ALFVÉN CASCADE EIGENMODES IN ADVANCED TOKAMAK SCENARIOS

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OUTLINE OF LECTURE 6

- Advanced tokamak scenarios and internal transport barriers
- Experimental scenarios for non-monotonic q(r)
- TAEs versus Alfvén Cascades
- Properties of Alfvén Cascade eigenmodes
- Correlation between ITB triggering and grand Cascades
- Summary

INTRO - 1

- "Advanced Scenario" in tokamak = improved plasma confinement at low inductive current. Achieved by optimising magnetic field topology.

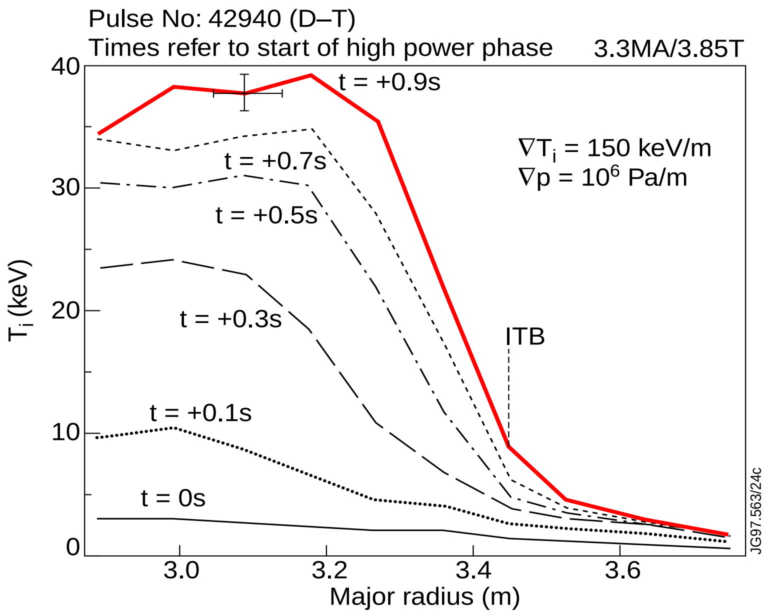
- Internal Transport Barriers (ITBs) could be triggered in AT scenarios

- JET record fusion performance in Deuterium plasma was achieved in the ITB scenario, $S_n = 5.5\times10^{16}$ sec^{-1} (JET pulse # 40554)

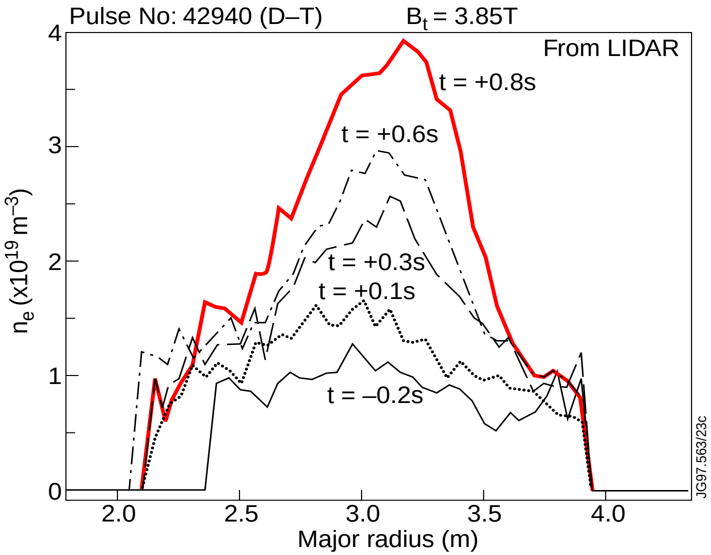
- JET record ion temperature, $T_i(0) \approx 40$ keV, radial gradient of ion temperature, ≈ 150 keV/m, and the ion pressure gradient, $\approx 10^6$ Pa/m were achieved in Deuterium-Tritium ITB discharge # 42940 (Gormezano et al Phys. Rev. Lett. 80, 5544 (1998))

INTRO – 2

- **Example of Deuterium-Tritium ITB plasma**



Ion temperature profile in JET discharge with ITB



Plasma density profile in JET discharge with ITB

C.Gormezano et al., Phys. Rev. Lett. 80, 5544 (1998)

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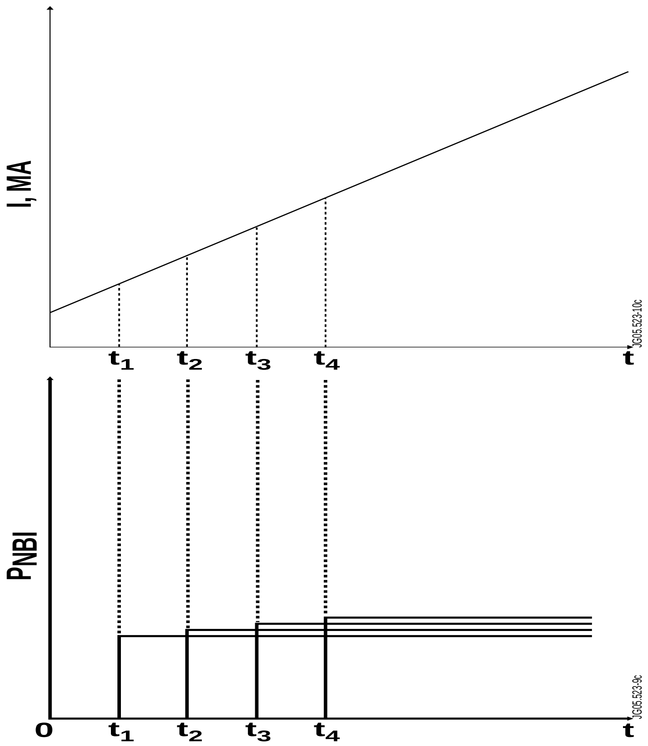
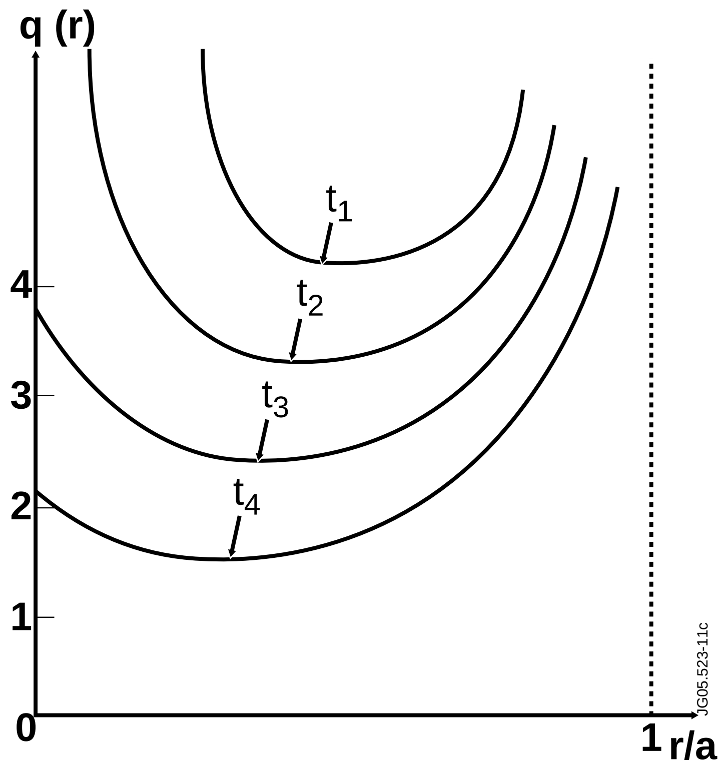
HOW ONE TRIGGERS AN ITB?
TIMING SCAN OF MAIN HEATING AT CURRENT RAMP-UP

