Mitigation of Alfvén Activity by Externally Applied 3D Fields in NSTX plasmas

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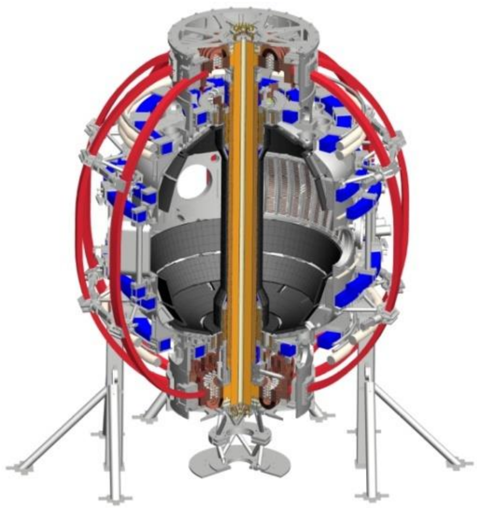
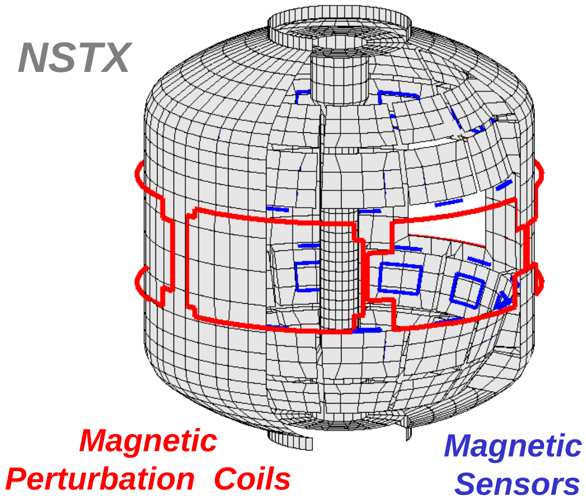


Introduction and motivation

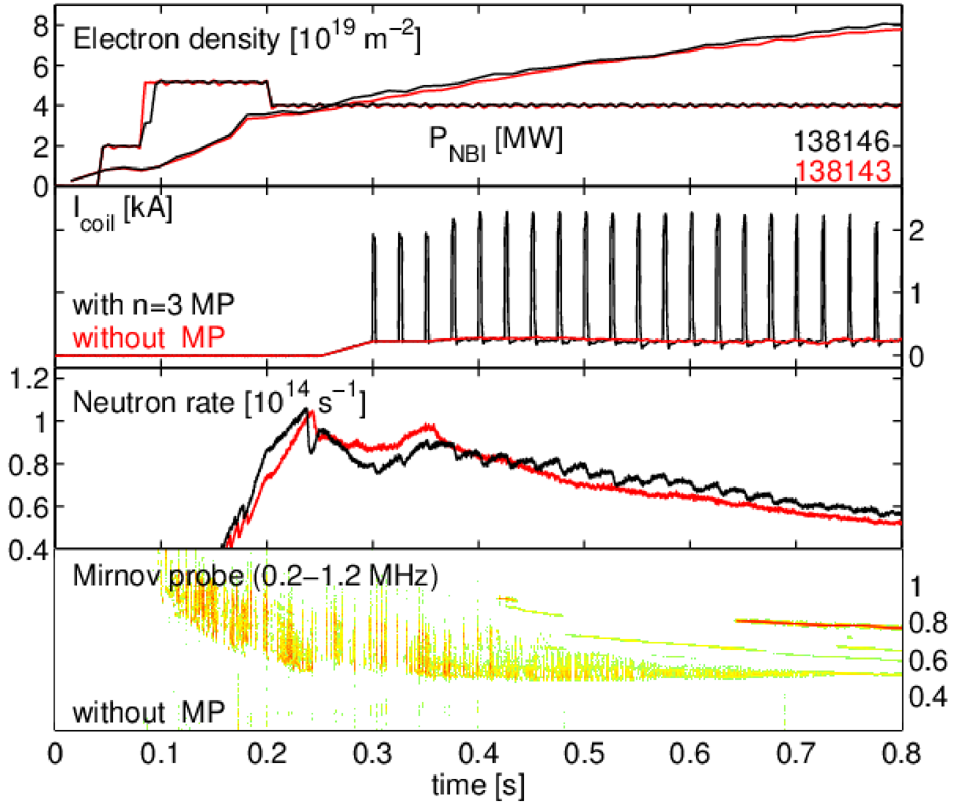
- Fast ion confinement is an important element of a fusion device
  - Optimize the plasma heating and current drive
  - Avoid damage from localized particle losses to wall
- Bursting, frequency-chirping modes driven by energetic particles can cause fast ion transport and losses
- Can external 3D magnetic perturbations (MP) be used to suppress or mitigate instability?

