Abstract.— Damping of fast Alfvén waves (FW) at high ion cyclotron harmonics ($\omega = n\Omega$, $n > 3$) can be an important competing damping mechanism where direct electron damping is intended. The DIII–D experiments described here have demonstrated strong ion cyclotron damping on energetic deuterons at harmonics as high as $4\Omega_D$. Most of the discharges in this study combine deuterium neutral beam injection (NBI; P_{NBI} 2 MW) with 60 MHz FW (P_{FW} ~ 1 - 2 MW, B_T = 2.0 T. We have also compared $4\Omega_D$ damping on an injected deuterium beam (deuterium majority) with $2\Omega_H$ damping on a hydrogen beam in hydrogen majority plasmas, and studied $3\Omega_{He3}$ damping on an injected He^3 beam in a deuterium plasma. In all cases, substantial central electron heating is observed. We attempt to determine the electron heating mechanism; direct electron damping of the FW via electron Landau damping and TTMP, electron heating by rf-accelerated deuterium beam ions, and electron heating from an rf-produced proton tail from the hydrogen minority at $2\Omega_H$ all occur to varying extents. Observations of the D-D reaction rate (neutrons) clearly indicate significant damping at the fourth harmonic, transitioning to second harmonic damping on hydrogen as the hydrogen fraction increases. These experiments indicate the importance of high harmonic damping in the presence of an energetic ion species and demonstrate the usefulness of this scenario for plasma heating. The accompanying poster by Heidbrink, et al. discusses the effect of the rf-accelerated fast ions on MHD and Alfven instabilities.

Abstract Submitted
for the DPP99 Meeting of
The American Physical Society

Sorting Category: 5.1.1.2 (Experimental)

High Harmonic Ion Cyclotron Heating in DIII-D: I. Beam-Ion Absorption[1] R.I. PINSKER, J.S. DEGRASSIE, C.C. PETTY, General Atomics, F.W. BAITY, ORNL, S. BERNABEI, PPPL, W.W. HEIDBRINK, UC Irvine, T.K. MAU, UC San Diego, M. PORKOLAB, MIT — Damping of fast Alfvén waves (FW) at high ion cyclotron harmonics ($\omega = n\Omega_{\mathrm{i}}$, $n > 3$) is an important competing damping mechanism where direct electron damping is intended. The DIII–D experiments described here have demonstrated strong ion cyclotron damping on energetic deuterons at harmonics as high as $4\Omega_{\mathrm{D}}$. Most of the discharges in this study combine deuterium neutral beam injection (NBI; $P_{\mathrm{NBI}} \geq 2$ MW) with 60 MHz FW ($P_{\mathrm{FW}} \sim$ 1–2 MW, $B_{\mathrm{T}} = 2.0$ T). We have also compared $4\Omega_{\mathrm{D}}$ damping on an injected deuterium beam with $2\Omega_{\mathrm{H}}$ damping on a hydrogen beam, and studied $3\Omega_{\mathrm{He}^3}$ damping on an injected He^3 beam. In all cases, substantial central electron heating is observed. Observations of the D–D reaction rate clearly indicate significant damping at $4\Omega_{\mathrm{D}}$. These experiments indicate the importance of high harmonic damping in the presence of an energetic ion species and demonstrate the usefulness of this heating scenario.

[1]Supported by U.S. DOE Contracts DE-AC03-99ER54463, DE-AC05-96OR22464, and DE-AC02-76CH03073, and Grant DE-AC03-95ER54299.

☐ Prefer Oral Session
☒ Prefer Poster Session

R.I. Pinsker
pinsker@gav.gat.com
General Atomics

Special instructions: DIII-D Poster Session 2, immediately following TE Evans

Date printed: July 16, 1999

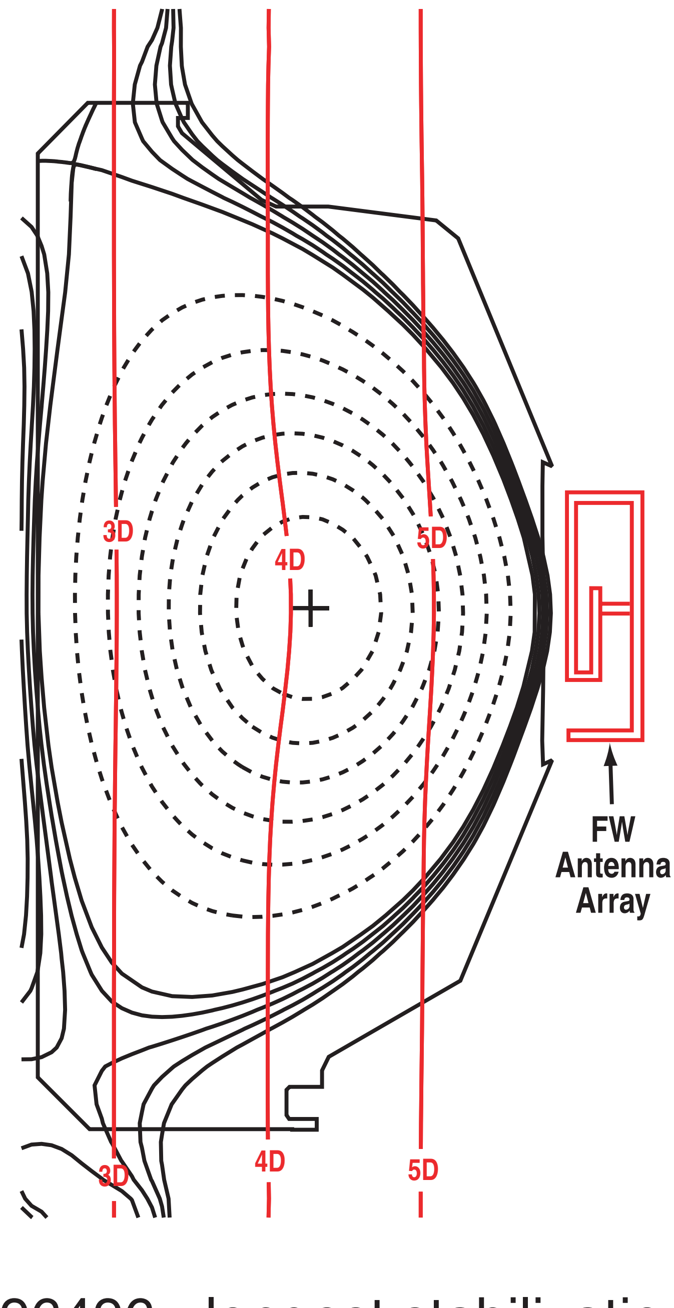
Electronic form version 1.4

Motivation

- Purpose: establish alternative fast wave heating scheme for DIII-D that uses the existing hardware (f > 60 MHz) based on ion cyclotron damping instead of direct electron damping
- 2nd harmonic H possible (2 T, 60 MHz) but requires undesirably large H fractions
- 2nd harmonic H damping on an injected H beam certainly possible, but has some distinct practical disadvantages for DIII-D (dilution, low P_{nbi})
- Consider higher harmonics - damping on beam almost certainly required (previous experiments on TEXTOR at 3rd D; JT-60 and JT-60U on 2nd, 3rd, and 4th H; JET 3rd D without beam)
- Everything else being equal, the single-pass damping would decline strongly with harmonic number, but the real situation is considerably more complex - hence, this study to compare damping at different harmonics on injected beams of different Z/m_i

Optimum placement of 4th harmonic resonance layer is ~ 5 cm inboard of magnetic axis

