12th US-EU Transport Task Force Workshop
San Diego, California
April 17 - 20, 2007

SUMMARY of
ENERGETIC PARTICLE SESSIONS

Boris Breizman, Nikolai Gorelenkov
and Energetic Particle Group

Statistics:

1 preview talk (S. Sharapov)
16 orals=9(experiment)+7(theory/modeling)
US BPO discussion (3presentations)

Positive Trends in Energetic Particle Area

- ☐ Growing benefits from MHD-spectroscopy (Crocker, Porkolab, Snipes, Zhang)
- ☐ Emerging phase space measurements (Heidbrink, Luo, Darrow, Hill)
- ☐ 5-D kinetic thinking in theory and simulations (related to bulk plasma transport) (Berk, Nishimura, Hauff, Van Dam)
- ☐ Interesting candidate phenomena for first-principle integrated modeling (Sharapov)
- ☐ Growing interest to low-frequency perturbations (closely related to bulk plasma turbulence) (Breizman, Gorelenkov, Chen)
- ☐ Active dialog between experiment and theory
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- ☐ Stronger focus on ITER-relevant physics (BPO discussion)

Highlights
of Presentations

S.E. Sharapov

Fast particle transport: from present day experiment and modelling towards control of burning plasmas

Summary

- Linear theory/ modelling tools for AEs are well developed. AE stability in advanced scenarios has still to be performed.

- Near-threshold nonlinear regimes are all observed in experiment and some are satisfactorily reproduced with existing numerical tools. Longer time scale involving collisional operator has still to be considered.

- Fishbones, which may become an issue in hybrid scenario on ITER, should be investigated more. Existing numerical tools are limited.

- Transition from single-mode to multiple-mode transport due to AEs has to be demonstrated experimentally.

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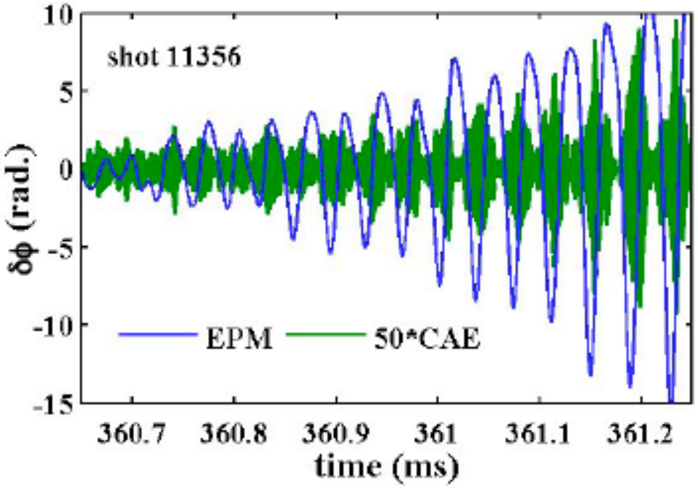
N. Crocker *"Investigation of fast-ion mode nonlinear dynamics and spatial structure in NSTX"*

CAE wave-packets formed by EPM interaction



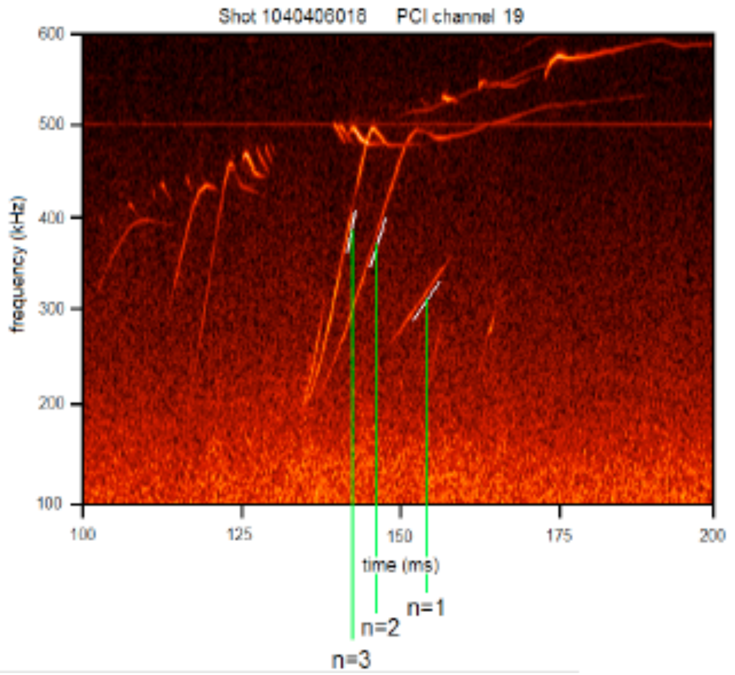
- Three wave interactions between fast-ion modes observed for first time
  - interaction across multiple scales: EPM—TAE, EPM—CAE, TAE—CAE
  - fast-ion loss events influenced
  - universal effect: wave-packet formation - lower frequency mode spatially concentrates energy of higher frequency mode

- Structure of Alfvén Cascade Modes and TAEs measured
  - structure measurements: multiple reflectometers ⇒ radial structure; radial interferometer ⇒ constrain reconstruction; toroidal mode number from array of Mirnov coils outside plasma
  - Alfvén Cascade Modes and evolution to TAEs observed

