TRANSPORT CAUSED BY TAE

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OUTLINE OF LECTURE 5B

- Qualitative estimates of fast ion transport induced by TAE
- Orbits comparable to a : enhanced prompt losses due to TAE
- Orbits smaller than a : onset of particle orbit stochasticity and transport due to the resonance overlapping
- Experimental measurements of confined and lost fast ions
- Trapped ion redistribution by TAE inside the q=1 radius (“tornado” modes)
- Multi-mode experiments on JET
- Summary

QUALITATIVE ESTIMATES – 1

- The *unperturbed* orbit of a particle is determined by three invariants:

$$\mu \equiv \frac{Mv_\perp^2}{2}\,; \qquad E \equiv \frac{Mv^2}{2}\,; \quad P_\varphi \equiv -\frac{e}{c}\psi(r) + RMv_\varphi$$

- In the presence of a *single TAE* mode with perturbed quantities $\propto \exp i(n\varphi - \omega t)$, the wave-particle interaction is invariant with respect to transformation

$$t \to t + \tau\,; \quad \varphi \to \varphi + \frac{\omega}{n}\tau$$

- In the presence of the TAE, neither E nor P_φ is conserved for particle orbit, but *their following combination is still invariant*:

$$E - \frac{\omega}{n}P_\varphi = const$$

- Change in the particle energy is related to change in particle radius produced by TAE

$$\Delta E = \frac{\omega}{n}\Delta P_\varphi \cong \frac{\omega e}{nc}\psi'\Delta r$$

- The relative change in particle energy is much smaller than in particle radius:

$$\frac{\Delta v}{v} = \frac{\omega}{\omega_{*\alpha}} \cdot \frac{\Delta r}{L_\alpha}\,; \quad \text{where } \omega_{*\alpha} \equiv \frac{nq\rho_\alpha v}{2rL_\alpha} >> \omega$$

QUALITATIVE ESTIMATES – 2

- **The interaction between TAE and fast particles causes *radial transport of the particles at nearly constant energy***

- **This type of interaction is extremely unpleasant as it may deposit a population of fusion born alphas too close to the first wall**

- **Losses of fusion born alphas must be minimised down to few percent (<5% on ITER) for avoiding the first wall damage**

- **The radial redistribution also gives a non self-consistent alpha-heating profiles etc. and may affect the burn**

TWO MAIN TYPES OF THE TAE-INDUCED TRANSPORT

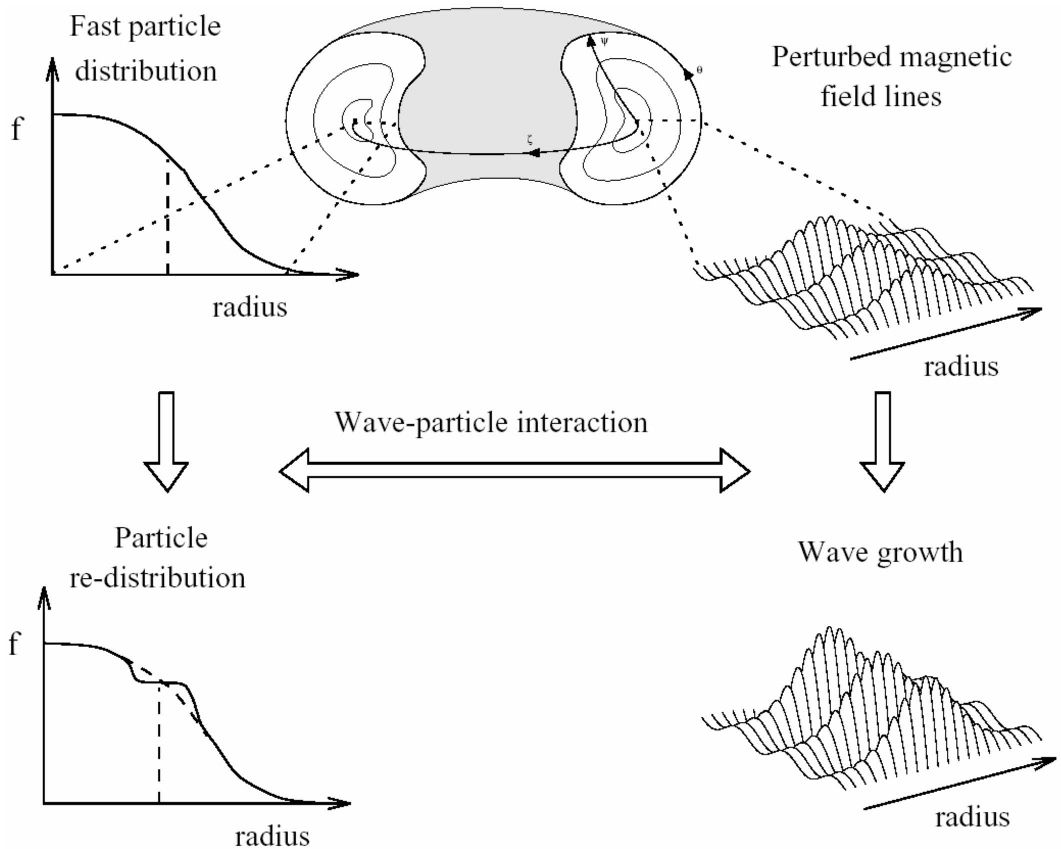
- **Fast ion orbits comparable to the machine radius, $\rho_\alpha / a \cong 10^{-1} \div 1$. A single-mode *'convective' transport* is observed in present-day machines (DIII-D, TFTR, JET, JT-60U). TAE-induced enhancement of prompt losses is important, losses $\propto \delta B_{TAE}$**

- **For ITER with parameter $\rho_\alpha / a \cong 10^{-2}$ the dominant channel of alpha-particle transport is predicted to differ from present-day machines.**

- **On ITER, higher-*n* (*n* > 10) TAEs will be most unstable. The radial width of a poloidal harmonic will be more narrow, $\Delta_{\mathrm{mode}} \propto r_{AE} / nq$, but the number of unstable modes may be significantly larger than in present-day tokamaks**

- **Resonance overlap will lead to a global stochastic diffusion of energetic ions over a broad region with unstable AEs, with transport $\propto \delta B_{TAE}^2$**

MODELLING TAE-ORBIT INTERACTION (HAGIS CODE)



S.D.Pinches et al., Computer Physics Communications 111 (1998) 133

HAMILTONIAN APPROACH FOR δf

Trajectory of each individual macro-particle follows the Hamiltonian approach [White & Chance, Phys. Fluids 27 (10) 1984] leading to equations of the type:

$$\frac{\partial \psi_p}{\partial \vartheta} = \frac{1}{D}\left[I \frac{\partial \tilde{A}_\zeta}{\partial \vartheta} - g \frac{\partial \tilde{A}_\vartheta}{\partial \vartheta} \right]; \quad \frac{\partial \psi_p}{\partial \zeta} = \frac{1}{D}\left[I \frac{\partial \tilde{A}_\zeta}{\partial \vartheta} - g \frac{\partial \tilde{A}_\vartheta}{\partial \zeta} \right]; \quad \frac{\partial \psi_p}{\partial P_\vartheta} = \frac{g}{D}; \quad \frac{\partial \psi_p}{\partial P_\zeta} = -\frac{I}{D}$$

For the shear Alfvén modes, the assumption $\tilde{\mathbf{A}} = \tilde{\alpha}(\mathbf{x}, t) \cdot \mathbf{B}_0$ is used;

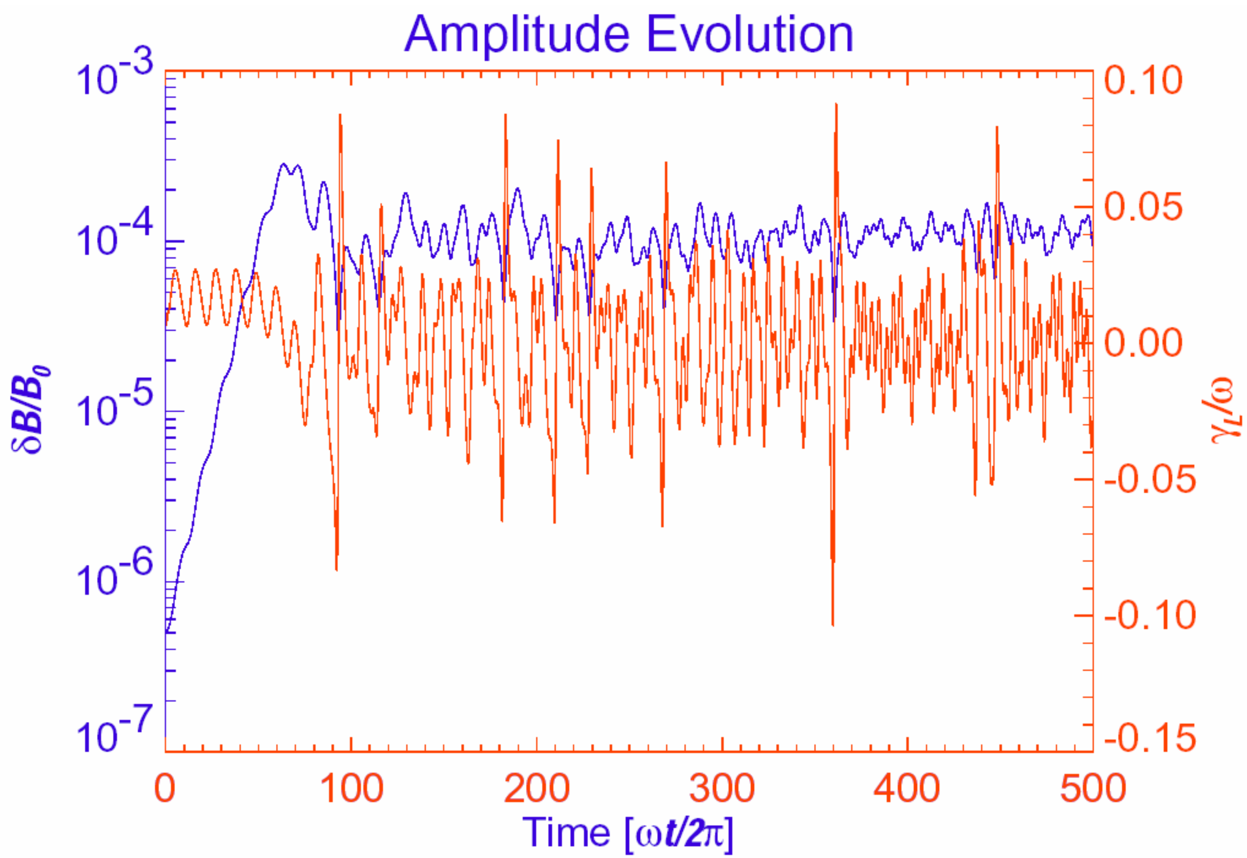
Nonlinear code: for the eigenmode structure provided by CASTOR or MISHKA, the mode amplitude and phase are evolving through (schematically):

