



# Onset of tearing modes in plasma termination on JET: the role of temperature hollowing and edge cooling

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with thanks to P. Lomas, S. Nowak, C. Sozzi



This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.



## ● Tearing modes in the flat-top phase

- sawteeth
- fishbones and edge localized modes

## ● Tearing modes in the termination phase

- temperature hollowing and edge cooling
- empirical stability diagram

## ● Onset and dynamics

- temperature hollowing only
- temperature hollowing and edge cooling
- edge cooling only

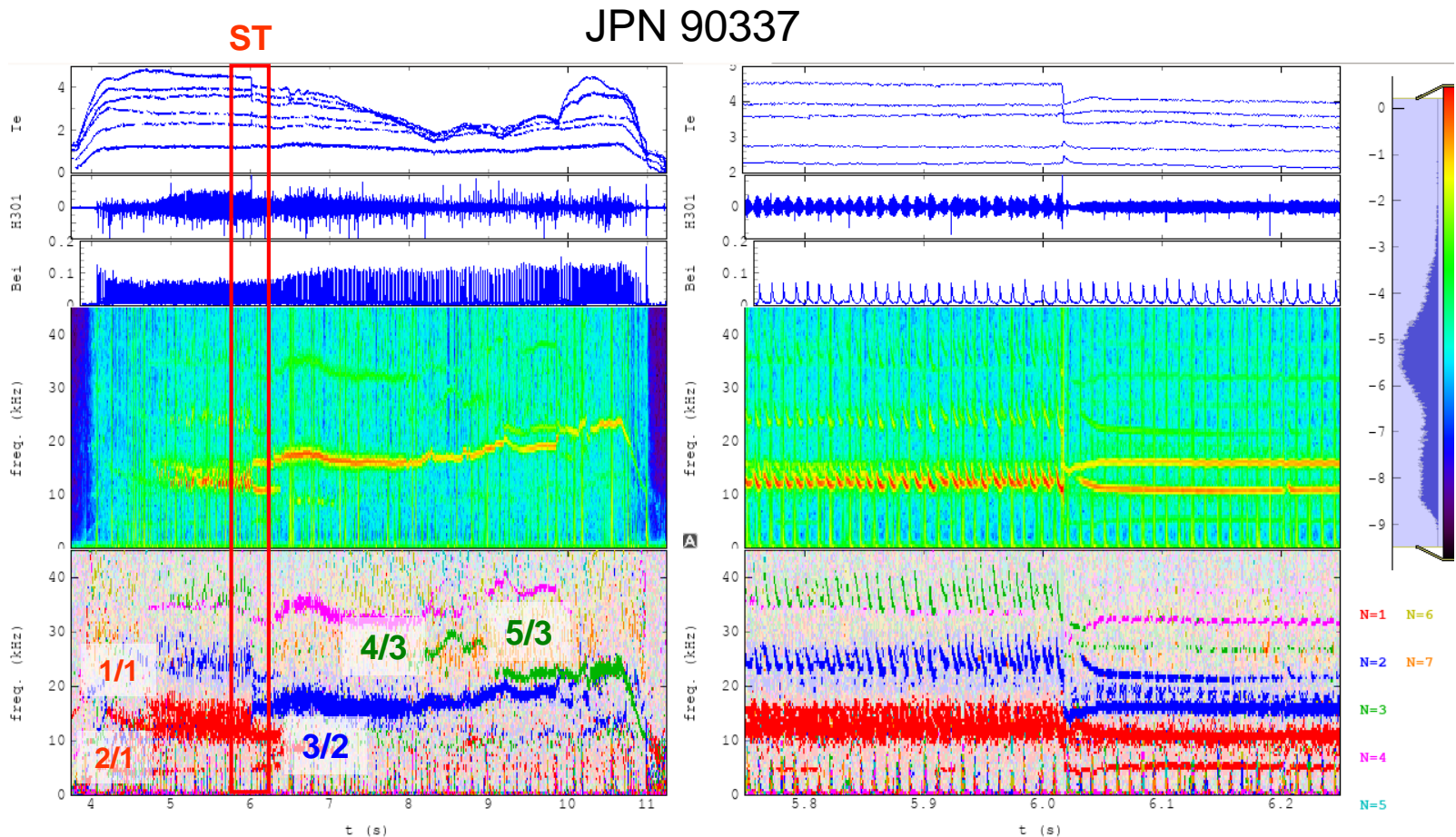
## ● Destabilization mechanisms

- analytical sequences
- TRANSP simulations
- linear stability analysis

# Tearing modes in the flat-top phase: sawteeth



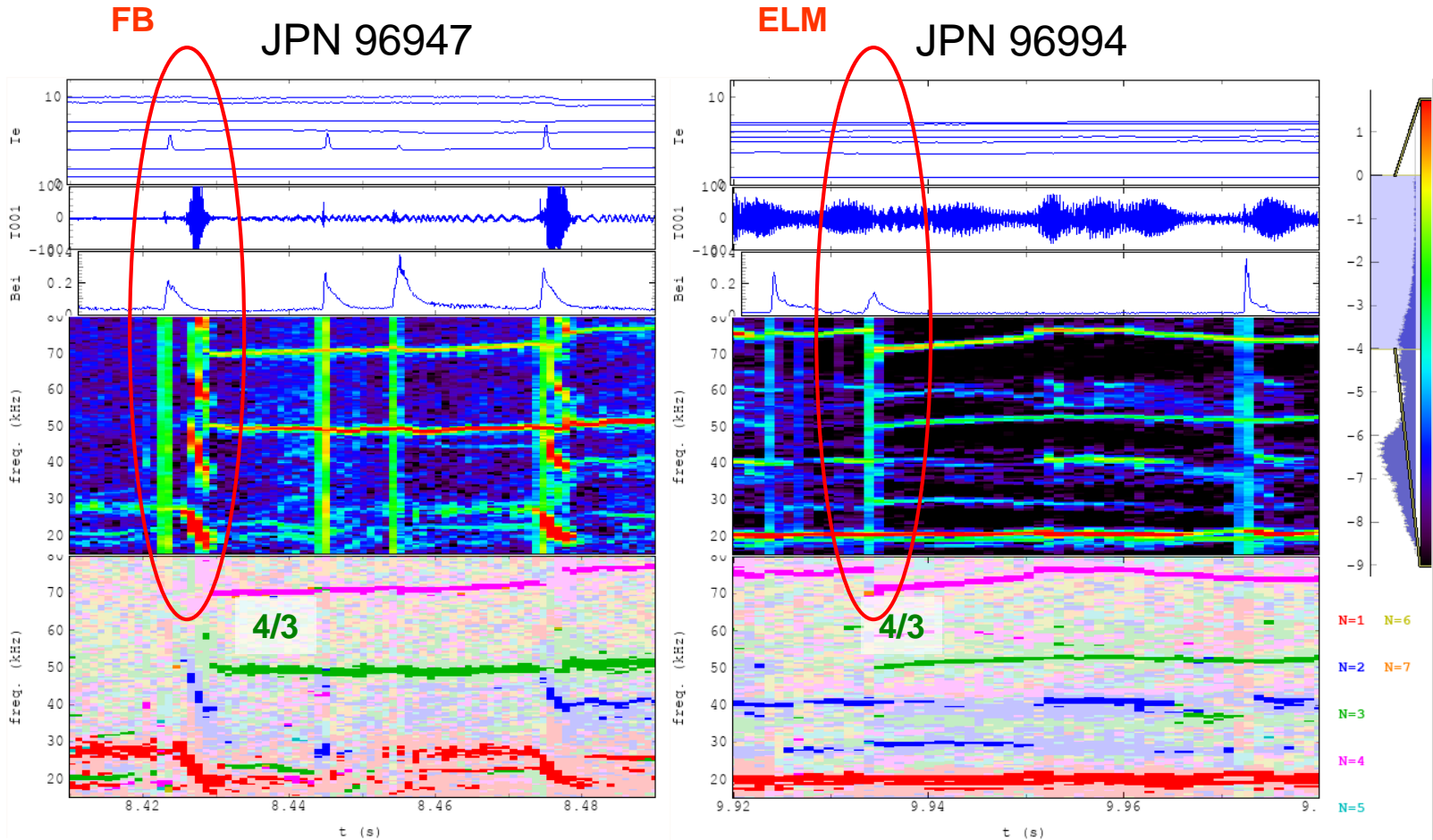
- **Tearing modes** characterized by different poloidal ( $m$ ) and toroidal ( $n$ ) mode numbers are sometimes observed during the flat-top phase of a plasma pulse at JET, triggered by **sawtooth crashes**, affecting plasma confinement.



# Tearing modes in the flat-top phase: fishbones, ELMs



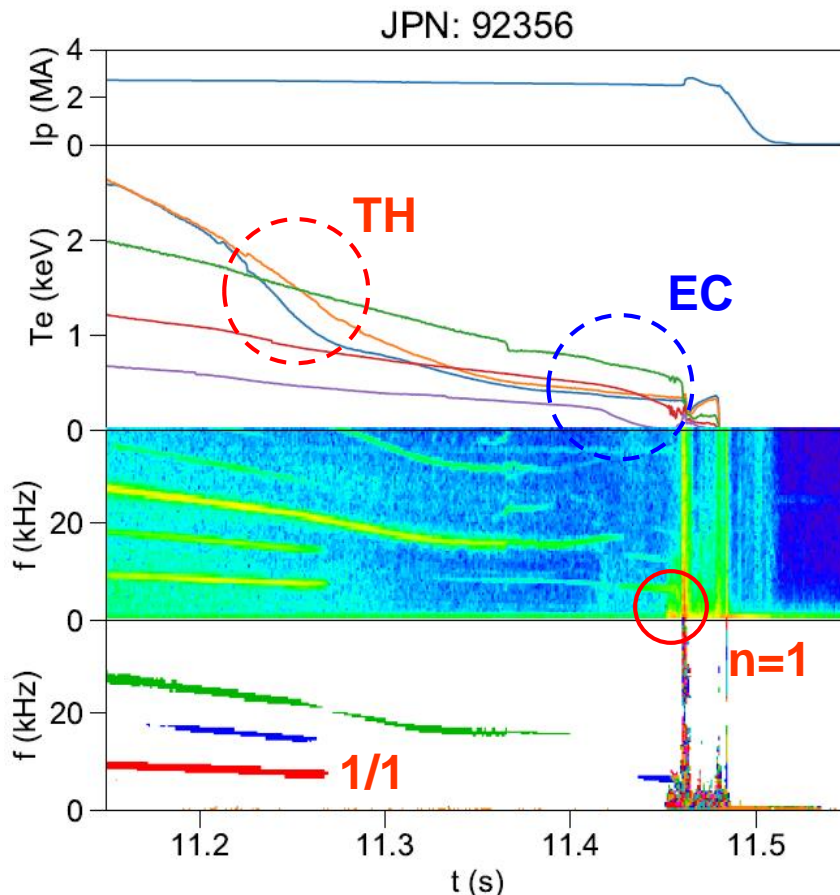
- **Fishbone** activity and perturbations associated to **edge localized modes** can also trigger tearing modes.