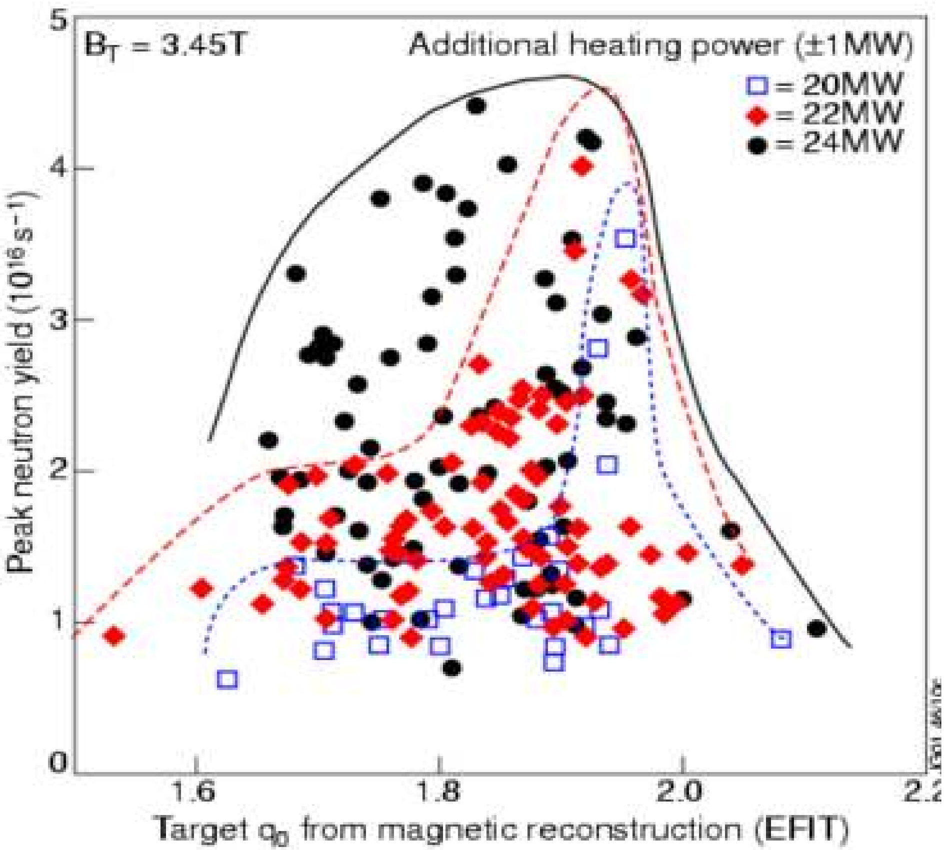


Current ramp-up (top) and main NBI heating applied at different times (bottom)



Target q(r)-profiles corresponding to the different time slices of main heating

TRIGGERING OF ITB AT INTEGER q_{min}

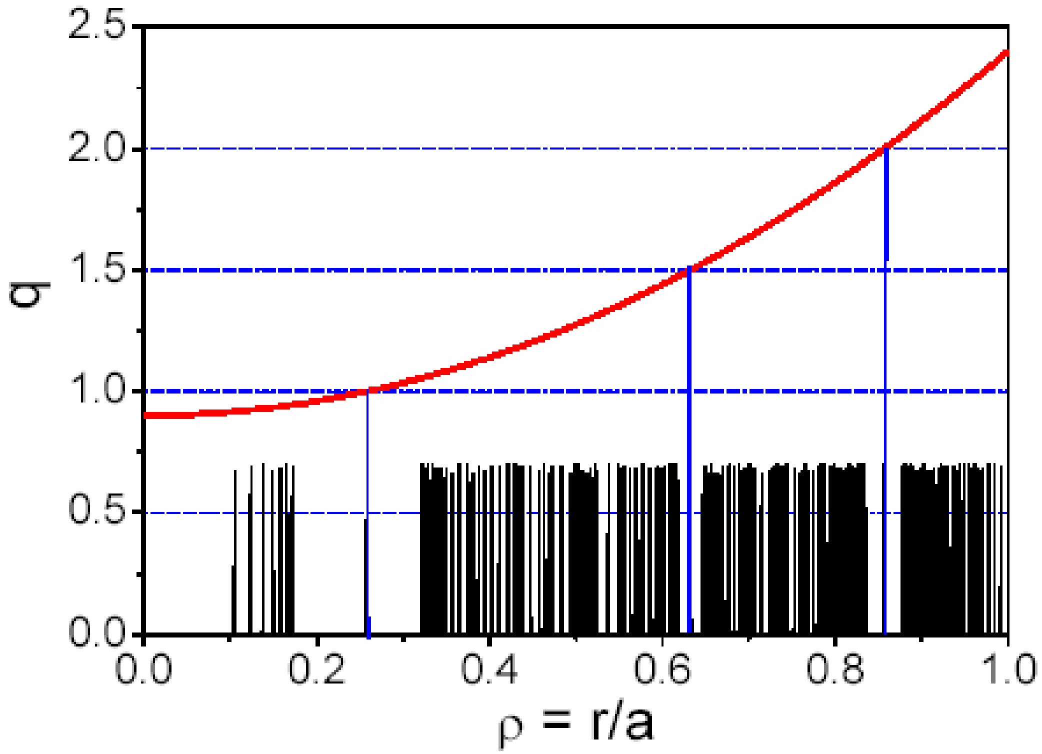


R_{nt} vs q_0 for three domains of input power. At 20 MW, ITBs are formed in narrow range of target q_0 close to 2. At 22 and 24 MW the domain is less sensitive to the q-profile.

E. Joffrin et al., Nuclear Fusion 43 (2003) 1167

How to explain this experimental observation?

PLASMA TRANSPORT AND RATIONAL MAGNETIC SURFACES



TRANSPORT AND INTEGER MAGNETIC SURFACES (THEORY)

TRANSPORT IS AFFECTED BY THE PRESENCE OF INTEGER q:

- Collisionless transport parallel to magnetic field depends strongly on irrational versus low-order rational q if heating source and sink are poloidally localised R.D. Hazeltine, Phys. of Plasmas v.6, p.550 (1999)
- Helical temperature perturbations due to tearing modes: R.Fitzpatrick, Phys. of Plasmas, v.2, p.825 (1995)

TRANSPORT IS AFFECTED BY THE GAP IN RATIONAL SURFACES

- Transport profiles induced by radially localised modes in tokamaks, A.D. Beklemishev and W.Horton, Phys. Fluids B4, p.200 (1992) – seems to be the earliest paper on this subject.

