Overview on Instabilities and Confinement of Energetic Ions on JET

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[*] See Annex of J Pamela et al., 20th IAEA Fusion Energy Conference, Vilamoura, Portugal, 1-6 November 2004, paper OV/1-X

Outline of the talk

Burning plasma and ITER

Confinement of ICRH-accelerated ^{4}He studied with gamma-ray diagnostics during the Alpha-simulation experiment

Experimental status and recent results on TAE-modes

Alfvén Cascade instability in shear-reversed plasmas

Recent progress in diagnosing Alfvén instabilities

Summary

ITER is supposed to provide information on fusion-born alphas:

1) Production of fusion-born alphas

2) Plasma heating by alphas

3) Confinement of alphas

4) Losses of alphas

ITER as a burning plasma machine

ITER burning plasma: $P_{\alpha}/P_{in} = 2$ for Q=10 ⇒
Different fast ions of comparable energy contents will co-exist in ITER:

Fusion-born alphas with temperature ≈ 1 MeV (isotropic distribution function)

Deuterium NB injected at ≈ 1 MeV (anisotropic distribution function with $E_{||} >> E_{\perp}$)

ICRH-accelerated ions of H, ^{3}He, … (anisotropic distribution function with $E_{\perp} >> E_{||}$)

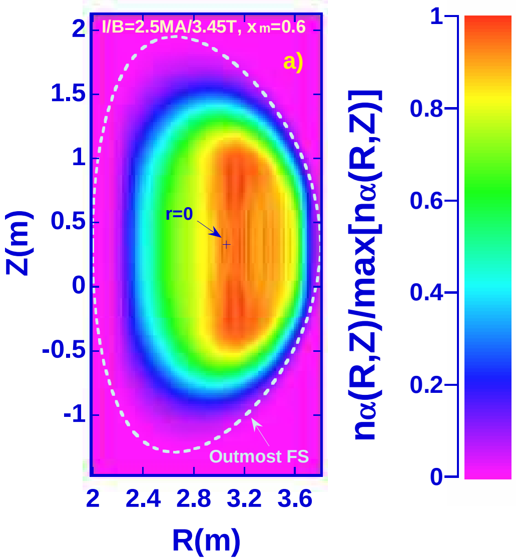
⇓

Study of alpha-effects will be hindered by competing effects from the other ions.

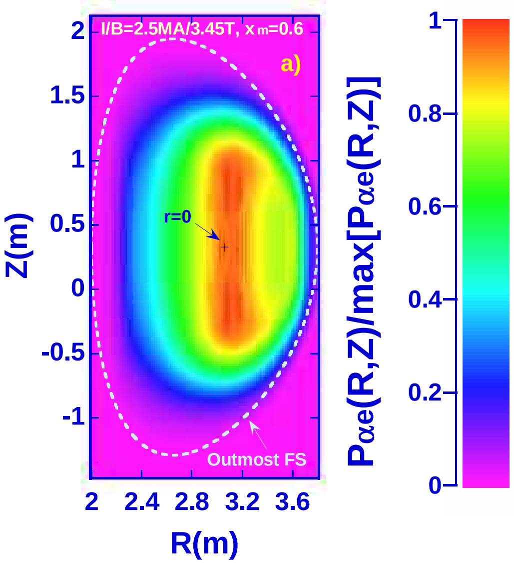
Example: TAE-drive from 1 MeV *anisotropic* NBI is ≈ 3 times higher than that from *isotropic* fusion-born alphas, for similar values of $d\beta_{fast}/dr$.

ITER as a burning plasma machine (continued)

ITER with high bootstrap current fraction may converge to 'self-organised' plasma equilibrium with strong reversed shear as on JET and JT-60U. Alpha confinement and heating profiles may be non-trivial in such equilibrium ⇒ further complications in addition to co-existence of several groups of fast ions



Density profile of alphas for JET #51976 with a 'current-hole' at r/a=0.6



Electron power deposition of alphas

From: Yavorskij et al., Nuclear Fusion 43 (2003) 1077

ITER as a burning plasma machine (continued)

Understanding of burning plasma in ITER =

1) identifying all the crucial fast ion problems and
2) measuring the fast ions with diagnostics, which

- **measure different groups of fast ions at the same time,**
- **have time and space resolution good enough to observe all the principal fast ion effects, and**
- **are compatible with DT operation.**

In order to be prepared for the burning plasma, targets (1), (2) have to be met on existin facilities.

JET is a unique test-bed for preparing for the burning plasma:

- **JET was designed to confine 3.5 MeV fusion-born alphas**
- **Capable of Tritium operations**
- **Has a flexible ICRH plant for accelerating various types of ITER-relevant ions up to the MeV range in a variety of different plasma conditions**

Two campaigns on alpha-studies were performed in 2003-2004:

- **Trace Tritium Experiment (use of T for real fusion-born alphas)**
- **Helium campaign (use of ICRH-acceleration for producing ‘artificial alphas’)**
  - **Alpha-simulation experiment**
  - **Fast ions in ^{4}He plasma experiment**

Helium campaigns on JET

Aim at developing alpha-diagnostics and studying the alpha-physics without use of Deuterium-Tritium plasma:

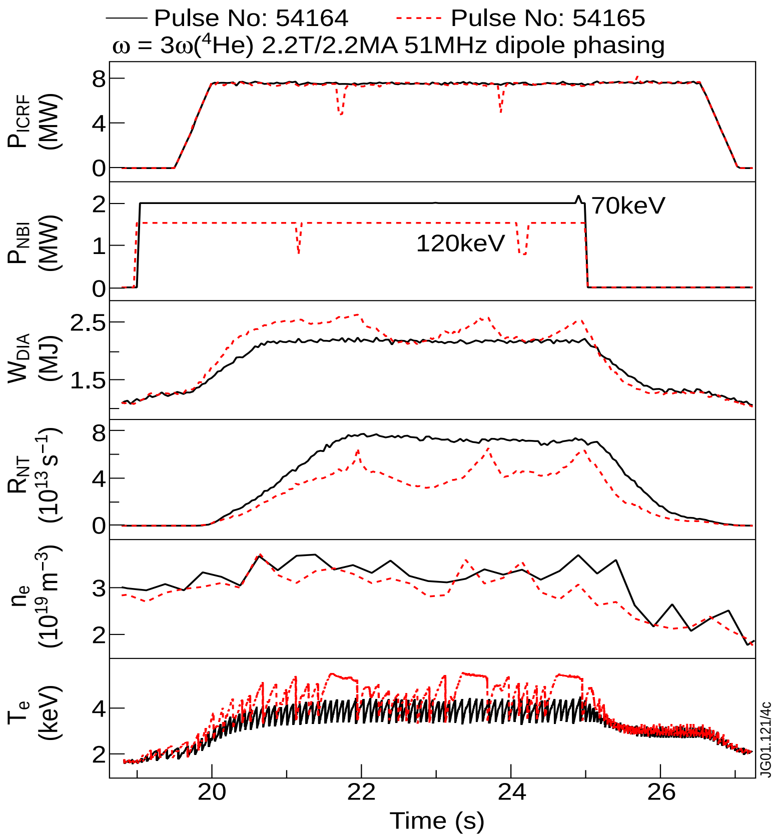
- **Investigate confinement and profiles of the MeV-range ^{4}He accelerated with 3rd harmonic ICRH in 'neutron-free' ^{4}He plasmas with monotonic and non-monotonic q(r).**
- **Develop nuclear gamma-ray diagnostics for simultaneous measurements of spatial profile and temperatures of ITER-relevant ^{4}He hot ions (E>1.7 MeV) and D hot ions (E>500 keV).**

Alpha Simulation Experiment in JET Helium Plasma

Studies of fast He^4 complimentary to Tritium experiments, but performed at very low neutron rates in not-activating environment

S.E.Sharapov et al, 2nd TM on Theory of Plasma Instabilities, Trieste, 3rd March 2005

^{4}He acceleration with 3ω(^{4}He) ICRF heating of ^{4}He NBI



^{4}He plasma + 8 MW of ICRH at 3ω(^{4}He) + 120 keV ^{4}He beam of power 1.5 MW

⇓

H-mode with MeV energy ^{4}He ions:

T_{Hot} = 1.1 ± 0.4 MeV,

$n_{Hot} / n_e \sim (\Delta W_{DIA}/W_{DIA})*(T_e/T_{Hot}) \sim 10^{-3}$

M.Mantsinen et al., Phys.Rev.Lett. 88 (2002)105002

Fast ion parameters are close to these in record DT discharge #42976:

