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

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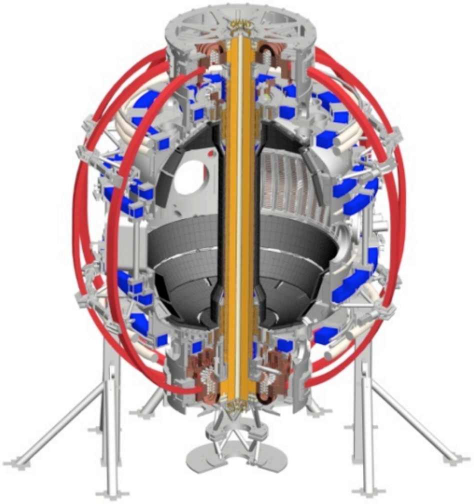

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Placeholder

photo of Alessandro

Bortolon et al., Phys. Rev. Lett. 110, 265008 (2013)

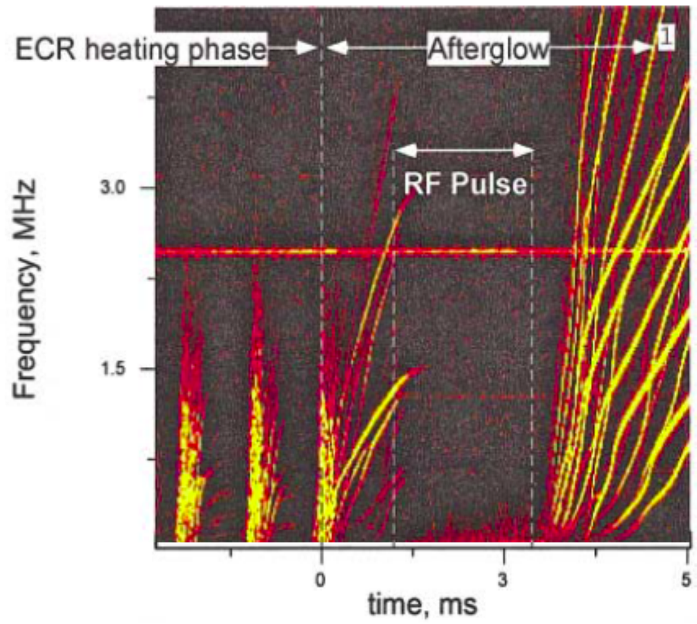
Introduction

- 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 are extremely common:
  - multiple frequency bands (from low to ion cyclotron frequencies)
  - configuration (tokamaks, spherical tokamaks, stellarators, etc)
  - energetic-particle populations (beams, rf, and energetic electrons)
  - Coupled avalanches of multiple bursting modes are observed*
  - Bursts can cause large, concentrated losses
- Methods are needed that suppress instability or mitigate its impact (without appreciable reduction in performance).

**Fredrickson, Nucl. Fusion 52 (2012) 043001*

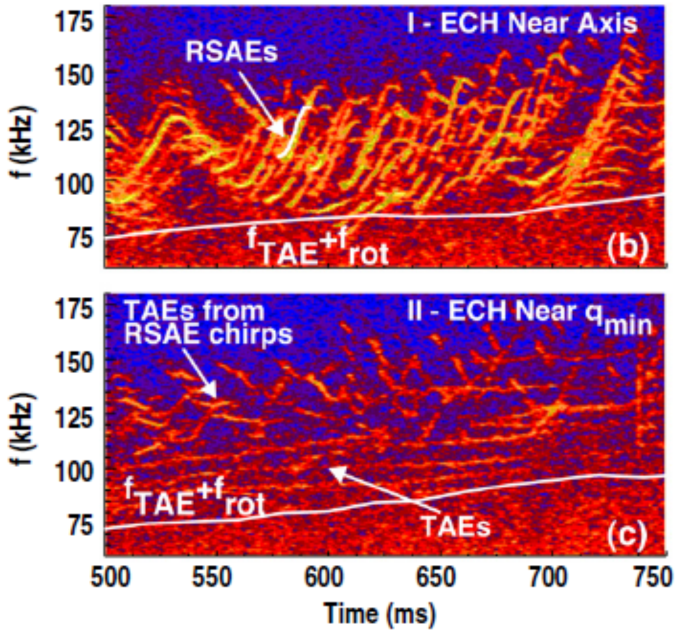
Examples of mitigation of EP driven instability

- Magnetic dipole experiment CTX
- RF fields suppress rapidly-chirping driven by fast electrons
- Fast electron scattering by rf destroys phase-space structures



Maslovsky et al. Phys.Rev.Letters 2003

- DIII-D tokamak
- RSAE activity is suppressed when EC heating is deposited near the of the shear reversal radius



VanZeeland et al. Nucl.Fusion 2009

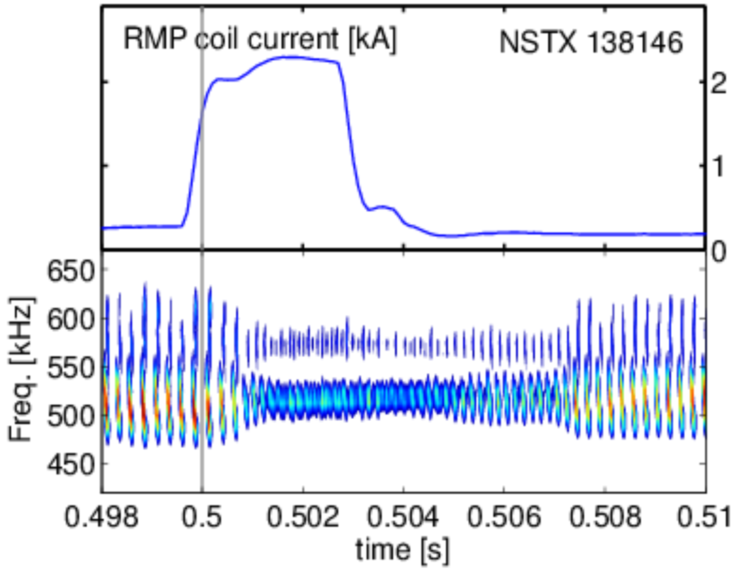
Outline of the talk

Mitigation of bursting AE by applied 3D fields observed on NSTX

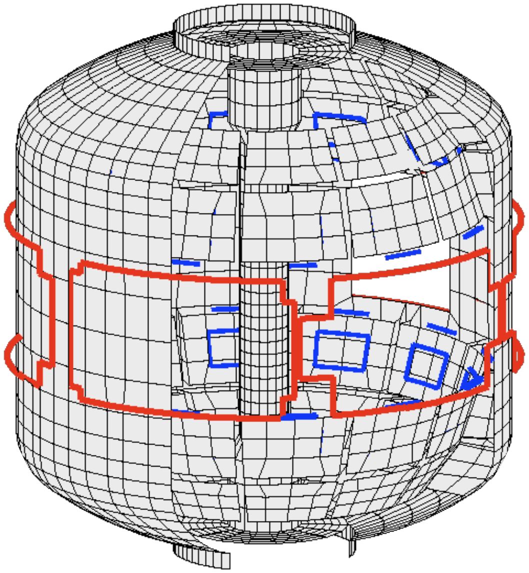
1. Observations of mitigation of high frequency modes

2. Role of fast ion transport
   - Modeling of magnetic perturbation
   - Simulation of fast ion transport
   - Effect on hf-mode drive