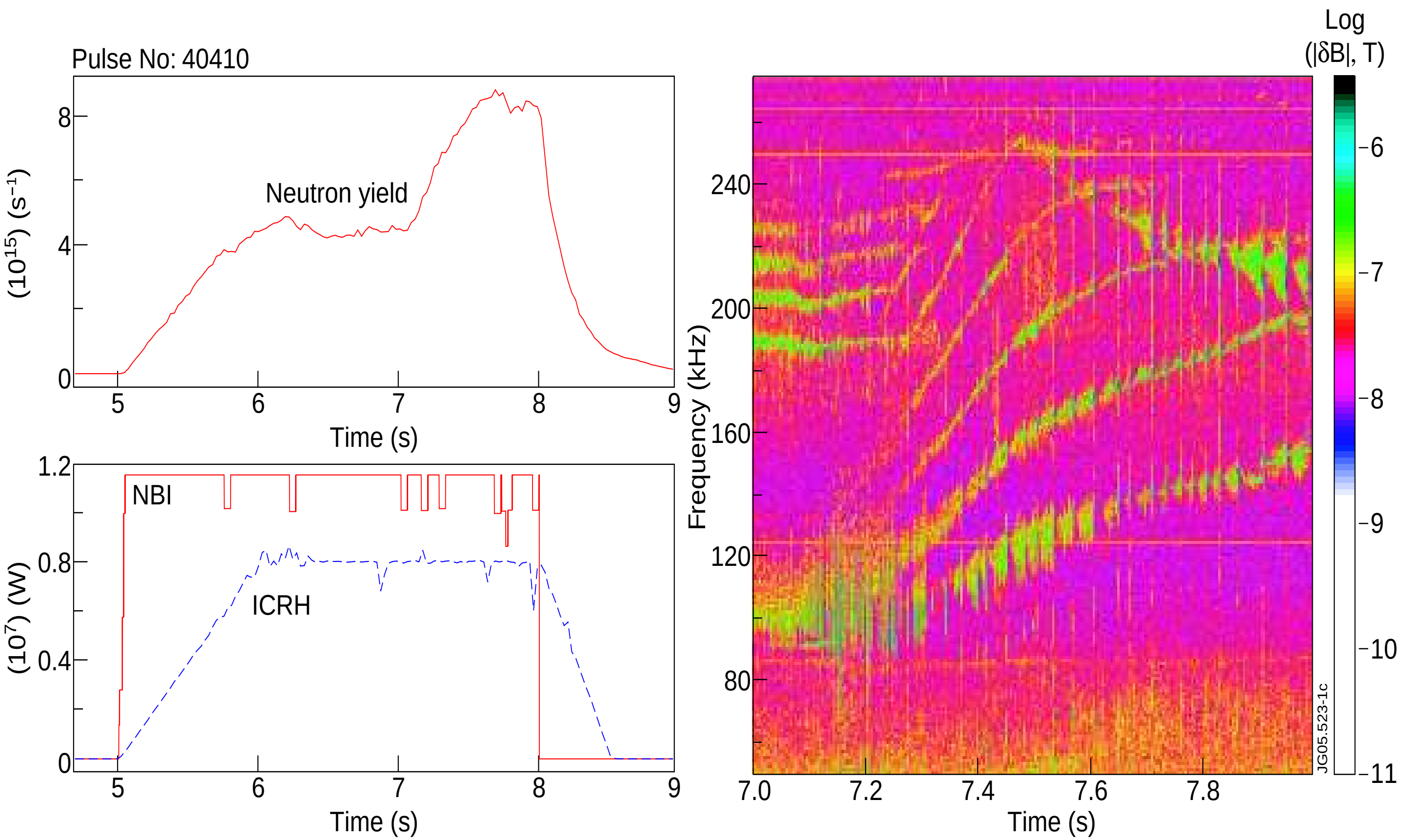
TRIGGERING OF ITB AT INTEGER q_{min}

- In larger devices, where the power density is expected to be relatively small, the ITB triggering by integer q-values may be decisive in creating an ITB in the advanced tokamak scenario

- Identification of t_{ITB} satisfying $q_{min}(t_{ITB})$ =… 4,3,2,1 are needed

- Can we employ Alfénic instabilities to mark times when $q_{min}(t)$=integer?

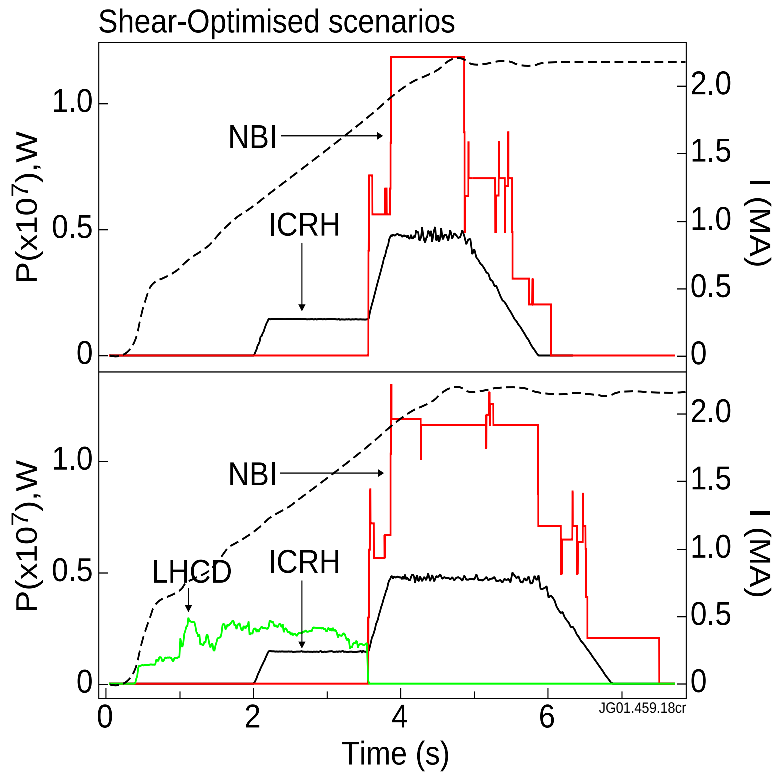
CORRELATION BETWEEN AN ALFVÉNIC MODE AND ITB



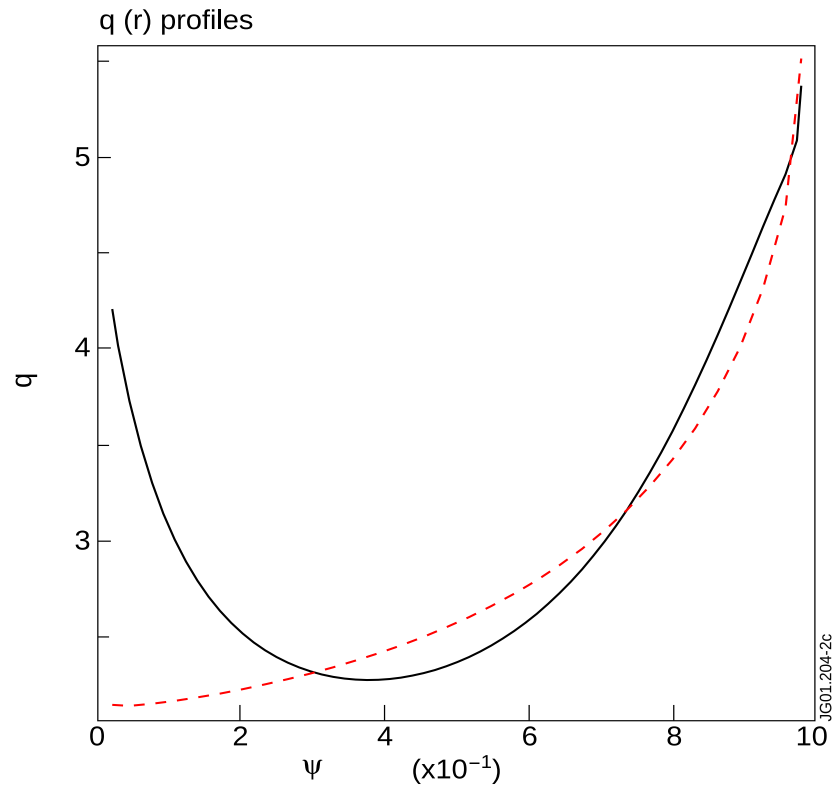
Left: Neutron yield, NBI and ICRH power in JET discharge #40410, B_T =3.4 T, I_P = 3 MA.