$T_{Hot} \approx$ 1MeV, $n_{Hot} / n_e \sim 4 \cdot 10^{-3}$,

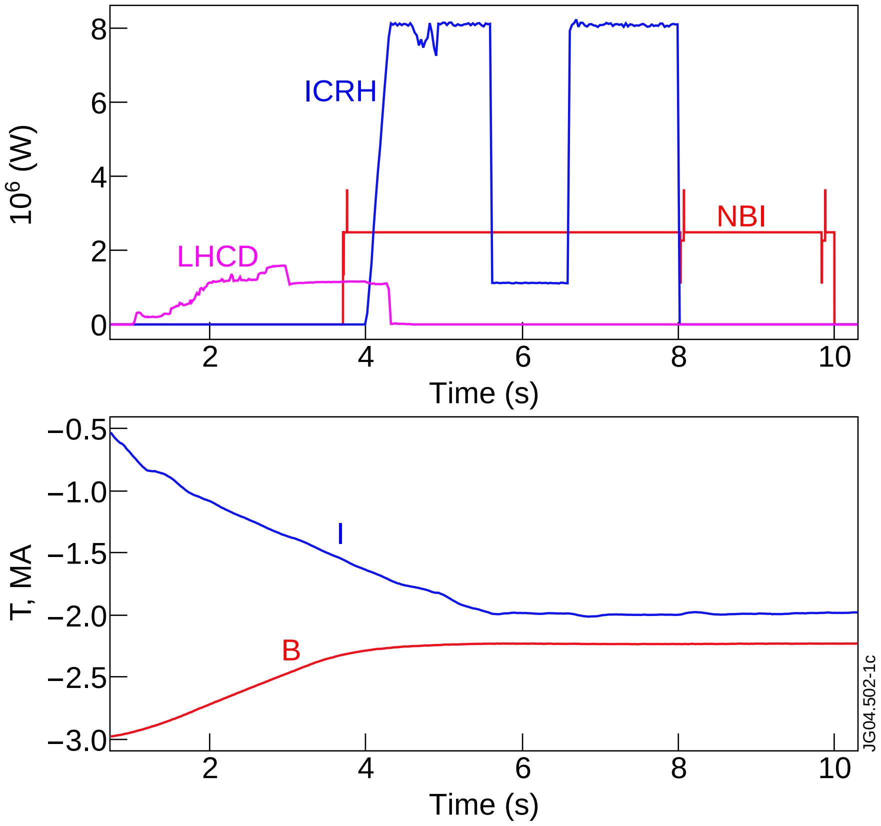
but at four orders lower neutron rates

⇓

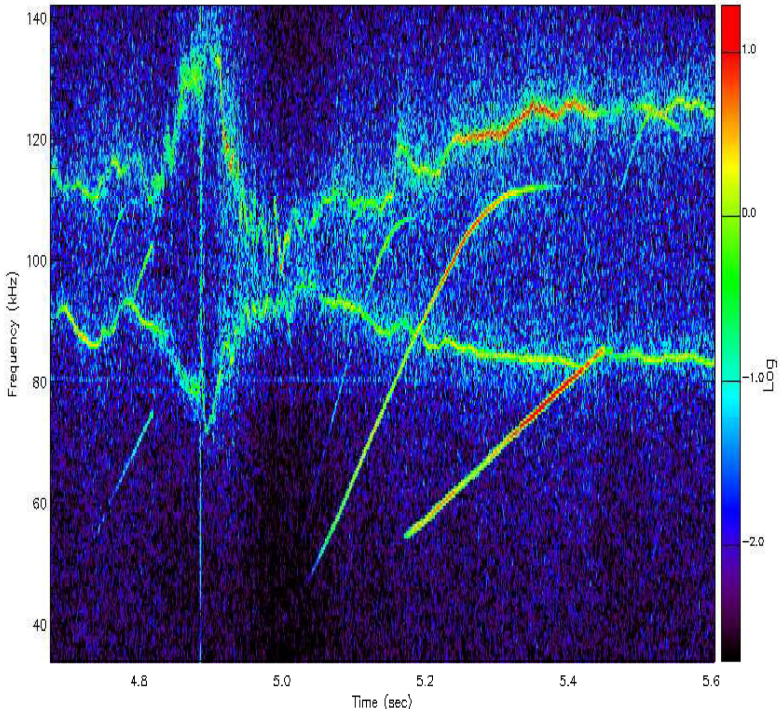
NO ACTIVATION

Very good scenario for developing and testing α-diagnostics !

^{4}He acceleration technique in reversed shear plasmas (2004)



B= 2.2 T, ω_{ICRH} = 51 MHz, I = 1.5÷2 MA



Alfvén Cascades excited by ^{4}He ions in JET reversed-shear discharge #63038.

Simultaneous Measurement of ^{4}He (E>1.7 MeV) and D (E>0.5 MeV)

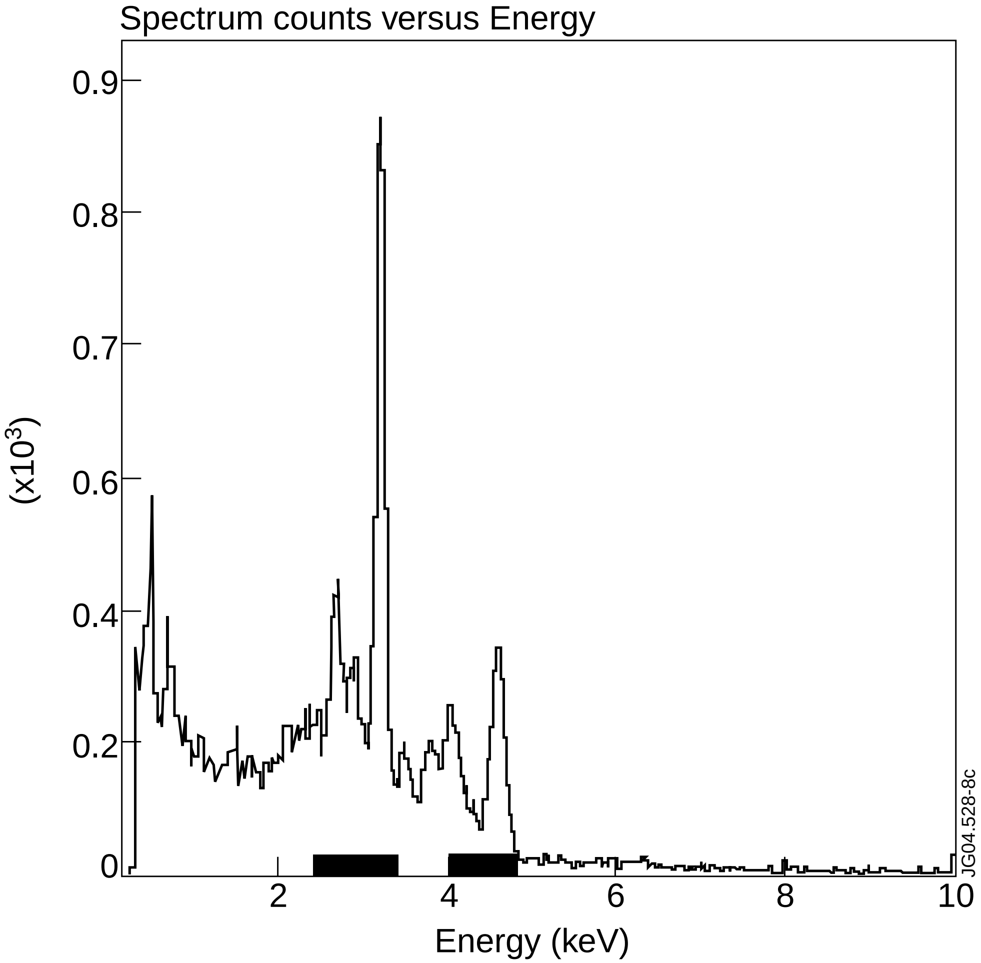
Energy windows for ALL Gamma Camera channels

I > 2.0 MeV (total)

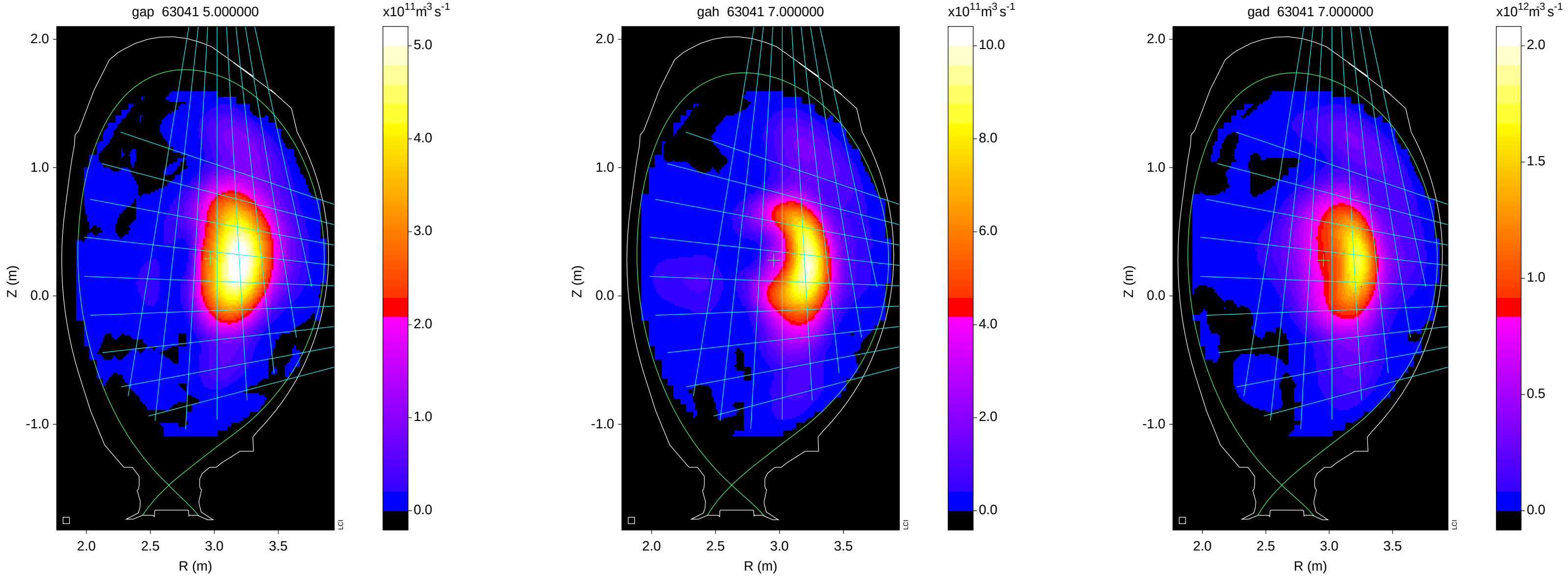
II 2.5 - 3.5 MeV (D+C)

III spare

IV 4.0 - 5.0 MeV (^{4}He+Be)



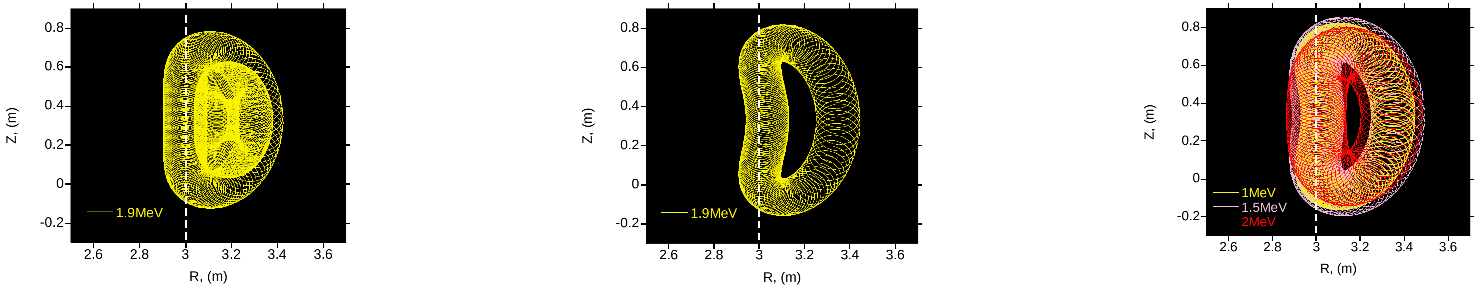
Gamma-ray Images of ^{4}He (E>1.7 MeV) and D (E>0.5 MeV)



^{4}He in reversed-shear discharge

^{4}He in monotonic q(r)-plasma

D in monotonic q(r)-discharge



Alfvén Instabilities Driven by Pressure Gradient of Fast Ions:

