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MHD detrimental effect on the confinement during flat-top eITB plasmas on TCV

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1) Introduction

Importance of eITB [1]:

- Transport in Tokamak is anomalous, i.e. measured confinement time is much less than calculated with neoclassical theory.
- Micro-turbulence is believed to be the cause of the loss of heat and particles.
- There exist states for which plasma confinement is strongly and suddenly enhanced --> relevant conditions for a reactor
- Reduction of turbulence is a key factor to reach these states
- Local reduction of transport leads to global increase in pressure;
- region of plasma with reduced transport are referred to as TRANSPORT BARRIER.
- Internal transport barriers refers to **core** barriers ($\rho_\psi \approx 0.4$ for the foot)
- H-factor gives ratio of measured to global energy confinement scaling-law

eITBs on TCV:

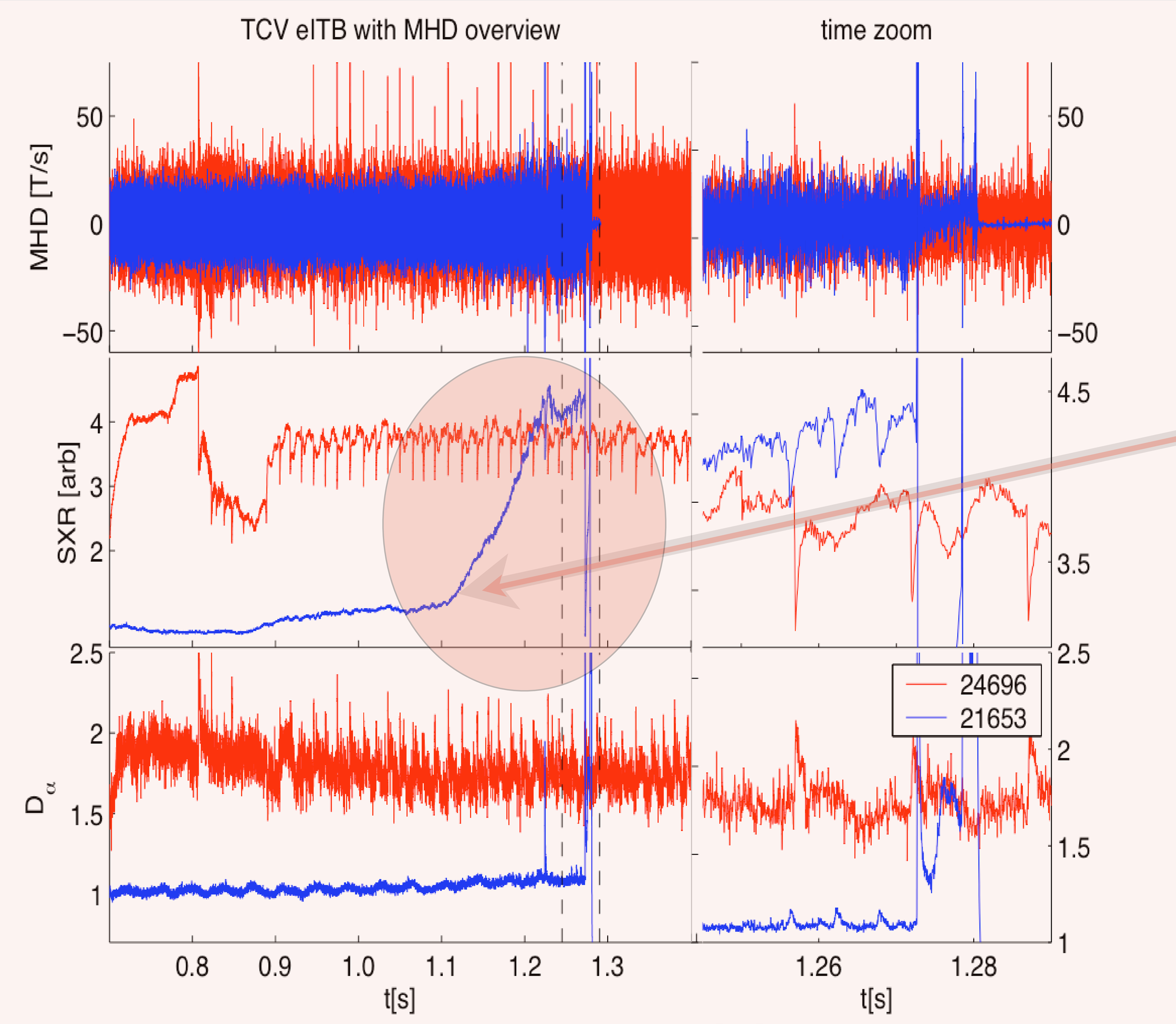
- Electron internal transport barriers (eITBs) generally obtained with a *hollow* current density profile.
- Rapid formation ($T < \tau_{eE}$)
- sustained with q and shear profiles completely relaxed
- Can be non-inductively sustained (ECCD) + bootstrap
- Limited by gyrotron pulse length
- **With or without MHD activity**

Infernal mode:

- Ideal MHD instability [2] with features of kink (current driven mode) and ballooning (pressure driven) modes.
- Becomes unstable with combination of large pressure gradients and **low-shear** conditions, where q-profile becomes flat or reversed in the core (typical conditions for eITBs)
- For reversed shear, maximum growth is for low *n* (1,2,3) [3]

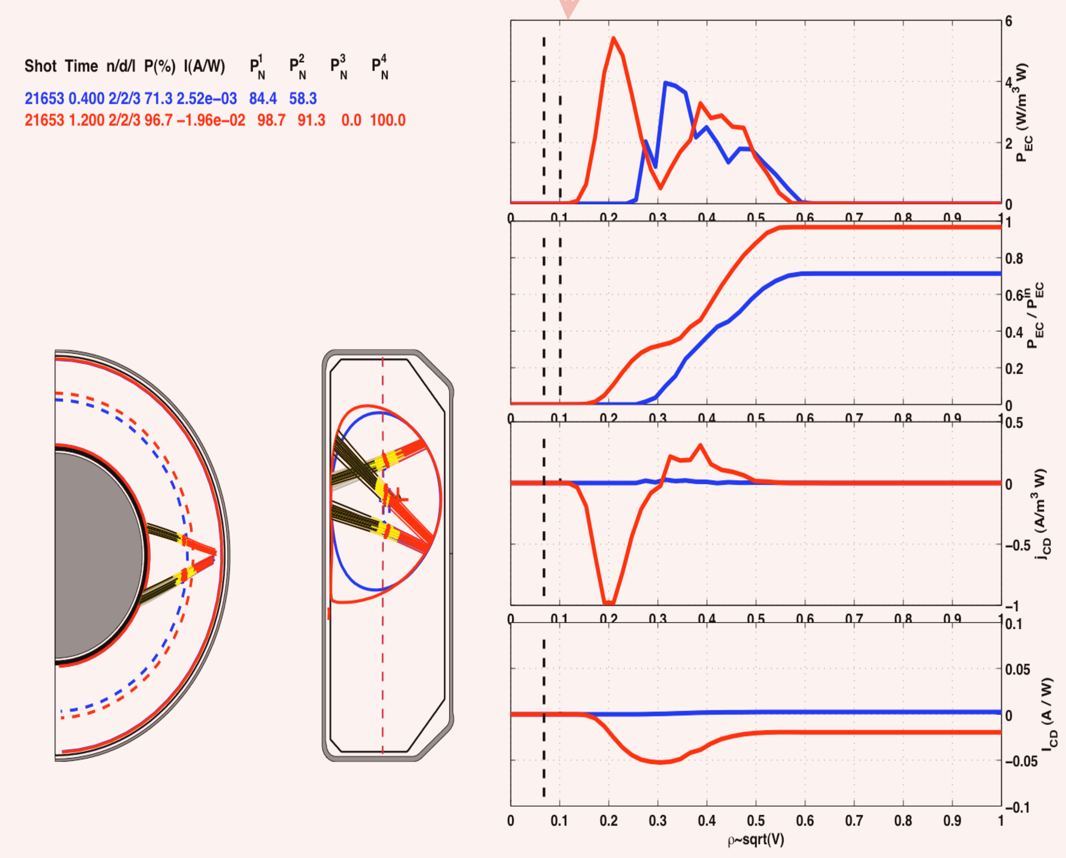
INFERNAL MODE [2] theory describes these modes