Explained by Doppler shift with
co-current beams, counter-current rf



96496 - longest stabilization
of sawtooth (~0.27 sec)

Doppler-shifted resonance absorption

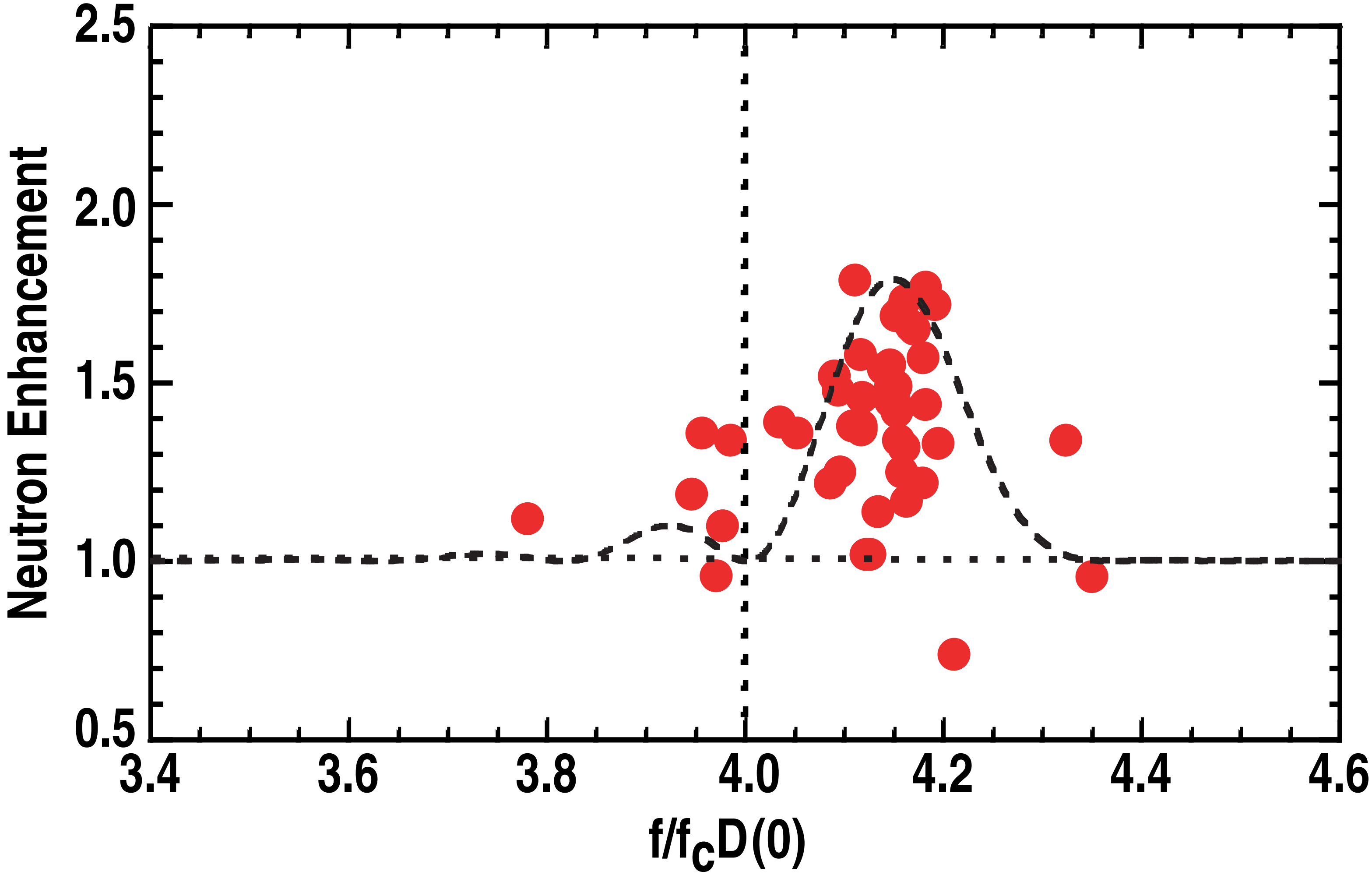
Taking into account toroidal upshift of coupled spectrum and beam geometry, condition for Doppler-shifted resonance absorption is

$$\frac{\omega}{n\Omega_{ib}} = \left[1 - n_{||}\Big|_{ant} \frac{R_{ant}\, R_{tan}}{R_o^2} \left(\frac{v_{ib}}{c} \right) \right]^{-1}$$

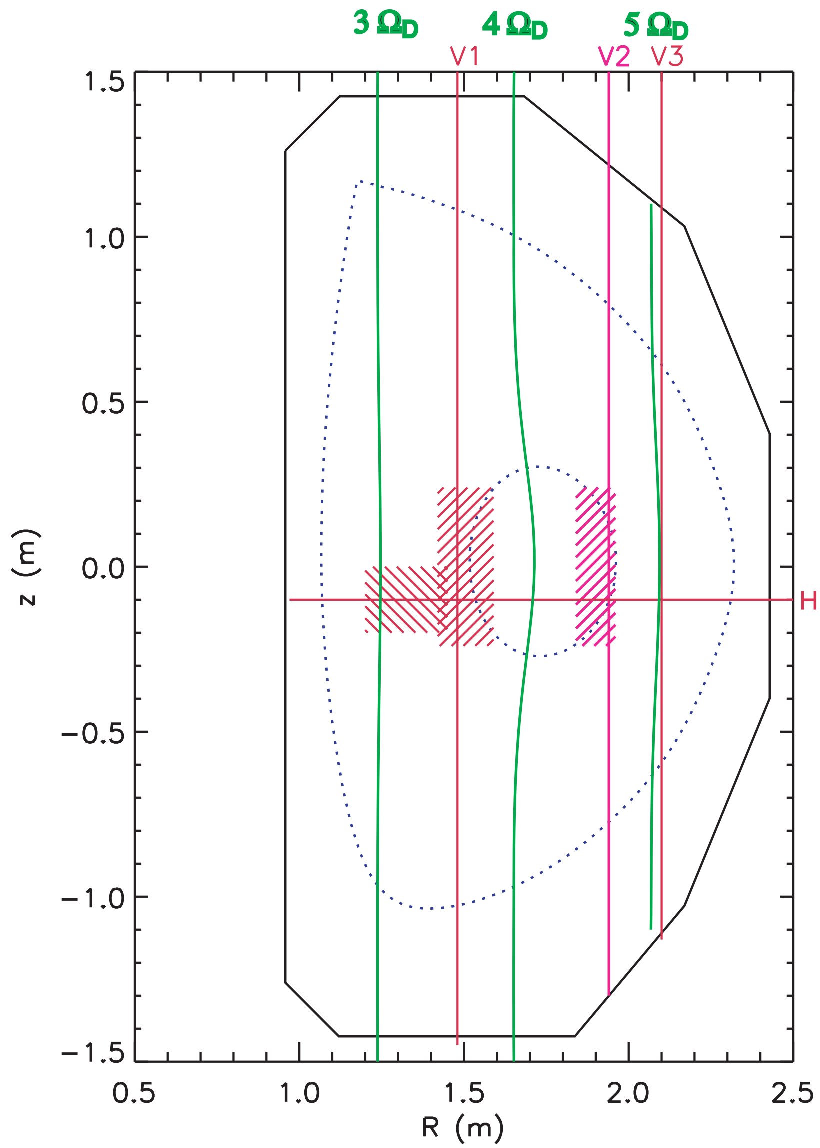
where assumption is that absorption occurs predominantly on beam ions at injection energy