3. Conclusions and outlook



NSTX is suitable to study effect of external perturbations



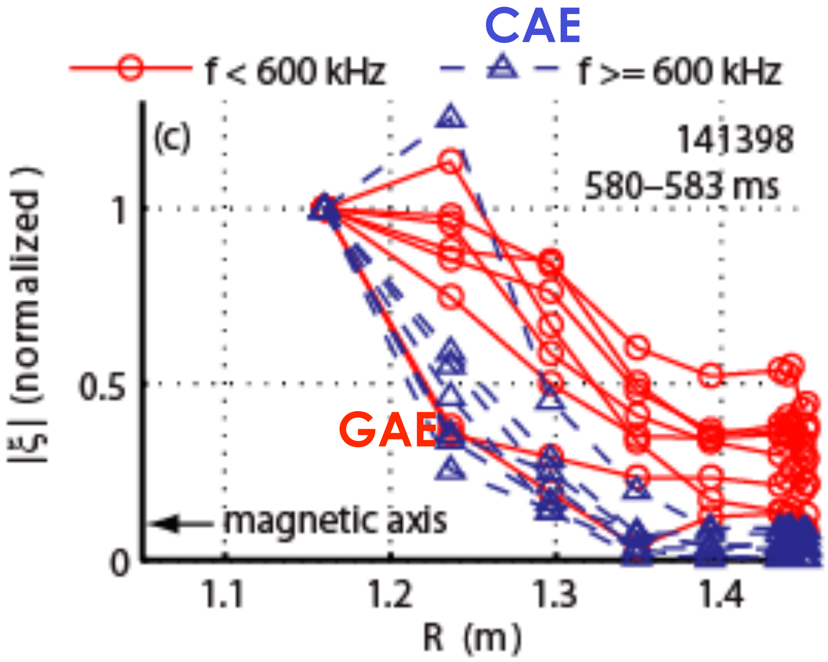
- Low $B_{tor,}$ high density → "low" Alfvén speed
  - large population of super alfvénic ions
  - favors the drive of Alfvén Eigenmodes (AE)
- RWM coils
  - n=1, n=3 perturbation
  - Effective in ELM triggering, plasma braking, RWM counteraction, error field compesation

NSTX parameters	
Major radius	0.85 m
Aspect ratio	~2
Plasma current	~1 MA
Toroidal field	<0.6 T

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

Resistive Wall Mode coils	
Coils/turns	6 /2 (external)
coil current	3kA per turn
dB in vessel	<50 mT
Rot. Freq.	<50 Hz

GAEs and CAEs are often observed in spherical tokamaks

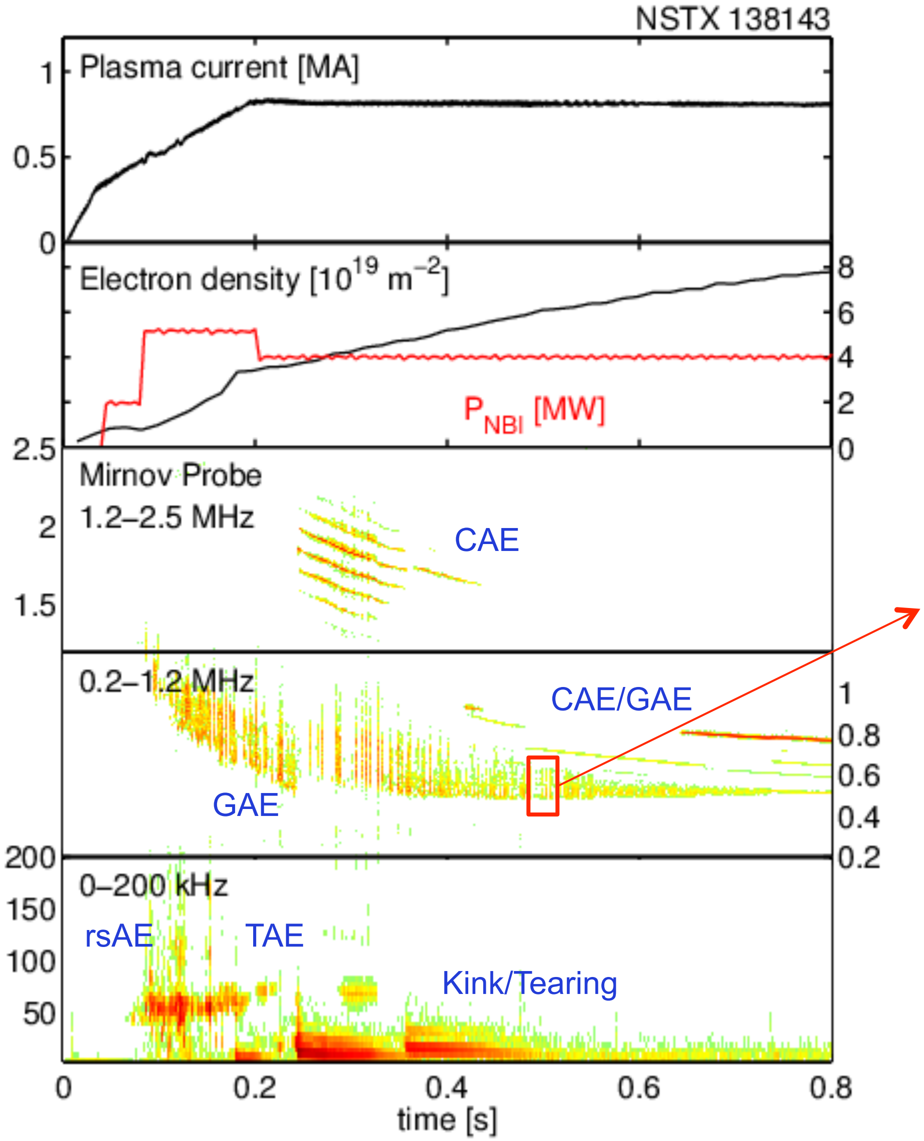


Crocker, Nucl. Fusion 53 *(2013) 043017*

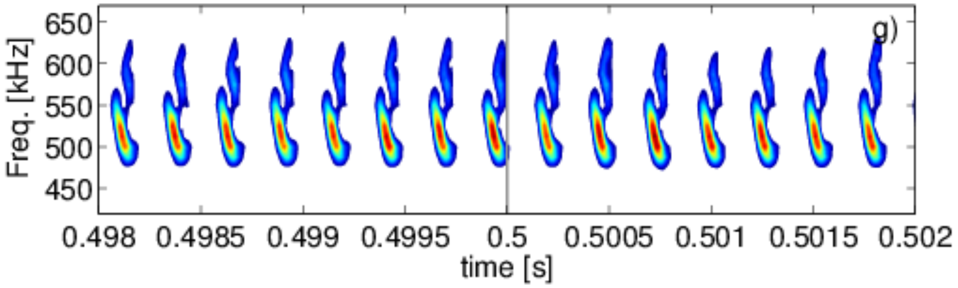
- Polarization: GAE is a shear wave, CAE is compressional
- Driven by velocity-space gradients at Doppler-shifted cyclotron resonances
- Time evolution of frequency assists identification
- GAE usually have larger toroidal mode numbers
- GAE has broad eigenfunction
- Implicated in enhanced electron transport

