# Mitigation of Alfvénic activity by 3D magnetic perturbations on NSTX

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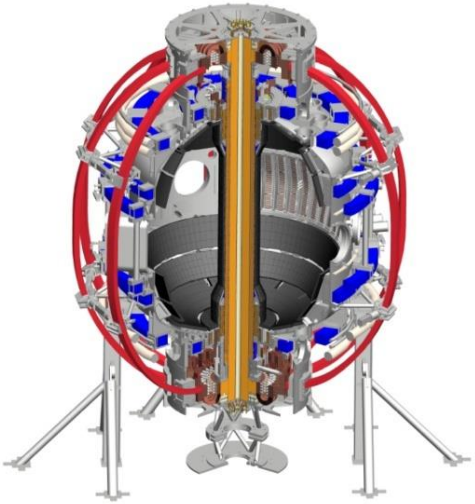

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# Mitigation of fast ion instabilities

- Good confinement of fast ions is a key aspect of a fusion device
  - Optimize the plasma heating and current drive
  - Avoid damage from localized particle losses to wall

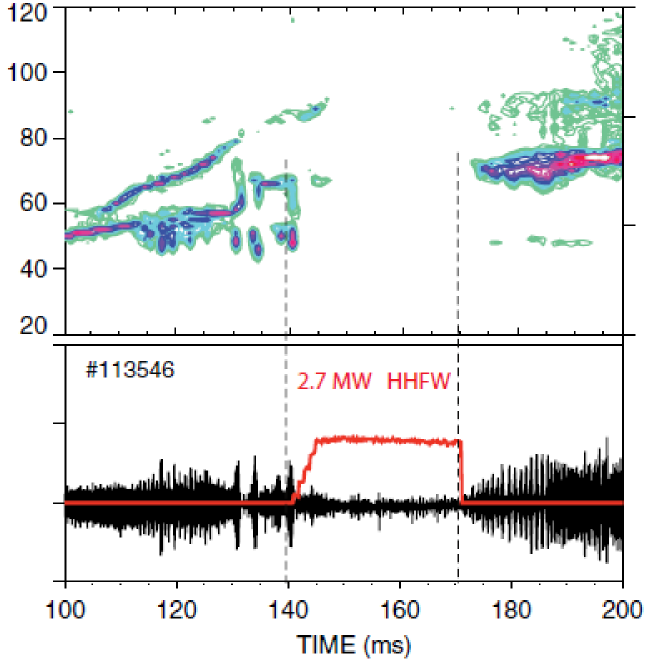
- Fast ions driven instabilities can compromise their confinement
  - multiple frequency bands (from low to ion cyclotron frequencies)
  - bursting, frequency-chirping are common
  - coupled avalanches of multiple bursting modes are observed*
  - bursts can cause substantial transport and losses of fast ions
- Can we actively control or mitigate the impact of fast ion modes?
  - Reduce drive of instability (fast ion distribution function)
  - Enhance damping mechanism (plasma parameters, geometry)
  - Destroy coherent structures in phase space (chirping modes)

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

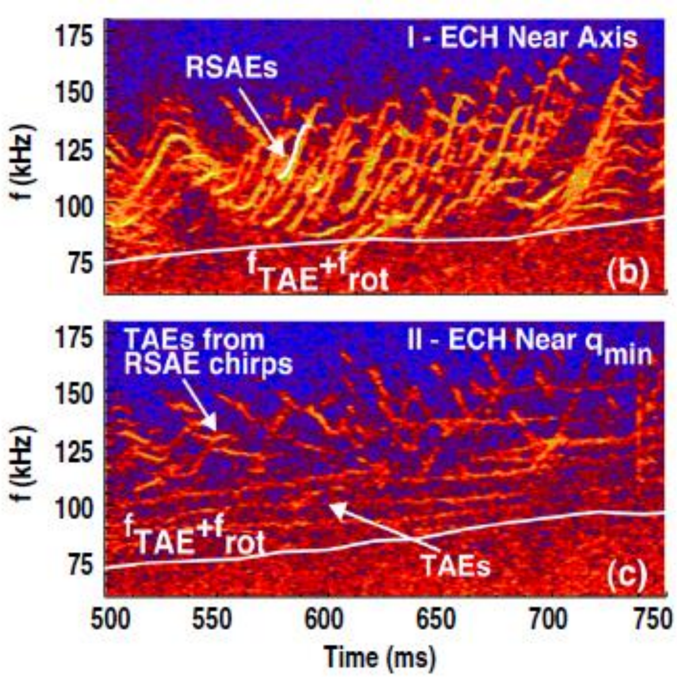
# Examples of mitigation of fast-ion driven instabilities

- On NSTX, HHFW heating observed to stabilize continuous TAE modes

- On DIII-D, RSAE activity is suppressed with EC deposition near the shear reversal radius



*Heidbrink, PPCF 48 (2006) 1347*



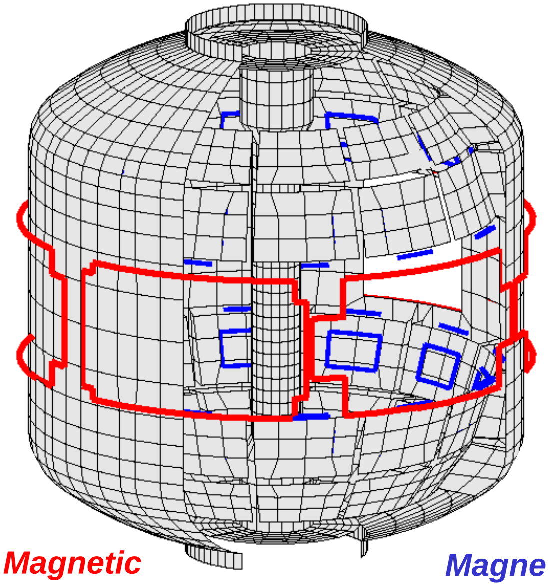
*VanZeeland, Nucl.Fusion 49 (2009) 065003*

# Plan of the work

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

1. High frequency Global Alfvén Eigenmodes (GAE)
    - Observation of altered bursting dynamic
    - Simulation of MP induced fast ion transport
    - Effect on ***fast ion drive***
2. Low frequency Toroidal Alfvén Eigenmodes (TAE)
    - Observation of amplitude reduction
    - Analysis of continuum in 3D perturbed equilibrium
    - Effect on ***mode damping***