Coupled spectrum can be estimated from a simple coupling model, and this equation used to map n-parallel to major radius to obtain an estimate of the absorption profile, which can then be compared with observed dependence of D-D neutrons on B_T - apparently absorption strongly maximized when power absorbed at magnetic axis

Doppler shift explains displacement of maximum absorption on beam from resonance layer



BEAM IONS ARE ACCELERATED



ACTIVE CHARGE EXCHANGE

Central ⊥ Ions Near Injection Energy on V2 Signal

DIAMAGNETIC LOOP

More ⊥ Stored Energy than Parallel

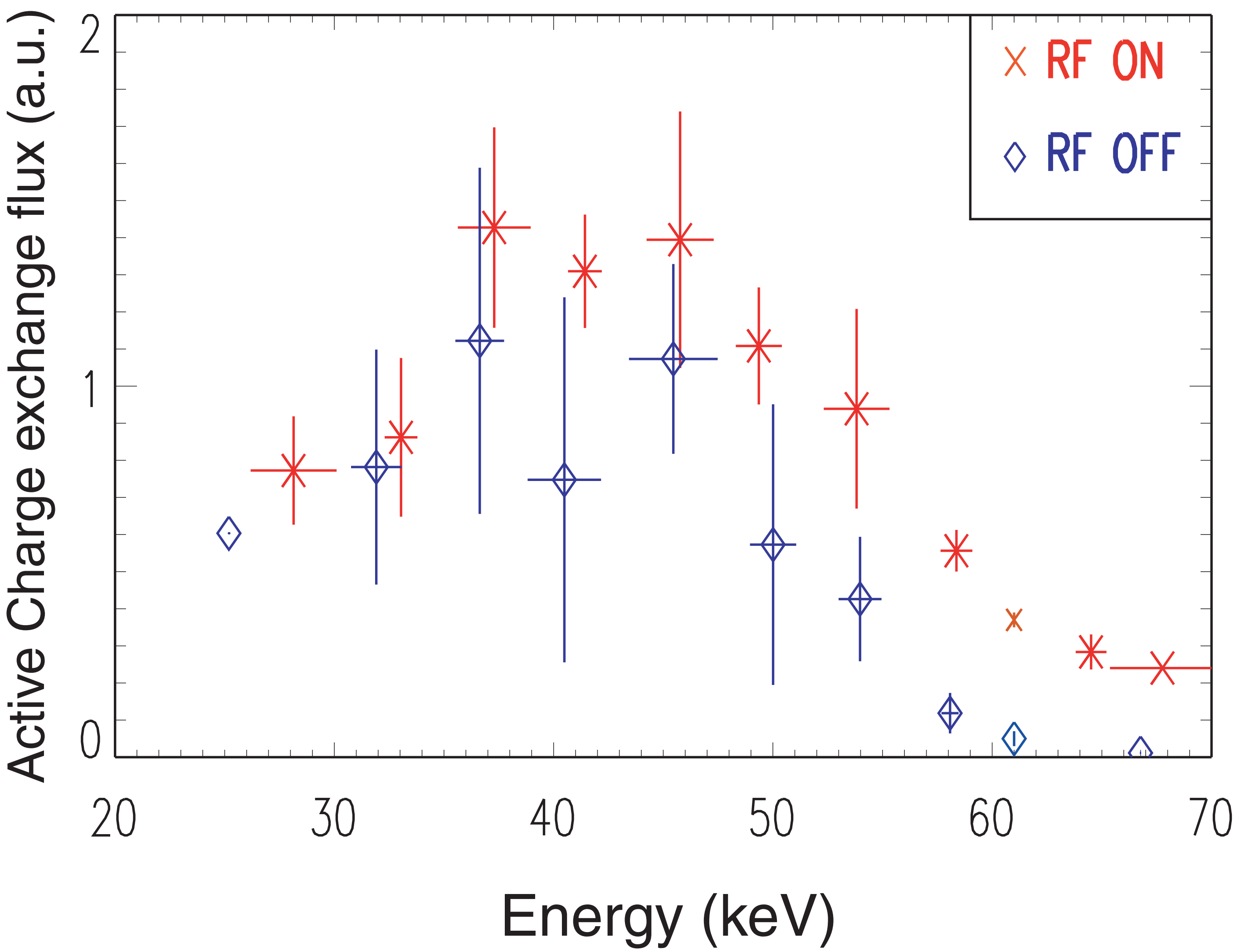
MAGNETIC AXIS

3 x Larger Central Beam Pressure than Classical Prediction

NEUTRON RATE

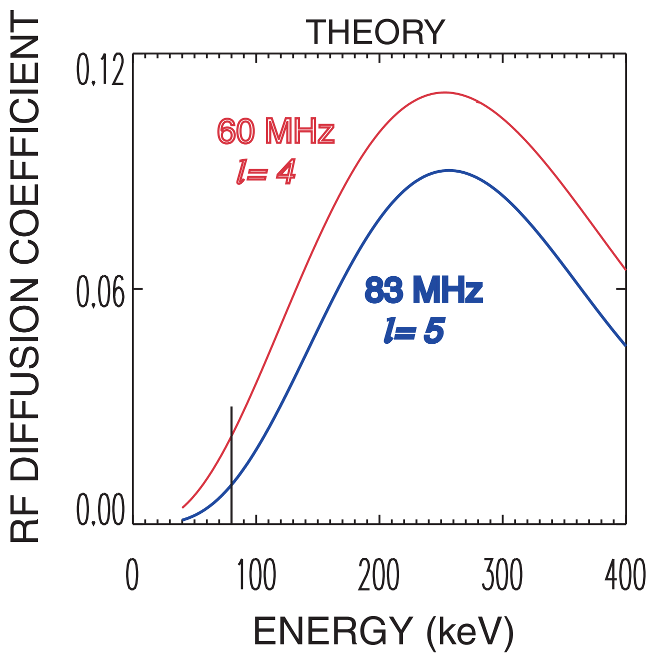
50% Larger than Classical Prediction

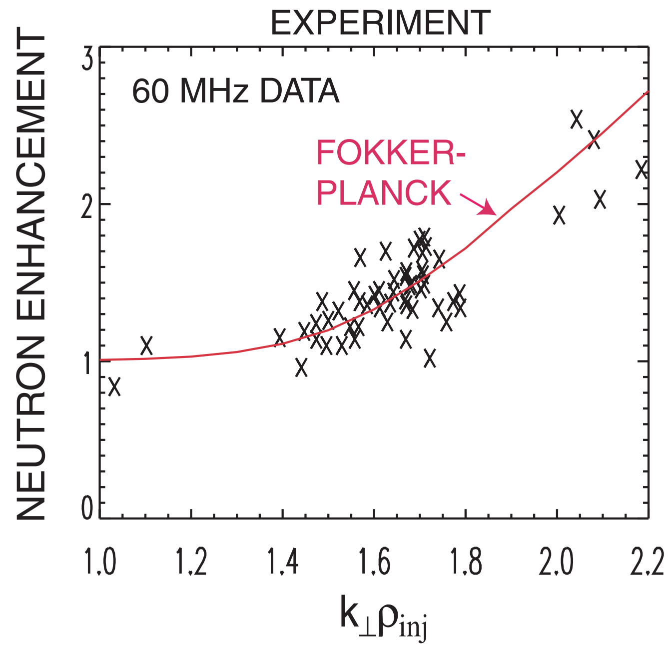
Active neutral particle charge exchange analyzer shows rf accelerated tail