M. Porkolab *“Observations of Alfvén Cascades during ICRF heating in Alcator C-Mod”*

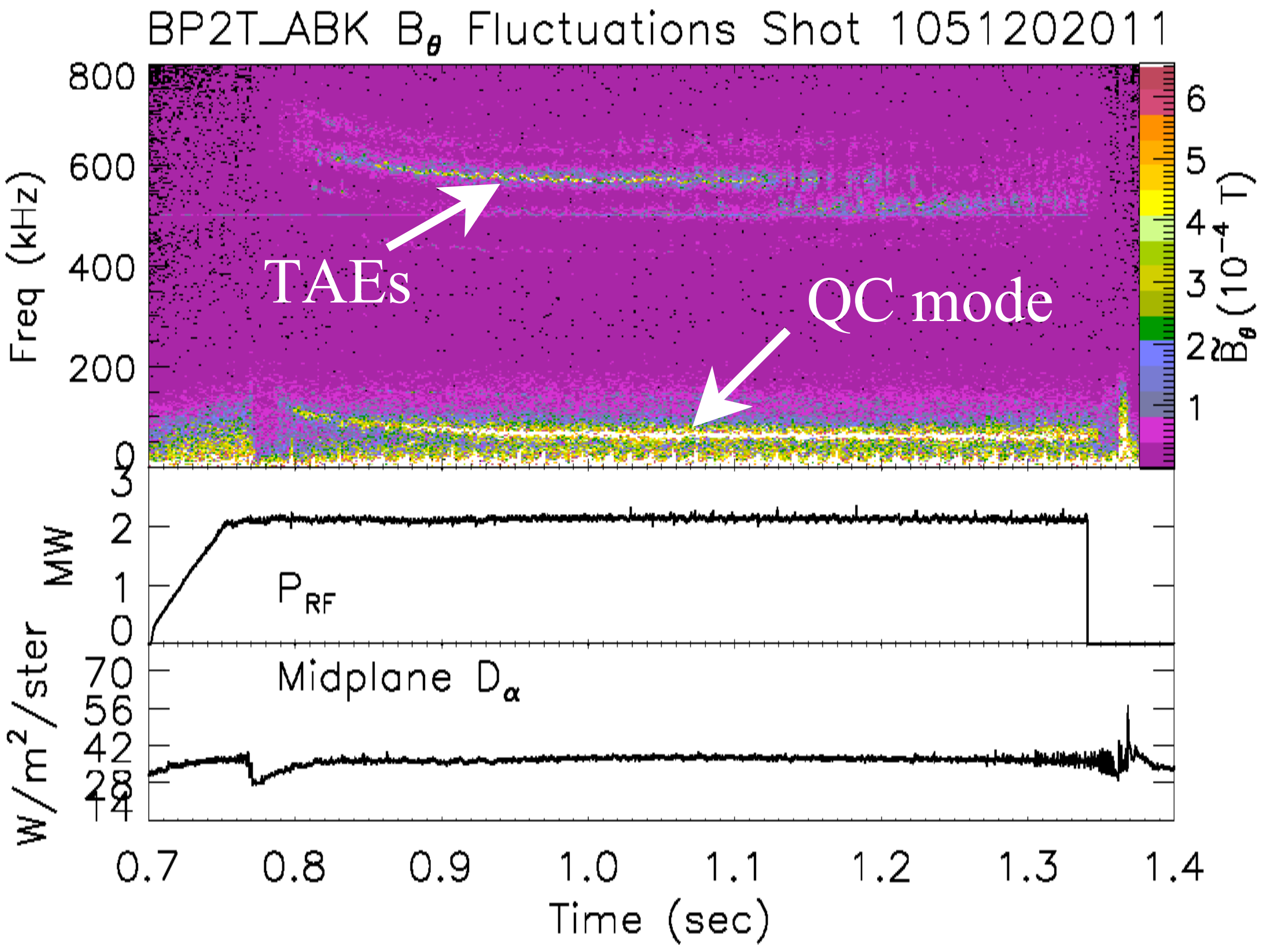
- Phase Contrast Imaging (PCI) and magnetic signals from Alfvén Cascades provide temporal evolution of q_{min} in C-Mod
- Can PCI be implemented in ITER?

PCI Diagnostic



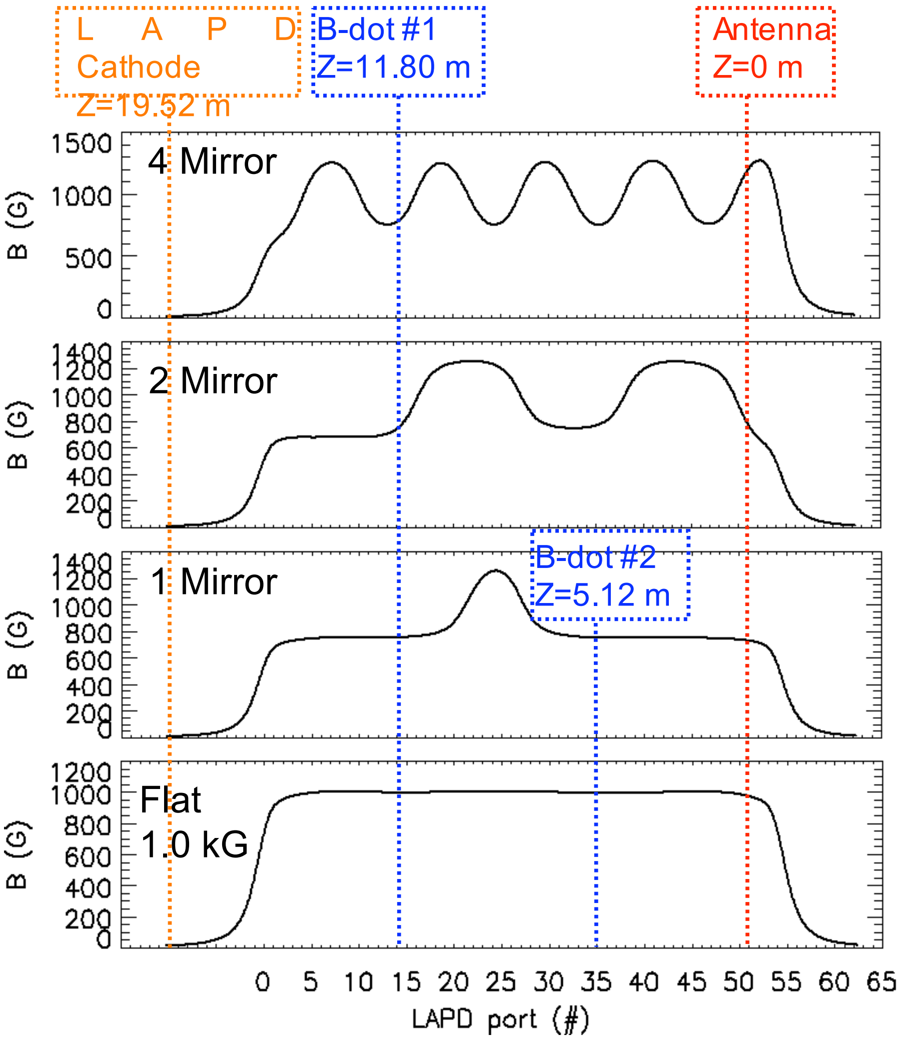
- Modeling of Alfvén Cascades now incorporates geodesic acoustic effect on mode frequency, which improves agreement with data
- It is conceivable that the minimum frequency of Alfven Cascades can be used to determine local T_e
- Nonlinear mode couplings have been observed

