Intrinsic Rotation in DIII-D

by
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for
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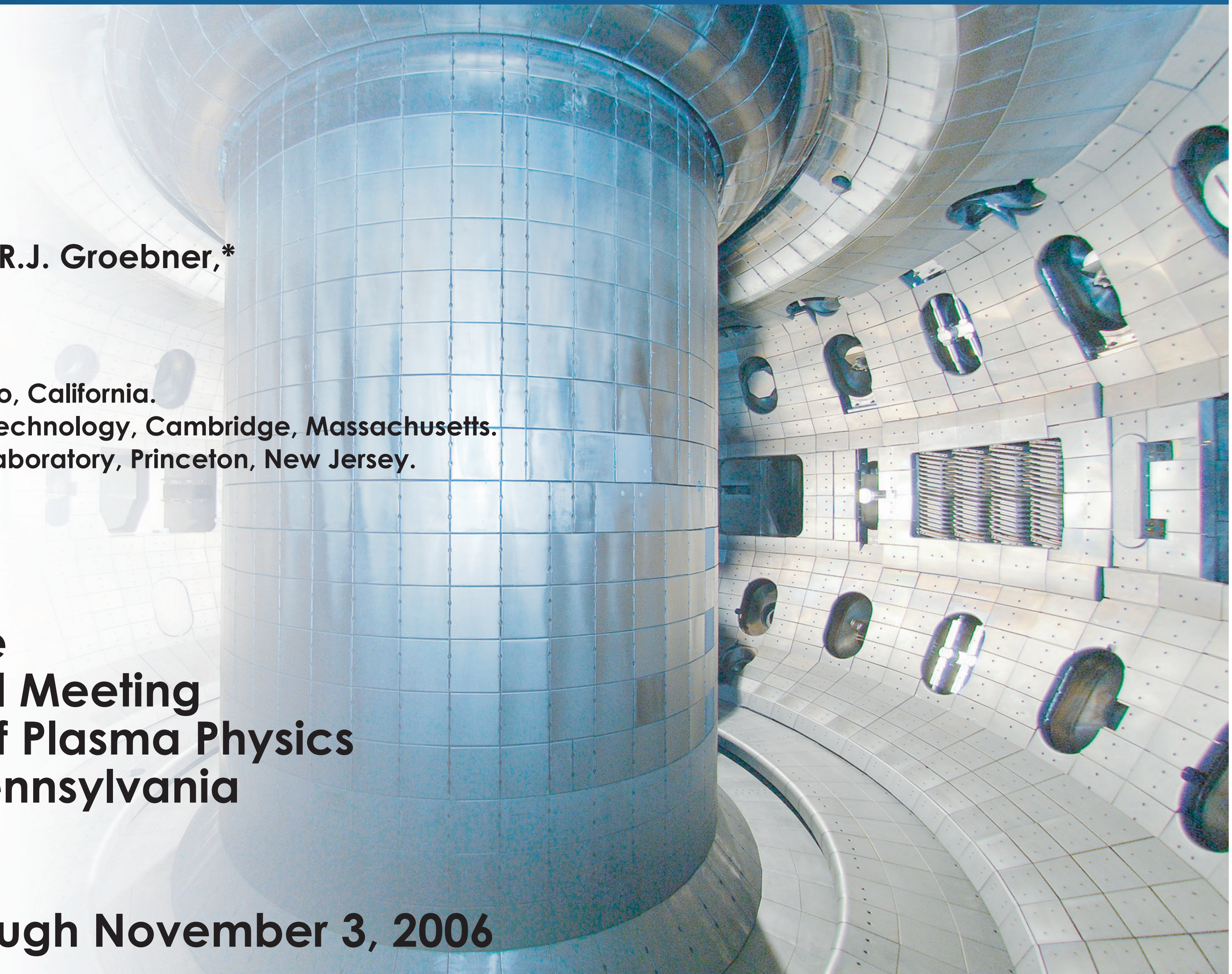

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GENERAL ATOMICS

301-06/JSD/jy

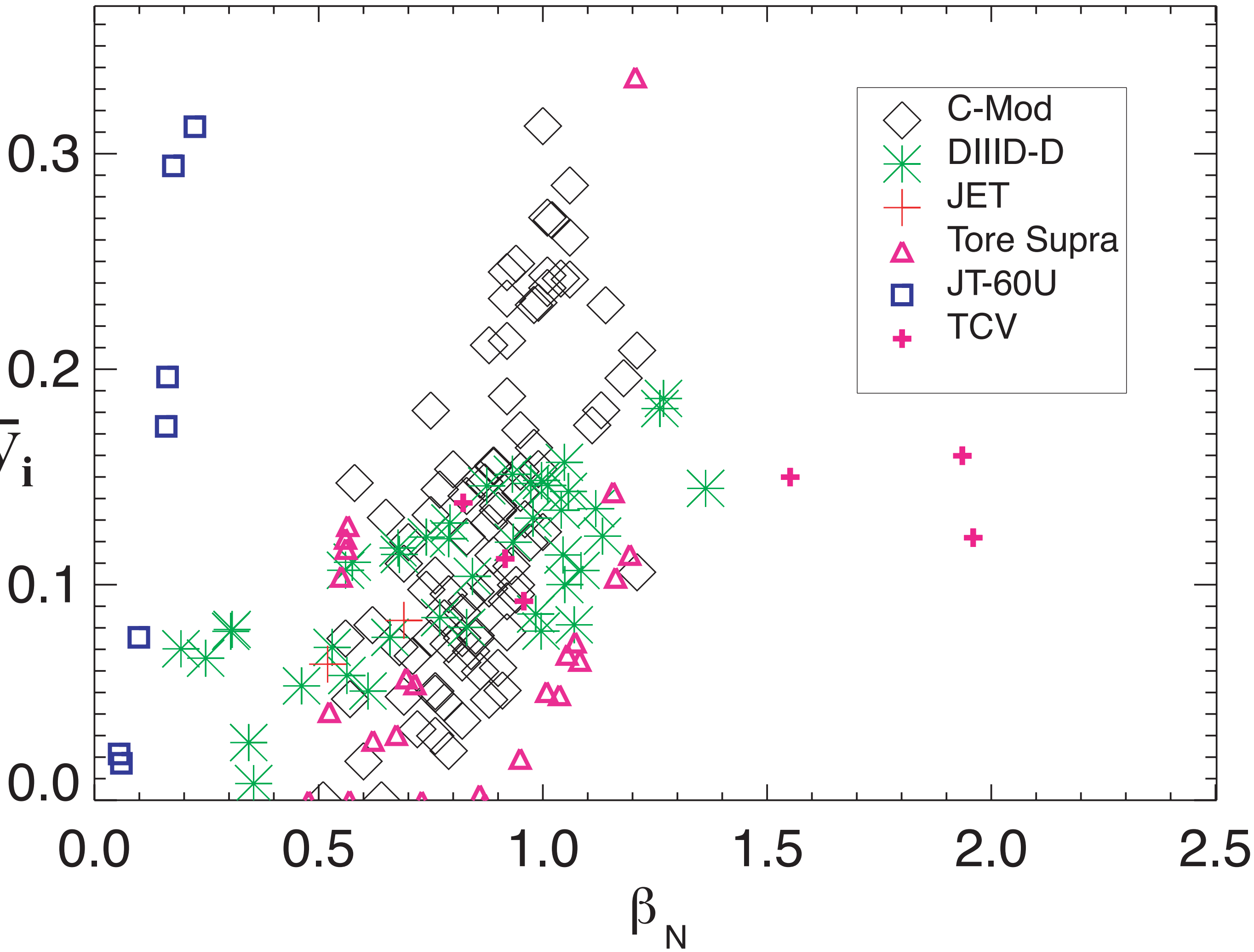
Intrinsic Rotation in DIII-D
Overview

- **Intrinsic rotation = Toroidal velocity without auxiliary injected torque**
  - It is commonly observed.
  - Recognized to be important for issues of stability and confinement in burning plasmas, with little auxiliary torque
- **In DIII-D we have investigated intrinsic rotation in H-mode discharges,**
  - Using Ohmic Heating (OH), Electron Cyclotron Heating (ECH), and
  - Using the new DIII-D co/counter Neutral Beam Injection (NBI) capability
  - NBI is an important tool to study intrinsic rotation at larger plasma β, but there must be balance in the torque profile
- **A scaling for intrinsic rotation is emerging, and an initial DIII-D/C-Mod similarity experiment is encouraging**
- **Theories presently provide qualitative explanations**
  - Neoclassical
  - Turbulence

Toroidal Intrinsic Rotation is Widely Observed In Tokamak Discharges

$$M_\phi = V_\phi / \bar{V}_i$$

$$\bar{V}_i = \sqrt{T_i / M_i}$$



From J.E. Rice, et al, IAEA, EX-P3-12, Chengdu 2006

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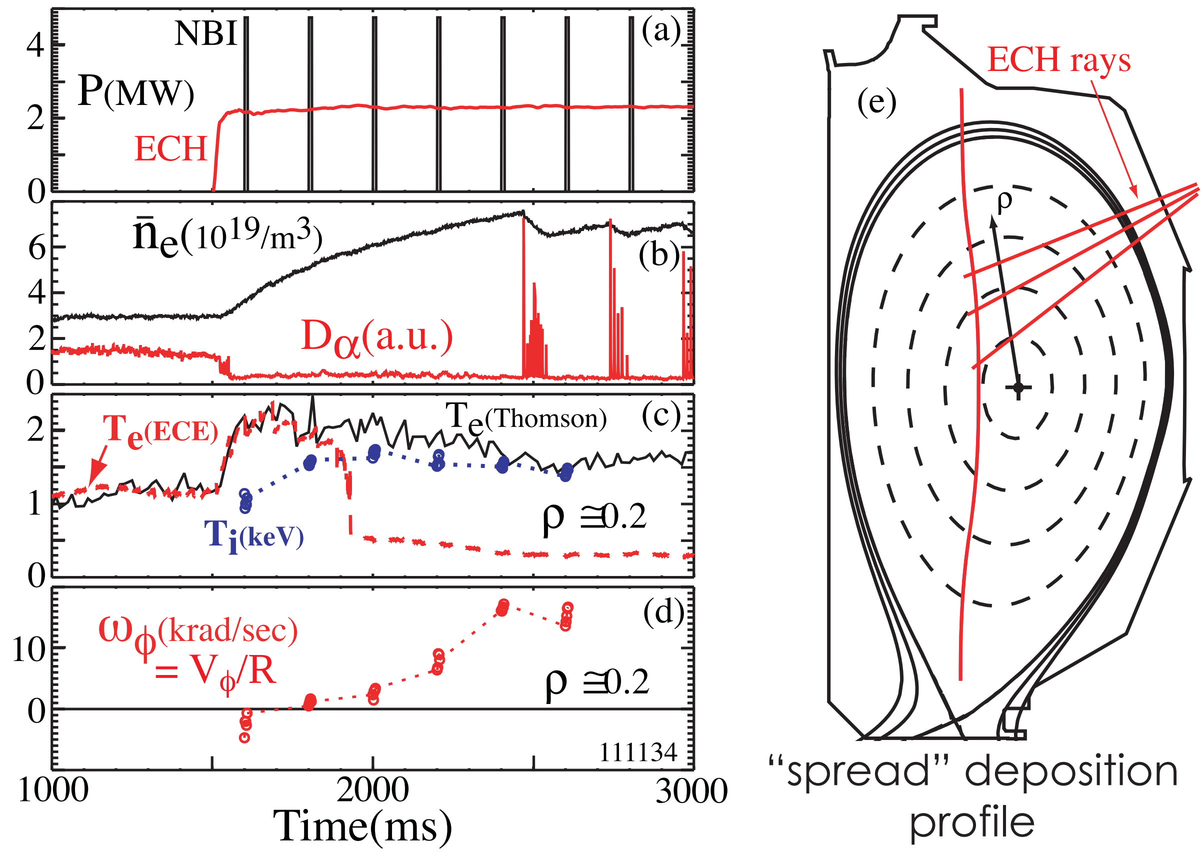
Alcator C-Mod

Ion Velocity and Temperature Measurements in DIII–D Require NBI: Intrinsic Measurement Limited By NBI Torque

- Only first ~ 2 ms of NBI 'blip' is nonperturbative; NBI torque-impulse persists.
- Move time of first NBI blip shot-to-shot to obtain time evolution.
- Long ELM-free period in D^+ discharges with "spread" and "core" ECH deposition, with evolution of the intrinsic rotation profile.
- We have also utilized ECH H-Modes in bulk ion He^{++} discharges, measuring the main ion velocity, as well as C^{6+}

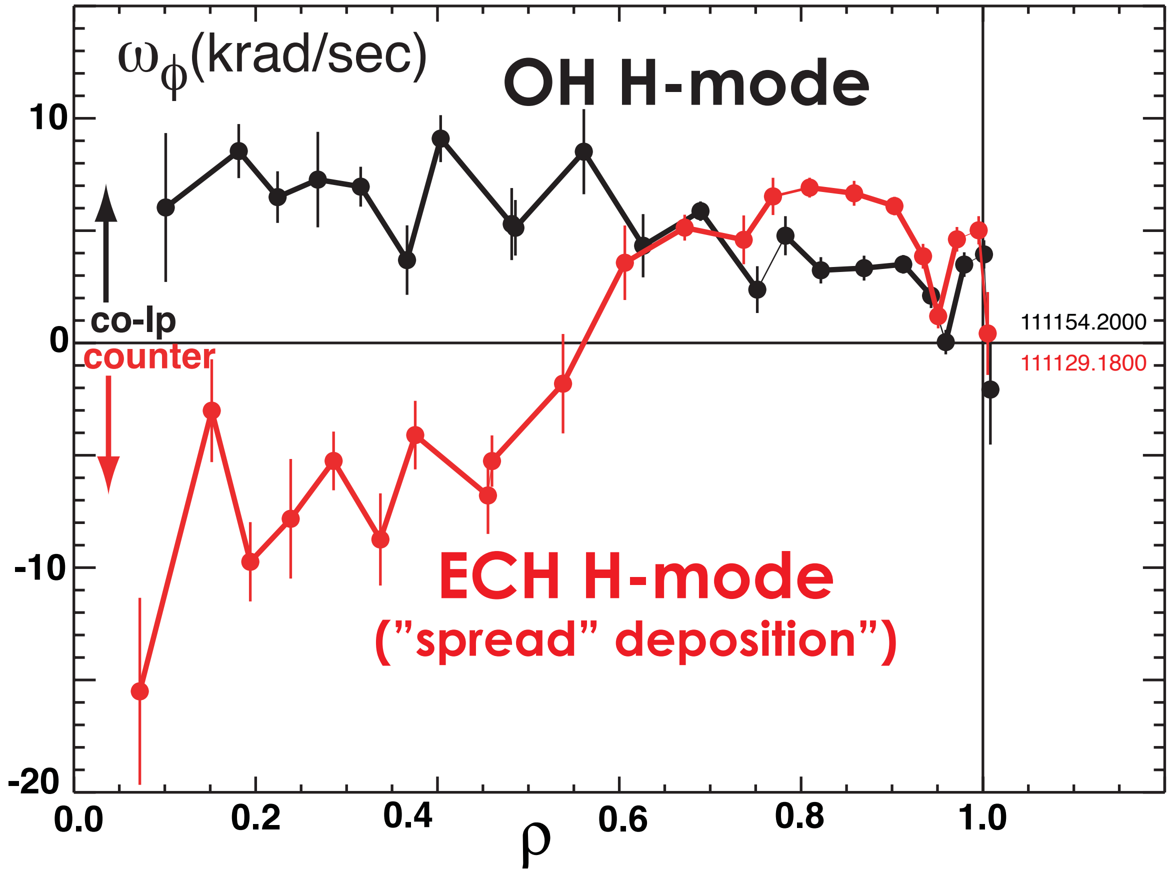
DIII-D ECH H-Mode discharge
main ion: Deuterium
velocity: C^{6+}