# NSTX suited to study effect of 3D fields on Alfvén modes



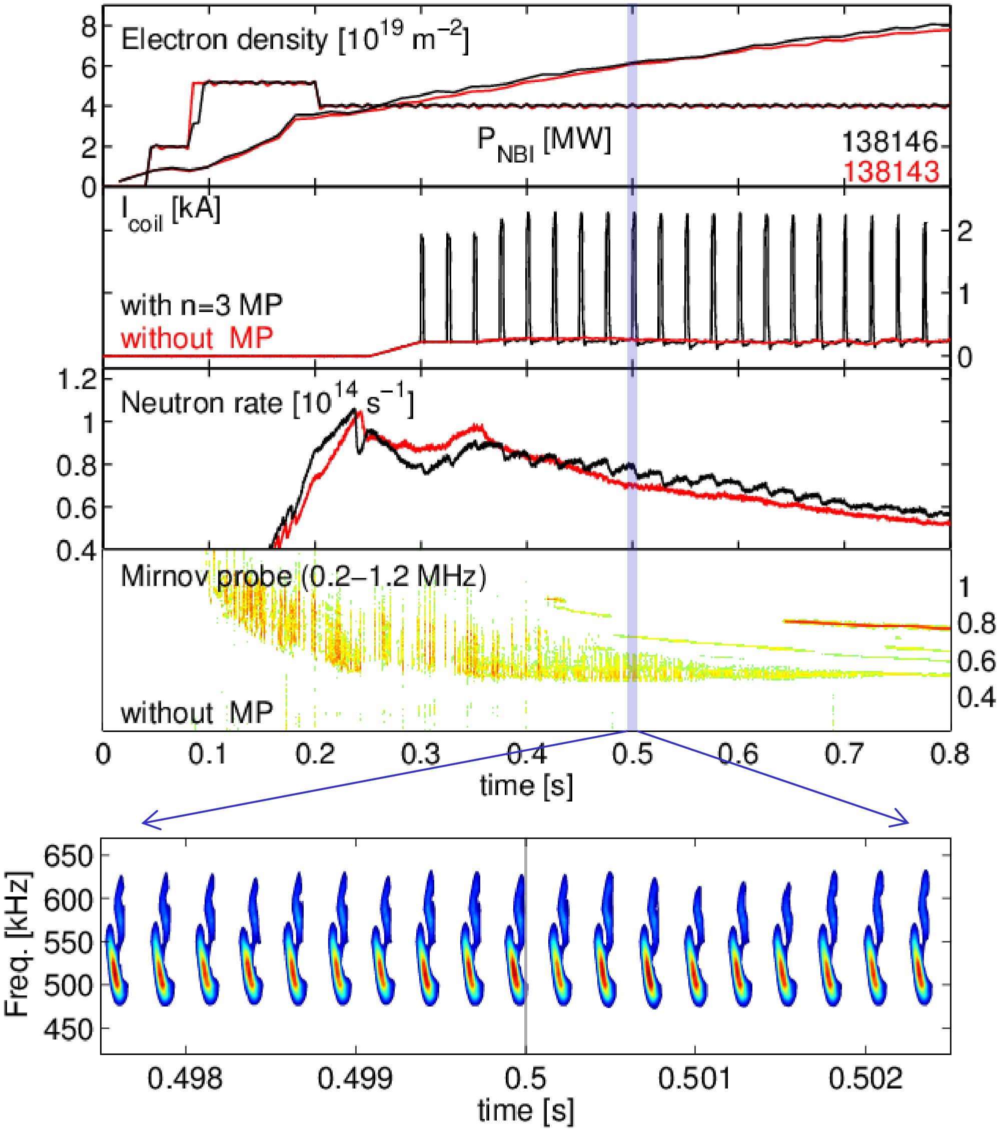
- Low $B_{tor,}$ high density → "low" Alfvén speed
  - large population of super alfvénic beam ions
  - favors the drive of Alfvén Eigenmodes (AE)
- 6 Magnetic perturbation (MP) coils
  - n=1, n=3 perturbation
  - Effective in ELM triggering, plasma braking, RWM feedback, error field compensation

| NSTX parameters | |
|---|---|
| Major radius | 0.85 m |
| Aspect ratio | ~1.3 |
| 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 | 6 (external) |
| Coil current | 6 kA · turn |
| δB in vessel | <50 mT |
| Rot. Freq. | <50 Hz |

# Application of 3D fields leads reduction of neutron rate

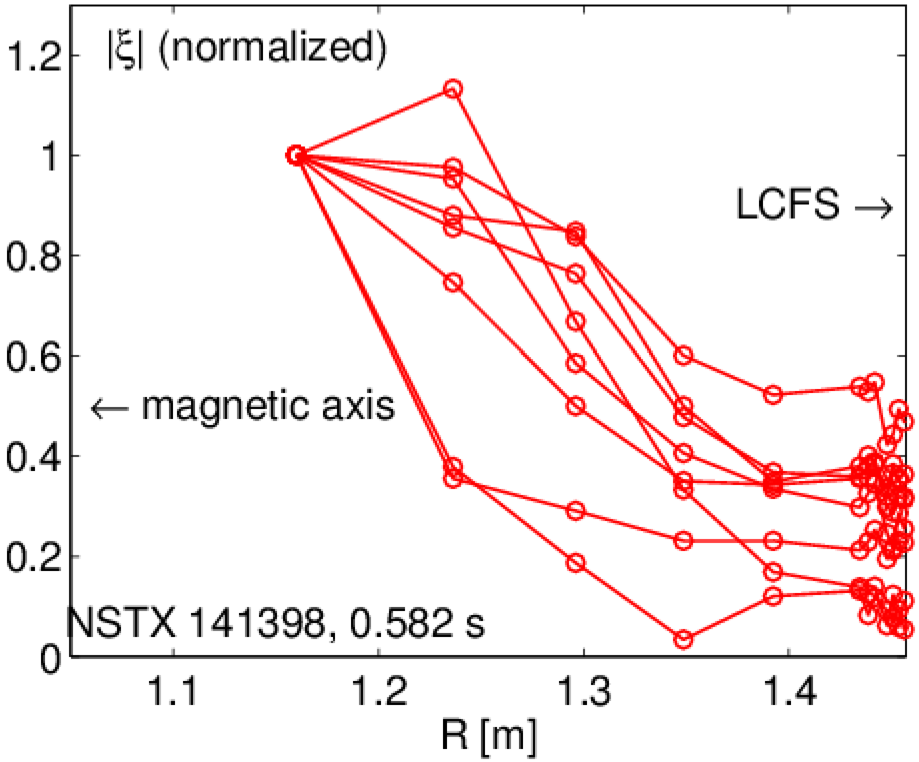


- ELM free H-mode
- Pulsed, n=3, static fields
  - Pulse duration 3 ms
  - Pulse frequency (40Hz)
  - $I_{coil}$< threshold for ELM trigger
- Sawtooth-like modulation of neutron rate observed
  - Relative drop of 7%
- Persistent bursting/chirping MHD
  - Repetition rate 4kHz
  - Frequency chirp 100 kHz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

