Experimental Study of Fast Wave Absorption Mechanisms in DIII-D in the Presence of Energetic Ions

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Introduction

- **Goal: Validate models of absorption of Fast Alfven waves (FWs) in the presence of competing absorption mechanisms: direct electron damping, ion cyclotron damping, and edge losses**
  - FWs can be damped on core electrons with minimal damping on fast ions at high harmonics, as shown in DIII-D previous work
  - Since FW Current Drive (FWCD) is an option for ITER, a validated model of damping on electrons and ions is needed
  - Damping on fast ions is a loss process for FWCD
  - Present experiments examine damping on injected 80 keV deuterons at 60, 90, and 116 MHz at cyclotron harmonics 4-8

Outline of poster

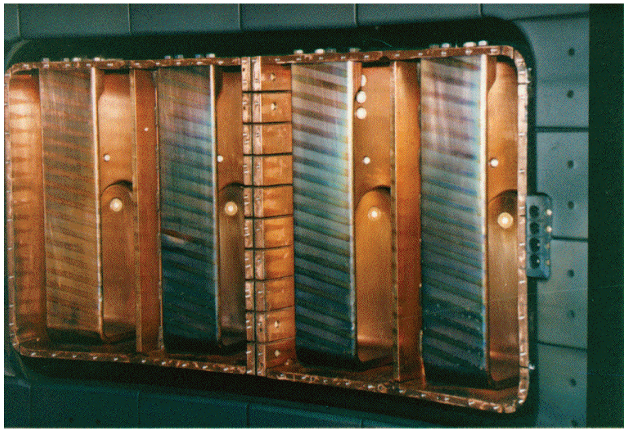
I) Experimental data at ~2 T varying frequency and plasma density, beam power, etc. shows correlation between single-pass absorption and global absorption efficiency, implying importance of edge losses

II) Varying harmonic number by lowering magnetic field at fixed FW frequency of 60 MHz shows importance of $v\ /v_A$, not only $/\ _i$

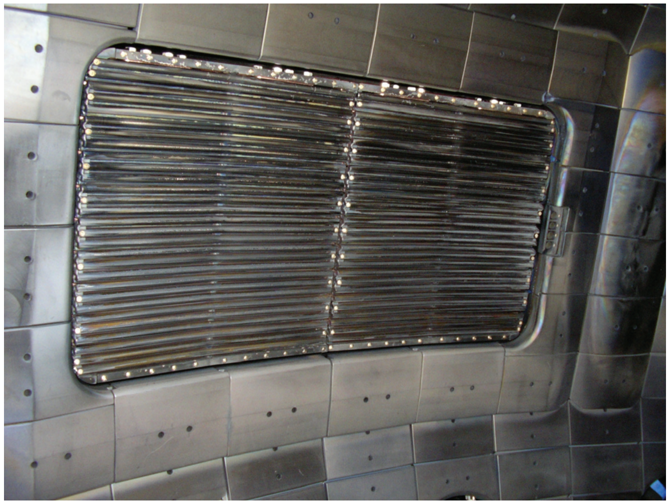
III) Combination of 60 and 90 MHz at 2 T shows ‘synergy’ of 4th and 6th harmonics

IV) Discussion of models, including edge losses

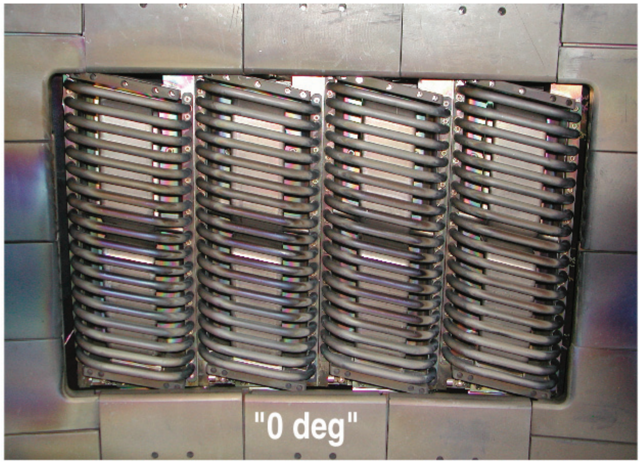
Three antenna arrays of two designs were used in these experiments



- 285/300 array without Faraday screen in place



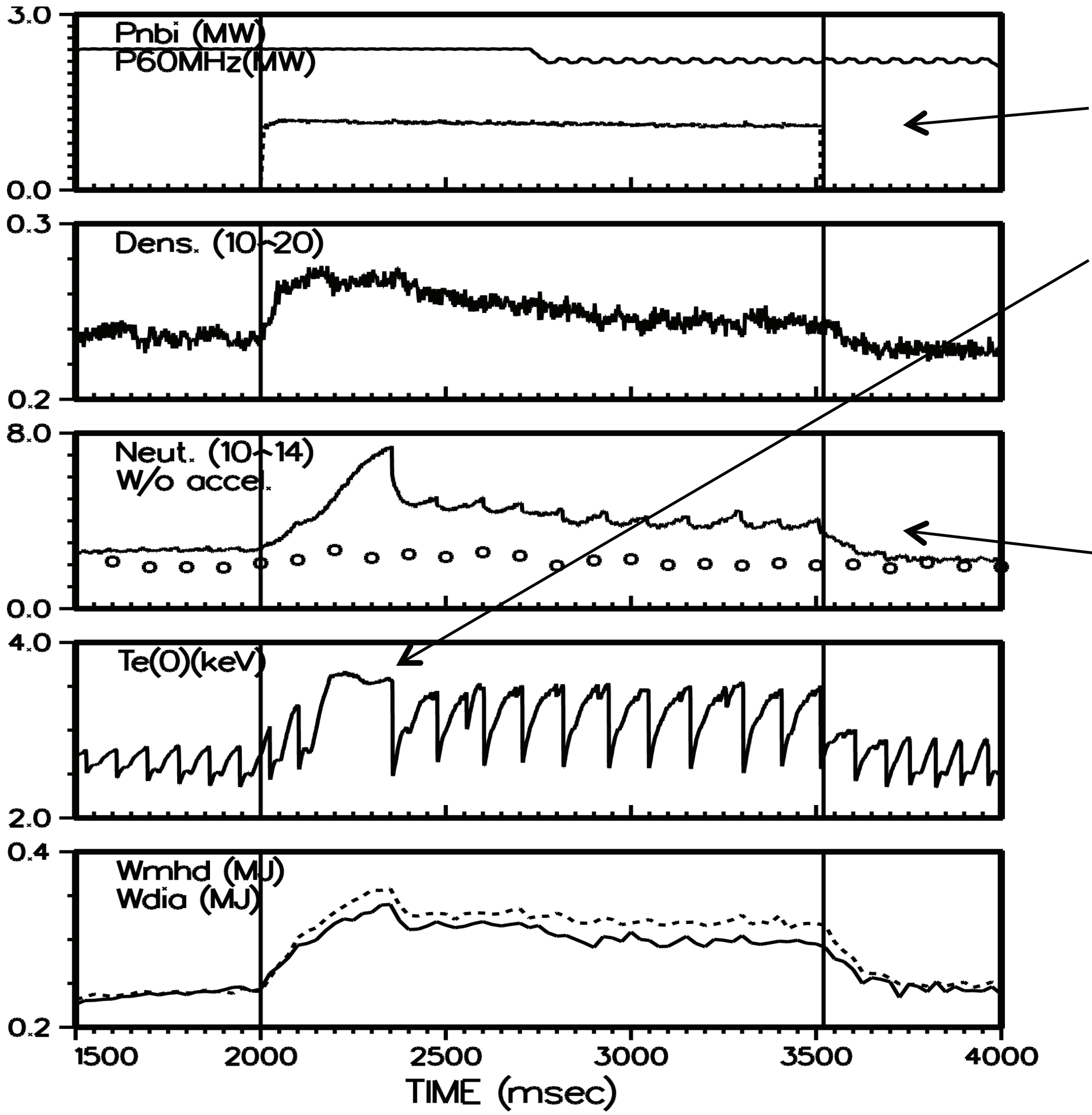
- 285/300 array with double-layer FS installed (1990-1992, 2006-)