Fast Ions from NBI
3 sources, total $P_{NBI} \leq 6$ MW
$E_{injection} \leq 90$ keV
$1 < V_{beam}/V_{Alfven} < 5$
Larmor radius <20 cm



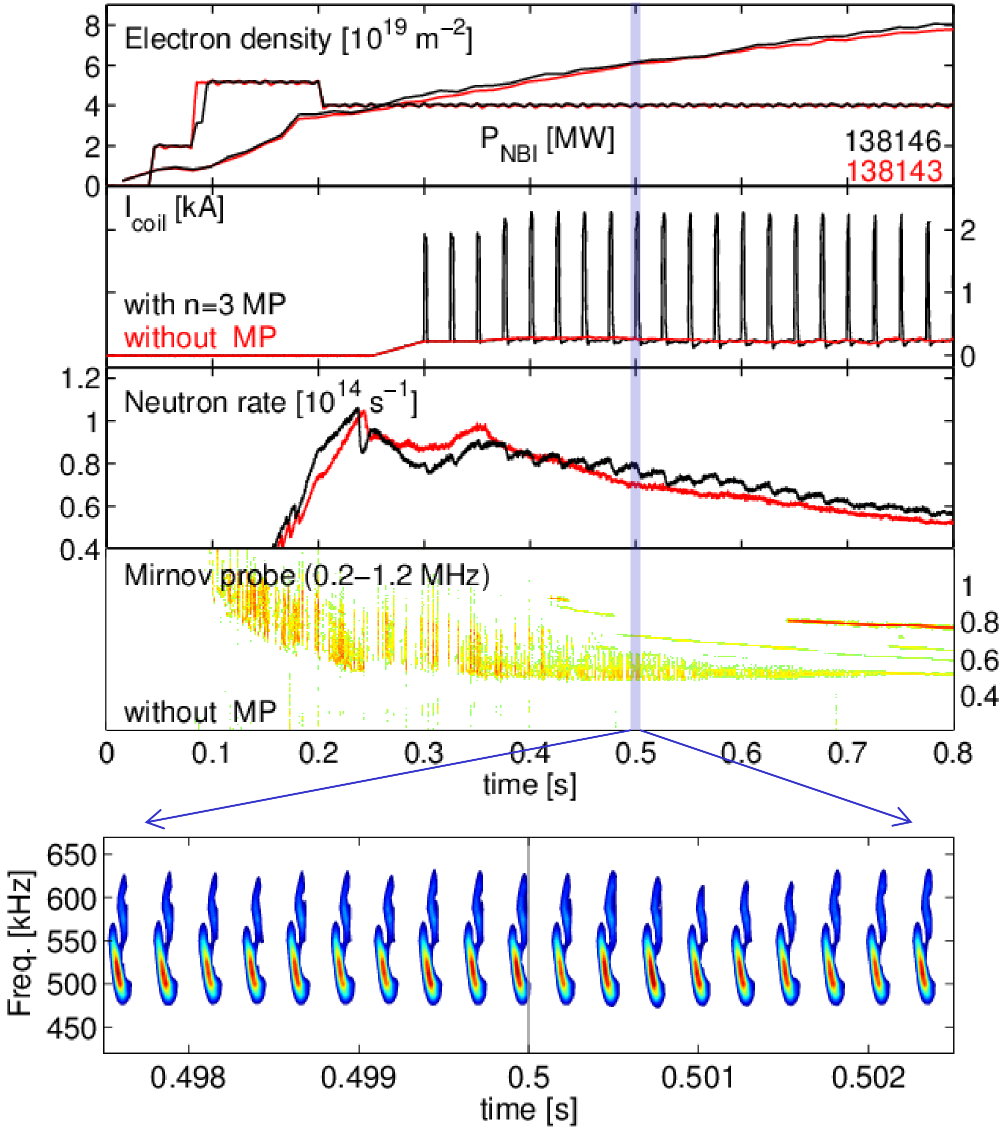
Magnetic perturbation coils	
Coils	6 (external)
Coil current	6 kA · turn
δB in vessel	<50 mT
Rot. Freq.	<50 Hz

