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
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 $\nu / \nu_A$, 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-)**

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

One of two identical double-poloidal-strap arrays in DIII-D.
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 $D_a$ 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)
4th harmonic absorption on beam is much stronger than 8th harmonic at same field in high density L-mode.

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

- Much higher neutron rate with 4th 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
6th harmonic absorption at 2 T (90 MHz) stronger at lower density (higher fast ion density)

- Lower target density (2 x 10^{19} m^{-3})
  - \( P_{\text{NBI}} \) (MW)
  - \( P_{\text{FW}} \) (MW)
  - \( W_{\text{MHD}} \) (MJ)
  - \( T_e(0) \) (keV)
  - Neutrons (x10^{14}/s)

- Higher target density (3.5 x 10^{19} m^{-3})
  - Dashed curves: no FW comparison

Time (ms)
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

**Low $n_e$**

R=1.8 m

**Higher $n_e$**

R=1.8 m

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

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

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)

0.75 (after s/t crash)
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 \( (\omega/W) \) 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 (6\textsuperscript{th} and 7\textsuperscript{th} harmonics near the magnetic axis) heating with 60 MHz was observed.
Strong 6\textsuperscript{th}/7\textsuperscript{th} harmonic absorption and beam acceleration observed at low toroidal field with 60 MHz FW

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

$I_p = 0.6 \text{ MA}$

$B_T = 1.2 \text{ T}$

$n_e = 3 \times 10^{19} \text{ m}^{-3}$
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= \frac{\langle \text{core} \rangle}{\langle \text{core} \rangle + \langle \text{edge} \rangle}
Discussion

• FWCD studies in similar DIII-D L-mode plasmas showed that $\langle \text{edge} \rangle$ 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 4\textsuperscript{th} harmonic on injected deuterium beams can be strong, but under the same conditions 6\textsuperscript{th} and 8\textsuperscript{th} 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.