One of two identical double-poloidal-strap arrays in DIII-D

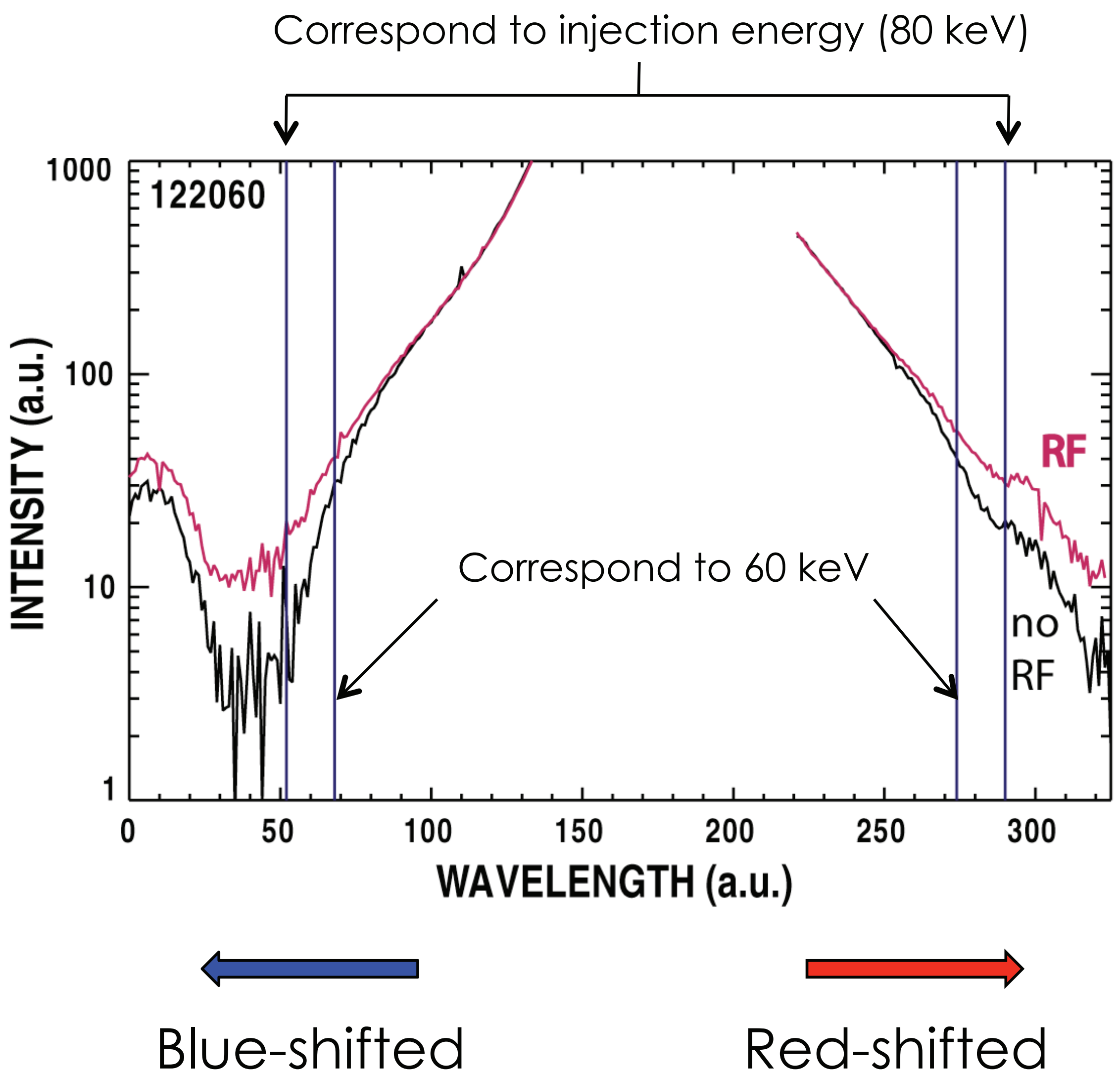
285/300 used at 60 MHz; 0 deg and 180 deg used at either 116 MHz or 90 MHz

Strong 4th harmonic absorption observed at 2 T (60 MHz) in low density L-mode with D NBI



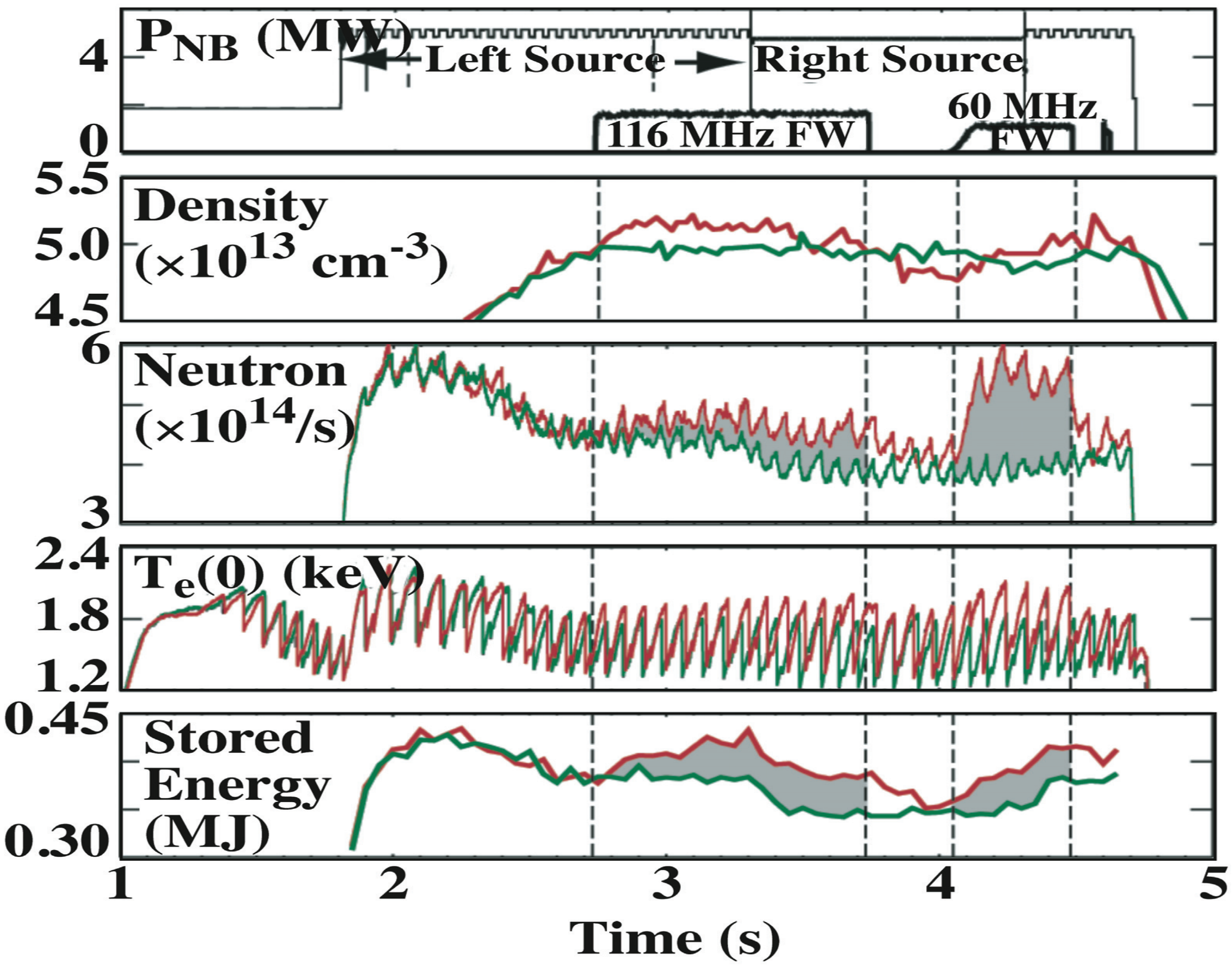
- **60 MHz FW: P_{FW} = 1.2 MW, P_{NBI} = 2.8 MW**
- **Partially stabilized sawteeth, particularly at rf turn-on**
- **Rf acceleration of beam ions observed via:**
  - Enhanced neutron rate
  - Effect on sawteeth
  - Vertically viewing Da CER (FIDA)