3) Data Analysis

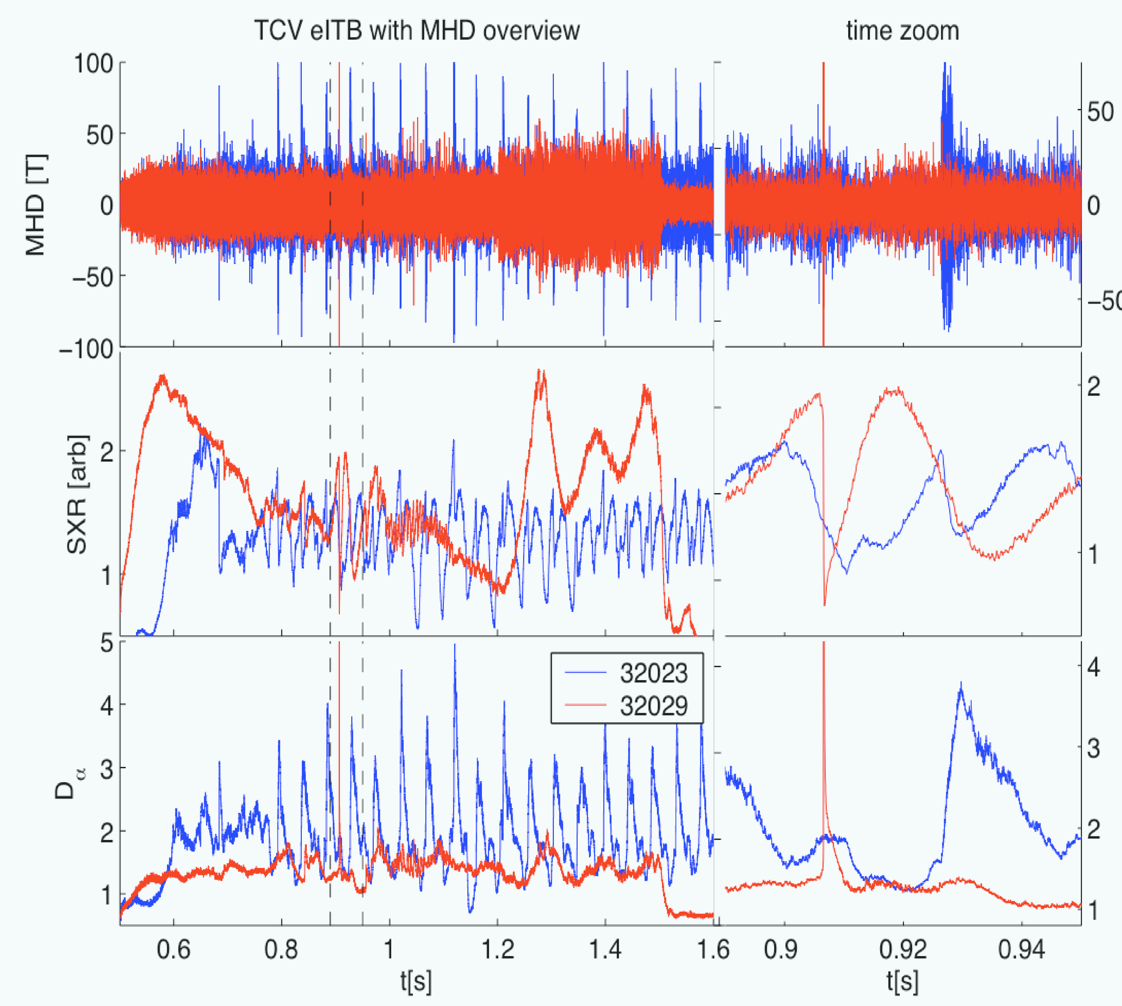


TCV eITB experiments:

- #21653 [4] bootstrap + ECCD; 3rd gyrotron at t=1.1s
- Current profile reconstructed with CQL3D [4]
- $q_{min} \approx 2.7$ at $\rho_\psi = 0.5$, where barrier is formed [4]
- *m/n*=3/1 with significant 2/1 component
- $\beta_N \sim 1$, i.e. close to ideal stability limit
- ILM (Internal Localized Mode) like effect on Dα
- **Limit reached for high ∇p in low-shear where the barrier is formed, τ_{MHD}=20μs**



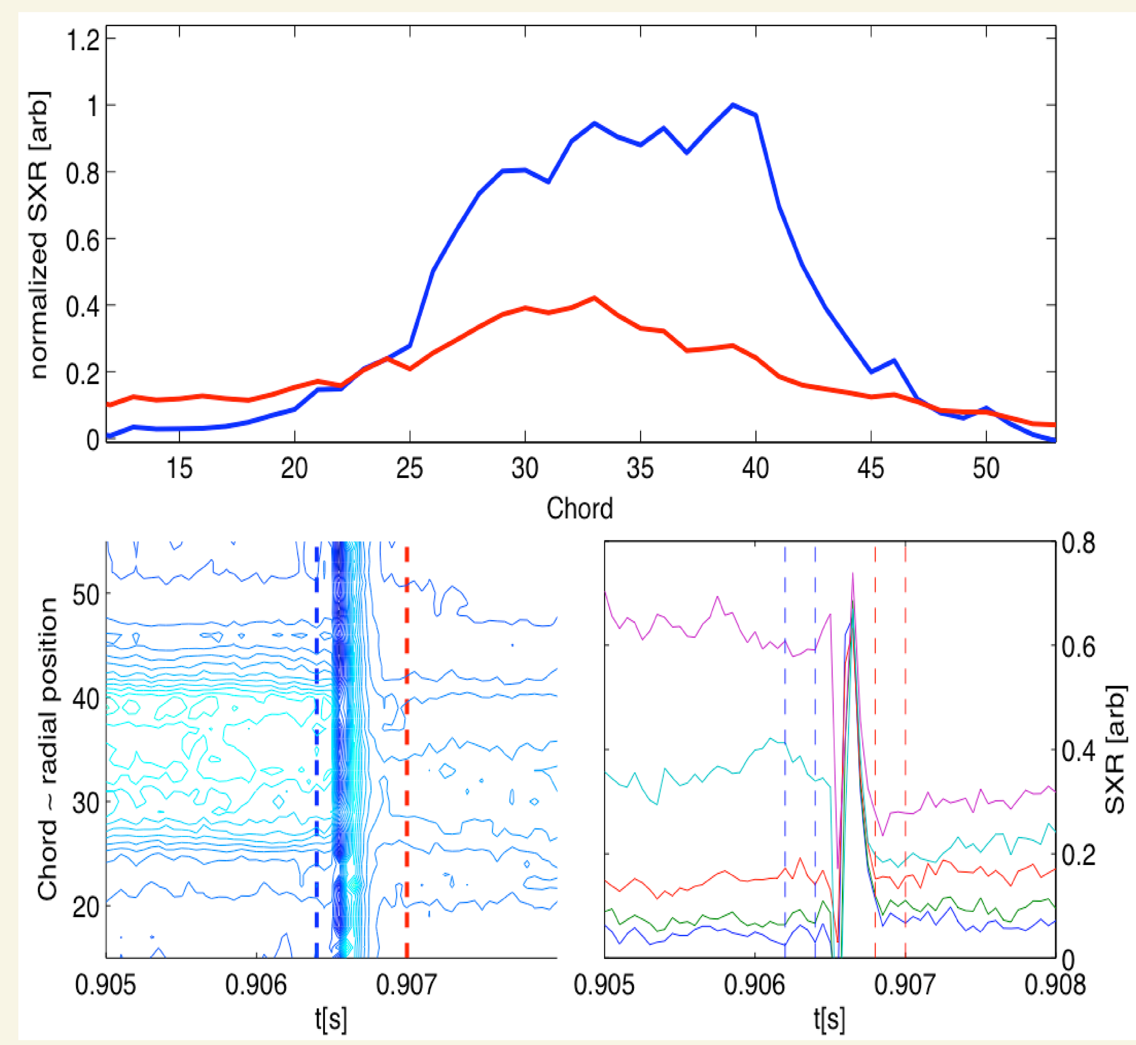
- #24696 on-axis counter-ECCD preceded by off-axis ECH
- Broader electron temperature profile (Ohmic contribution)
- q=2 sawtooth crash character, aka Periodic Relaxation Oscillations (PROs) [5]
- Ideal kink-like, dominated by high ∇p in the barrier
- resemble β-collapse seen in JT-60U [6].