Stutman, PRL 102 (2009) 115002

Bursting high frequency MHD in ELM free H-mode

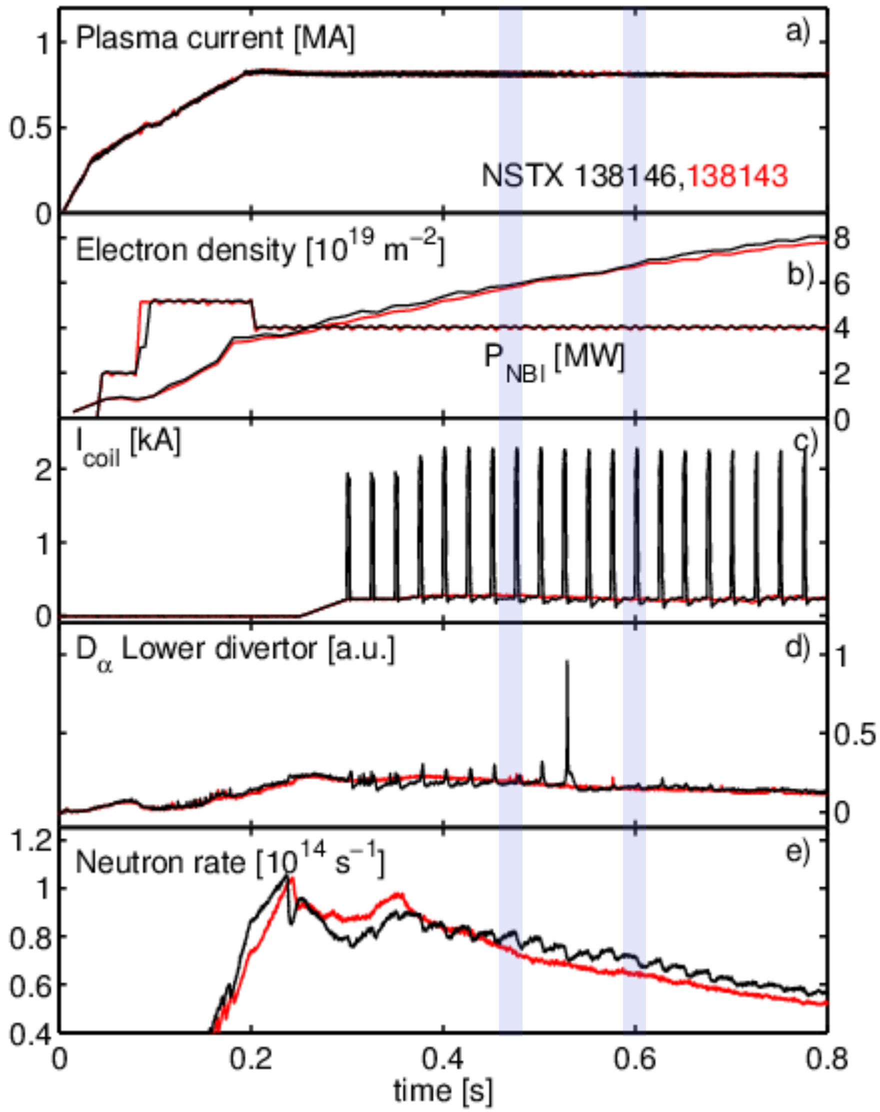


- H-mode, B_{tor}=0.35T, I_p=900k
  - P_{NBI}=4-6 MW,
- Multiple types of MHD activity:
  - Alfvén Eigenmodes (bursting)
  - Kink, Tearing



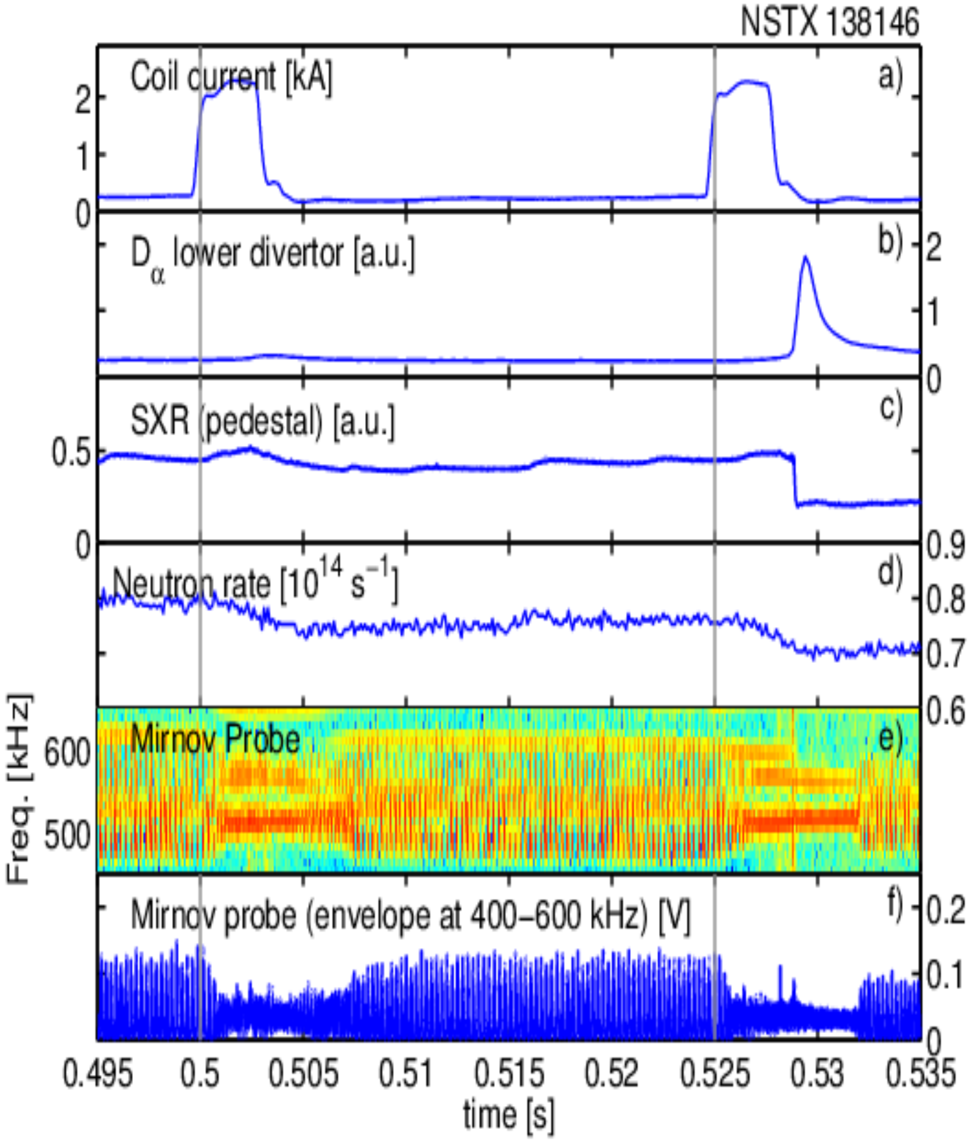
- Persistent bursting/chirping modes
  - Repetition rate 4kHz
  - Toroidal periodicity n=7-9
  - Frequency chirp 100 kHz
- Thought to be GAEs