3D fields application modifies neutron rate



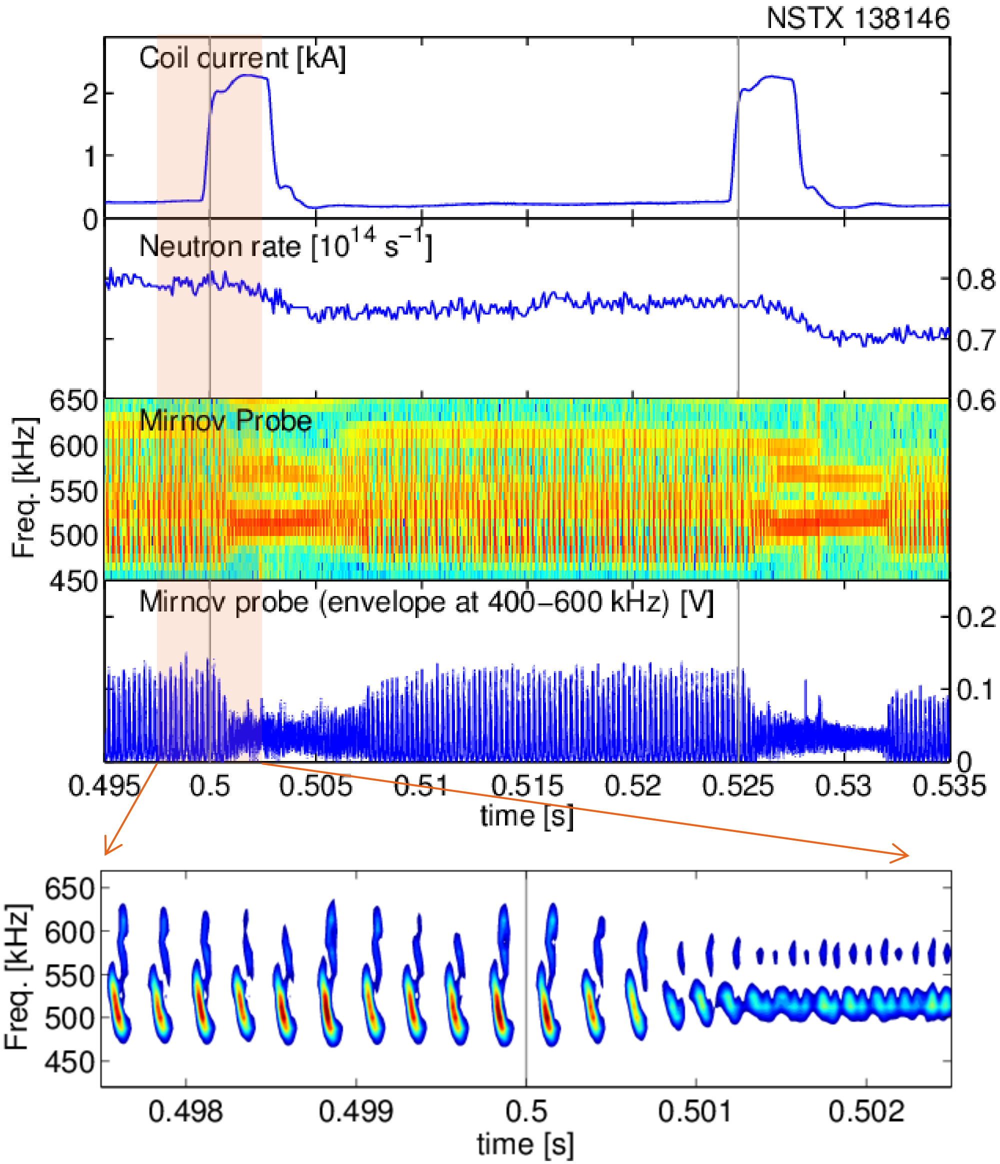
- ELM free H-mode
- Pulsed, n=3, static fields
  - Pulse duration 3 ms
  - Pulse frequency (40Hz)
- Sawtooth-like modulation of neutron rate observed
  - Relative drop of 7%

3D fields application modifies neutron rate



- ELM free H-mode
- Pulsed, n=3, static fields
  - Pulse duration 3 ms
  - Pulse frequency (40Hz)
- Sawtooth-like modulation of neutron rate observed
  - Relative drop of 7%
- Persistent bursting/chirping MHD
  - Repetition rate 4kHz
  - Frequency chirp 100 kHz
  - Toroidal periodicity n=7-9
- Global shear AE (GAE)

Magnetic perturbation mitigates bursting GAE



When n=3 pulse is applied:

- Burst amplitude reduced (x 1/2)
- Frequency sweep reduced (100→40kHz)
- Burst freq. increased (4→12kHz)

Bursting is reduced before drop of neutron rate

- Timescale ~0.1 ms (orbital)

- Slower recovery after pulse end
  - Timescale ~1-3 ms (collisional)