- Toroidal Alfvén Eigenmodes (TAEs) in monotonic q(r)
- Alfvén Cascade (AC) egenmodes + TAEs in non-monotonic q(r)
- Energetic Particle Modes (EPMs, Talk by F. Zonca)

- Three main parameters characterise instability and radial transport:

- Alfvén Mach Number	$V_\alpha / V_A(0)$ (=1.9 in ITER, 1.6-1.9 in JET DT)
- Pressure Gradient (scaled)	$R\nabla\beta_\alpha$ (=0.05 in ITER, 0.02-0.037 in JET DT)
- Number of Drift Orbits per Radius	$\Delta_f / a \sim q\rho_\alpha / a$ (=0.016 in ITER, 0.1 in JET)

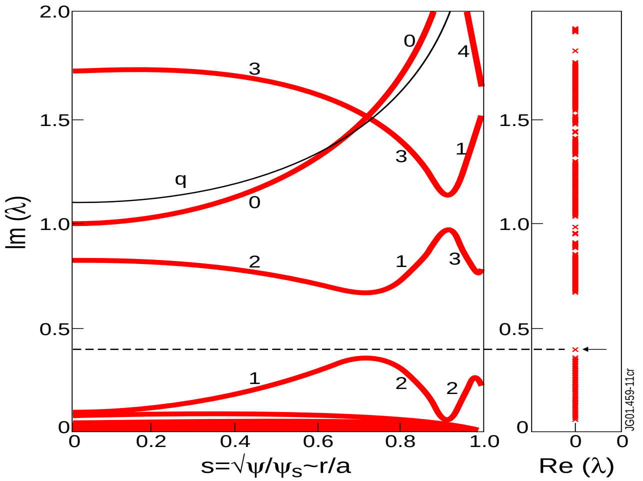
Weakly-damped Toroidal Alfvén Eigenmodes

- **C.Z.Cheng, L.Chen, M.S.Chance, Ann. Phys. 161 21 (1985):**

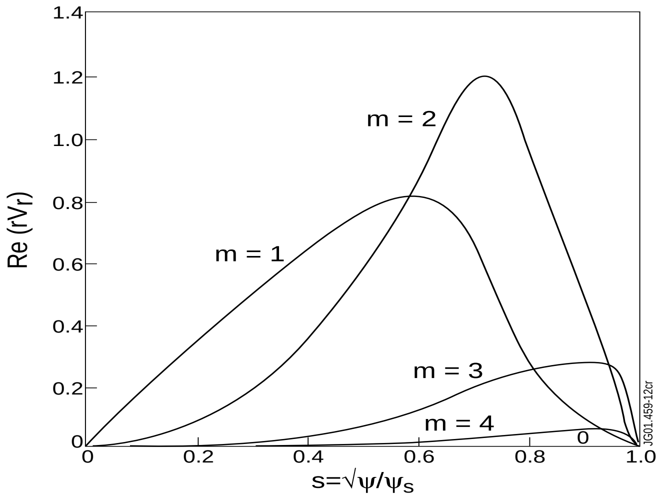
1) In toroidal geometry, gap in the Alfvén continuum appears at frequency

$\omega = k_{\parallel m}(r)V_A(r) = -k_{\parallel m+1}(r)V_A(r)$ **giving two extremum points in** ω_A

2) In addition to the continuum, weakly-damped Toroidal Alfvén Eigenmode (TAE) may exist in the gap if magnetic shear is finite



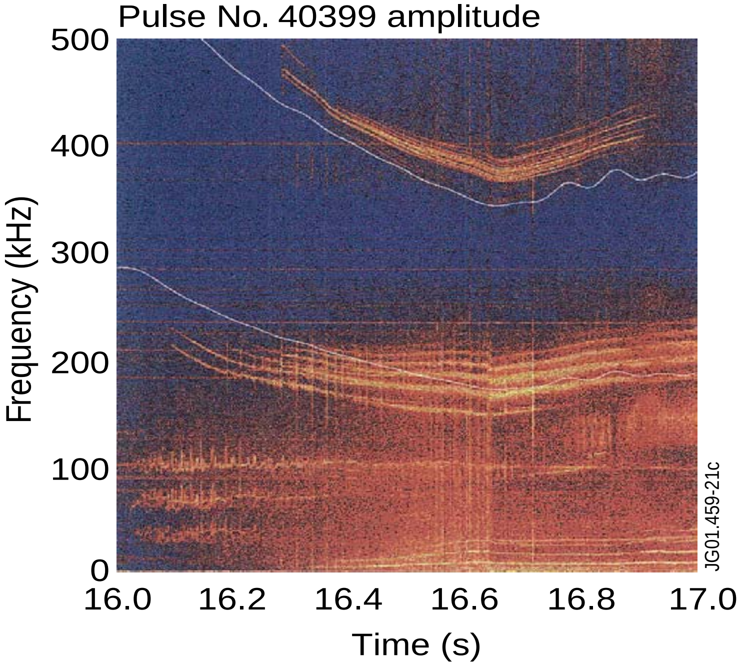
Ideal MHD continuous spectrum of n=1, m=0-4 Alfvén and SM frequencies versus $s=\sqrt{\psi_p/\psi_p^{edge}} \propto r/a$



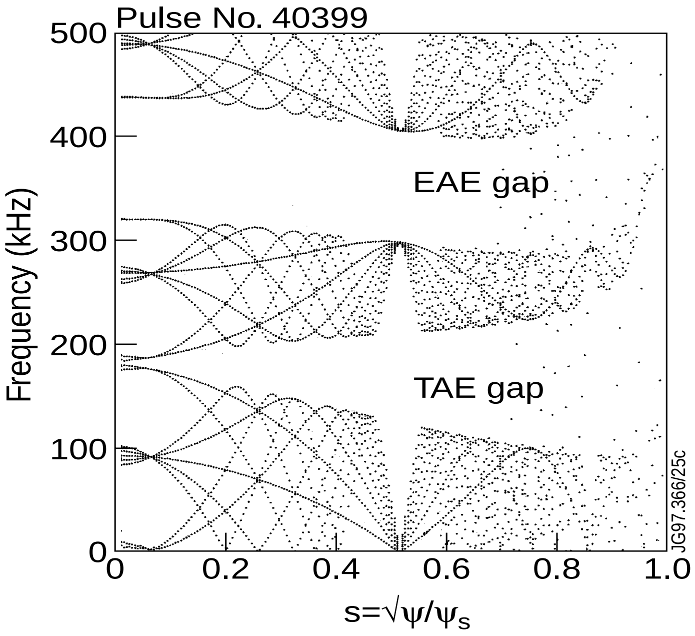
Radial dependence of the Fourier harmonics of TAE with a frequency located in the TAE-gap

TAEs Observed on All Tokamaks with Fast Ions

- **TAE instability excited by NBI- and ICRH-accelerated ions is commonly observed on all existing tokamaks (TFTR, JET, JT-60U, DIII-D, C-Mod…)**
- **First observation of α-driven TAE in DT plasma was made on TFTR by R.Nazikian et al., Phys. Rev. Lett. 78 2976 (1997)**

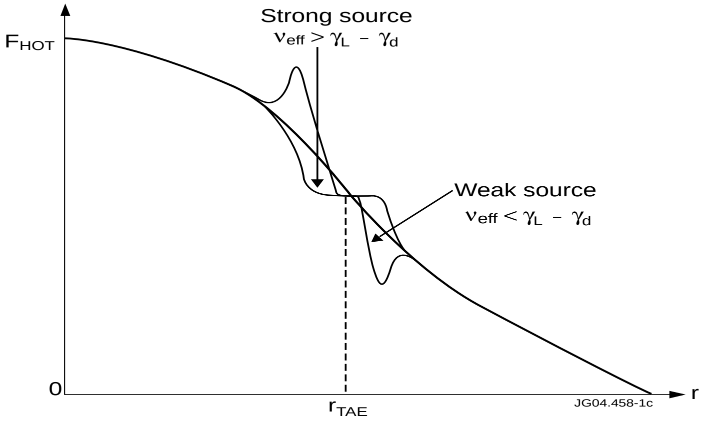


AE activity excited by ICRH ions on JET



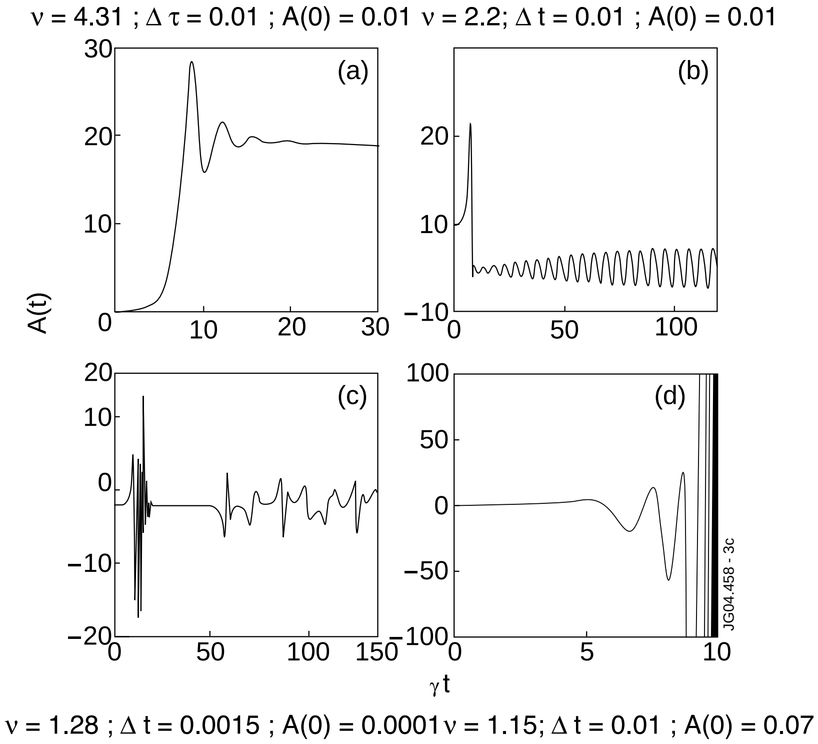
Continuous spectrum gaps for n=1…6 as functions of radius

Nonlinear Evolution of a Single TAE



- **Non-linear TAE behaviour depends on competition between the field of the mode that tends to flatten distribution function near the resonance (effect proportional to the net growth rate $\gamma \equiv \gamma_L - \gamma_d$) and the collision-like processes that constantly replenish it (proportional to ν_{eff})**

