far from antenna

- **Decay instabilities are observed sporadically**



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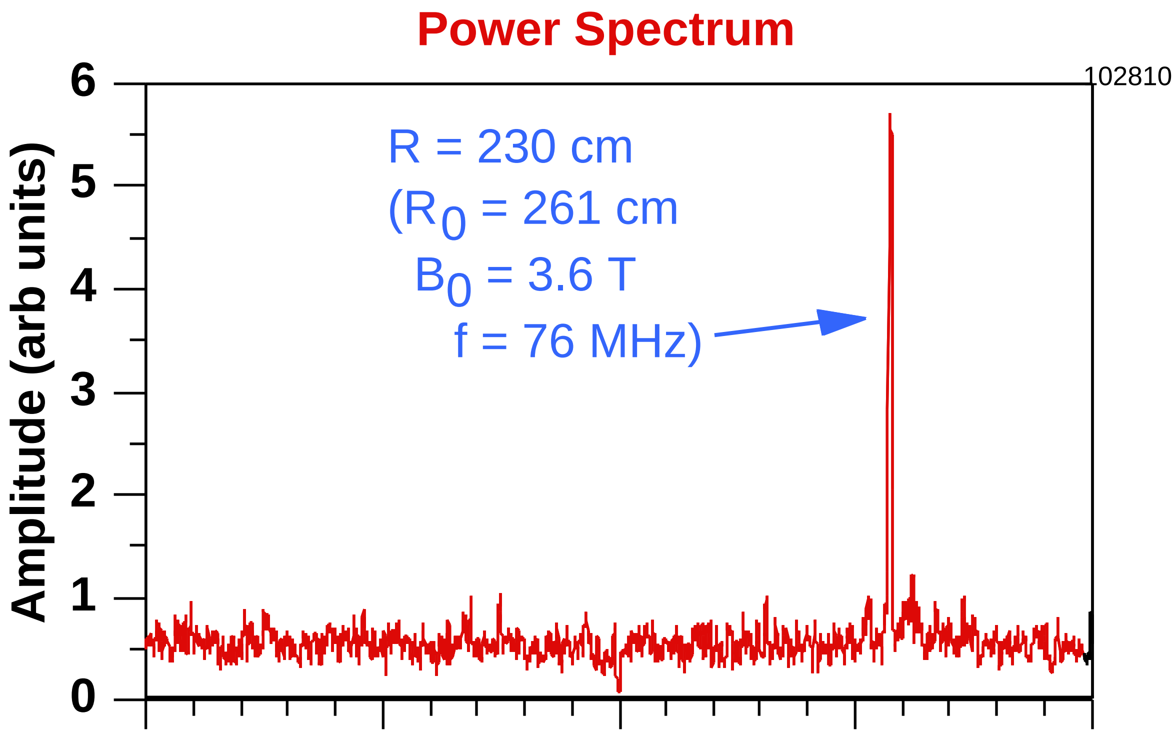
With EPW launch, core reflectometer only observed wave on high field side



- **Wave signal on high field side cannot be IBW, suggests surface wave.**

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IBW Summary

- Antenna phasing is observed to have the strongest effect on IBW Heating and loading
- Parasitic surface wave excitation is a strong candidate to explain the low efficiencies observed

Mode Conversion Heating and Current Drive

- $D\text{-}He^3$ experiments demonstrated that Mode Conversion of the fast wave to a IBW can result in efficient localized heating and current drive on and off axis.
- Initial D-T mode conversion experiments did not behave as expected.
- ^7Li ions present from machine conditioning were believed to be responsible for this behavior.

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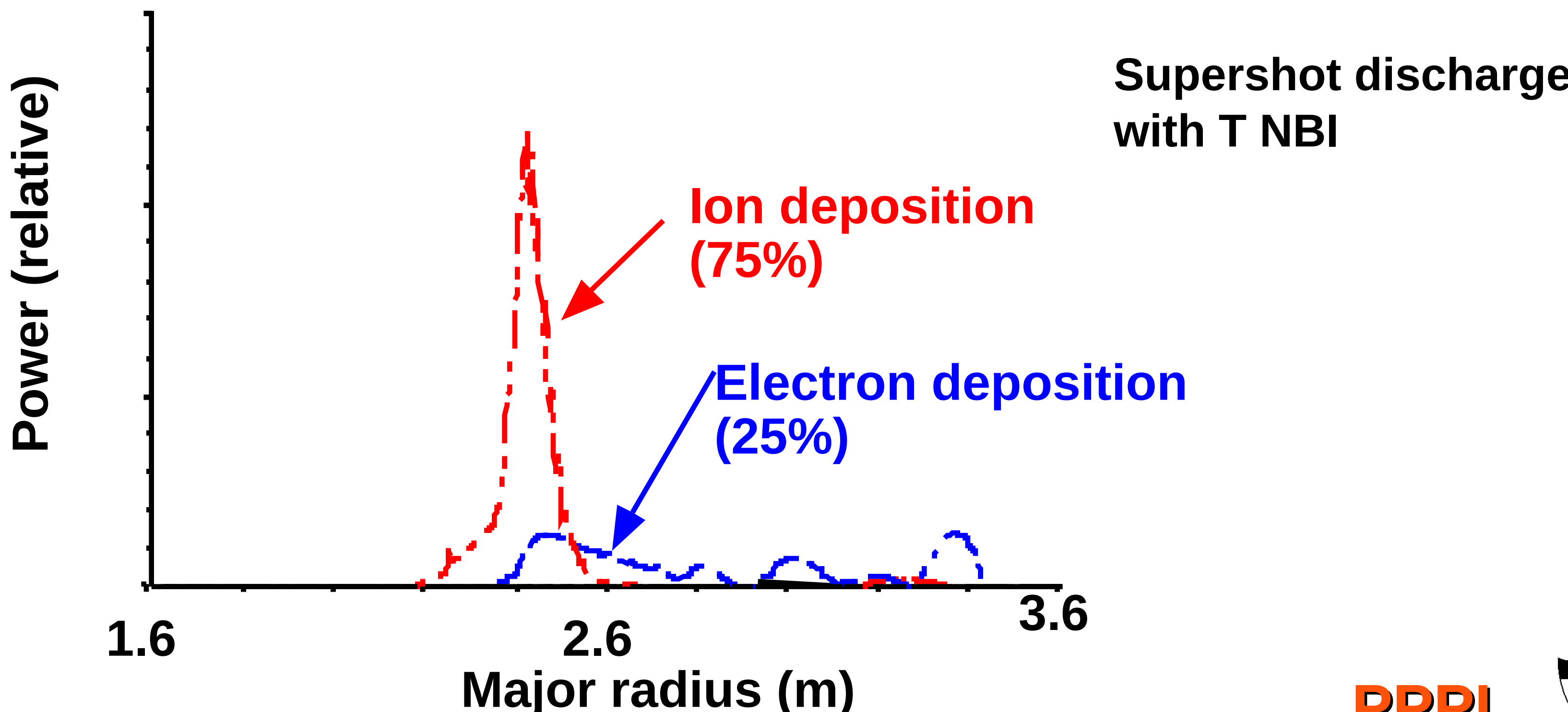
Mode converted IBW will damp on ions for $T_i > 30$ keV