# GAEs have radially broad eigenfunction

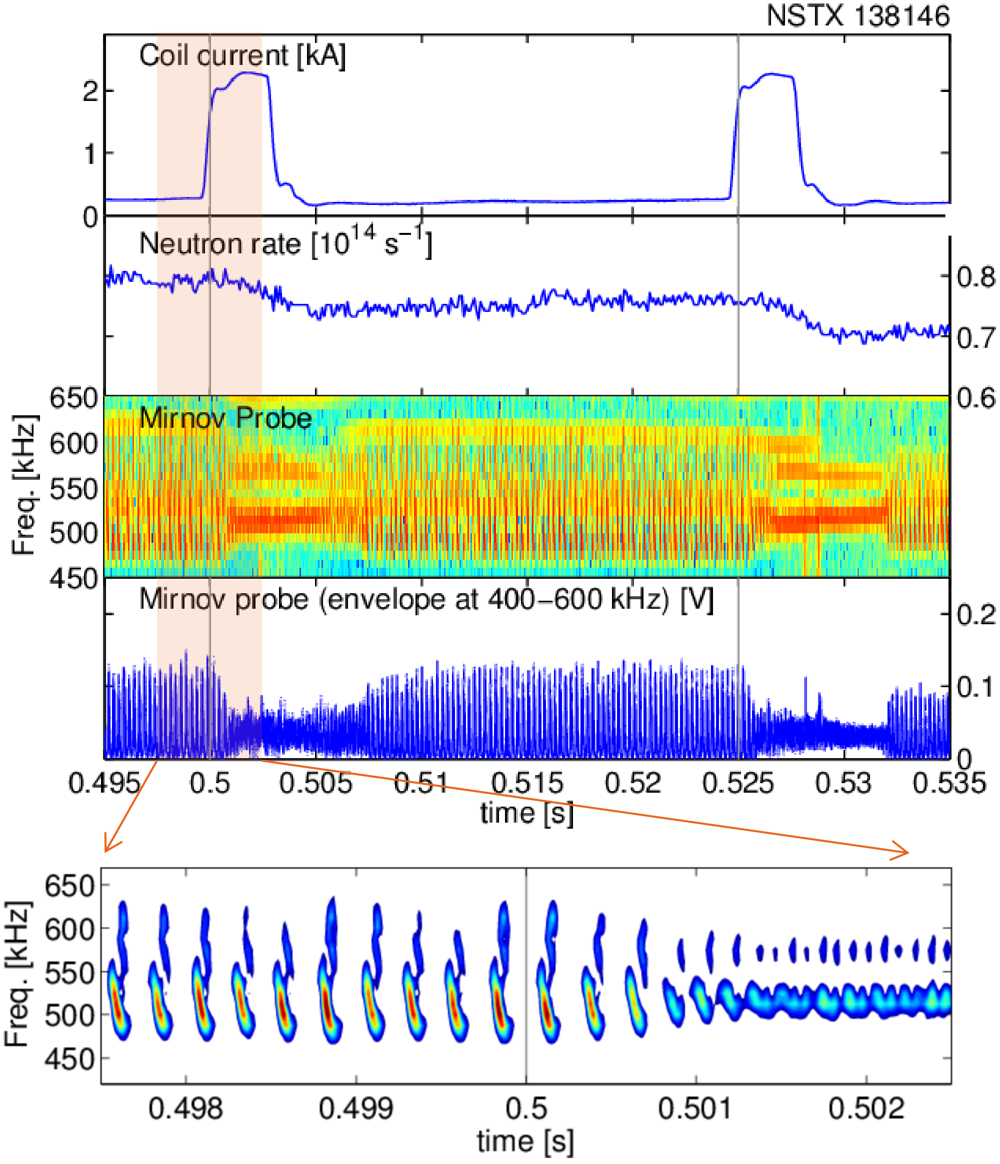
- GAE often observed in
  - 0.4-1.2 kHz (0.2-0.6 $f_{ci}$)
- Driven by velocity-space gradients at Doppler-shifted cyclotron resonances
- Identification based on time evolution of frequency as the safety factor evolves

- Mode structure measured by reflectometry in H-modes
  - GAE tend to peak toward the axis
  - Finite amplitude at boundary



*Crocker et al. Nucl. Fusion 53 (2013) 043017*

# Magnetic perturbation (MP) mitigates bursting GAE



- When n=3 pulse is applied:
  - Burst amplitude reduced (x 1/2)
  - Burst frequency increased (4→12kHz)
  - Range of freq. sweep reduced (100→40kHz)

- Bursting is reduced prior than neutron rate decay
  - Timescale ≤1 ms (drift orbit)
- Slower recovery after end of MP
  - Timescale ~1-3 ms (collisional)

# Summary of observations

- A series of ~20 discharges collected during this experimental program
  - Pulse duration 2-6 ms, pulse frequency 20-40Hz
- Response of hf-AE to MP fields is consistently observed
  - Effectiveness can vary, mode suppression is not observed
- Concurrent strong low frequency MHD masks or weakens the mitigation
- MP pulses with coil current <1 kA have little or no effect

- ***Neutron drops*** and ***timescales*** suggest direct role for fast ions
- ***Hypothesis***:

1. MP causes rapid transport and/or loss of resonant fast ions, affecting the drive for instability
2. After MP is removed strong bursting resumes as the distribution function is restored

# MPs are amplified by plasma response

Magnetic sensors measure MP amplitude near the wall

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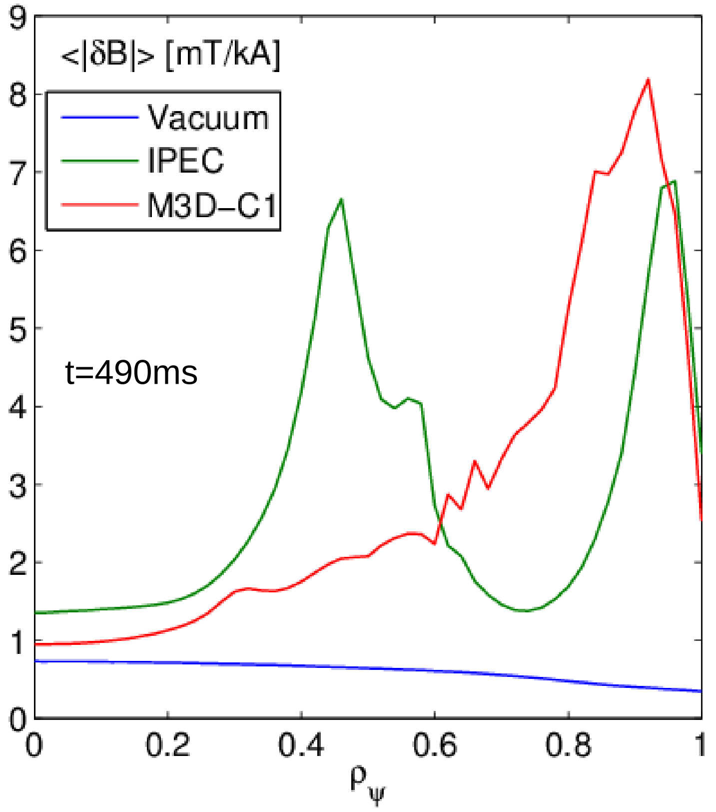
Modeling required for MP structure in the plasma volume