Fast ion transport likely to play key role

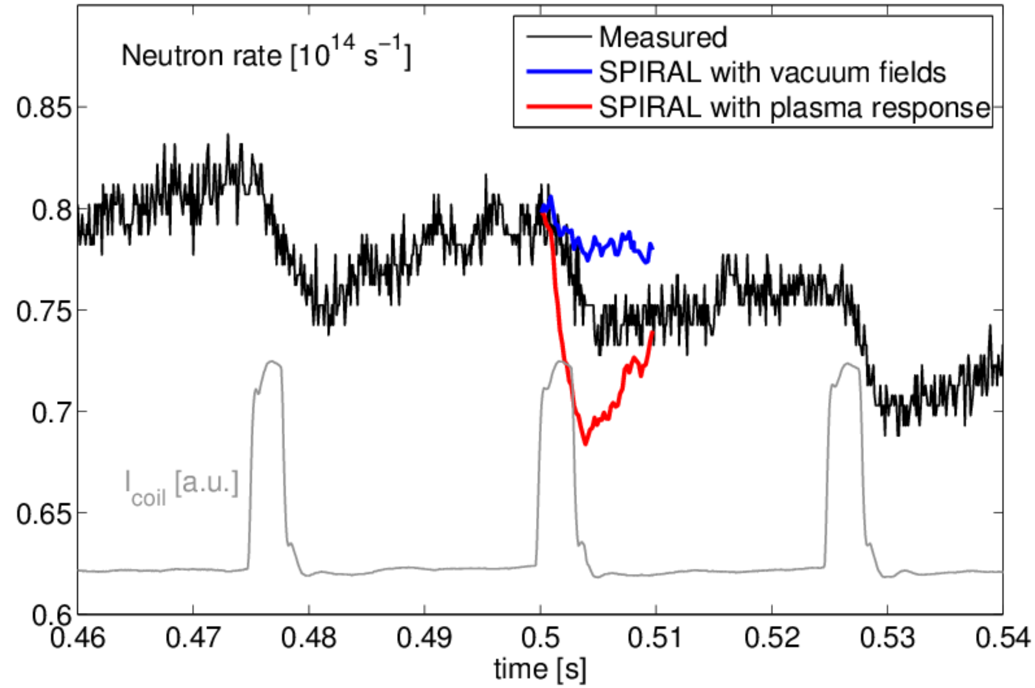
- ***Neutron drops*** and ***timescales*** suggest direct role for fast ions
- ***Hypothesis***:
  1. MP causes rapid transport and/or loss of resonant fast ions, reducing the drive for instability
  2. After MP is removed strong bursting resumes as the distribution function is restored

- In order to test this hypothesis we need to:
  1. Compute the perturbed fast-ion distribution function
  2. Evaluate how resonant particles are affected by MP

Full-orbit simulations predict dynamic evolution of fast ion distribution function in presence of MP

SPIRAL[1] computes the orbit of test particles with collisions and pitch angle scattering
IPEC[2] computes ideal equilibria linearly perturbed by non-axisymmetric fields

- Slowing down d.f. from a 35 ms run with equilibrium fields
  - Constant fueling rate
  - Birth location and velocity from attenuation code (NUBEAM)
- Simulation continued for 10 ms, including MP
  - MP structure from IPEC
  - Ideal plasma response
- MP amplitude dynamically scaled to match measurement of in-vessel magnetic sensor