# Plasma termination: changes in $T_e$



- Tearing modes without evident external triggers are observed in the termination phase of disruptive pulses in presence of an increased radiation emission in core or edge plasma, leading to **temperature hollowing** (TH) and **edge cooling** (EC), respectively.

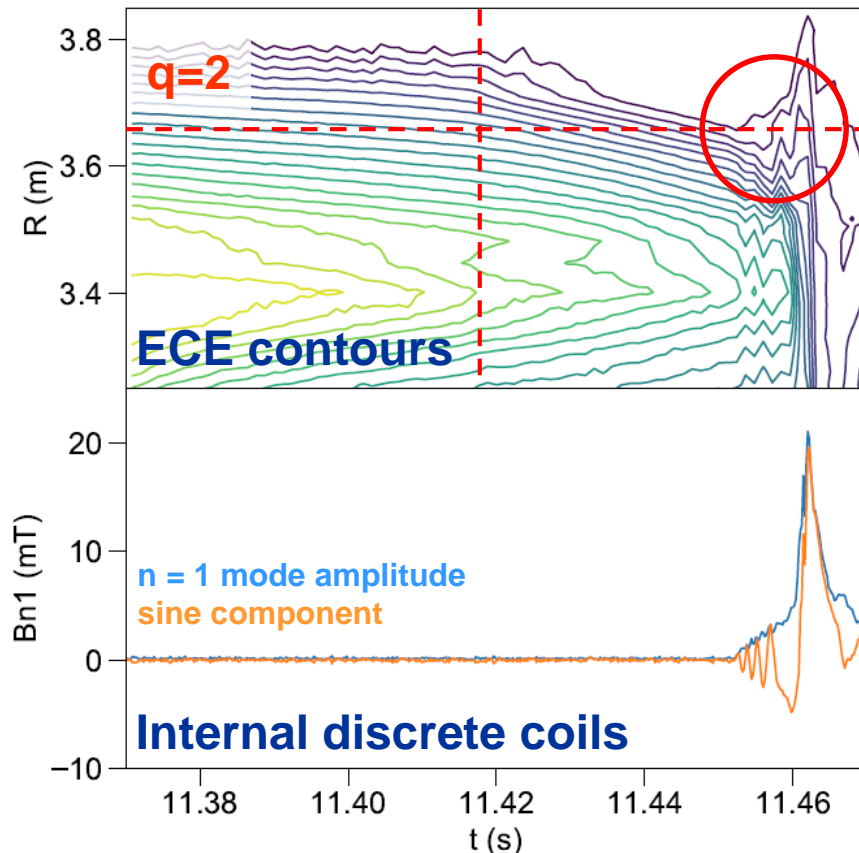


- After switching off the heating power (from 10.8 s to 11.2 s), a hollowing of the temperature profile is observed, likely due to heavy impurity accumulation.
- Following the change in the temperature profile, an increase in central safety factor is expected, as confirmed by disappearing of 1/1 mode related to  $q=1$  magnetic surface in the plasma.
- Few tens of ms before the disruption an edge cooling is observed, likely due to a high edge density level, and a  $n=1$  tearing mode is excited.

# Plasma termination: 2/1 TM destabilization



- The electron temperature contours from ECE radiometry show rapidly increasing variations when the edge cooling affects the region of the  $q = 2$  surface and signals from internal discrete coils confirms that an explosive growth of a  $m/n = 2/1$  magnetic island is present.



- In the termination phase the current profile is dominated by the ohmic contribution and the resistivity is large due to the low temperatures:

$$\eta \propto Z_{eff} / T_e^{3/2}$$

- The current profile changes on a relatively fast resistive time scale reflecting the changes in the electron temperature profile:

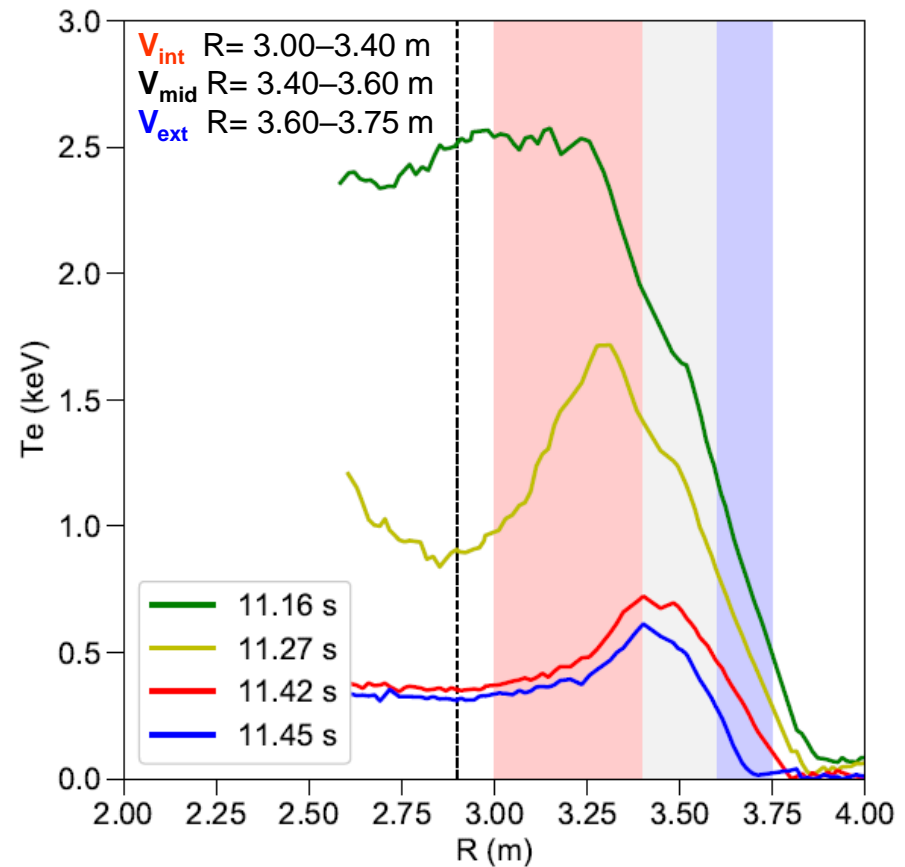
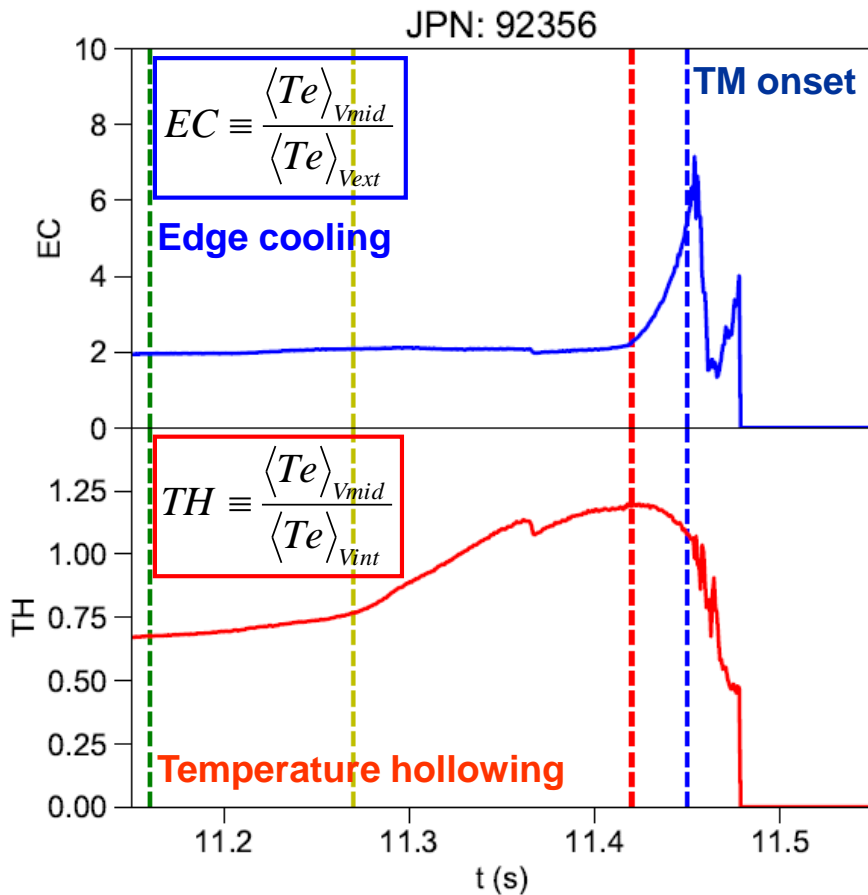
$$\tau_R \approx \mu_0 L^2 / \eta$$

- The role of changes in the electron temperature profile in the onset of a **2/1** tearing mode on plasma termination is investigated.