3D fields application modifies neutron rate

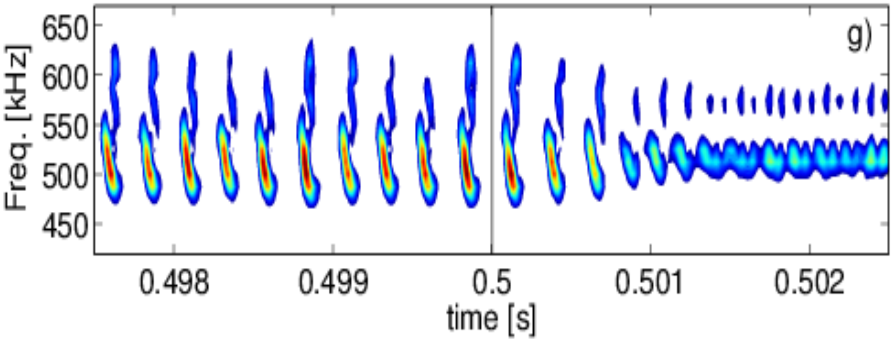


- RWM stabilization coils used to modify edge transport
- Pulsed, n=3, static fields
  - Pulse duration 3 ms
  - Pulse frequency (40Hz)
- Amplitude lower than threshold for ELM trig
- Sawtooth-like modulation of neutron rate is observed
  - Relative drop of 7%
  - Long scale decrease due to carbon accumulation

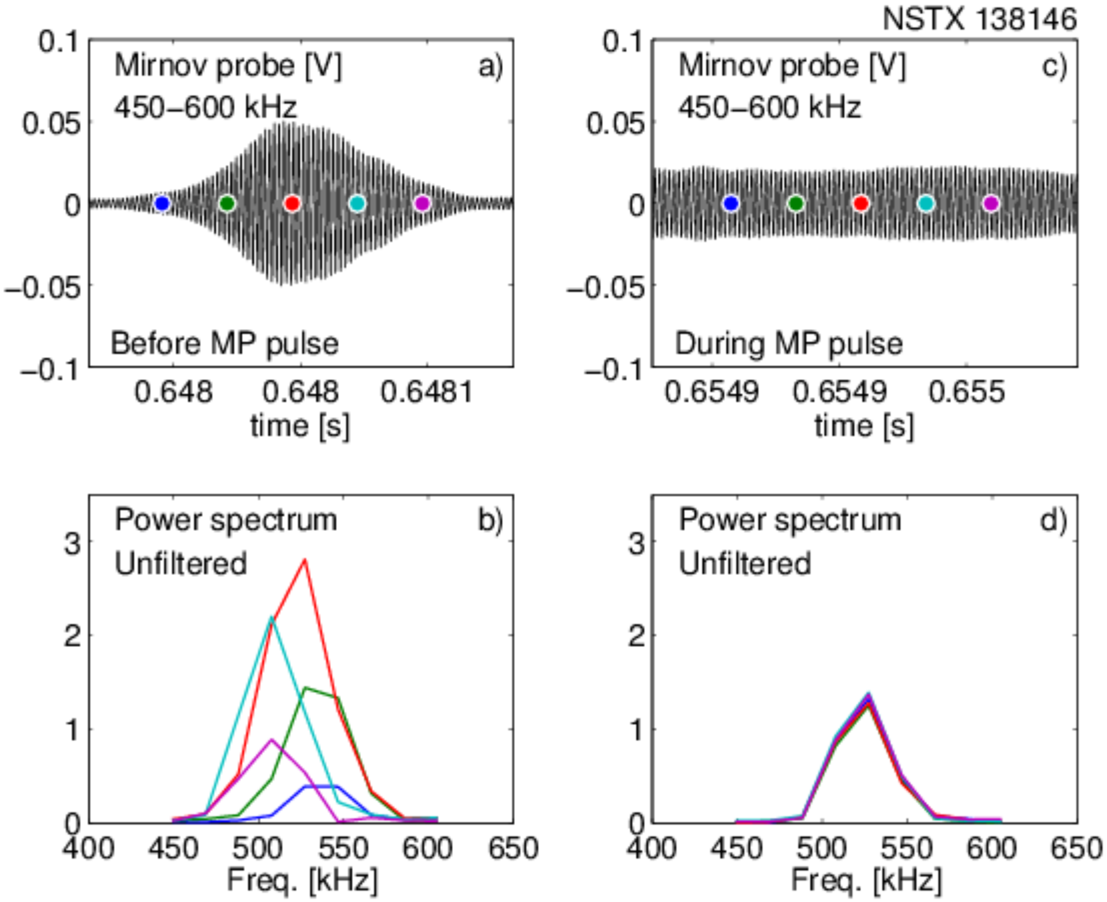
Magnetic perturbation mitigates bursting GAE



- When n=3 pulse is applied:
  - Burst freq. increased (4→12 kHz)
  - Burst amplitude reduced (x 1/2)
  - Freq. sweep reduced (100 → 40 kHz)
- Fast response (~0.1ms)
  - Precedes neutron drop
  - Effect extends beyond pulse end
- Effect decoupled from ELMs
  - ELM crashes come later
  - Observed in ELM-free phases



Transition from bursting to continuous



- At 0.65s n_{e0} larger by 30%
  - Lower fast ion content
  - GAE activity is less violent
- Before the MP pulse
  - Single mode at ~540 kHz
  - Periodic burst (6kHz)
  - τ_{growth}=65 ~ τ_{decay} =80 ms
  - Chirp down by ~30kHz
- During the MP pulse
  - Continuous at 523 kHz
  - Constant amplitude
  - n=8, directed counter beam injection

Summary of observations

- A series of ~20 discharges collected during this experimental program
  - ~10 MP pulses per discharge
- Response of hf-AE to MP fields is consistently observed
  - Effective on >50% of pulses
- MP pulses with coil current <1 kA have little or no effect
- Concurrent strong low frequency MHD mask or weakens the mitigation

- Generally, burst frequency increases while mode amplitude and chirp frequency range are reduced
  - Mode suppression is not observed
- Attenuation and recovery of bursting occur on different fast-ion timescales
  - Bursting is reduced in ~0.1 ms (orbital timescale)
  - Slower recovery after MP end 1-3 ms (collisional timescale)

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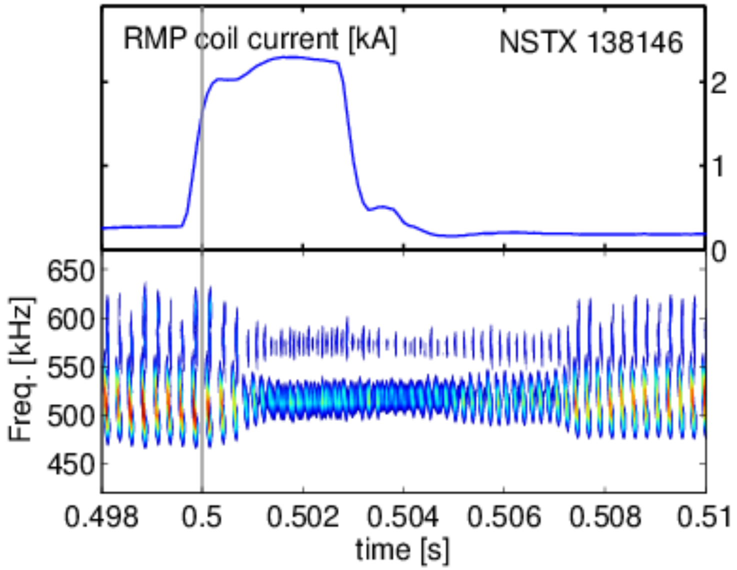