Nonlinear Evolution of a Single TAE



Nonlinear equation for amplitude A(t)

$$\frac{dA}{dt} = A - \exp(i\phi)\int_0^{t/2}\tau^2 \int_0^{t-2\tau}\exp\left[-\nu^3\tau^2\left(2\tau/3+\tau_1\right)\right]$$

$$\times A(t-\tau)A(t-\tau-\tau_1)A^*\left(t-2\tau-\tau_1\right)d\tau_1 d\tau$$

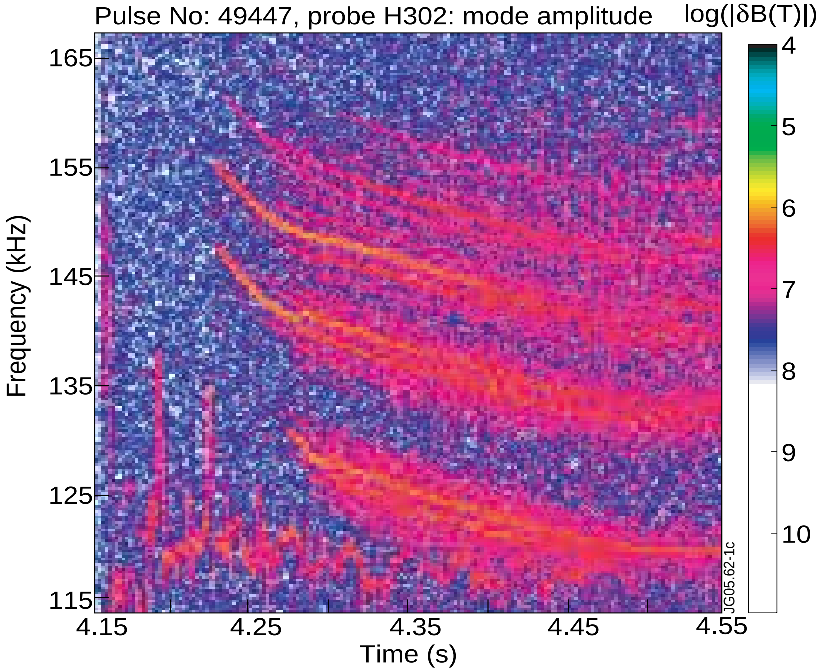
derived in [*] describes four different regimes of TAE amplitude A:

- **a) Steady-state A=const;**
- **b) Periodically modulated (observed as ‘pitchfork-splitting’ effect);**
- **c) Chaotic;**
- d) **Explosive regime**

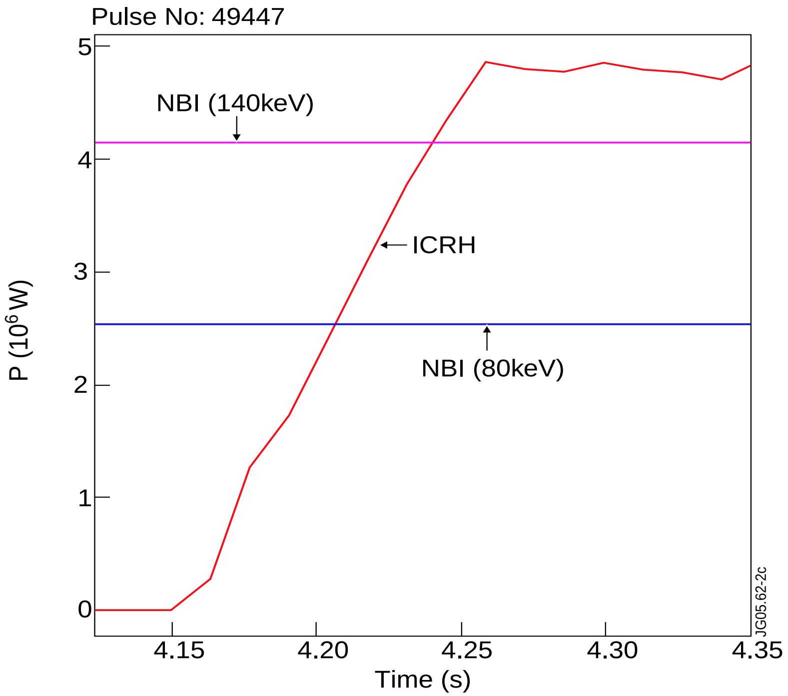
as ratio $\nu \equiv \nu_{eff}/\gamma$ decreases

[*] H.L.Berk, B.N.Breizman, and M.S.Pekker, Plasma Phys. Reports 23 (1997) 778

STEADY-STATE → PITCHFORK → CHAOTIC TAE ON JET



Spectrogram of magnetic fluctuations on JET (#49447). Amplitudes of TAEs with n=3 to 6 change in time from steady-state to pitchfork to chaotic

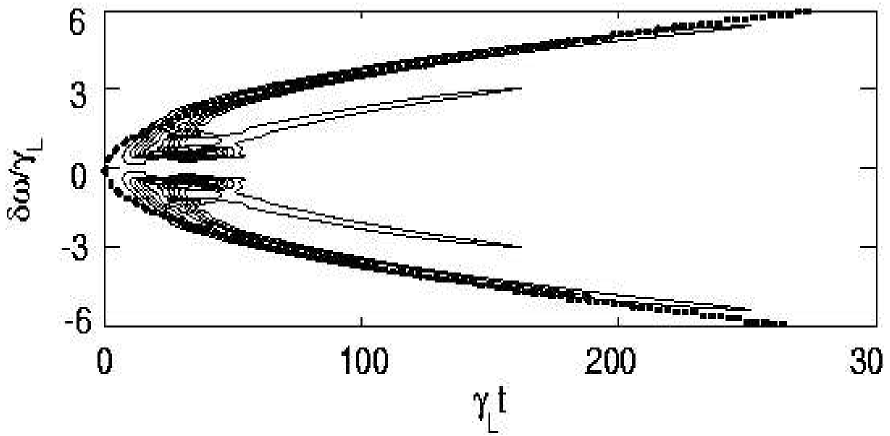


ICRH power increases from 0 to 5 MW during the observed TAE-amplitude transition

[*] A. Fasoli et al., Phys. Rev. Lett. 81 5564 (1998)
[**] R.F. Heeter et al., Phys. Rev. Lett. 85 3177 (2000)

THE HOLES AND CLUMPS THEORY

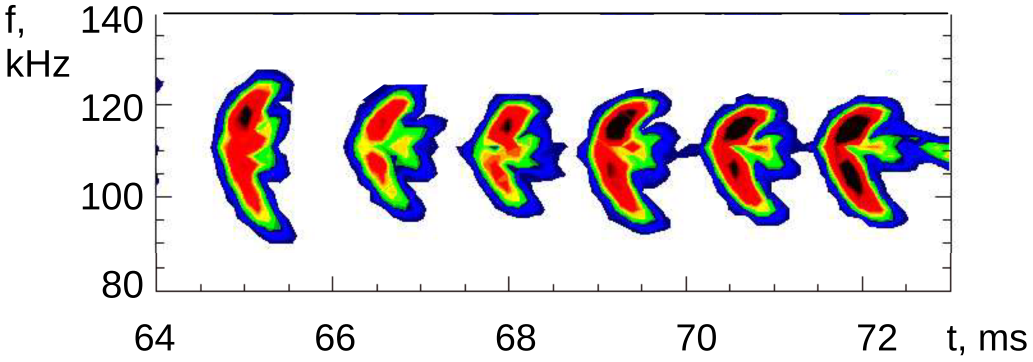
- **Explosive regime in a more complete non-linear model leads to frequency-sweeping 'holes' and 'clumps' on the perturbed distribution function. (H.L.Berk, B.N.Breizman, and N.V.Petviashvili, Phys. Lett. A234 (1997) 213)**



- **These long-living Bernstein-Greene-Kruskal (BGK) nonlinear waves sweep in frequency away from the starting frequency, with frequency sweep**

$$\delta\omega \propto \omega_b^{3/2} t^{1/2}; \quad \omega_b(t) \propto \left|\delta B_{TAE}\right|^{1/2}$$

MAST: FREQUENCY-SWEEPING MODES ARISING FROM TAEs

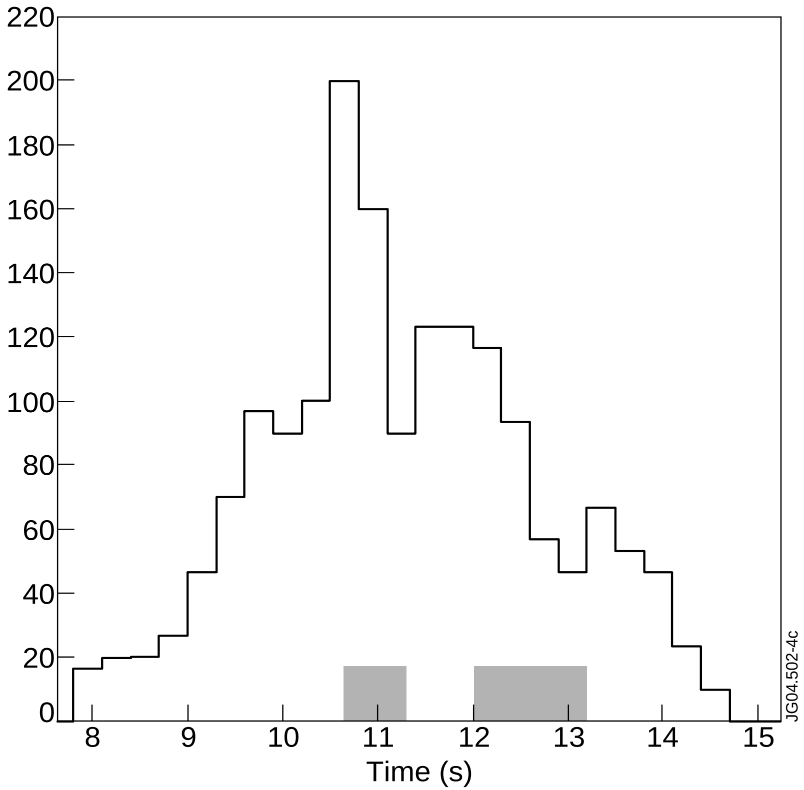


Identified as hole-clump frequency-sweeping pairs (Talk by S.Pinches)