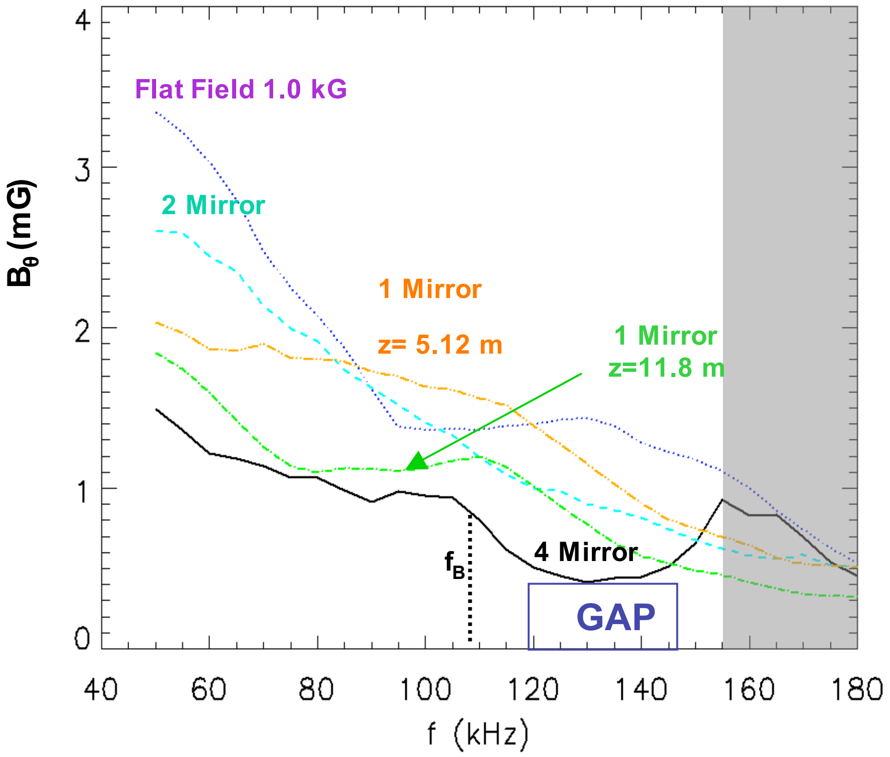
J. Snipes *"Comparison of Alfvén eigenmode stability in L- and H-mode"*



- Toroidal Alfvén Eigenmodes with f_{TAE} ~ 600 kHz occur in ICRF heated H-mode but not in L-mode
- This TAE mode rotates in the electron direction suggesting a hollow fast ion profile as found with AORSA/CQL3D in other discharges.
- TRANSP/TORIC5 fast ion profiles are peaked near the axis which would only excite TAEs rotating in the ion direction

Spectral Gap Demonstrated in LAPD with Multiple (4) Mirrors





Bragg reflection condition:

$f_B = v_{A//}/2\lambda_m$ =108 kHz.

4-Mirror case shows the spectral gap in frequency.

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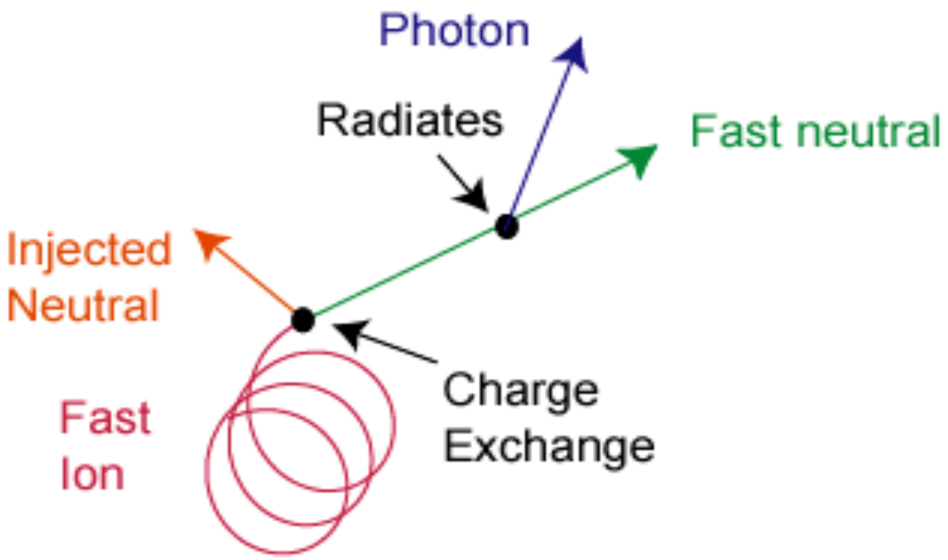
FIDA diagnostic successfully benchmarked