# Temperature hollowing and edge cooling



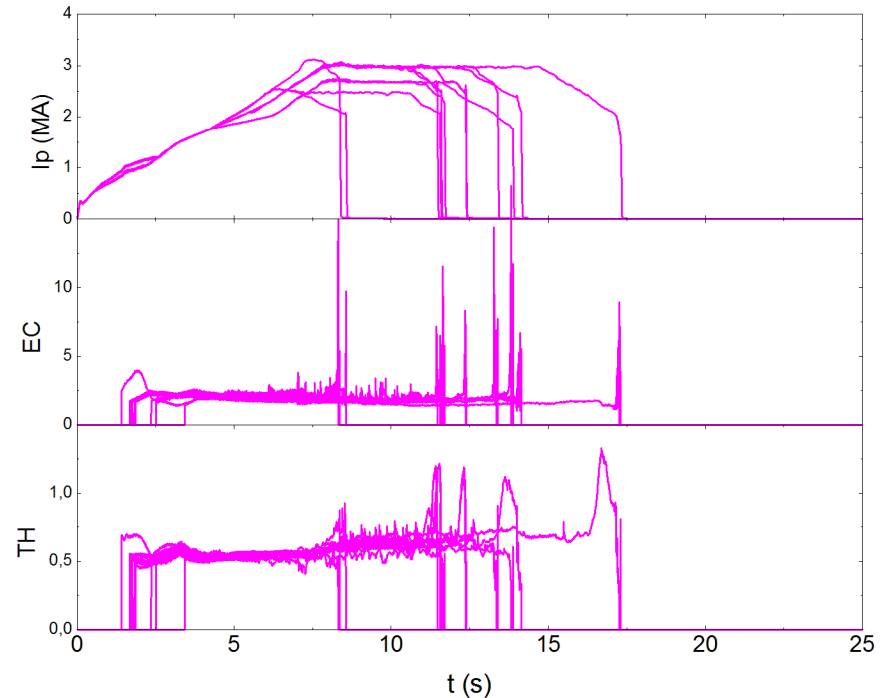
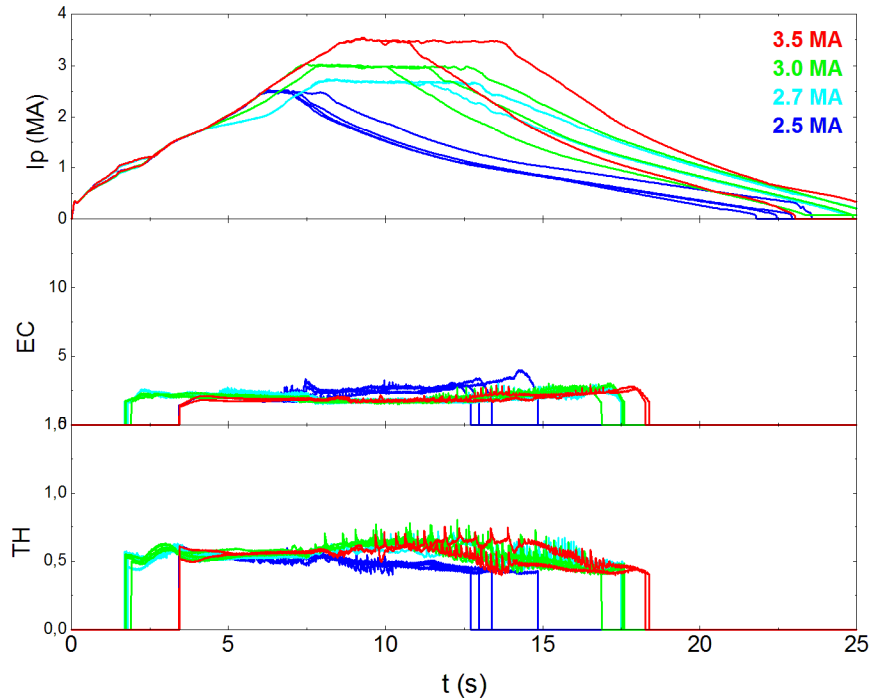
- Two parameters are defined, from **ECE radiometry**, to characterize the shape of the electron temperature profile, namely the **temperature hollowing TH** and the **edge cooling EC** and the time evolution of such parameters is studied to highlight the correlation with mode onset in disruptive pulses.



# Non-disruptive and disruptive pulses



- The time evolution of the two parameters TH and EC has been evaluated for a dataset of 268 pulses carried out in the baseline scenario in the period 2016-2020.

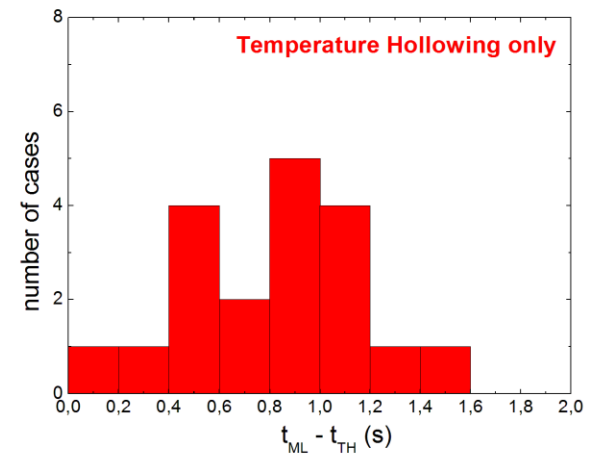
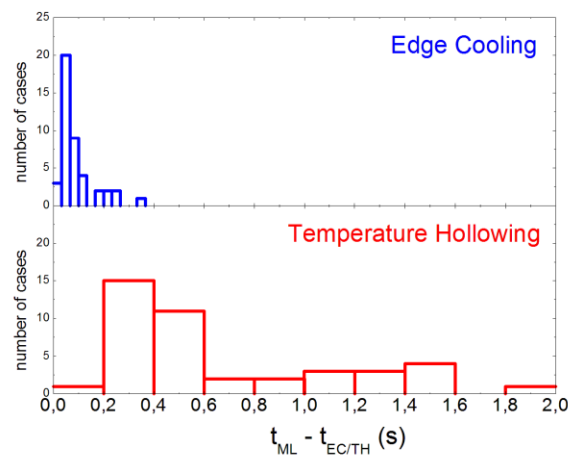
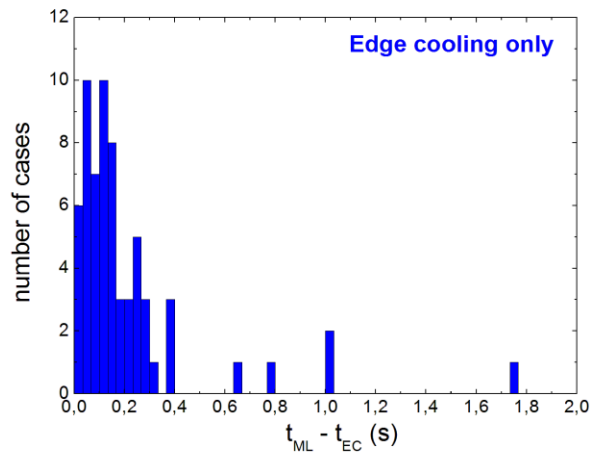


- Non-disruptive pulses are generally devoid of temperature hollowing and edge cooling, with stable values for both parameters TH and EC.

- Only in the last two seconds before the disruption an increase on one or both parameters TH and is observed in disruptive pulses.



- The distributions of the time interval between the increase of the parameters TH and EC and the mode locking, identified by saddle flux loops, have been evaluated for 134 disruptive pulses, classified according to the simultaneous or separated occurrence of edge cooling and temperature hollowing.

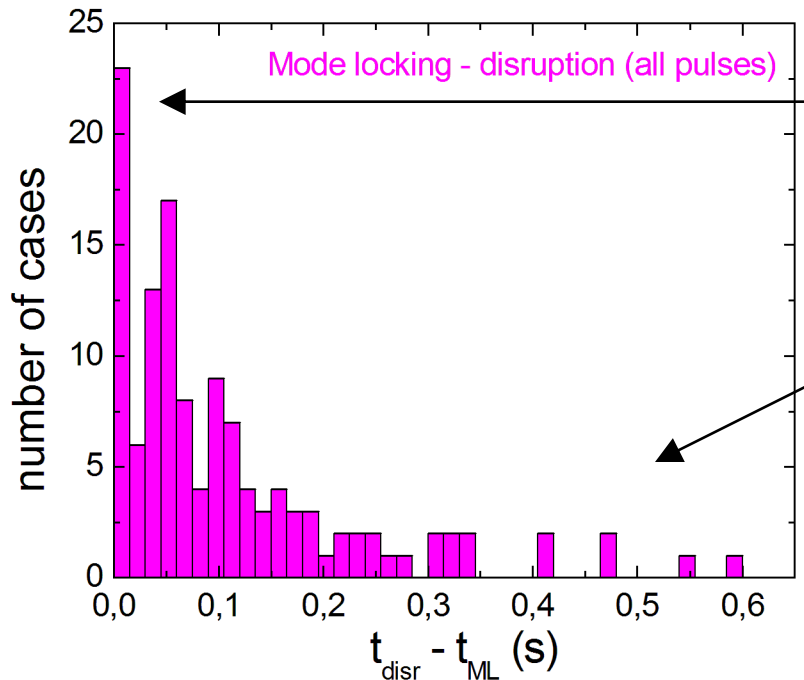


- The parameter **EC** could provide alerts falling within **200 ms** from the mode locking, namely not sufficient to correct the termination but enough to anticipate **mitigation** actions.

- The parameter **TH** could provide alerts up to **2 s** from the mode locking, so an attempt to correct the termination **avoiding** the disruption is possible.



- The time corresponding to the mode locking has been used as a reference as it is directly related to the mode onset and growth up to a given amplitude, whilst the time from locking to disruption can vary from few milliseconds to hundreds, depending on the mode dynamics and on the logic of the mitigation actions.