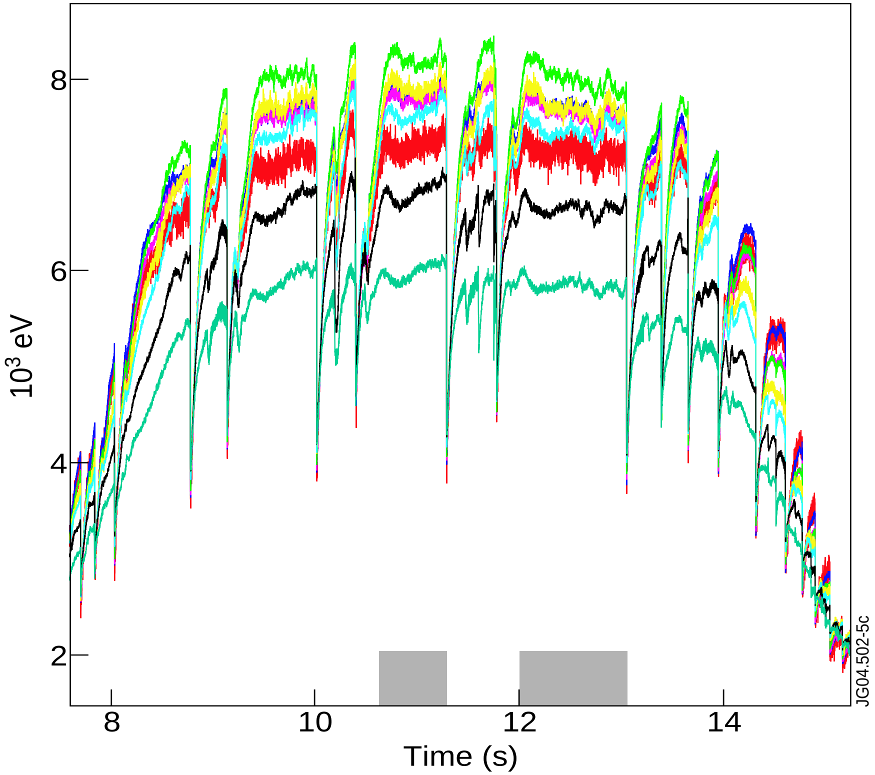
Effect of Alfven Eigenmodes on ICRH-accelerated protons in q=1 plasmas in JET

This JET data supports previously published results from
JT-60U (Saigusa et al., PPCF 40 (1998) 1647)
TFTR (Bernabei et al., Phys. Rev. Lett. 84 (2000) 1212)
DIII-D (Heidbrink et al., Nuclear Fusion 39 (1999) 1369)

Gamma-ray intensity from 5MeV protons decreases 0.5–1 sec before sawtooth crashes

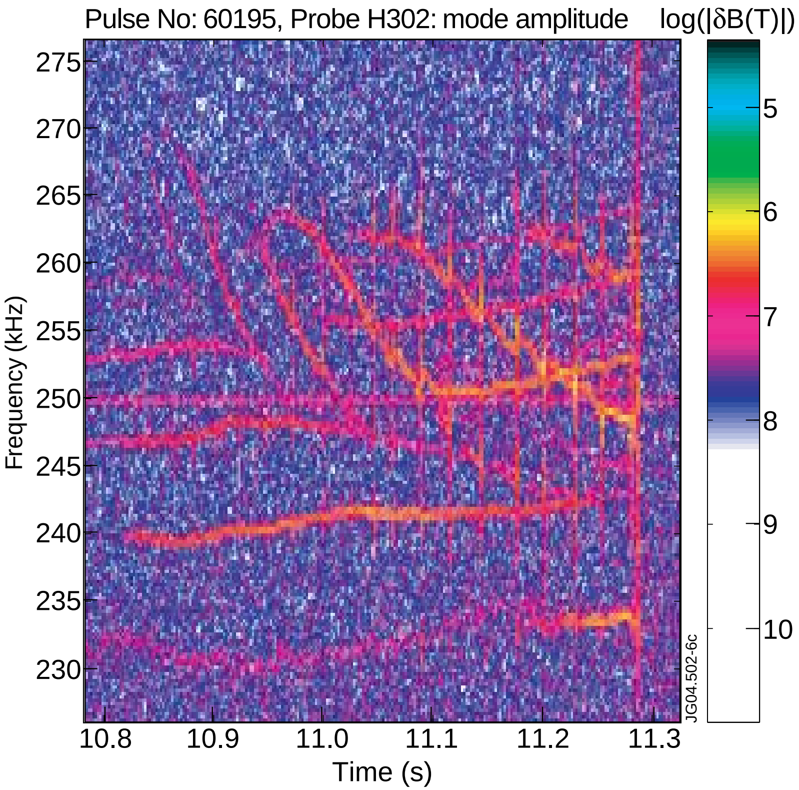


γ-rays from reactions ^{12}C(p, p'γ)^{12}C

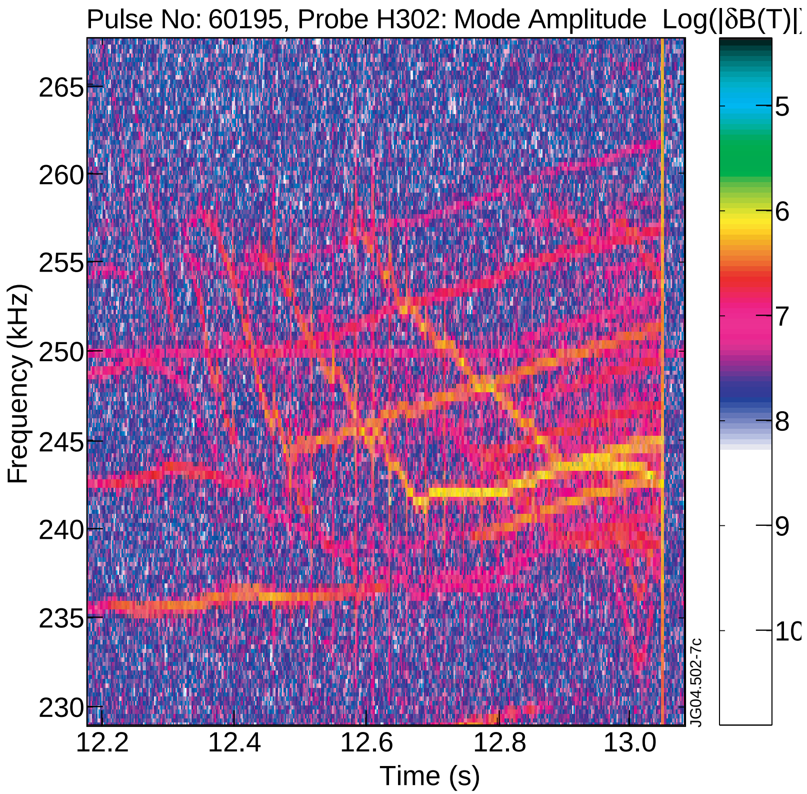


T_e at different radii show sawteeth at t=11.4, t=13 s occuring after decreases of γ- intensity

The Gamma-ray Decrease Happens when TAEs within q<1 (tornado modes) and TAEs outside q=1 coexist

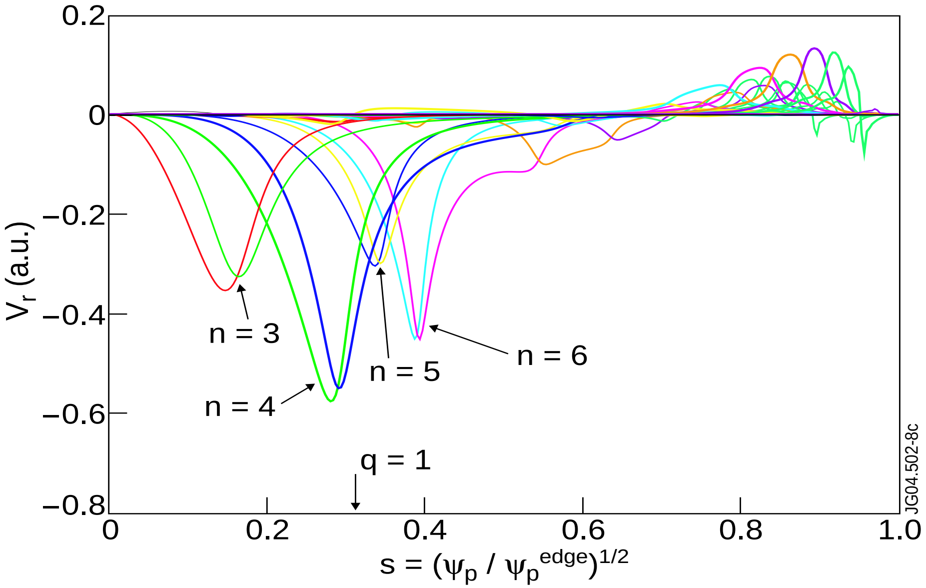


TAEs & tornadoes during first shaded time interval

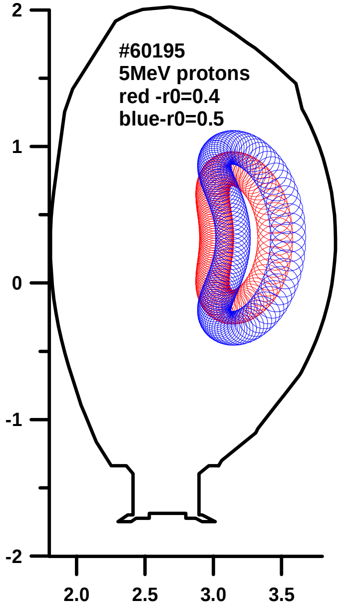


TAEs & tornadoes during second shaded time interval

The Gamma-ray Decrease Happens when TAEs within q<1 (tornado modes) and TAEs outside q=1 coexist



TAEs with n=3, 4 within the q=1 radius (tornado), and n=5,6 TAEs outside the q=1



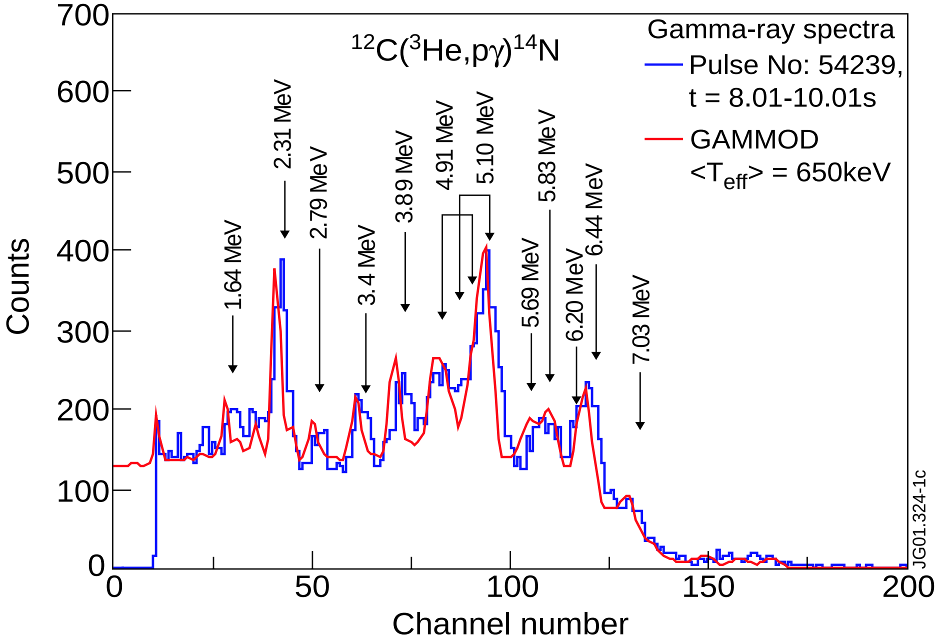
Orbits of 5 MeV protons

- **Prompt losses of protons with E>5 MeV (orbit width $\Delta_f/a \le 0.5$) enhanced by the TAEs are considered as a primary channel of proton losses.**