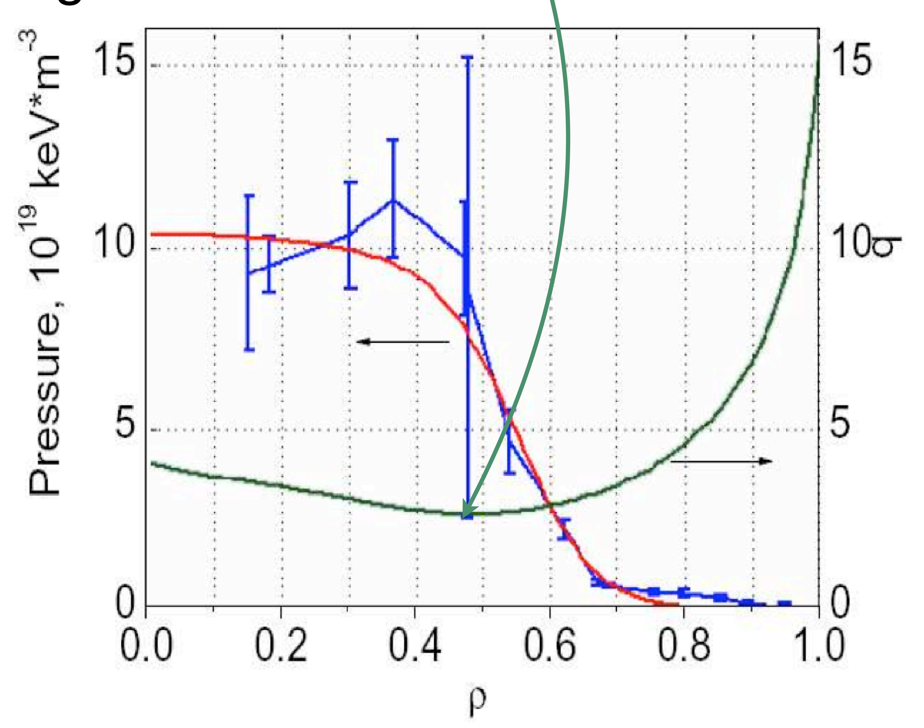
- #32023, small periodic infernal mode crashes
- Bursts of ideal activity followed by resistive mode
- Fast collapse, accompanied by Dα light emission
- Ideal mode of main periodicity *m/n*=2/1
- #32029, *minor disruption* at t=0.9s during first huge O-regime like oscillation, at the top confinement phase
- loss of barrier, due to continuous small infernal modes, ILM-like
- When ideal modes are stabilized, t≈1.22s, the barrier grows quickly, together with resistive MHD
- Character seems to be consistent with *NTM*, due to growth-decay dynamic and large bootstrap fraction

MHD confinement effect:

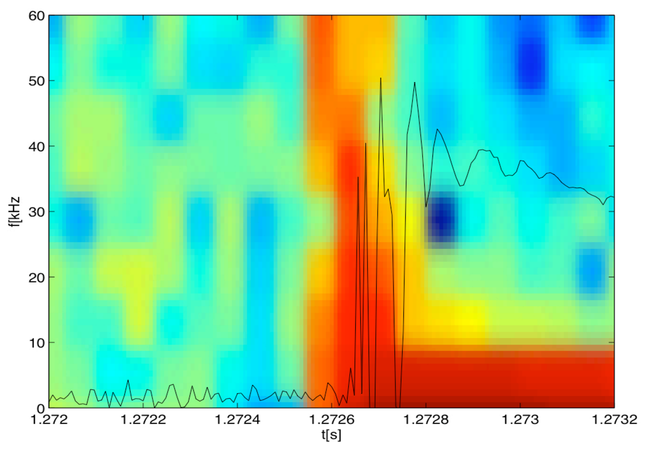
- #32029 shows major crash during first large oscillation
- loss of confinement estimated through SXR, 60% radiation reduction in the core
- gradient in the barrier region is lost, comparing pre (blue) and post (red) crash states.
- Particles and heat expulsion, visible in chords outside the core
- q=2 involvement
- quick recover in the core, with heating phase that makes the plasma infernal-unstable again in following cycle
- KINX and CHEASE --> evidence of plasma close to ideal stability limit at minor disruption



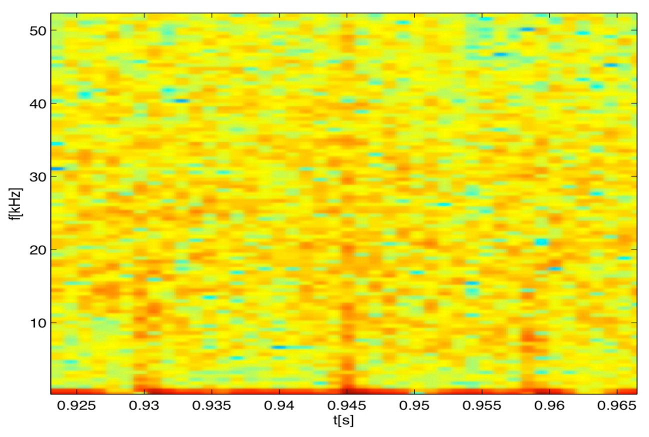
- stability limit calculations [3] shows lower β_N limit near near low rational q_{MIN}
- CQL3D + KINX for #21655, shows location of q_{MIN} and proximity to β limit (factor 1.2)
- experiments (21653) shows [4] agreement with theoretical results