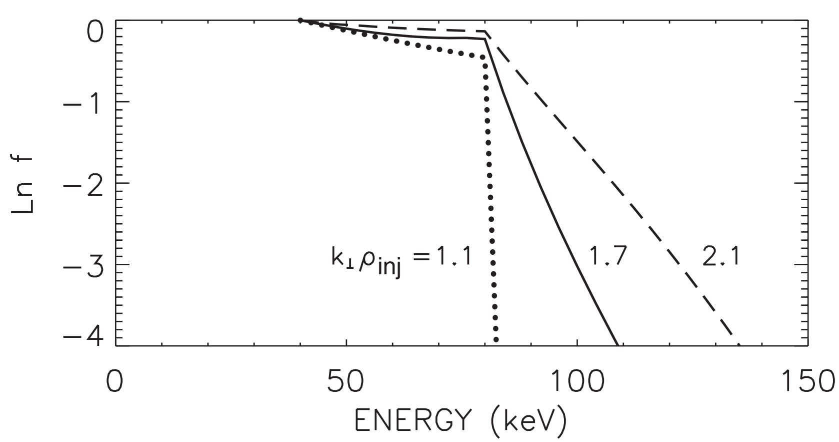
Shot-to-shot scan of analyzer voltage, 4th harmonic deuterium ICRH, deuterium 80 keV beam injected into deuterium plasma

STRONG GYRORADIUS DEPENDENCE EXPECTED AND OBSERVED

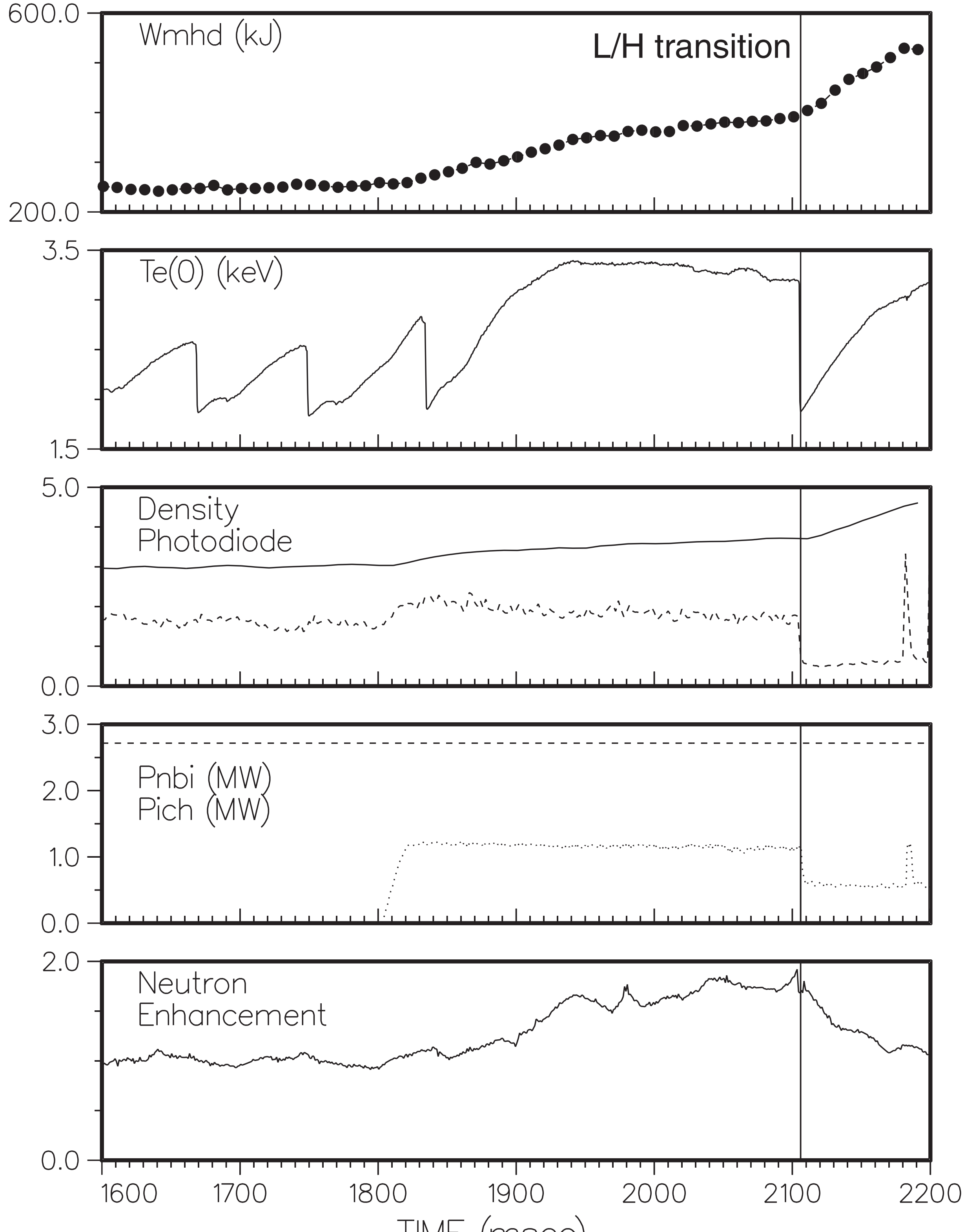




Distribution functions predicted from model solutions to Fokker-Planck equation



Time history of shot with longest sawtooth



96496

Theory/modeling efforts

- Two approaches so far:
  1. Ray-tracing for wave fields using CURRAY and thin-banana approximation Fokker-Planck code CQL3D
  2. Full-wave code PICES for wave fields coupled with the orbit following Monte Carlo FP solver FIDO

- CURRAY without CQL3D can use model ion distribution functions from analytic models for quick parameter surveys

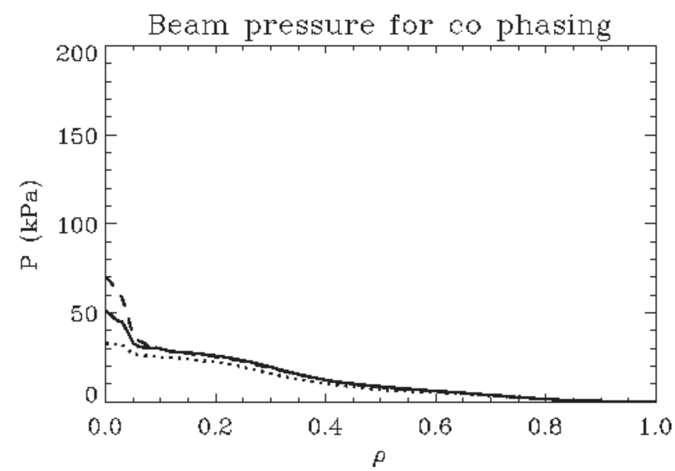
- Significant differences between co- and counter-current phasing can be seen in ray-tracing runs, and other co/counter differences are seen in FIDO, in that case stemming from finite-orbit width effects