FIDA = Fast Ion Dα



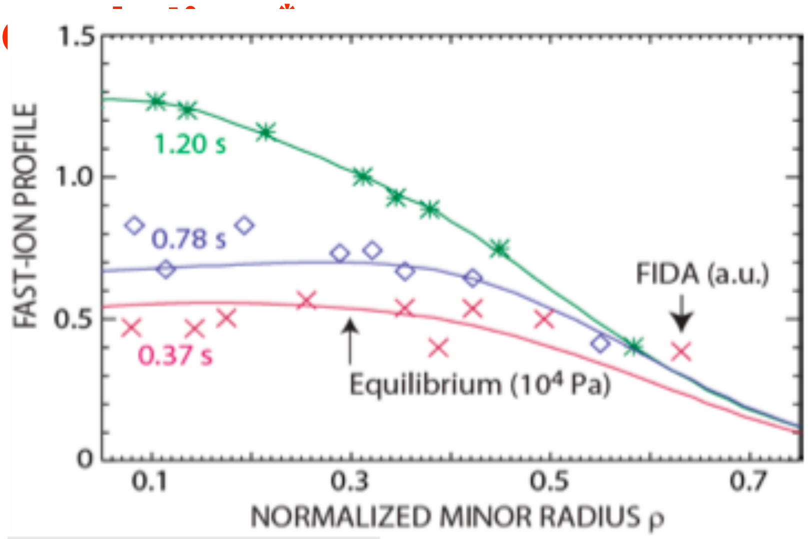
$D^+ + D^0 \Rightarrow D^{0*} + D^+$

$D^{0*} \Rightarrow h\nu + D^0$

- **Excellent spectral shape agreement (Coulomb collision model validated)**
- **Reasonable magnitude agreement**
- **Expected parametric dependences**
- **Corroborated by other fast-ion diagnostics**
- **Good relative radial profile (beam-ion diffusion coefficient within 0.1 m^2/s)**

- Volume-averaged neutron rate is below the classical TRANSP prediction during the strong Alfvén activity

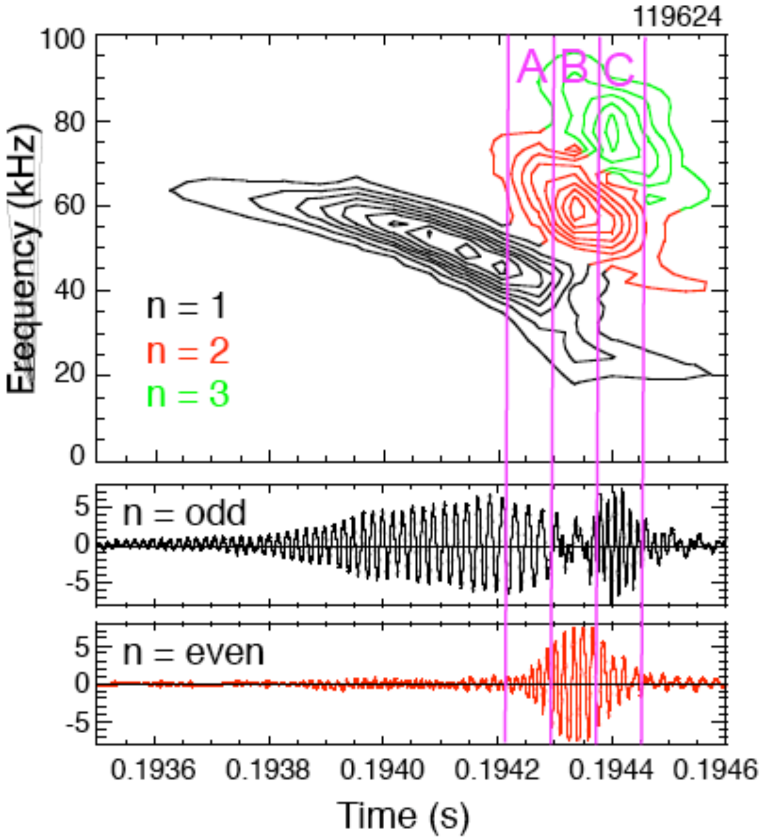
- Fast-ion D_a (FIDA) diagnostic measures the spectrum of fast ions with 4 cm spatial r

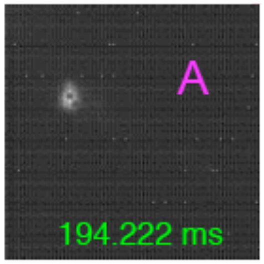


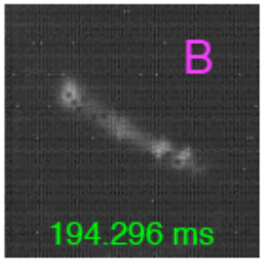
- FIDA shows that beam ion density is reduced during the strong Alfvén activity

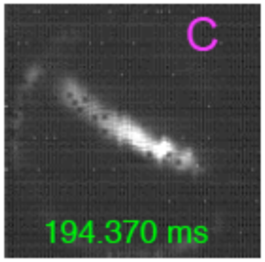
- Can the measured Alfvén modes explain the flattened profile? To be determined in ongoing modeling.

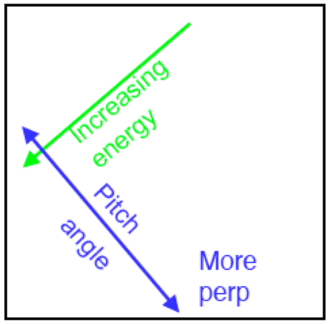
D. Darrow (N. Crocker) *“MHD-induced neutral beam ion loss from NSTX”*







