Abstract Submitted
for the DPP99 Meeting of
The American Physical Society

Sorting Category: 5.1.1.2 (Experimental)

Plasma Rotation and Direct Electron Heating in DIII-D[1] J.S. DEGRASSIE, K.H. BURRELL, C.M. GREENFIELD, C.C. PETTY, G.M. STAEBLER, Y.R. LIN-LIU, General Atomics, W.W. HEIDBRINK, University of California, Irvine, M.R. WADE, Oak Ridge National Laboratory — In a wide variety of neutral beam heated discharges on DIII–D it is observed that the addition of direct electron heating, either with electron cyclotron or fast wave (FW) power, results in a reduction of the core toroidal rotation speed and in most instances also a reduction in the ion temperature. At present, the best explanation for this result is that the confinement of toroidal momentum decreases with increasing electron to ion temperature ratio. Ion thermal confinement increases with increasing $T_\mathrm{e}/T_\mathrm{i}$ and is consistent with anomalous transport due to turbulent ion temperature gradient modes.[2] No evidence of any direct rf induced torque has been observed. In particular, a FW experiment was done with minority absorption by fast ^{3}He to try to induce a torque to increase the toroidal speed. However, only the typical reduction was measured. Results from these experiments will be described.

[1]Supported by U.S. DOE Contracts DE-AC03-99ER54463, DE-AC05-96OR22464, and W-7405-ENG-48.
[2]C.C. Petty *et al.*, submitted for publication Phys. Rev. Lett.

J.S. deGrassie
@fusion.gat.com
General Atomics

☐ Prefer Oral Session
☒ Prefer Poster Session

Special instructions: DIII-D Poster Session 2, immediately following R Prater

Date printed: July 16, 1999

Electronic form version 1.4

Plasma Rotation and RF Heating in DIII-D

- Core plasma toroidal rotation, U_ϕ, and ion temperature, T_i, are reduced with RF electron heating.

- Target discharges for RF heating have toroidal rotation driven by unbalanced Neutral Beam Injection (NBI).

- RF electron heating can be with Electron Cyclotron Heating (ECH) or Fast Wave Electron Heating (FWEH).

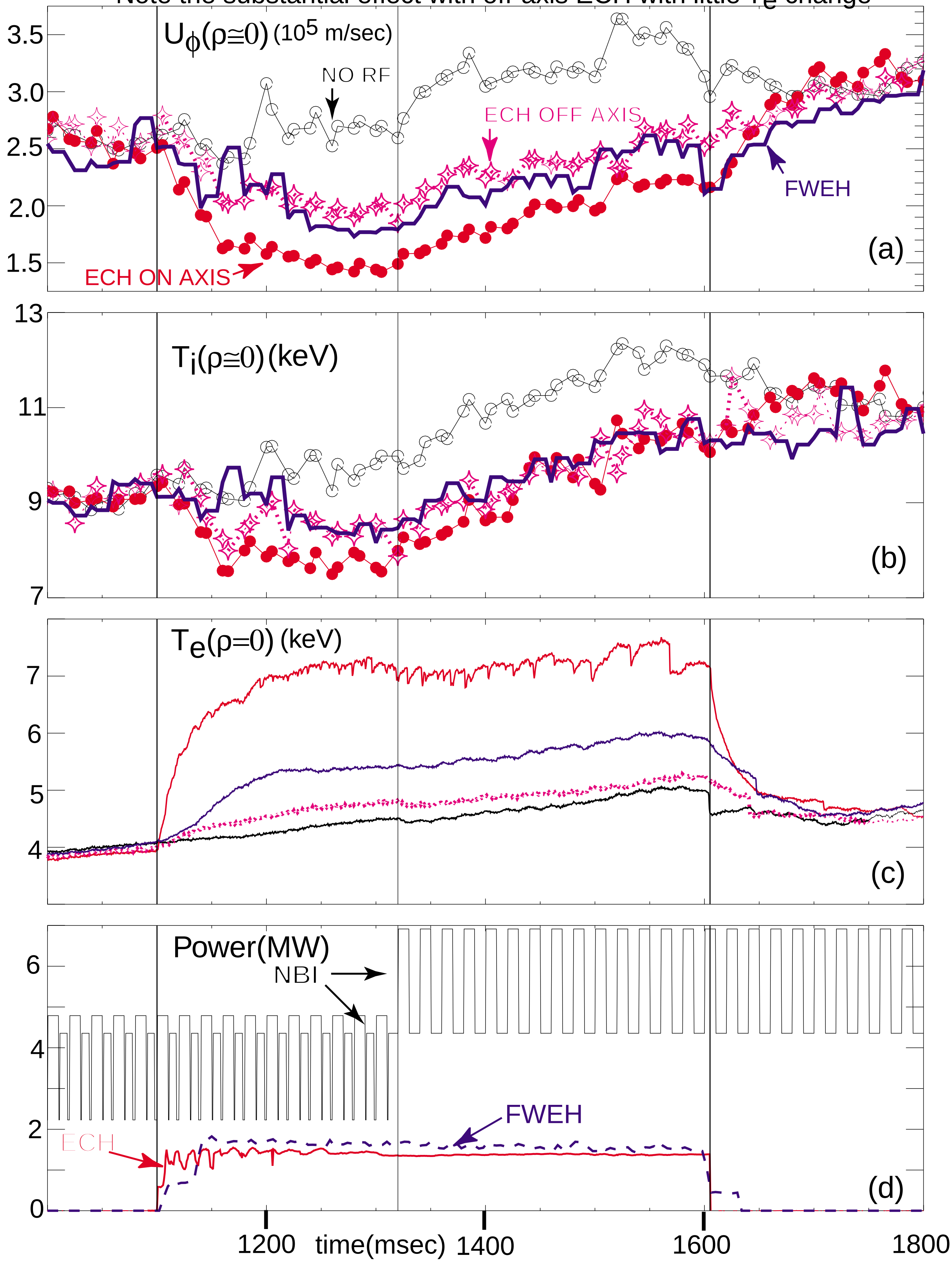
- This effect is observed with a variety of discharge conditions:
  - ❋ Clearest in low density discharges with ion internal transport barrier, and high rotation.
  - ❋ Occurs for ECH in radial or oblique launch (independent of $k_{//}$).
  - ❋ Occurs with ECH deposited on or off axis.
  - ❋ Occurs for FWEH co and counter phased (+/- $k_{//}$).
  - ❋ Occurs for co and counter NBI target driven rotation.

- These experiments indicate an enhanced ion thermal and momentum transport accompanying the increase in electron temperature, T_e. [1,2]

[1] C.M. Greenfield et al., proc. 17th IAEA Fusion Energy Conf., Yokohama, 1998.
[2] C.C. Petty et al, Phys. Rev. Lett. **83**, 3661 (1999).