"spread" deposition profile

ECH H-modes in DIII–D Exhibit Hollow Intrinsic Rotation Profiles. The Core Rotation Can Be Reversed, to the Counter-Ip Direction

- **Relatively flat intrinsic rotation profile also seen in C-Mod EDA H-modes, as in DIII-D OH H-modes.**



Ip= 1.5 MA

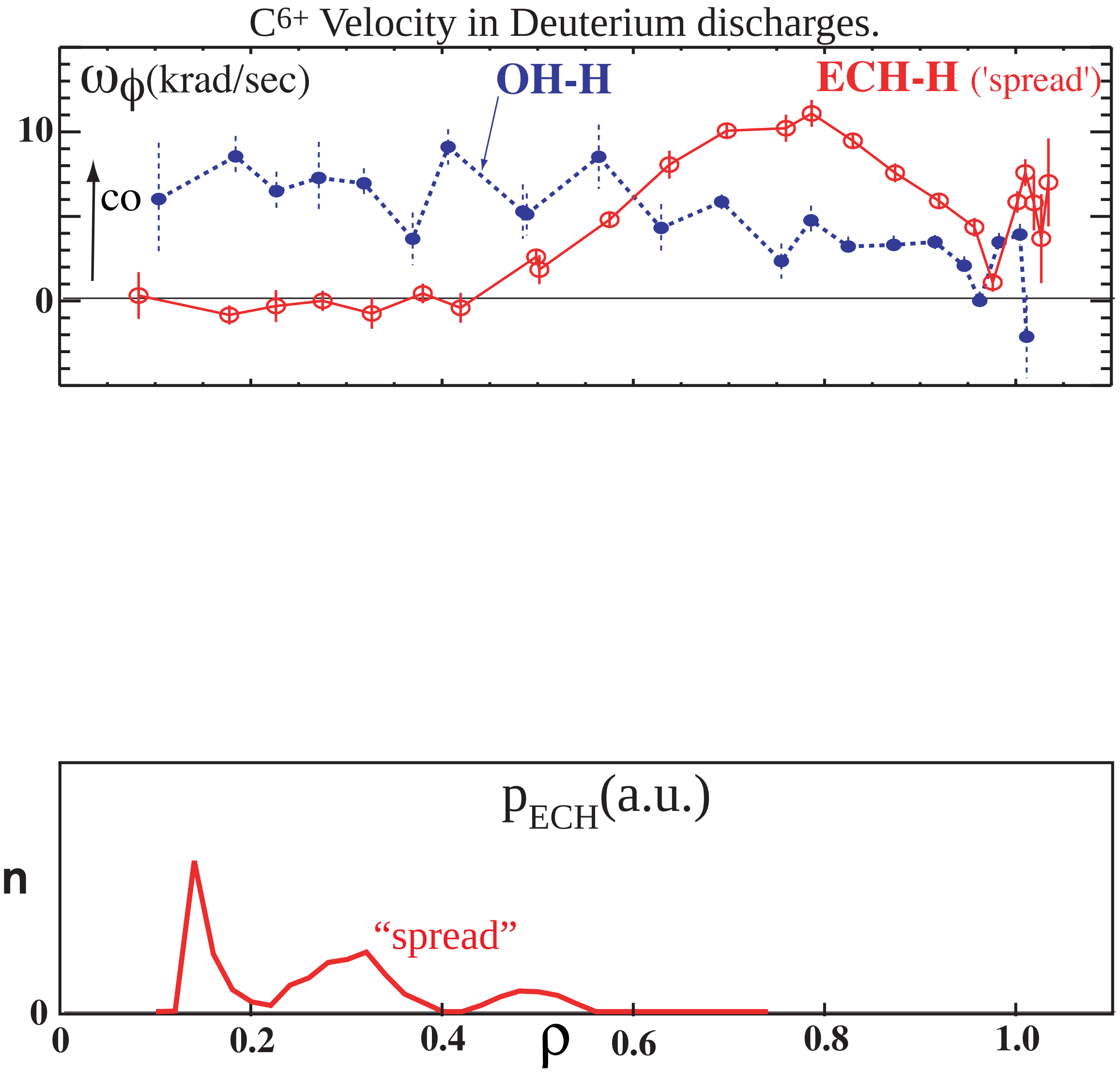
BT = -1.75 T

Ip= 1.3 MA

ρ = normalized toroidal flux radial coordinate.

ECH Deposition Profile In ECH H-modes Correlates With the Hollow Intrinsic Rotation Profile

- OH H-mode and "spread" ECH H-mode



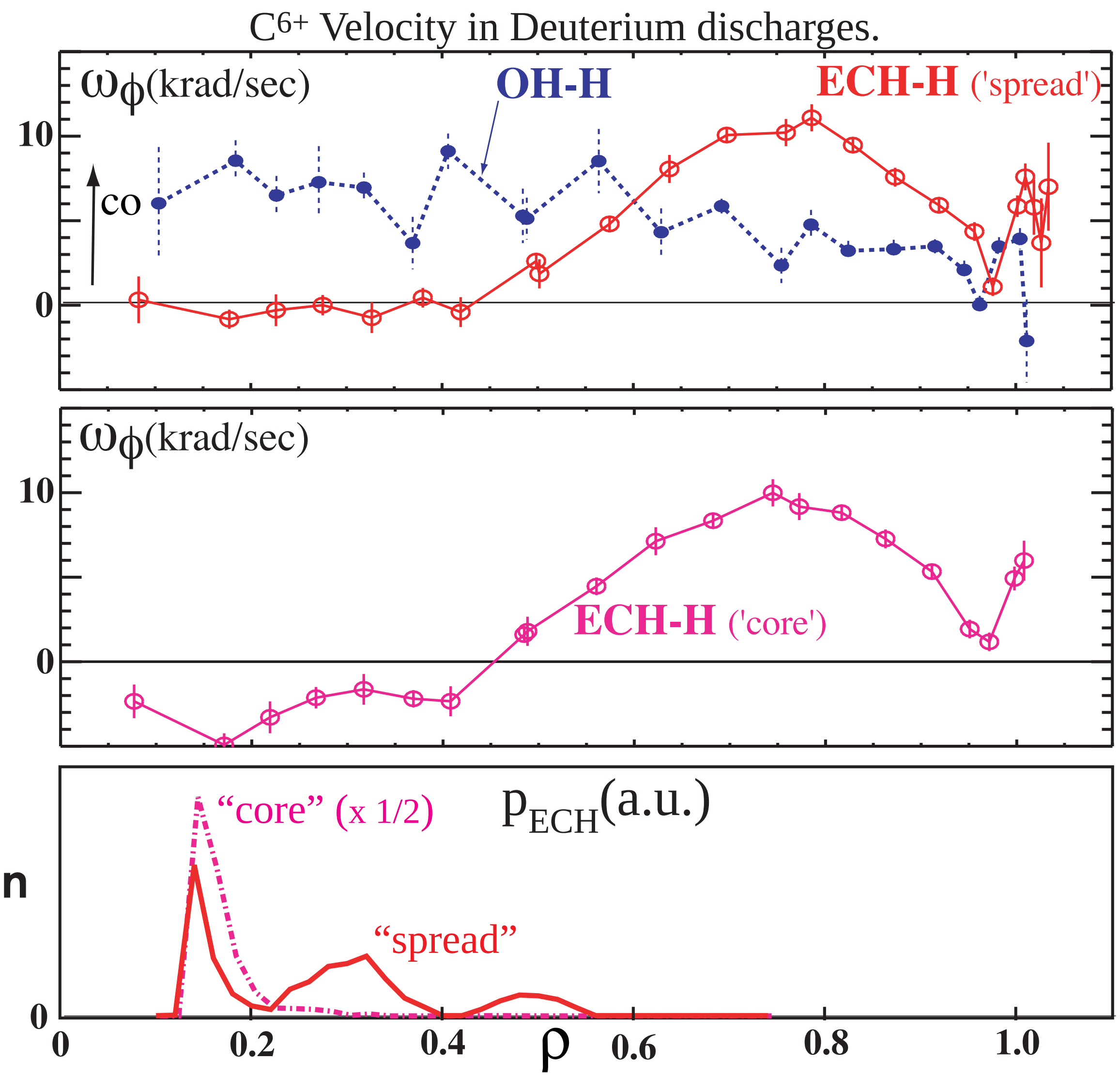
ECH deposition profiles

ECH Deposition Profile In ECH H-modes Correlates With the Hollow Intrinsic Rotation Profile

- OH H-mode and "spread" ECH H-mode

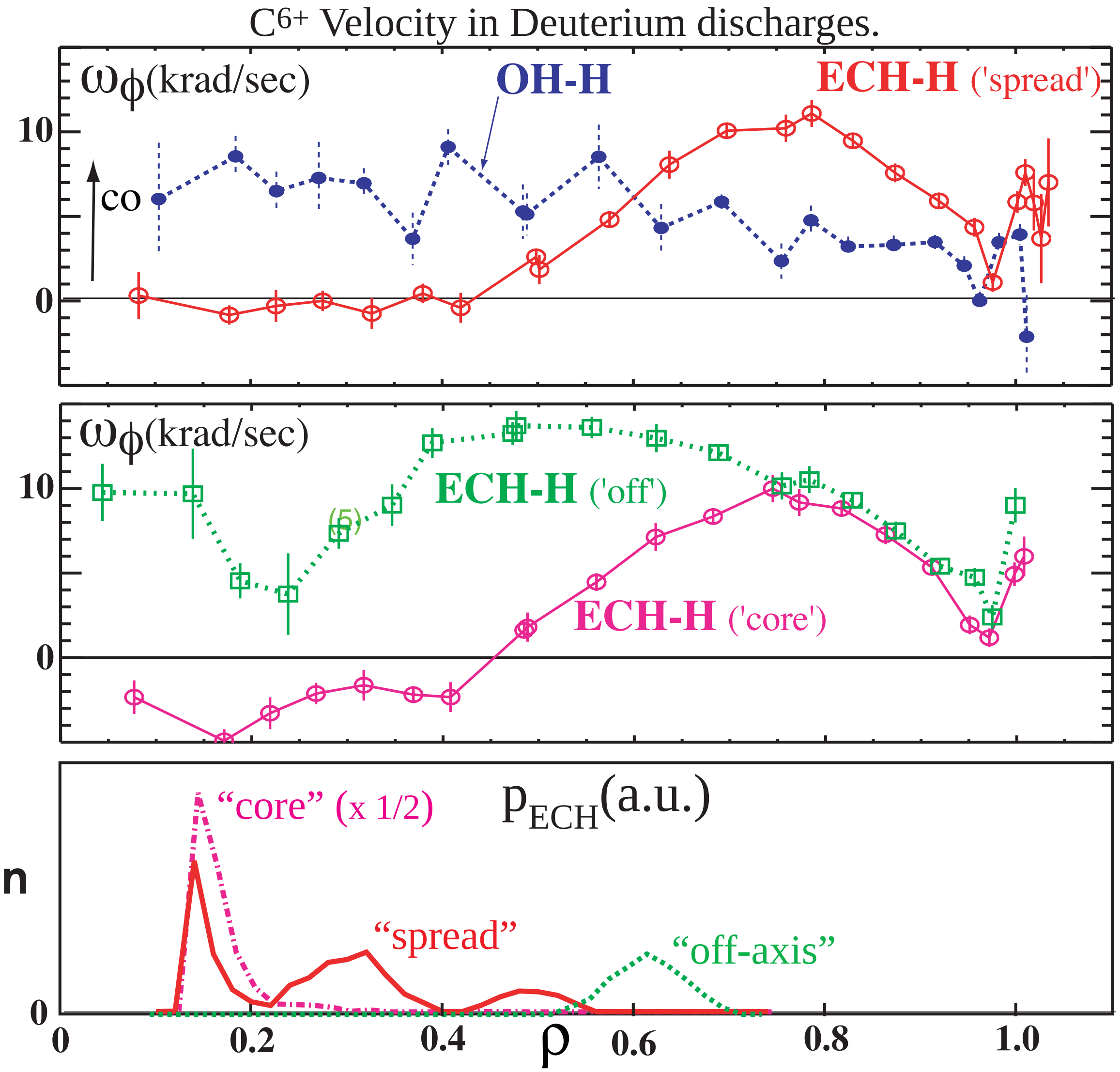
- ECH H-mode with "core" deposition

ECH deposition profiles



ECH Deposition Profile In ECH H-modes Correlates With the Hollow Intrinsic Rotation Profile