Vertically viewed D_a spectrum (FIDA): perpendicular fast ion tail observed during 4th harmonic heating



- Spectrum altered at high energies (expected from high harmonic heating)
- Ions accelerated above injection energy of 80 keV
- Integrated signal between 60–80 keV increases 65% with FW (showing increased energy in tail)

4^{th} harmonic absorption on beam is much stronger than 8^{th} harmonic at same field in high density L-mode



40% more 8^{th} harm. power than 4^{th}, but:

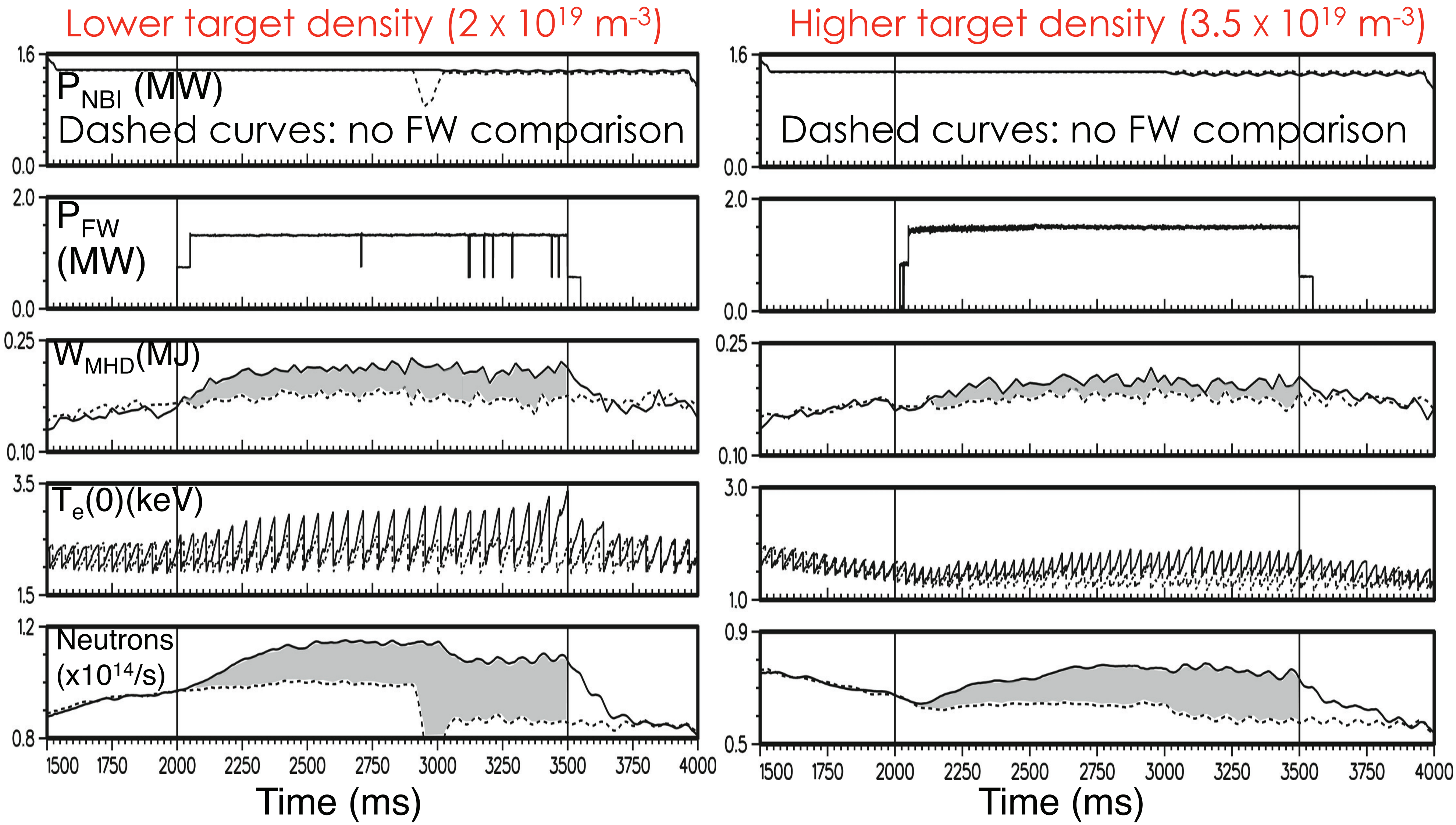
Much higher neutron rate with 4^{th} harmonic FW