U_ϕ and T_i reduced in core with different electron heating scenarios

Note the substantial effect with off-axis ECH with little T_e change



I_p= 1.5 MA, B_T= 2T, $n_e \cong$ 2e19 FW: 60MHz 0.6 MW $n_\phi \cong$ 14 / 83MHz 1.1 MW $n_\phi \cong$ 18

Reduction in U_ϕ Correlates Best with T_i/T_e

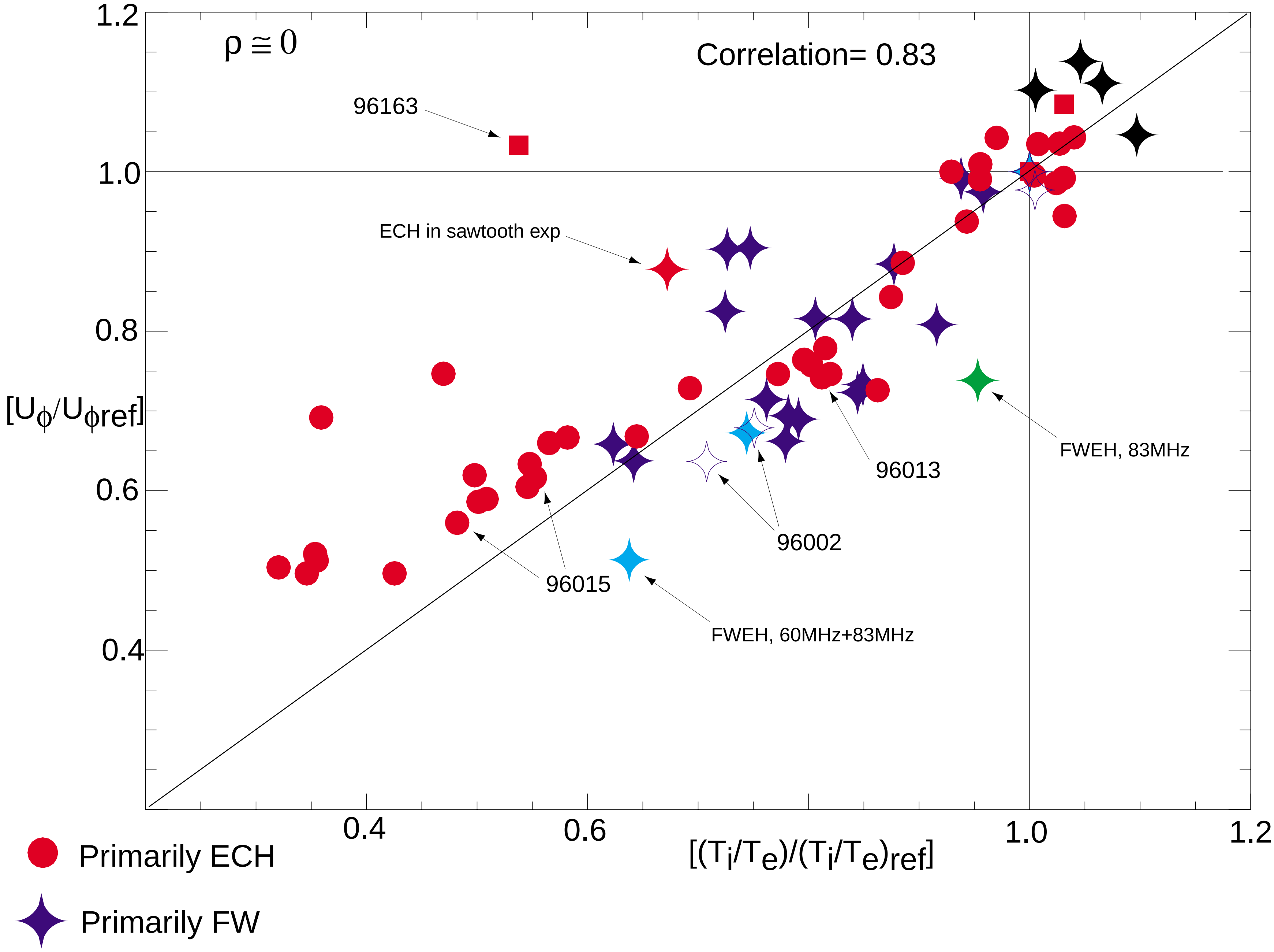
- Figure (1) shows time traces of electron heating induced slowing for ECH on and off axis, FWEH and a comparison **no-RF** discharge.

- Figure (2) shows the correlation of the reduction in U_ϕ with the decrease in T_i/T_e. These data are from a variety of experiments and discharge conditions.

Reduction in Rotation Correlates Best with T_i / T_e

Better than with either T_i or T_e alone, or other parameters

Data are from a variety of ECH and FW experiments; most FW data from sawtooth experiment



Can ICRH Induce a Toroidal Rotation?

- Recent model proposes a mechanism for ICRH induced toroidal rotation [3].
- But, the evidence on DIII-D indicates that electron heating enhances momentum transport, leading to a reduction in toroidal rotation.
- Two questions about the model for ICRH induced rotation:
  - Does this induced rotation exist? (does inter-species friction cancel?)
  - If so, can it be observed in the face of enhanced momentum transport ?
- Design an experiment to look for ICRH induced rotation:
  - Use counter NBI target to distinguish a counter torque from enhanced viscosity.
  - Select ion resonance interactions to induce a counter torque on the bulk, according to the model.
  - Use a ^{3}He beam to enhance ion absorption over electron absorption.
  - Result -> Enhanced transport still appears to dominate.

[3]. C.S. Chang et al, Phys. Plasmas **6**, 1969 (1999).

ICRH CAUSES RADIAL TRANSPORT OF RESONANT IONS

- Numerous authors have described this transport (see below for examples).
- Resonant ions can cross ψ surfaces on average, leading to a nonambipolar radial current, at least transiently.
- Recently, C.S. Chang has argued that the plasma return current due to such a current of resonant ions can produce a torque on the bulk plasma, resulting in a toroidal velocity.
  [C.S. Chang et al, Physics of Plasmas **6**, 1969 (1999).]
- However, there is a competing torque in the friction between the radially transported resonant ions and the bulk plasma.
  [M.N. Rosenbluth and F.L. Hinton, Nuclear Fusion **36**, 55 (1996)]
- A steady state equation for toroidal momentum has the form (cylindrical):

$$M\overline{\nabla}[\chi\overline{\nabla}\bullet(n\bar{U}_\phi)] + F_\phi + J_\rho B_\theta - f_\phi = 0$$