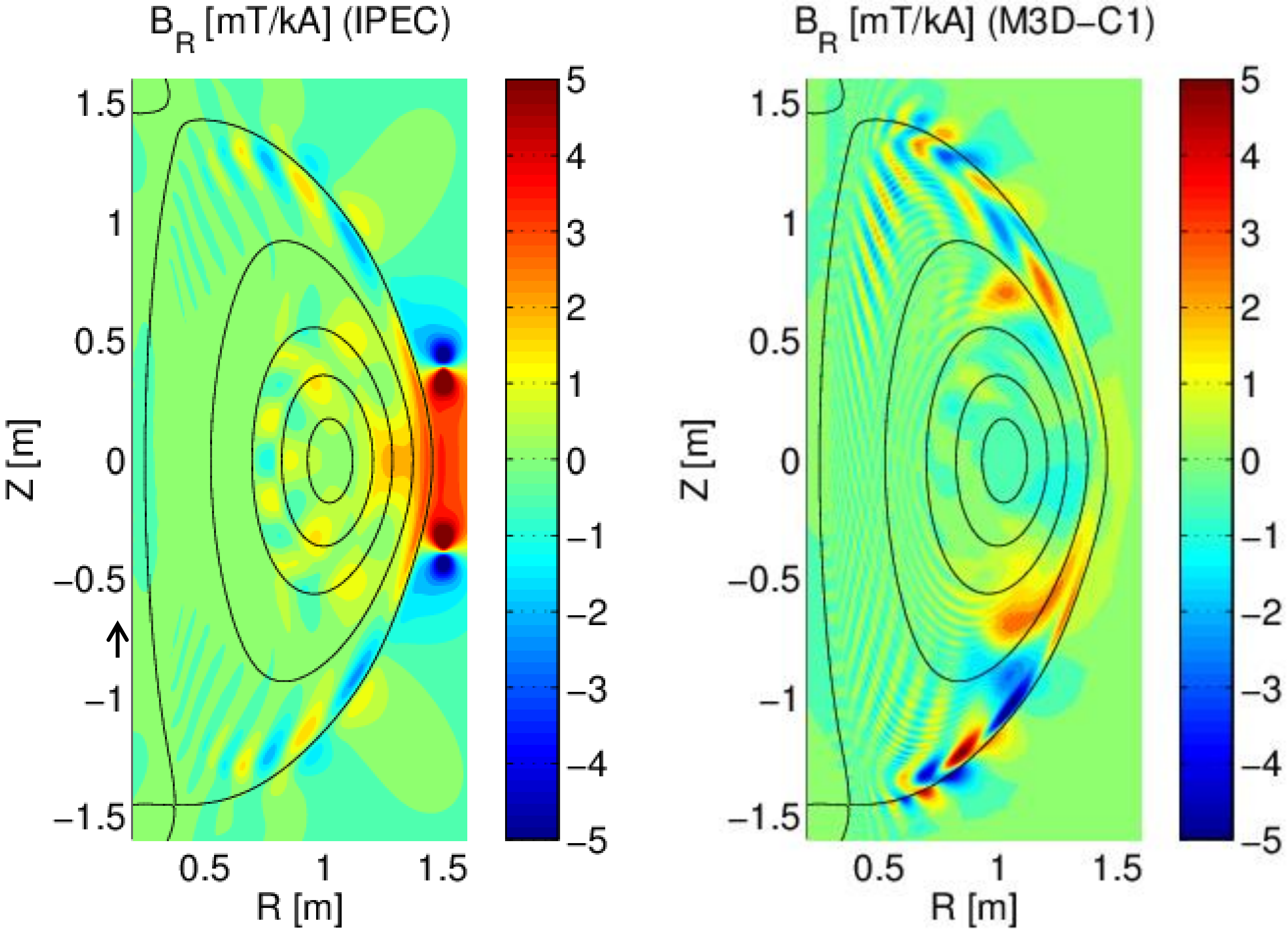


- Structure of vacuum fields from Ampere's law
- 1-fluid, linear simulations used to predict plasma response:
  - Ideal plasma response IPEC [1]
  - Resistive plasma response M3D-C1 [2]
- Substantial field amplification compared to vacuum fields is predicted in the plasma

*[1] Park et al, Phys.Plasma 14 (2007) 052110*

*[2] Ferraro et al Nucl. Fusion 53 (2013 ) 073042*

# MPs develop a complex spatial structure



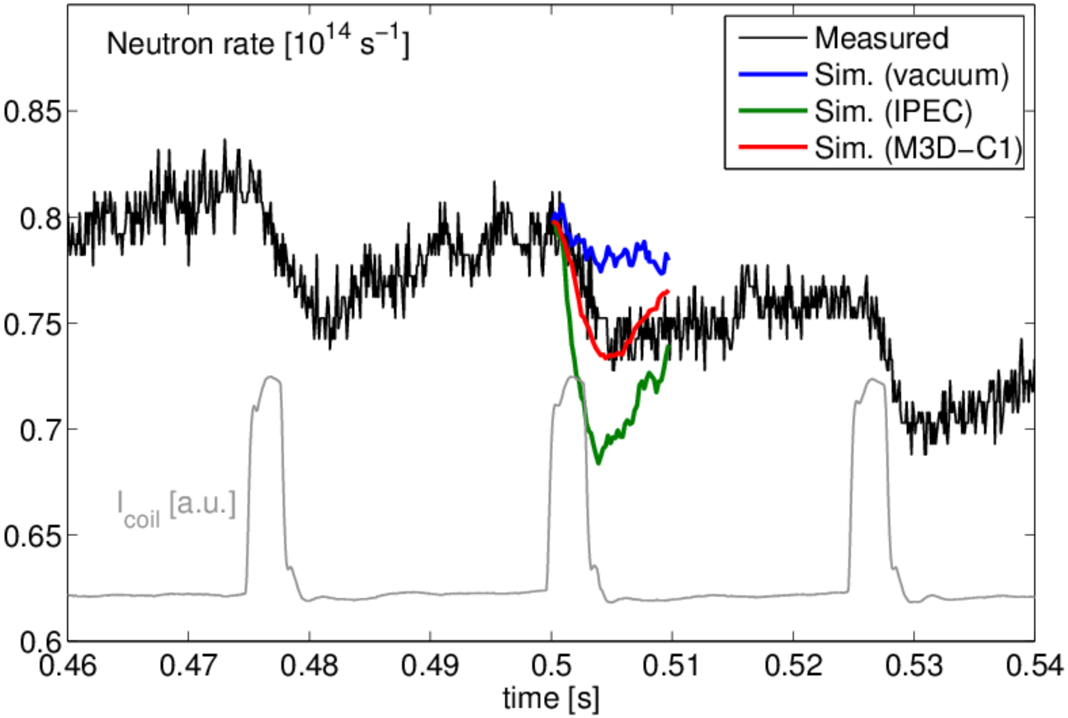
Plasma response fields structure of scale of beam ion Larmor radius