Fast ion transport likely to play key role

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

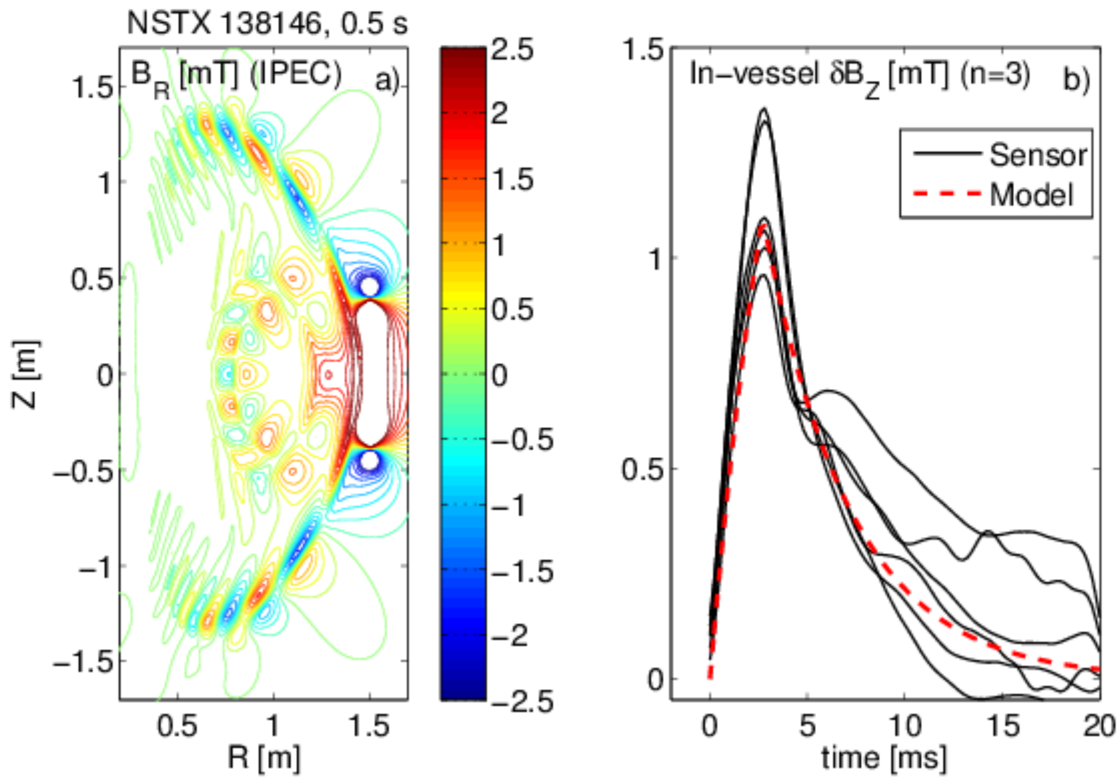
- In order to test this hypothesis we need to:
  1. Determine the structure of MP in the plasma
  2. Compute the perturbed fast-ion distribution function
  3. Evaluate how MP affect resonant particles

MP structure modeled including ideal plasma response

Magnetic sensors measure the MP amplitude at few in-vessel locations

→

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

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

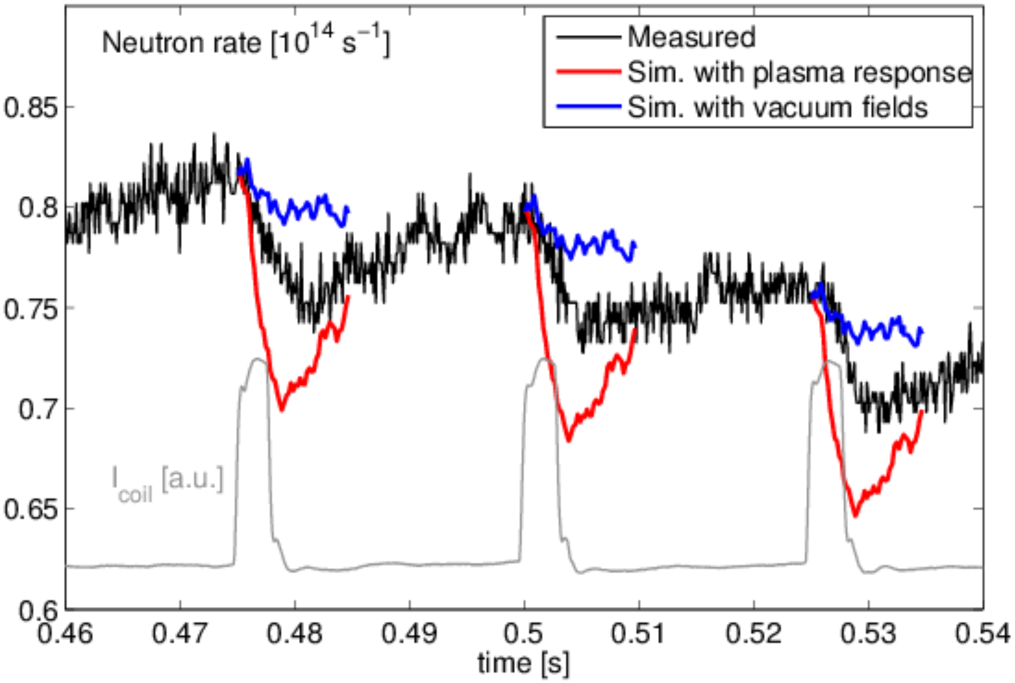
- A(t) adjusted to match the poloidal field measured by a magnetic sensor

**Park, PoP 14 (2007) 052110*

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

SPIRAL* computes the orbit of test particle in equilibrium and perturbed fields

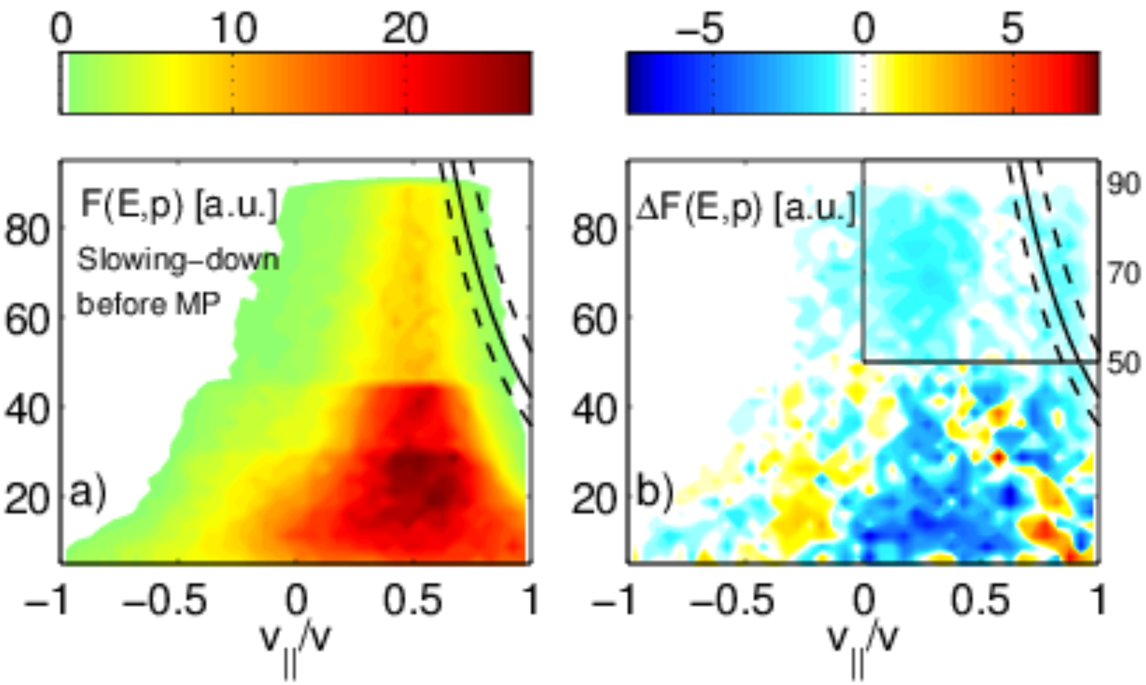
- Slowing down d.f. from a 35 ms run with equilibrium fields only
  - Particles injected at constant rate
  - Birth location and velocity from attenuation code (NUBEAM)
- Simulation continued for 10 ms, including MP
  - Fast-ion d.f. tracked every 0.02ms
  - Vacuum fields
  - Vacuum + plasma response
- Predicted evolution of neutron production rate compares reasonably with experiment