M = bulk ion mass

n = bulk ion density

χ = momentum diffusivity

$\bar{U}_\phi$ = toroidal velocity

F_ϕ = NBI force

B_θ = poloidal field

f_ϕ = friction; fast -> bulk

J_ρ = bulk radial current

$J_\rho + J_{fast} = 0$

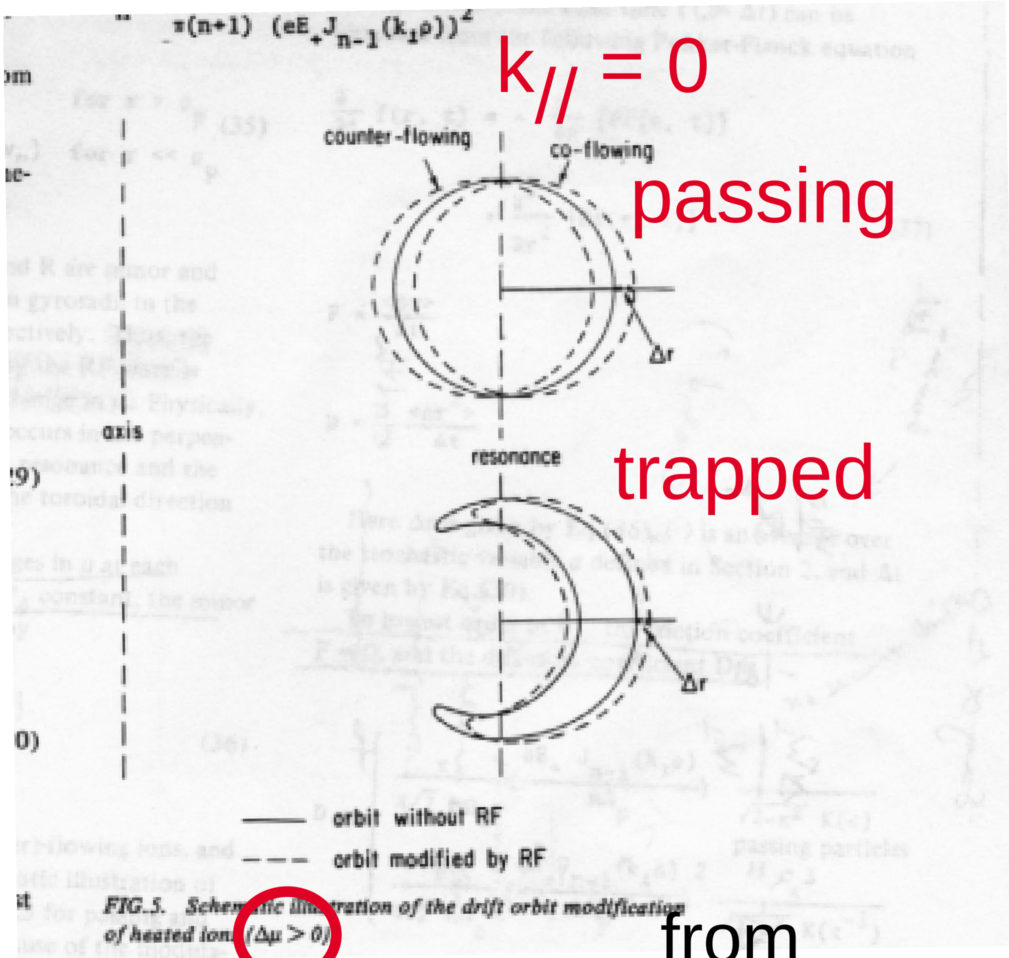


FIG. 5. Schematic illustration of the drift orbit modification of heated ions ($\Delta\mu > 0$)

from
Whang & Morales
NucFus 23, 481 ('83)

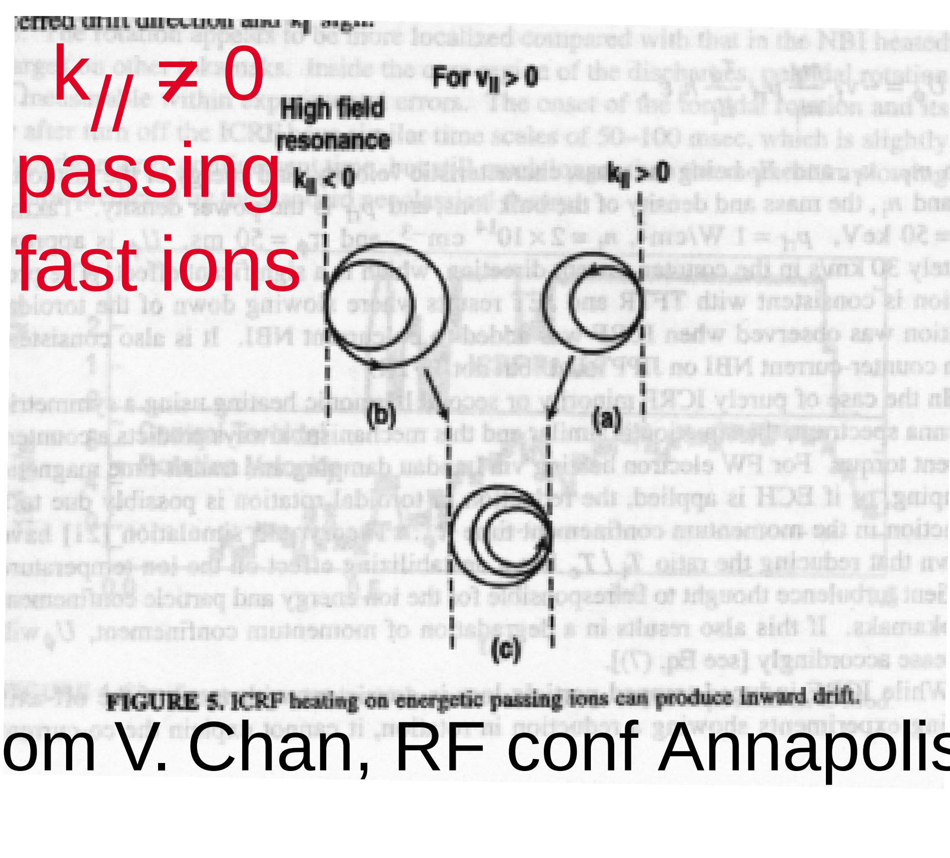


FIGURE 5. ICRF heating on energetic passing ions can produce inward drift.

from V. Chan, RF conf Annapolis '99

$k_{//} = 0$ trapped

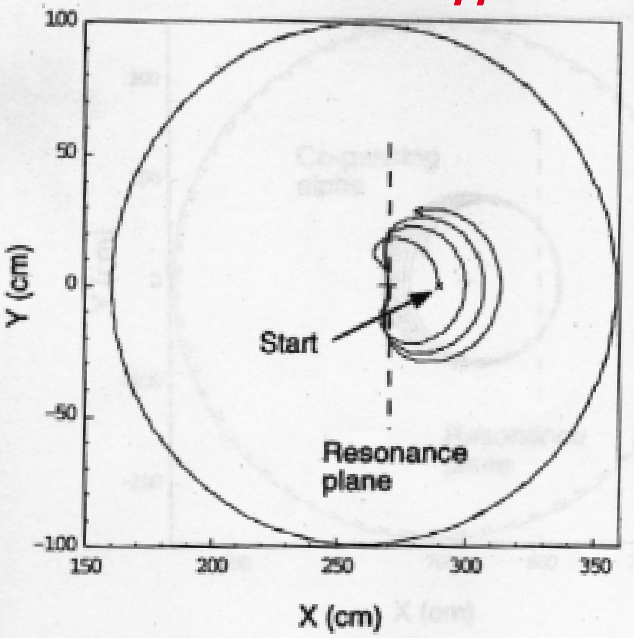


FIG. 1. Projection of a collisionless guiding center orbit on poloidal plane for a trapped hydrogen ion in TFTR geometry under an exaggerated perpendicular heating. The dashed straight line shows resonance surface. X is the horizontal distance from the toroidal axis and Y is the vertical distance from the magnetic axis.