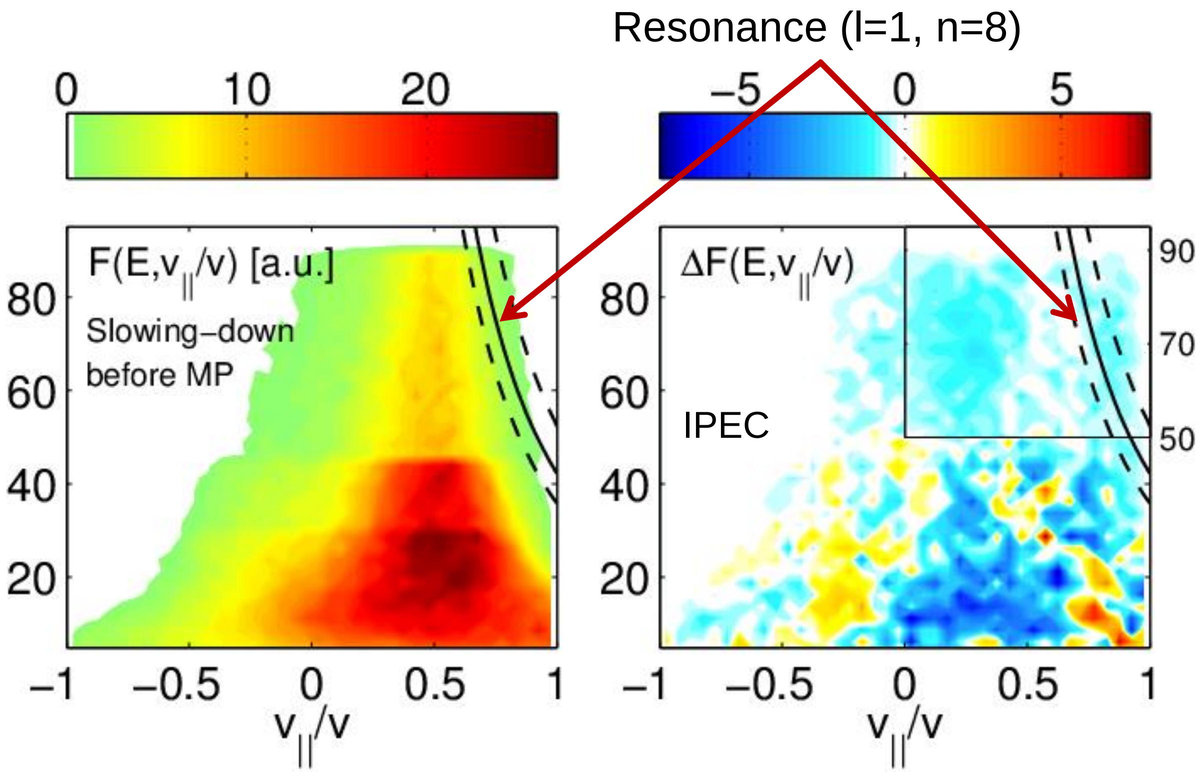


Predicted evolution of neutron rate compares reasonably with experiment

[1]*Kramer, PPCF 55 (2013) 025013* [2]*Park, PoP 14 (2007) 052110*

The MP reduces the number of resonant fast ions

- Fast ion d.f. $F(E, v_{||}/v)$
  - integrated over GAE location (r/a < 0.5)
  - before MP starts
  - 2 < t < 4 ms after MP starts
- Depletion found for:
  - E<50 keV, $0 < v_{||}/v < 0.6$
  - E>50 keV, $v_{||}/v < 0.4$
    $v_{||}/v > 0.7$