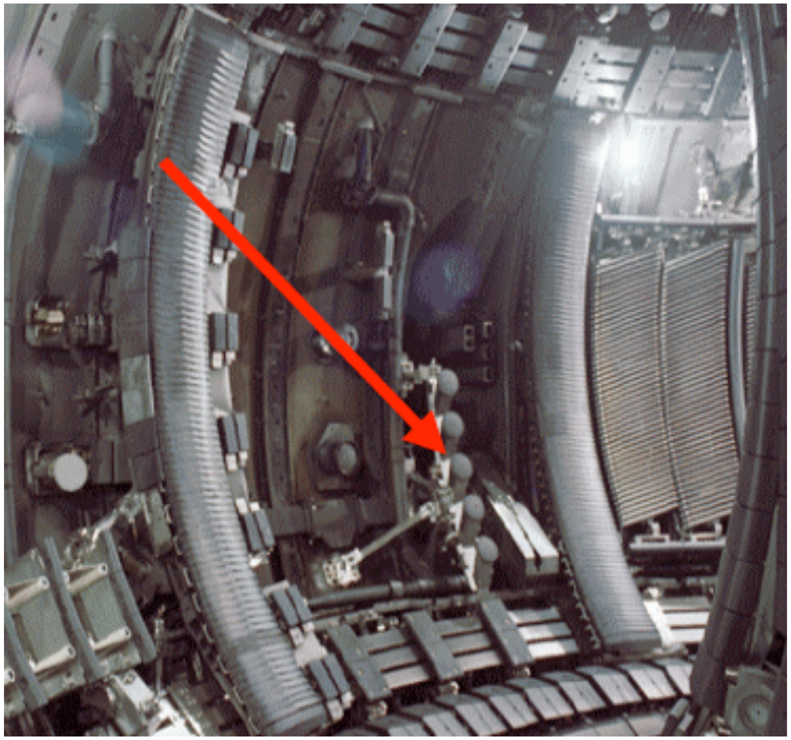




- Scintillator images recorded by fast videocamera
- Particles with a broad range of pitch-angles are lost when multiple modes are present

K. Hill *"Measurement of fast ion losses from JET"*

- Faraday cup and scintillator probe measure fast ion losses in the keV and MeV ranges
- The observed significant dependence on Dα suggests that substantial ion losses may take place due to ELMs
- Fast ion losses decrease with moderate ripples and increase for larger ripples
- The sawtooth frequency depends on the ripple amplitude
- MeV-ion losses (fusion products and ICRF accelerated ions) observed in AT scenarios



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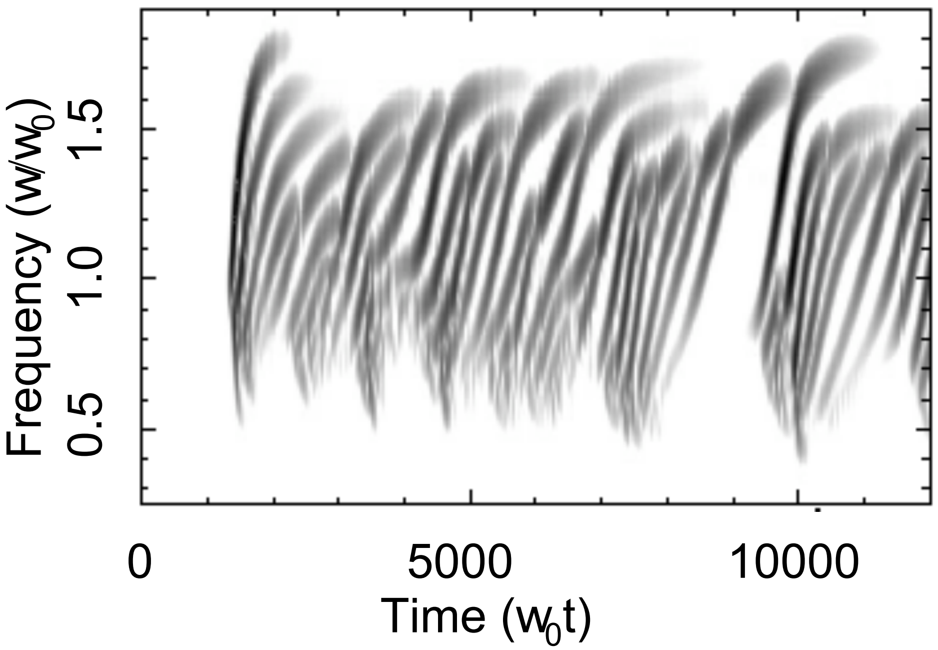
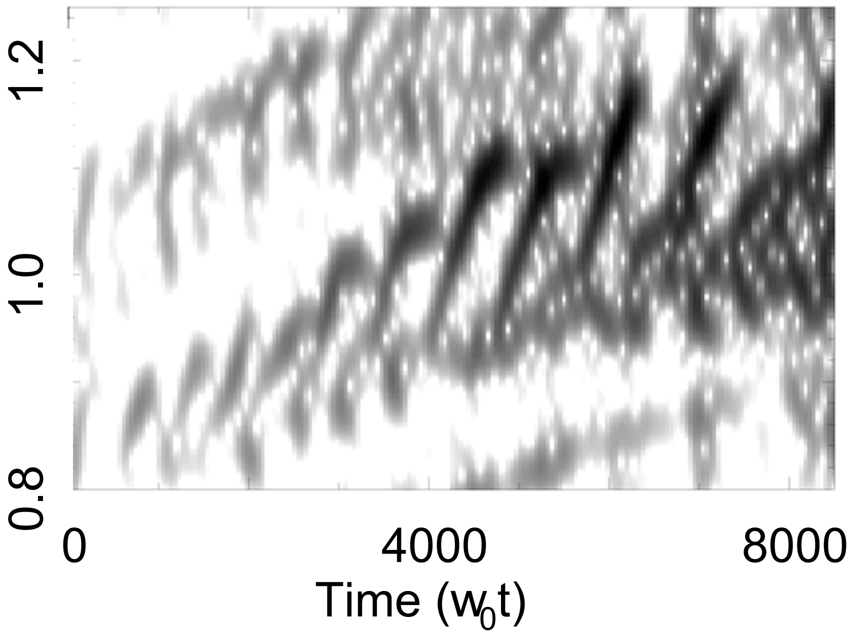
Calculated pattern is similar to MAST experimental data