Similar stored energy for both harmonics

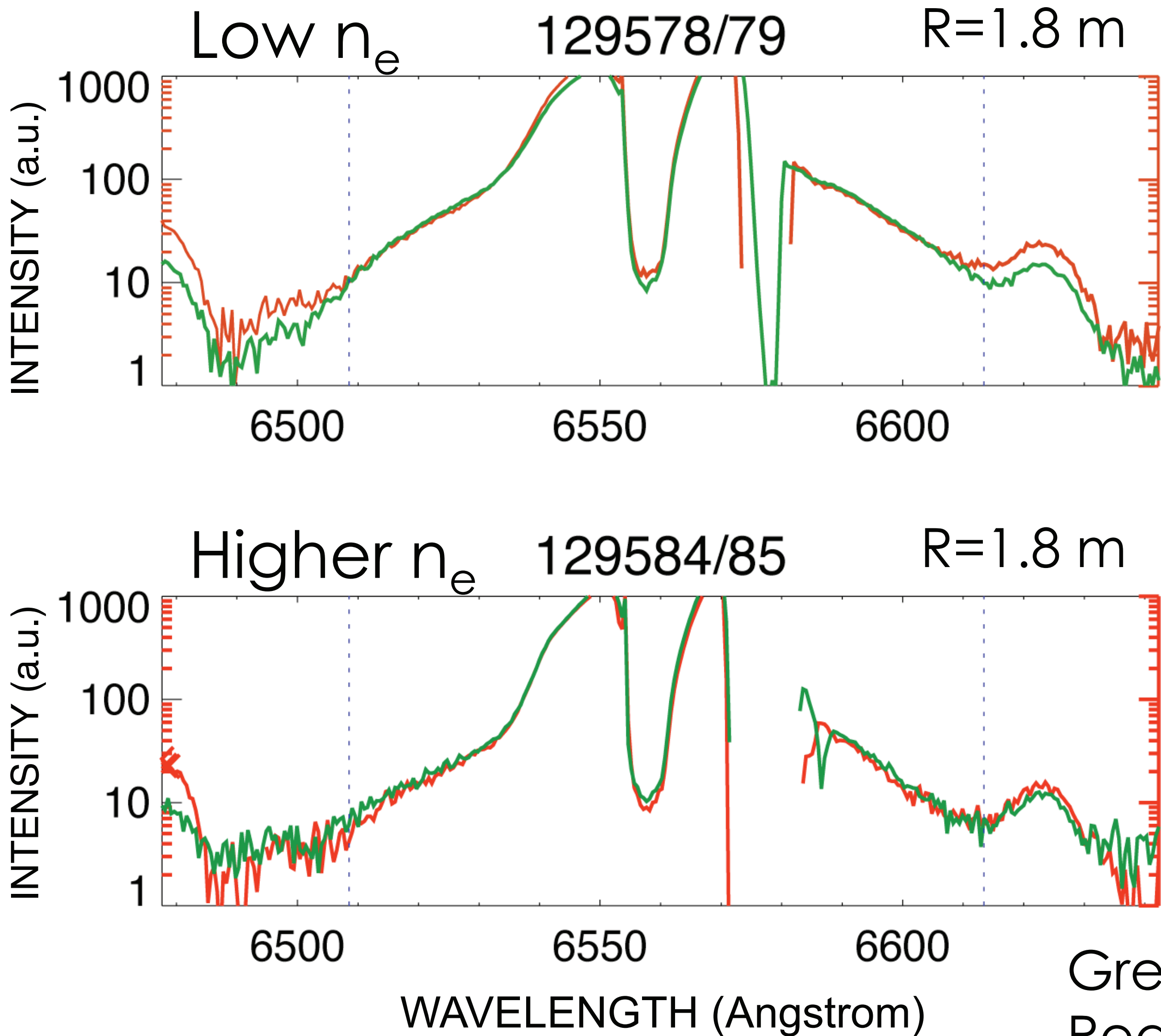
Plasma current 1.2 MA, toroidal field 1.85 T

Green traces: no FW comparison, red traces: FW

6^{th} harmonic absorption at 2 T (90 MHz) stronger at lower density (higher fast ion density)



FIDA shows weak 6th harmonic acceleration of beam in low n_e case; no evidence of acceleration in higher n_e case



- **Vertical dashed lines at effective injection energy**
- **Low density case has significant neutron enhancement; higher density case shows small but clear neutron enhancement**
- **Reason for lack of evidence of acceleration in FIDA signal for higher density case is not known at present**

Green curves: no FW
Red curves: with FW

Confinement analysis using offset linear scaling

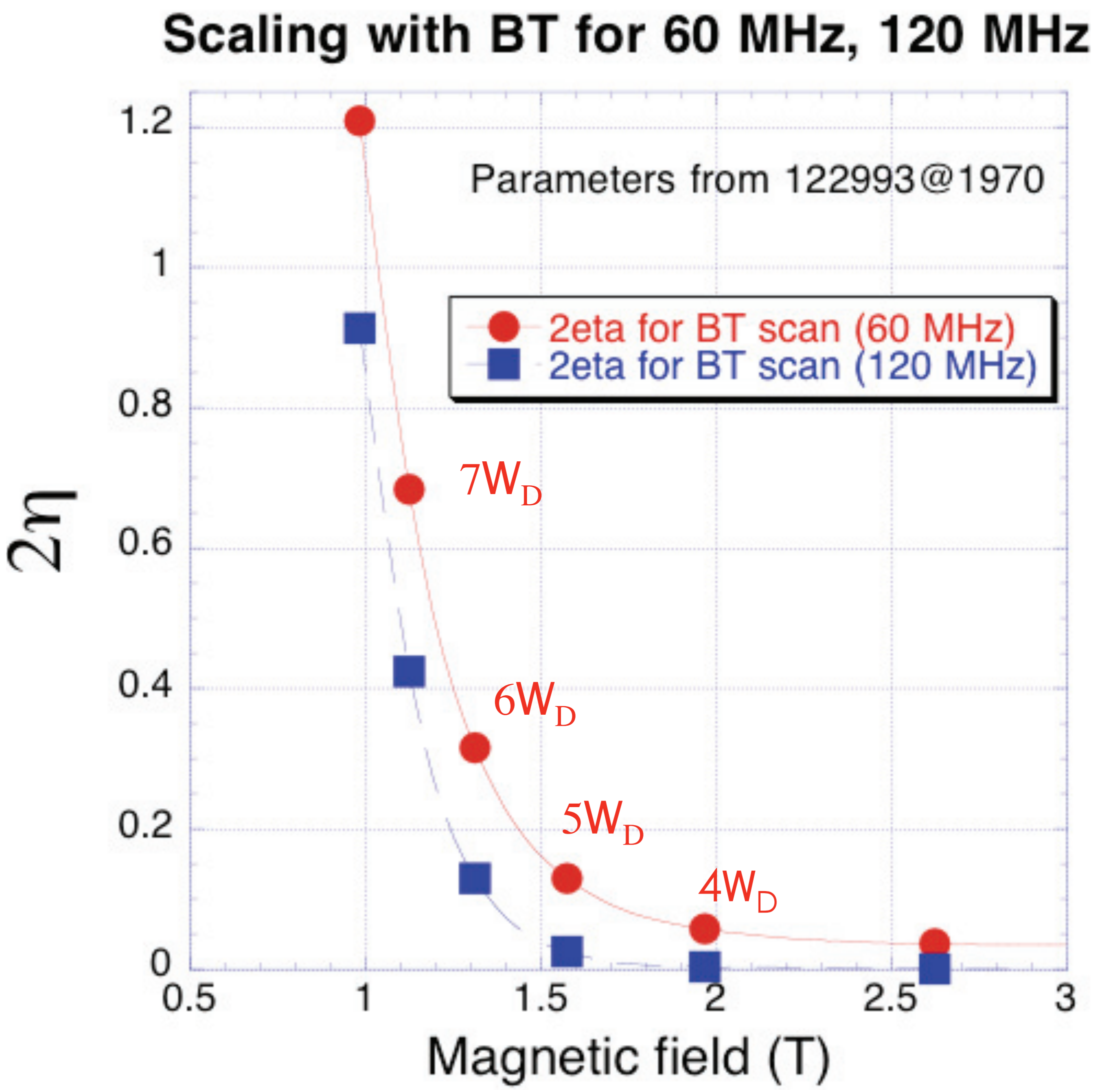
- **Alternate analysis technique: increment in stored energy DW due to the addition of FW power DP to equilibrium with steady NBI and ohmic power yields incremental confinement time t_{inc} = DW/DP**
- **Confinement time before adding the FW power is $t_0 = W_0/(P_{NBI} + P_{OH})$**
- **Form the ratio of t_{inc}/t_0**
- **We expect this ratio to be less than 1 due to normal confinement degradation with power**
- **Compare ratio in different scenarios to assess:**
  - effect of substantial fast ion density from FW acceleration
  - fraction of coupled FW power that is absorbed in core
- **Advantage over power-law scaling: relative effect not dependent on the exact value of exponent in power law**