$$\frac{dA}{dt} = A_0 + \sum_{particles} (\ldots) - \gamma_{damp} A; \qquad \frac{d\varphi}{dt} = \varphi_0 + \sum_{particles} (\ldots),$$

for unchanged mode structure

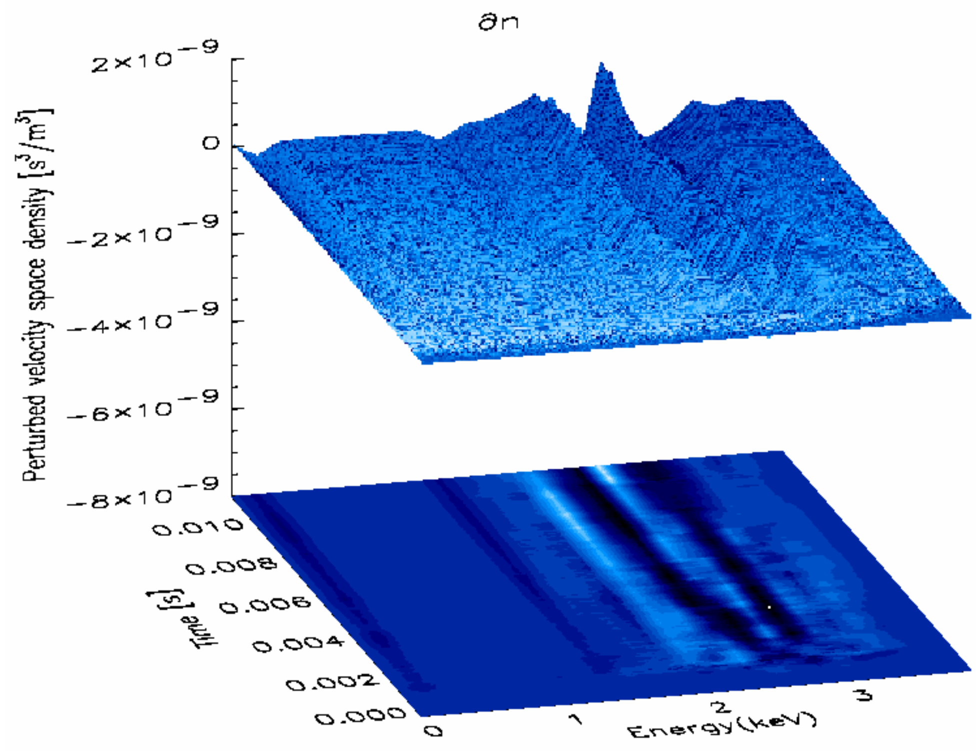
δf low-noise technique is used for deviation from f_0 computed by launching >10^5 macro-particles

MODE EVOLUTION FROM HAGIS

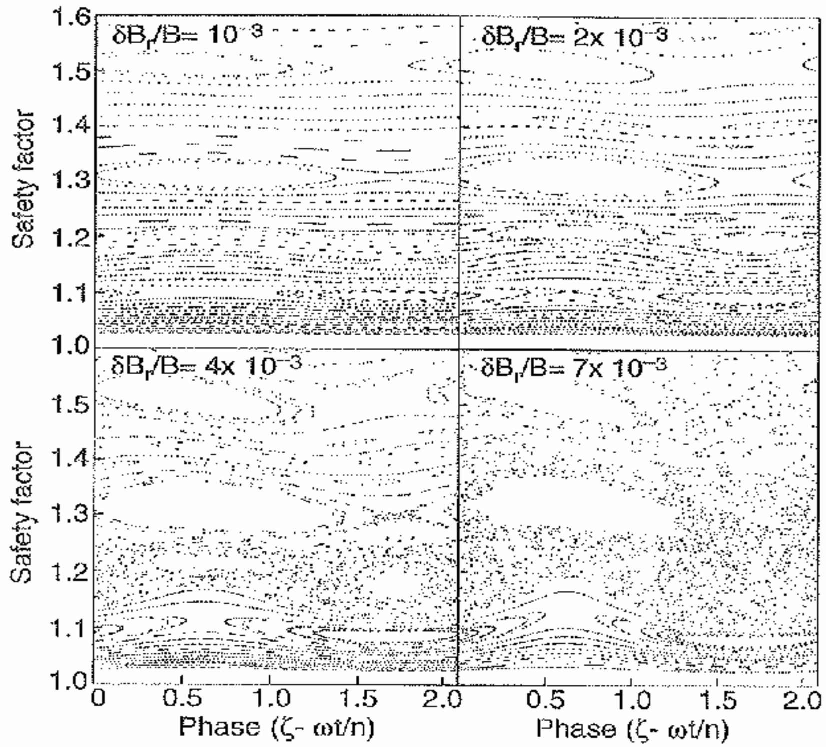


γ_d/ω = 2%, $\beta\langle f\rangle = 3\times10^{-4}$

FAST ION REDISTRIBUTION



DRIFT ORBIT STOCHASTICITY (HAGIS MODELLING FOR JET)



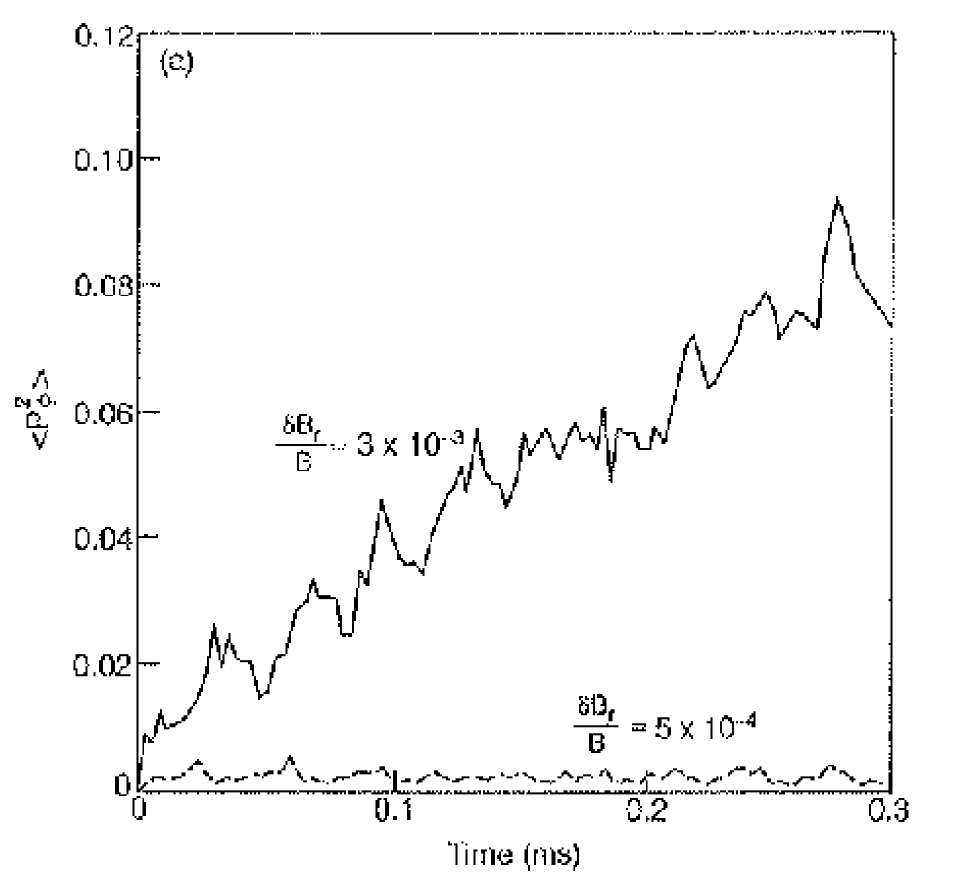
- **The analytically derived stochasticity threshold (Berk et al Phys. Fluids B5, 1506, 1993) is close to that obtained numerically:**

$$\delta B_r / B_0 > r_{TAE} \cdot \left(64 m R_0 q S\right)^{-1} \cong 1.5 \times 10^{-3} / m$$

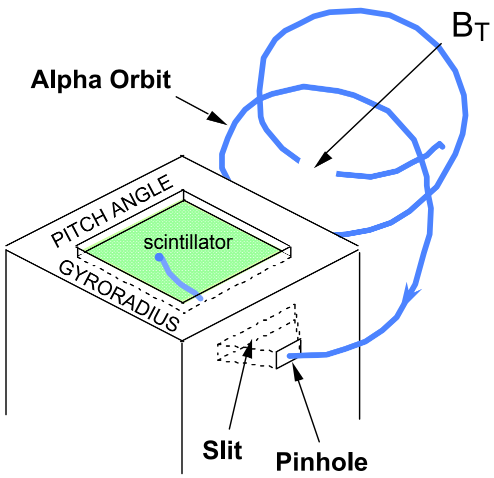
NOTE

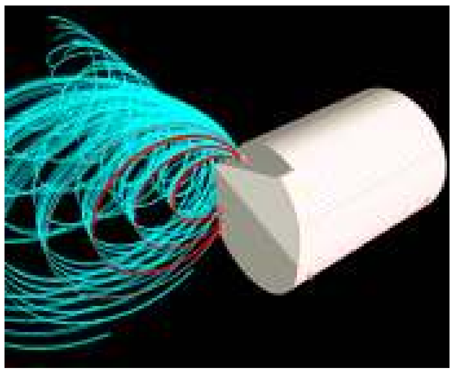
- **TAE is ideal MHD mode and does NOT cause stochasticity of magnetic field**
- **The stochasticity affecting the fast ions arises in the DRIFT surfaces of the fast ions, NOT in the magnetic flux surfaces**

STOCHASTIC TRANSPORT OF ALPHAS ON JET (HAGIS-95)