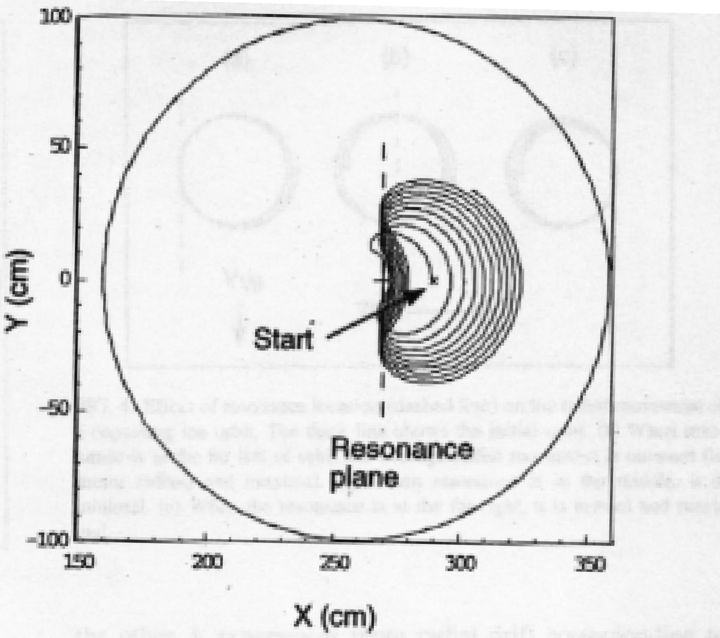


FIG. 2. Poloidal projection of guiding center orbit in TFTR for a trapped hydrogen ion under exaggerated on-axis perpendicular heating when Coulomb slowing-down collisions are turned on.

passing

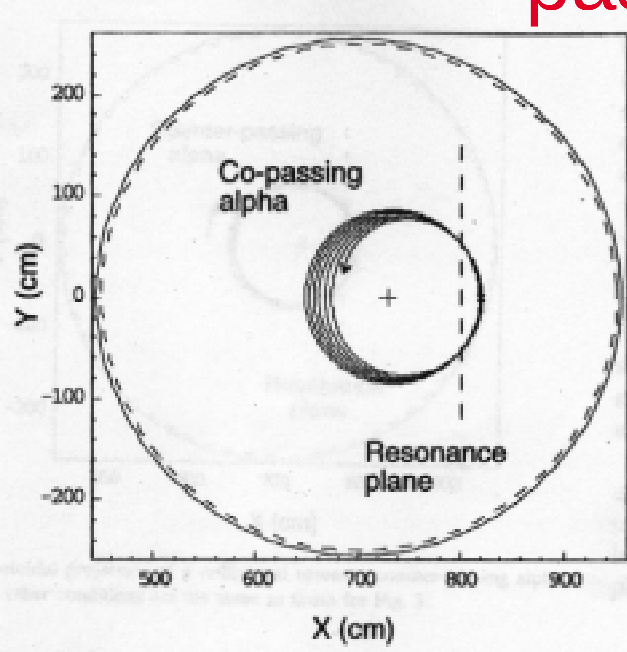


FIG. 3. Poloidal projection of a collisionless resonant co-passing alpha orbit driven by an exaggerated perpendicular heating on a low-B side resonance surface (dashed line) in a reactor grade tokamak device. 0.5 MeV perpendicular energy kick per pass is used during 18 toroidal transit motions shown. The particle starts at 2 MeV and ends at 8.5 MeV.

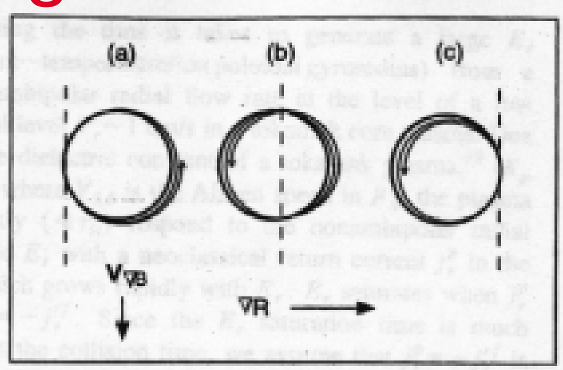


FIG. 4. Effect of resonance location (dashed line) on the radial movement of a copassing ion orbit. The thick line shows the initial orbit. (a) When resonance is at the far left of orbit the average radial movement is outward (in minor radius) and maximal. (b) When resonance is in the middle, it is minimal. (c) When the resonance is at the far right, it is inward and maximal.

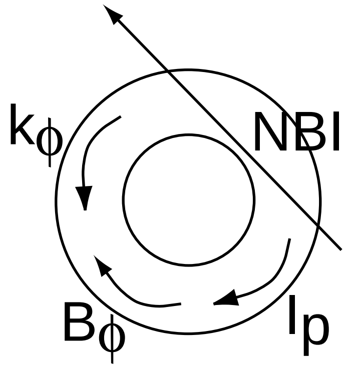
the other, it experiences more radial drift corresponding to that side. The direction and magnitude of the time-averaged net radial transport are thus determined by the imbalance in the radially outward and inward, time-averaged excursions between each side of the resonance surface. In the case shown in Fig. 3, the inward excursion portion is greater,

from C.S. Chang et al
Phys Plasmas 6, 1969 ('99)

[Experimental verification of passing transport: Finken et al, Phys Rev Lett 73, 436 (1994)]

Resonant Ion Absorption and Radial Transport

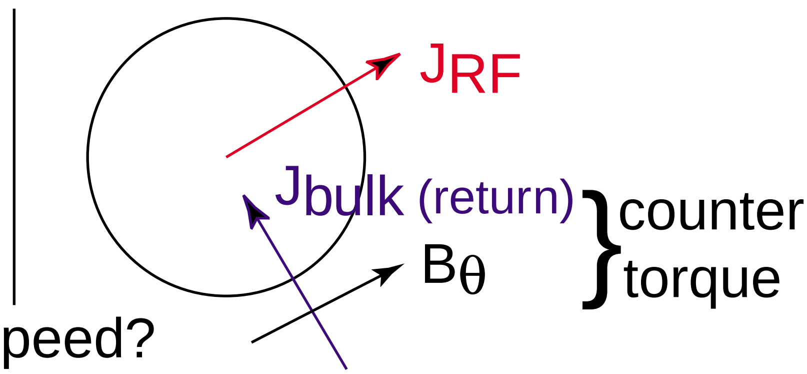
(in ψ or ρ space)



- We want a net outward RF driven flow of the resonant ions.

- Counter torque in direction of NBI counter torque.

- => increase toroidal speed?



- ICRH moves trapped ions out (on average) ($k_\phi = 0$ effect)

- Passing ions: outboard resonance drives counter passing beam ions outward. On axis resonance minimizes RF transport of passing ions.($k_\phi = 0$ effect)

- $k_\phi \mp 0$ Trapped ions - must supply counter toroidal force for outward transport => phasing $\bar{k}_\phi \bullet \bar{I}_p < 0$

- $k_\phi \mp 0$ Passing ions - counter passing ion resonance Doppler shifted outboard => drives outward transport

Target Discharge - Ion resonances selected to transport resonant ions out of the core