Confinement measurements show ion cyclotron damping at fixed field increases with decreasing harmonic number, density

n_e (10^{19} m^{-3})	FW Freq. (MHz)	Harmonic	P_{FW} (MW)	$P_{NBI} + P_{OH}$ (MW)	t_{inc}/t_0
5	116	8	1.66	5.5	0.24 ±0.06
3.5	90	6	1.2	1.4	0.24
2	90	6	0.9	1.4	0.5
5	60	4	1.12	5.5	0.45
2	60	4	0.9	2.4	1.0
3	60	4	1.1	2.7	1.0 (before s/t crash)
					0.75 (after s/t crash)

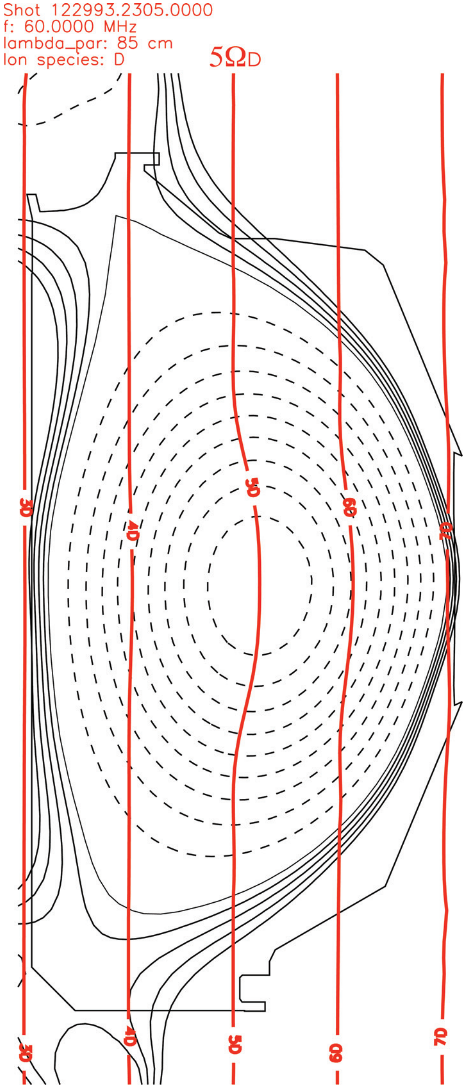
All data at 2 T; ratio of incremental confinement time to confinement without FW rises as harmonic number falls and as density falls (fast ion density increases)

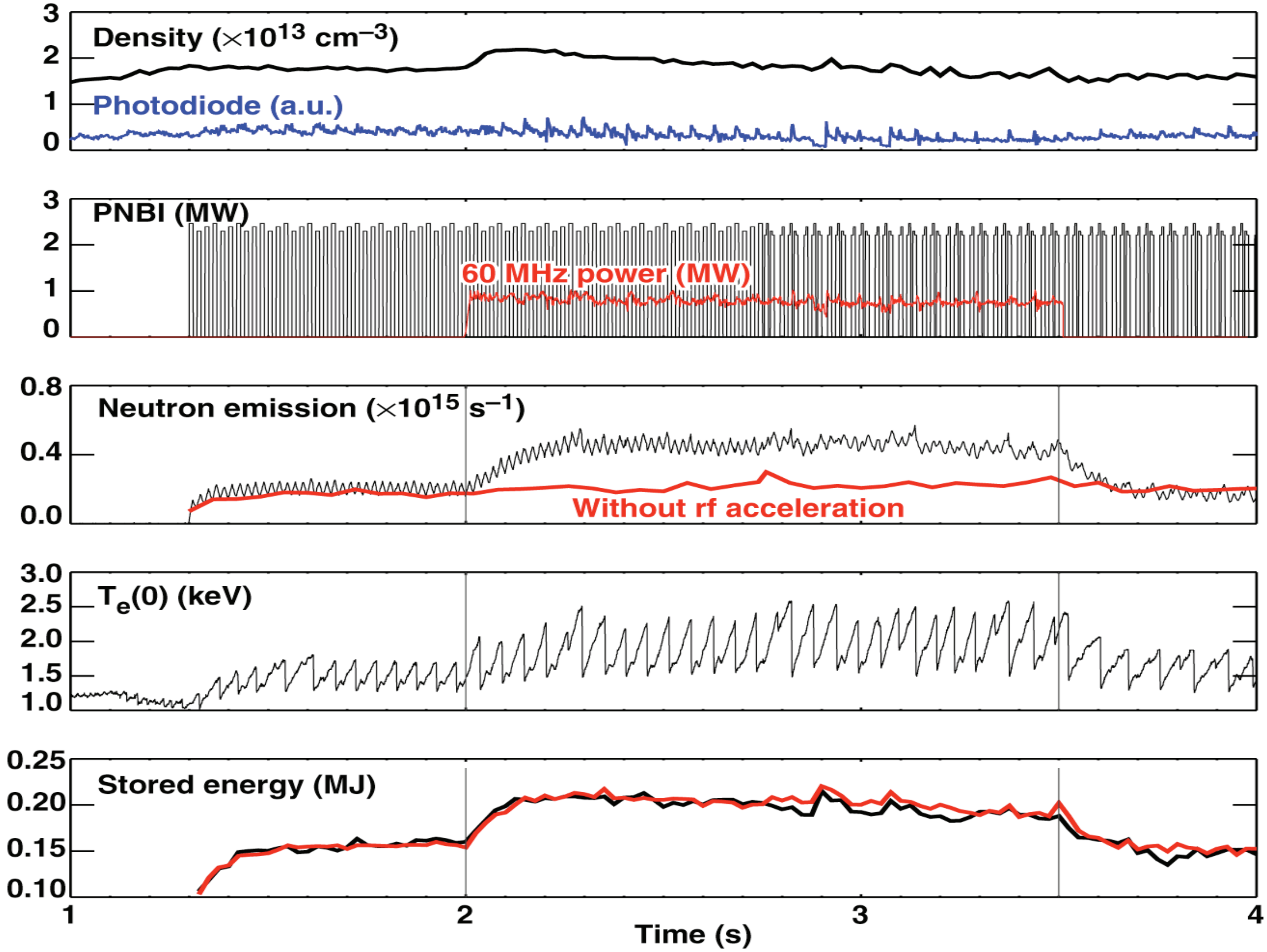
Linear model predicts harmonic damping goes up strongly as toroidal field is reduced at fixed FW frequency