**Kramer, Pl. Phys. Cont. Fusion 55 (2013) 025013*

The MP reduces the number of resonant fast ions

- F(E,p), p = $v_{||}/v$
  - integrated over r/a<0.5
  - 2<t<4 ms after MP start
- Depletion found for:
  - E<50 keV, 0<p<0.6
  - E>50 keV, p<0.4 & p>0.7



- GAE is attributed to resonant fast ions
- Possible Doppler shifted cyclotron resonances (l=1) on the flank of the d.f.
- MP alters the d.f. at resonance locations

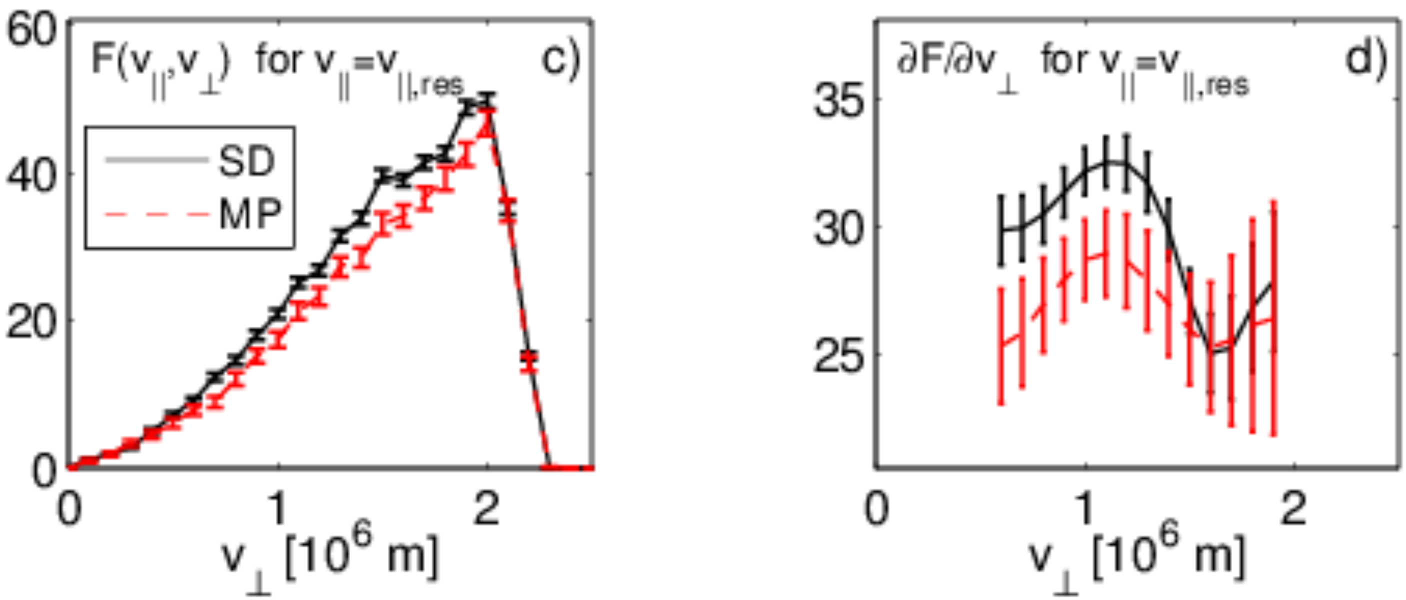
Resonance condition

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

Dispersion relation

$$\omega = k_{\|}\, v_A$$

Simulations suggest reduction of mode drive

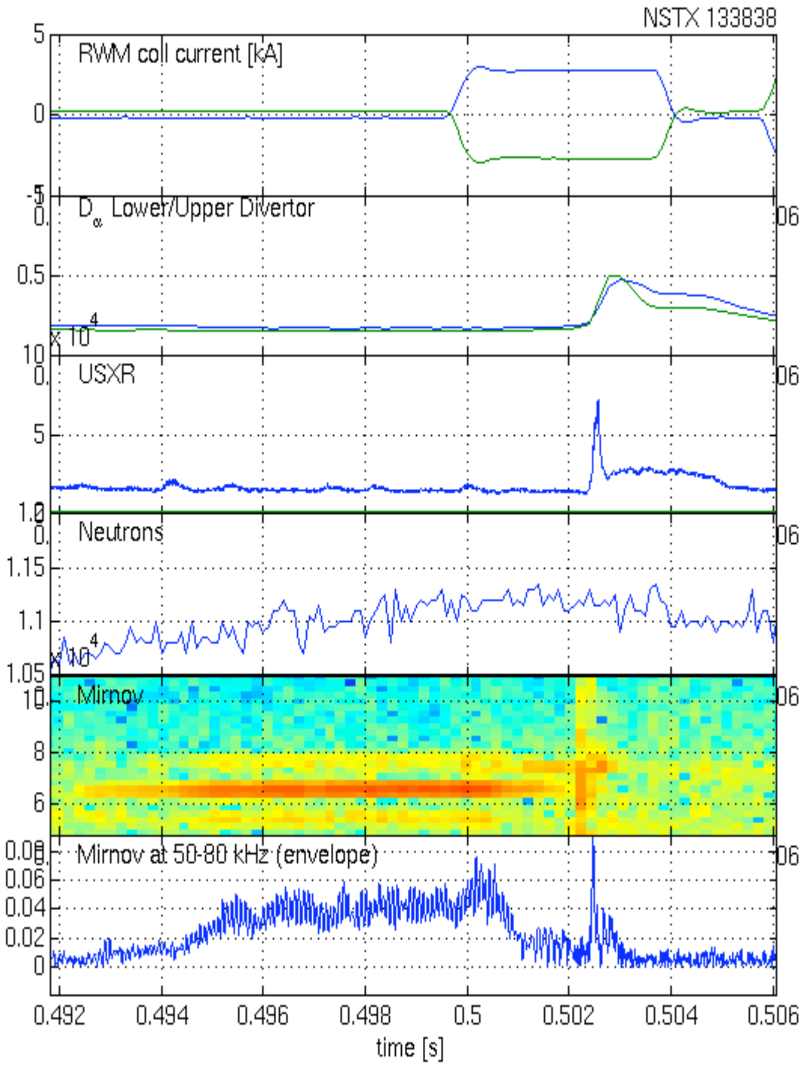


- Instability depends on gradient of d.f. in velocity space
- Perpendicular gradient along the resonance is main driving term
- Reduction of $\partial F/\partial v_\perp$ by 10-20% suggest smaller drive with MP
- Detailed computation requires accurate description of the mode
  - No measurement available of mode internal structure