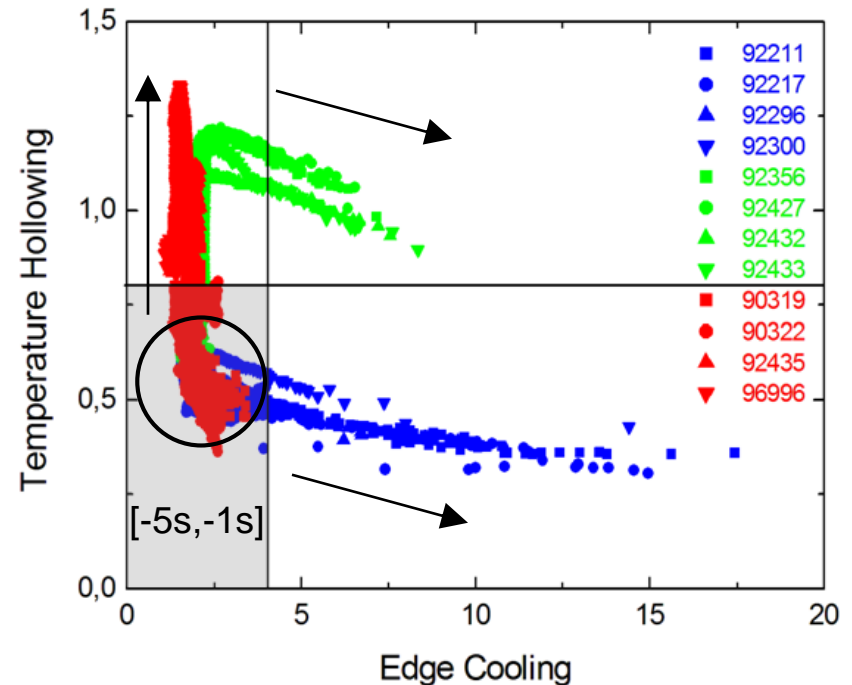
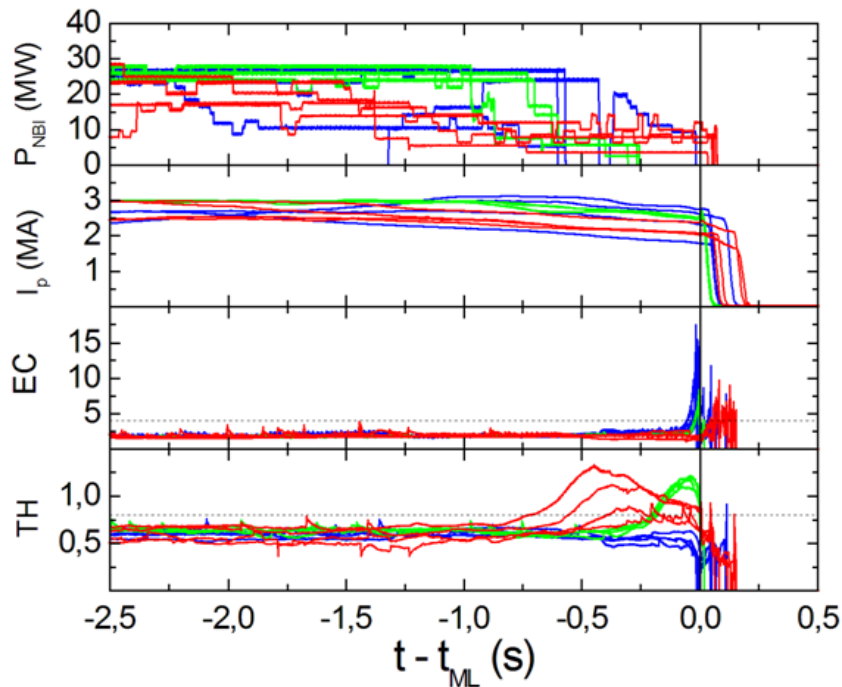


- The first bin (0-15 ms) correspond to **unmitigated pulses** (thermal quenches before disruption mitigation valve intervention).
- Long delays correspond to low amplitude lock modes (triggering late the mitigation actions) and to pulses with sequences of soft disruptions.

# Empirical stability diagram



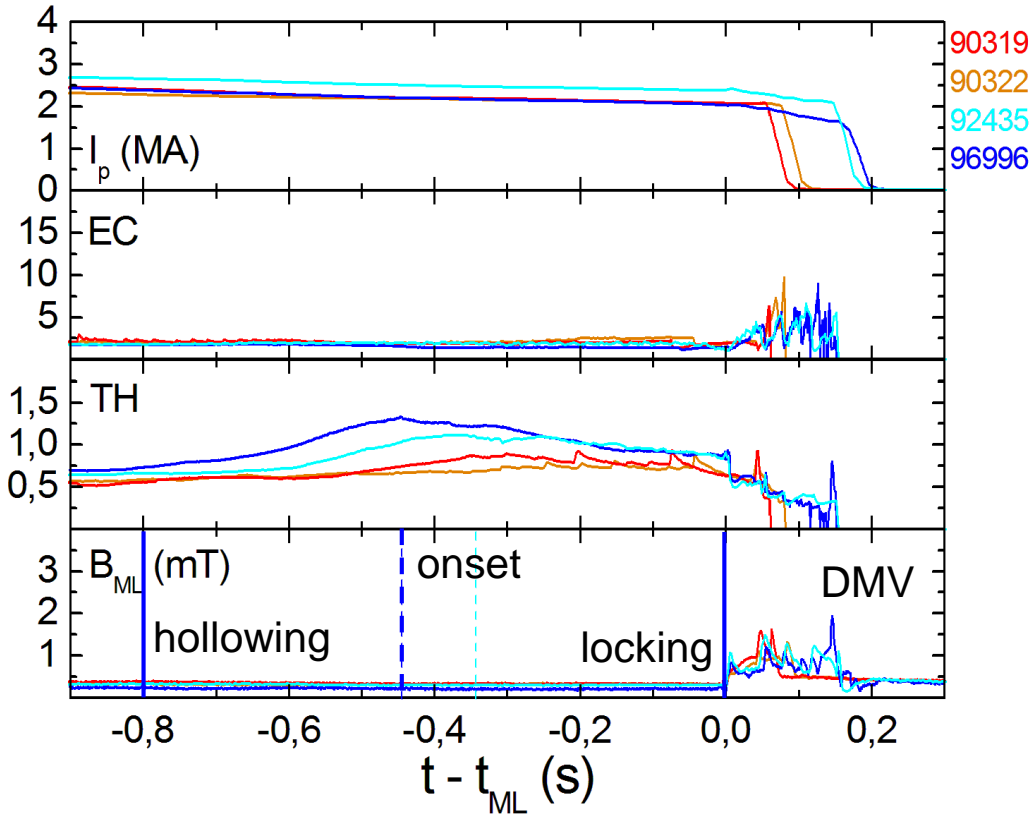
- Temporal evolution of the plasma current and neutral beam power and of the two parameters TH and EC for 12 representative disruptive pulses.
- For time interval between 5s and 1s to mode lock the EC-TH pairs are located in a well defined quadrant (gray shadow), where also the EC-TH pairs for non-disruptive pulses are usually located, so this quadrant identifies the **stability region** for parameters EC and TH.



- Depending on simultaneous or separated occurrence of temperature hollowing and edge cooling, three different kind of pulses can arise.



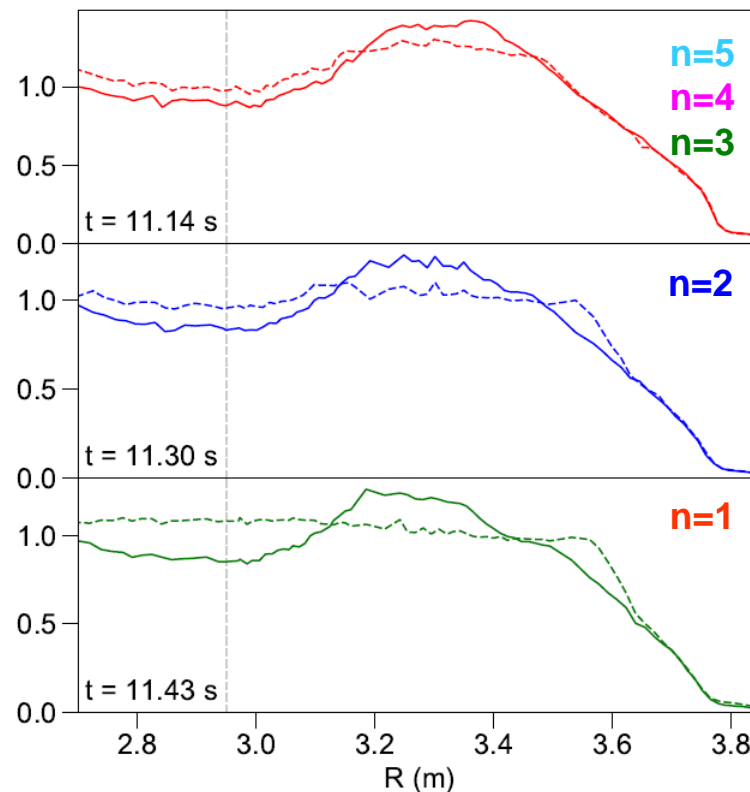
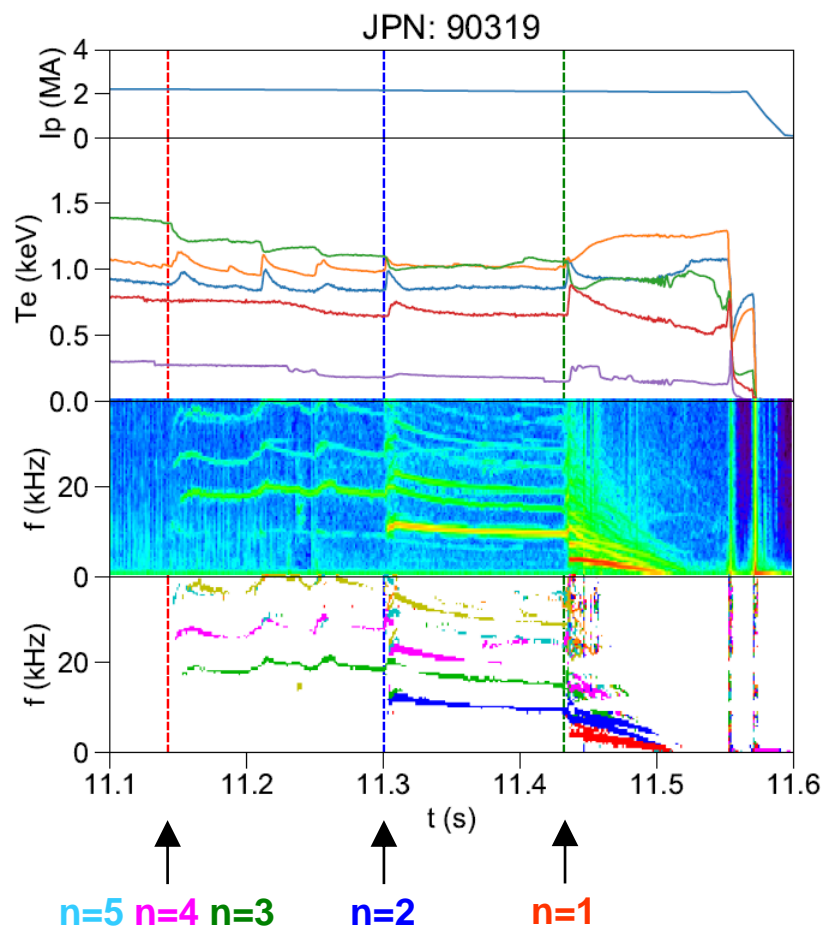
## 1. Pulses with temperature hollowing only