Simulation



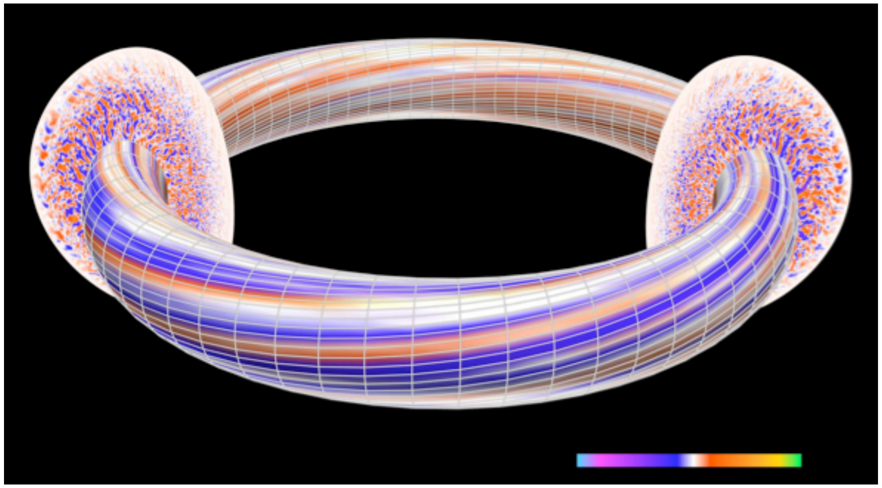
MAST shot 11005



Simulation		Experiment
w_p	Characteristic frequency w_0	2p x 100kHz
3.6×10^{-4}	Sweeping rate dw/dt	2.9×10^{-4}
0.7	Sweeping extent Dw	0.18

Y. Nishimura *“Alfvén continuum and toroidal gap generation in global electromagnetic gyrokinetic simulations”*

GLOBAL FIELD ALIGNED MESH PROVIDES HIGH COMPUTATIONAL EFFICIENCY

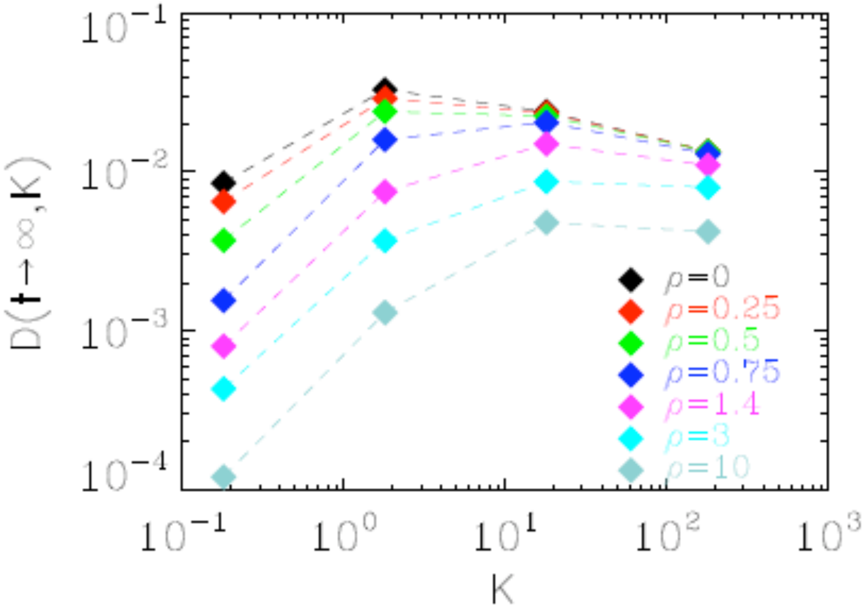


RESULTS AND PLANS

- ☐ Demonstrated Alfvén wave propagation and continuum damping
- ☐ Demonstrated Alfvén frequency gap in toroidal geometry

- ☐ TAE to be found
- ☐ Simultaneous simulation of long- and short-wavelength electromagnetic phenomena to be performed

FLR effects: Direct numerical simulations



$$\phi(\vec{x},t) = \sum_{i=1}^{N} A_i \sin(\vec{k}_i\vec{x}+\omega_i t+\varphi_i),$$

Kubo number:

$$K = \frac{V\tau_C}{\lambda_c} = \frac{\tau_c}{\tau_{fl}}$$

Observations:

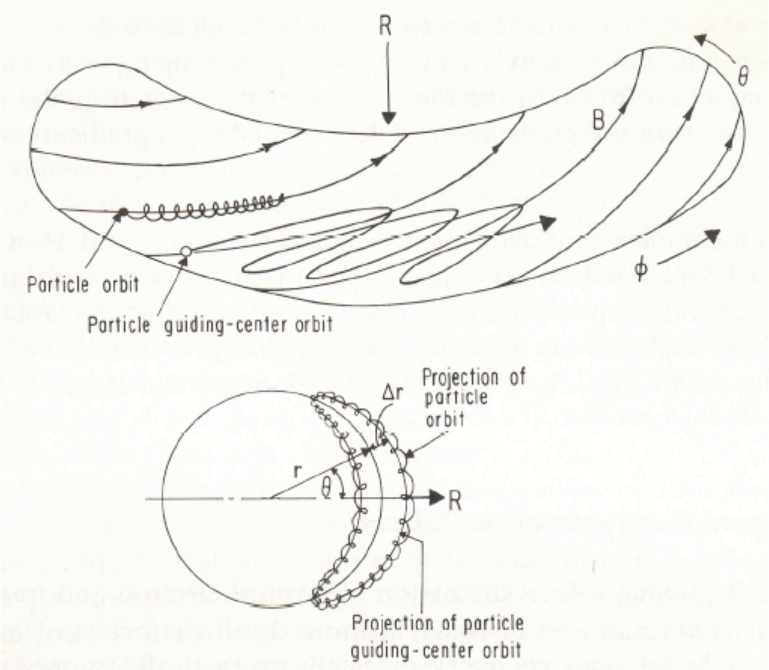
- $K \lesssim 1$: Monotonic reduction of D with increasing ρ
- $K \gtrsim 1$: D stays constant for $\rho \lesssim 1$
  Slow fall-off for $\rho > 1$

J. Van Dam *"Direct drive from cyclotron heating can explain spontaneous rotation in tokamaks"*

New explanation for intrinsic rotation of core plasma during ion cyclotron heating of tokamaks involves toroidal precession of the trapped ions

Theoretical predictions agree with key experimental features, such as:

- Scaling of toroidal rotation velocity
- Direction of rotation
- Magnitude of rotation
- Radial profile of rotation