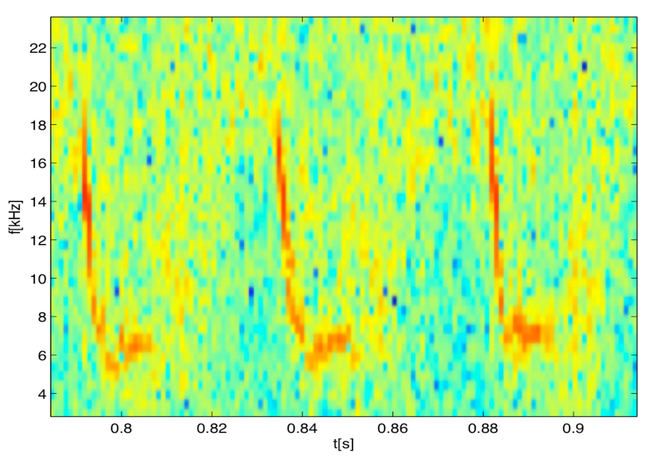
Spectrograms



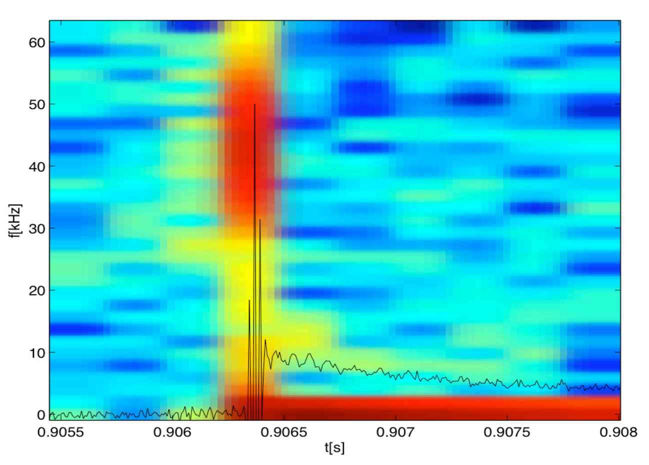
#21653 *major disruption*



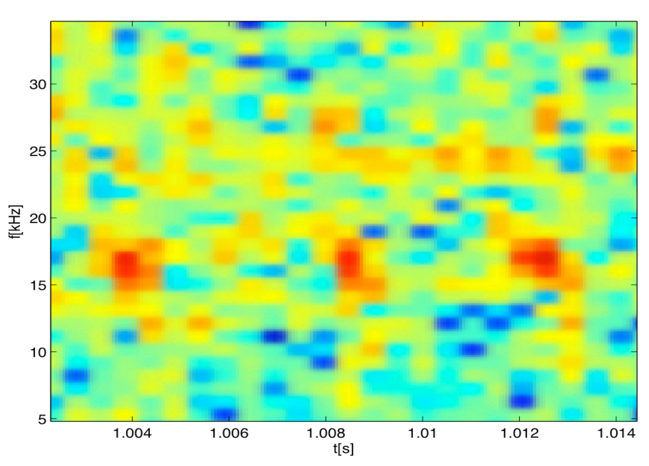
#24696 *PROs*



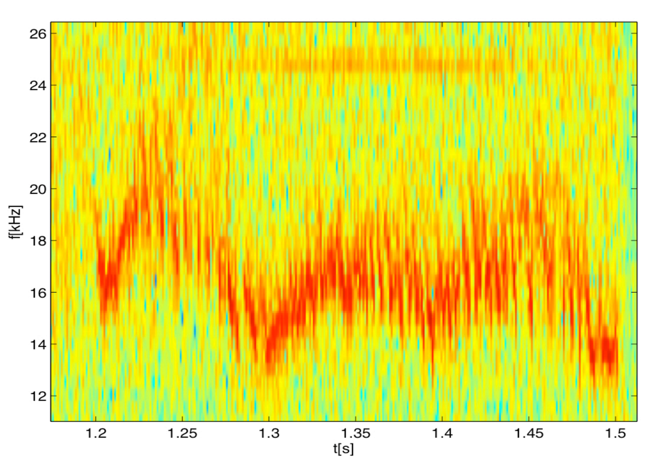
#32023 *small periodic infernal modes*