# 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***

- Slowing down d.f. from a 25 ms run with equilibrium fields
  - Constant fueling rate
  - Birth location and velocity from attenuation code
- Simulation continued for 10 ms, including different MP models
  - vacuum fields
  - ideal response (IPEC), resistive response(M3D-C[1])
- MP amplitude scaled to match measurements of in-vessel sensor

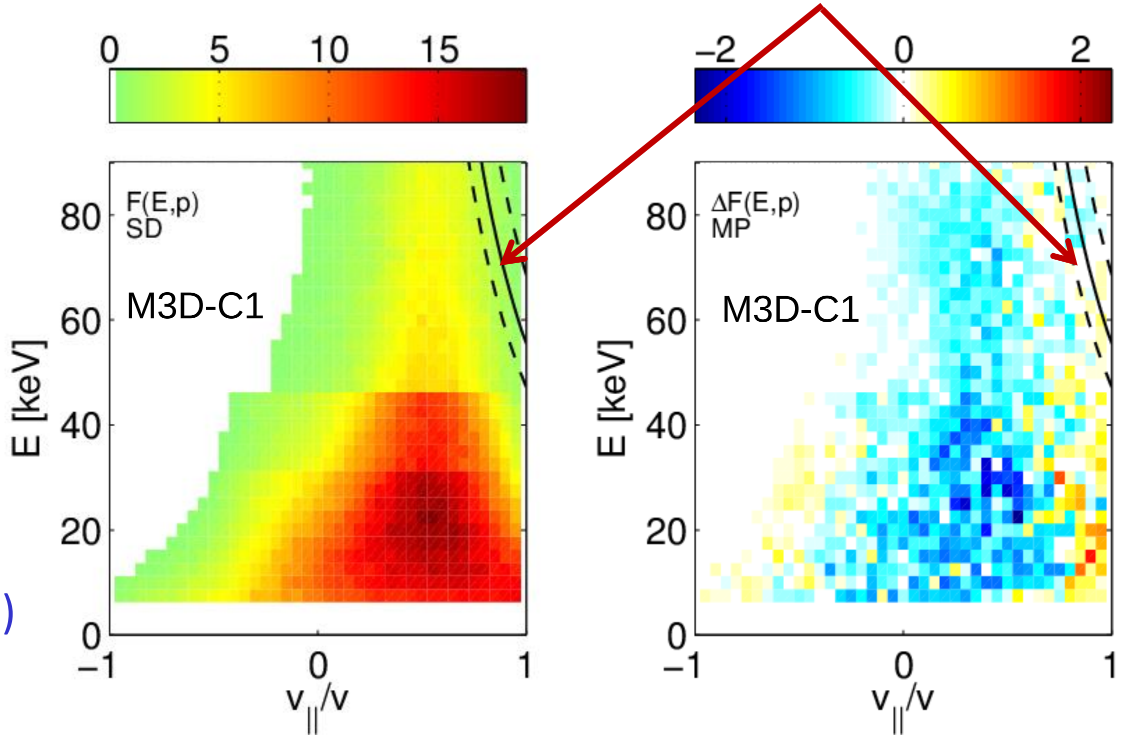
*[1] Kramer, PPCF 55 (2013) 025013*



***Evolution of neutron rate predicted with resistive plasma response in good agreement with experiment***

# MP affects the number of resonant fast ions

- Fast ion d.f. F(E,$v_{||}$/v)
  - integrated over $\rho_{pol}< 0.6$ (GAE location)
  - 2<t<4 ms after MP starts
- Depletion for:
  - $0.0 < v_{||}/v < 0.6$ (trapped)
  - $0.8 < v_{||}/v < 0.6$, E>70 keV
- Increment for:
  - $v_{||}/v > 0.6$, E>70 keV (passing)



Resonance (l=1, n=8, f=520kHz)