Shot: 99873

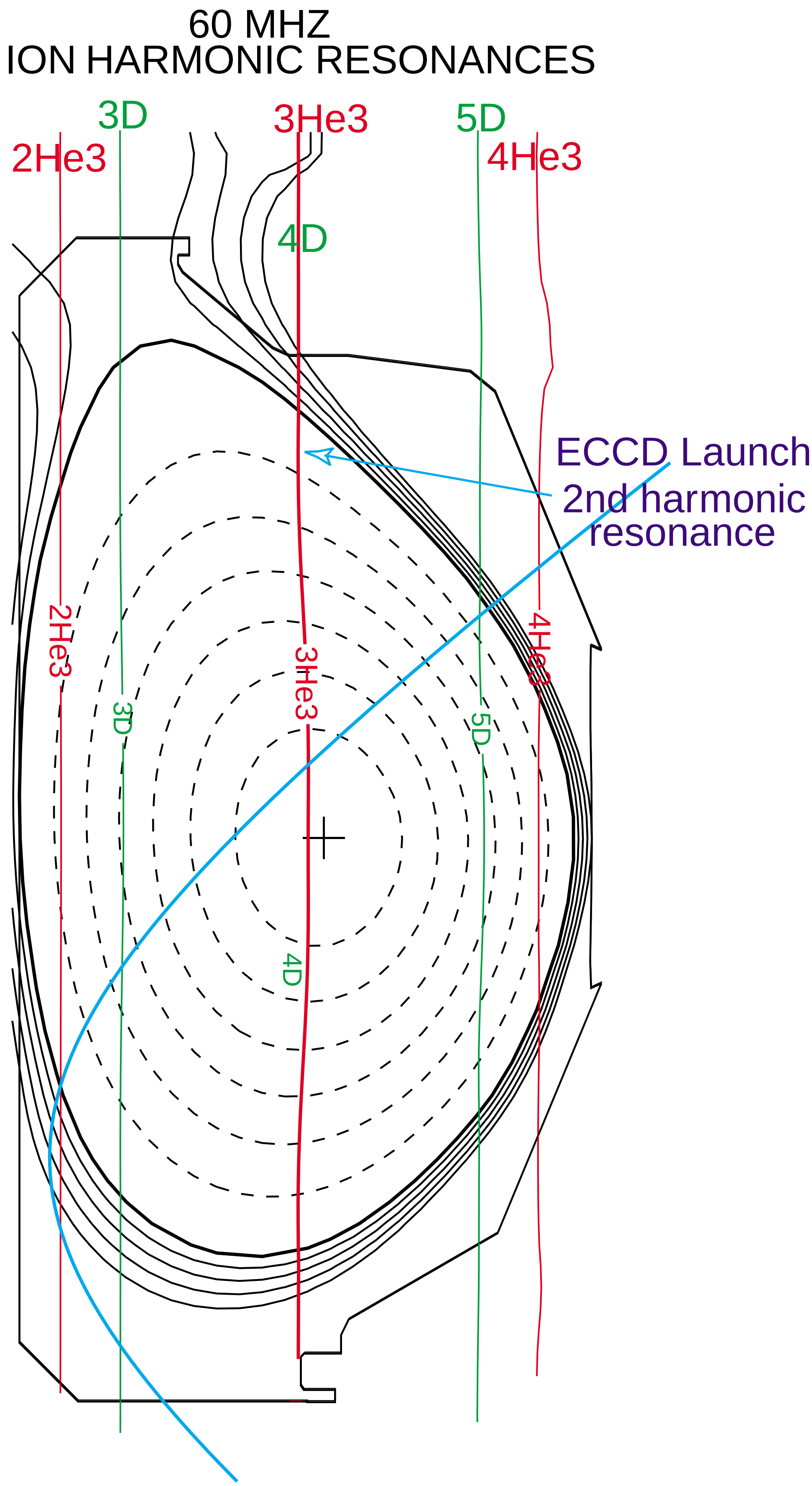
Time: 1000 ms

Ip = 1 MA (cw)

BT = 1.94 T (cw)

q95 = 5.9

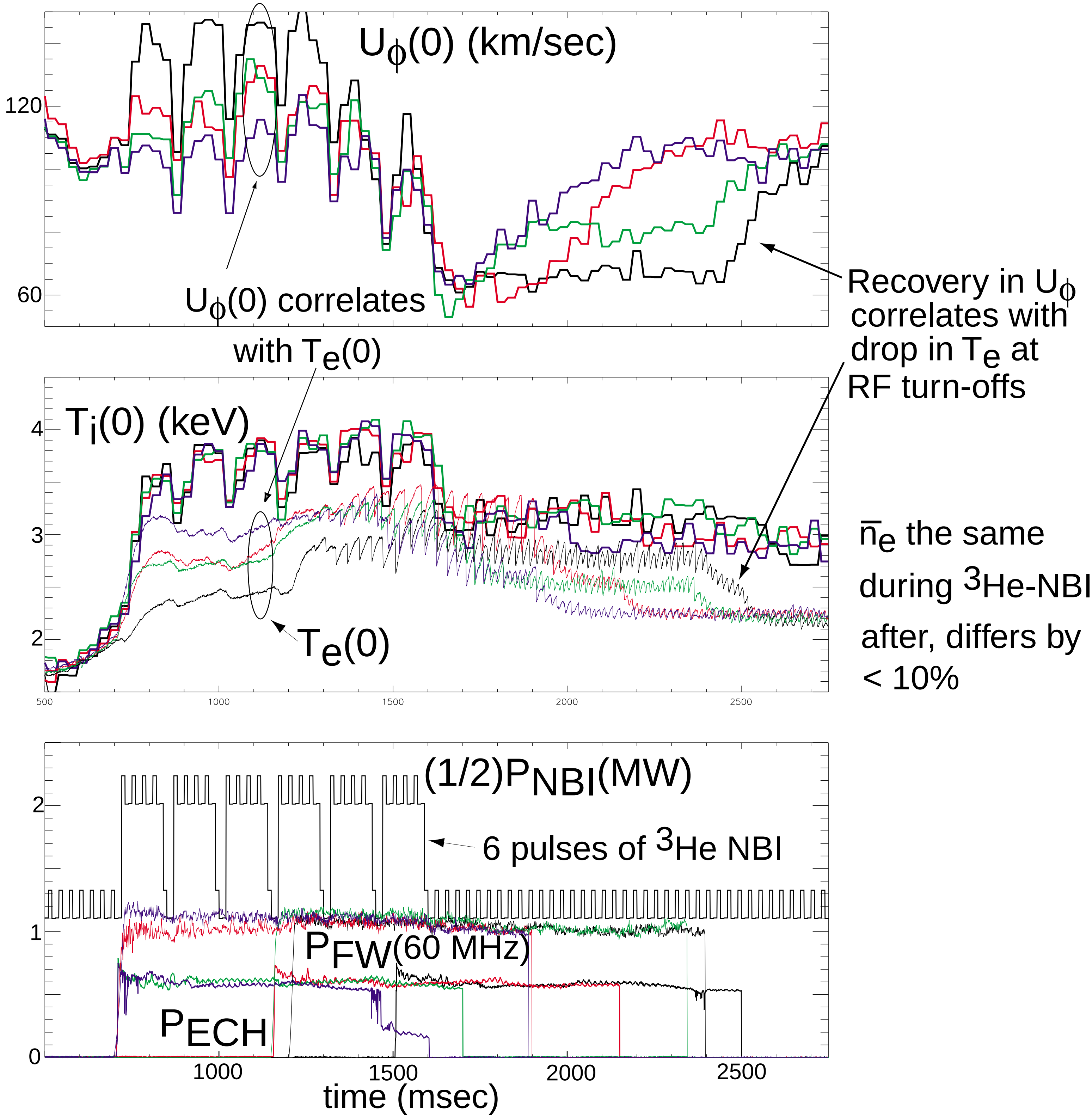
$\overline{n}_e$ = 1.9 e19



Reduction in $U_\phi(0)$ still correlates best with $T_e(0)$
[little/no consistent change in $T_i(0)$]