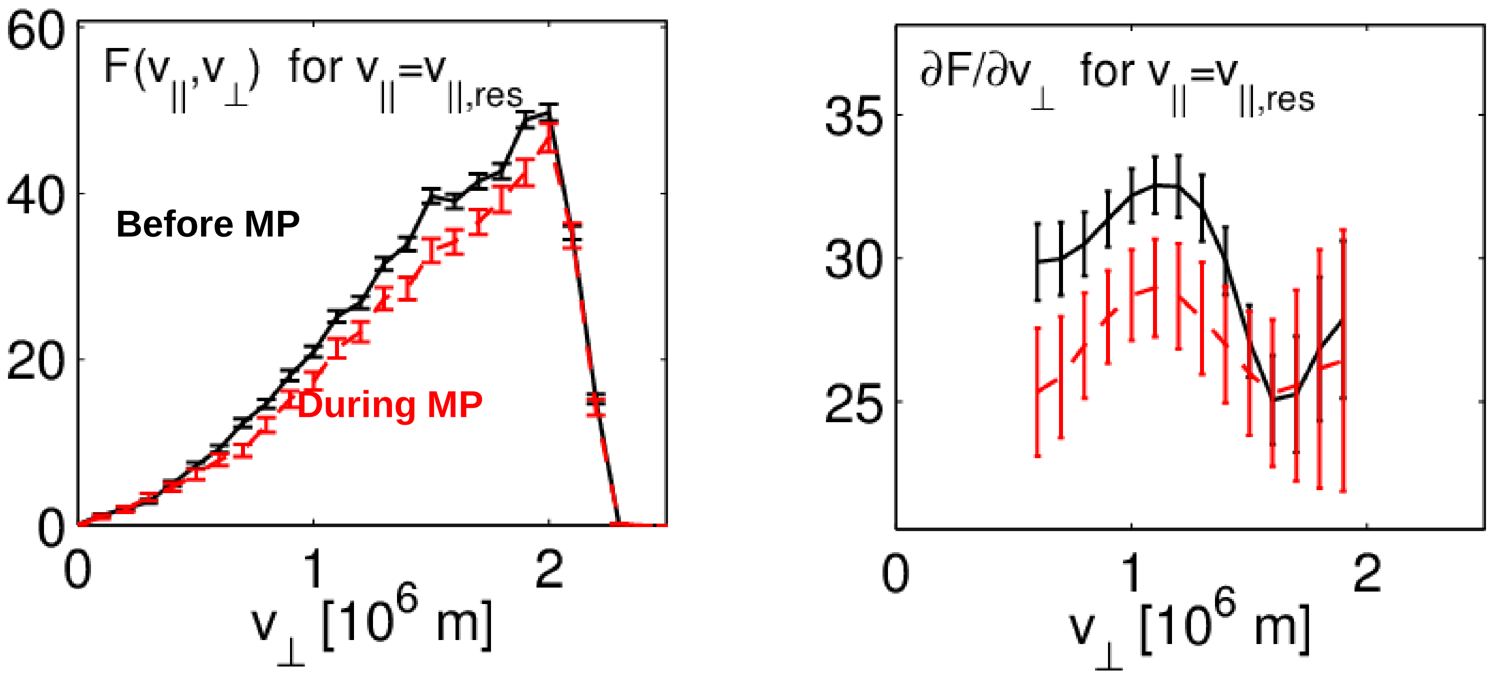


- GAE Doppler-shifted cyclotron resonances on the flank of the distribution function

Resonance condition

$$\omega = k_{||}\, v_{i,||} + l\, \Omega_{ci}$$

Simulations suggest reduction of mode drive



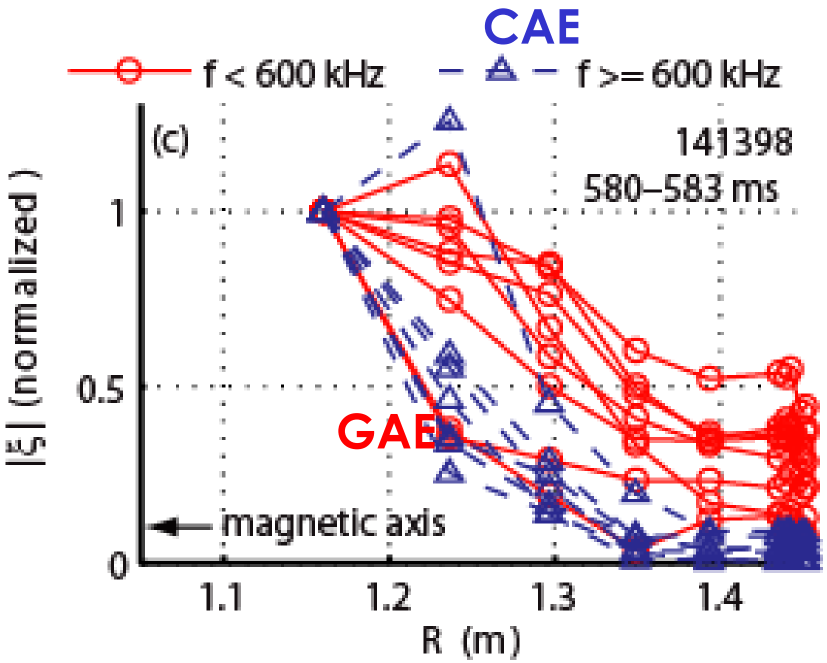
- Instability depends on gradient of d.f. in velocity space
- Gradient $\partial F/\partial v_{\perp}$ along the resonance is main driving term
- Reduction of $\partial F/\partial v_{\perp}$ by 10-20% suggest smaller drive with MP
- Can affect bursting dynamics of marginal instability modes

Conclusions

- Externally imposed 3D fields can alter the nonlinear evolution of a tokamak fast-particle driven instability
- Full-orbit simulations reproducing the evolution of neutron production rate indicate that MP can reduce the fast ion drive by depletion of the resonant fast ions
- The observations suggest the possibility of controlling fast-ion instabilities by tailoring the fast-ion distribution function with appropriate magnetic perturbations