- The two pulses with lower TH values are characterized by a sequence of modes with decreasing toroidal mode number, where each mode is triggered by an **Internal Reconnection Events**.
- The two pulses with higher TH values are characterized by a **fast initial mode rotation**, which is visible by standard Mirnov coil signals.

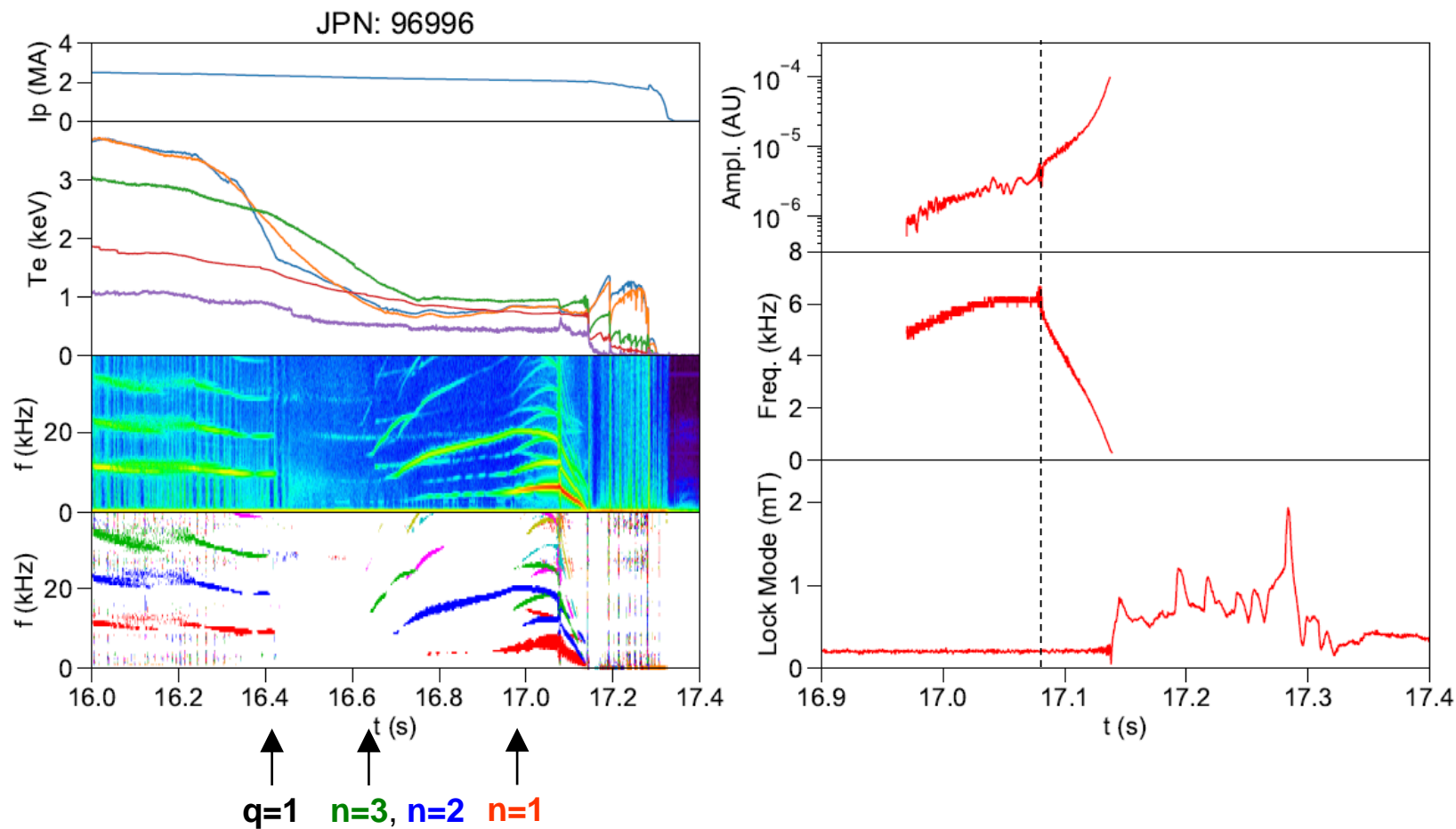


## 1. Pulses with temperature hollowing only: internal reconnection events

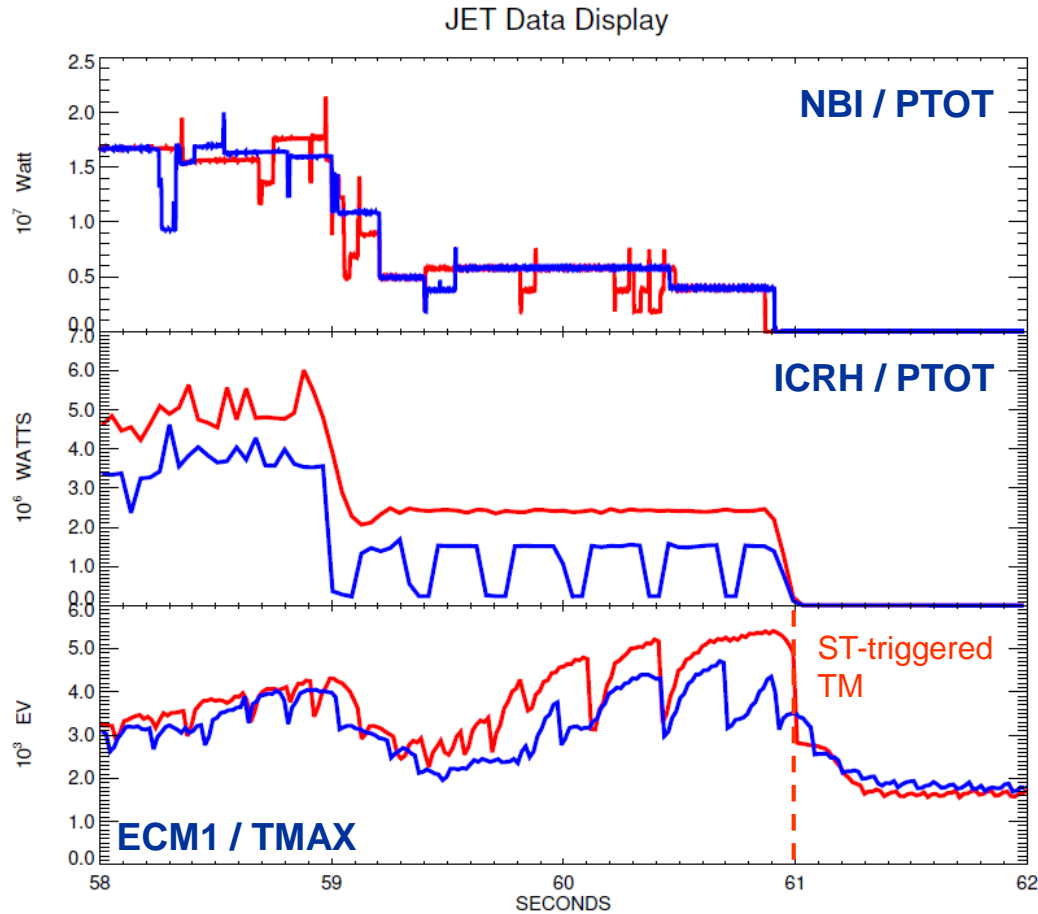




## 1. Pulses with temperature hollowing only: spontaneous onset



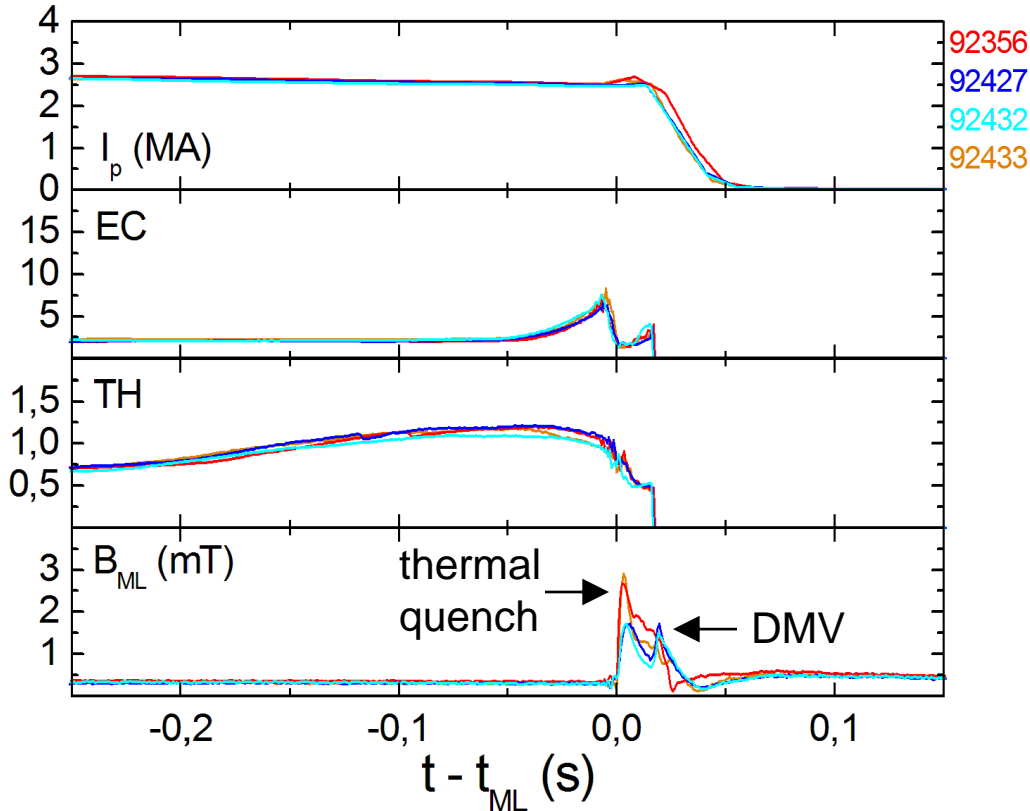
# ICRH in “landing”: 94887 vs. 94894



- An attempt to correct the termination of pulses with temperature hollowing avoiding the disruption is possible, e.g. providing central additional heating to counteract the inward transport of high-Z impurities.