Conclusions

- Externally imposed 3D fields can alter the nonlinear evolution of a tokamak fast-particle driven instability
- Full orbit simulation reproducing the neutron rate production indicate that MP can reduce the fast ion drive by depletion of the resonant fast ions
- Other explanations, invoking and increased mode damping or changes of the deposition profile are considered unlikely
  - Changes of the kinetic profiles under MP are of the order of those observed during normal discharge evolution, having little or no effect on persistent AE activity
- The observations suggest the possibility of controlling fast-ion instabilities by tailoring the fast-ion distribution function with appropriate magnetic perturbations

Preliminary data: possible mitigation of lower frequency modes

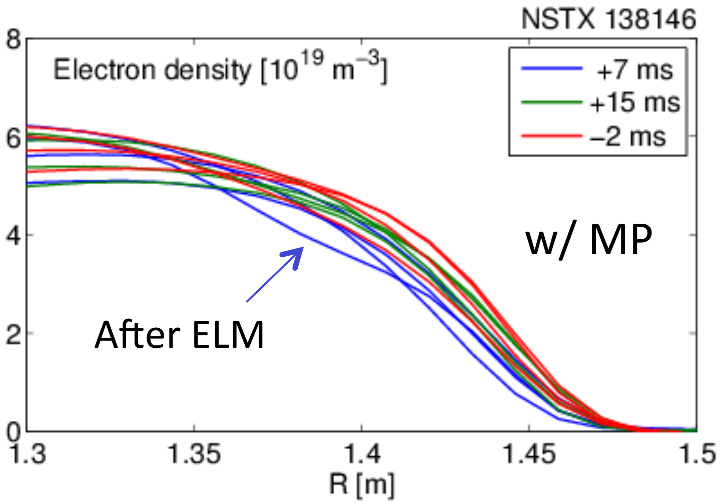


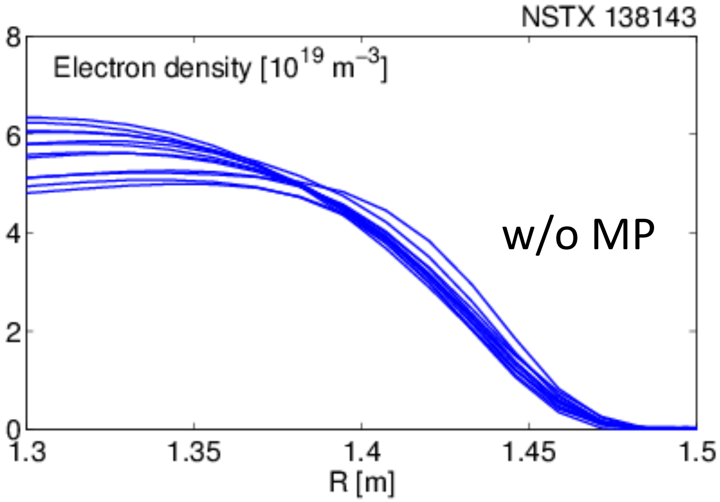
- 60 kHz continuous mode
- Suppressed after MP
- ELM is also destabilized
- In some cases mode attenuated before ELM crash

Several mechanism can play a role

- Modification of drive/damp from resonant fast ions
  - loss/redistribution on perturbed orbits
  - different ion deposition
- Modification of transport of phase space structures associated with bursting/chirping instabilities
  (e.g. hole-clump models)
- Increase of damping (continuum/Landau) due to modification of profiles

Relatively small modification of density profiles by MP

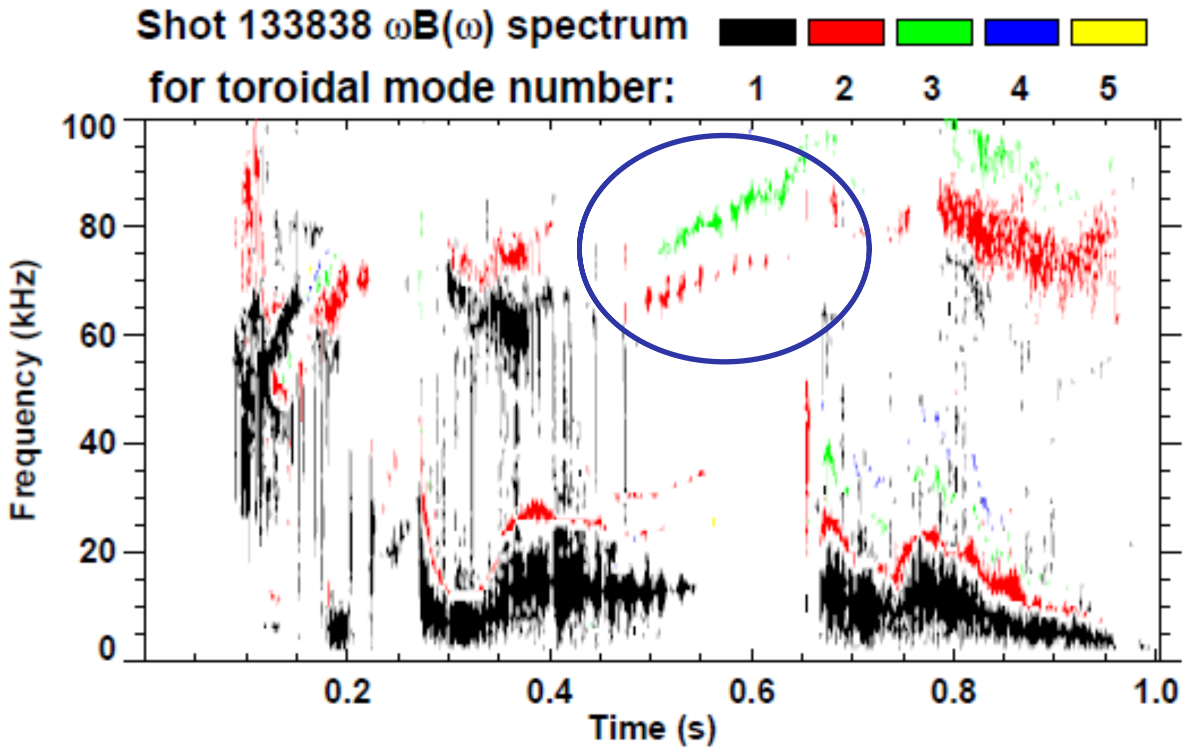




- Pedestal location from Thomson scattering
  - Low repetition rate 16.7 ms (MP's 25 ms)
  - Measurement in front of one coil
- Pedestal location (n_e=2x10^{19}) varies in time
  - Maximal excursion observed ~2 cm
- On average, 5 ms after MP, pedestal is 1 cm inboard compared to before MP

- w/o MP, pedestal location fluctuates by 1 cm
  - No effect on neutrons or AE evolution
- Modification of density profiles alone is unlikely to explain the observations