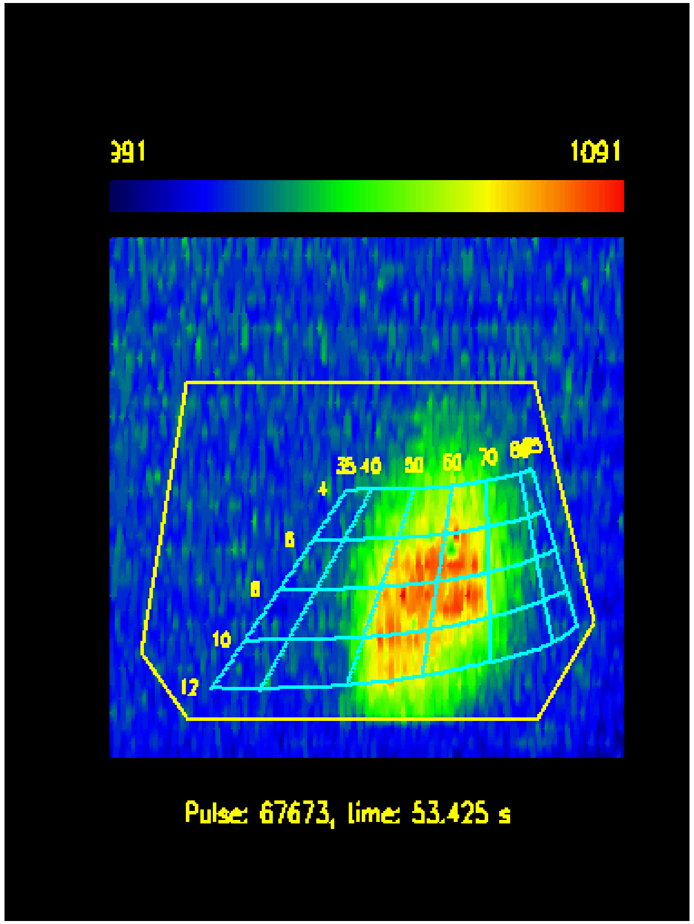


EXPERIMENTAL MEASUREMENTS OF LOST FAST IONS ON JET





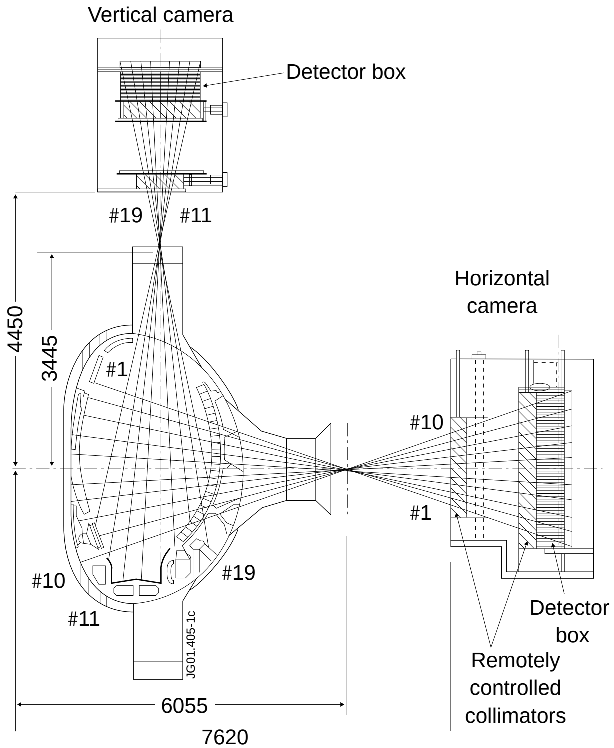
THE SCINTILLATOR DATA



EXPERIMENTAL MEASUREMENTS OF CONFINED FAST IONS

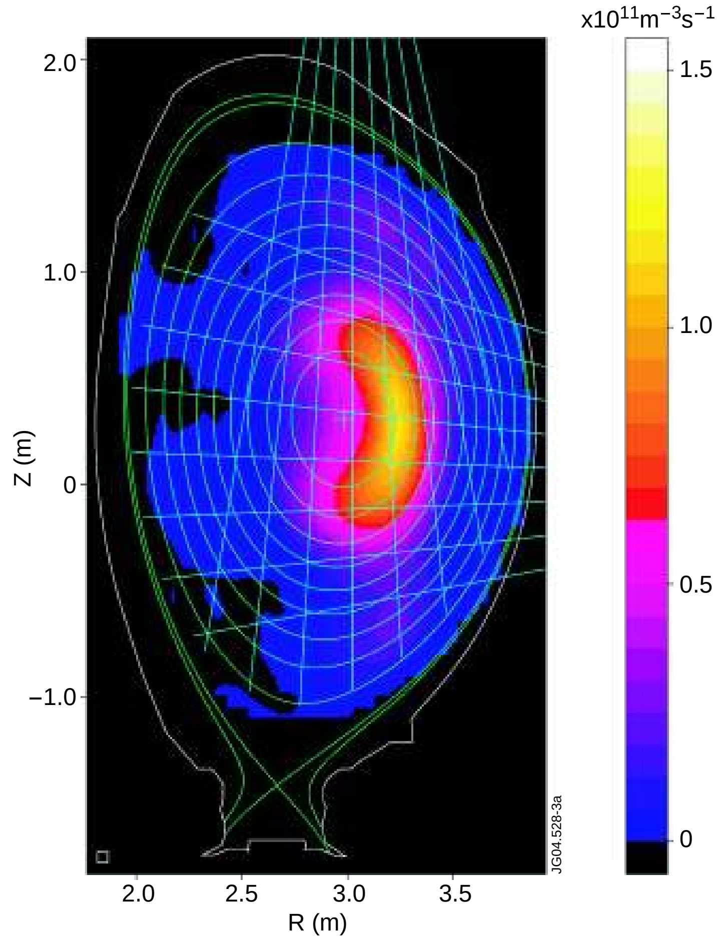
- **Intense gamma-ray emission comes from JET plasmas**
- **These gamma-rays come from nuclear reactions between *fast* ions with E > E_{crit} and main plasma impurities C and Be**
- **The gamma ray spectrum is *discrete,* each nuclear reaction gives gamma-ray of *certain* energy**

GAMMA-CAMERA ON JET

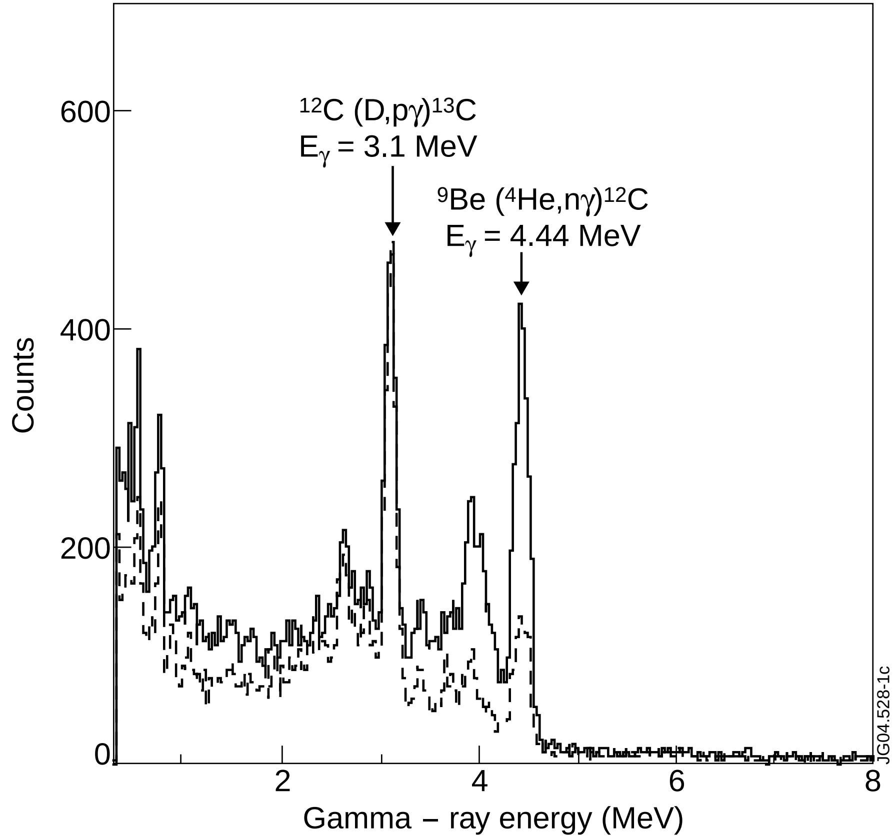


Schematic of the JET gamma camera used for the spatial gamma-ray emissivity measurements.