- **Modeling with FELICE (M. Brambilla) for $T_i = 30$ keV + 25% beam ions, $T_e = 8$ keV, $B_0 = 5.1$ T, $n_e(0) = 4.5 \times 10^{19}$ m^{-3}**



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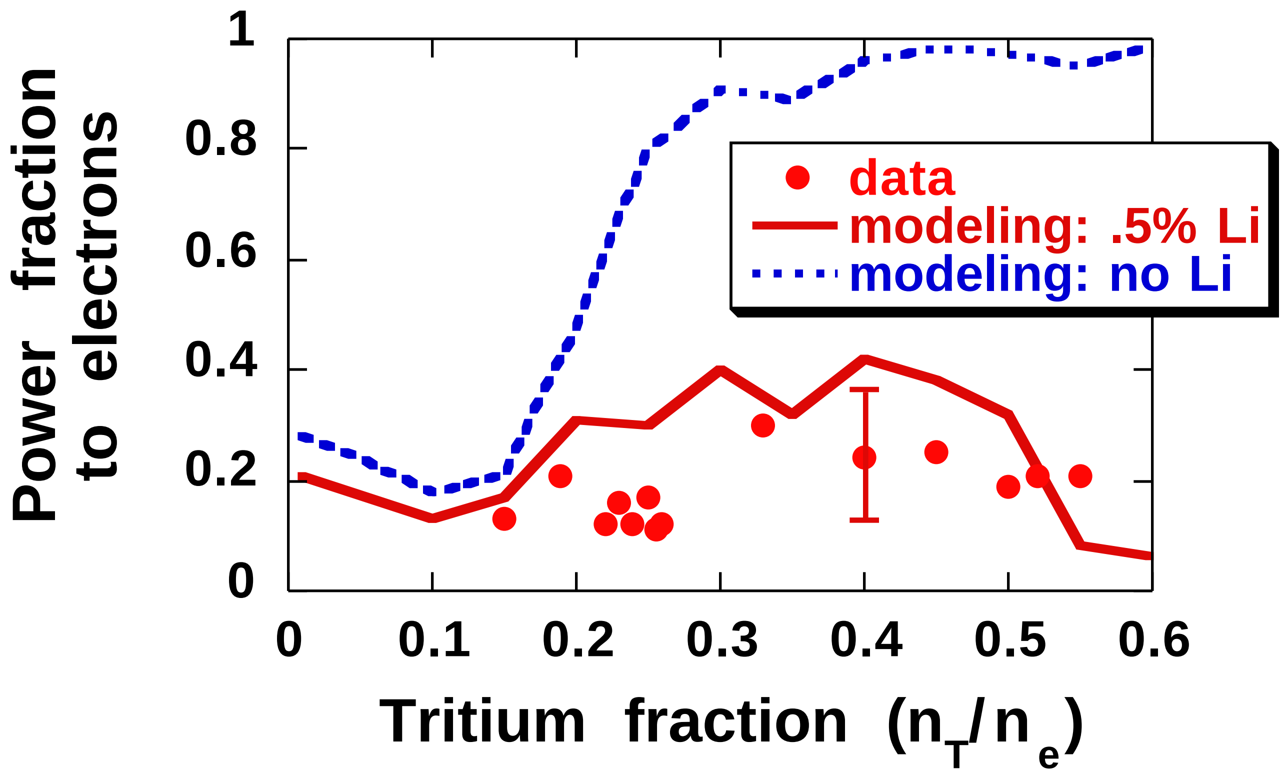
DT Mode Conversion was dominated by ^{7}Li Damping



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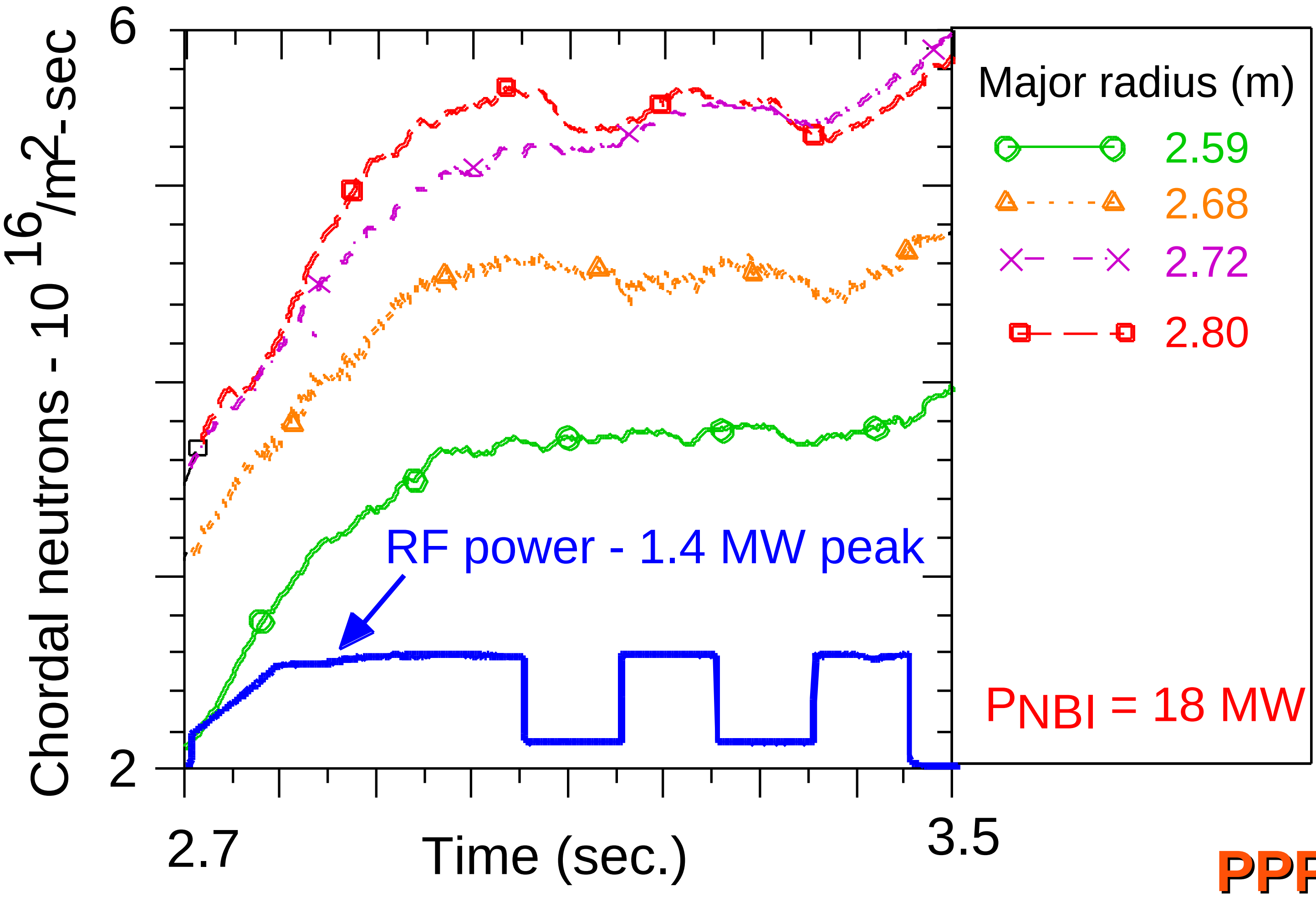
D-T MC with hot ions affects the core strongly enough to modify neutron rate