Back up material

GAEs and CAEs are often observed in spherical tokamaks



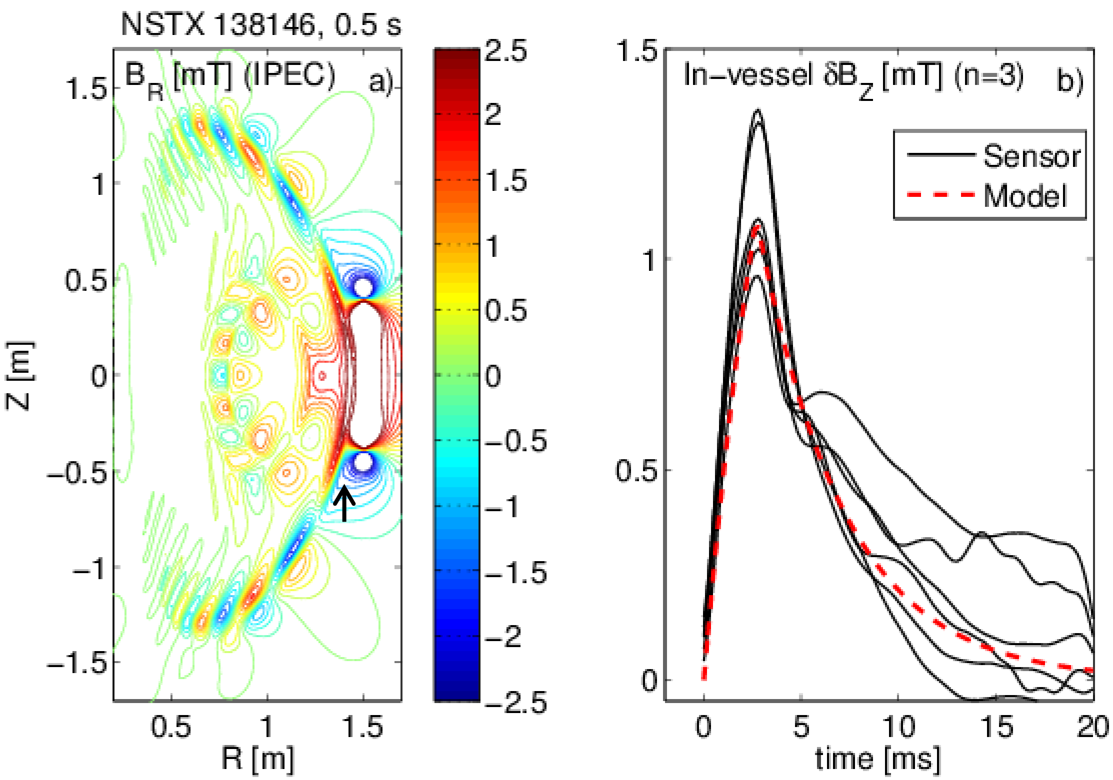
Crocker, Nucl. Fusion 53 (2013) 043017

- Polarization: GAE is a shear wave, CAE is compressional
- Driven by velocity-space gradients at Doppler-shifted cyclotron resonances
- Time evolution of frequency assists identification
- GAE usually have larger toroidal mode numbers
- GAE has broad eigenfunction
- Implicated in enhanced electron transport

Stutman, PRL 102 (2009) 115002

MP structure modeled including ideal plasma response

Magnetic sensors measure the MP amplitude near the wall → Modeling required for MP structure in the plasma volume



Finite amplification in the plasma core

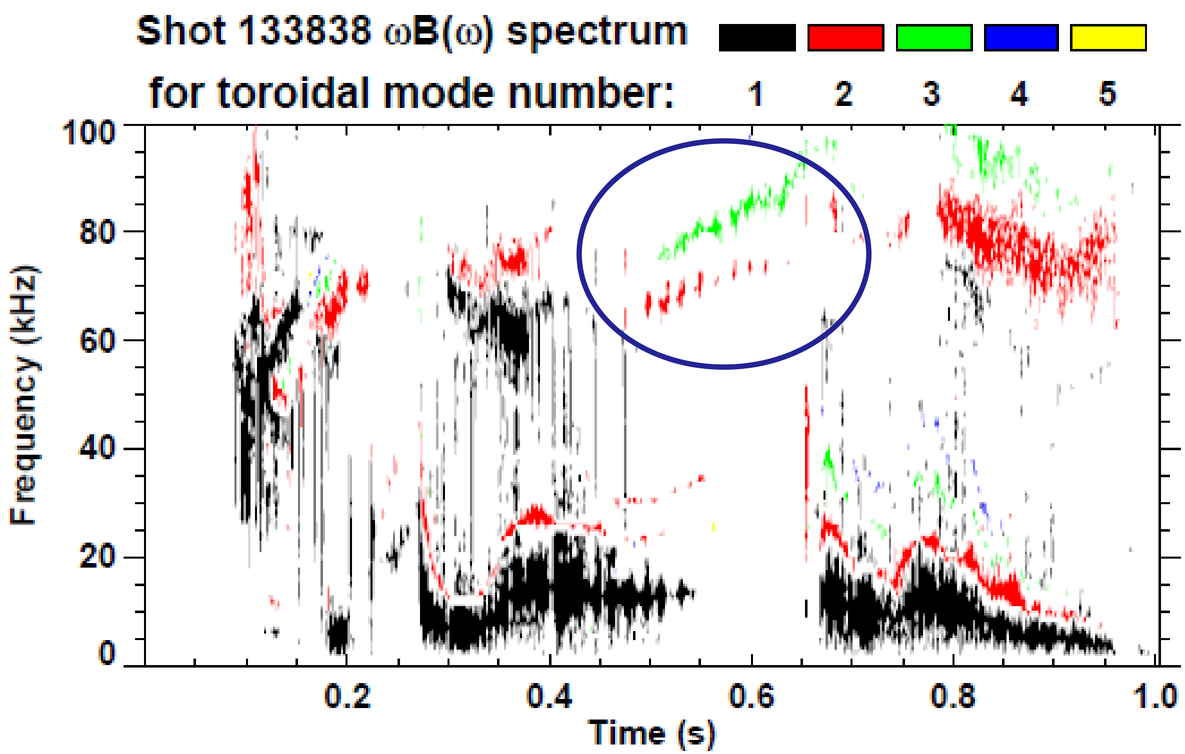
- Structure of vacuum fields from Ampere's law
- IPEC* code used to compute MP within the plasma
  - Assumes ideal plasma response
- Simplified model to account for field penetration