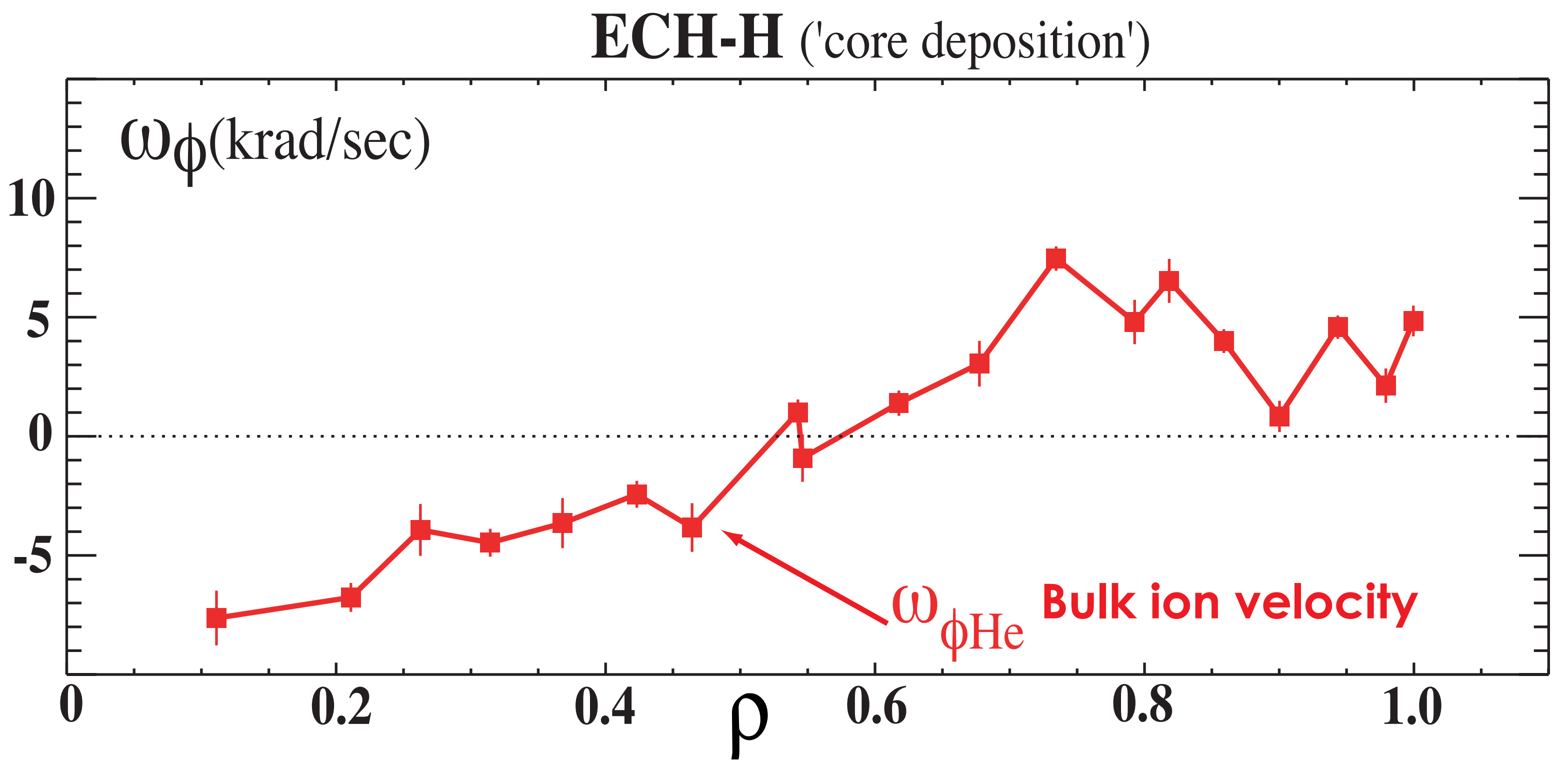
- **OH H-mode and "spread" ECH H-mode**
- **ECH H-mode with "core" deposition and "off-axis" deposition**
- **OH H-modes and "off-axis" ECH H-modes are ELMing.**



ECH deposition profiles

Hollow Intrinsic Rotation Profiles Do Not Depend on Ion Species. Bulk Ion (He^{++}) ECH H-mode Profiles Are Also Hollow.

- Bulk ion He^{++} velocity profile is also hollow.
- These discharges are ELMing => ELMs do not preclude hollowness.



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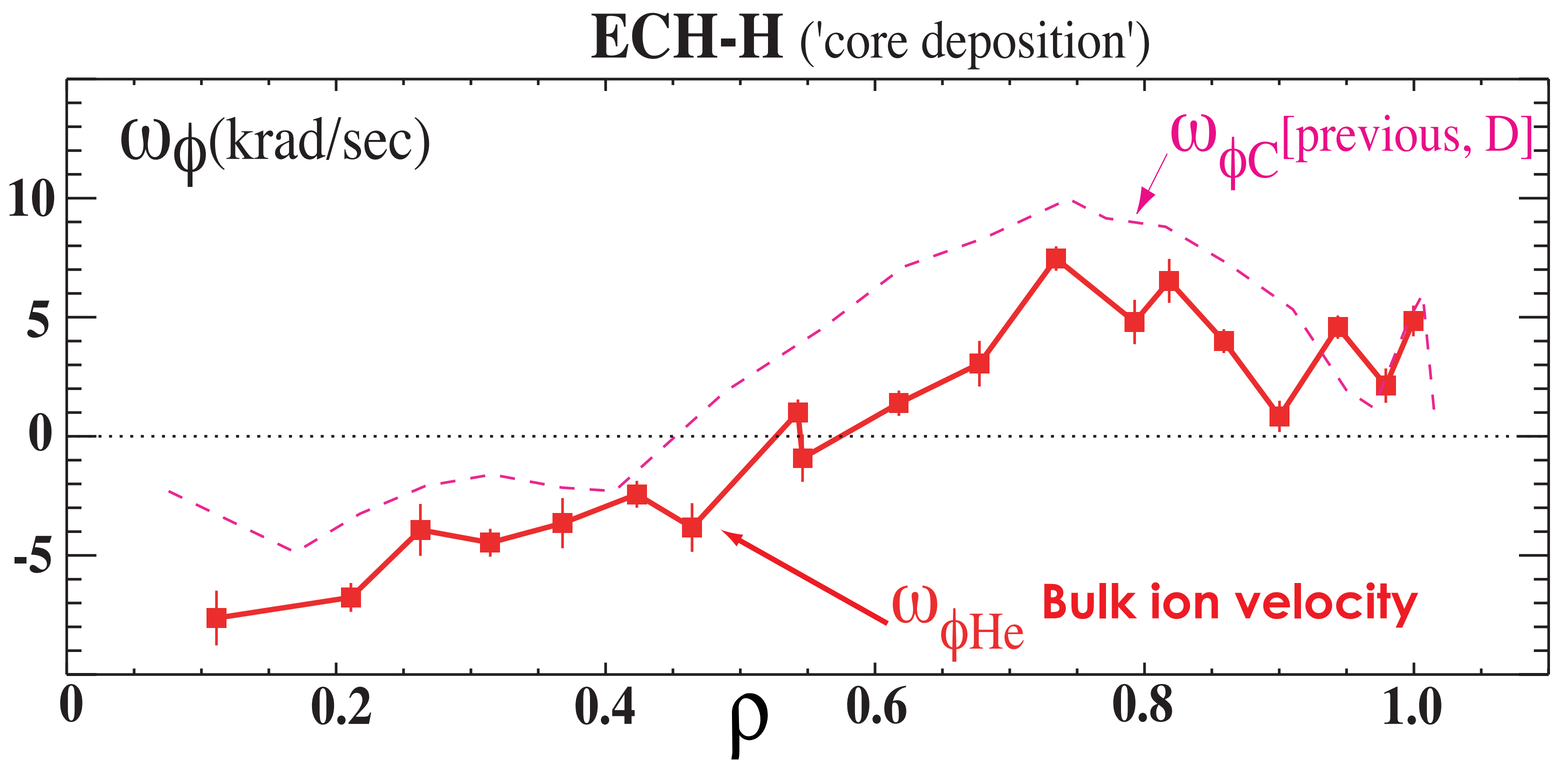

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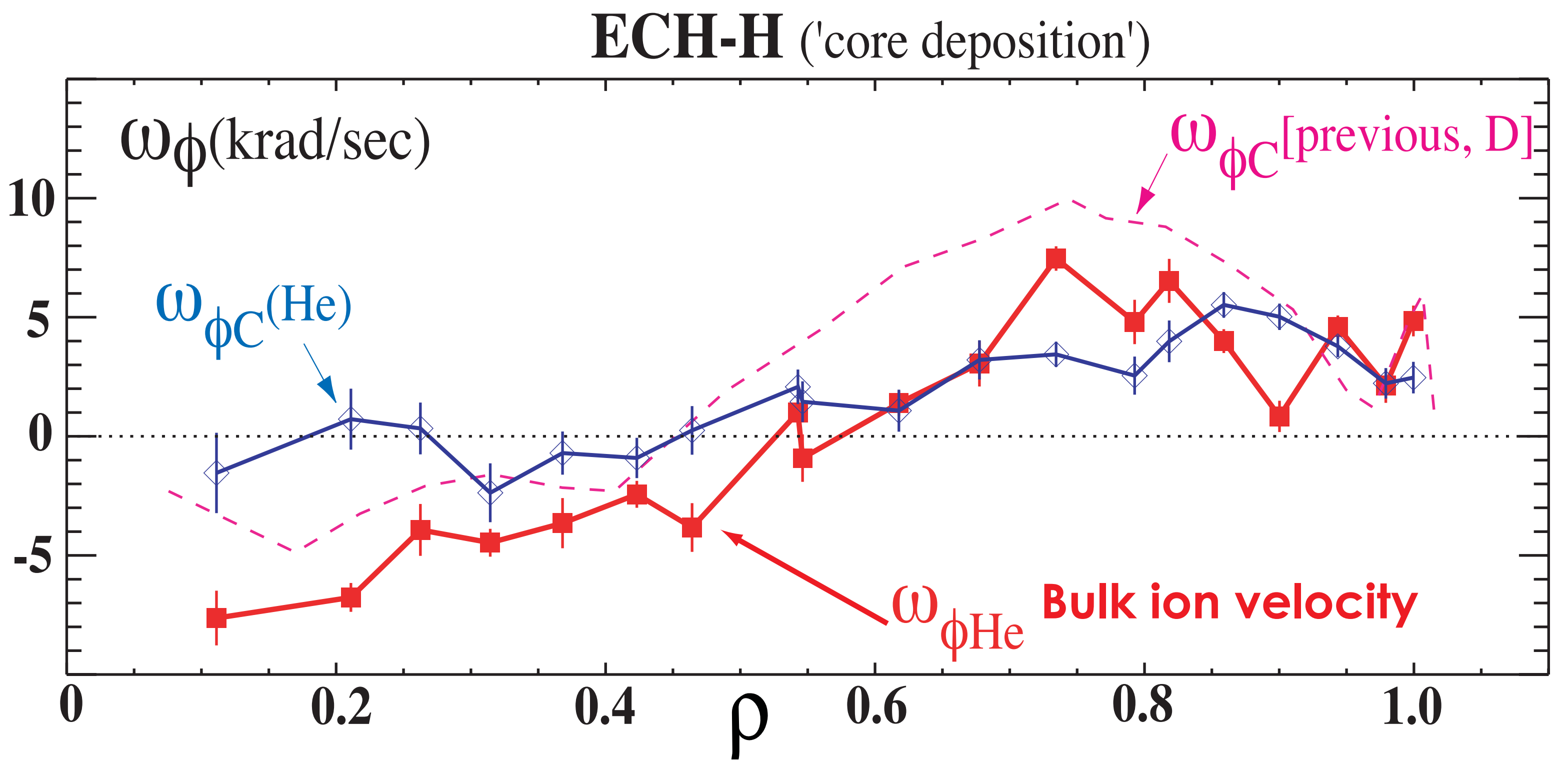

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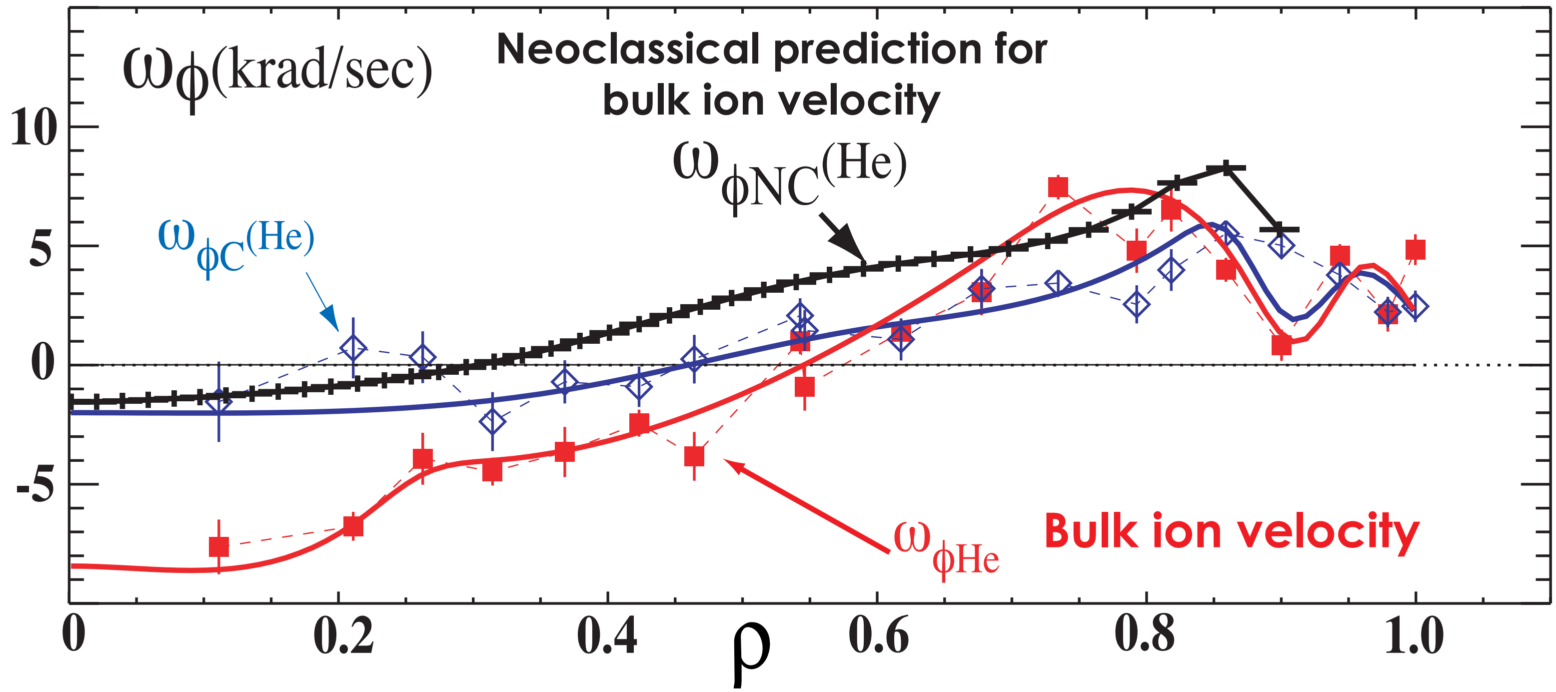
Measuring bulk ion and impurity ion velocity allows a test of the standard neoclassical prediction for the bulk ion

- The predicted velocity for He^{++} does not match the measured profile
- The discrepancy is most likely that the poloidal velocity is not the neoclassical value. [W. Solomon, *et al*, PoP 13, 056116 (2006)]
- V_{pol} is too small in these intrinsic discharges to measure accurately.