Right: Alfvén mode observed at the time of S_n and T_e increase

Positive and negative shear AT Scenarios

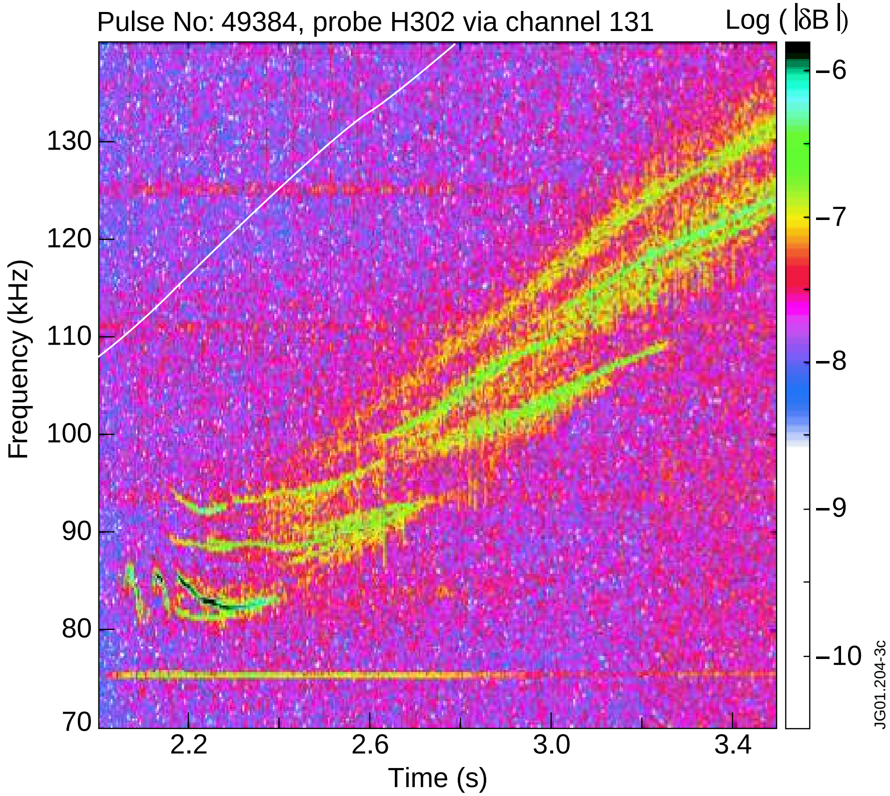


Top: **Power and current waveforms for positive shear plasma #49384**
Bottom: **Same for negative shear plasma #49382**

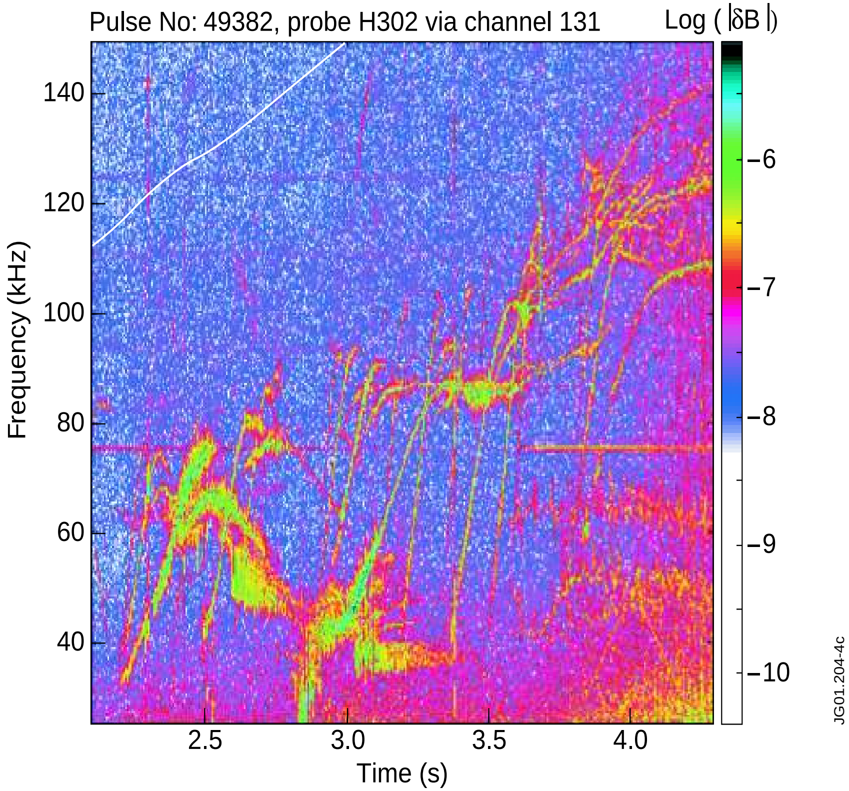


***q*(*r*)-profiles for positive (#49384) and negative (#49382) shear plasmas**

Measured Spectrum of Alfvén Waves Excited by ICRH-accelerated Ions



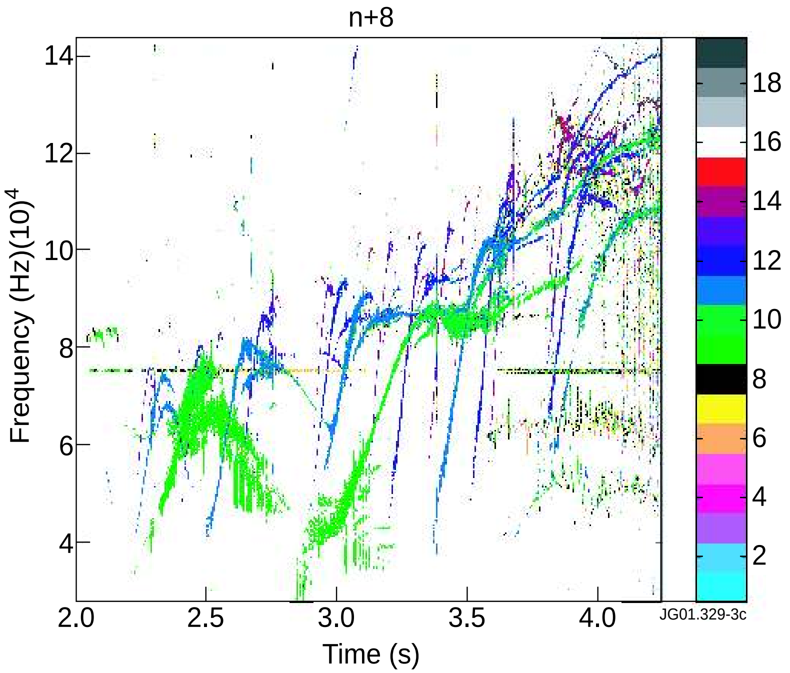
TAE modes observed in pulse #49384 with monotonic q(r)-profile