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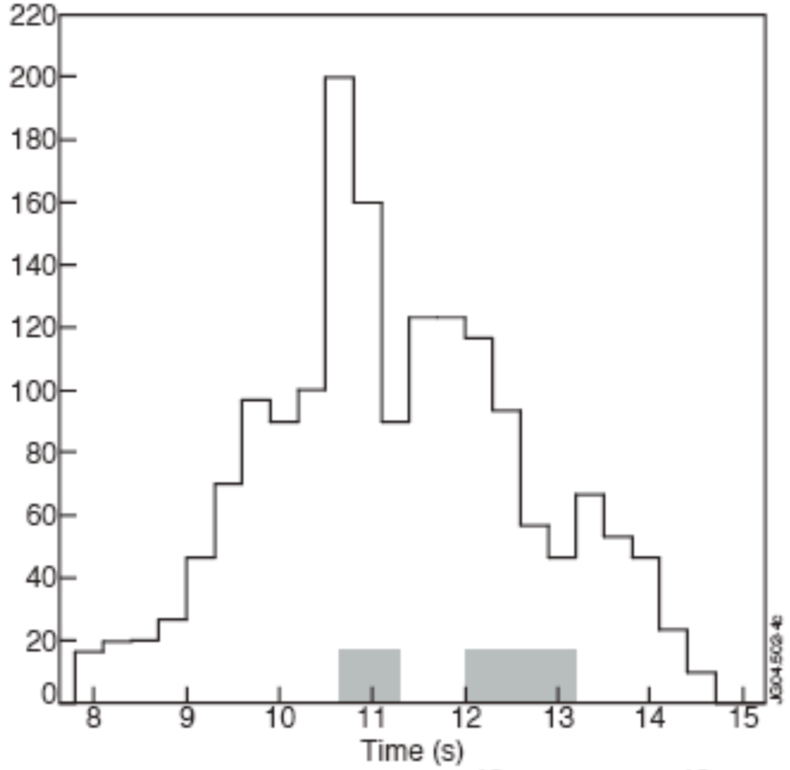
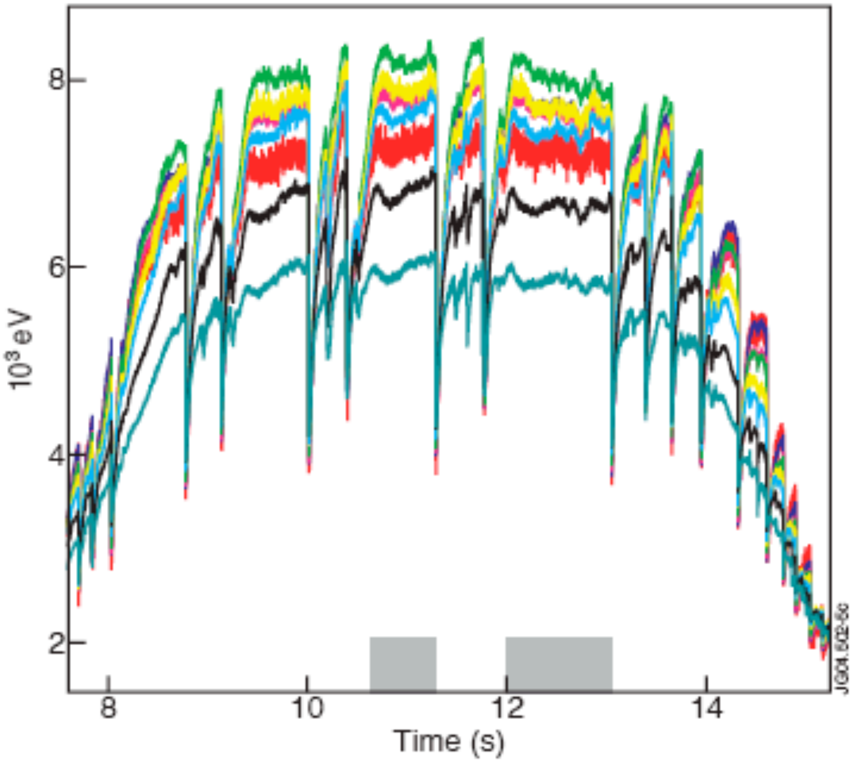
S. Sharapov *"Fast particle transport" (Preview talk)*

Experimentally observed fast ion redistribution on JET: decrease in gamma-ray intensity from 5MeV protons



γ-rays from reactions $^{12}C(p, p'\gamma)^{12}C$



T_e at different radii show sawteeth at t=11.4, t=13 s occuring after decreases of γ-intensity

NPA measurements of alphas on JET (1997)

Surprising results from NPA measurements in DT experiments:

- significant flux of $^4He^0$-like atoms (i.e. atoms of the same charge/mass ratio) is observed with NPA in the small energy range, $E \leq 1$ MeV, at time shorter than the alpha-particle slowing-down time,

- this low-energy flux is from one to two orders of magnitude excessive as compared to the alpha-particle flux estimated for the given fusion reactivity.

- Interpretation:

- As $e_\alpha / m_\alpha = e_D / m_D$, NPA in fact measures both fluxes of helium and deuterium atoms

- Deuterium in the MeV energy range may be explained by nuclear elastic scattering (knock-on collisions) effect between fusion born alphas and thermal deuterium

D-He^3 fusion in JET

Actually, apart from NES, another branch of D-He^3 nuclear interaction exists. This is the fusion reaction

$D + He^3 \Rightarrow p(14.7\ \mathrm{MeV}) + He^4(3.6\ \mathrm{MeV})$

With cross-section about 2.5 times larger than NES at peak He^3 energy ~ 700 keV

For JET discharges with ICRH of He^3 minority, a record fusion power 140 keV from this reaction was obtained in 1991 (J.Jacquinot, G.Sadler, Fusion Technology 21, p.2254 (1992)

In our experiment, fusion power about 30 kW could have been generated ($2x10^{16}$ reaction/sec) but not measured

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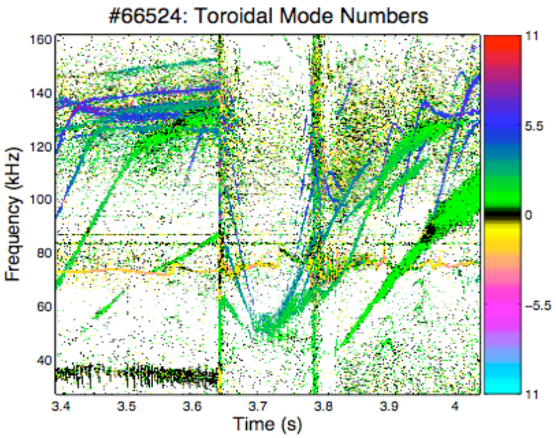
B. Breizman *"Alfvén cascade quasi-modes"*

- Alfvén Cascades are closely related to shear Alfvén waves. Their frequencies tend to be more robust than the radial mode structure.