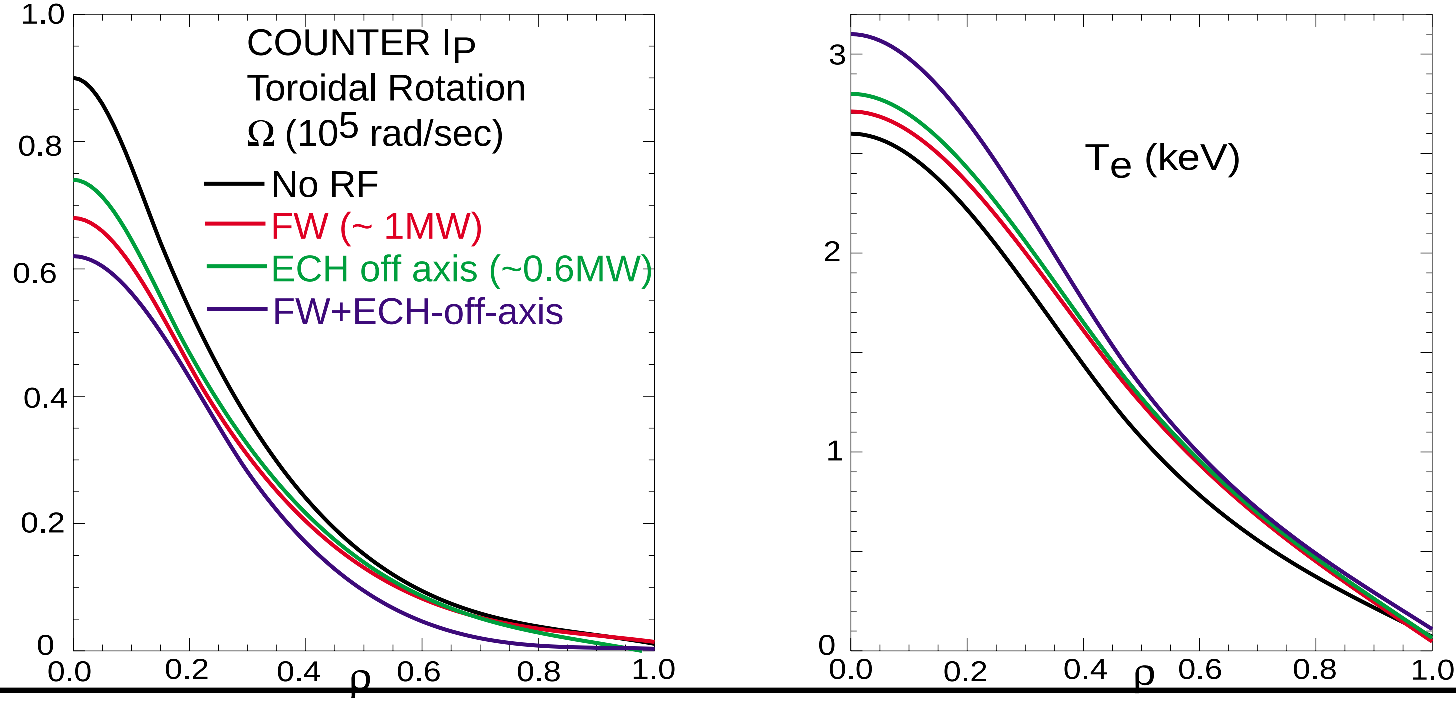
4 shots with 2.4MW D-NBI and 6 pulses at 2MW ^{3}He-NBI

99869 - FW @ t=1250 ECH @ t=1500
99873 - FW @ t=700 ECH @ t=1150
99872 - FW @ t=1150 ECH @ t=700
99871 - FW @ t=700 ECH @ t=700



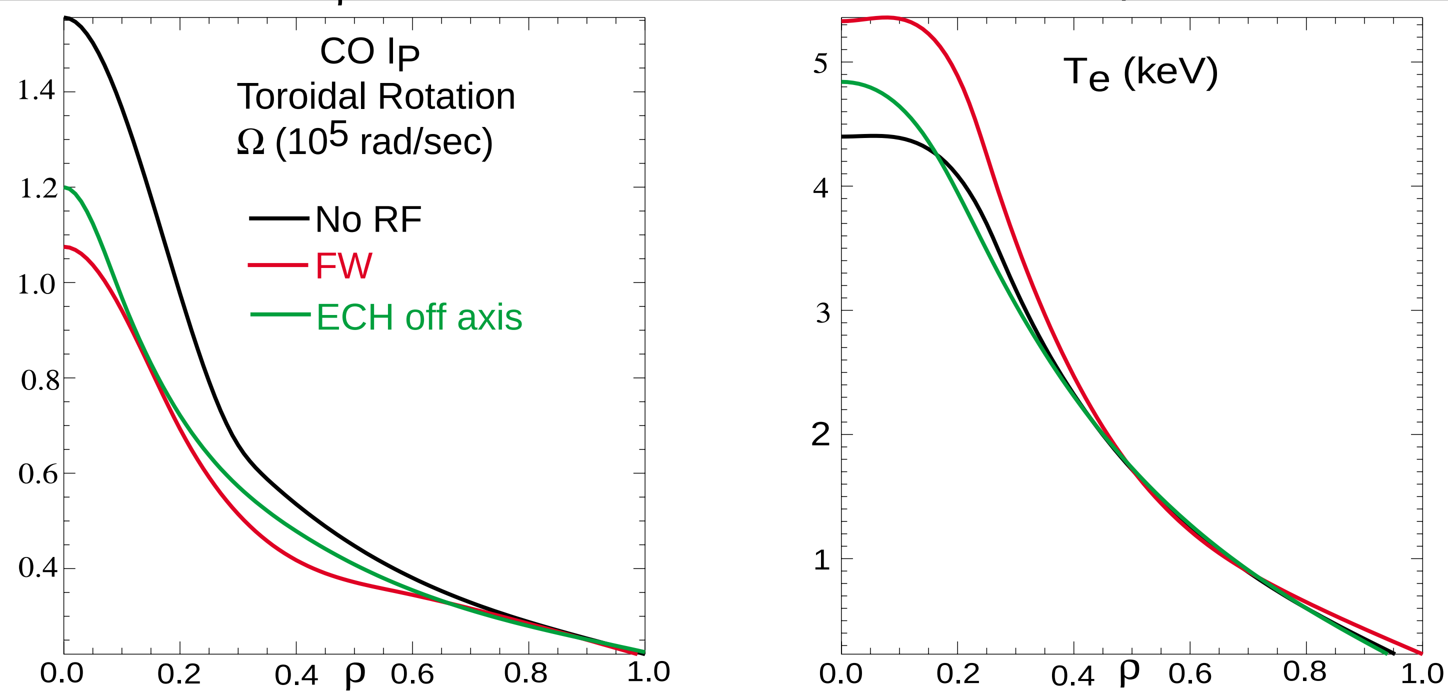
Both CO and COUNTER NBI Driven Target Discharges Exhibit Slowing with Electron Heating