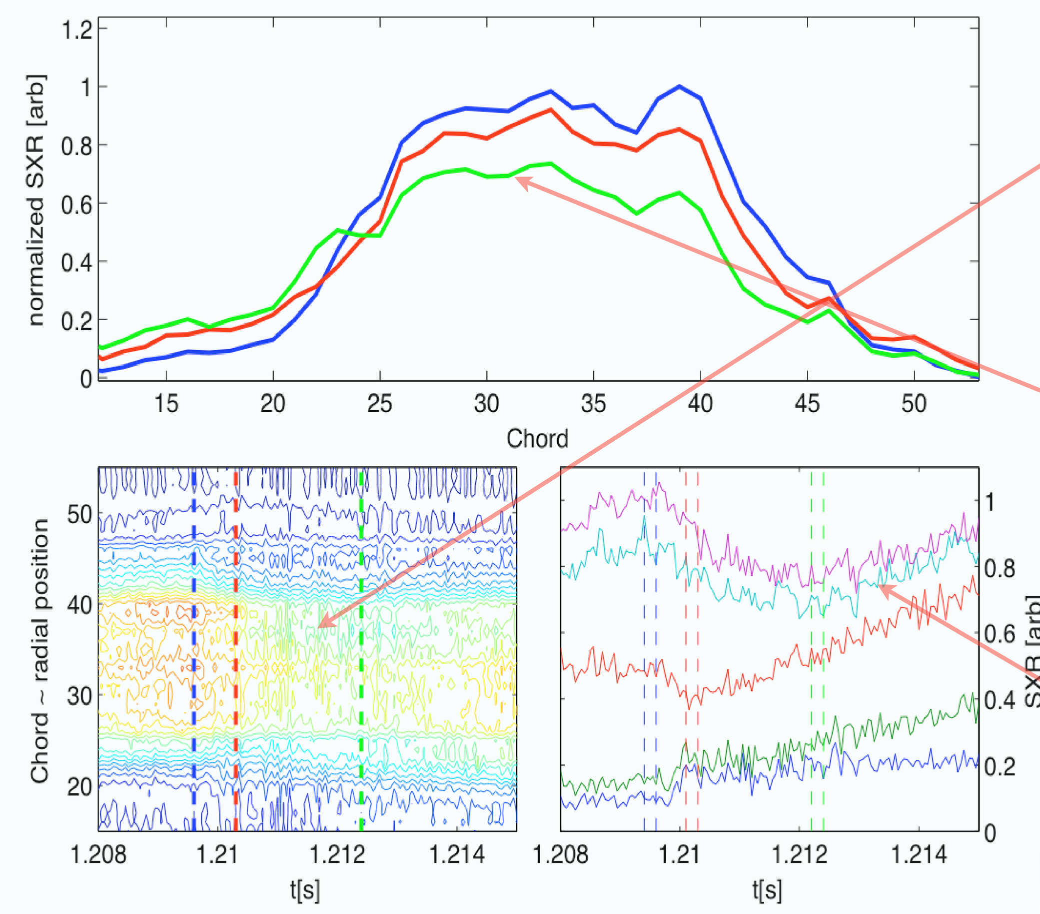
#32029 *Large infernal mode*



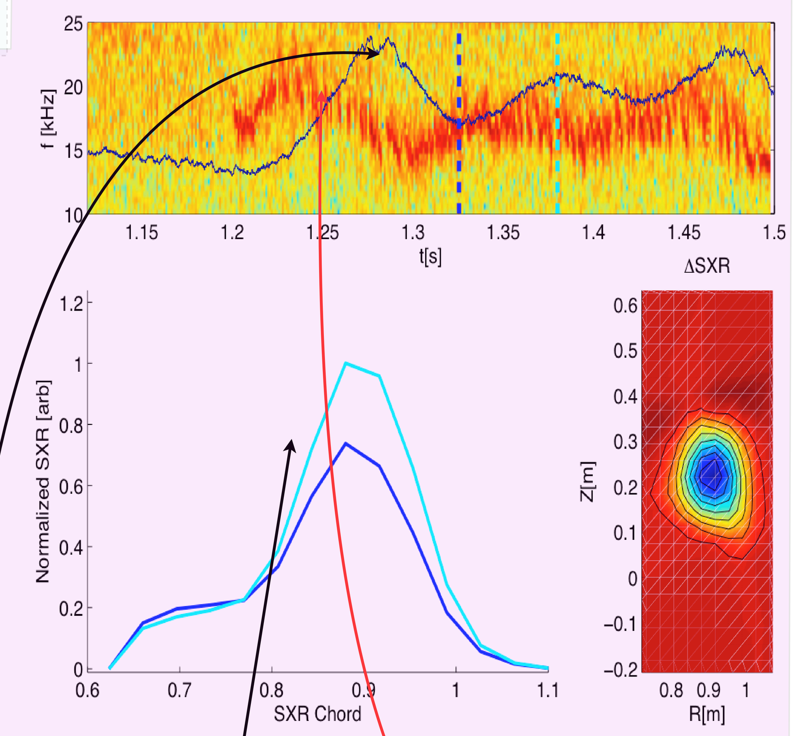
#32029 *Small periodic infernal modes*



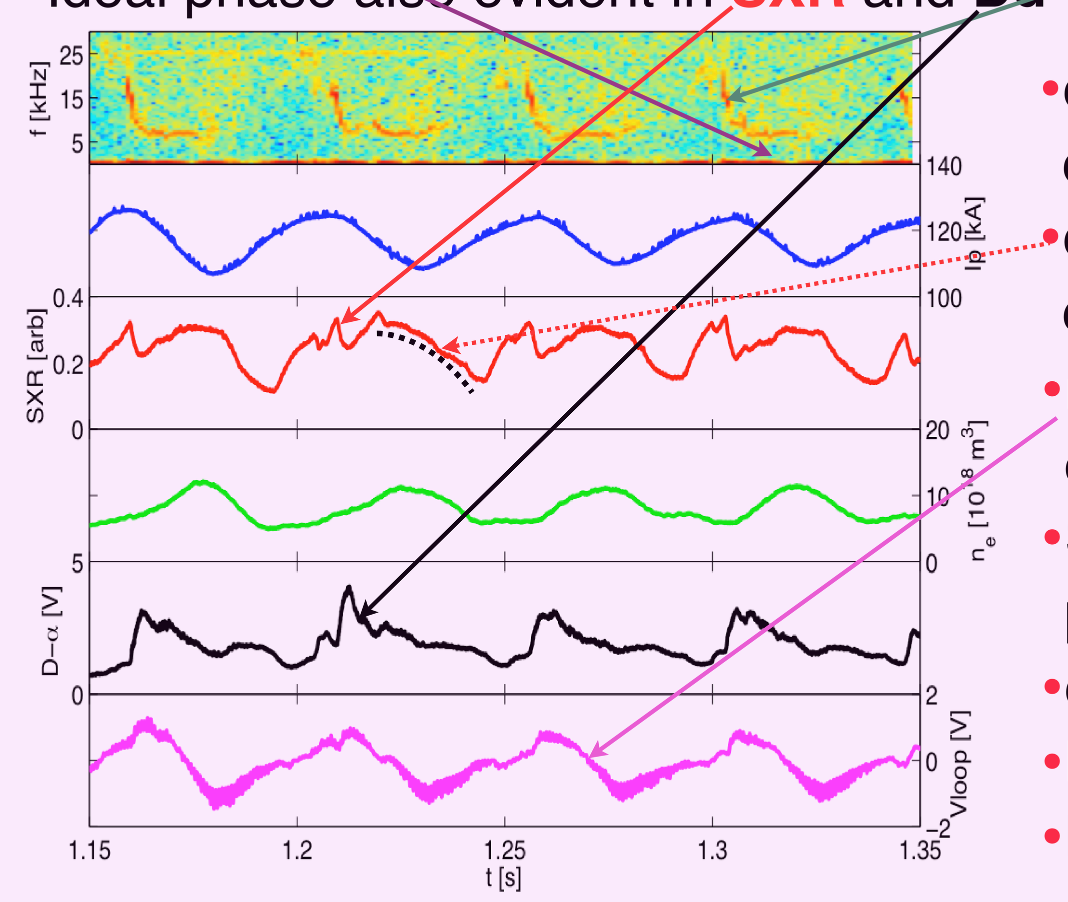
#32029 *Continuous resistive mode: O-regime*