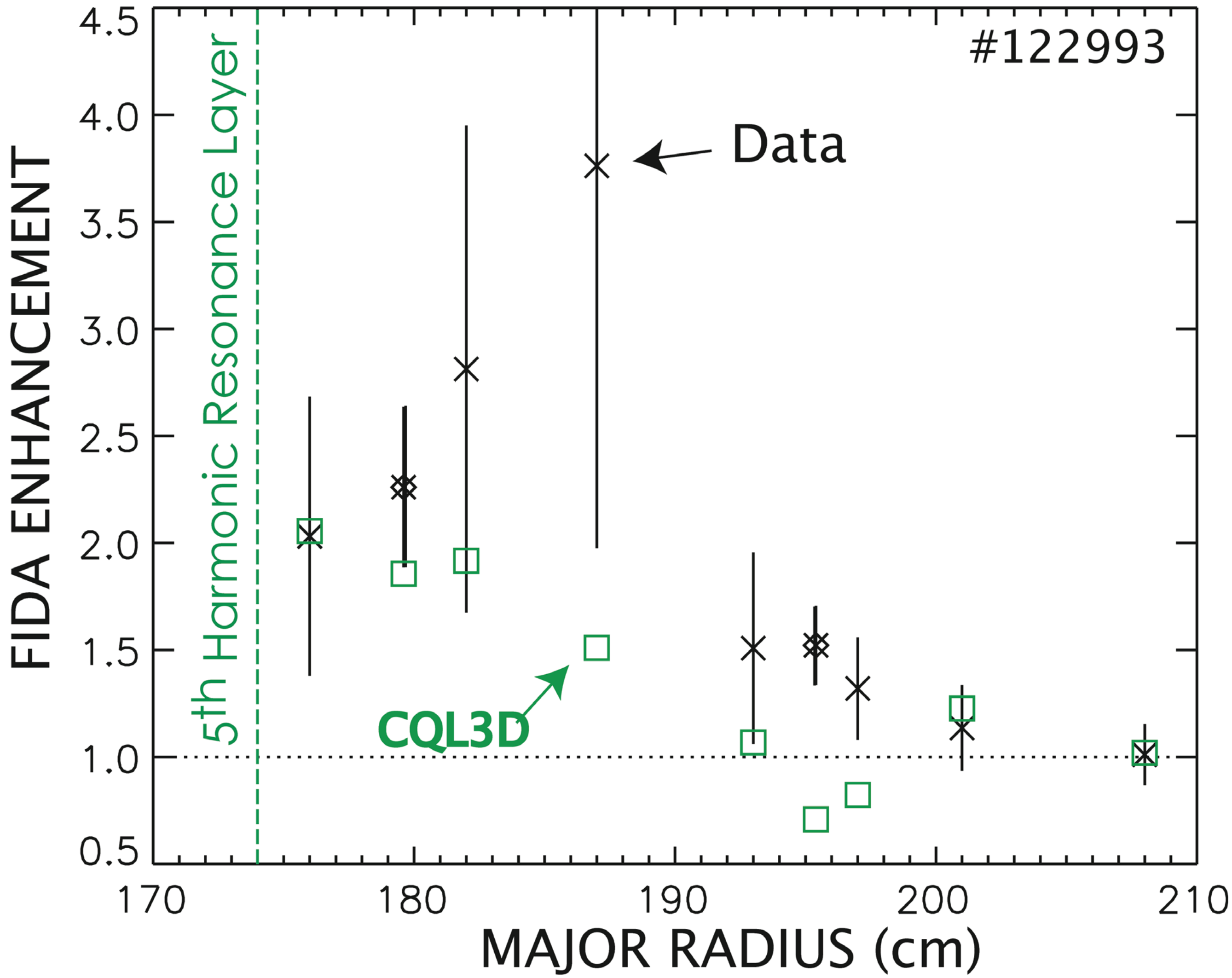
- **Strength of ion cyclotron damping is function not only of harmonic number (w/W_D) but also of ratio of perpendicular speed of absorbing ions to Alfven velocity (v $/v_A$)**
- **Latter parameter tends to win as toroidal field is lowered at fixed frequency**
  - Ion cyclotron damping increases even though harmonic number is increasing