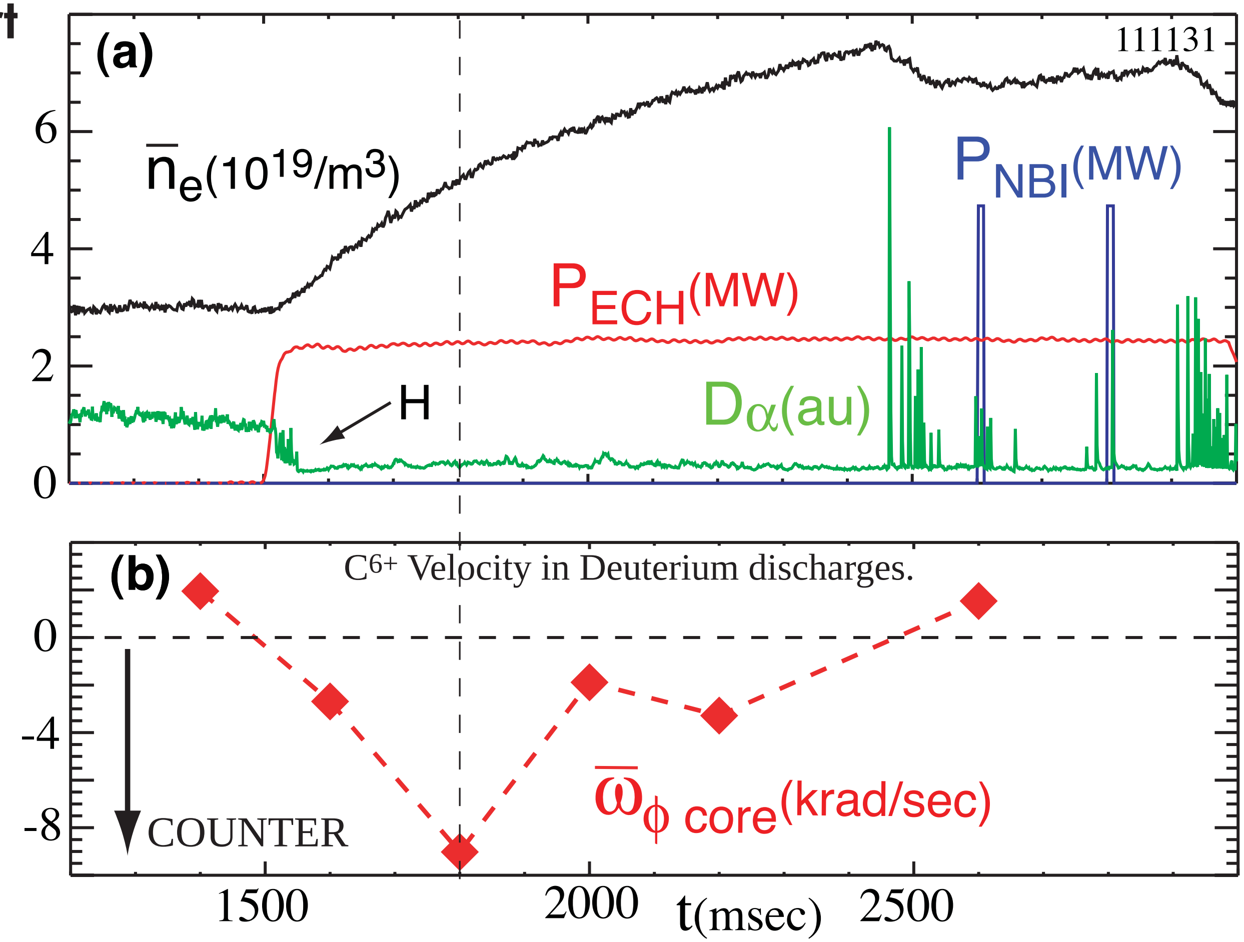


- Intrinsic E field?

Core counter intrinsic rotation develops in time, after L->H It is not due to an ECH-driven viscosity.

- **Diffusive momentum transport alone cannot reproduce the rising counter-I_p rotation.**

Averaged over the interior channels, $\rho < 0.25$



Such Rotation Profiles Can in Principle Be Generated Without Any Total Injected Torque With Momentum Diffusion and A Pinch.

- L.-G. Eriksson and F. Porcelli, NF 959 (2002).

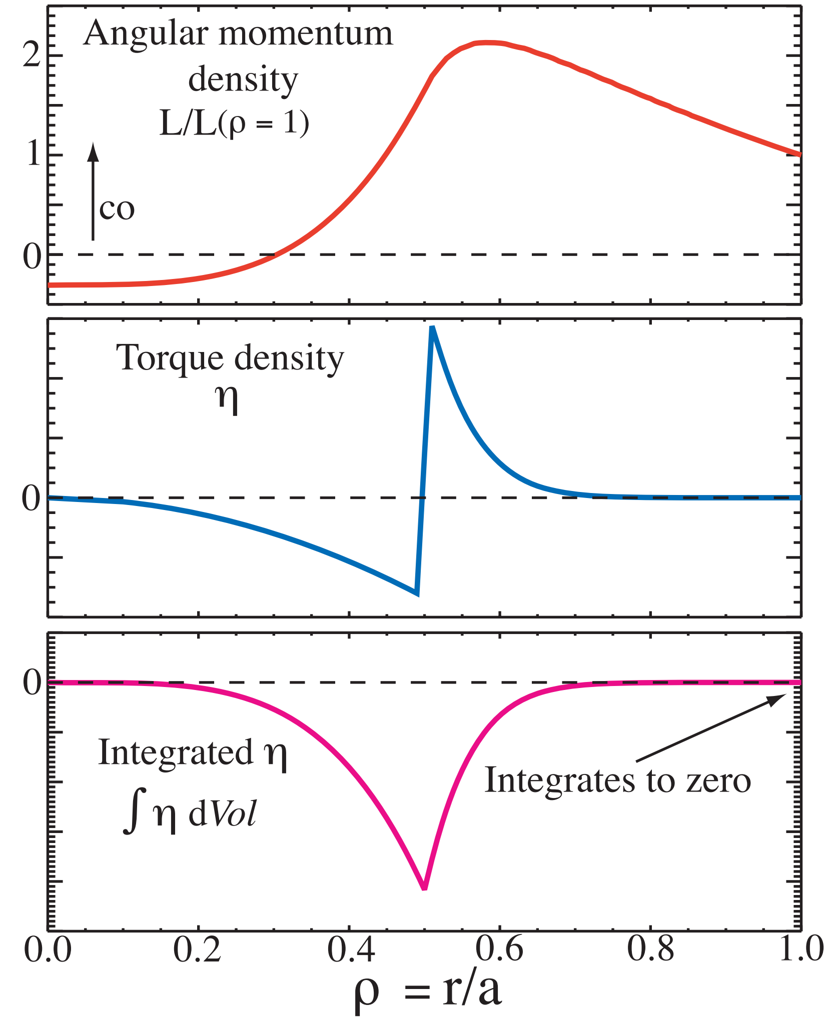
$$\frac{\partial L}{\partial t} = \eta + \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(V_{pinch}L + D\frac{\partial L}{\partial r}\right)\right]$$

$$L(a) \neq 0$$

- ECH may cause an interior momentum “rearrangement”?

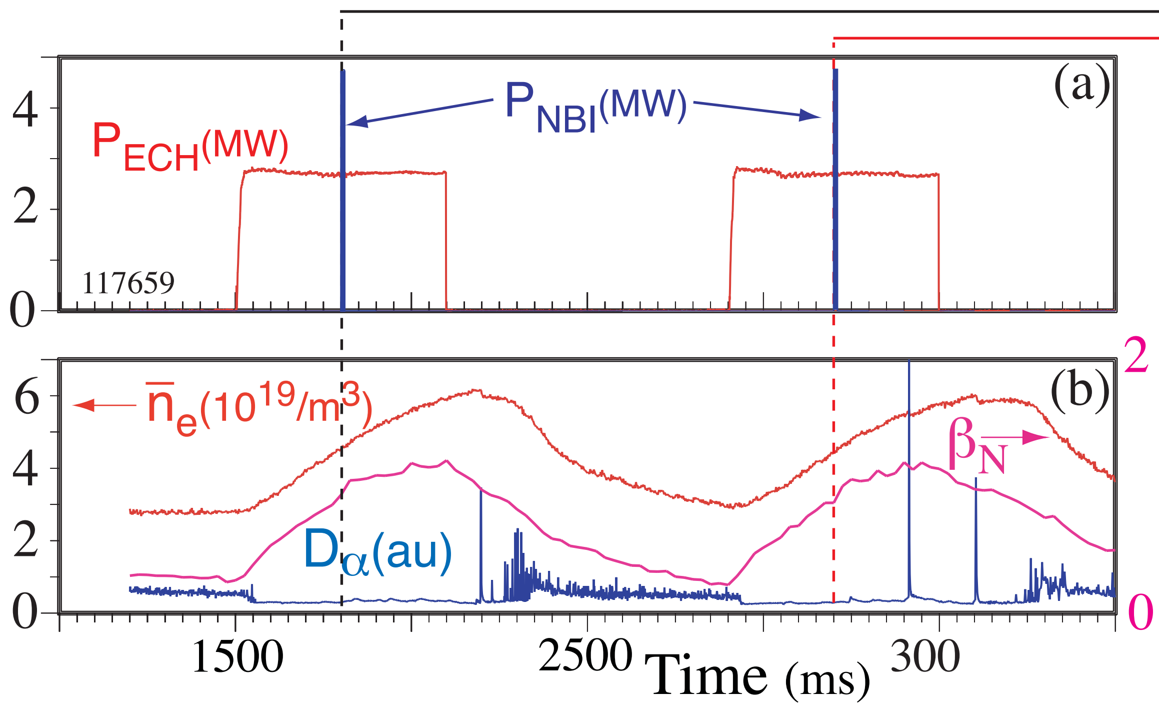
An examle, D = const, U = const

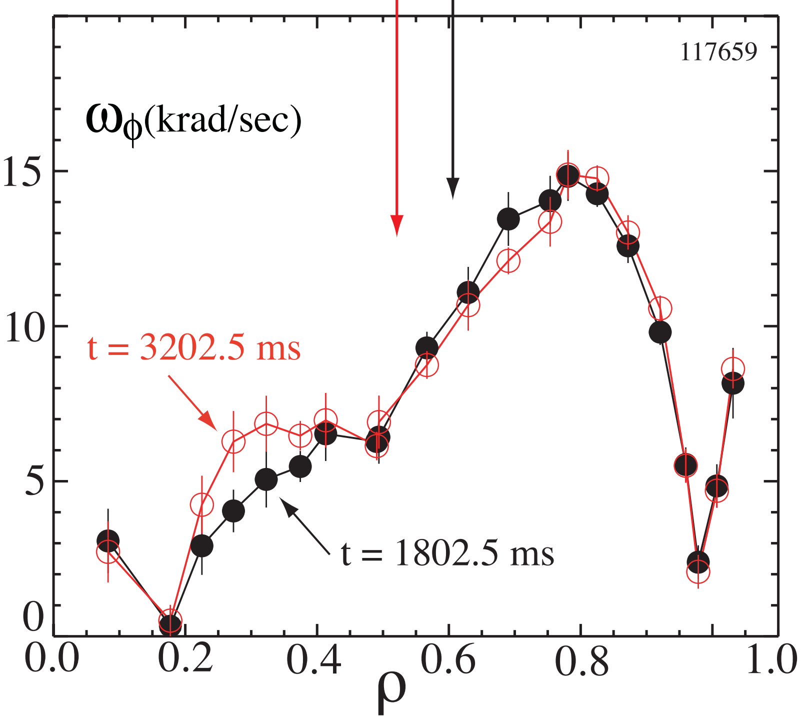
$V_{pinch} = rU/a$



Intrinsic Rotation is Reproducible in the Same Plasma Conditions

- **Double ECH H-mode in the same DIII-D shot**
- **Same intrinsic profile measured**





- **Plasma resets to ~ Ohmic state in between**

  Intrinsic rotation ~ quenched

- **Density and temperature profiles reproduce to < 10% at the time of "first NBI blips"**

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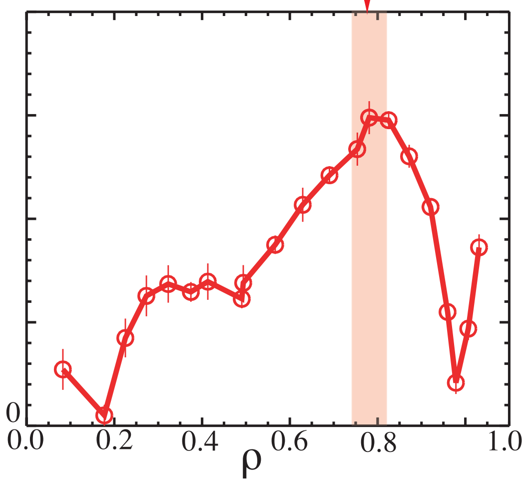
There is A Scaling for Intrinsic Rotation in DIII–D

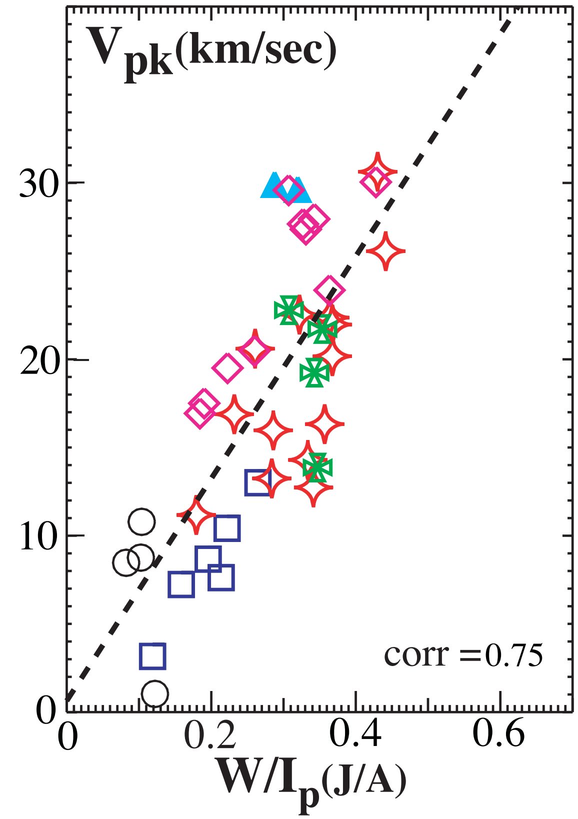
- John Rice's C-Mod intrinsic rotation scaling[1], $\Delta V_\phi \sim \Delta W/I_p$ is observed in V_{pk} in DIII-D.