Consistent with a ~5 keV modulation in the ion temperature



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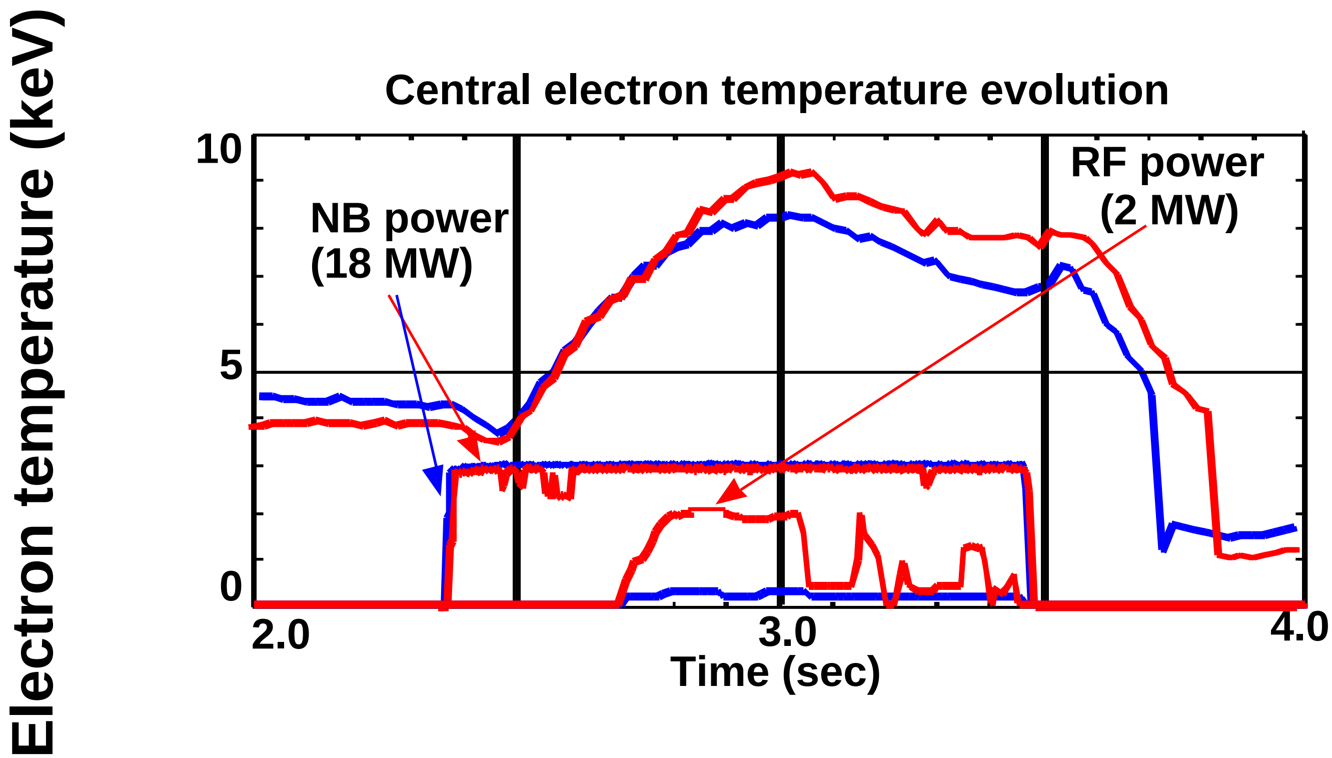
Lower Target Ion Temperature leads to Electron Heating



