### 1) Introduction

**Importance of eITBs [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 (\(p=m \times 0.4\) 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 (\(T<T_{E}\))
- 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 \(q_{min} \approx 0.5\), where barrier is formed [4]
- \(m/n = 3/1\) with significant 2/1 component
- \(\beta_n \approx 1\), i.e., close to ideal stability limit
- ILM (Internal Localized Mode) like effect on Da
- Limit reached for high \(V_p\) in low-shear where the barrier is formed, \(\tau_{ECCD}=20\mu s\)

**#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 \(V_p\) in the barrier
- resemble \(\beta\)-collapse seen in JT-60U [6].

**#32023**, small periodic infernal mode crashes
- Bursts of ideal activity followed by resistive mode
- Fast collapse, accompanied by Da 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 $\beta_N$ limit near low rational $q_{\text{MIN}}$.  
- CQL3D + KINX for #21655, shows location of $q_{\text{MIN}}$ and proximity to $\beta$ limit (factor 1.2).  

**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

**4) Stability Analysis**

- $q_{\text{MIN}}$ 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 $q_{\text{MIN}}$ 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 $\beta$ limit.

**5) Conclusions**

- Role of MHD of fundamental importance for the development of steady state eITBs.
- Values of $H_{\text{RLW}}$ 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 on a low-shear region. Thus it is likely that: 
  
- $\beta$-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 $q_{\text{MIN}}$ and $\rho^2/p$. $p$ and shear.

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

---