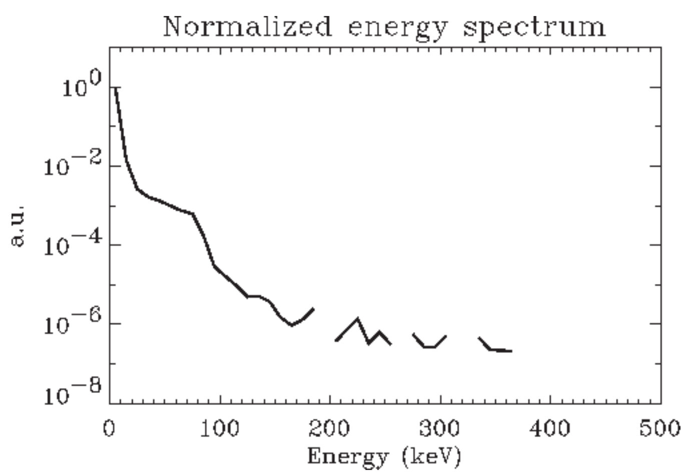
- Both approaches are subjects of ongoing work in collaboration with JET, ORNL, UCSD, CompX, MIT, and other institutions

Results from PICES/FIDO code iteration (courtesy E.F. Jaeger and J. Carlsson, ORNL)

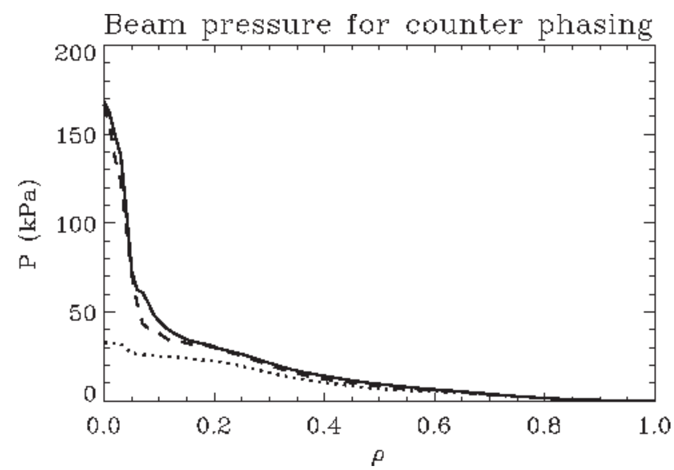
Pinch of resonant particles (counter current phasing) versus anti-pinch in co- case leads to substantial enhancement of absorption in counter-current case

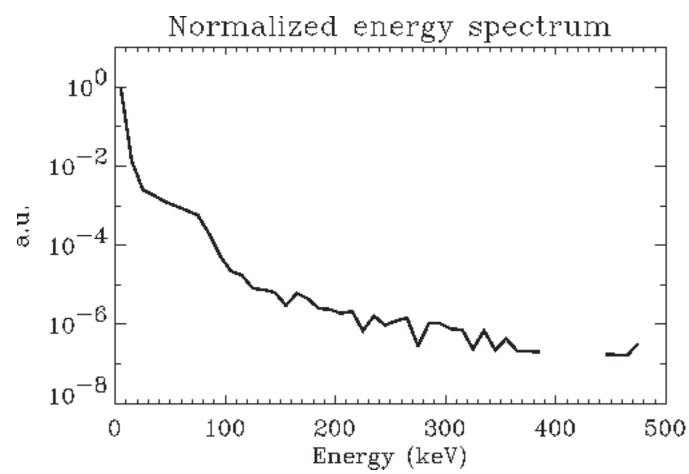
Co-current phasing





Ctr-current phasing





$B_T(0)$ = 1.9 T, 1.0 MW FW at 60 MHz, 1.6 MW D beam, $n_e(0)$ = 4x19 m^{-3}, $T_e(0)$ = 2.9 keV, $T_i(0)$ = 2.6 keV, 2% H

High Harmonic Ion Cyclotron Damping Experiment

Goal: improve understanding of ion cyclotron harmonic damping on an energetic ion species

Motivation: so far, lack of quantitative understanding of FW damping at high IC harmonics has prevented the application of this heating technique as a tool in ongoing DIII–D studies. Need benchmarked modeling codes. Also, the feasibility of FWs in D-T reactors is critically dependent on the level of (undesired) damping on fusion alphas.

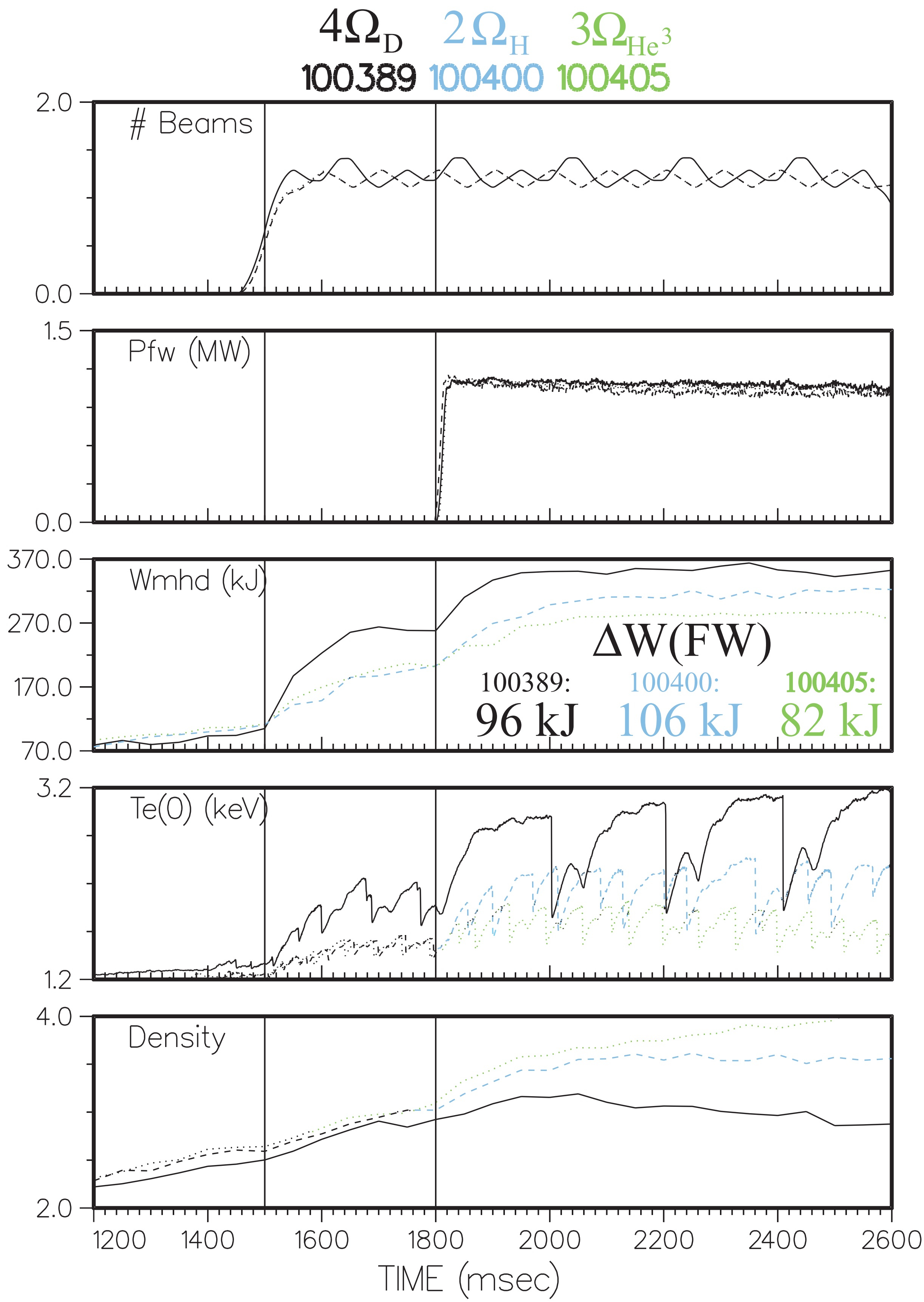
Approach: compare damping at 2nd, 3rd, and 4th harmonics with identical plasmas by damping on injected H, He^3, and D beams, and compare damping on different species at the same harmonic by varying the toroidal field. Use neutral particle charge exchange analyzers, effect of rf on sawteeth and *AE modes to monitor fast ion population.