Common, co-I_p velocity in this region

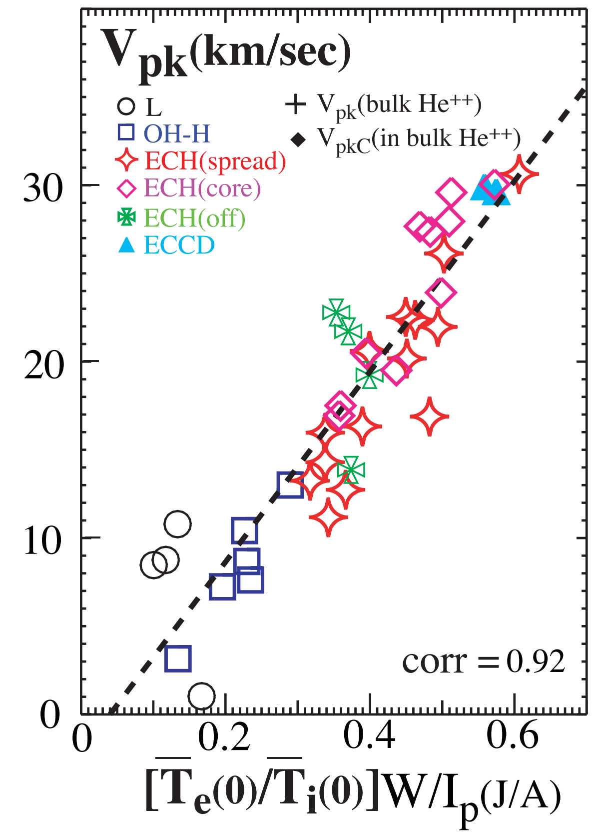
$$V_{pk} = V_\phi(\rho \cong 0.8)$$



Rice scaling



Modified by T_e/T_i



- Fits are done for V_ϕ C^{6+} in bulk D

1. J.E. Rice et al, NF 41, p 277 (2001).

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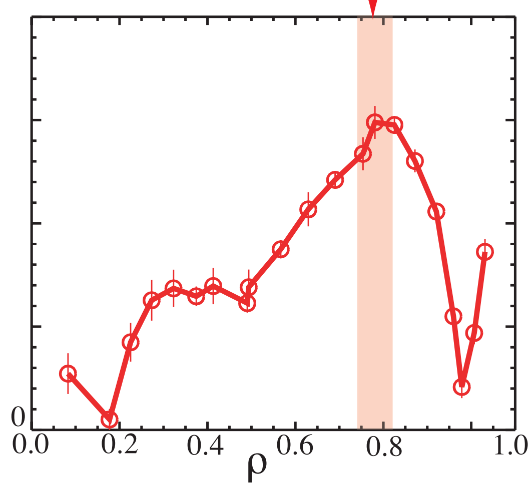

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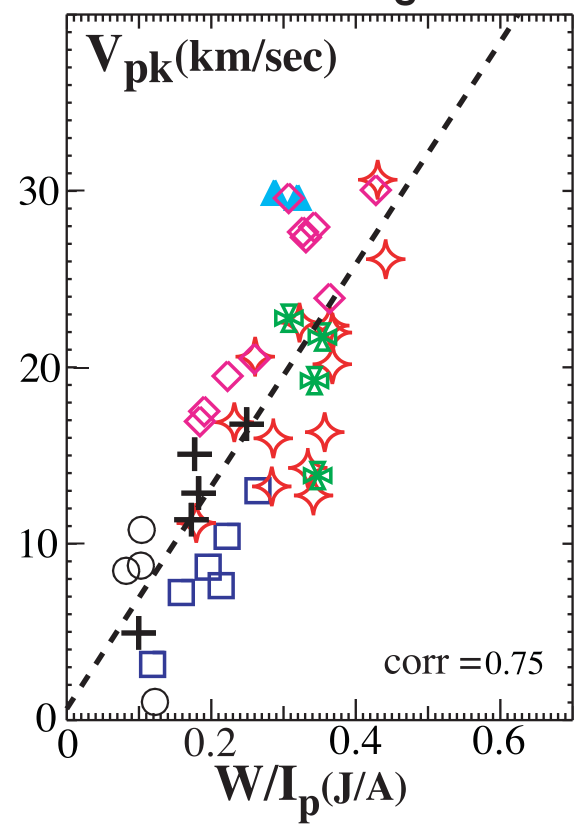

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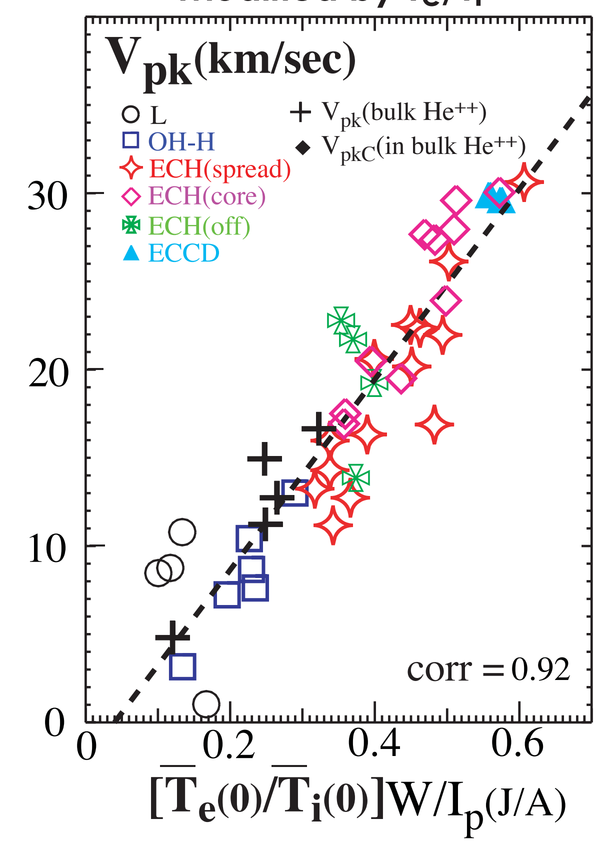

- **Fits are done for V_ϕ C^{6+} in bulk D**

Data points for V_ϕ He^{++} (+)

1. J.E. Rice et al, NF 41, p 277 (2001).

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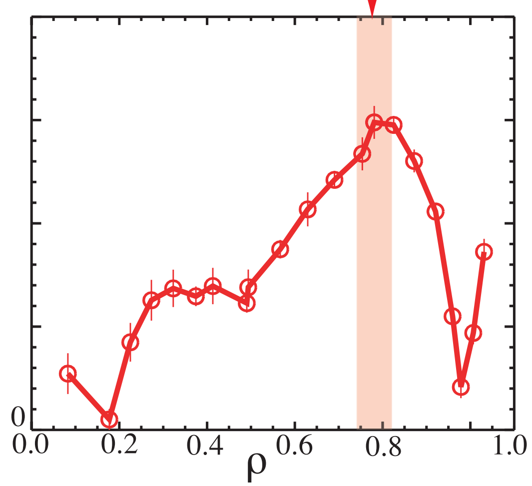
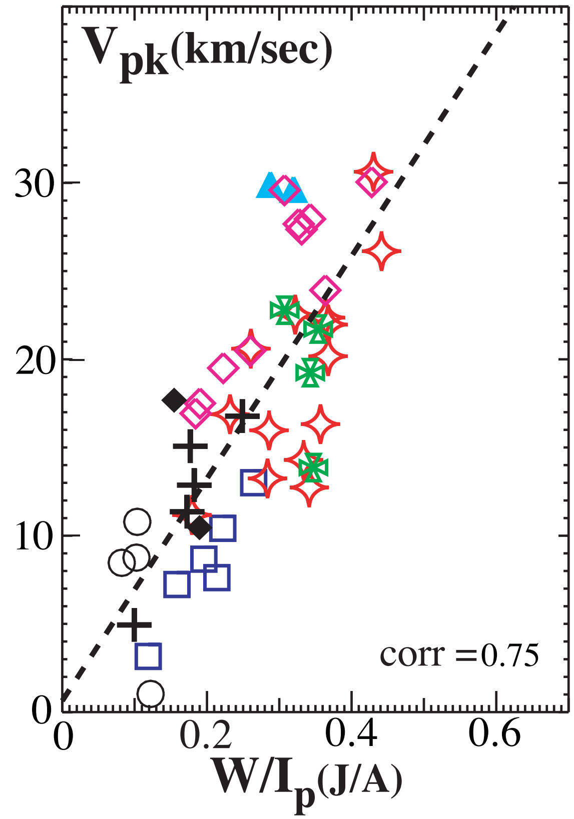


Rice scaling



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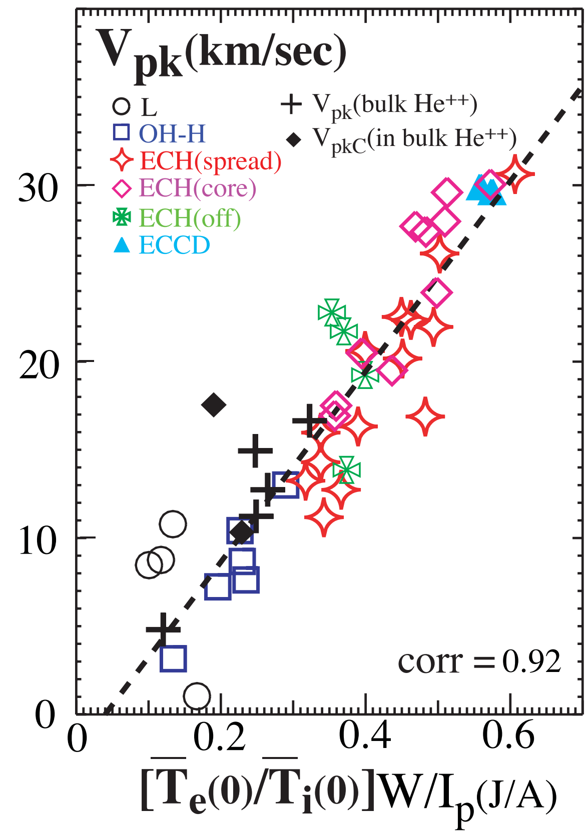


- Fits are done for V_ϕ C^{6+} in bulk D

Data points for V_ϕ He^{++} (+) and C^{6+}(◆) in bulk He fall in line.

1. J.E. Rice et al, NF 41, p 277 (2001).

This Common Scaling Motivated an Intrinsic Rotation Similarity Experiment Between DIII–D and C-mod

- **Dimensionless parameters**

$$\beta \propto nT/B^2 \equiv \hat{\beta}$$

$$\nu^* \propto an/T^2 \equiv \hat{\nu}$$

$$\rho^* \propto \sqrt{T}/aB \equiv \hat{\rho}$$

$$q \propto B/B_\theta \equiv q_{95}$$

- **Dimensionless Velocity**

$$M_\phi = V_\phi / \bar{V}_i$$

- **Match:**

$\hat{\beta}$ $\hat{\nu}$ $\hat{\rho}$ q_{95} (absolute parameters)

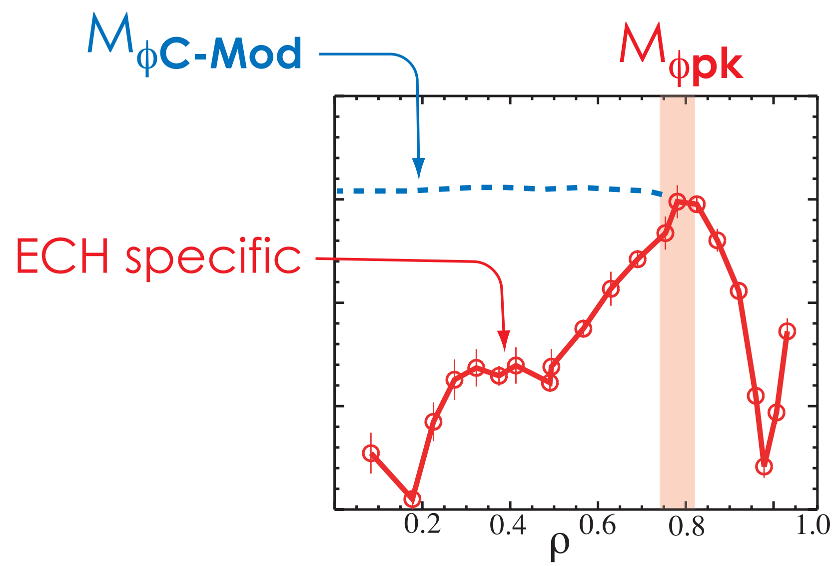
shape ($\varepsilon = a/R_0$, κ ....)