ICRF acceleration of ^{3}He minority: a step towards time resolved profiles of fast ions and ITER-relevant ratio of Δ_f/a

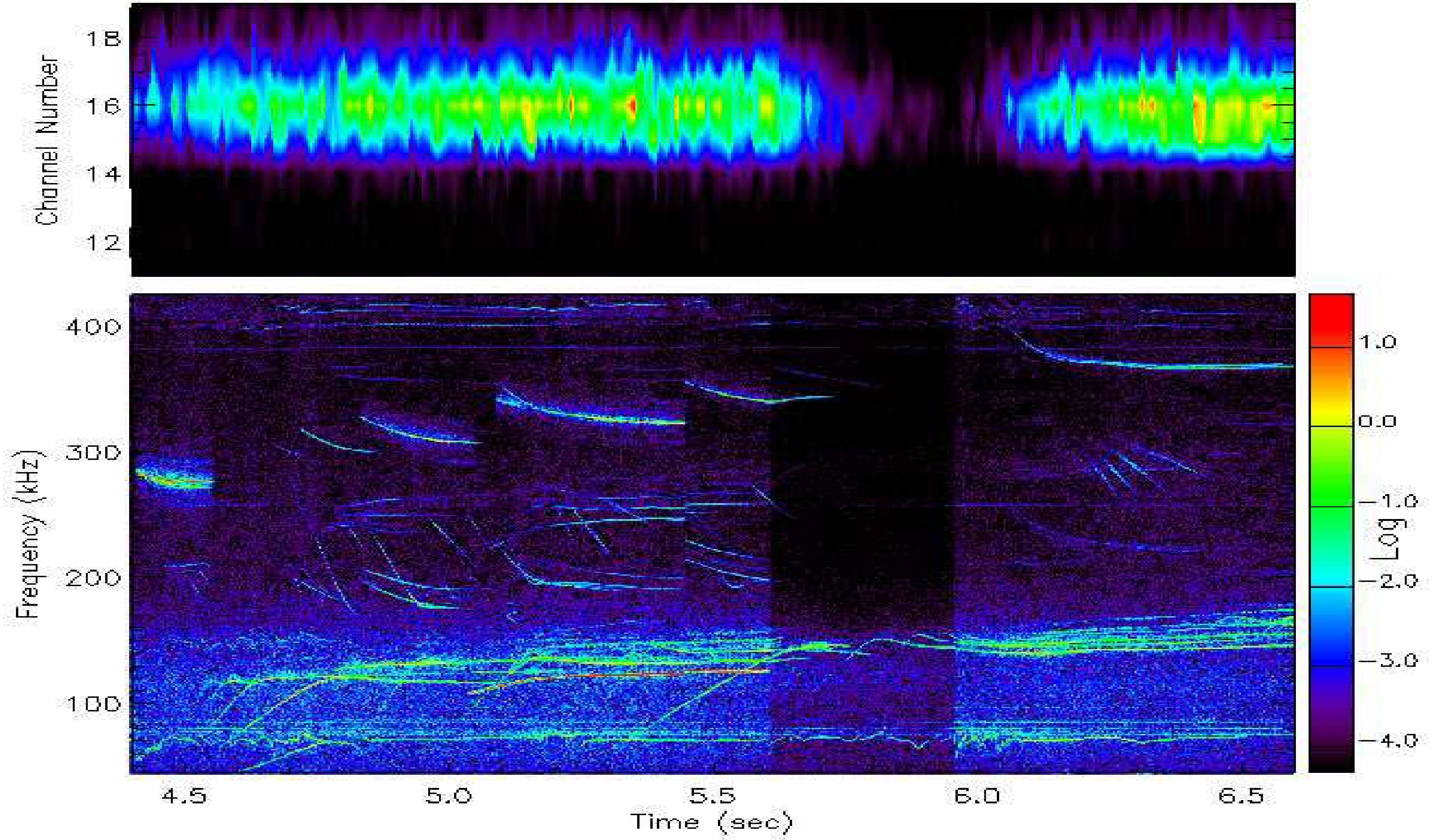
Why Fast ^{3}He in ^{4}He Plasma?

^{3}He with E>500 keV generates lots of gamma-rays when it collides with C and Be:



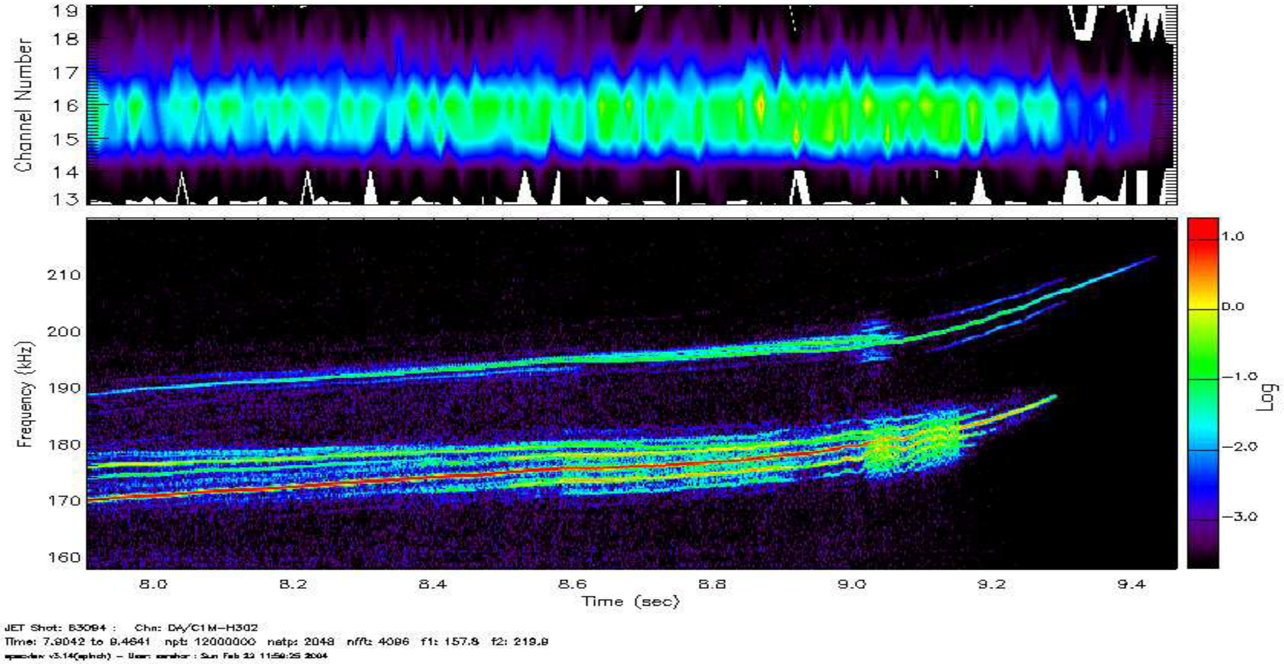
- For given n_e , T_i V_A / V_{Ti} is higher in He plasma ⇒ smaller AE damping on thermal ions
- Low neutron yield in ^{4}He plasma ⇒ excellent conditions for gammas

Profile of Fast Ions (Top) Measured Simultaneously with AEs (Bottom)



Notches of ICRH power (5 MW →1MW) show modes most sensitive to ^{3}He ions

Linear and Nonlinear Characteristics of AEs Assessed from *Measured* Profiles of Fast Ions

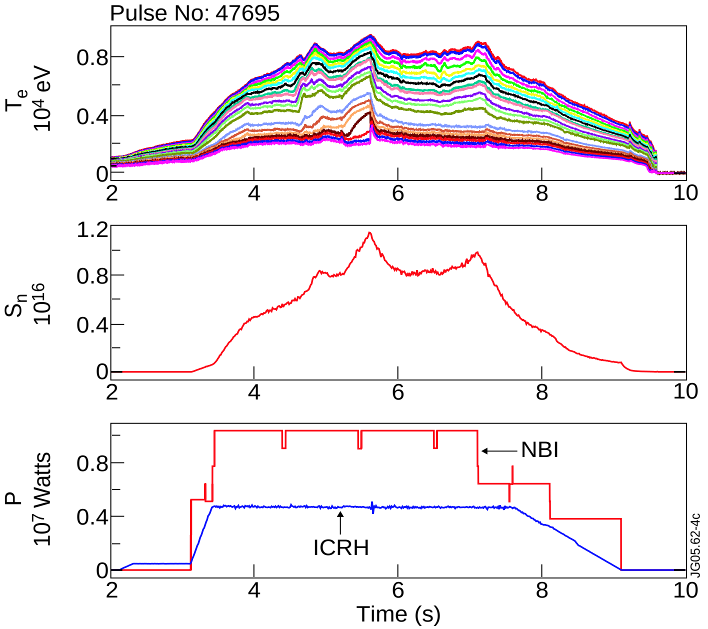


Nonlinear pitchfork splitting of ICRH-driven TAE as dβ_{fast}/dr increases by ~40%

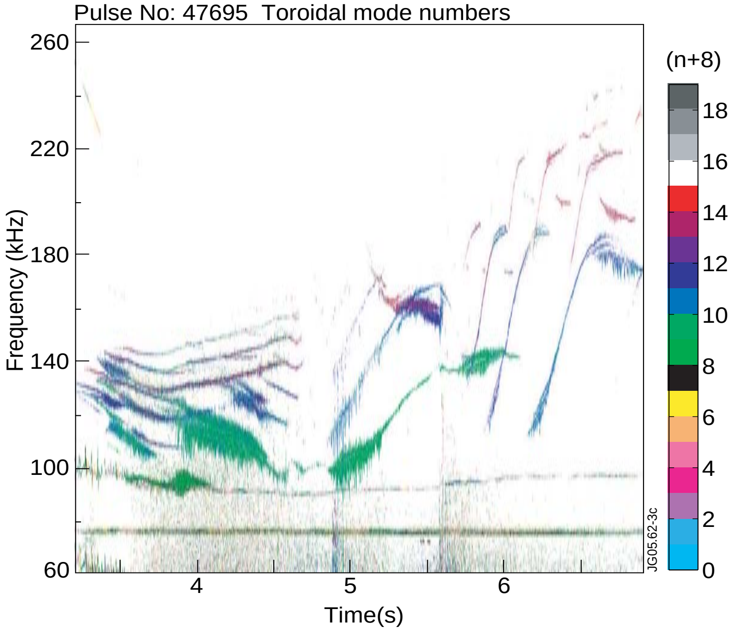
Tens of AEs were excited, but no degradation of fast ^{3}He observed in these I=2.3 MA discharges with orbit width of ^{3}He ions Δ_f / a <<1.