$$B_{tot}(t) = A(t)(B^I_{vac} + B^I_{res})$$

- A(t) adjusted to match the poloidal field measured by a magnetic sensor

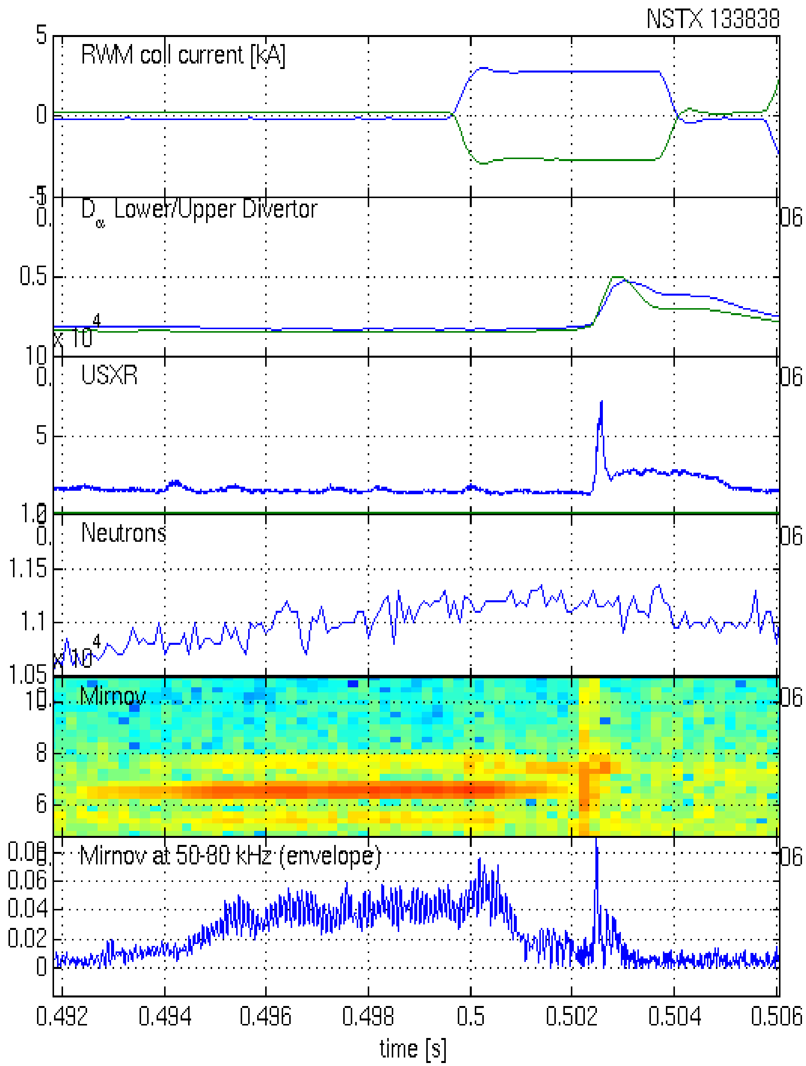
***Park, PoP 14 (2007) 052110**

Preliminary data in for lower frequency modes



- Modulation of n=2-3 modes in the TAE range of frequencies
- Modes appearing in small number of ELM pacing experiments

Preliminary data: possible mitigation of lower frequency modes



- 60 kHz continuous mode
- Suppressed after MP
- ELM is also destabilized
- In some cases mode attenuated before ELM crash