- **Measure:** M_ϕ

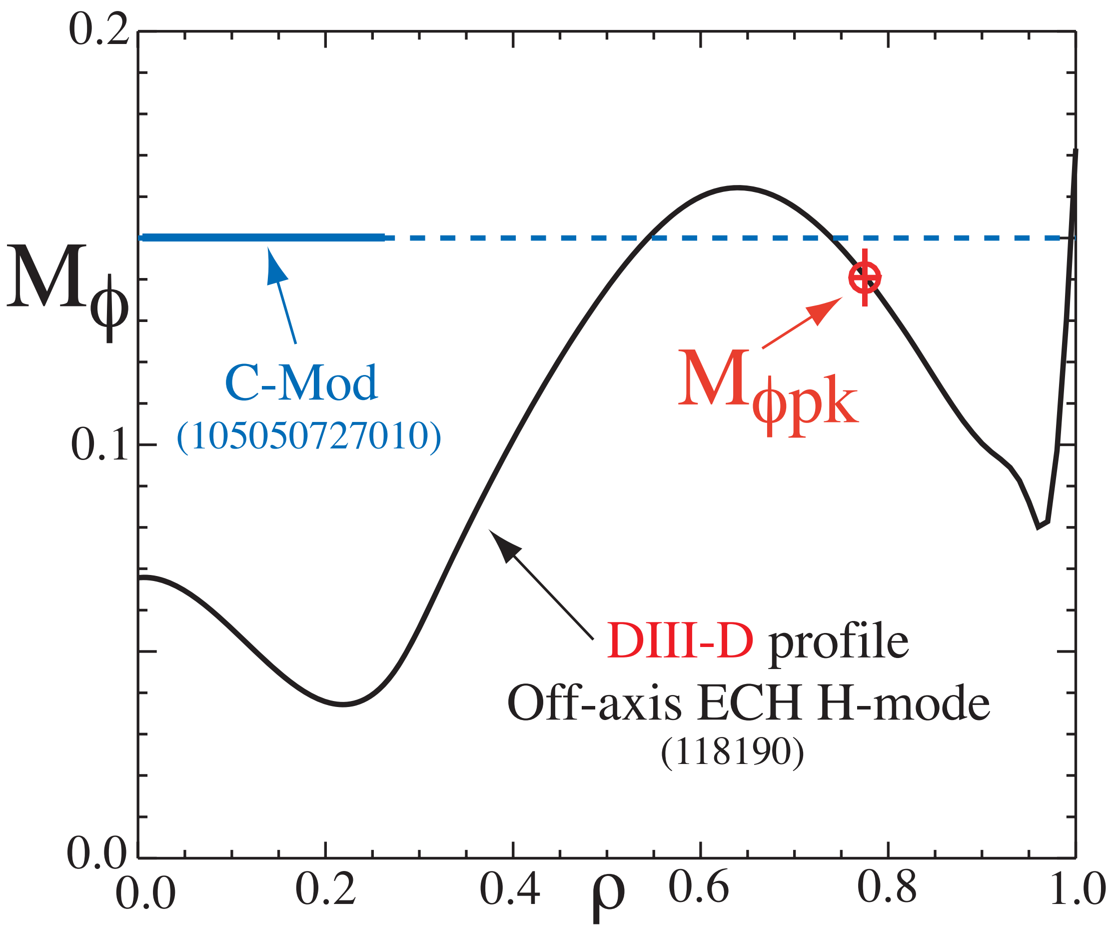
- **DIII-D Target Shot**

ELMing H-mode; ~ *steady state*
("off-axis" ECH H-mode) $T_e \sim T_i$

- **Single point M_ϕ comparison, not profile**
- **Assumptions required to compare:**



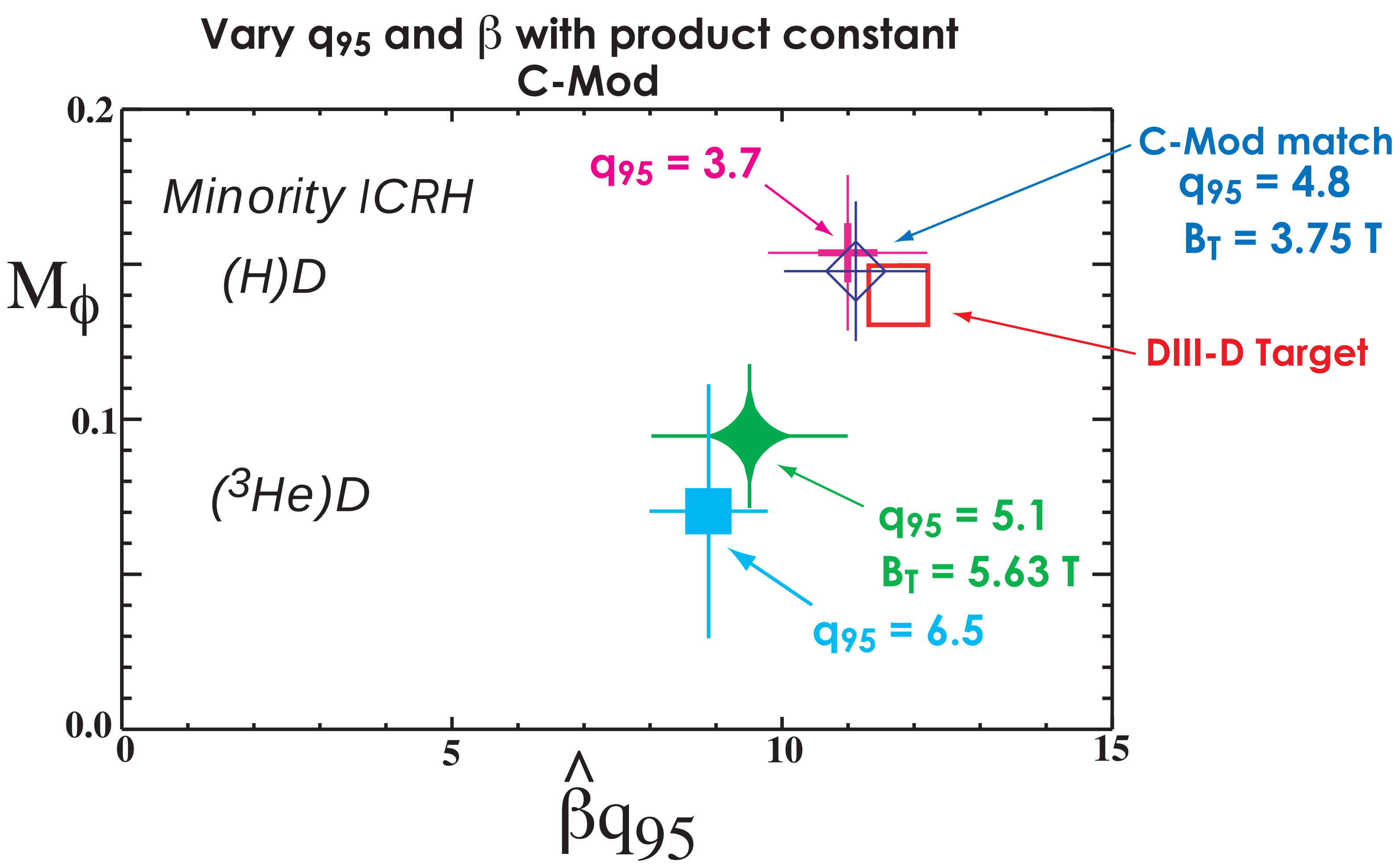
Initial DIII-D/C-Mod Similarity Experiment Shows a Good Match in the Intrinsic M_ϕ



	DIII-D	C-Mod
B_T(T)	**1.75**	**3.75**
a(m)	**0.60**	**0.22**
ε	0.35	0.32
κ	1.87	1.64
q_{95}	4.9	4.8
$\hat{\beta}$	2.4	2.3
$\hat{\nu}$	1.7	2.2
$\hat{\rho}$	1.1	1.5
M_ϕ	**0.14**	**0.15**
$n_e(10^{19}/m^3)$	**5.4**	**22.**
T(keV)	1.4	1.5

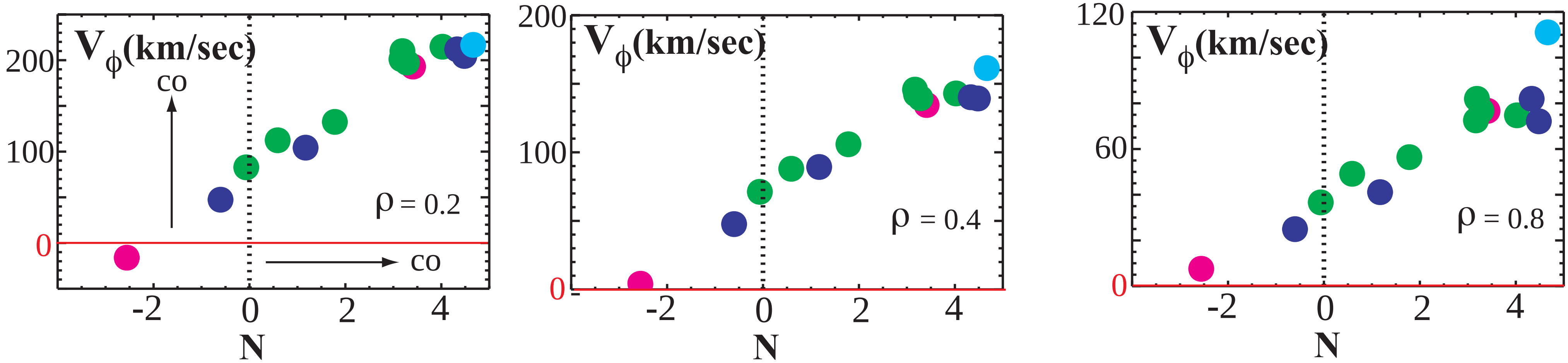
The Rice Scaling Motivates a Search for a Similarity Path in βq

$$W/I_p \longrightarrow nT/B_\theta \longrightarrow [\hat{\beta} q_{95}]^{1.25}[\nu,\rho,..]^\delta$$



Intrinsic Rotation and NBI Torque:
NBI Does Not Quench The Intrinsic Rotation

- Local co-directed velocity persists, with zero volume integrated torque.
- Linear variation of velocity near zero torque indicates NBI impulse is additive.
- We will also look into the details of the torque and momentum profiles.

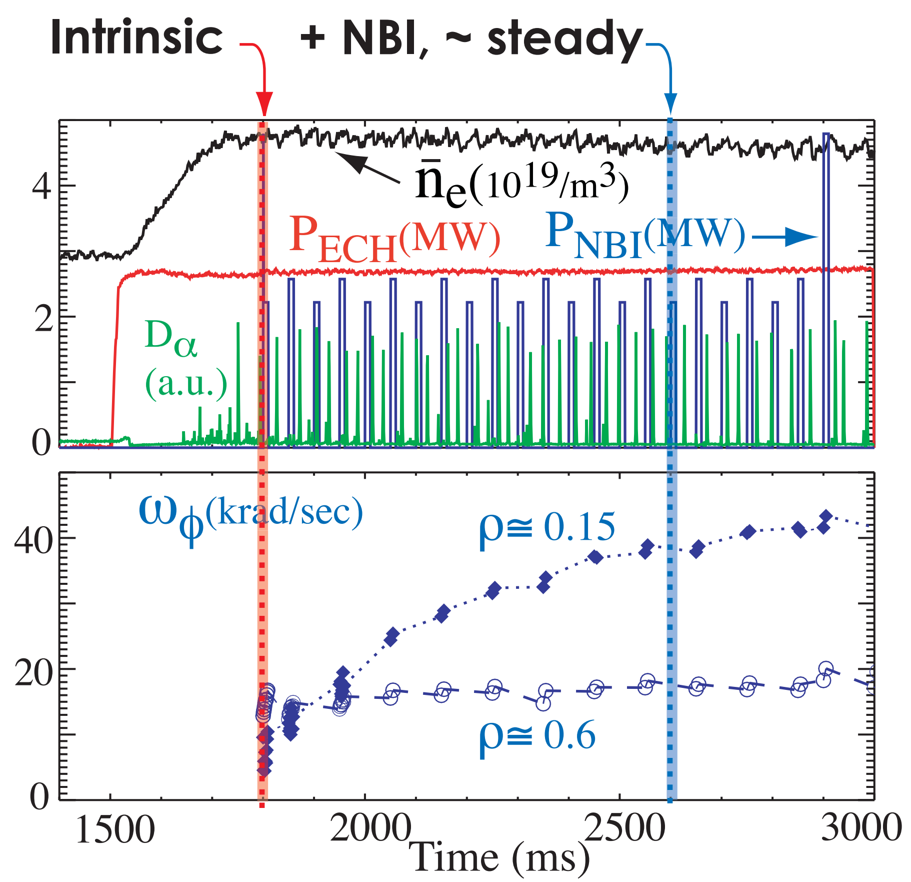


Volume integrated NBI torque, N (Nt-m)
varied with DIII-D simultaneous co/counter NBI

** Data from Wayne Solomon, CO1.0006*

NBI Does Not Quench Intrinsic Rotation: Confinement Time Analysis for Incremental NBI Torque-impulse

- **ECH H-mode target; add NBI incremental torque**



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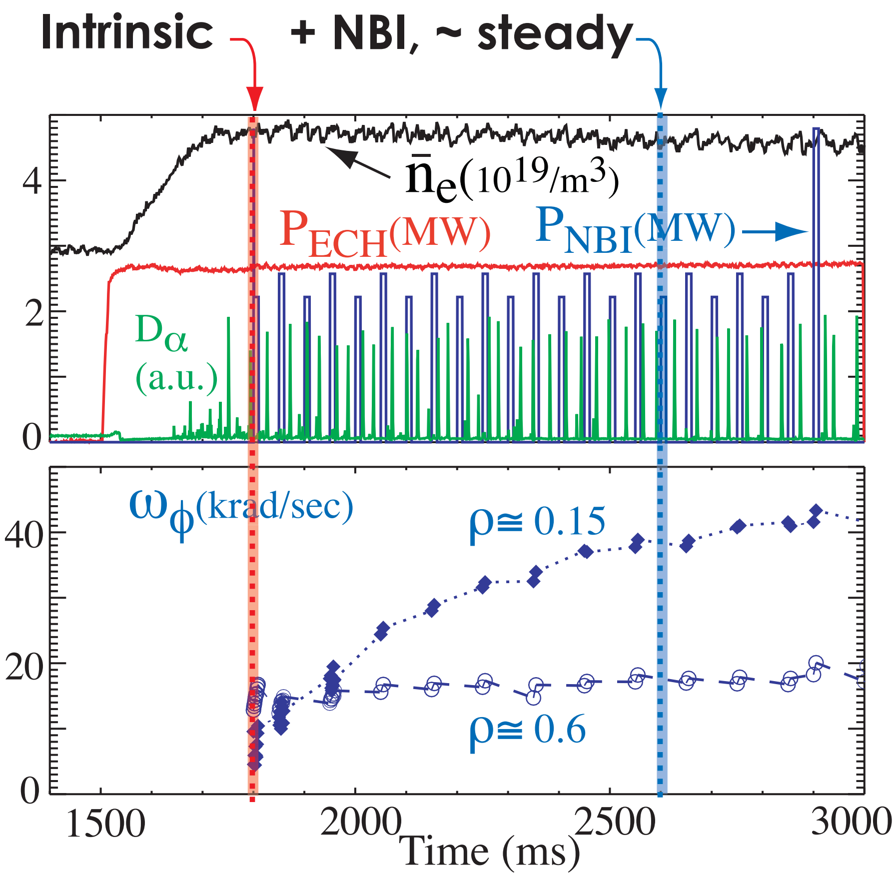
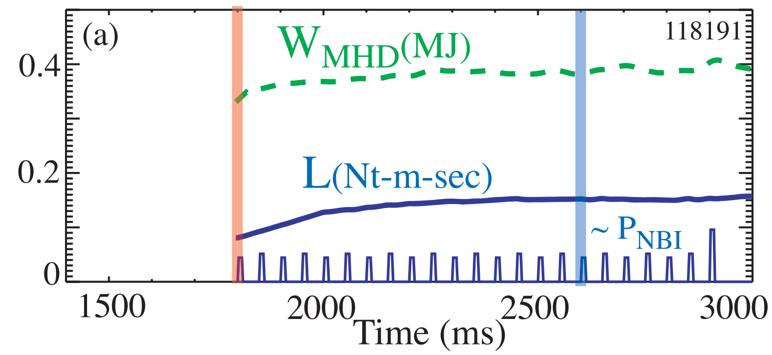