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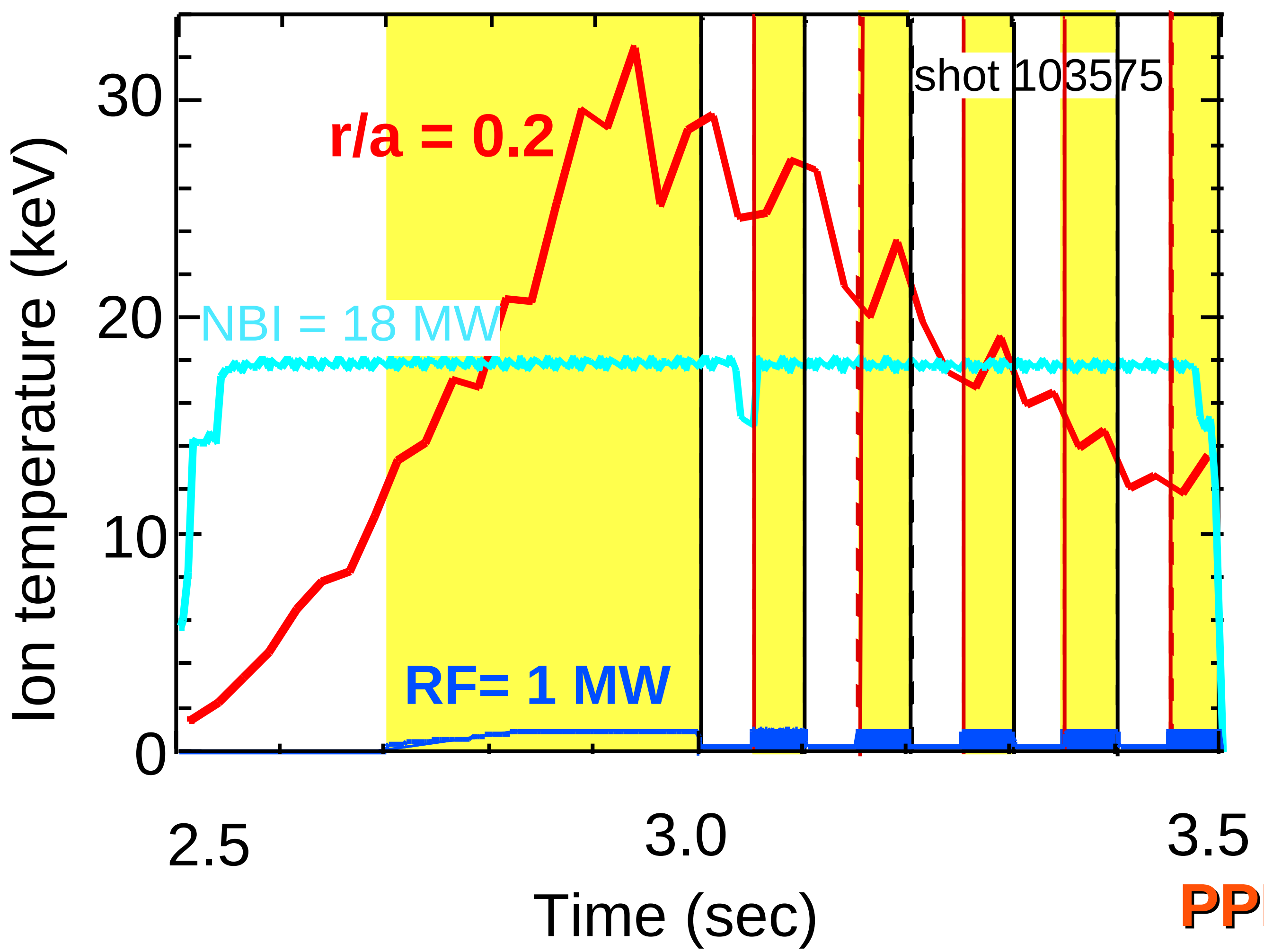
D-T mode conversion experiments show evidence for strong, localized ion heating



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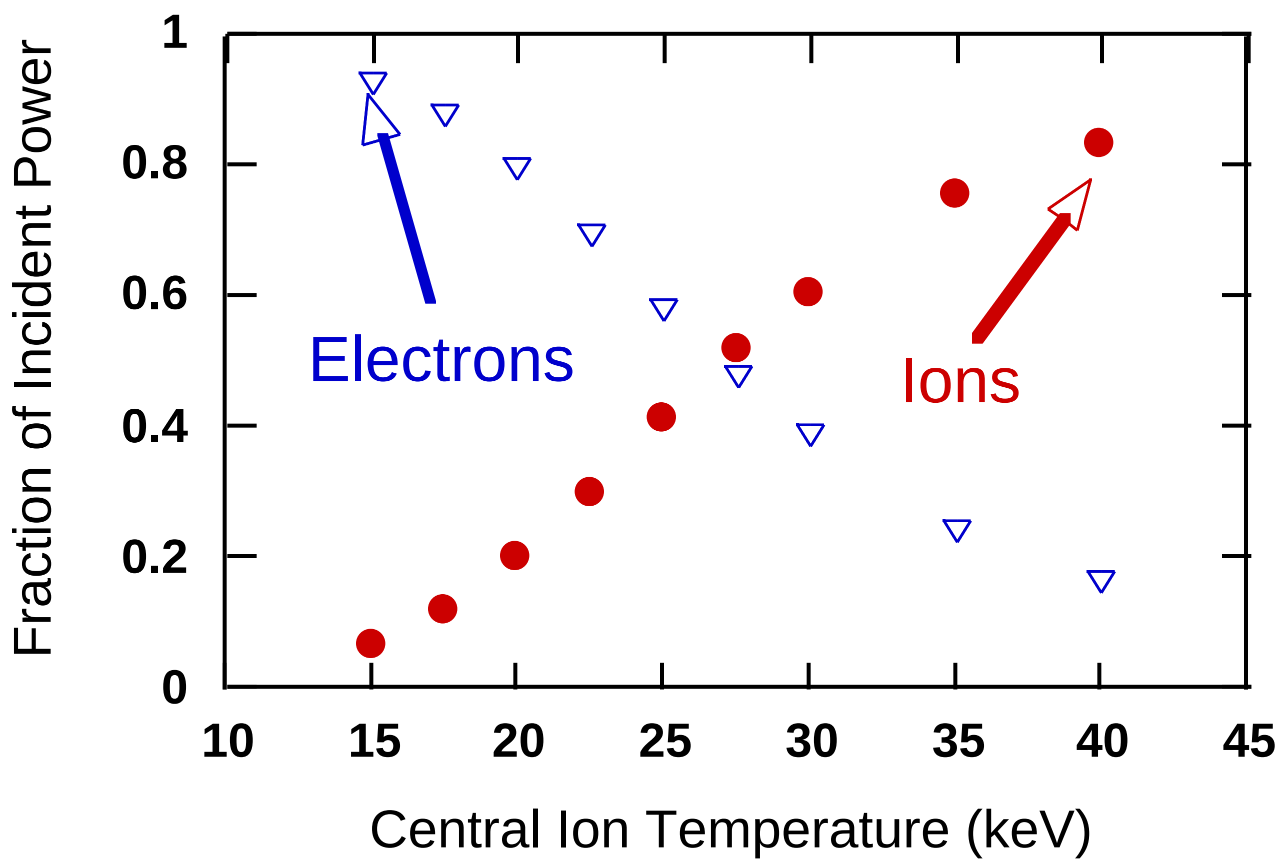
Switchover to ion heating is predicted for sufficiently hot target plasmas



Modeling with the *Felice* code (M. Brambilla, N.F. 28, 5 p.49 1988) PPPL

Poloidal Flows can be Driven by RF Waves

Momentum Balance Equation

$$\rho_m \left[\langle \tilde{\boldsymbol{v}} \quad \tilde{\boldsymbol{v}}_\theta \rangle + \mu_{neo} \langle V_\theta \rangle \right] = \langle \tilde{\rho}_q \quad \tilde{E}_\theta \rangle + \frac{1}{c} \langle (\tilde{\boldsymbol{J}} x \tilde{\boldsymbol{B}})_\theta \rangle$$

Reynolds Stress | **neoclassical damping** | **Charge-separation induced flow** | **Electromagnetic correction**

Dominant for IBW

Normally ignored (small)

$$\frac{dV_\theta}{dr} = -\frac{d}{dr} \left[\frac{ (\tilde{\boldsymbol{v}} \quad) \tilde{\boldsymbol{v}}_\theta }{ \mu_{neo} } \right]$$