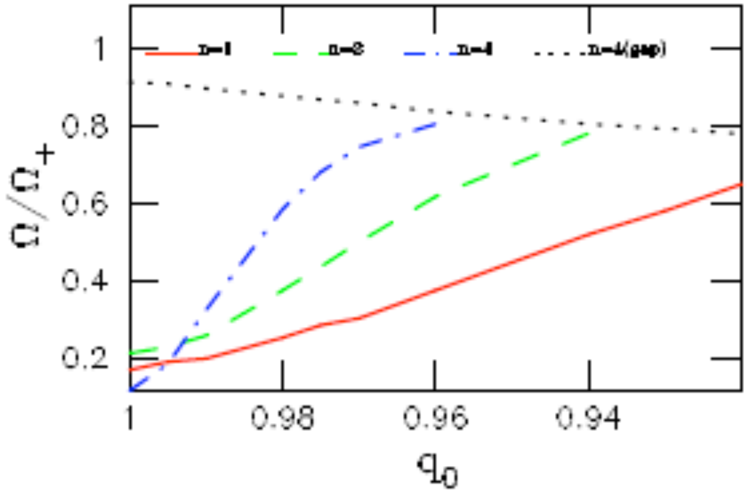
- It is likely that some of the observed Alfvén Cascades are transient perturbations (quasi-modes) rather than true eigenmodes. They represent traveling waves as opposed to standing waves in radial direction.

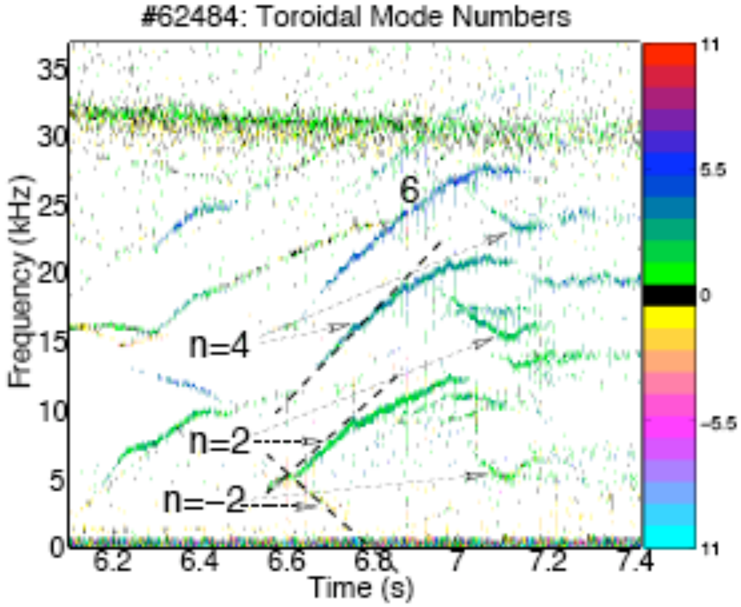


- Radial structure of Alfvén Cascade Quasimodes is determined by their damping rates rather than frequencies.

N. Gorelenkov *“Global beta-induced Alfvén-acoustic modes in JET and NSTX”*

- Characterization of low-frequency gap in Alfvén-acoustic continuum (below Geodesic Acoustic Mode frequency)
- Global modes found numerically in the gap via MHD calculations
- The calculated modes resemble those observed in JET and NSTX
- Kinetic analysis is required to reconcile theory with observations and to address ion Landau damping issue





L. Chen (Z. Lin) *"Radial structures and nonlinear excitation of Geodesic Acoustic Modes"*

- Geodesic Acoustic Modes have a continuous spectrum due to radial inhomogeneities
- These modes convert into short-wavelength kinetic modes via finite ion Larmor radii
- GAM's are identical to Beta induced Alfvén Eigenmodes in the long-wavelength limit
- Nonlinear excitation of GAM's by drift waves can be described in terms of predator-prey model

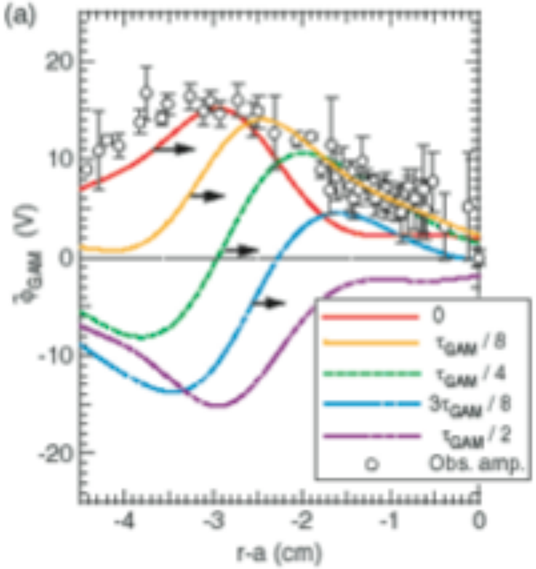
☐ Radial wave equation and mode conversion of GAM

- In nonuniform plasma $k_r = -i\partial/\partial r$

$\Rightarrow$ Radial wave equation

$$\frac{\partial}{\partial r}\left\{N_0(r)\left[\rho_i^2(r)C(r)\frac{\partial^2}{\partial r^2}+\omega^2-\omega_{GAM}^2(r)\right]\overline{\delta E_r}\right\}=0$$

Evidence of outward propagating GAM in JFT-2M [Ido etal. PPCF 2006]



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