- The additional power has to be carefully calibrated to avoid the onset of tearing modes triggered by sawtooth crashes, as observed in pulses characterized by long-period sawtooth activity.



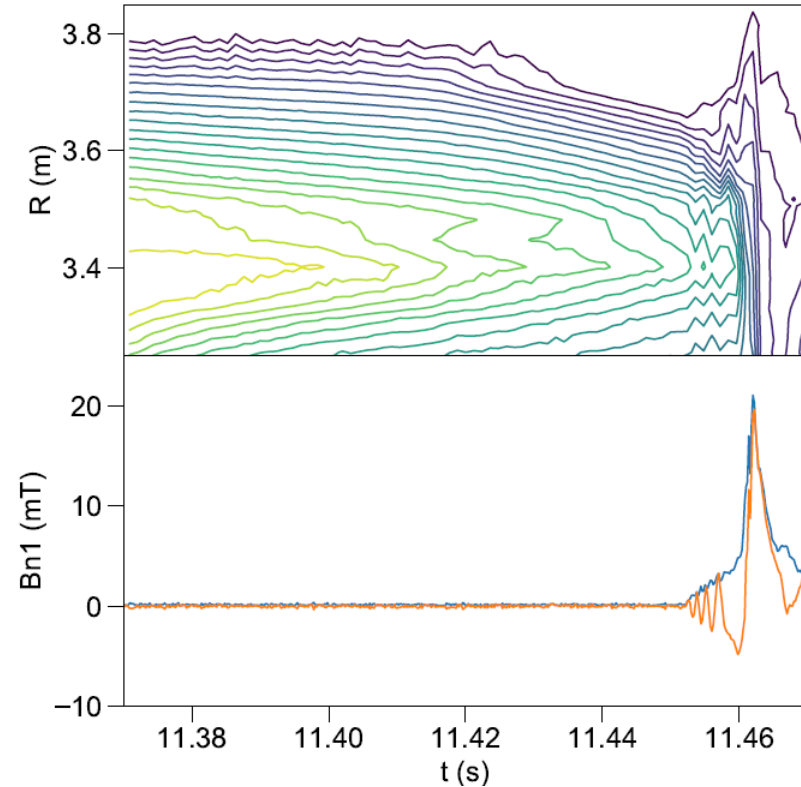
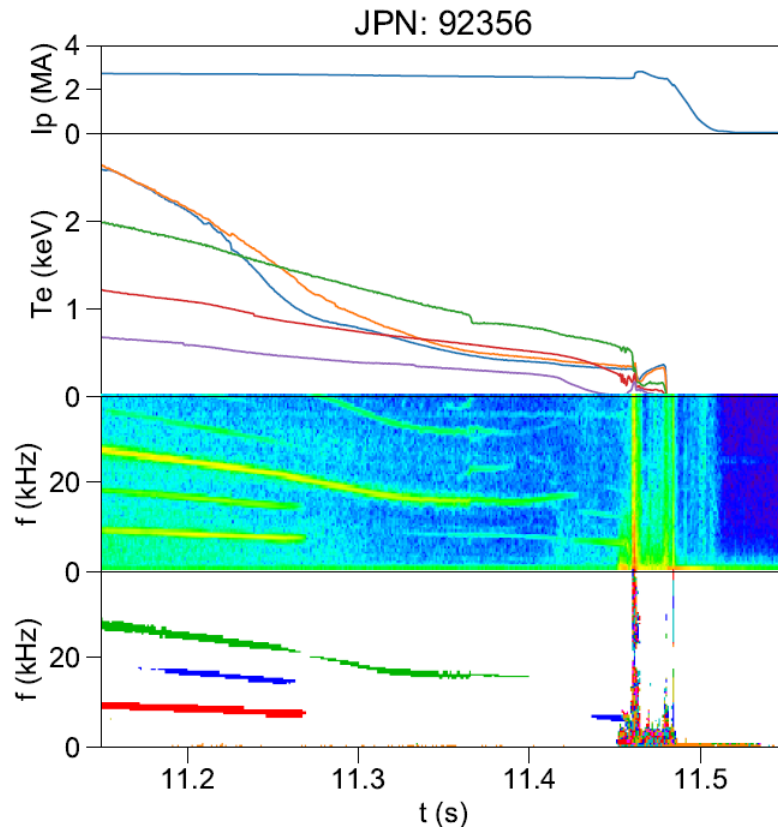
## 2. Pulses with temperature hollowing and edge cooling



- Temperature hollowing always precedes edge cooling. Some times the cause of mode onset is the temperature hollowing. Other times is the edge cooling.
- The thermal quench occurs only 10 ms after the mode onset (first fast increase in ML signal), so before the actual DMV intervention (spikes in ML signal), which requires about 15 ms from the trigger.