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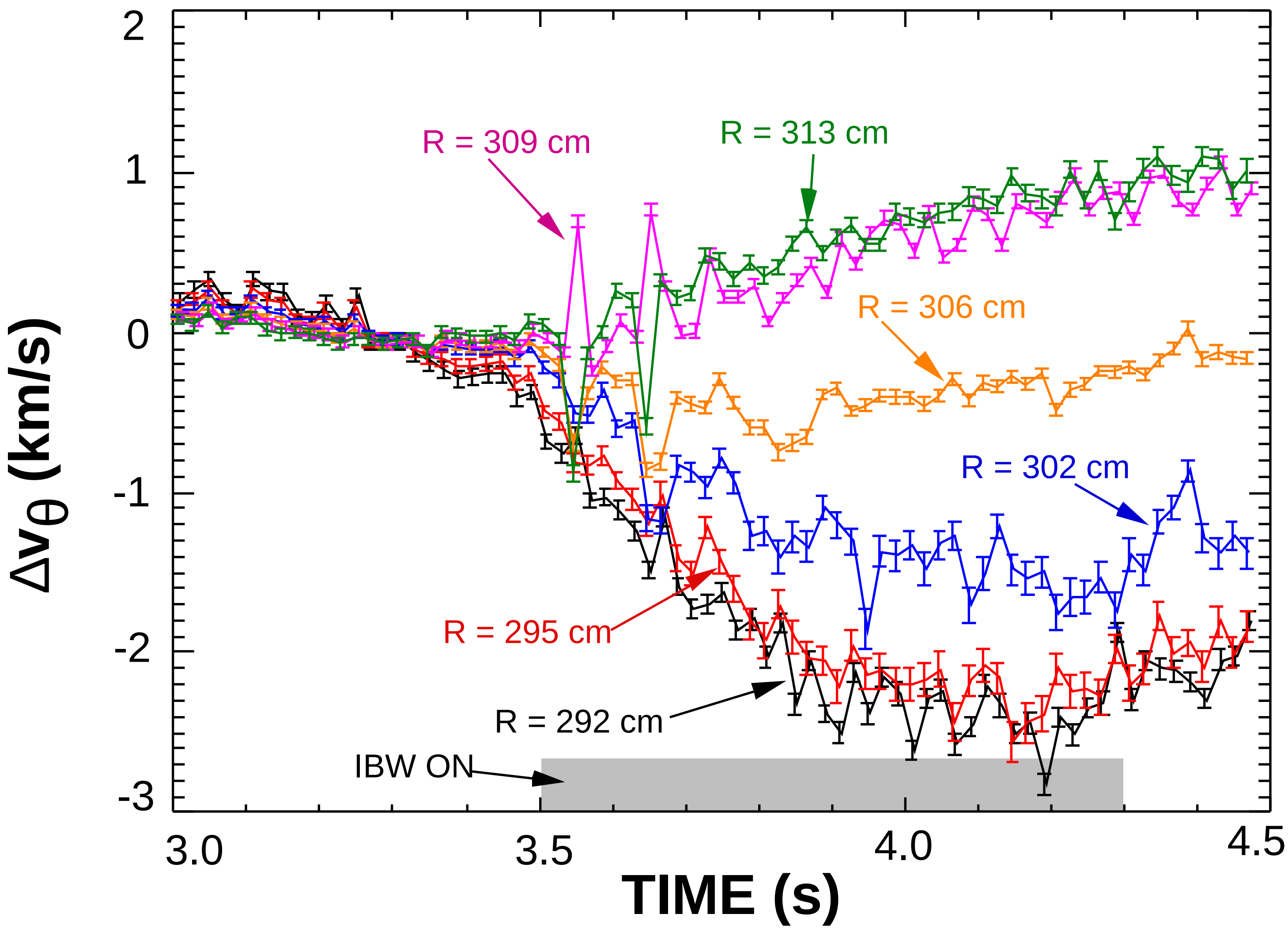
Poloidal Flows are Observed for both Direct IBW and MC Heating

- Magnitude of observed flows are smaller than those believed to be necessary to suppress fluctuations:

$$dV_{pol}/dr \sim C_s/R$$

- Direction of flows is in agreement with simple theory

Sheared Poloidal Flow Develops During IBW Heating



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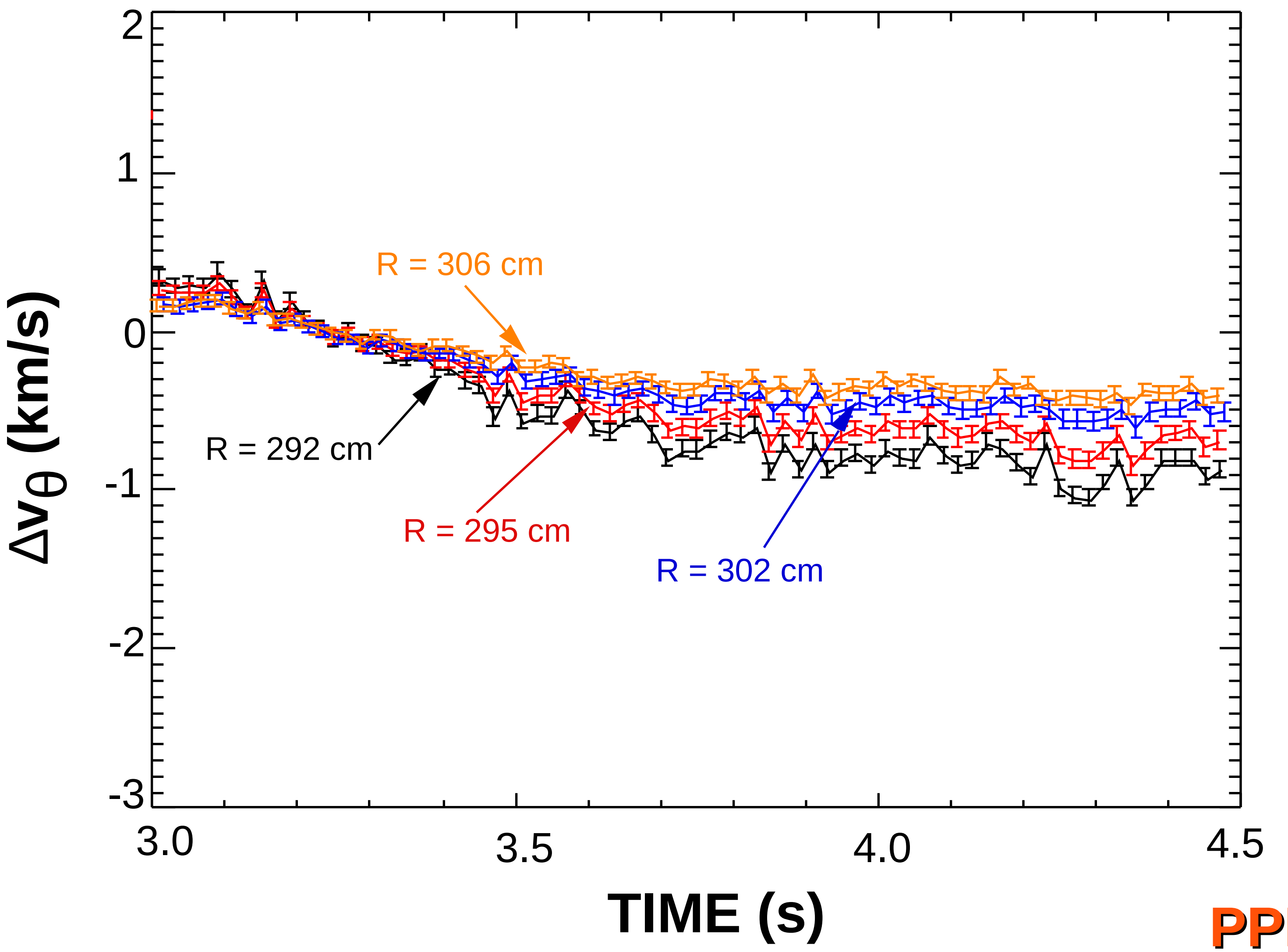
Absence of Sheared Flow in the Absence of IBW