Dispersion relation

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

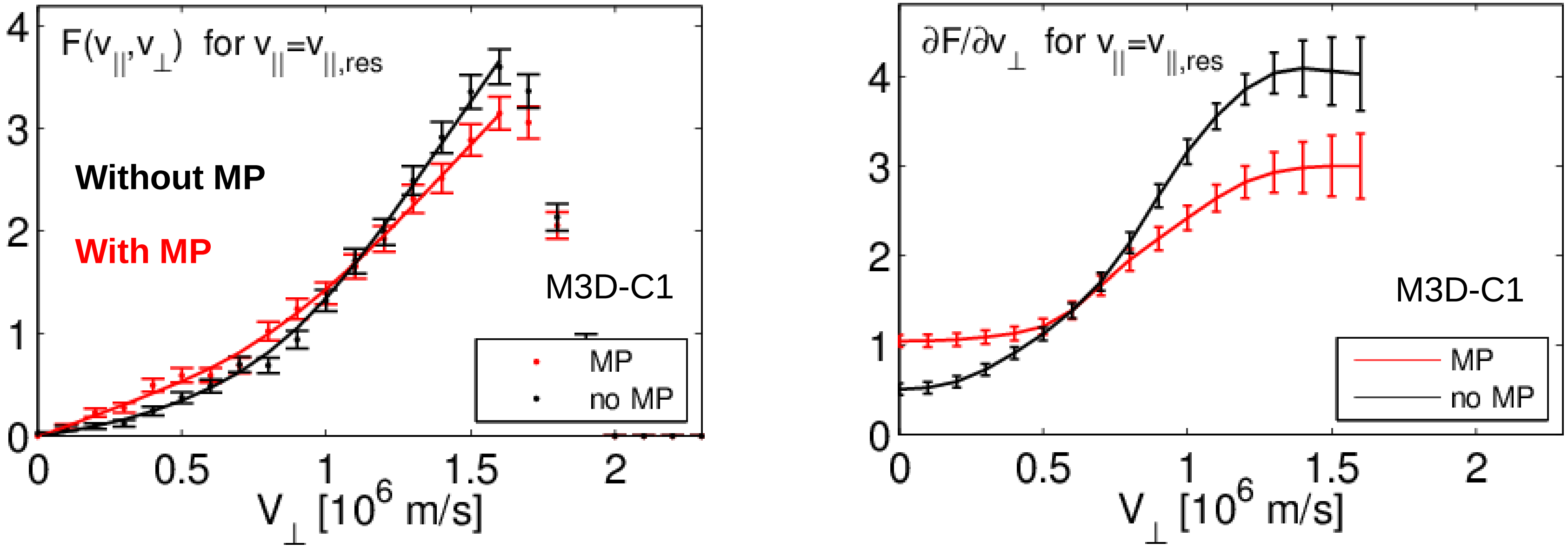
$$\downarrow$$

Resonance condition

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

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

# 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 instable modes
- Non-linear behavior requires self-consistent treatment of d.f.

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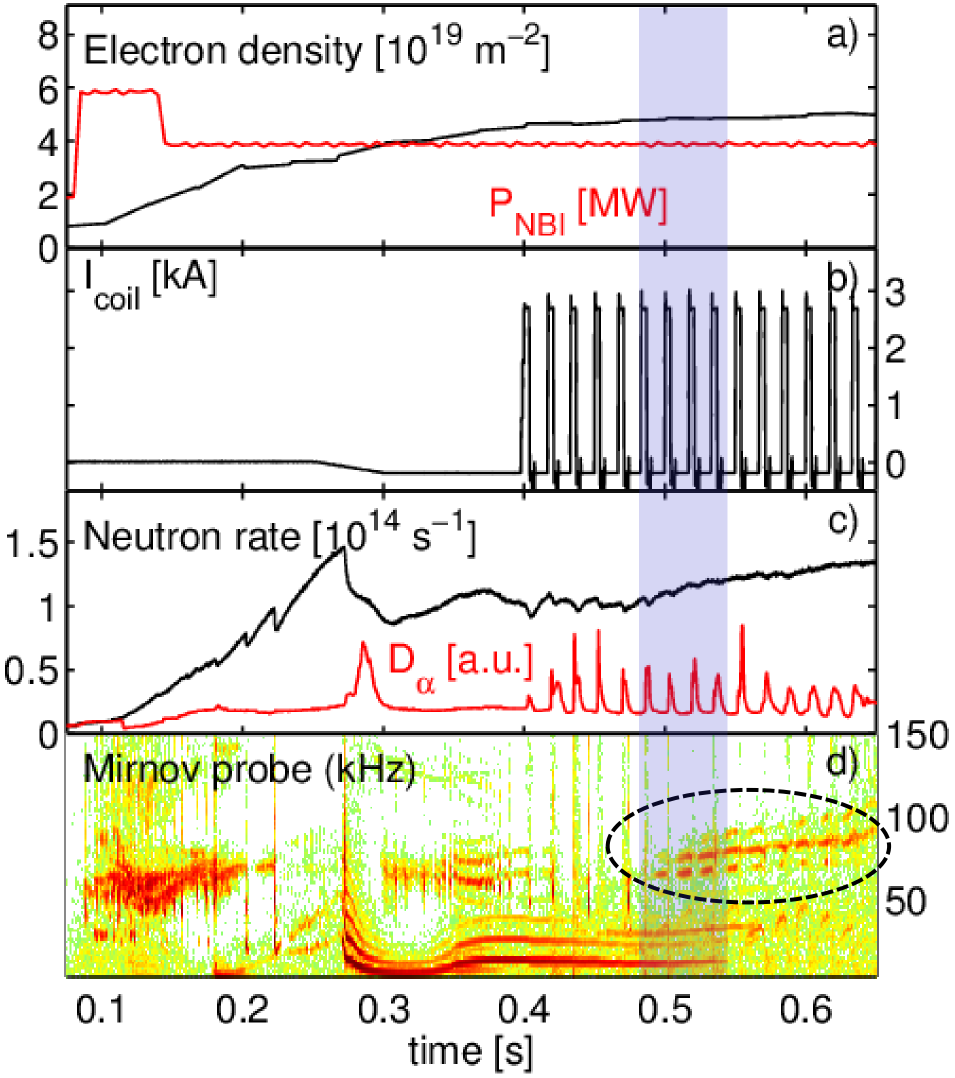
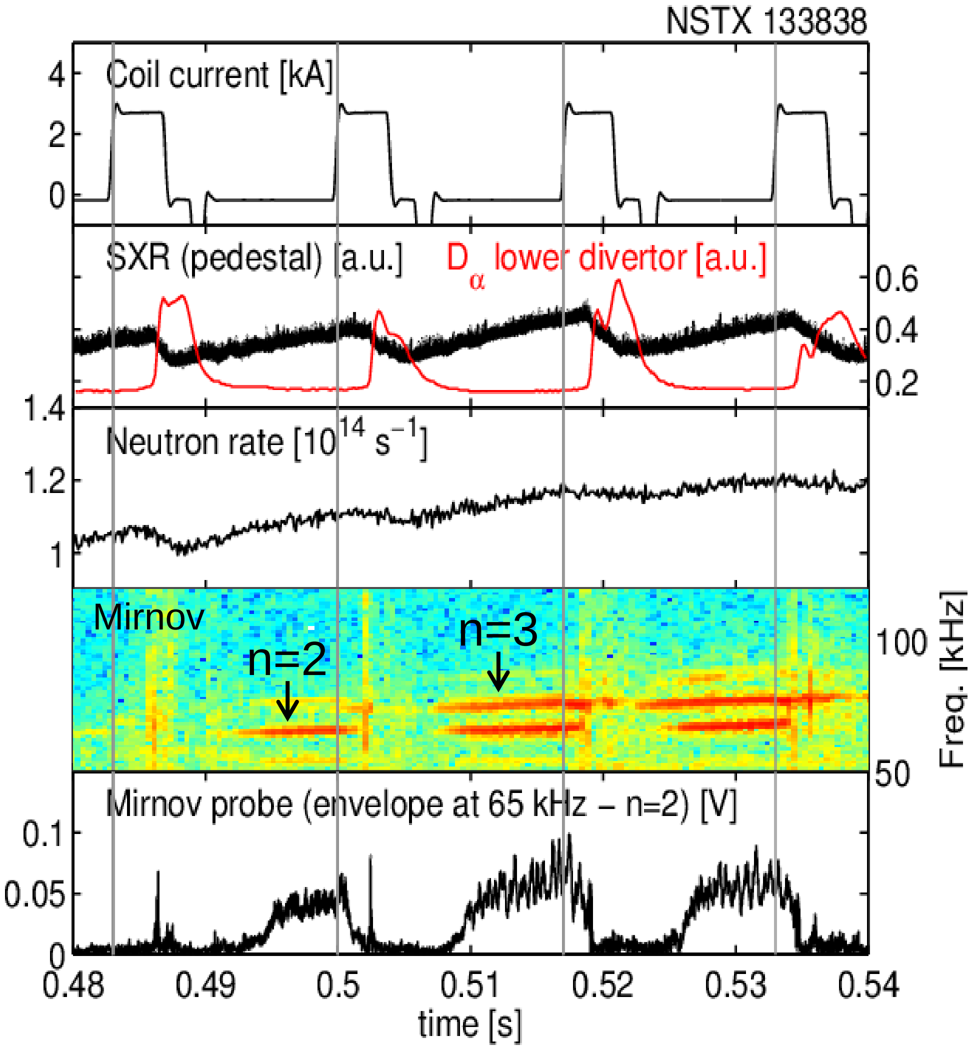
# Low frequency AEs modulated in ELM pacing experiments