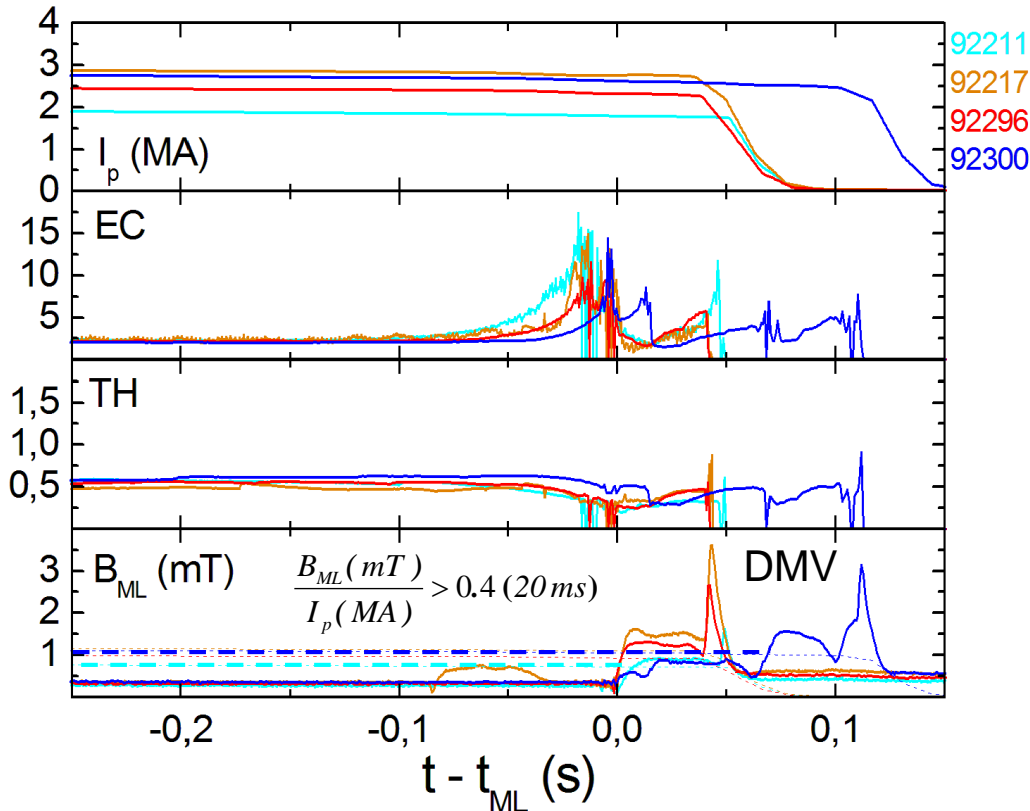


## 2. Pulses with temperature hollowing and edge cooling





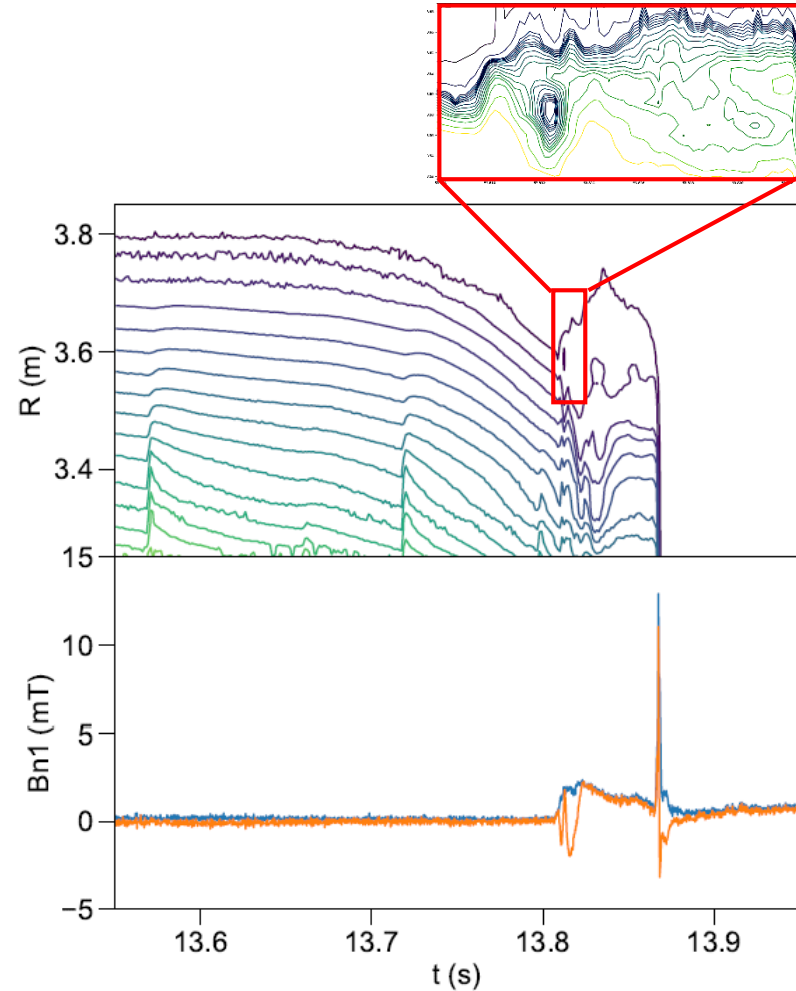
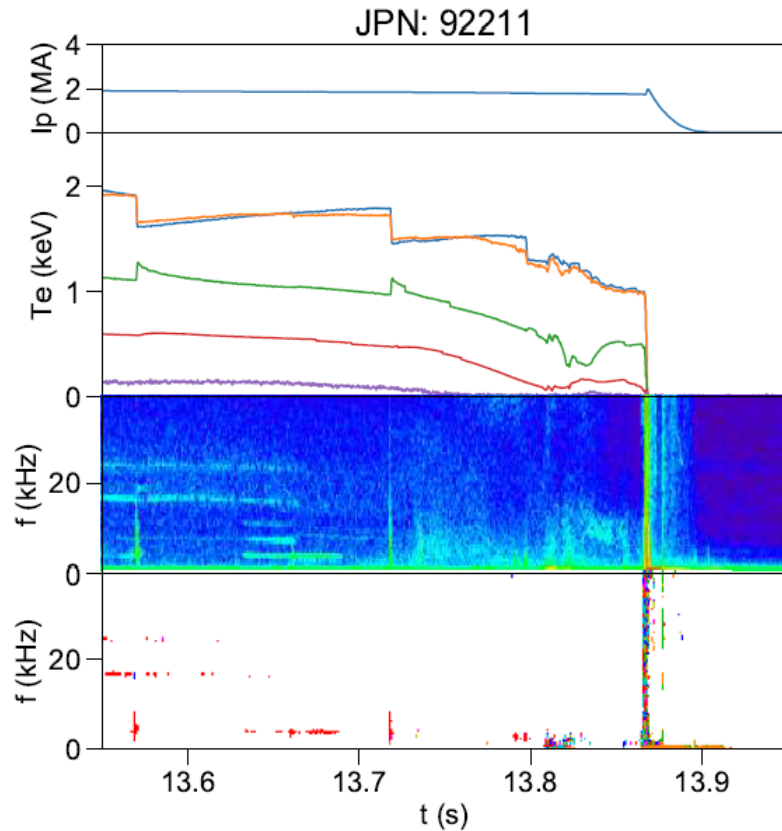
## 3. Pulses with edge cooling only



- The time delay between edge cooling and mode onset seems to be approximately constant, confirming that if edge cooling is present then it causes the instability.
- The DMV intervention is triggered at different time intervals from the locking, depending on different values of mode lock amplitude and plasma current.



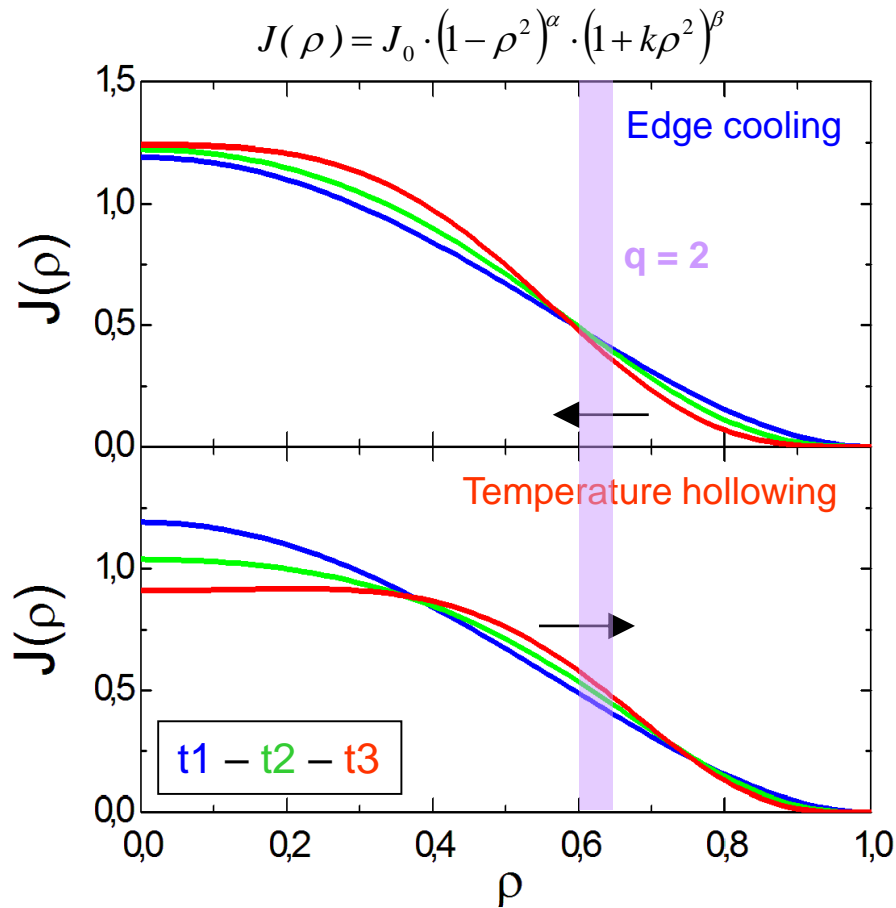
## 3. Pulses with edge cooling only



# Destabilization mechanisms



- The correlation between temperature hollowing or edge cooling and the onset of tearing mode in the termination phase is based on the picture of  $n=1$  tearing modes generated by changes in the current density profile reflecting, on a relatively fast resistive time scale (due to higher resistivity), changes in the electron temperature profile.



- Qualitatively, both temperature hollowing and edge cooling can lead to an unstable MHD scenario, as a consequence of a continuous increase of the current density gradient near the mode resonant surface.

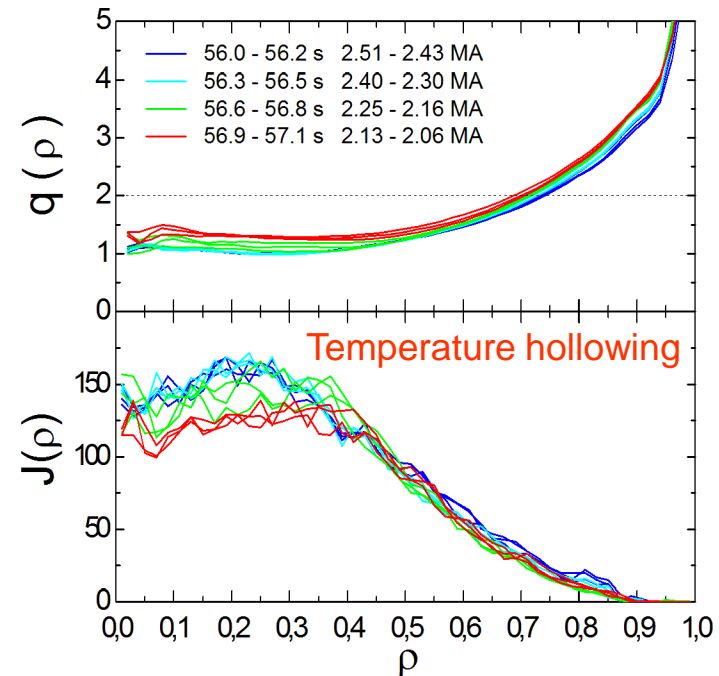
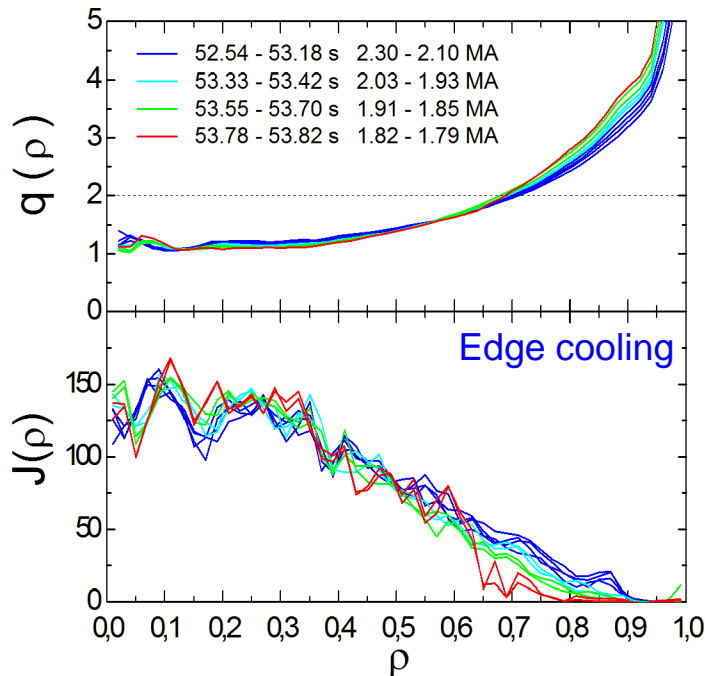
This could be due to:

- erosion of the current density profile from outside in the case of **edge cooling**
- broadening of the current density profile from inside in the case of **temperature hollowing**

$$\frac{d}{dr} \left[ r \frac{d}{dr} (rB_{r1}) \right] = \left[ m^2 + \frac{dj_\phi/dr}{(B_\theta/\mu_0 r^2)(1-nq/m)} \right] B_{r1}$$



- TRANSP simulations have been carried out for two pulses, representative of the **edge cooling** (JPN 92211) and **temperature hollowing** (JPN 96996) scenario, respectively.
- Electron temperature profile from high resolution Thomson scattering are considered, with classical Spitzer resistivity, and the current density profile evolution is calculated according to the poloidal field diffusion equation.