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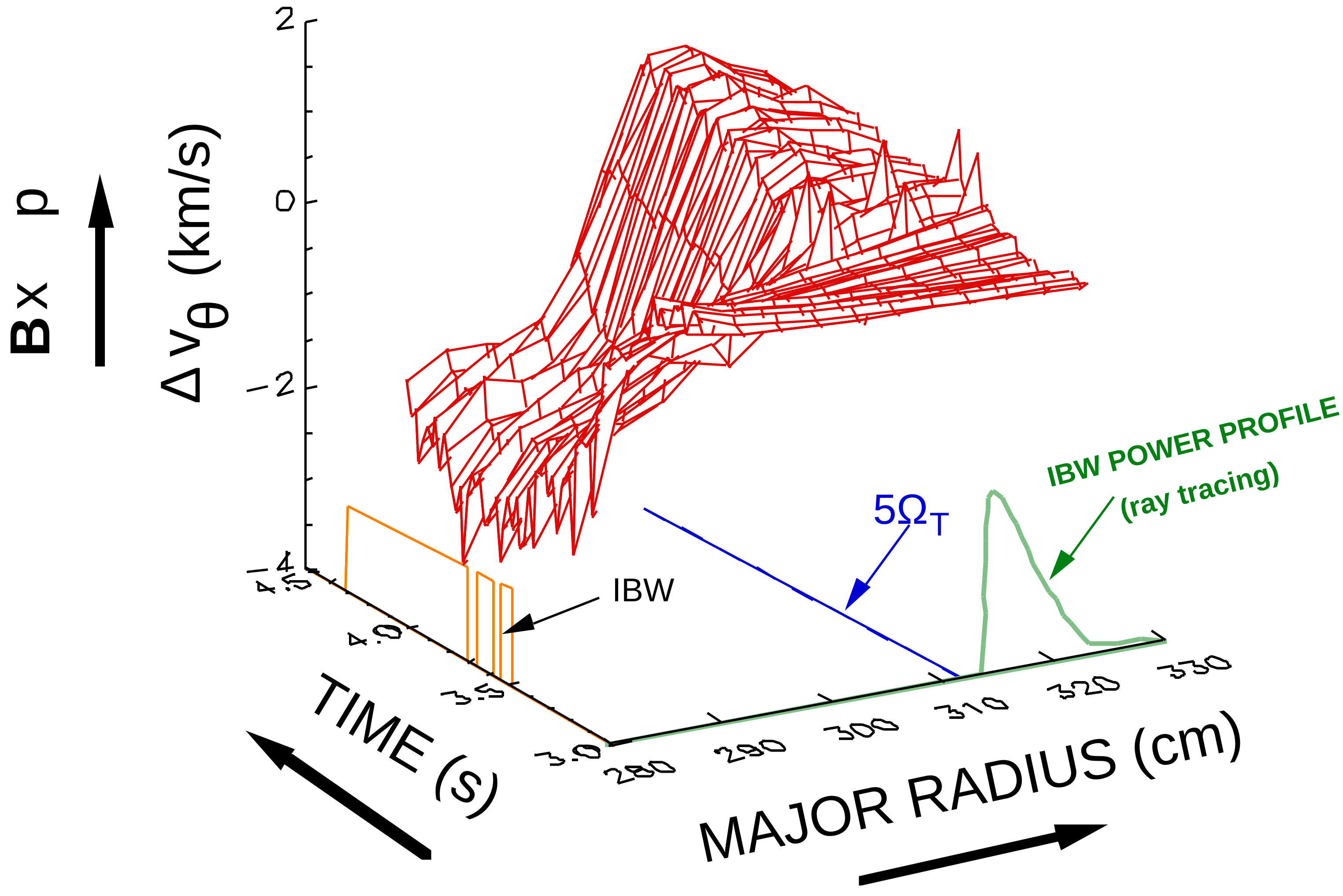
Sheared poloidal flow observed near IBW Absorption Layer