Alfvén Cascades observed in reversed-shear pulse #49382

S.E.Sharapov, Lecture 6, Australian National University, Canberra, 7-9 July 2010

Properties of Alfvén Cascades



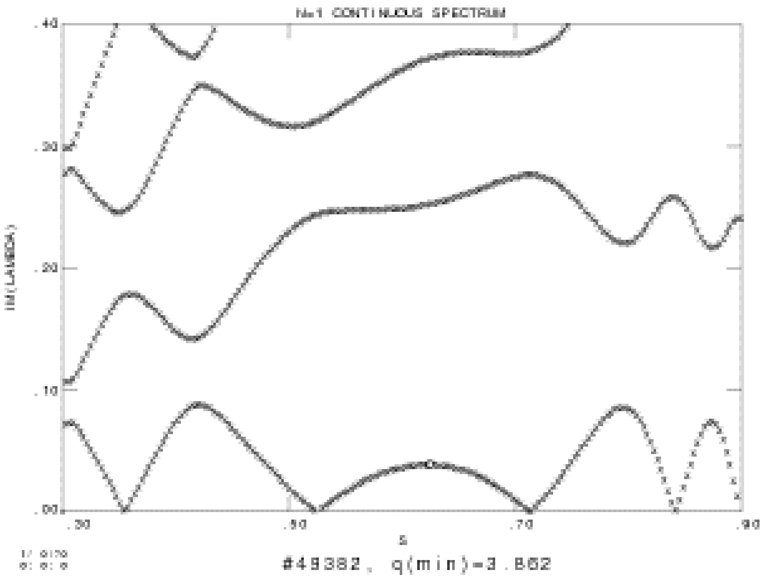
Magnetic perturbations in JET with non-monotonic q(r). **ACs** of n=1 to n=6 are observed **below TAE** frequency.

1) **Time scale** of the frequency sweeping ~0.1-1 s, is comparable to time scale **of *q*(*r*) evolution**
2) Each cascade may consist of **many modes** with different *n*'s from *n*=1 to *n*=6
3) The **frequency** of the cascades starts from below the TAE frequency. During the evolution, the frequency increases up to the TAE frequency.
4)The modes with **higher mode numbers** exhibit a **more rapid frequency sweeping,** $df/dt \propto n$.
5)The **higher** *n* modes **re-occur more often** than the lower *n* modes
6) Internal measurements show that Alfvén Cascades are localised in the region of q_{min}

S.E. Sharapov et al., Phys. Of Plasmas **9**, 2027 (2002)

Shear Alfvén Continuum for Non-monotonic q(r) profile

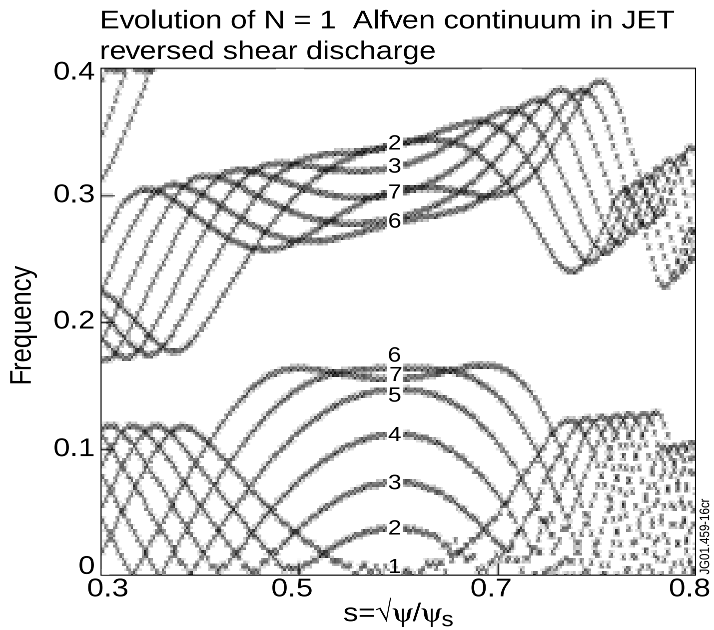
$$\omega(r) = k_{\parallel m}(r)\, V_A(r), \qquad k_{\parallel m}(r) = \frac{1}{R}\left(n - \frac{m}{q(r)}\right), \quad q = q_{\min} \text{ at } s = \left(\psi/\psi_{edge}\right)^{1/2} \cong r/a \approx 0.6$$



Time Evolution of the Alfvén Continuum Tip at q_{min}

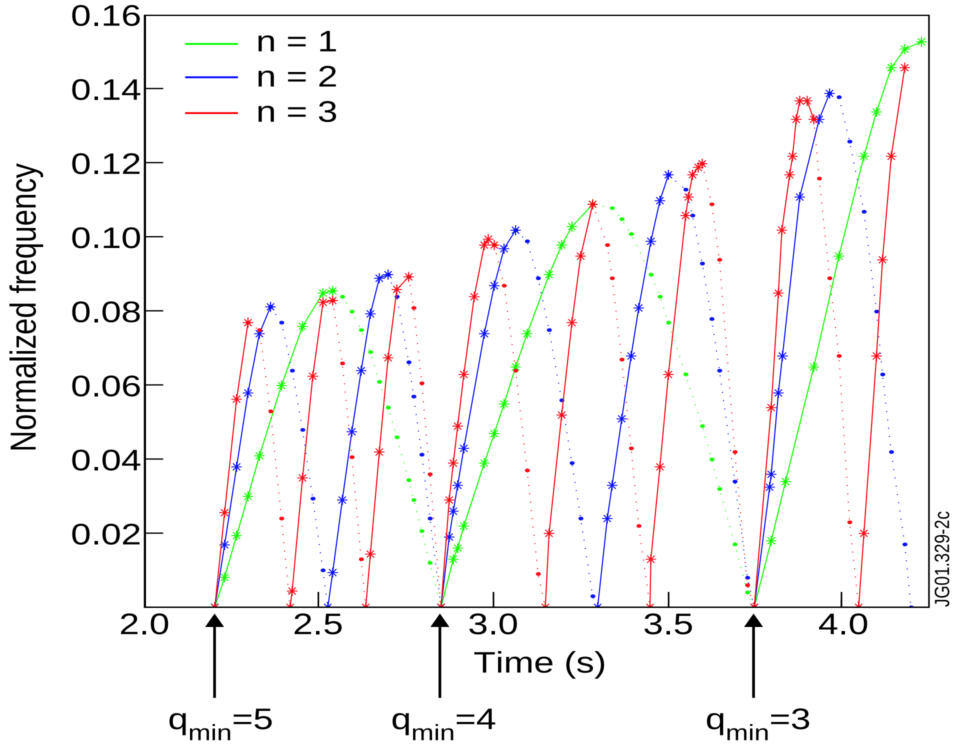
- Temporal evolution of Alfvén continuum **at the point of zero magnetic shear**