TYPICAL GAMMA-RAY IMAGE OF FAST IONS



ENERGY SPECTRUM OF THE GAMMA EMISSION

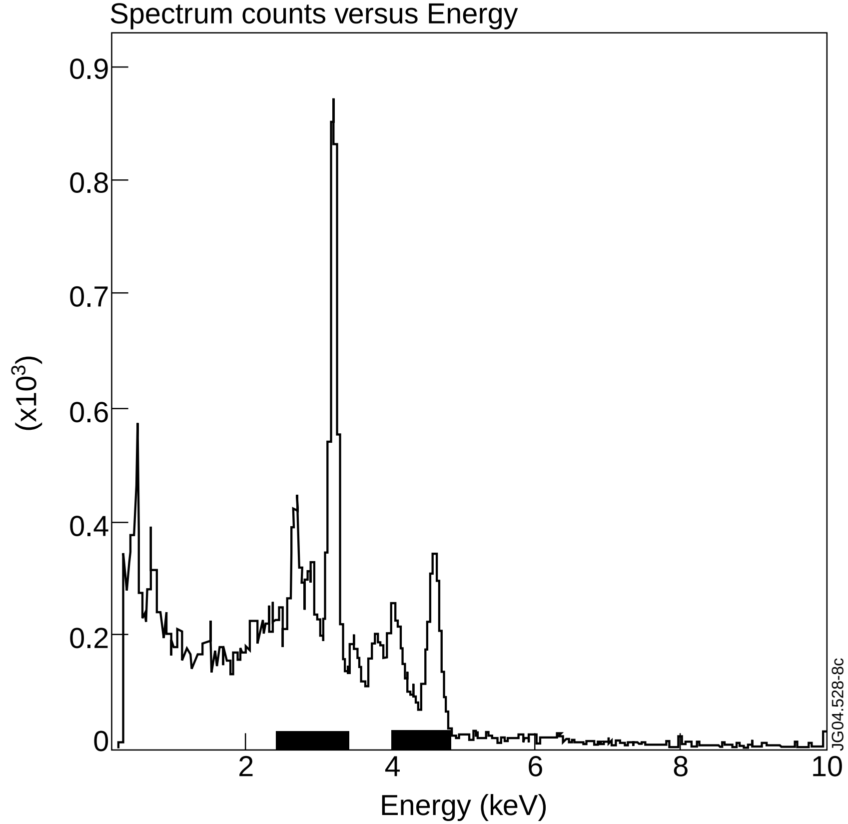


Gamma-ray spectra measured by the NaI(Tl) detector

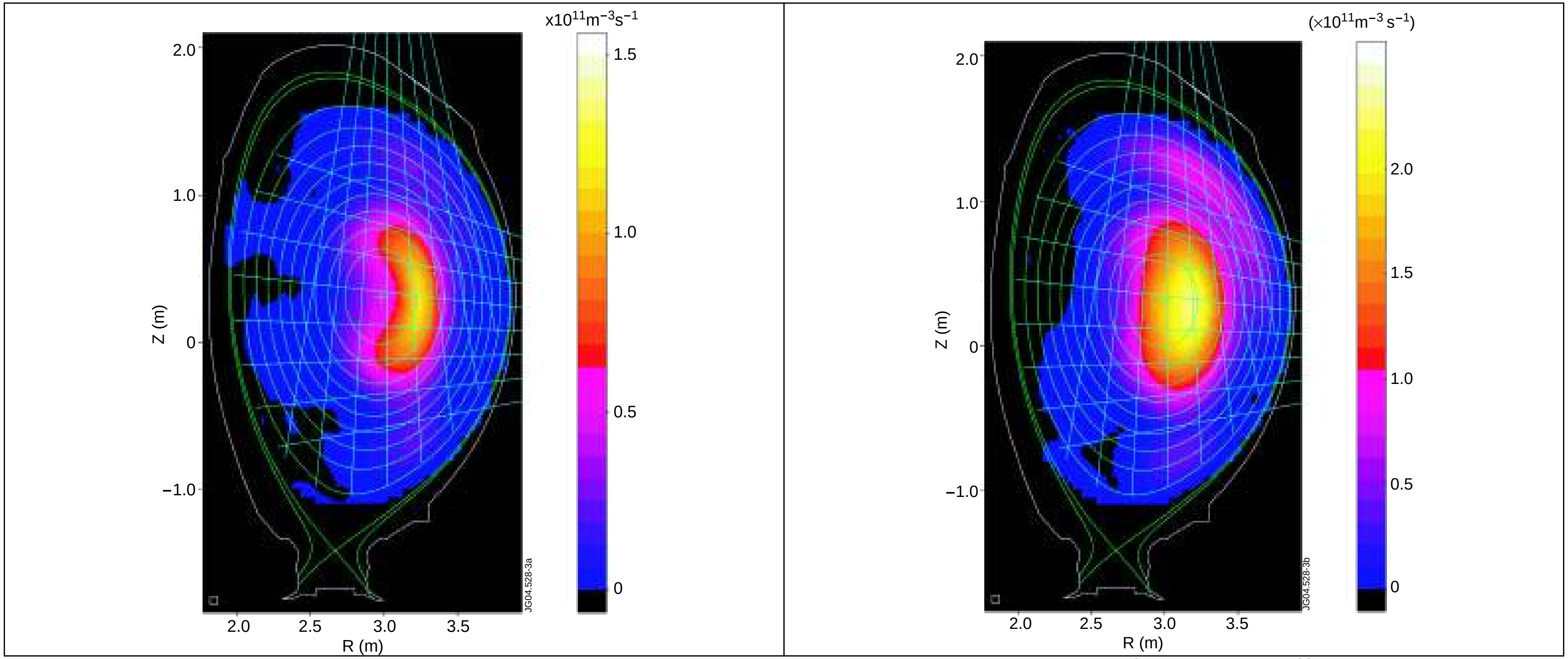
SIMULTANEOUS MEASUREMENTS OF ^{4}He AND D FAST IONS

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)



Tomographic reconstructions of 4.44-MeV γ-ray emission from the reaction $^{9}Be(^{4}He,n\gamma)^{12}C$ (left) and 3.09-MeV γ-ray emission from the reaction $^{12}C(D,p\gamma)^{13}C$ (right) deduced from simultaneously measured profiles

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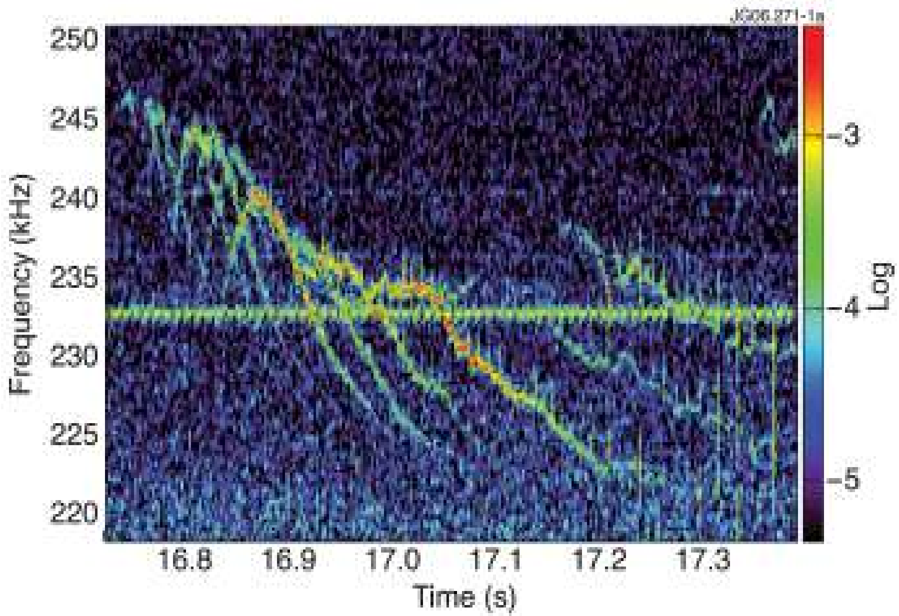
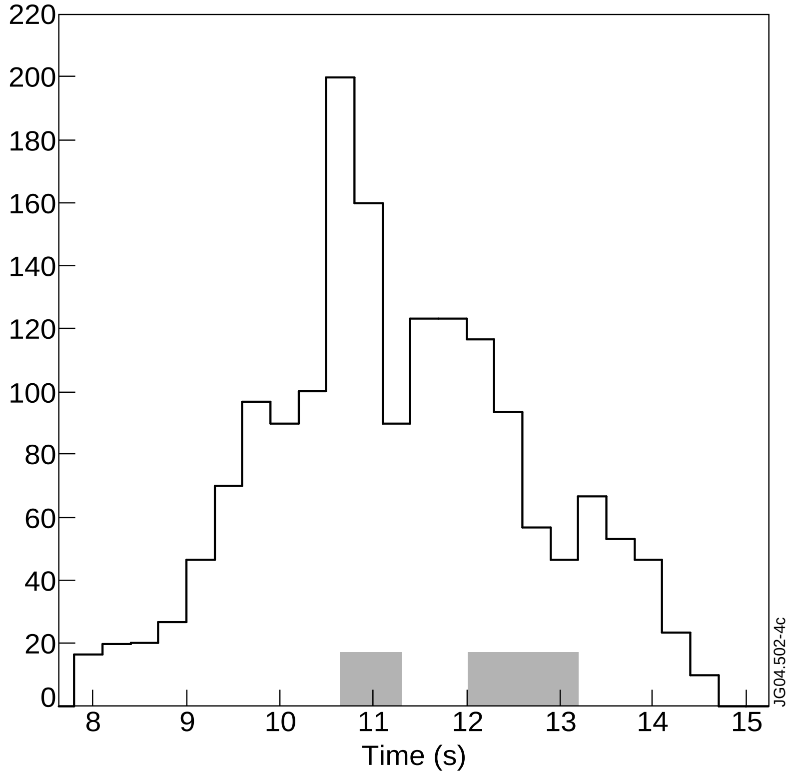
"TORNADO" MODES AND ENERGETIC ION TRANSPORT ON JET

- **Tornado mode = TAE inside the q=1 radius. Usually precedes monster sawtooth crash.** (Kramer, Sharapov et al, PRL 2004)

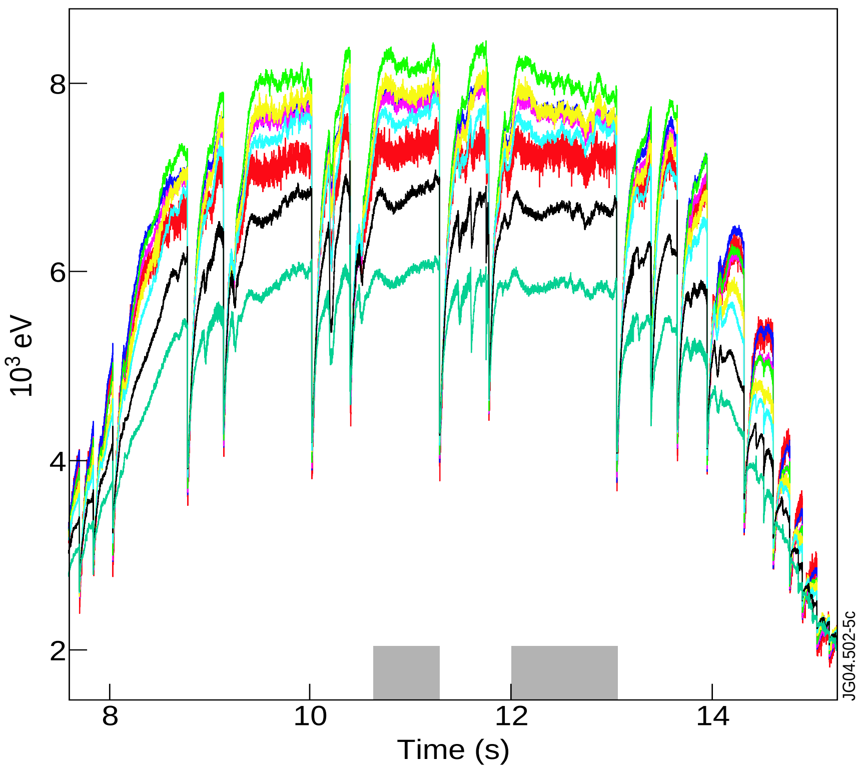
- **Tornado modes are considered to be possible reason for expelling fast ions from the q=1 region and causing monster sawtooth crash due to the loss of fast ion stabilisation**