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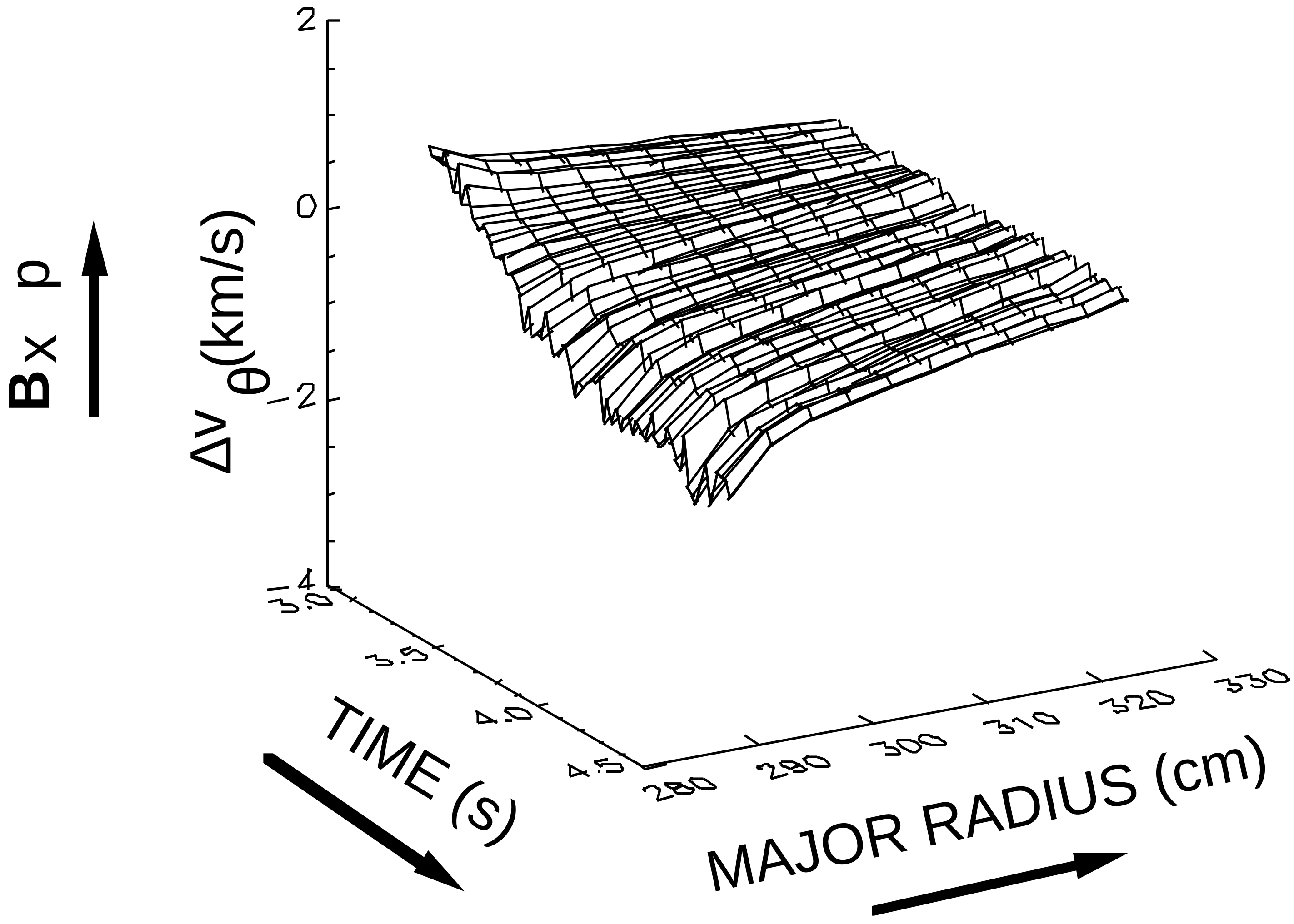
ΔV_θ for no IBW Discharge



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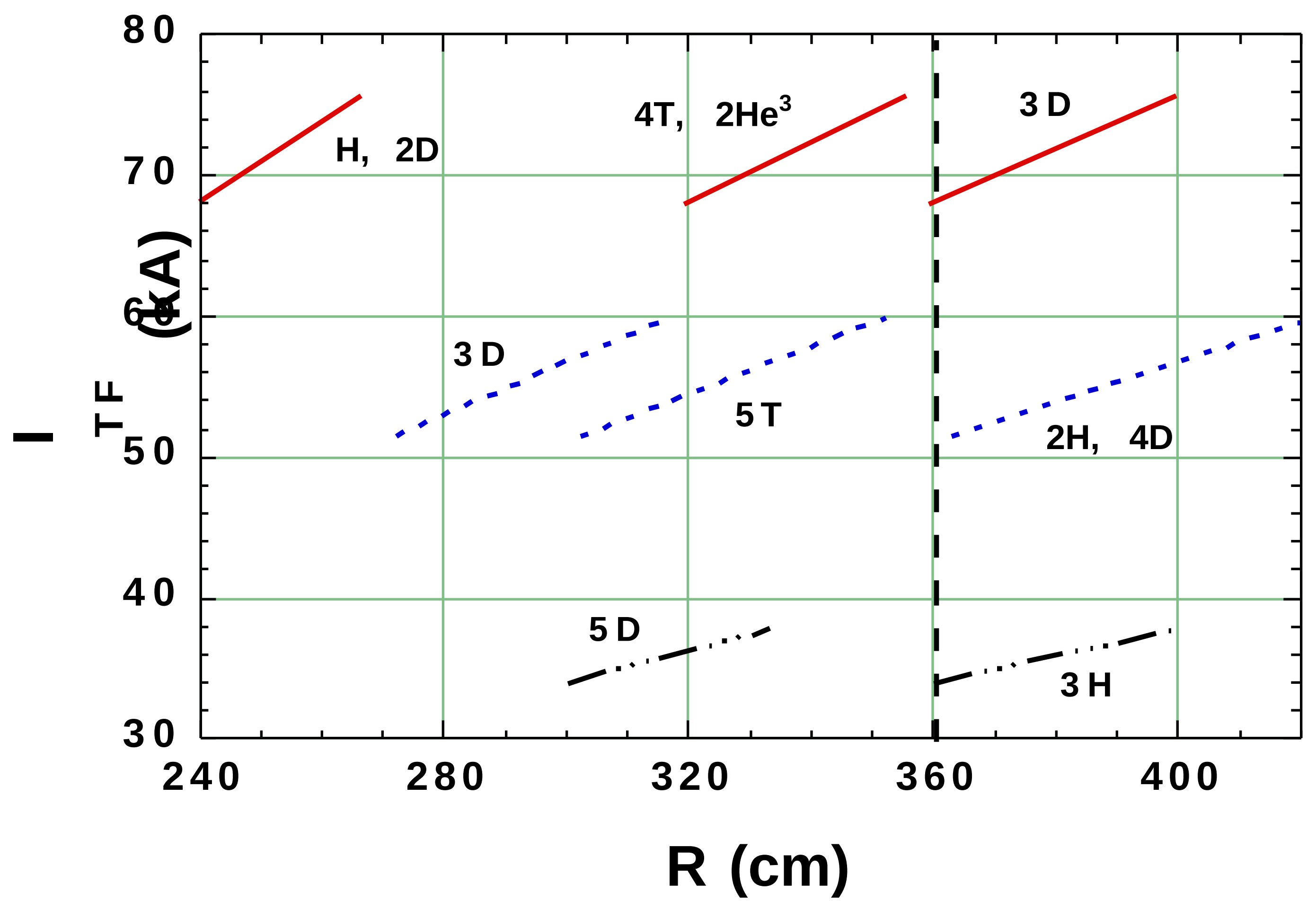
Summary

- Elimination of surface waves by poloidal phasing improves IBW heating efficiency
- Elimination of ^{7}Li ions resulted in successful DT Mode Conversion Heating
- Poloidal flows were driven with both direct IBW and Mode Conversion heating