$$\omega_{AC}(t) = \left| \frac{m}{q_{\min}(t)} - n \right| \frac{V_A(t)}{R_0}$$

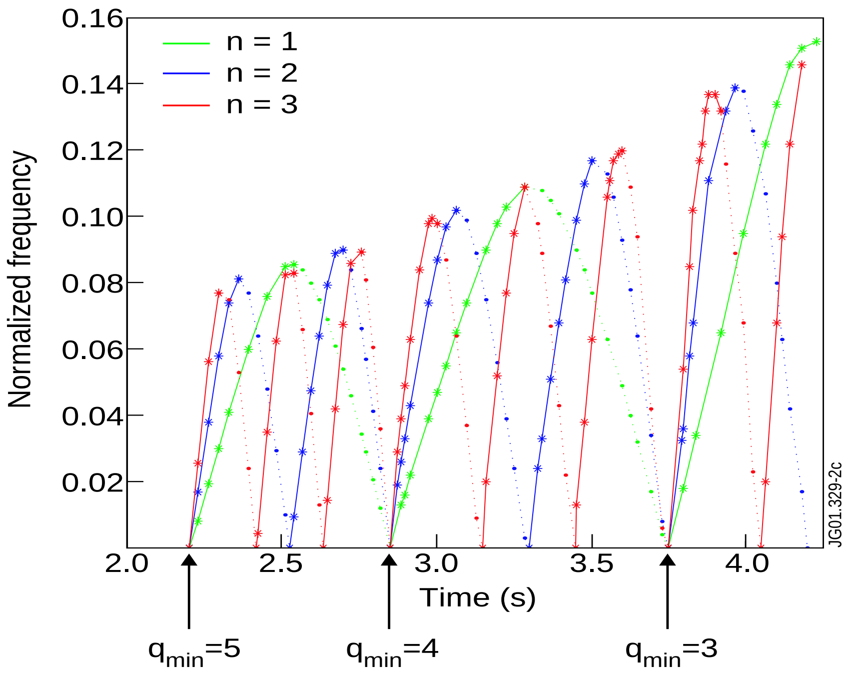


Time Evolution of Alfvén Continuum Tip at q_{min}

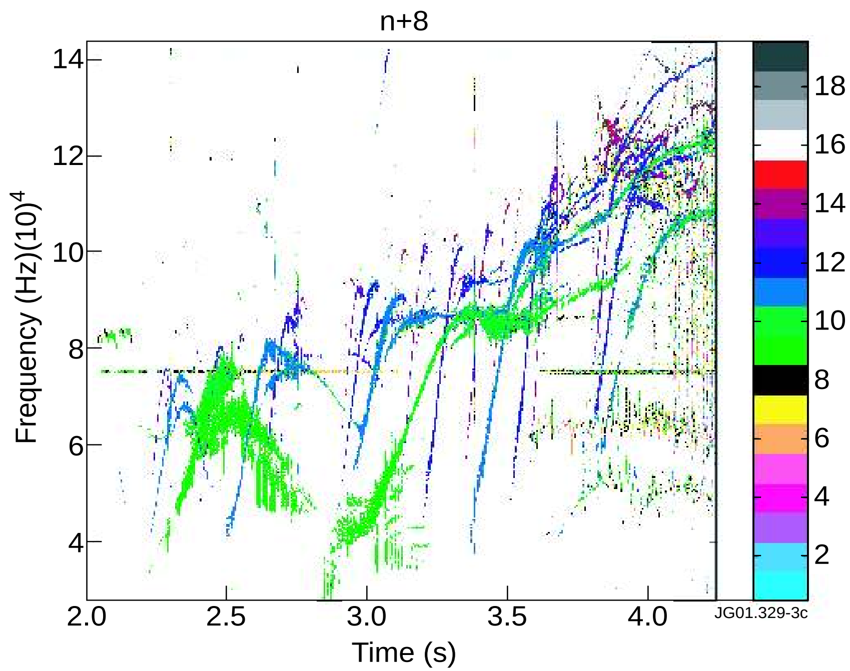
$$k_{\parallel m}(t,\ r_{min}) = \frac{1}{R}\left(n - \frac{m}{q_{min}(t)}\right),\quad \omega_{AC}(t) = \left|\frac{m}{q_{min}(t)} - n\right| \frac{V_A(t)}{R_0}$$



Time Evolution of Alfvén Continuum Tips vs Experimental Data



CSCAS: evolution of **n=1**, n=2, and **n=3** continuum tips during $q_{min}(t)$ evolution



Alfvén Cascades observed in JET reversed-shear pulse #49382

Time Evolution of Alfvén Cascades as $q_{min}(t)$ diagnostics

- **Frequency of Alfvén cascades approximately satisfies**

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

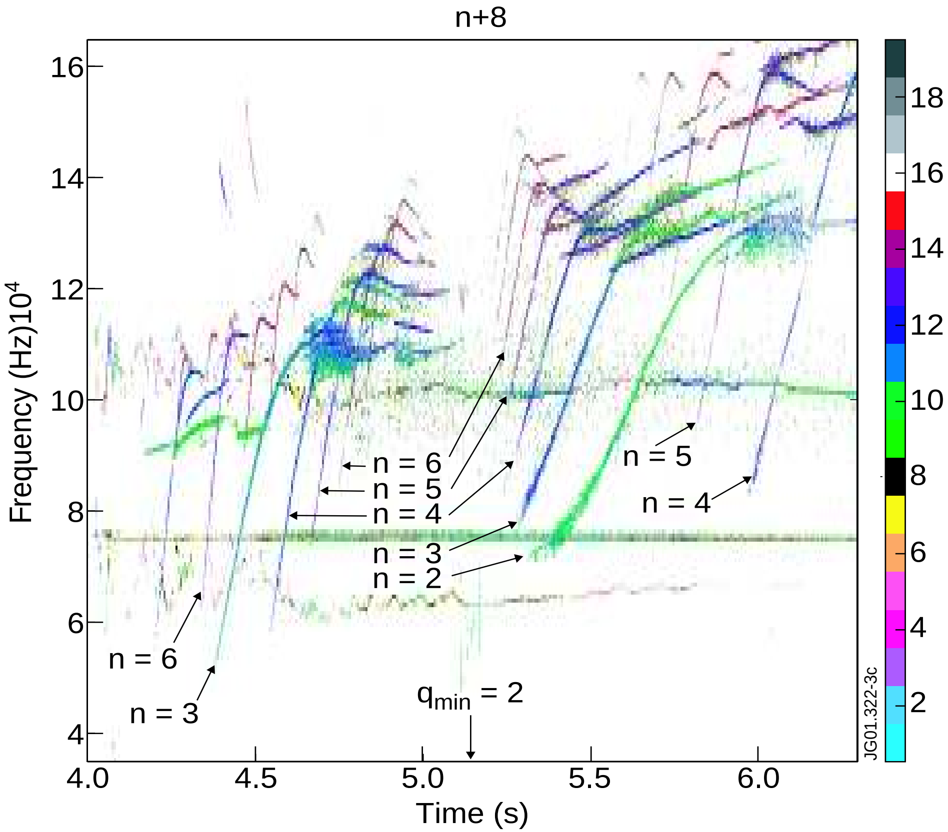
and it traces evolution of $q_{min}(t)$ in time as

$$\frac{d}{dt}\omega_{AC}(t) \approx m \frac{V_A}{R_0} \frac{d}{dt} q_{\min}^{-1}(t)$$

- **Time of the "Grand cascade" when ACs with all mode numbers are excited simultaneously marks well times when $q_{min}(t)$=integer**

S.E.Sharapov et al., Phys. Lett. A289, 127 (2001)

MHD spectroscopy from the clustering of different *n*'s in time



Condition for Alfvén cascade to appear:

$$m - nq_{\min}(t) = 0,$$

n and m are integers

$\Downarrow$

***n*=1** ACs occur when **q_{min}=1,2,3…**;
***n*=2** ACs occur when **q_{min}=1, 3/2, 2, 5/2, 3…**;
***n*=3** ACs occur when **q_{min}=1, 4/3, 5/3, 2, 7/3, 8/3, 3…**

Alfvén Cascade, in which all n's are present ⇒ **Grand Cascade**. It occurs when $q_{\min}(t)$ passes an integer value.