Counter



ECH launched counter ECCD

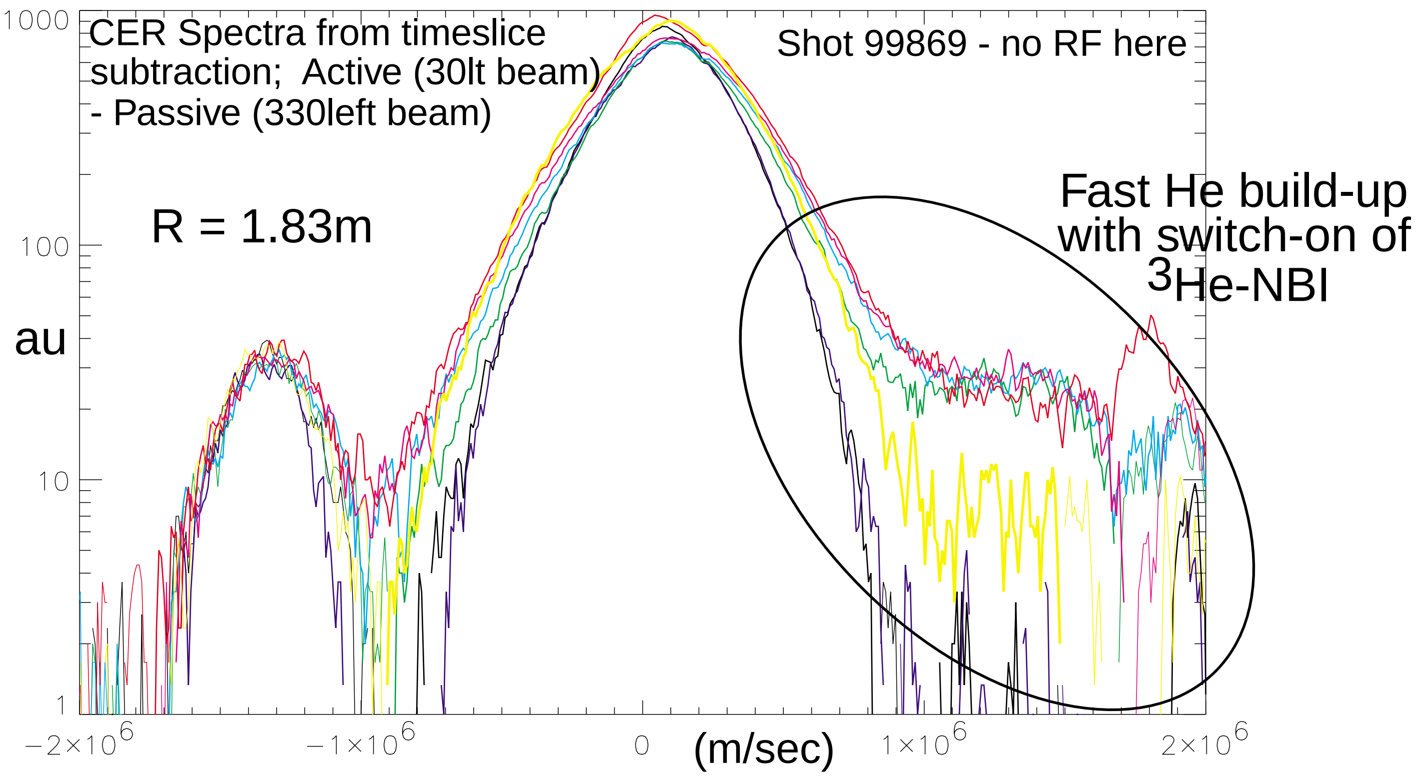
Co

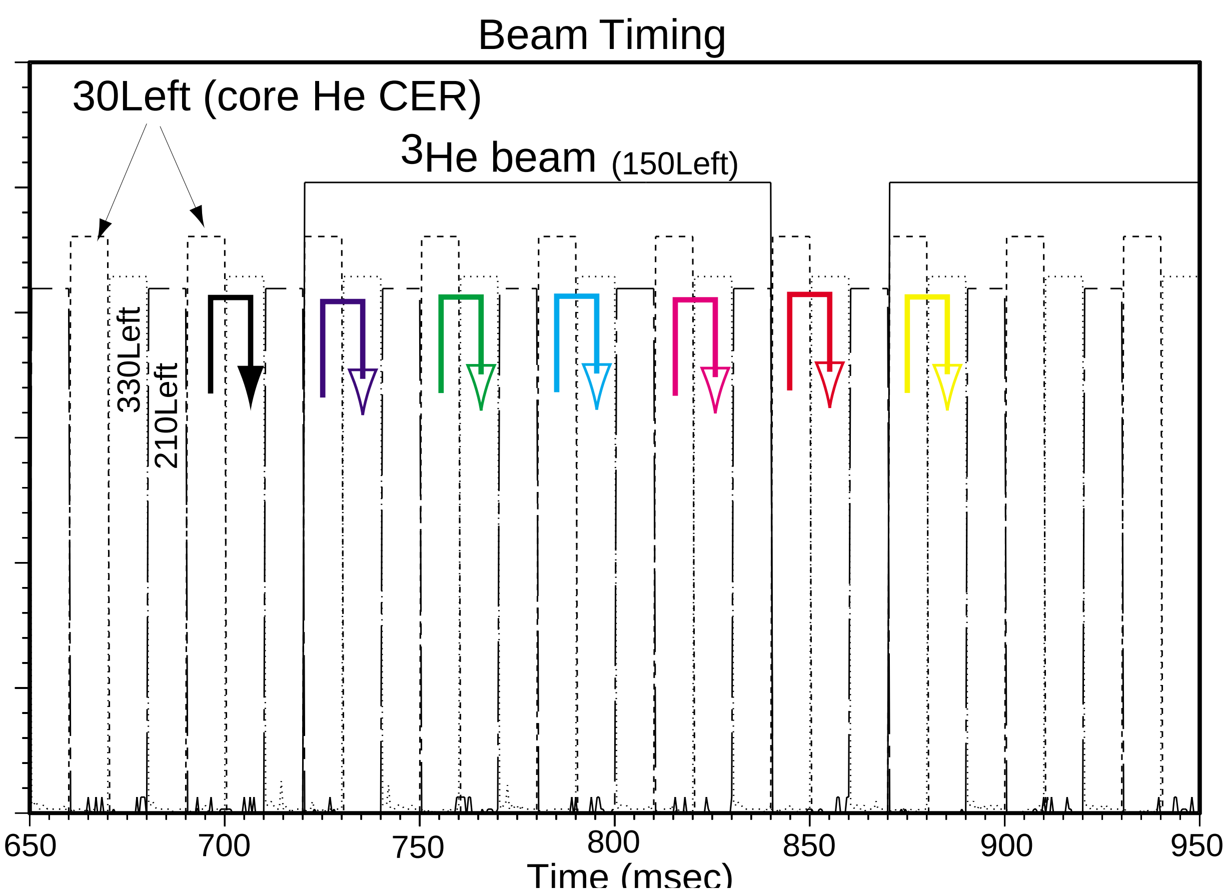


ECH launched radially ($k_{//}$=0)