JET (2004): GAMMA-RAY INTENSITY FROM 5MeV PROTONS

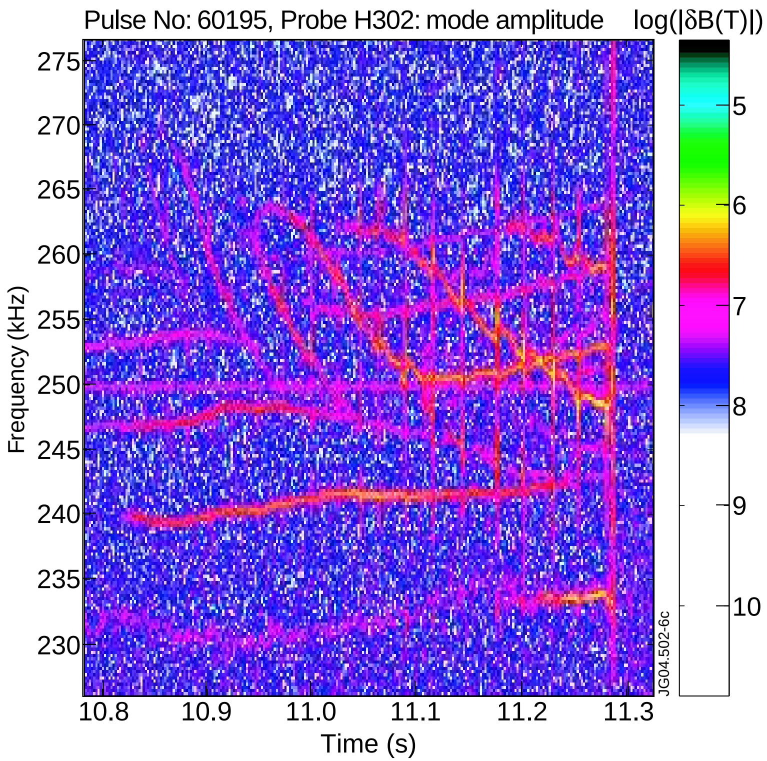


γ-rays from reactions $^{12}C(p, p'\gamma)^{12}C$

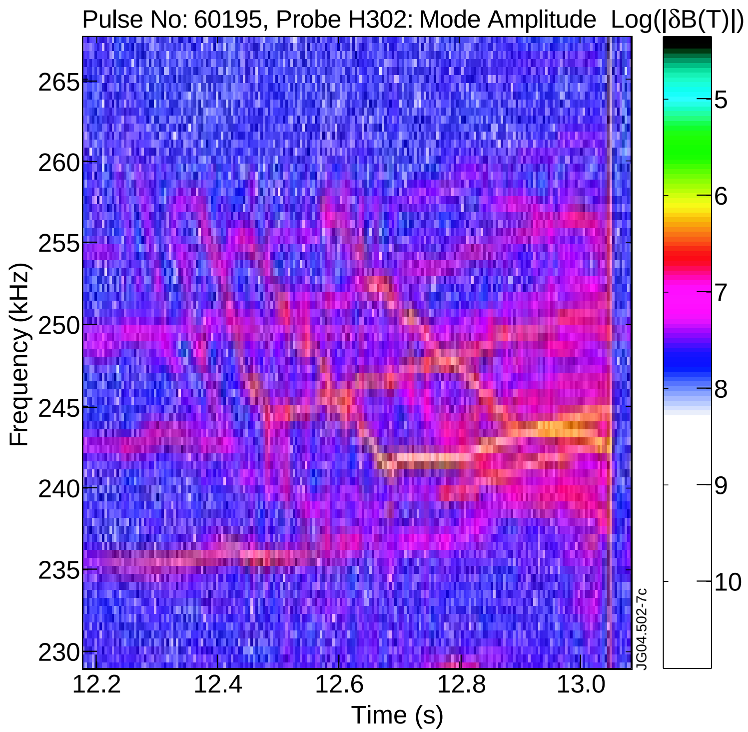


T_e at different radii show sawteeth at t=11.4, t=13 s occuring after decreases of γ-intensity

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

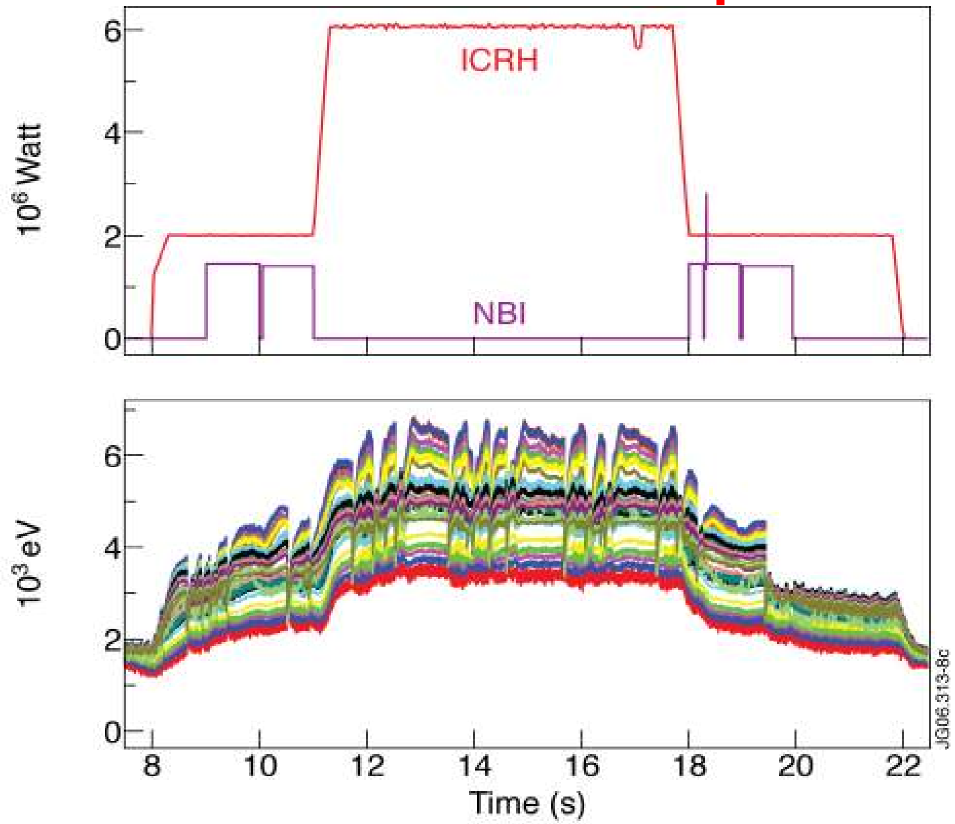


TAEs & tornadoes during first shaded time interval



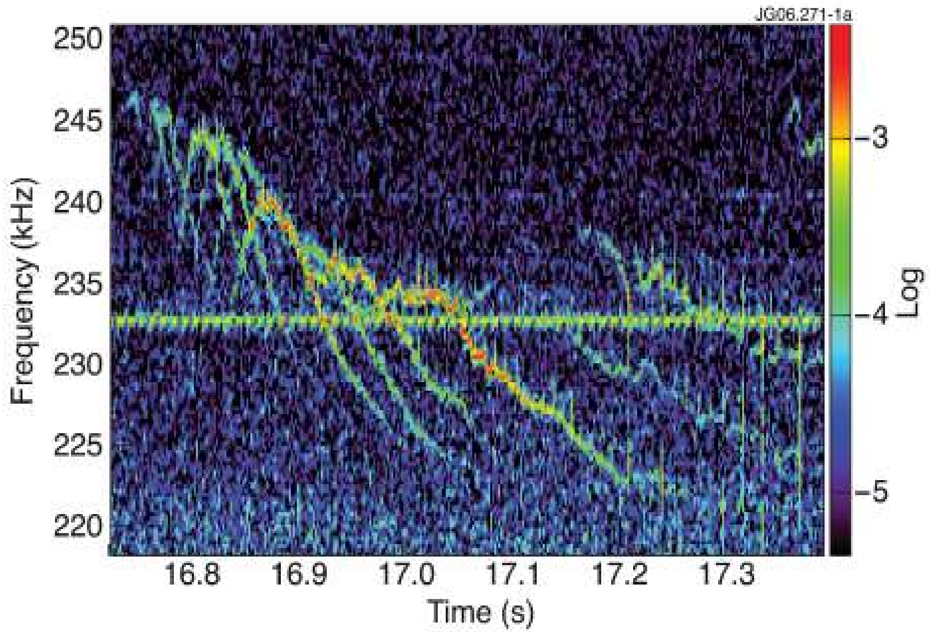
TAEs & tornadoes during second shaded time interval

JET (2006): experiment with a more complete set of diagnostics

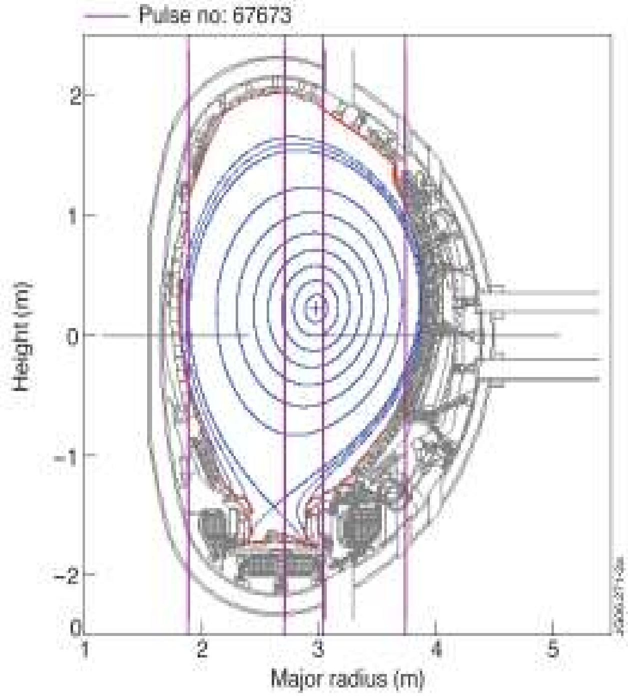


ICRH (hydrogen minority) and NBI power waveforms and T_e measured with multi-channel ECE diagnostics in typical tornado mode discharge on JET (pulse #67673)

New high-quality detection of core-localised modes with far infra-red interferometry (JET discharge #67673)



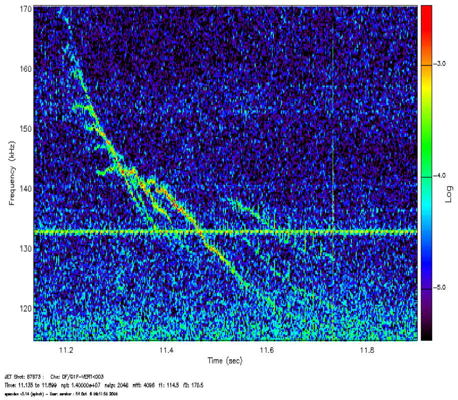
Tornado modes detected with vertical channel passing through the magnetic axis of the JET interferometer

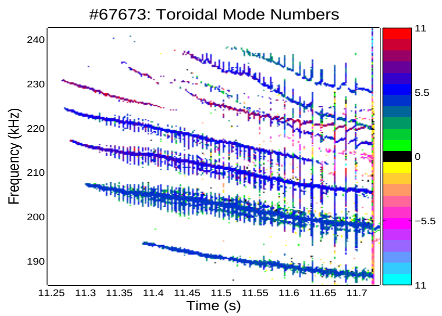


Geometry of JET interferometer with vertical lines-of-sight

Four sets of tornado modes precede four monster crashes in #67673:

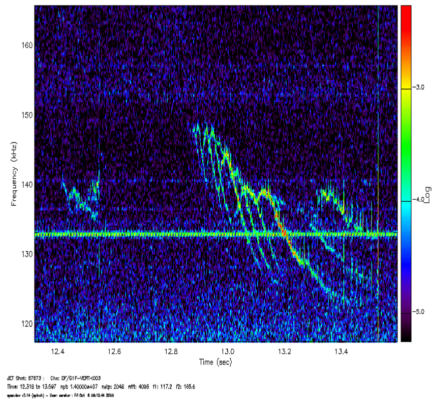
t=11.25 – 11.75 sec

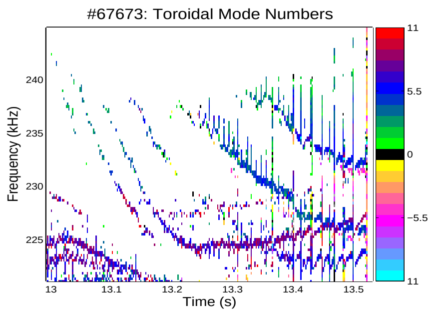




n decreases one-by-one:
n= 8→7→6

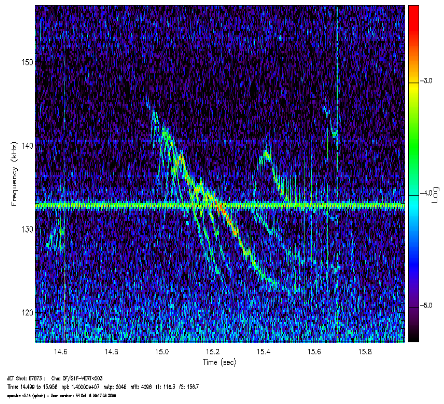
t=13.0 – 13.53 sec

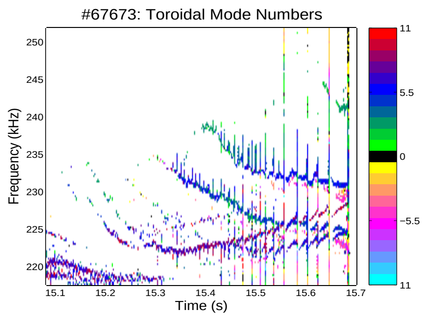




n decreases one-by-one:
n=9→8→7→6→5→4

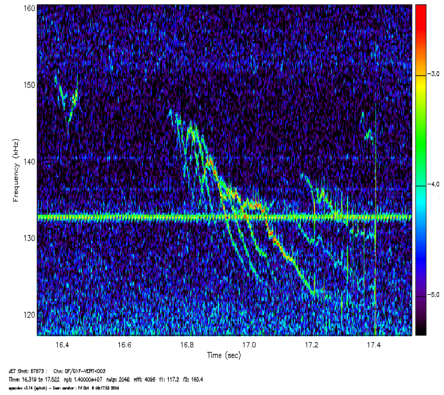
t= 15.1 – 15.68 sec

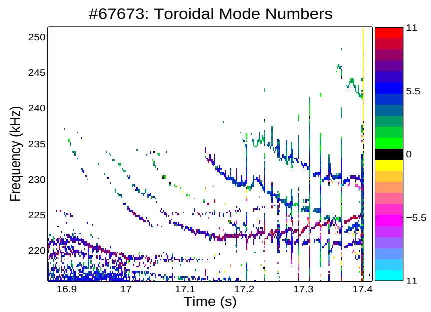




n decreases one-by-one
n=8→7→6→5→4→3

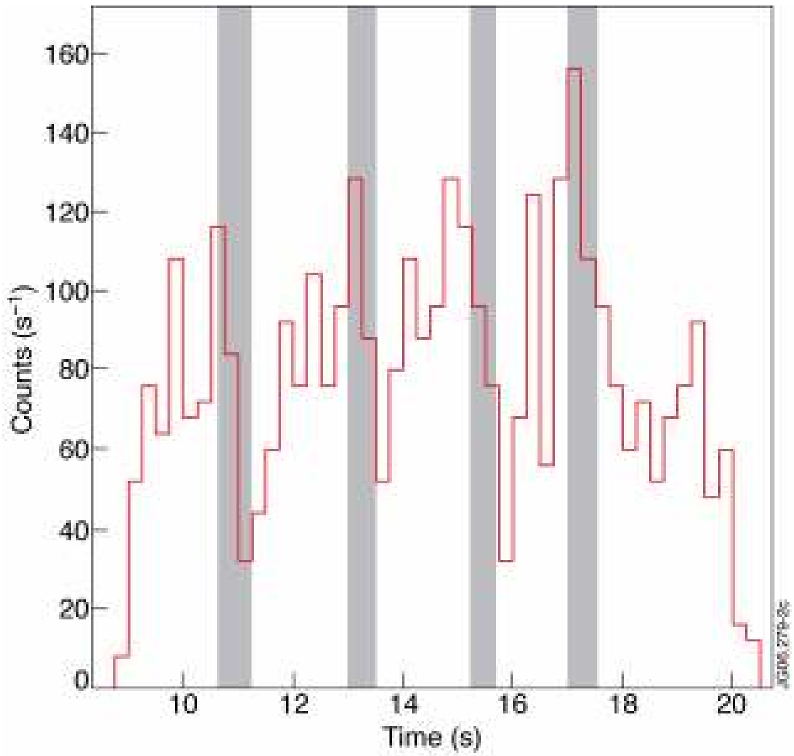
t = 16.9 – 17.4 sec



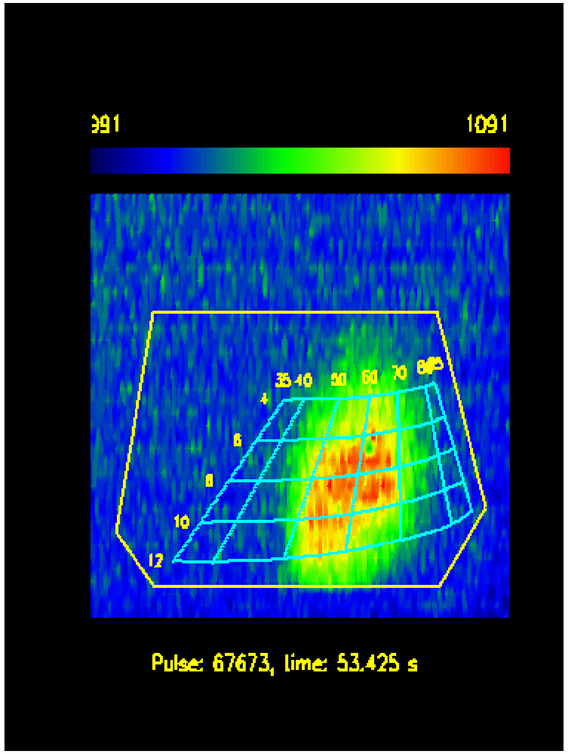


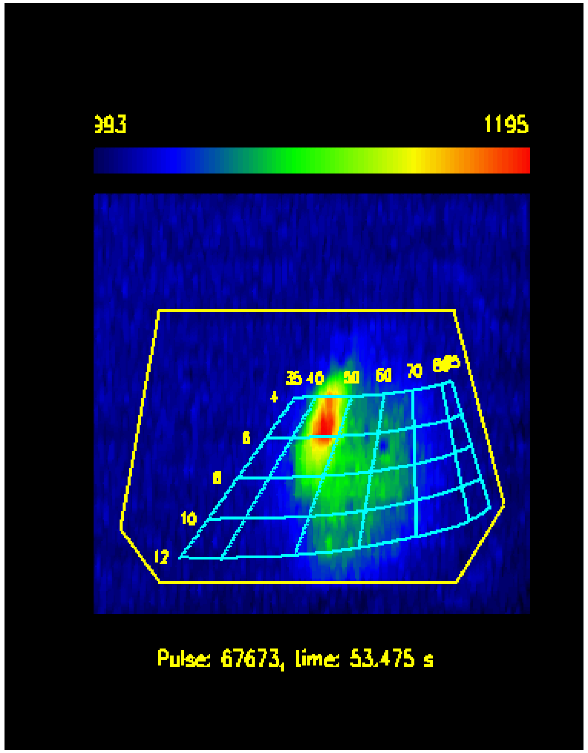
n decreases one-by-one
n=9→8→7→6→5→4→3

Gamma-ray emission from deuterons (E>500 keV) colliding with carbon, $^{12}C(d,p\gamma)^{13}C$ decreases before crashes



Losses of energetic ions measured with scintillator outside plasma are different before and during sawtooth crashes