Strong $5W_D$ heating with 60 MHz was observed

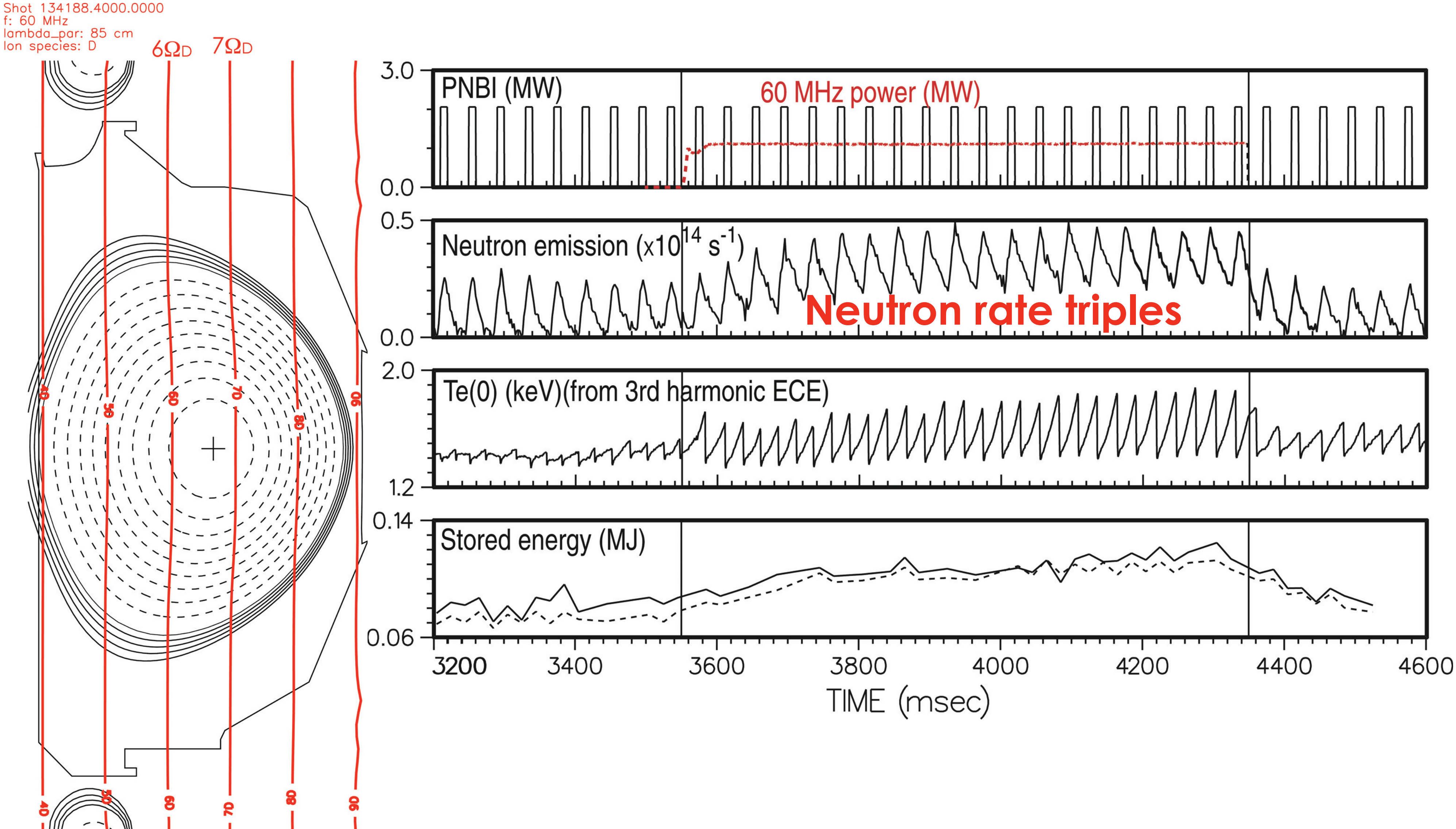




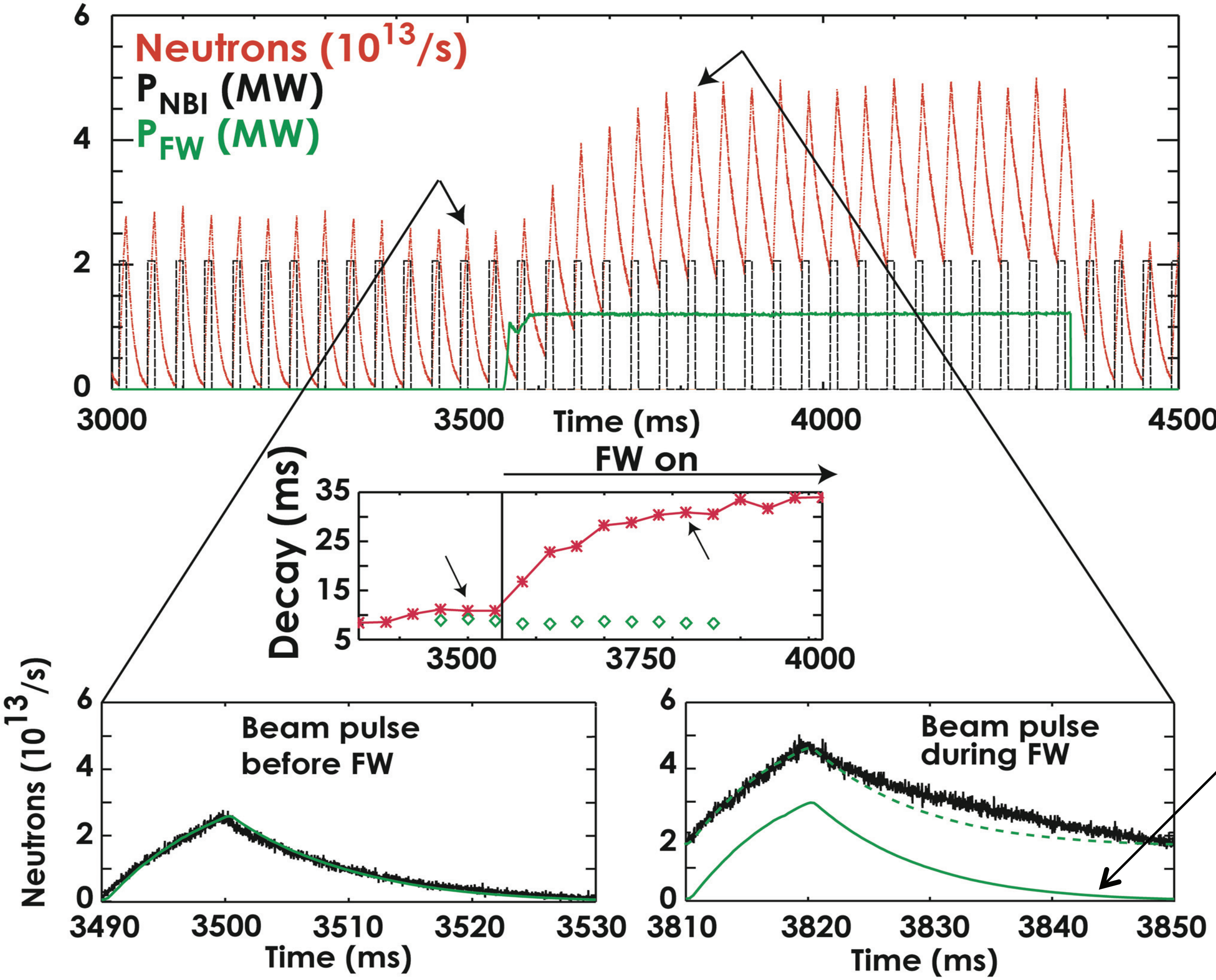
Profile of fast ion enhancement measured with FIDA in 5th harmonic case; peak shifted towards larger R



Strong high harmonic (6th and 7th harmonics near the magnetic axis) heating with 60 MHz was observed



Strong 6th/7th harmonic absorption and beam acceleration observed at low toroidal field with 60 MHz FW

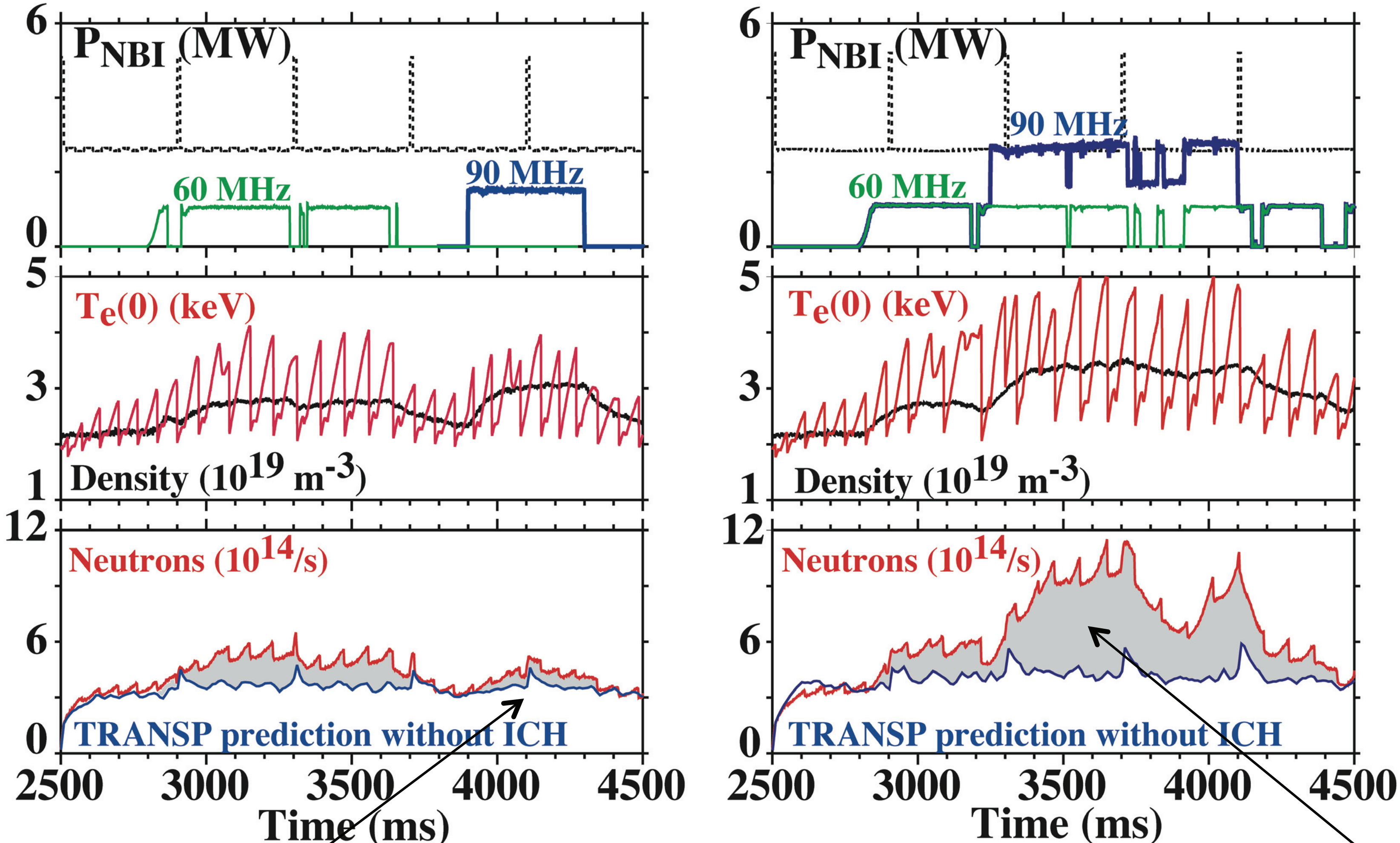


I_p=0.6 MA
B_T=1.2 T
n_e= 3 x 10^{19} m^{-3}

Average beam -target neutron rate triples with FW; due to acceleration of beams ions