Experiment: received one day in 1999 - 9 July.

Harmonic:

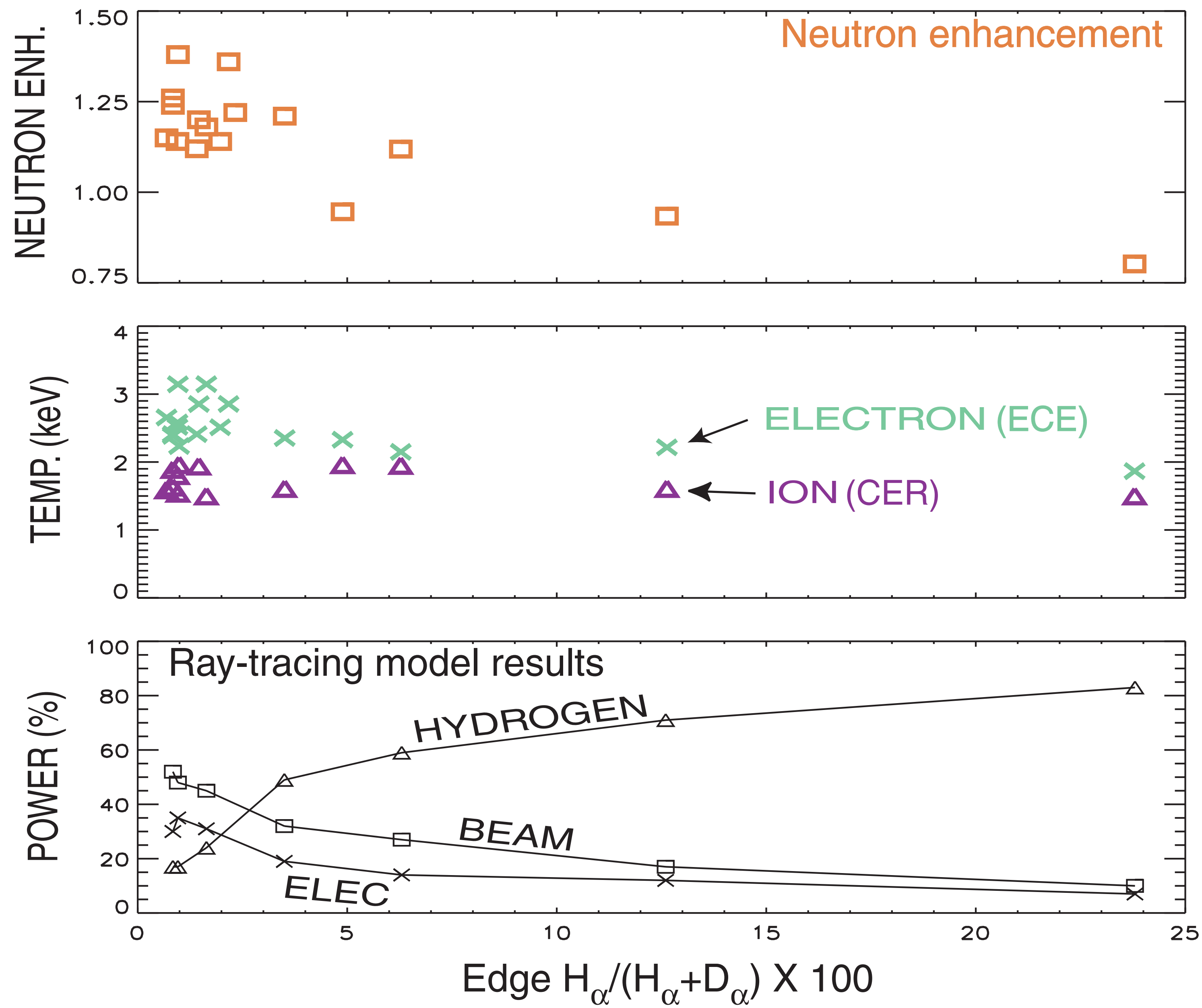
beams:	2nd	3rd	4th
none	(H plasma)	(He3 plasma)	✓
D	○	○	✓
He3	○	✓	✓
H	✓	✓	

○ = requires f < 60 MHz (not available in 1999)