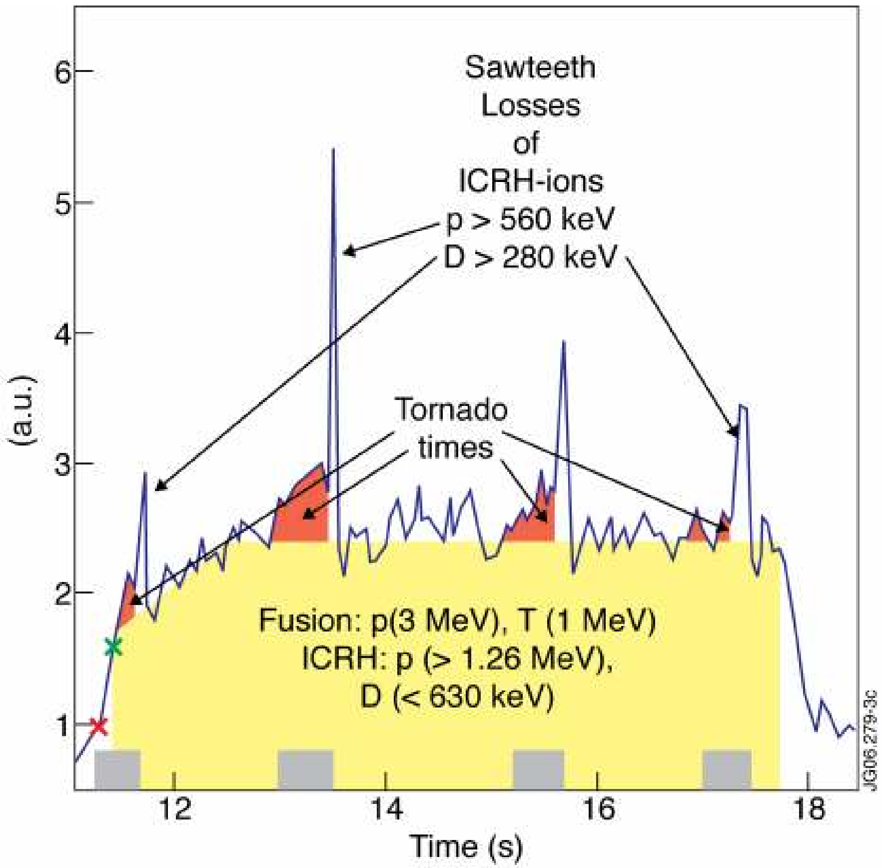




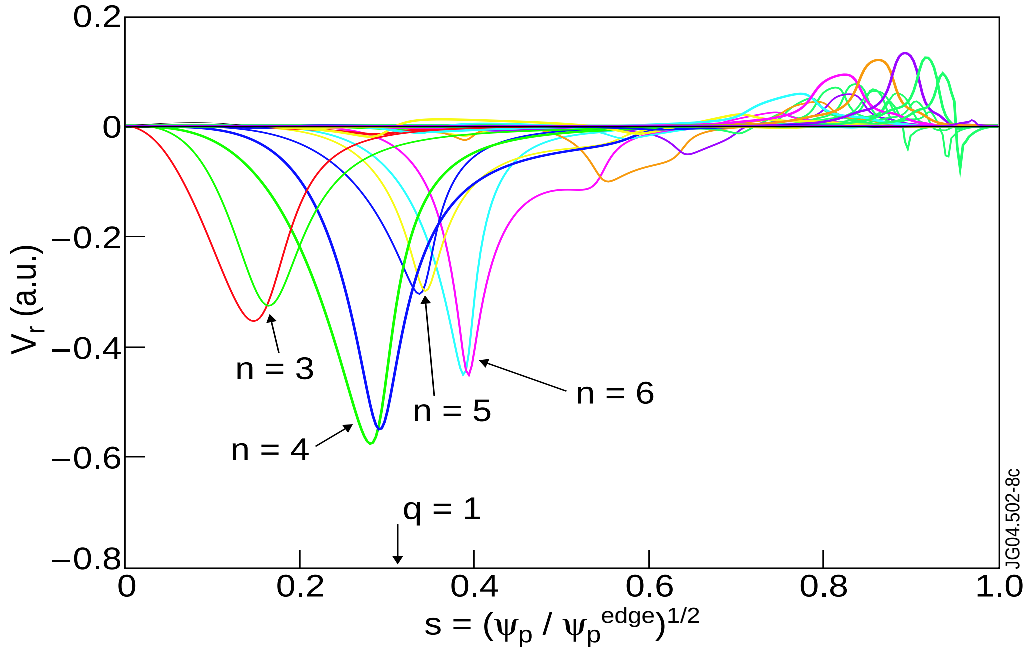
Ions with gyro-radii 6-10 cm are lost before sawtooth crash

Ions with gyro-radii 4-6 cm are lost during sawtooth crash

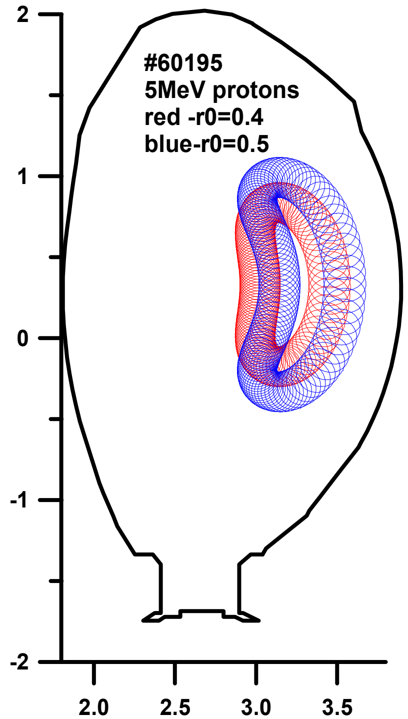
Loss measurements indicate increase during tornado activity



MODELLING TORNADO MODES



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



Orbits of 5 MeV protons

- **Ideal MHD code used for computing these modes in JET with monotonic q-profile**
- **Redistribution of protons from the q=1 radius by tornadoes considered main cause of the decrease in gamma-ray intensity**

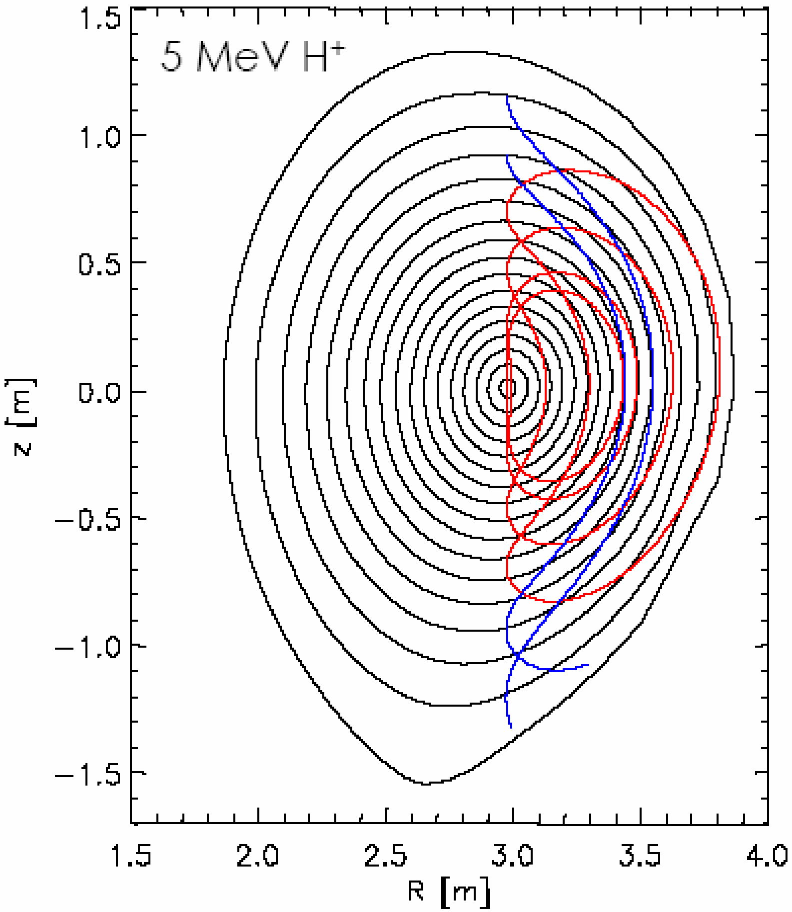
TAE DRIVEN BY ICRH-ACCELERATED FAST IONS

- **For trapped ions, the resonance $V_{II} = V_A$ does not work, and drive comes via**

$$\Omega = \omega - n \cdot \omega_{\varphi} - p \cdot \omega_{\theta}$$

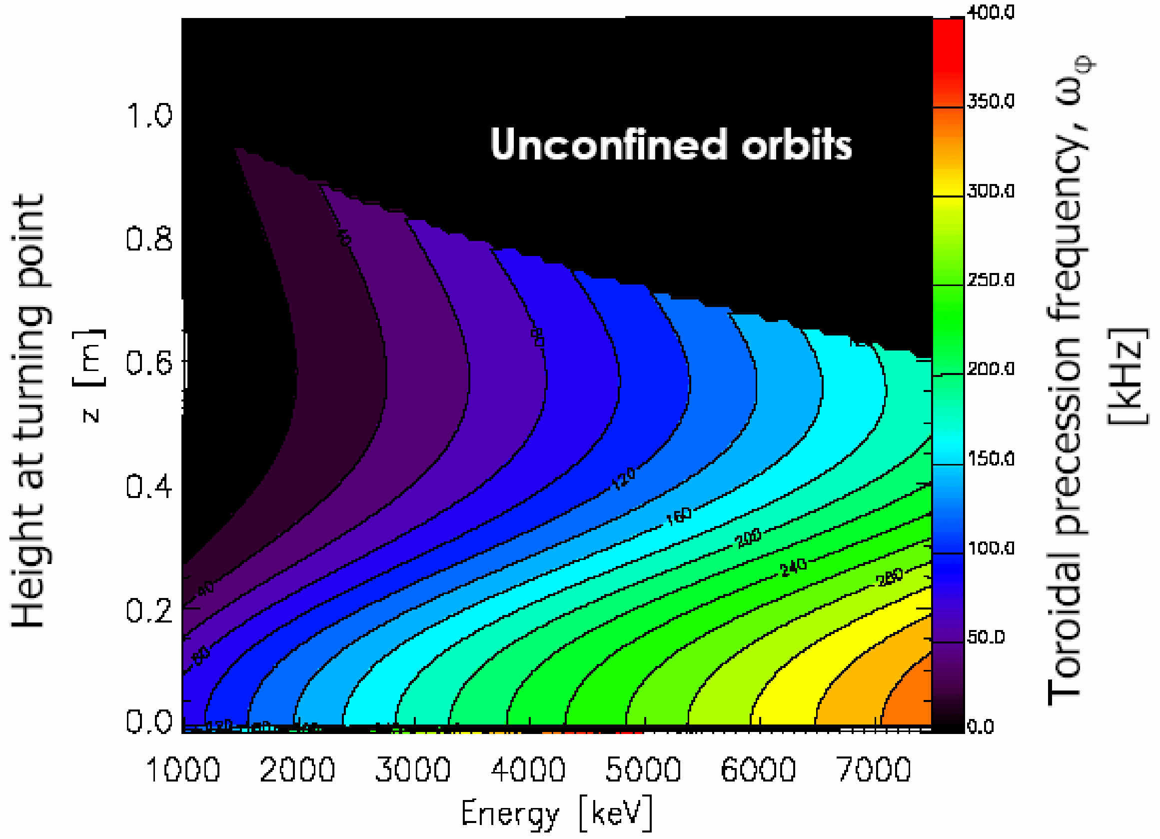
FAST ION ORBITS – ICRH

- ICRH auxiliary heating
- Distribution function described by
  $\Lambda = \mu B_0/E = 1$
  - Trapped orbits with turning points at ICRH resonance layer
- Orbit properties investigated using HAGIS code