- MP used to trigger ELMs
- Static fields , n=3, pulsed
  - Pulse duration 4 ms
  - Pulse frequency 60 Hz
  - $I_{coil}$ = 2.9 kA
- Weak effect on neutron rate

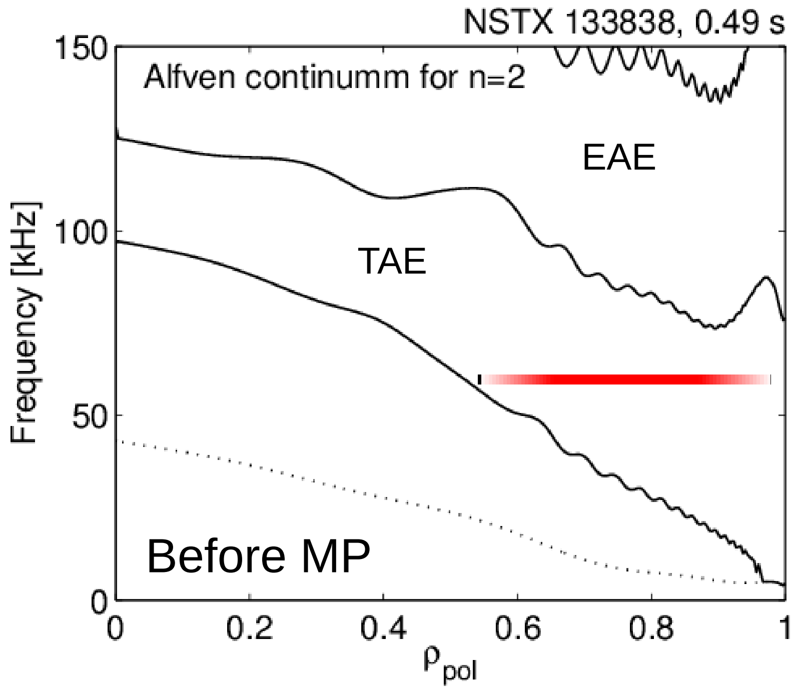
- Modulation of modes in TAE frequency range
  - Freq. = 60-100 kHz
  - Toroidal number n=2-4
  - Propagation co-NBI

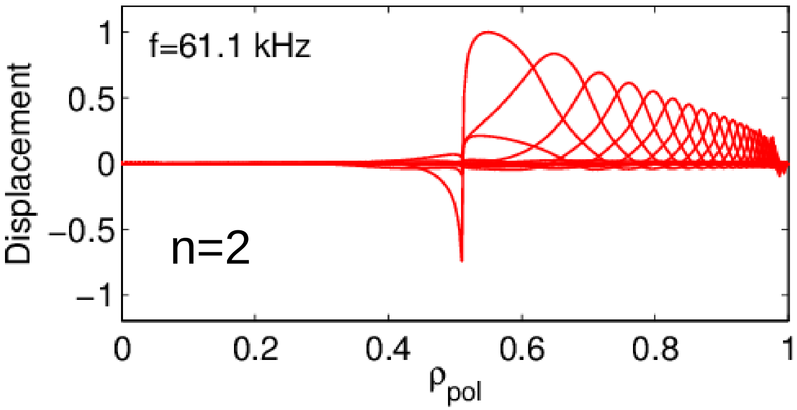
# Low frequency AE are modulated by MP pulses



- Two dominant  observed
  - n=2, 65 kHz
  - n=3, 75 kHz
- Radial displacement at plasma edge from reflectometer:
  - $\xi_r \approx 0.14$ mm (n=2)
  - $\xi_r \approx 0.04$ mm (n=3)
- ELMs crash 2 ms after MP begin
- Modes amplitude response:
  - Suppressed after ELM
  - Decreased ***before*** ELM
- Neutron rate drop < 2%

# MHD computations find TAEs consistent with observations





- Ideal MHD simulations (NOVA-K)
  - t=490 ms (before MP)
  - Realistic fast ion d.f.
  - Includes toroidal rotation
- Alfvén continua distorted by rotation
- Unstable modes in TAE gap
  - n=2, f=55-60 kHz
  - n=3, f=65-70 kHz
- Weak coupling with lower continuum at mid-radius
- Modes extend to the plasma edge
  - overlap with MP ($\rho_{pol}$>0.8)