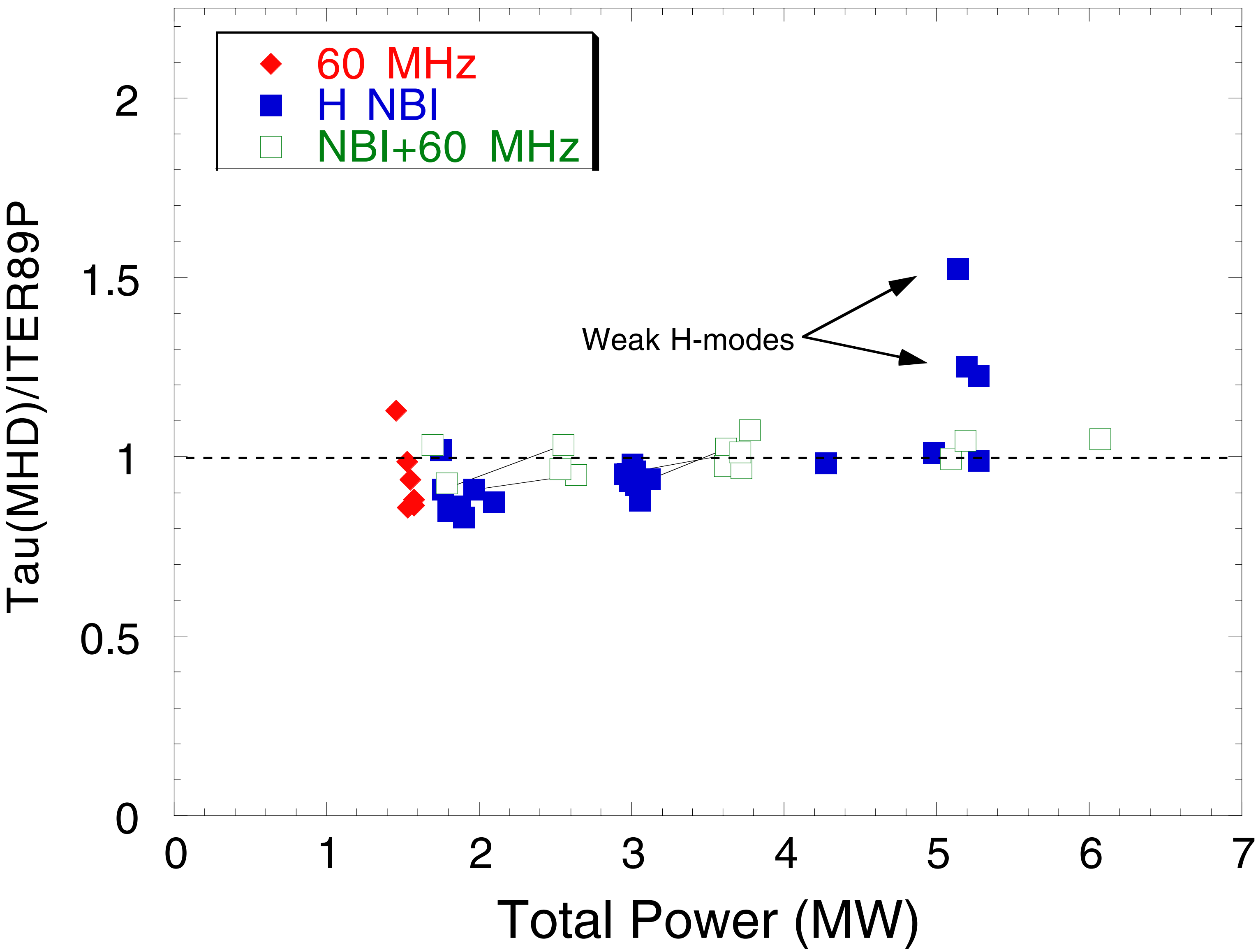


$4\Omega_D$ $2\Omega_H$ $3\Omega_{He^3}$
100389 100400 100405
2.0
Beams
0.0
1.5
Pfw (MW)
0.0
370.0
Wmhd (kJ)
270.0
170.0
70.0
ΔW(FW)
100389: 100400: 100405:
96 kJ 106 kJ 82 kJ
3.2
Te(0) (keV)
1.2
4.0
Density
2.0
1200 1400 1600 1800 2000 2200 2400 2600
TIME (msec)

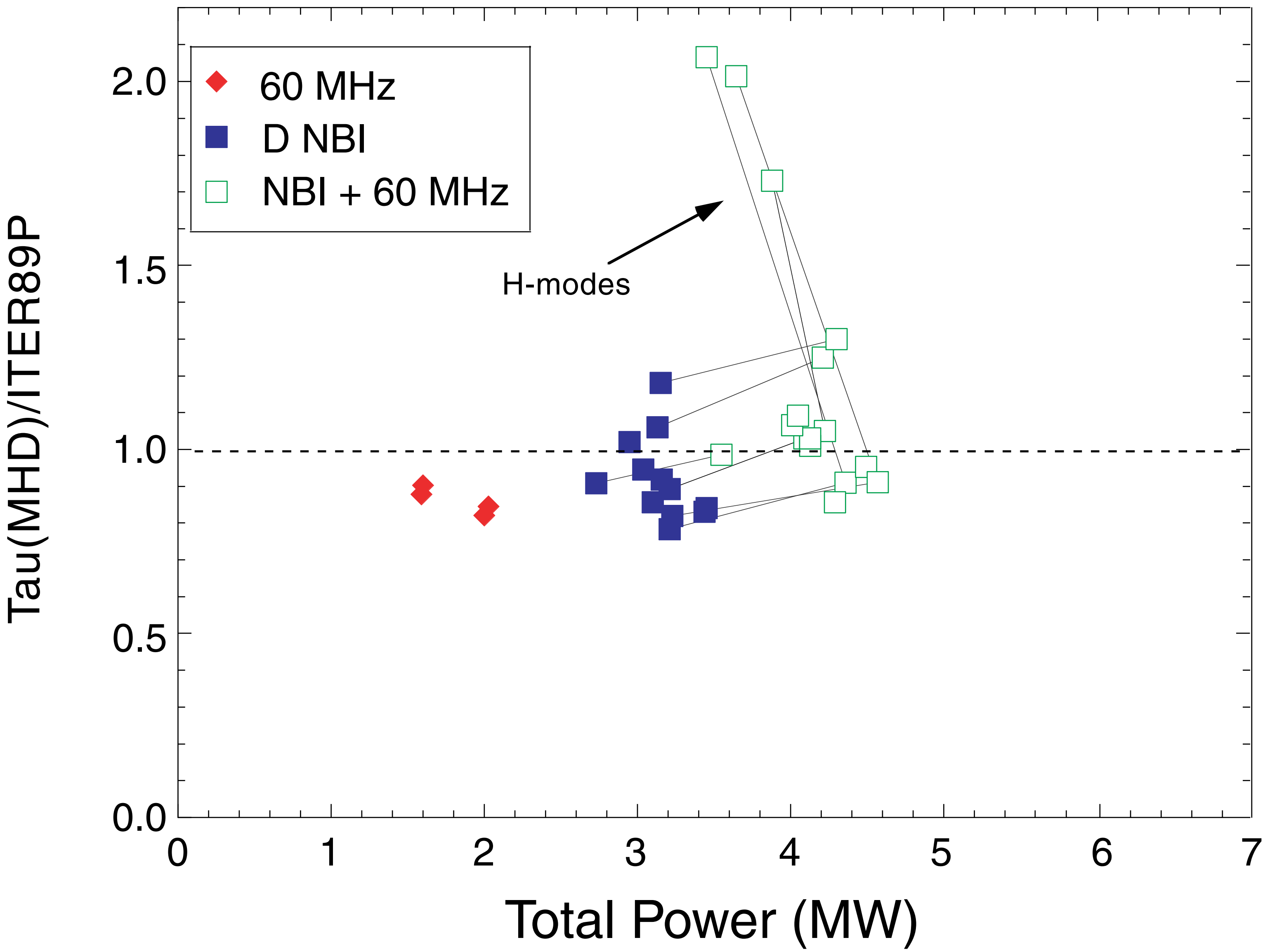
Hydrogen puffing into $4\Omega_D$ shot shows switch-over to absorption on thermal H ($2\Omega_H$) at sufficiently high H/(H+D)



Confinement data with H into D/H mix, 2nd harmonic heating



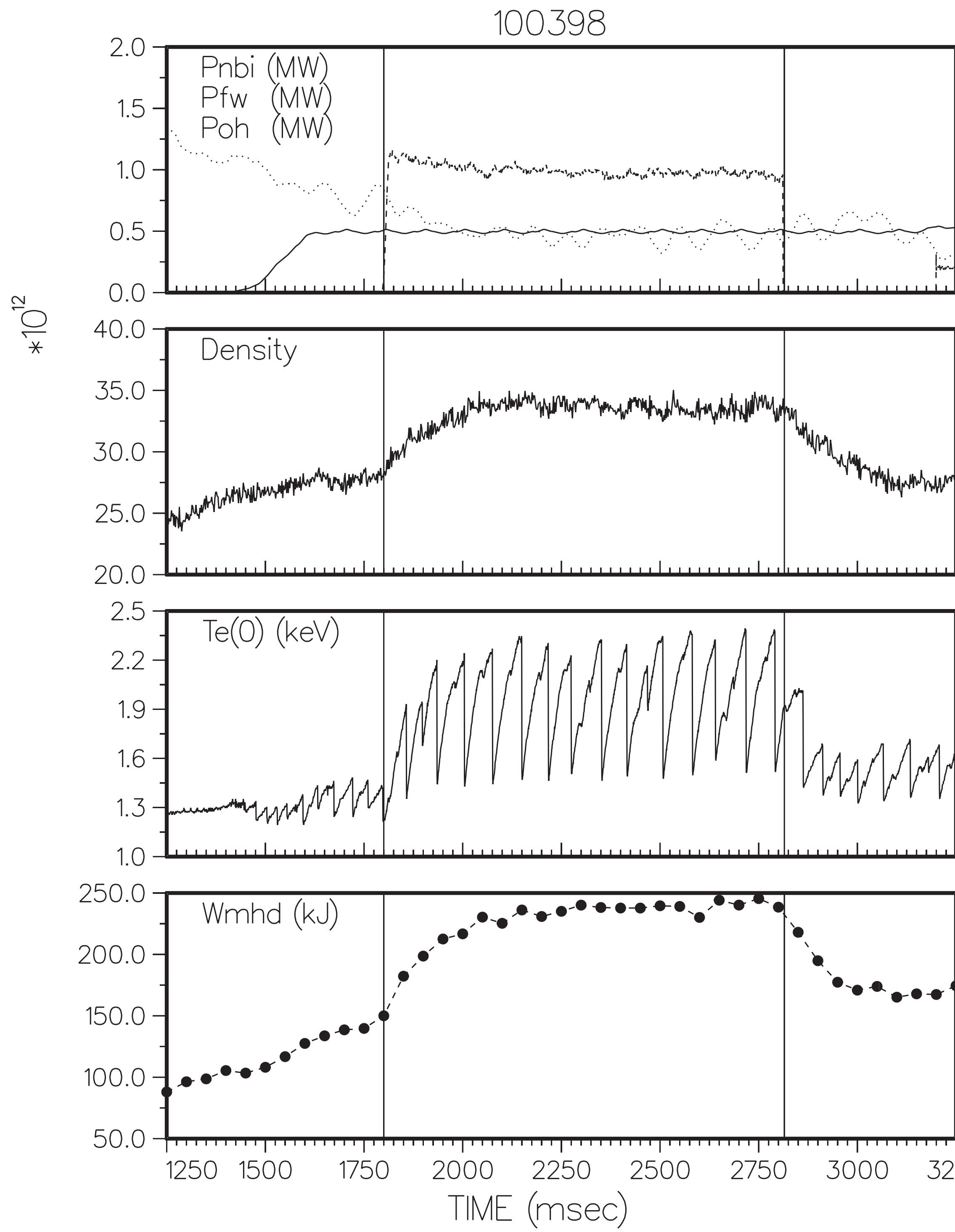
Confinement data with D into D, 4th harmonic heating