Ion Resonances for 76 MHz



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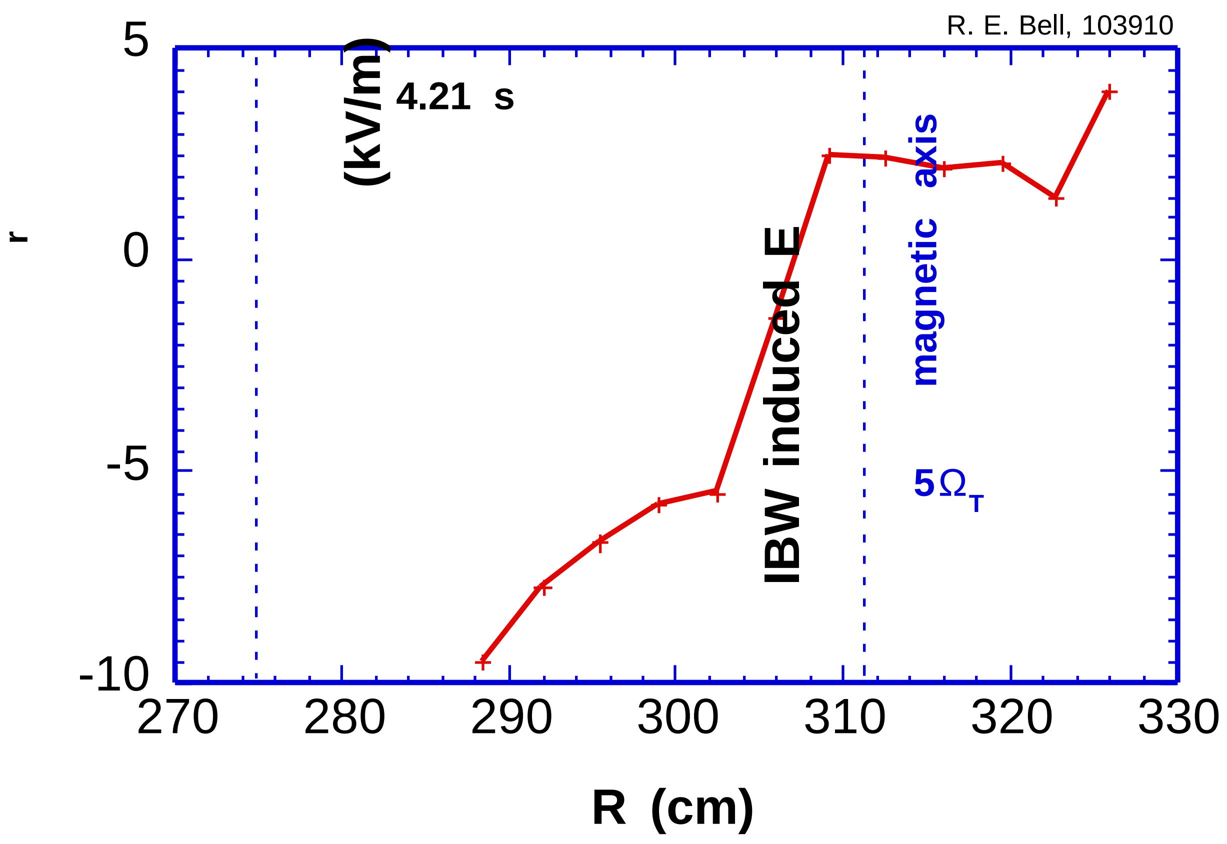
Radial Electric field derived from Force Balance



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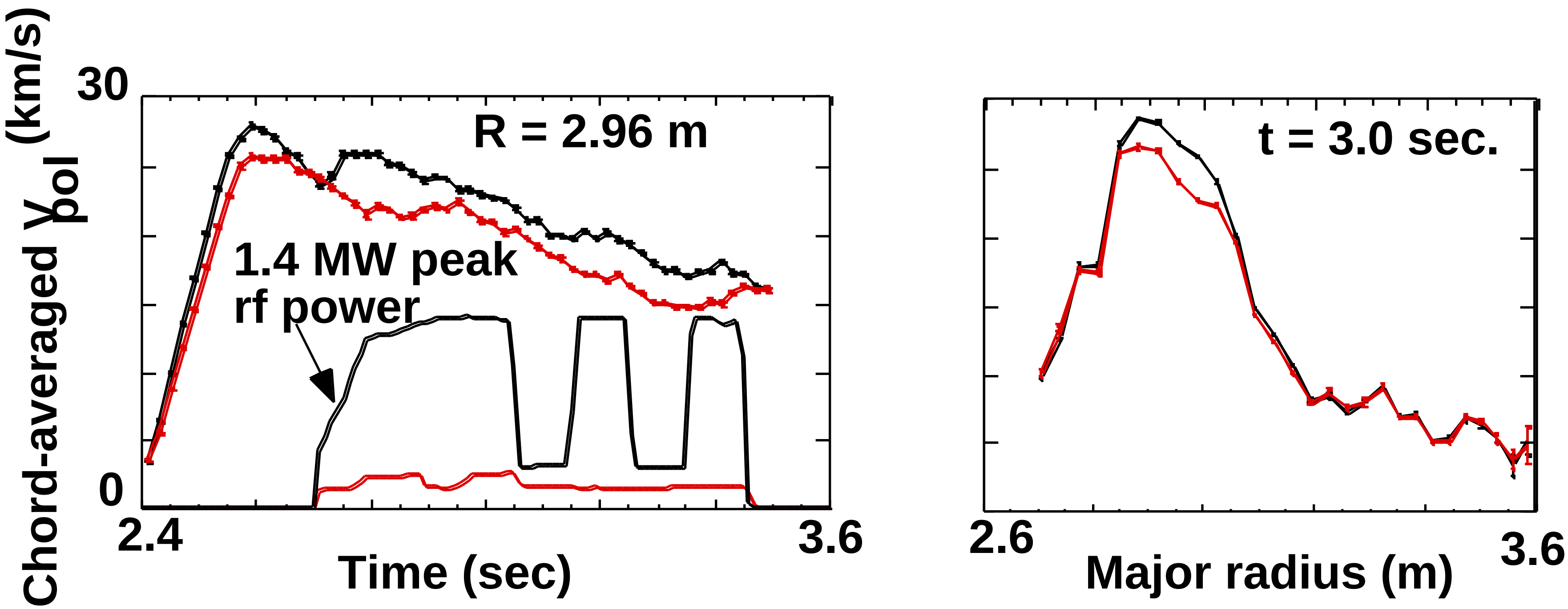
Change in Poloidal Velocity Observed during DT Mode Conversion Heating

Mode Conversion layer on low field side of plasma R ~ 2.95 m



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