- **Confinement time analysis globally integrated:**



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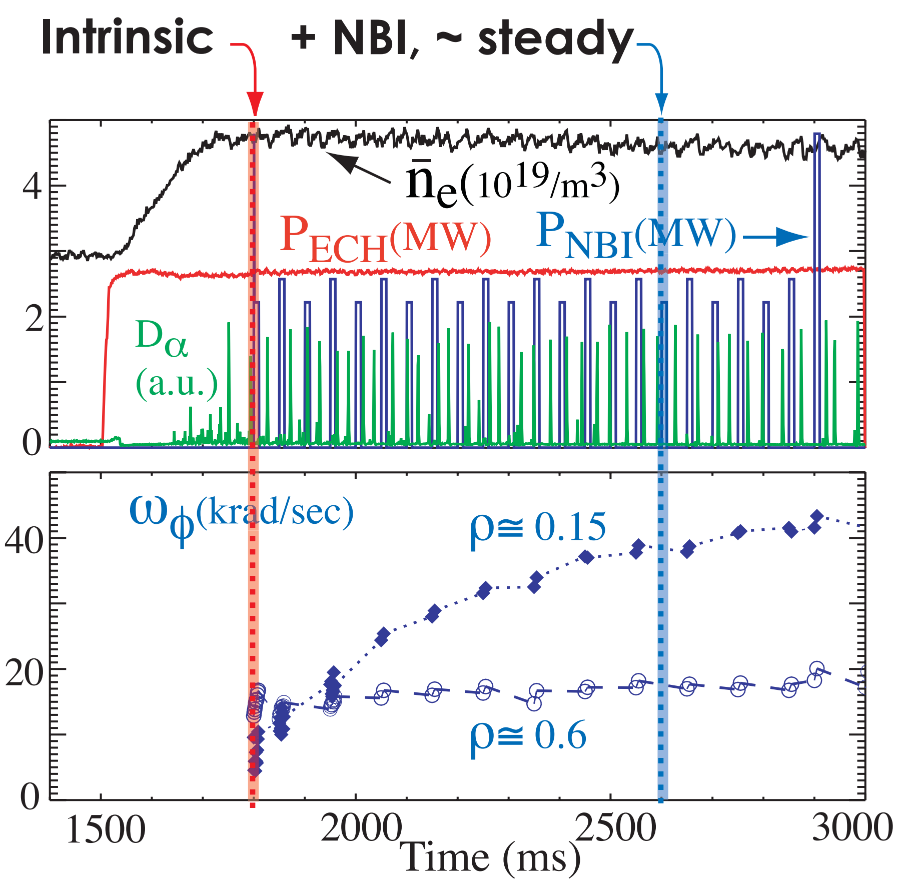

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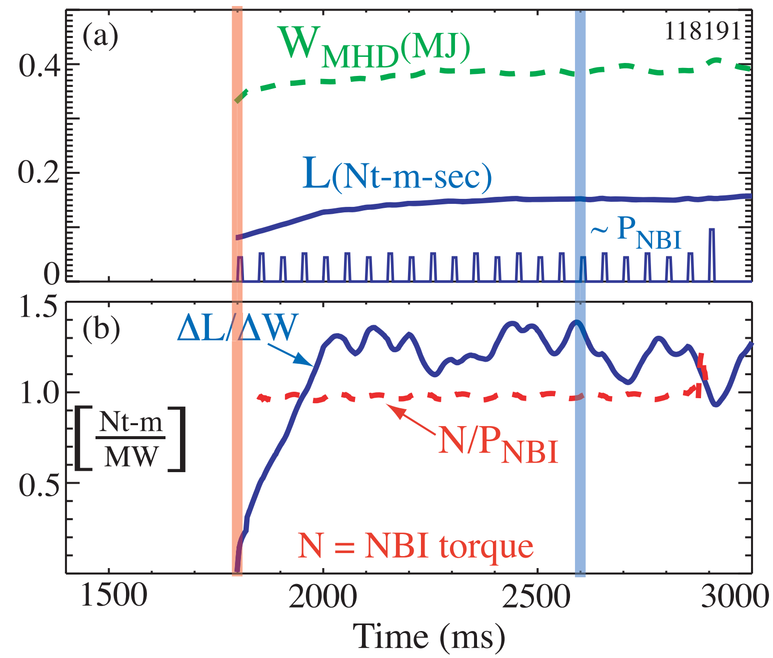
response follows source



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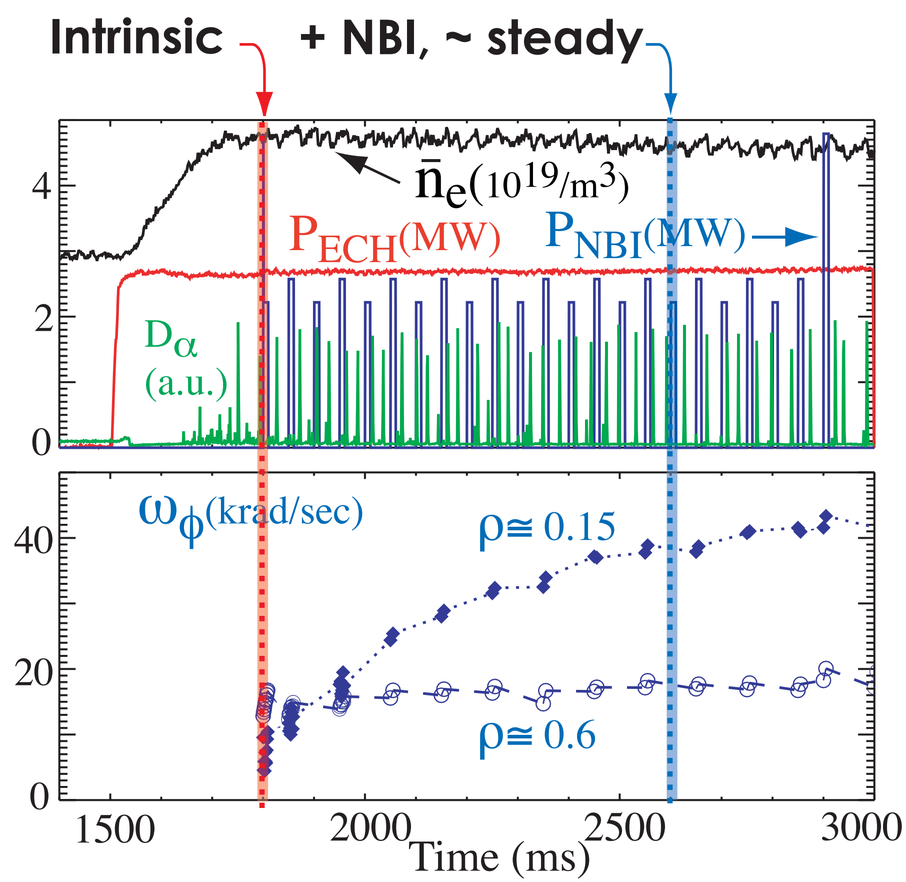

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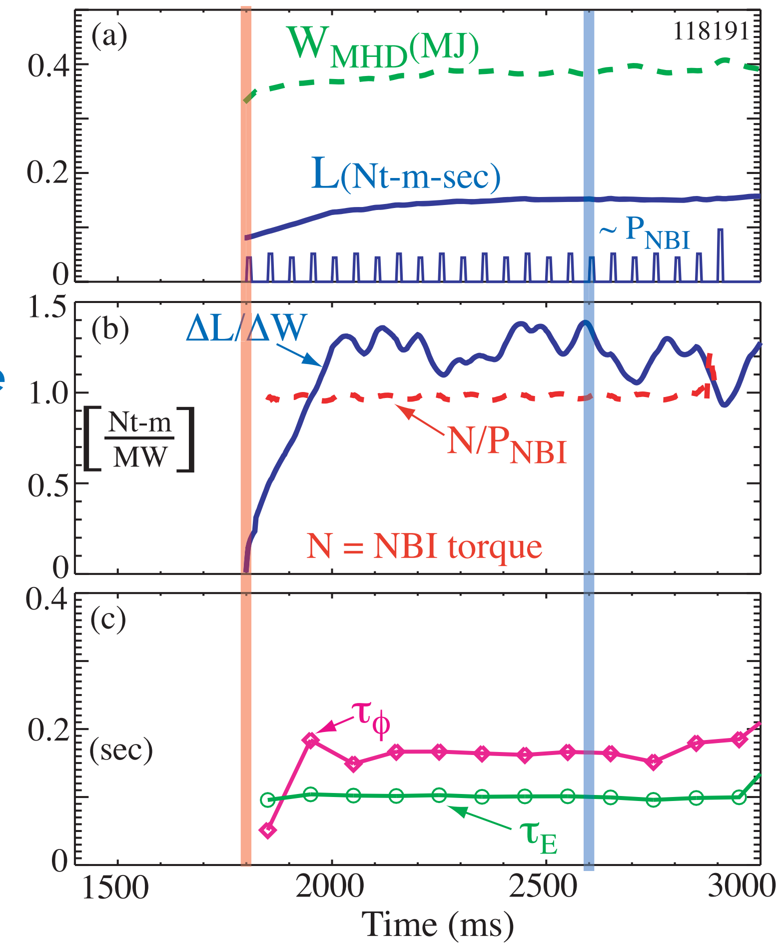
response follows source

$\tau_\phi \sim \tau_E$



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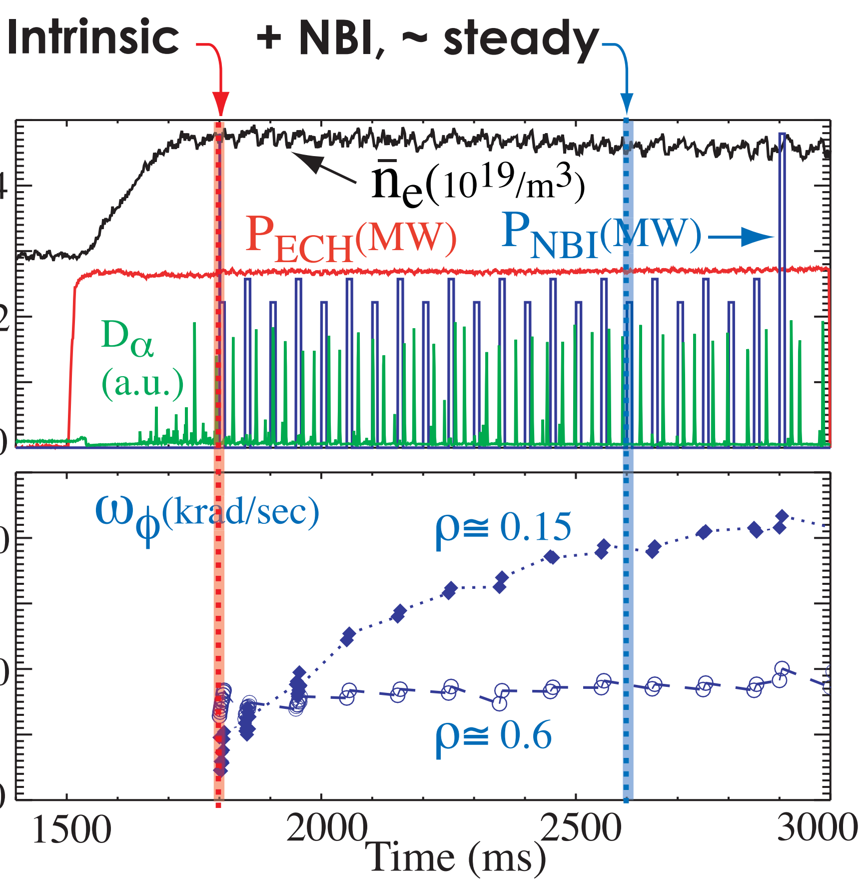
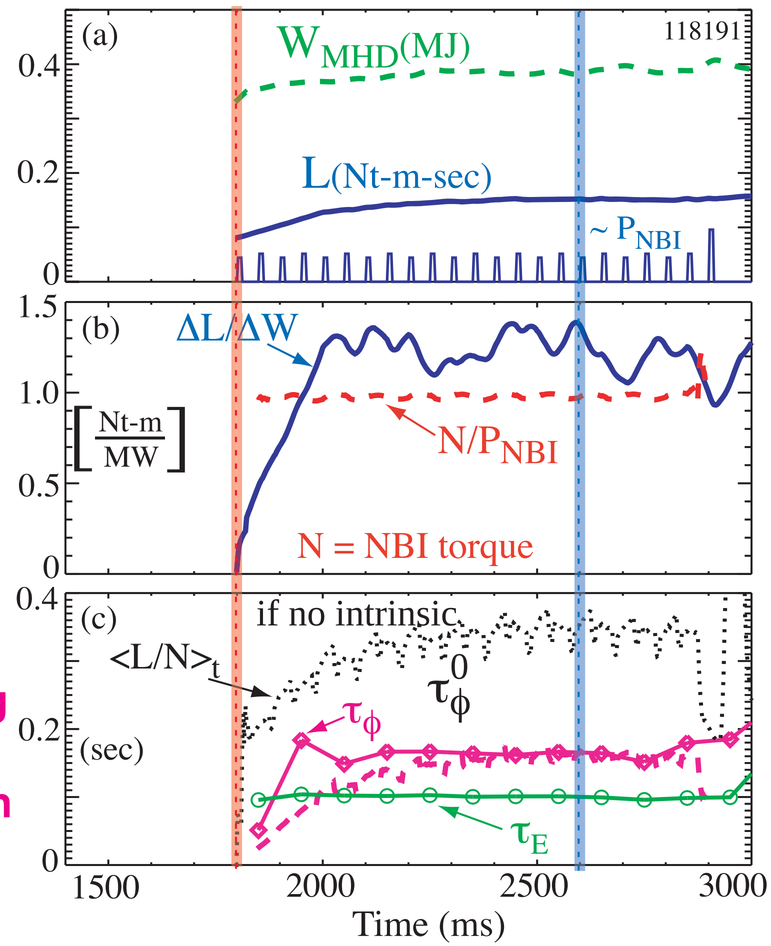