- **#32023,** periodic small crashes
- Contour plot shows the less global effect of the crash
- loss of confinement estimated through SXR, 10% radiation reduction in the core (red trace)
- transport barrier partly preserved
- effect of the secondary more (resistive, green) plus possible late effect of ideal infernal mode
- SVD + Fourier + tomographic analysis -> *m/n*=2/1 (q=2 near channel 43 for LIUQE)
- quick recover in the core, periodically unstable with frequency *f*=20Hz



- **#32029**, spectrogram indicates dual character: **ideal** and **resistive**
- Ideal phase also evident in **SXR** and **Dα**

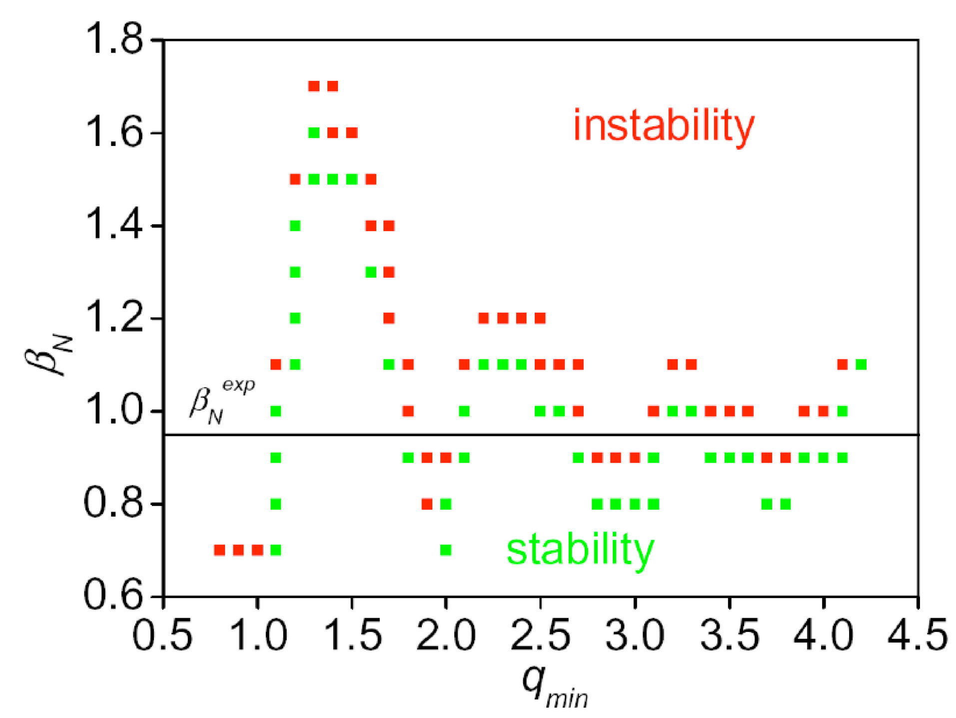


- crashes at top of confinement
- drop in confinement due to Ideal + resistive
- resistive mode lifetime ~ 20ms, magnetic configuration evolving
- Second phase with global **O-regime**, NTM mode present
- confinement drop between high-low H_{RLW} phases
- high bootstrap current fraction + dw/dt to infer character
- NTM with main periodicity *m/n*=2/1

4) Stability Analysis

- **q_{min}** value **importance**: stability analysis shows

windows of increased stability between resonant integer numbers for the safety factor [4].



- **infernal** modes appear in regions of low-shear. In this region the development of low-*n* pressure-driven modes is possible, [2,3] for reversed shear profiles.
- **Role of pressure in combination with value of q_{min} of fundamental importance**
- Slight changes in plasma parameters determine difference in character of this mode, the **infernal** mode, inherent for plasmas with high gradients and reversed shear. In these reverse low-shear plasmas, the pressure peaking factor is an important parameter to determine ideal β limit.

5) Conclusions

- Role of MHD of fundamental importance for the development of steady state eITBs.
- Values of H_{RLW} higher than 4 are obtained with and without MHD
- Various manifestation of MHD, depending on the fine details of the current and pressure profiles
- Pure ideal type (major and minor disruptions, infernal modes, kink), resistive (tearing, NTMs) and mixed character are found.

ITBs are created mainly with reversed shear and in the region of minimum safety factor. Therefore there are large pressure gradients an a low-shear region. Thus it is likely that:

- β -collapse,
- q=2 sawteeth,
- PRO,
- O-regime,
- minor and major disruptions

in reverse shear are all related to the nearby stability limit of infernal modes

This is why they are sensitive to **q_{MIN}** , **p_0/<p>**, **p'** and **shear**.

- effect of these modes is detrimental, thus avoidance (ideal) or control (resistive) is necessary for optimal performances

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[2] J. Manickam, N. Pomphrey, and A.M.M Todd. NF, **27**:1461, 1987. [3] T. Ozeki, M. Azumi, S. Tokuda, and S. Ishida. NF, **33**(7):1025–1035, 1993.
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[6] Y Nakamura *et al.*, PPCF, 38(10):1791–1804, 1996.