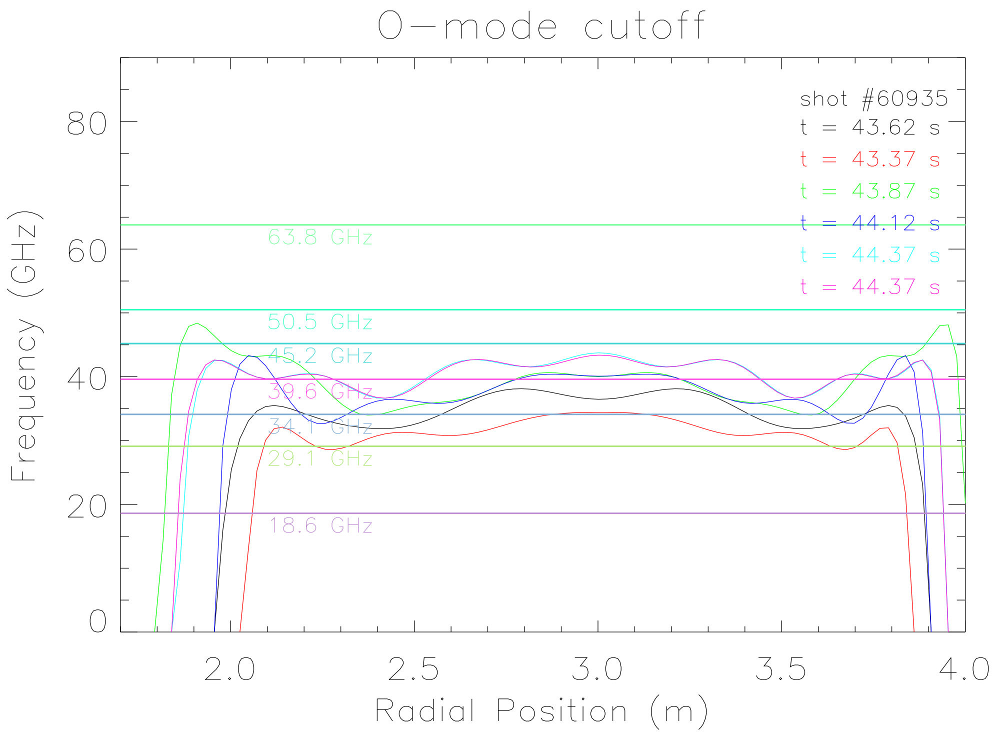
GRAND CASCADES VERSUS ITB

Correlation between Alfvén grand-cascades and the ITB triggering events was established with different types of the pre-heating, i.e. with LHCD, ICRH+LHCD, ICRH only, NBI only, and with pellets, for a large variety of plasma conditions,

- **$1.5 < I_P < 2.2$ MA**
- **$2.45 < B_T < 3.4$ T**
- **$3 < P_{total} < 17$ MW.**

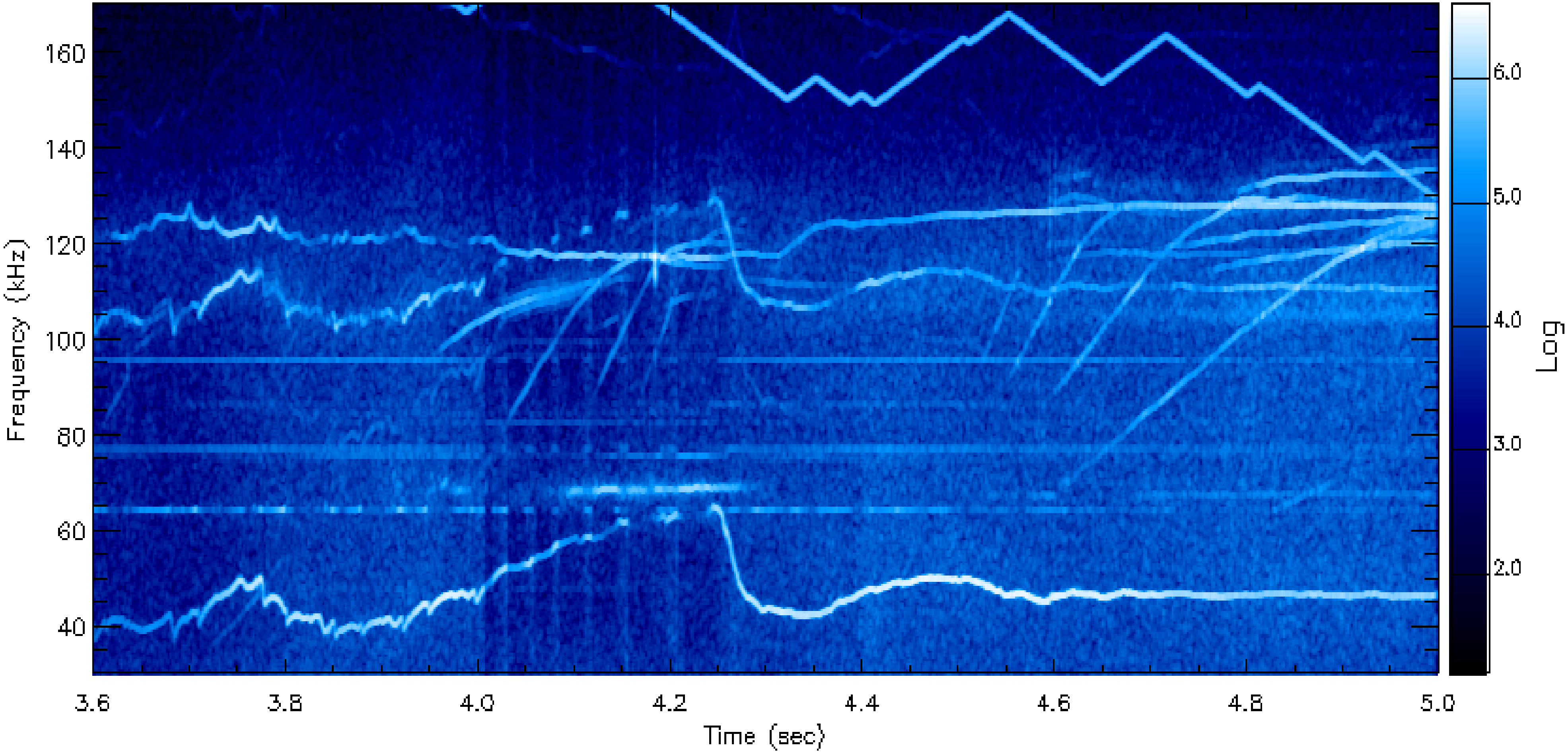
Can we improve time resolution for ACs in order to detect what happens first, the ITB formation or the appearance of integer q_{min} in plasma?