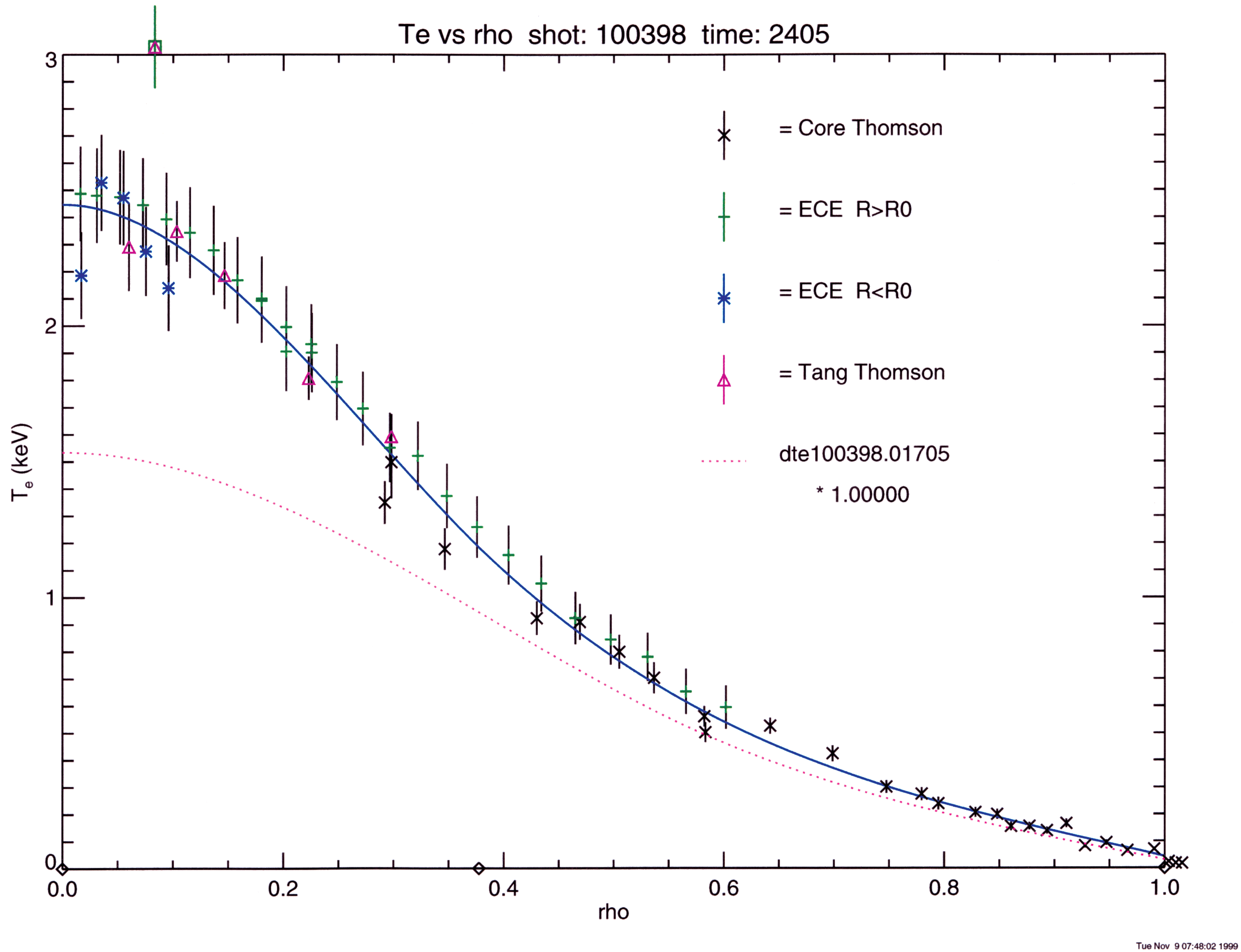


Conclusions from confinement data

- The hydrogen beam data into an H/D plasma are consistent with the standard $\tau_E \sim A^{-1/2}$ isotope scaling
- The fact that the data with and without rf agree with the L-mode scaling relation implies that the rf power is efficiently absorbed in the plasma core
- The addition of rf power to the beam always improves the confinement relative to the scaling relation, which was not corrected for non-thermal ion populations; this implies that there is acceleration of the beam by the rf
- These statements are true for both $4\Omega_D$ and $2\Omega_H$ heating; $3\Omega_{He^3}$ heating appears to be somewhat less efficient, possibly as a result of the enhanced collisional drag on the He-3 making it more difficult to pull out a tail at the relatively low rf power used in these experiments (~1 MW)
- The H-mode threshold power scaling roughly as A^{-1} is consistent with results from JET

4th Harmonic absorption effective even in discharge with only 0.5 MW NBI power - direct electron damping?





Te vs rho shot: 100398 time: 2405
= Core Thomson
= ECE R>R0
= ECE R<R0
= Tang Thomson
dte100398.01705
* 1.00000
T_e (keV)
rho
0
1
2
3
0.0
0.2
0.4
0.6
0.8
1.0
Tue Nov 9 07:48:02 1999

Conclusions

- 4th harmonic heating of an injected deuterium beam is a surprisingly effective form of central heating in DIII-D
- The injected beam is accelerated by the rf, enhancing the D-D reaction rate, and strongly affecting MHD stability (sawteeth, TAE, etc.)
- 2nd harmonic damping on an injected hydrogen beam also is efficient, but no advantages of this scheme over the 4th harmonic of D have been found to date
- Third harmonic heating of an injected He-3 beam is somewhat less efficient than either of the other two schemes, possibly due to enhanced collisional drag on the He-3
- Accurate modeling of these results with Fokker-Planck codes in conjunction with rf field solvers has just begun