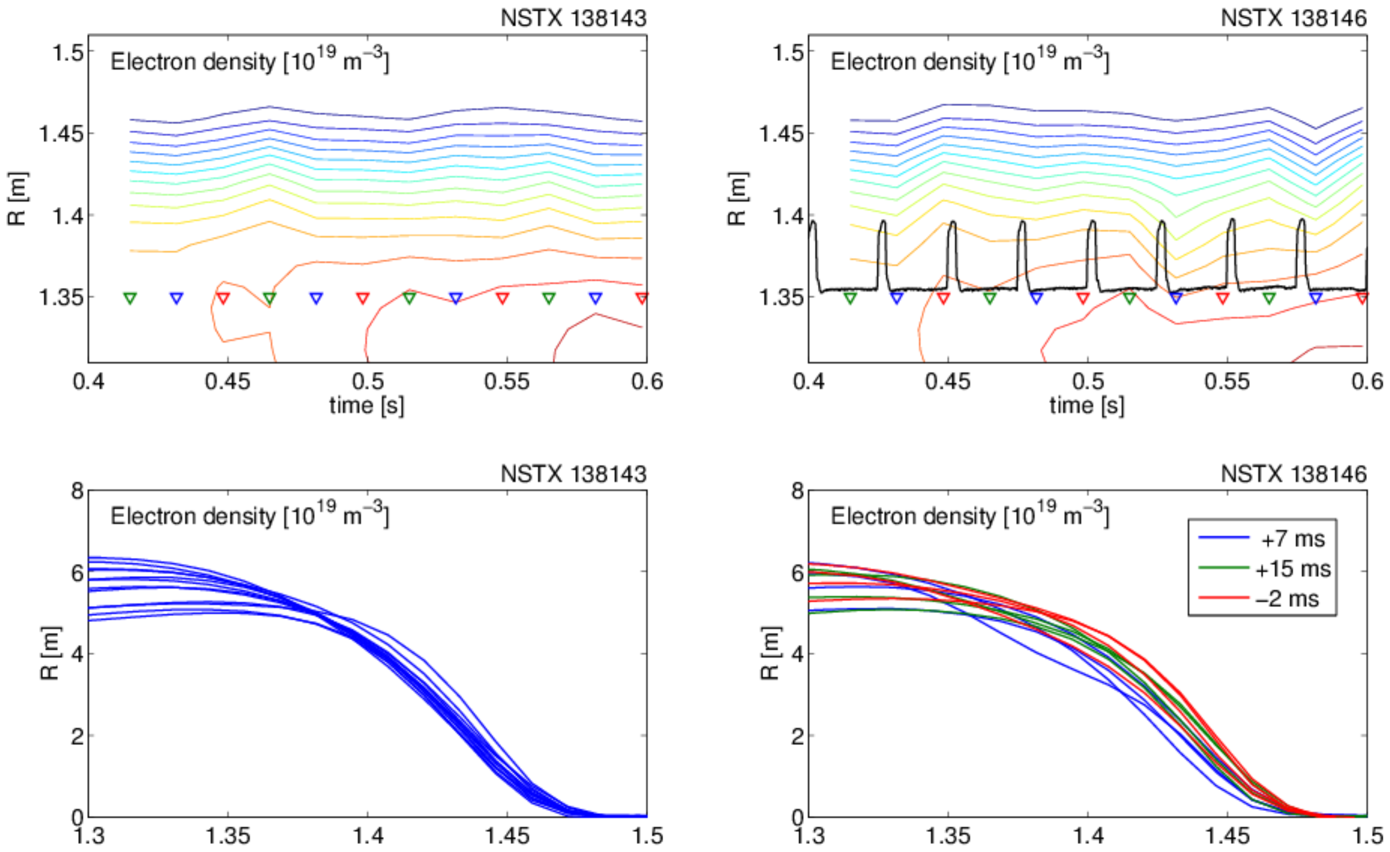
Preliminary data in for lower frequency modes



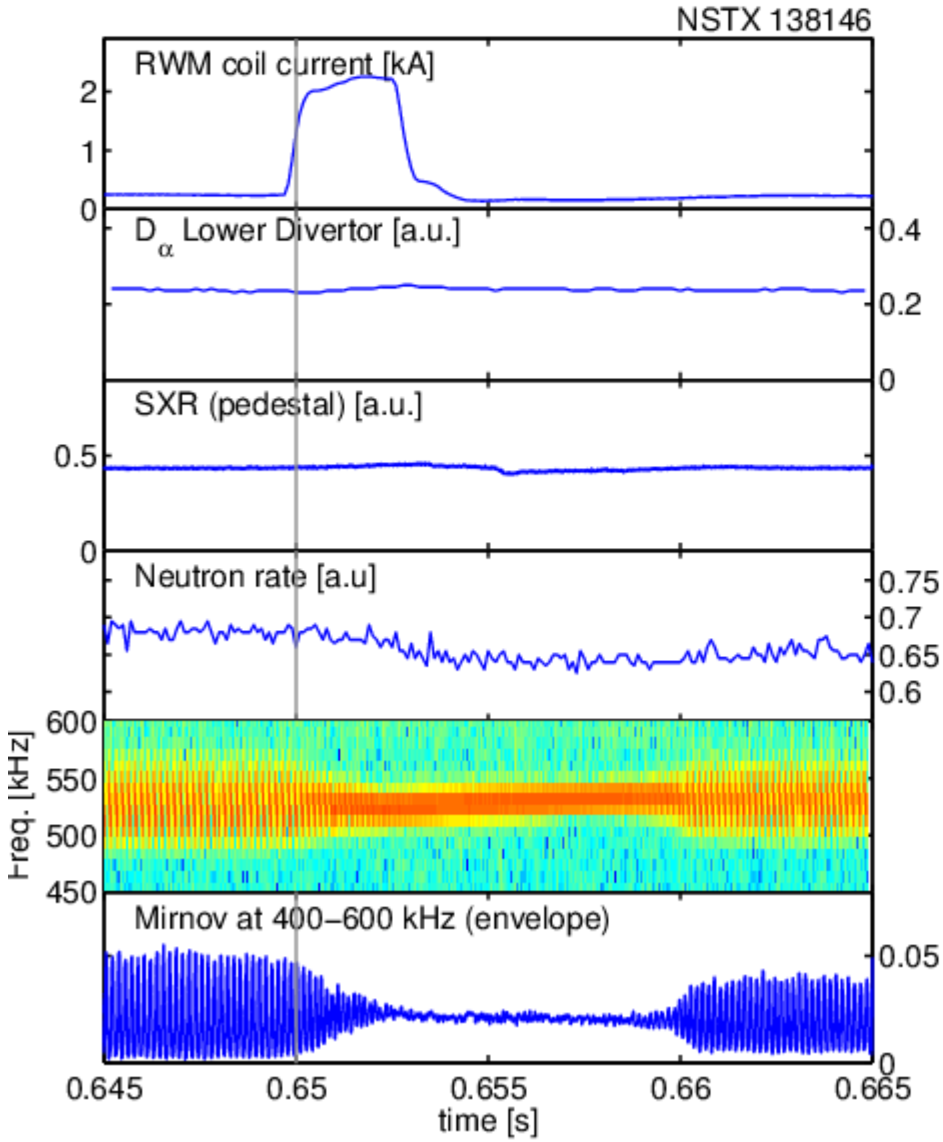
- Modulation of n=2-3 modes in the TAE range of frequencies
- Modes appearing in small number of ELM pacing experiments

Alfvén continuum

Modification of density profiles



Weak bursting modes transforms to continuous



- At Higher density No Low Frequency MHD
- Baseline Bursting activity
  - 1 chirping mode
  - Weaker amplitude
  - Higher burst frequency (~6kHz)
- Clear effect of n=3 pulse