- **Confinement time analysis globally integrated:**

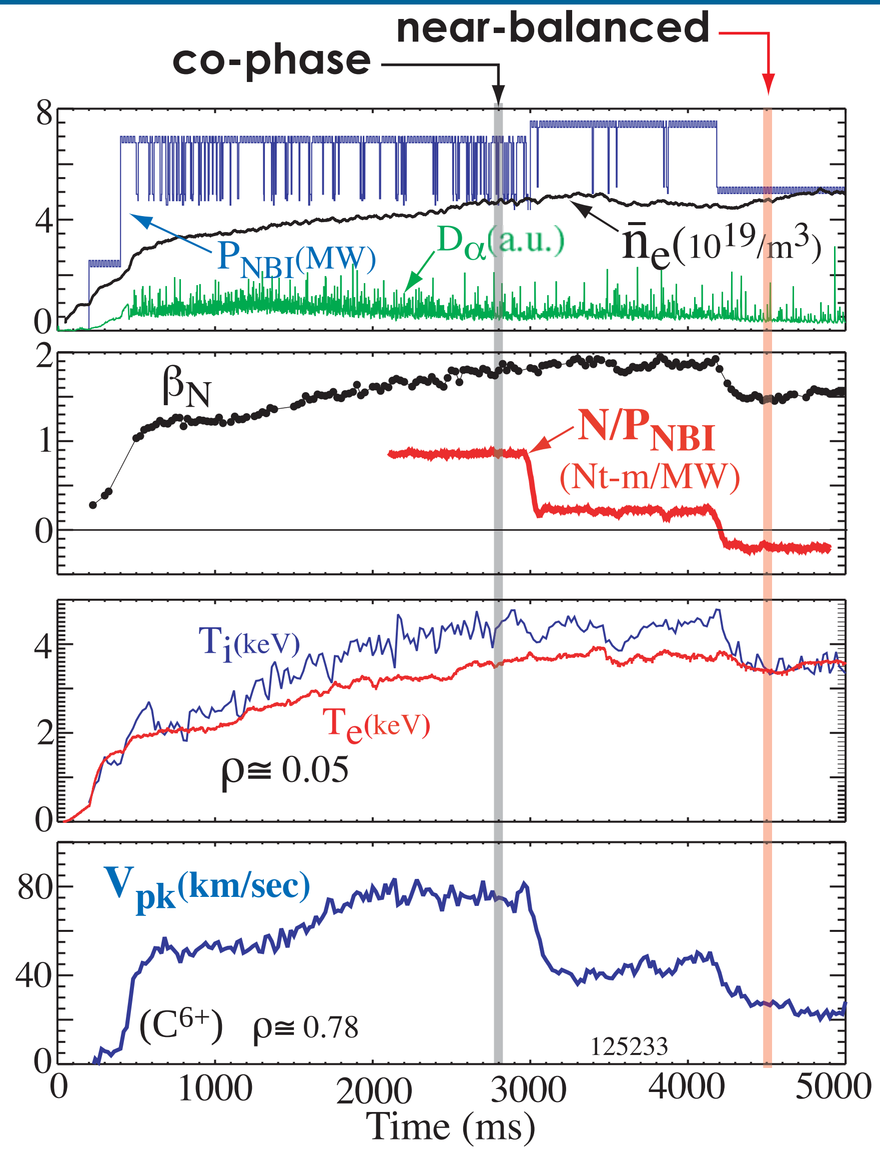
response follows source

$\tau_\phi \sim \tau_E$ subtracting intrinsic momentum



High Power Locally Balanced NBI Reveals Intrinsic Rotation

- Use new DIII-D simultaneous co/counter NBI capability
- The goal will be to push intrinsic rotation scaling to higher β values with high power NBI.
- This shot, no ECH, add counter beam in steps.



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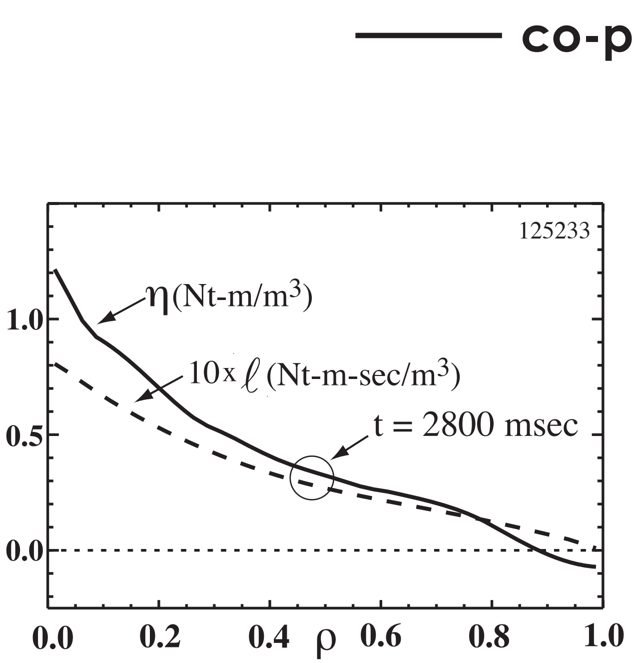
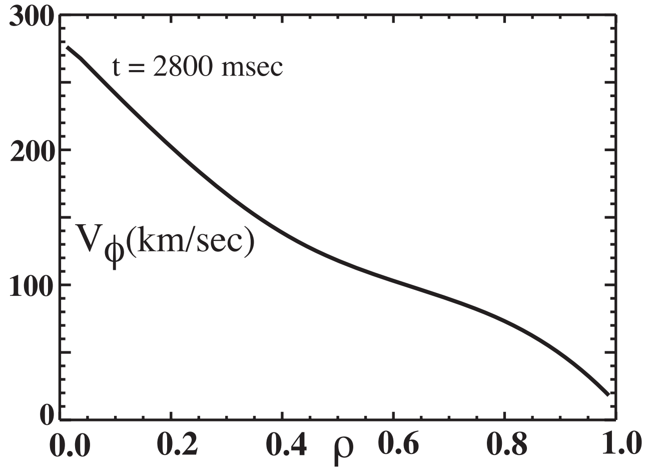
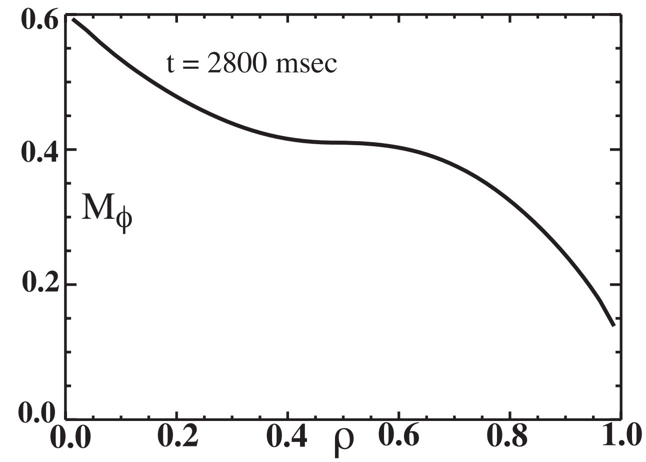


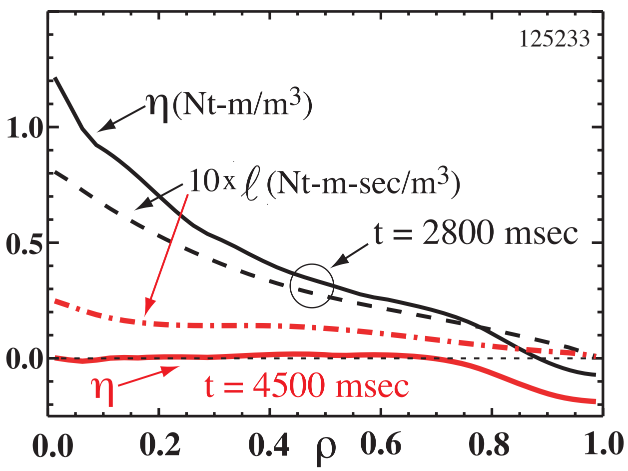


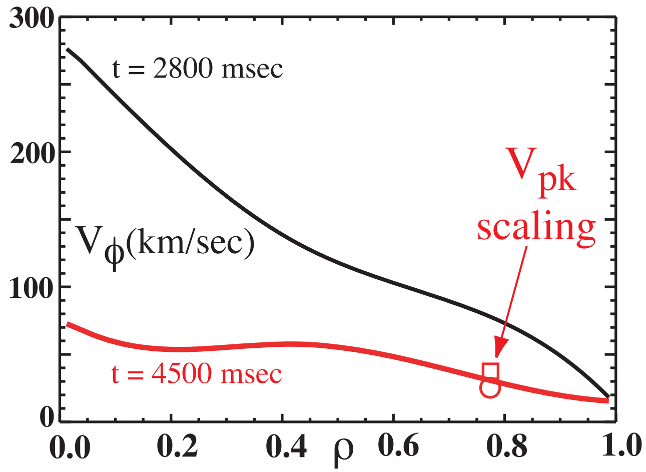


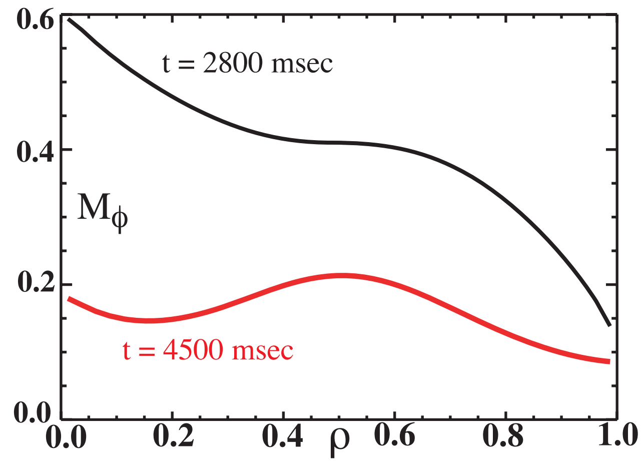
- M_ϕ profiles

High Power Locally Balanced NBI Reveals Intrinsic Rotation

co-phase — near-balanced







torque density, $\eta \sim 0$, for $\rho < 0.75$, and $\eta < 0$ outside

- yet, plasma momentum density, $\ell > 0$, everywhere

- V_{pk} scaling describes the "intrinsic" value!

□ W/I_p
○ $(T_e/T_i)W/I_p$

- M_ϕ profiles

Theories predict intrinsic rotation: Extensions to Neoclassical theory

- 2nd order neoclassical theory; off-diagonal elements

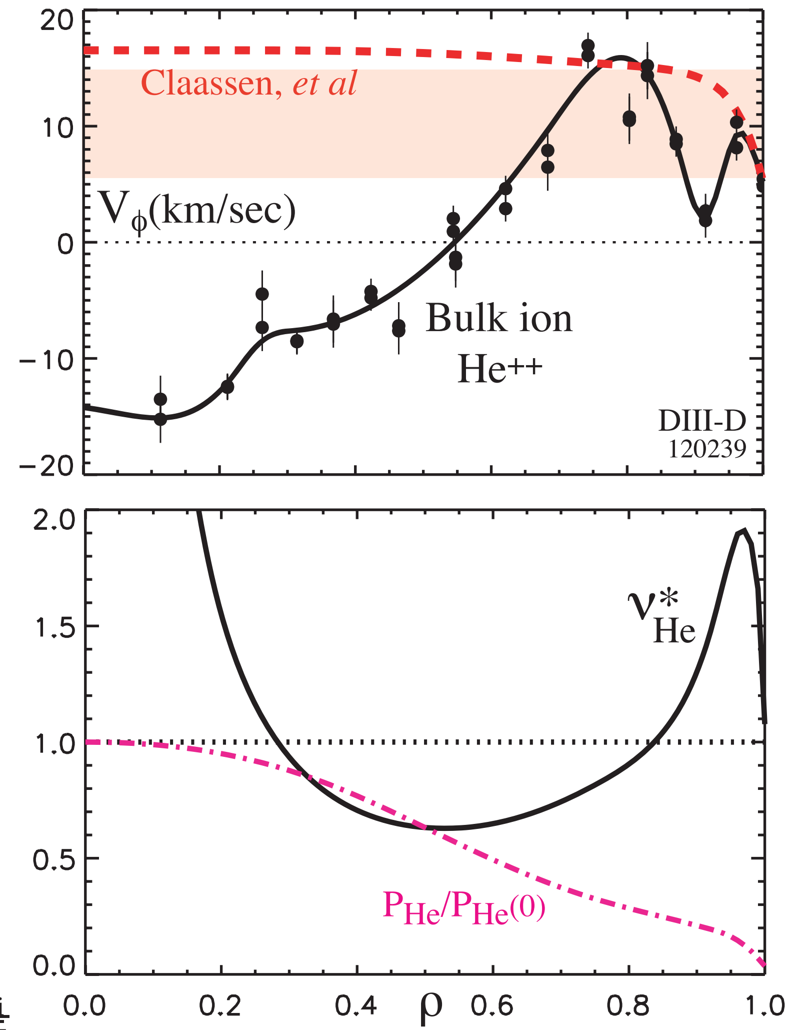
  S.K. Wong, V.S. Chan PoP 12, 2005.

  H.A. Claassen, *et al*, PoP 7, 2000.

  P.J. Catto and A.N. Simakov, PoP 12, 2005.

  A.L. Rogister, *et al*, NF 42, 2002.

- Not yet the complete story, but the predicted pedestal value cannot be ignored



$$\nu^* = \frac{R_0 q \nu_i}{\varepsilon^{3/2} \bar{V}_i}$$

Theories predict intrinsic rotation: Turbulence

- Turbulence theories to date provide motivation, qualitative predictions.

R.R. Dominguez and G.M. Staebler, PF, 11 (1993) — slab: ITG, DTE produce different intrinsic profiles

G.M. Staebler, PoP, 11 (2003) — toroidal: theoretical framework in which to include turbulence stress

B. Coppi, NF 42, (2002)
B. Coppi, IAEA, Lyon (2002) — ITG modes in outer region. Model diffusion and pinch

B. Coppi et al, EPS Rome (2006) — Edge turbulent mass ejection (blobs)

J. Thomas and B. Coppi UP1.00072

P.Nataf and B. Coppi UP1.00073

- As with energy confinement, we will need to measure the turbulence characteristics!

Summary

- Intrinsic rotation exists, independent of ion species. It increases in the co-Ip direction with increased plasma stored energy
- In ECH H-modes, the details of the core profile, including a transition to counter-Ip rotation, depend upon the ECH power deposition profile
- Intrinsic rotation is reproducible, with repeated plasma profiles
- There is a scaling; The Rice scaling is a starting point and now we are searching for the dimensionless result
- An initial DIII-D/C-Mod similarity experiment is encouraging; much more to do
- It will be possible to measure intrinsic rotation using near-balanced NBI torque in DIII-D, pushing β_N to 2, and beyond
- Theories are coming to the point that direct comparison with experiment can be made