# Can 3D perturbations alter TAE damping rates?

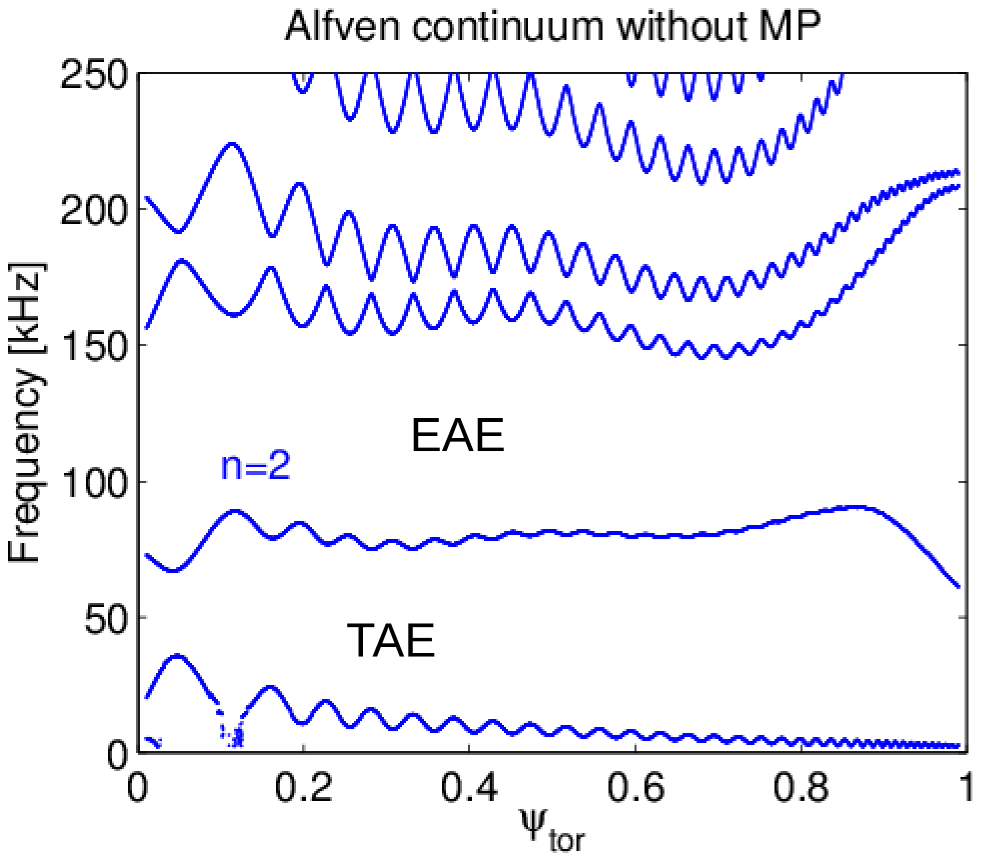
- Ion/electron temperature, density → Landau damping (ion/electron)
- Rotation , safety factor profile → Continuum structure (gaps)
- Substantial change of background profiles required
  - not observed before ELM crash

- ***MP break axisymmetry → toroidal coupling (as in stellarators) [1]***
  - Families of toroidally coupled modes n, $n \pm n_{MP}$ , $n \pm 2\, n_{MP}$, …
  - AE stability can be significantly altered (e.g. continuum structure)

- Problem addressed with computational tools from stellarator research:
  - VMEC computes ideal MHD equilibrium for 3D configurations [2]
  - STELLGAP computes Alfvén continuum for 3D magnetic equilibria [1]

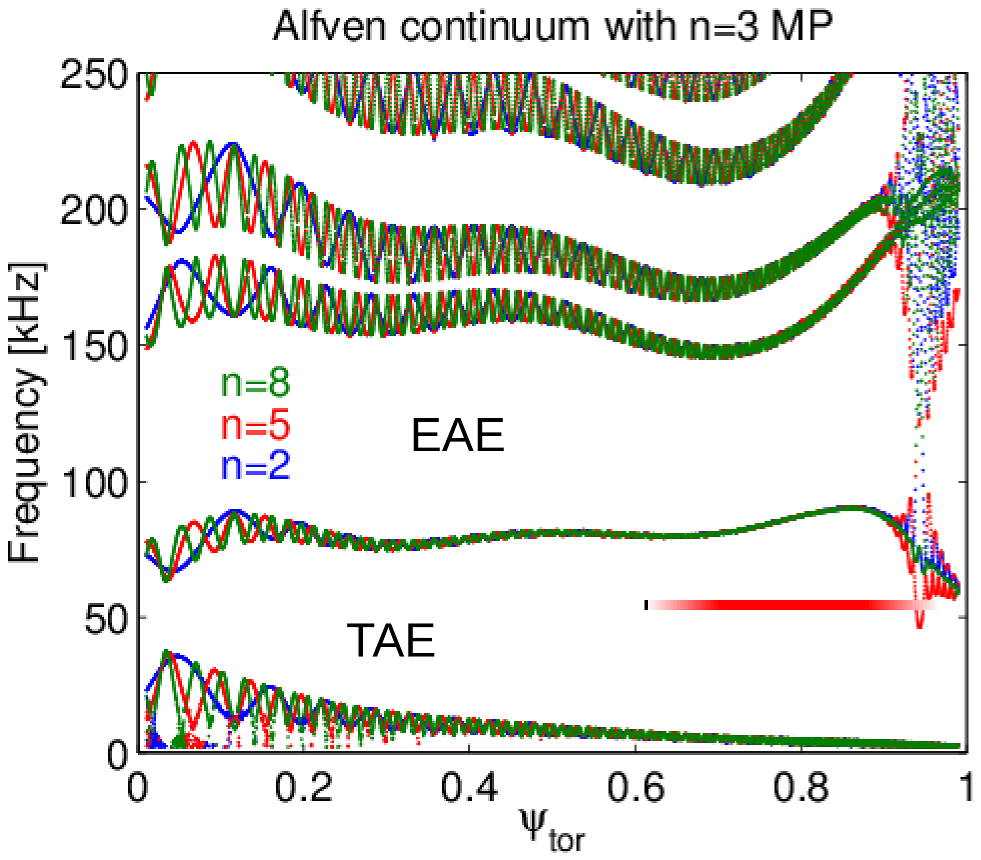
*[1] Spong et al, Phys.Plasma 8 (2003) 3217* *[2] Hirshman & Whitson, Phys.Fluids 26, (1983) 3553*

# Without MP, Alfvén continua are toroidally uncoupled



- VMEC equilibrium (**no MP**)
- STELLGAP continuum for n=2
  - Rotation not included
- TAE and EAE gaps identified
  - Extend from axis to edge

# Including MP, toroidal coupling reduces continuum gaps



- VMEC equilibrium (**with MP**)
- STELLGAP continuum for n=2
  - including sidebands n=5, 8
- Toroidally coupled continuum modes in edge region
  - EAE gap is closed
  - TAE gap shrinks
- Could enhance damping of TAE by interaction with continuum

Modifications of continuum due to couplings in the 3D metric tensor

→

Optimize the MP to get 3D perturbed equilibria stable against AE

# Conclusions

- NSTX observations show that externally imposed 3D fields can alter the dynamic evolution of fast-particle driven instabilities (GAE, TAE)
- Modeling of MP induced fast-ion transport supports controlling fast-ion instabilities by tailoring the distribution function with appropriate MP
- Computations of Alfvén stability in perturbed equilibria suggest MP induced toroidal coupling as a way to control AE

- Dedicated experiments would be desirable to test and optimize the MP effect in controlled fashion
- NSTX-Upgrade physics operations will begin in spring 2015
  - New tangential, off axis NBI → tailor fast ion distribution function
  - In-vessel antenna → excite AE and measure damping rates