Alfvén Cascade (AC) Eigenmodes in Reversed-Shear Scenarios

ITER scenarios with high bootstrap current fractions may converge to ‘self-organised’ plasma equilibrium with strong reversed shear/current-holes as on JET and on JT-60U:



2.6T/2.5MA JET discharge without LHCD (#47695). ITB is triggered at t=44.6 and it increases plasma pressure gradient and bootstrap current.



Magnetic spectrogram shows TAEs before ITB trigger ⇒ flat/monotonic q, and Alfven Cascades after ITB trigger ⇒ reversed-shear

Alfvén Cascade (AC) Eigenmodes in Reversed-Shear Scenarios

H.Kimura et al., Nucl. Fusion 38 1303 (1998): First report on observing mysterious frequency-sweeping modes in JT-60U reversed-shear plasmas

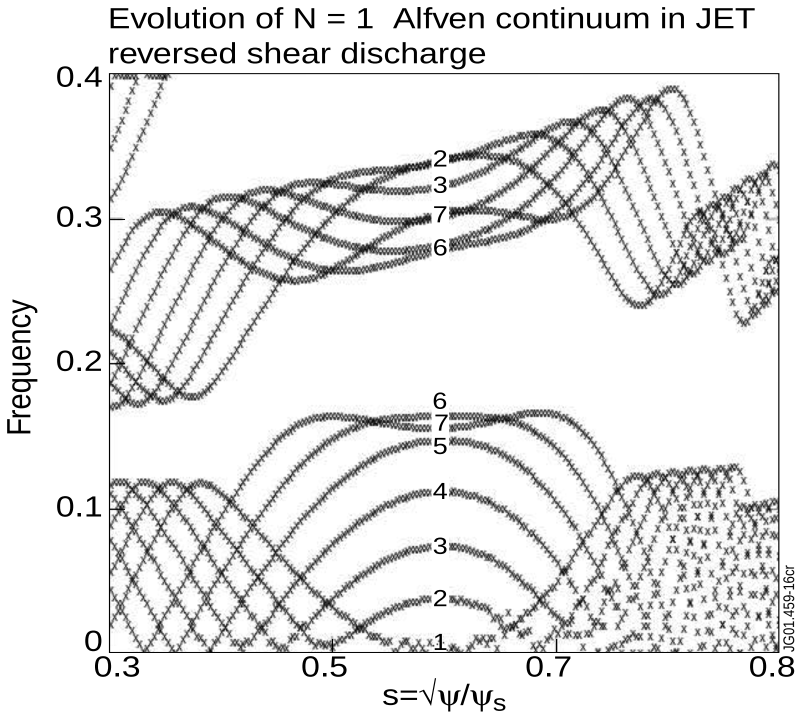
H.L.Berk et. al, Phys. Rev. Lett. 87 185002 (2001)
S.E.Sharapov et. al, Phys. of Plasmas 9 2027 (2002): Interpretation given

- ACs are localized in the vicinity of magnetic surface associated with minimum of $q(r)$
- The mode is associated with extremum of Alfvén continuum at $q_{\min}$
- As the value $q_{\min}(t)$ evolves in time due to current changes, the AC frequency changes:

$$\omega_{AC}(t)=\left|\frac{m}{q_{\min}(t)}-n\right|\frac{V_A(t)}{R_0}+\Delta\omega \Rightarrow \frac{d}{dt}\omega_{AC}(t)\approx m\frac{V_A}{R_0}\frac{d}{dt}q_{\min}^{-1}(t)$$

R.Nazikian et al., Phys. Rev. Lett. 91 125003 (2003): Alpha-particle driven AC identified in old TFTR data for DT plasma

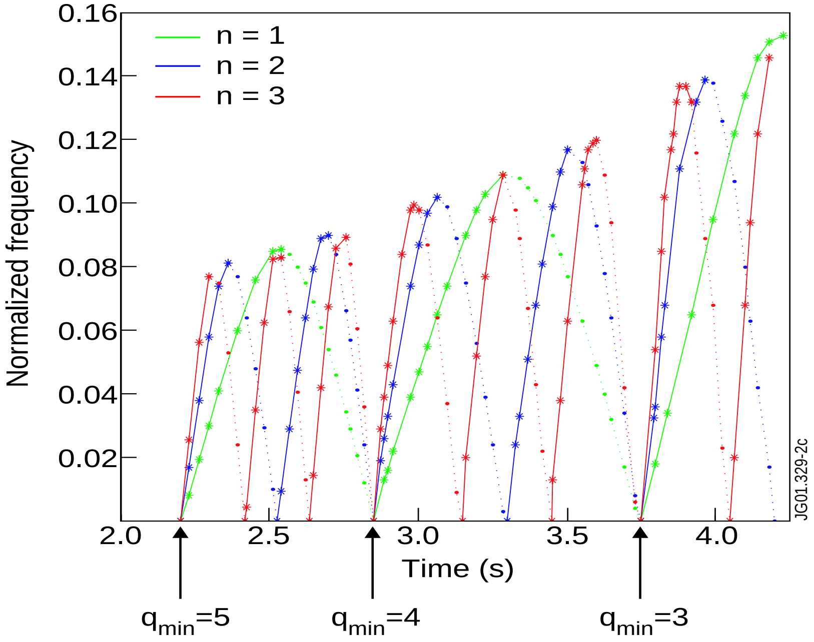
Alfvén Cascade (AC) Eigenmodes in Reversed-Shear Scenarios



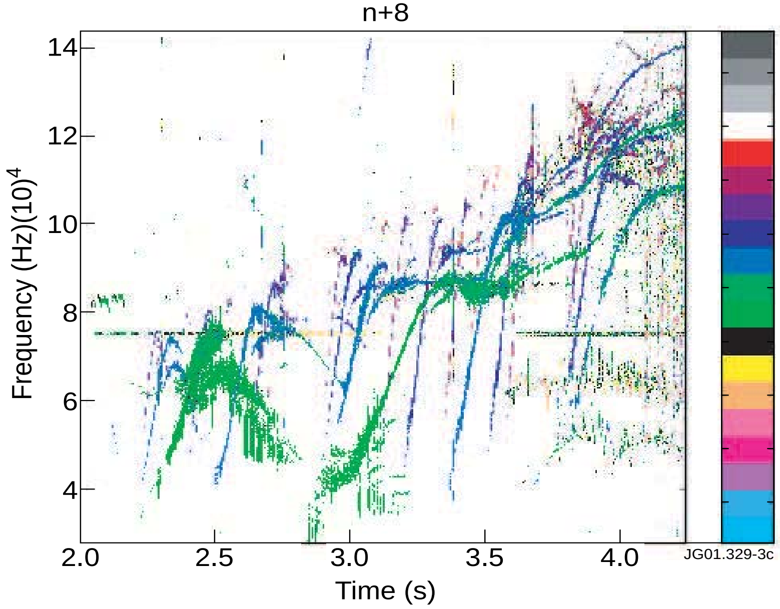
Evolution of n=1 Alfvén continuum as a function of r/a

with $q_{min}(t)$ evolving from q_{min}=3 to 2.9,…, 2.4

Alfvén Cascade (AC) Eigenmodes in Reversed-Shear Scenarios



Time evolution n=1, n=2, and n=3 continuum tips during $q_{min}(t)$ evolution



Magnetic spectrogram showing Alfven Cascade Eigenmodes in reversed-shear JET plasma (pulse #49382)

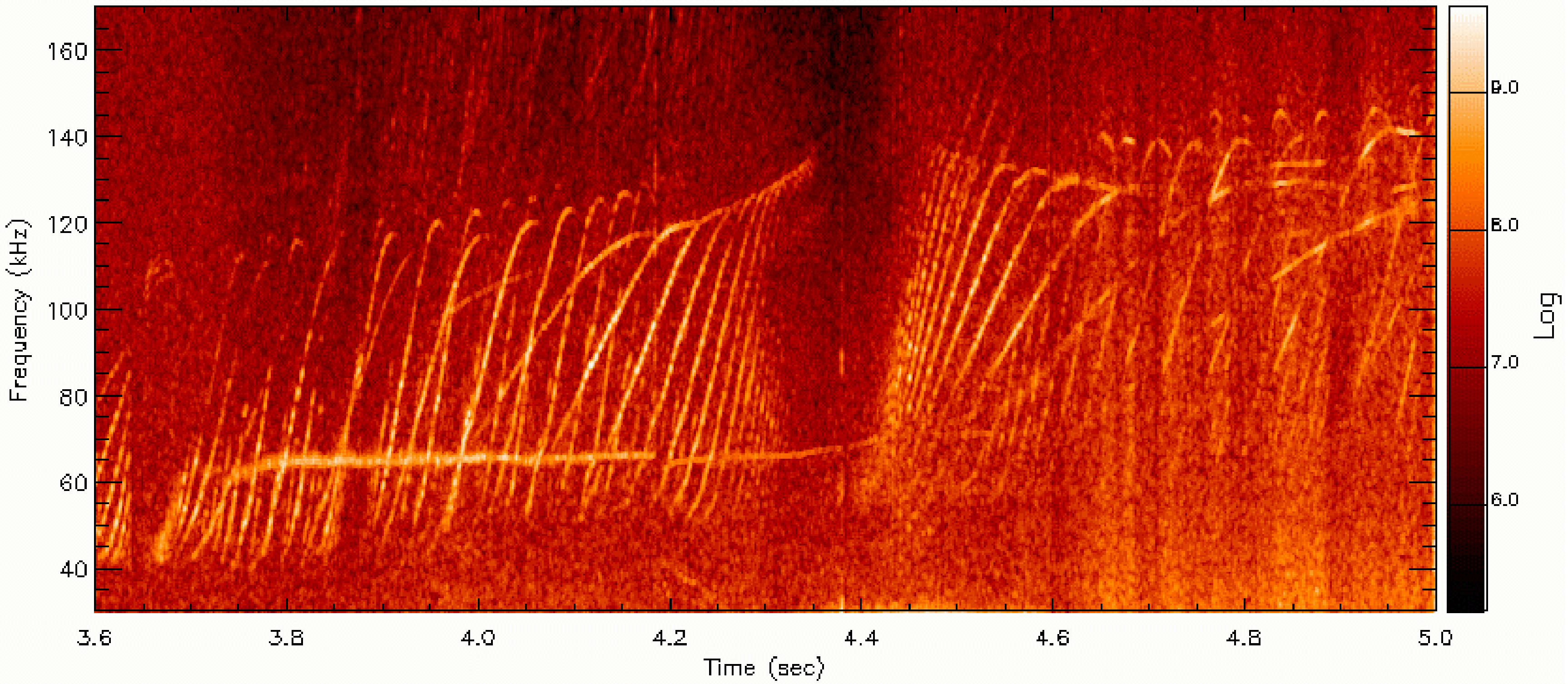
Alfvén Cascades are routinely used on JET for diagnosing $q_{min}(t)$ evolution