CER Spectrometer Tuned to He Shows Buildup of Fast He

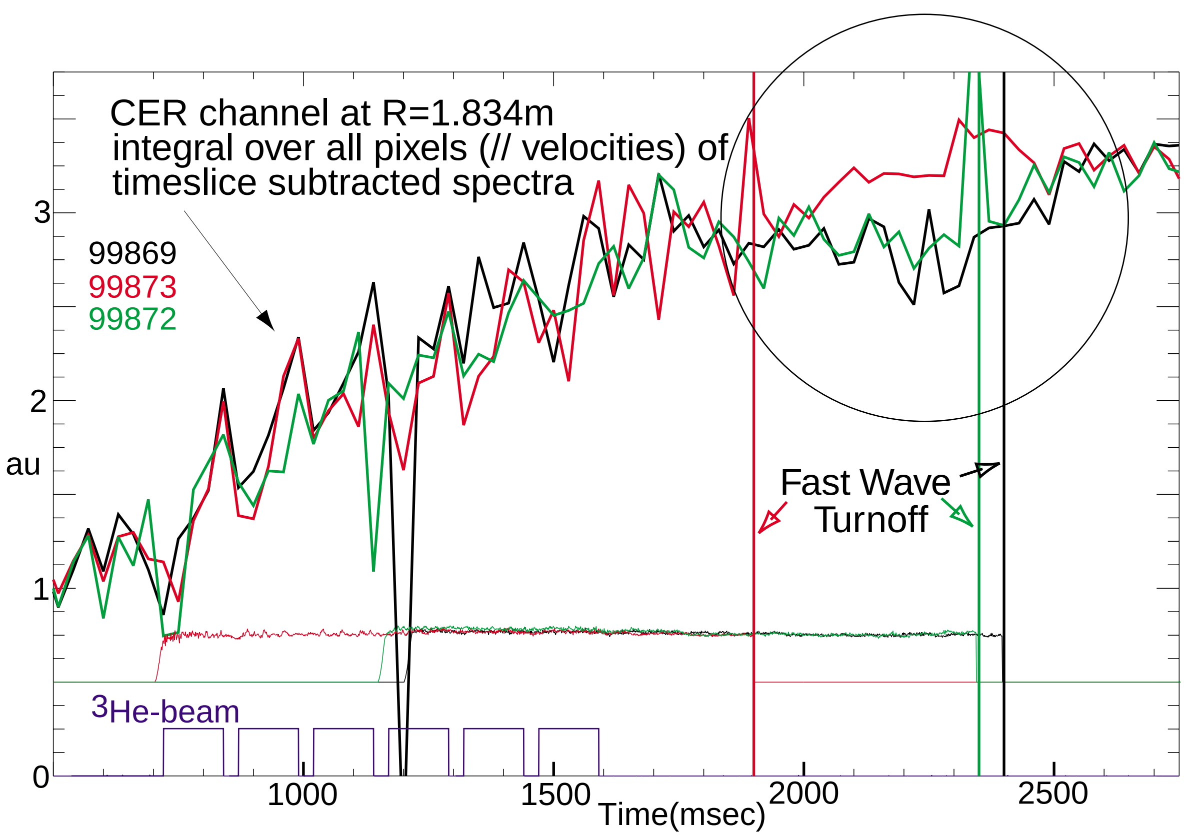
Question - can any RF induced transport of fast He be seen?
Preliminary analysis shows nothing clear in fast He population





There is some experimental evidence for RF redistribution of helium in the core

- Look at timeslice subtracted CER signal to localize to the intersection radius (here R = 1.843 m)
- Integrate spectra over all pixels for a measure of helium density
- Helium density roughly integrates up with beam source
- At Fast Wave turn-off, there is a recovery of core helium density
- ECH does not seem to correlate



Extensive Analysis in Progress for these ^{3}He-Beam Data

Experiment indicates an enhanced viscosity due to electron heating, just as indicated for Co-NBI experiments on DIII-D.

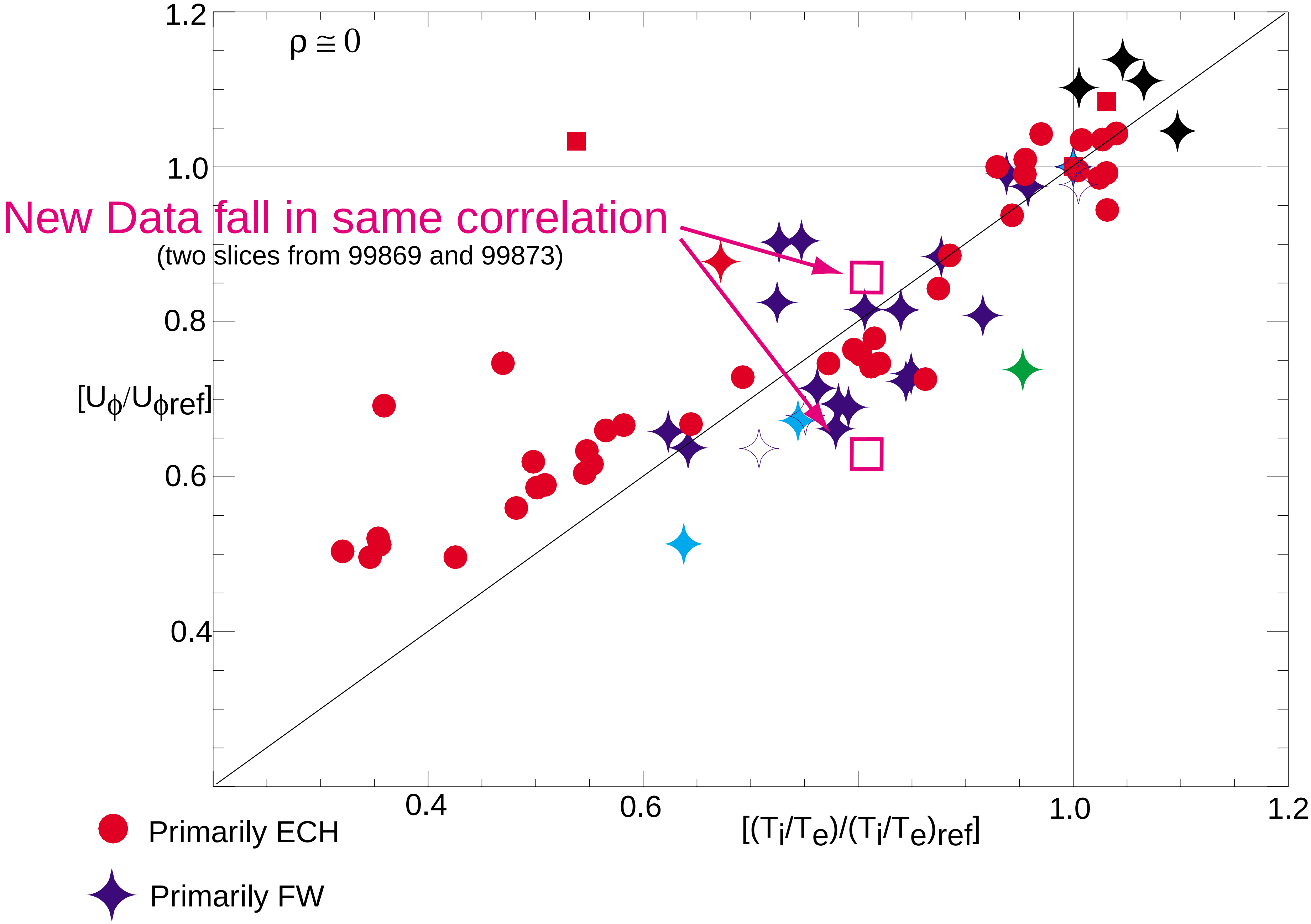
The question to ask of the data is if we would have expected to see any RF induced change in rotation =>

- Perform transport analyses to compute ion thermal and momentum diffusivities.
- Use Curray Code for prediction of Fast Wave power absorption by electrons, ^{3}He-beam and D-beam ions and thermals.
- Estimate amount of resulting radial transport of RF resonant ions.
- Use this radial transport estimate to compute the maximum possible torque induced on the bulk plasma. Ascertain if this torque would be observable given the computed momentum diffusivity.
  - ❋ If not, no conclusion regarding RF induced torque can be drawn from this experiment (not enough fast ion power absorption). We certainly needed more Fast Wave power.
  - ❋ If so, we might conclude that RF induced transport results in no net torque due to the cancellation by interspecies friction. Or, this torque may havebeen overcome by the T_e enhanced viscosity.

Reduction in Rotation Correlates Best with T_i / T_e

Better than with either T_i or T_e alone, or other parameters

Data are from a variety of ECH and FW experiments; most FW data from sawtooth experiment



CONCLUSIONs

- U_ϕ was not increased in magnitude with ICRH/FW with counter-NBI target discharge in DIII-D. Rather, U_ϕ is reduced as seen with co-NBI targets.

- Data indicate that an enhanced toroidal viscosity due to electron heating dominates.

- No direct evidence of resonant ^{3}helium tail. Too collisional?

- Detailed analyses must sort out upper limit on any possible RF induced torque.