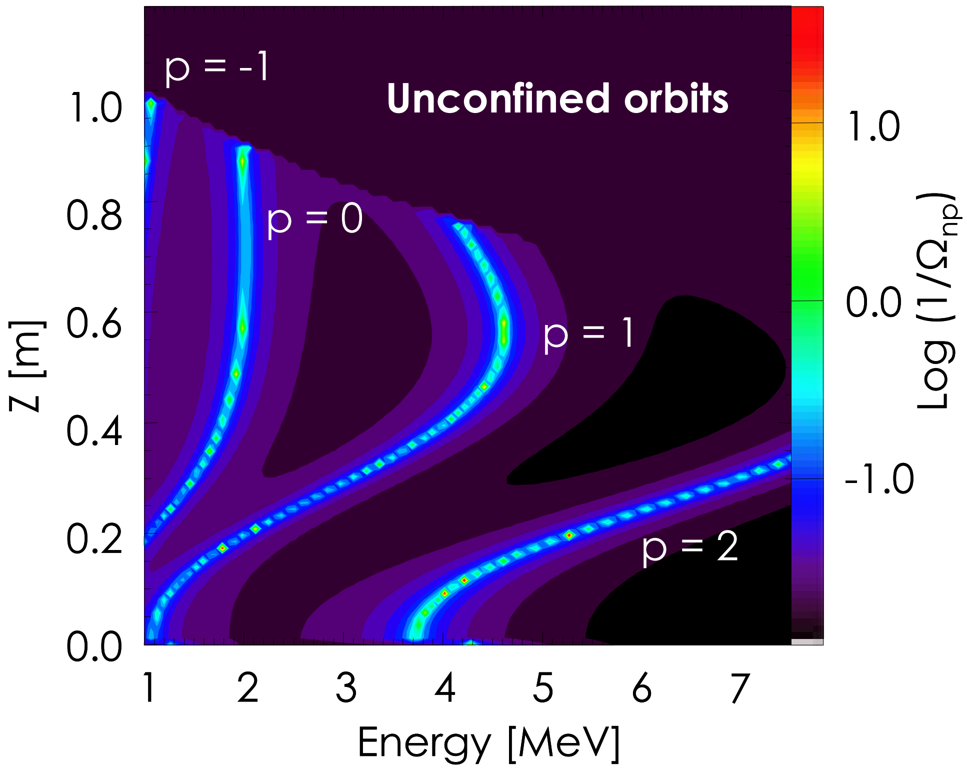
FAST ION ORBITS – ICRH

- Determine natural particle frequencies, ω_φ and ω_θ



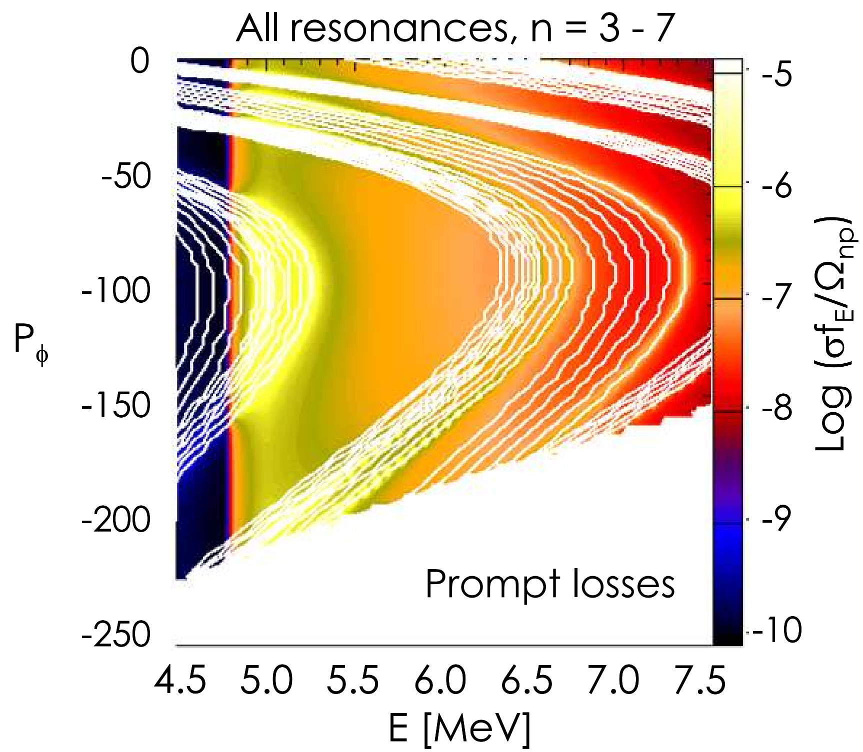
THE RESONANCES

$$\Omega_{np} = n\omega_{\phi} - p\omega_{\theta} - \omega = 0$$



Regions of phase space where ICRH-accelerated ions resonate with n=3 tornado

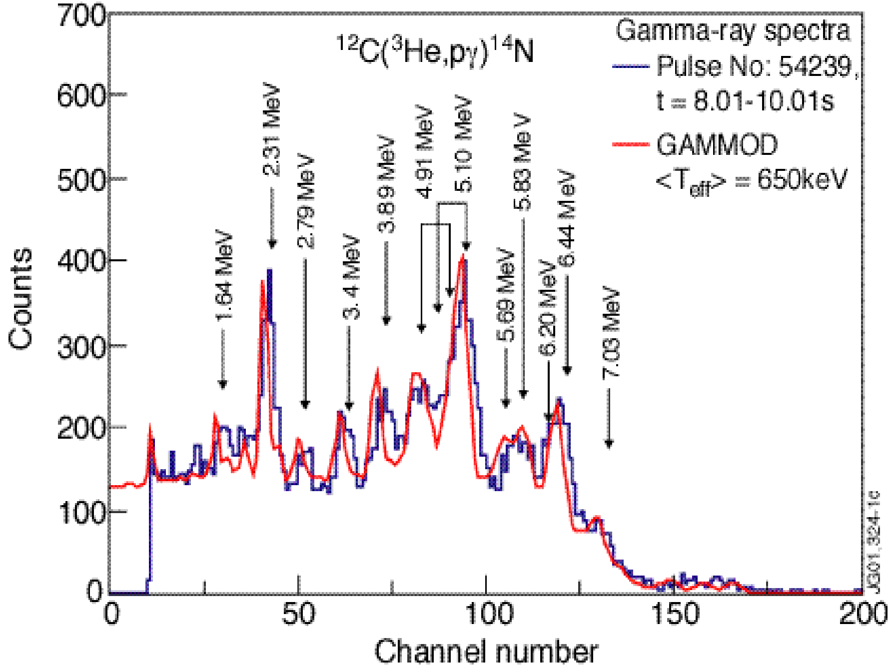
EVOLUTION OF THE RESONANCES WITH MODE FREQUENCY



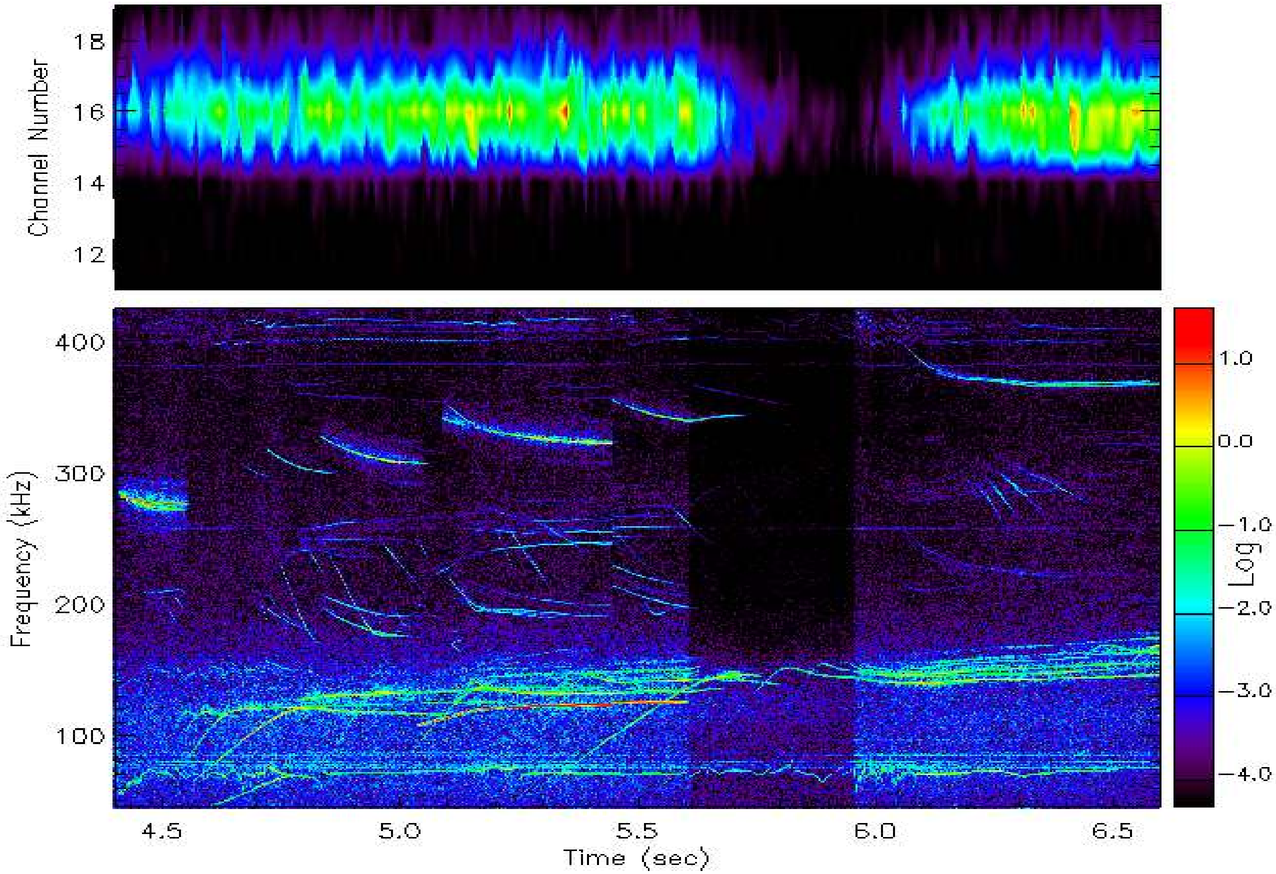
Movement of resonant lines due to ALL tornado modes by sweeping frequency in 3% steps over 15%.

ATTEMPT TO OBSERVE STOCHASTIC TRANSPORT DUE TO MULTIPLE MODES

EXPERIMENTS ON MULTI-MODE TRANSPORT ON JET: ^{3}He WITH E>500 keV MEASURED



Profile of Fast He^3 (Top) Measured Simultaneously with AEs (Bottom)



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

NO GLOBAL STOCHASTICITY FOR SUCH AMPLITUDES

- **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.**

SUMMARY

- Interaction between fast ion and a wave in the form $\propto \exp i(n\varphi - \omega t)$ has invariant $E - \frac{\omega}{n} P_{\varphi} = const$
- TAE causes a radial transport of resonant fast ions at nearly constant energy
- Two main transport mechanisms can be identified depending on the ratio ρ_{α} / a : convective single mode transport for large ρ_{α} / a and global milti-mode stochastic transport for small ρ_{α} / a
- Most present-day machines are in the regime of large ρ_{α} / a . Example: tornado modes on JET
- ITER will be in the regime of small ρ_{α} / a . Modelling of global stochasticity on, e.g. JET shows that amplitudes $\delta B_r / B_0 > 10^{-3}$ are required for that. Direct JET experiments on multi-mode transport could not achieve such numbers yet