Novel approach to diagnosing Alfvén Eigenmodes based on interferometry of internal density fluctuations shows many more unstable modes:

Collaboration between EFDA-JET and G.Kramer, R.Nazikian (PPPL),

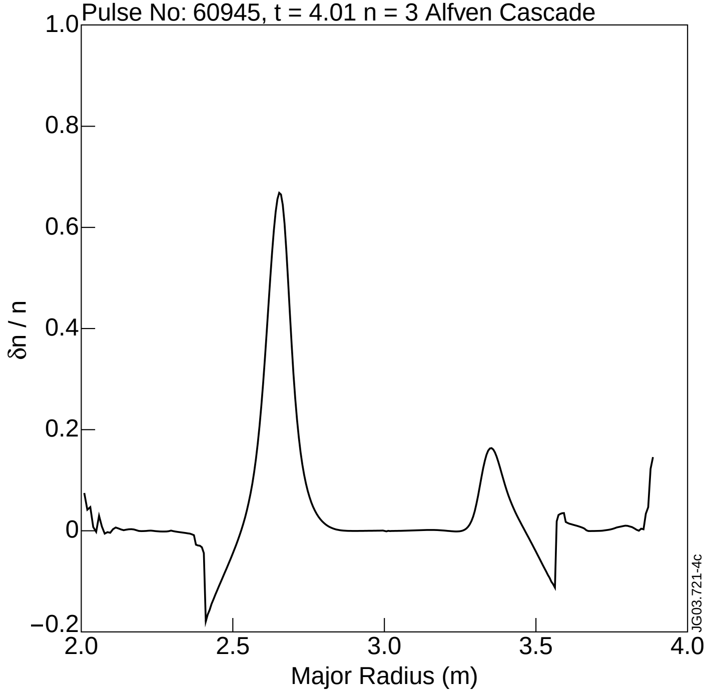
S.E.Sharapov et al., Phys. Rev. Lett. 93 (2004) 165001;
R.Nazikian et al., 20th IAEA Fuion Energy Conf., Vilamoura, Portugal, paper EX/5-1 (2004)

Alfvén Cascades detected with O-mode interferometry

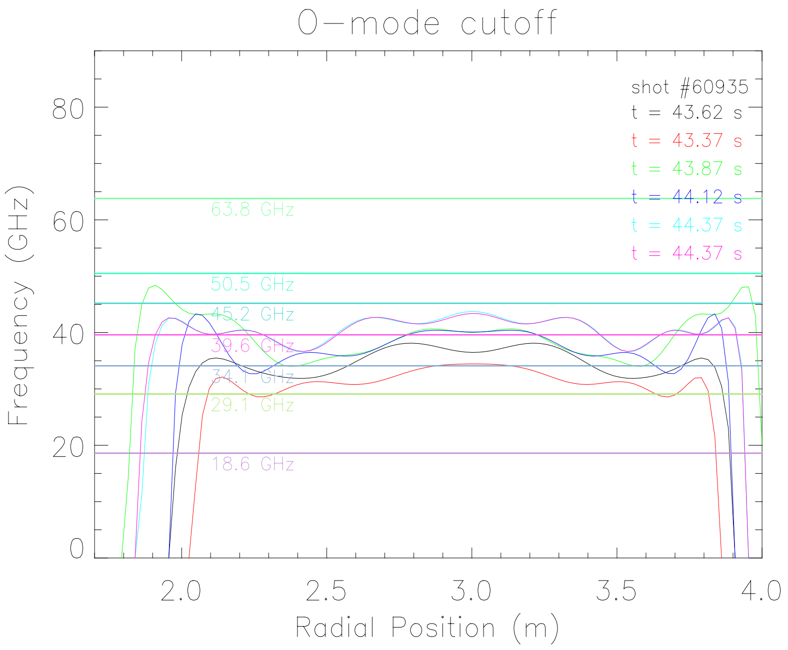


Perturbed density versus perturbed magnetic field

$$\frac{\delta\rho}{\rho} = -\nabla\cdot\xi - \xi\cdot\frac{\nabla\rho}{\rho} \cong \left(\frac{-2\hat{\mathbf{R}}}{R^2} + \frac{\hat{\mathbf{n}}}{L_\rho}\right)\cdot\xi$$

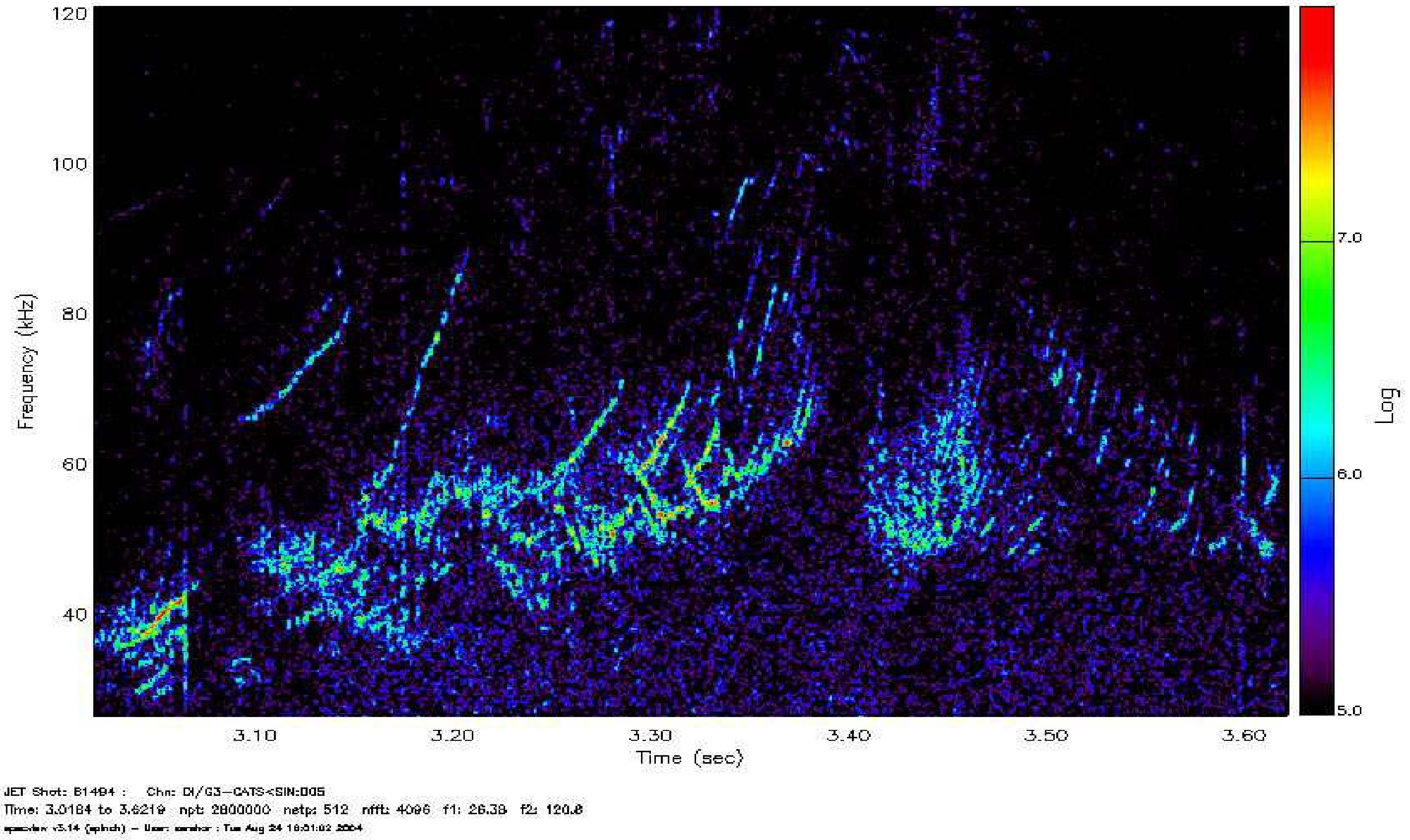


Profile of density perturbations caused by n=3, m=6 Alfvén Cascade, as a function of R



O-mode cut-off vs. R. Frequencies of six micro-wave beams launched from R=4 m are also shown

Further development: detection of ACs driven by sub-Alfvénic NBI ($V_{||}$~0.2 V_A)



Further development

Successful use of interferometry on DIII-D (R.Nazikian) and PCI on C-Mod (J.Snipes) for mode detection from density perturbations

Observation of ACs excited by sub-Alfvénic tangential NBI on DIII-D (R.Nazikian)

Detection of ACs with “usual” JET interferometry (B.Alper)

Summary

- α-simulation experiment: fast ^{4}He profiles measured in shear-reversed and monotonic-q(r) plasmas.
- Simultaneous measurements of ^{4}He with E>1.7 MeV and D with E>500 keV
- Theories of TAE spectrum and nonlinear evolution without overlapping resonances are in a broad agreement with experimental data
- Decrease of γ-rays from 5 MeV protons during "tornado" and TAE activity is interpreted as TAE-enhanced loss of protons with $\Delta_f \leq a$
- Time-resolved profile of ^{3}He ions (E>500 keV) measured simultaneously with AEs $\Rightarrow$ study with measured fast ion profiles becomes possible. No losses.
- Alfvén Cascade instability in shear-reversed advanced scenarios explained
- Interferometry diagnostics for Alfvén Eigenmodes shows significantly larger number of unstable modes driven by fast ions, including sub-Alfvénic NBI
- Understanding of AEs is generally good, but extrapolation to ITER-relevant high-n AE and search for stabilising techniques has to be performed yet