O-MODE "INTERFEROMETRY" ($\omega > \omega_{cut\text{-}off}$) ON JET: MICROWAVES LAUNCHED AND RECEIVED AT R=4 m

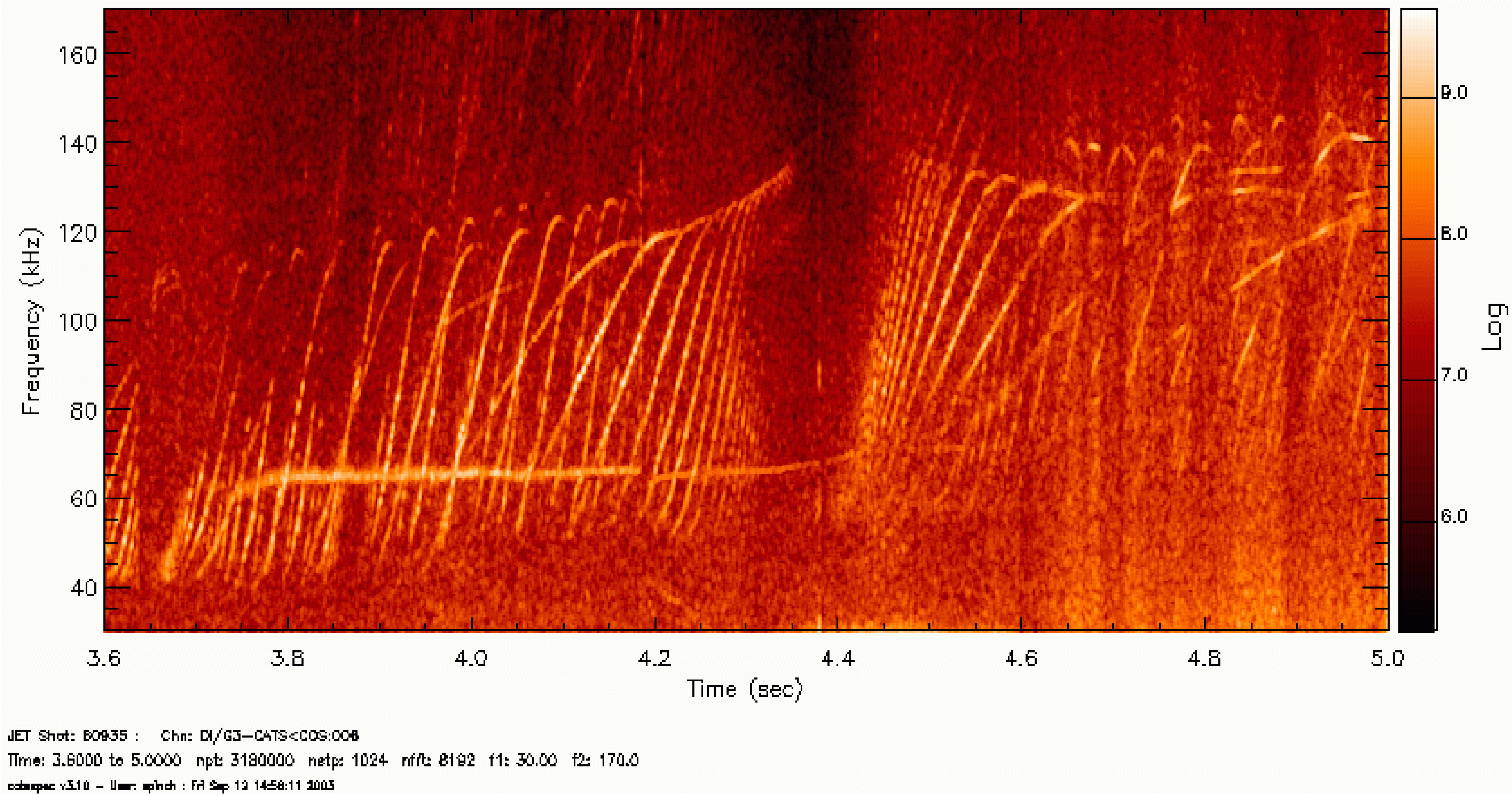


S.E. Sharapov et al., PRL 93, 165001 (2004)

ACs DETECTED WITH EXTERNAL MIRNOV MAGNETIC COILS



ACs DETECTED WITH INTERFEROMETRY



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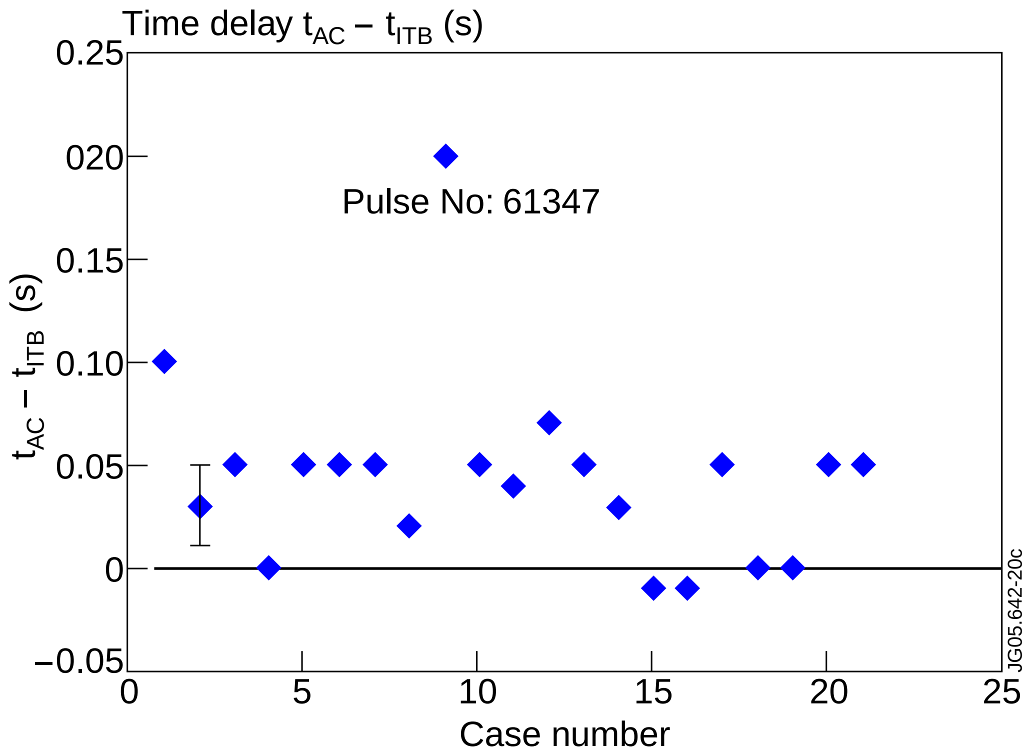
GRAND-CASCADES VERSUS ITB TRIGGERING EVENTS



- **Both AC and T_e diagnostics have now very high time resolution**

GRAND-CASCADES VERSUS ITB TRIGGERING EVENTS

- Grand ACs and ITB triggering events found to correlate within $\Delta t < 0.2$ sec in JET plasmas with densities up to $\sim 5\ 10^{19}\ m^{-3}$

- In most cases, Grand ACs happen after ITB triggering events $\Rightarrow$ improved confinement in most cases is associated with "gaps" in rational surfaces BEFORE appearance of q_{min}=integer in the plasma

SUMMARY

- Alfvén Cascade eigenmodes (also called Reversed Shear AE) associated with q_{min} are used successfully for monitoring the $q_{min}(t)$ evolution and the ITB triggering events

- A new way to see the Alfvén Cascades with interferometry mode was found

- The interferometry measurements offer a superior mode detection with higher time resolution than Mirnov coils

- It was found that ITB triggering happens on JET before integer q_{min} enters the plasma