Solid green traces TRANSP simulation without acceleration but with measured electron heating

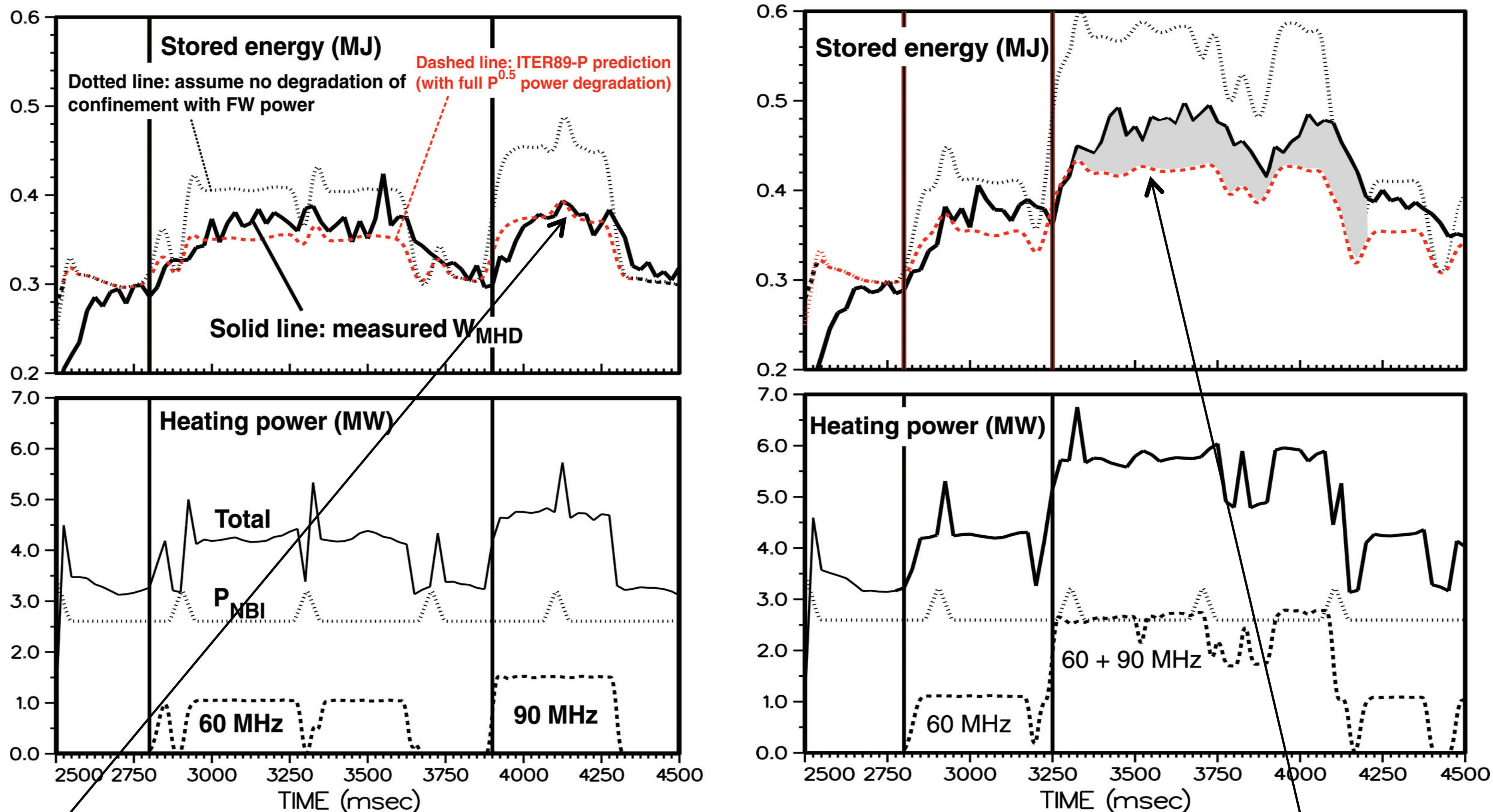
Strong neutron 'synergy' observed in combination of 4th and 6th harmonic heating at 2 T



Plasma current 1.2 MA, toroidal field 2 T

Neutron enhancement much smaller for 90 MHz alone than with 90 MHz + 60 MHz

Some synergy in stored energy observed in combination of 4th and 6th harmonic heating at 2 T



Difference between stored energy and ITER-89P prediction much smaller for 90 MHz alone than with 60 MHz preheating

Discussion

- **Total single-pass core absorption of FW is sum of:**
  - Ion cyclotron damping on thermal and non-thermal ion species
  - Direct electron damping via ELD and TTMP
- **Edge dissipation from another set of mechanisms:**
  - Rectified rf sheaths at wall
  - Parametric decay and absorption of daughters
  - Collisional damping
- **If core and edge absorption are both weak (multiple-pass regime), partition between core and edge absorption determined by relative strength: fraction in core=** $\langle\ _{core}\rangle / \left(\langle\ _{core}\rangle + \langle\ _{edge}\rangle\right)$

Discussion

- **FWCD studies in similar DIII-D L-mode plasmas showed that $\langle {}_{edge} \rangle$ was about 0.04, which is not very much less than the total core absorption per pass expected in these plasmas**
- **Therefore simulations that do not include edge losses will overestimate core absorption**
- **Modeling to date has been done by US RF SciDAC group with:**
  - AORSA/CQL3D (full wave plus bounce-averaged F-P)
  - GENRAY/CQL3D (ray tracing plus F-P)
  - TORIC/ORBIT-RF (full wave plus Monte Carlo)
- **Results do not yet agree with each other; rough agreement with experiment obtained in some cases**
- **Incorporation of edge losses in these wave field solvers ongoing**

Conclusions

- Correlation between expected single-pass absorption (<< 100%) and measured global core absorption efficiency implies significant role of edge losses (without edge losses, global core absorption would always be 100%)
- For moderate to high harmonic ion cyclotron absorption, strength is determined both by harmonic number and by ratio of speed of absorbing ions to Alfven velocity $v\ /v_A$
- Partition between multiple absorption mechanisms is sensitive to initial conditions, demonstrated by synergy in two-frequency ion cyclotron absorption results

Summary and conclusions

- Absorption at 4th harmonic on injected deuterium beams can be strong, but under the same conditions 6th and 8th harmonic absorption is weak
- Raising harmonic number at fixed FW frequency by lowering toroidal field shows absorption at high harmonics can be significant for $v \sim v_A$
- Dependence of global absorption efficiency on single-pass absorption points to importance of edge losses
- Application of two frequencies simultaneously can lead to a synergistic increase in high harmonic absorption
- Quantitative modeling must incorporate edge losses unless core absorption is much stronger than losses
- Models being developed for ITER will be benchmarked against DIII-D results