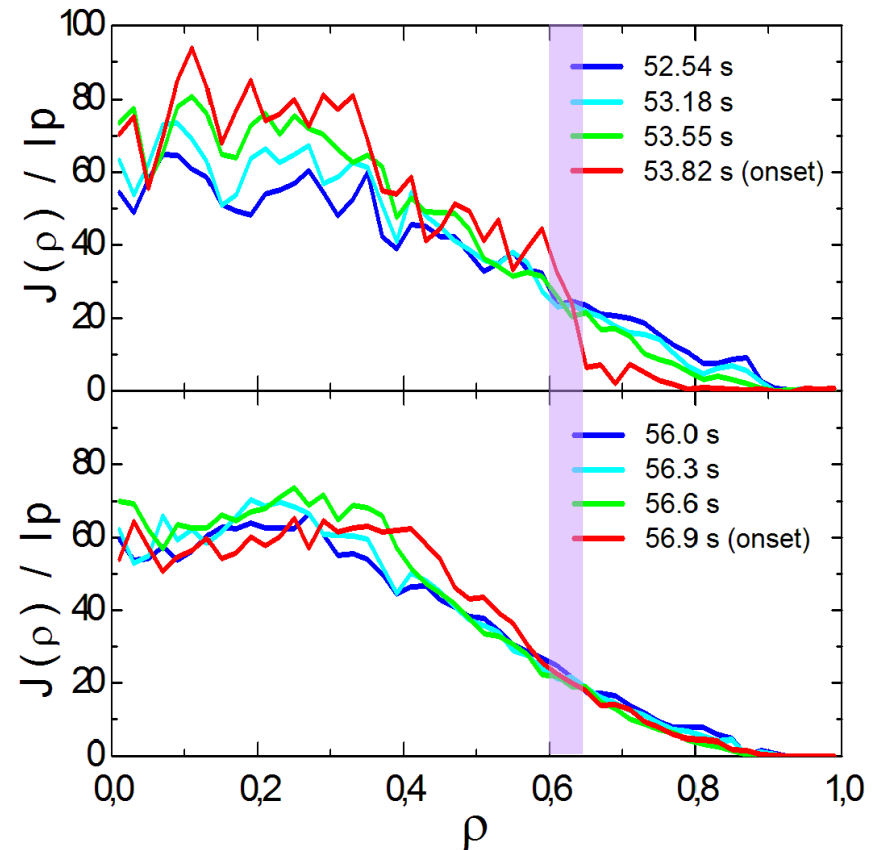
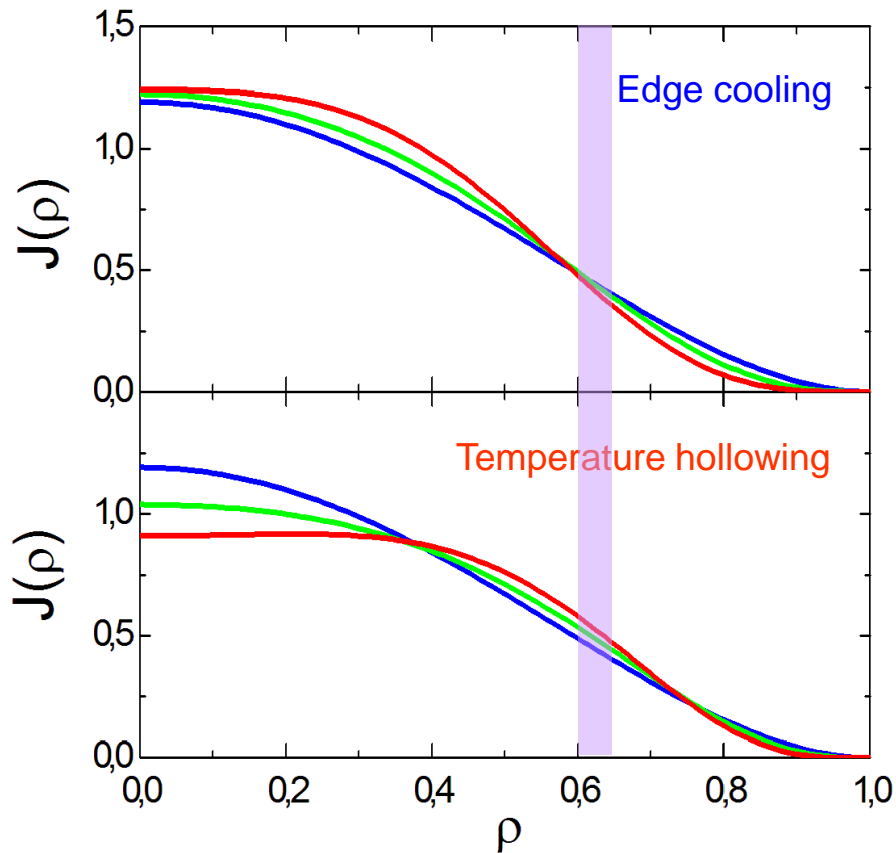


- Changes in current density profile reflect the expected evolution following changes in the electron temperature profile and in both cases an increase in the gradient near the  $q=2$  surface is observed, suggesting an ongoing destabilization process.

# Analytical sequences vs. TRANSP simulations



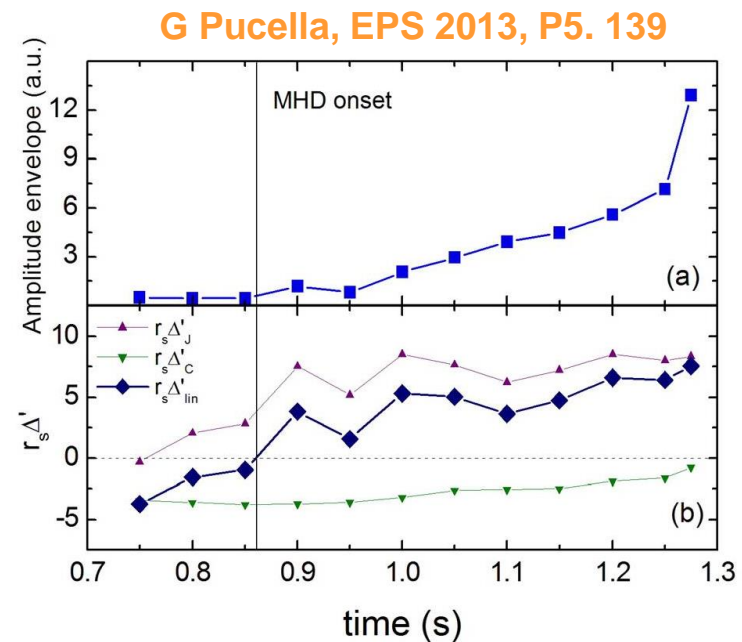
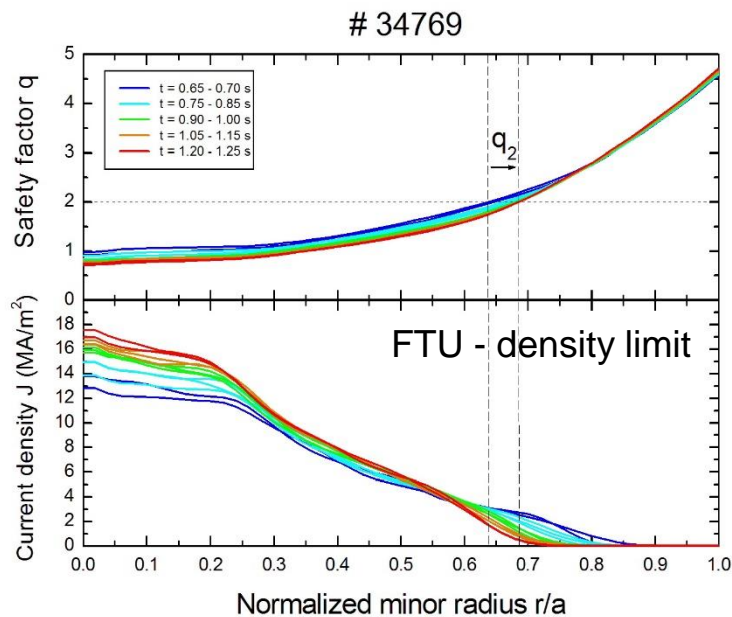
- Two different temporal evolutions of current density profile have been utilized in an analytical form to represent the experimental evidences. Preliminary linear stability analysis have been performed in the zero pressure large aspect ratio approximation, showing in both cases a continuous increase of the current driving term. The same kind of analysis will be performed for TRANSP simulations.



# Linear stability analysis



- The time evolution of the linear stability parameter  $\Delta'$  will be evaluated in the zero pressure approximation, with a shooting-type code. For plasmas with no pressure gradient,  $\Delta'$  is proportional to the change in magnetic energy, so that  $\Delta' > 0$  implies instability.
- Assuming the neglected stabilizing contributions (related to pressure and curvature effects) to be not increasing, being directly proportional to the pressure and inversely proportional to the resistivity, a destabilization mechanism could be claimed when  $\Delta'$  overcomes a distinct positive threshold:  $\Delta' > K$ .





- The correlation between temperature hollowing and edge cooling and the onset of 2/1 tearing modes in the termination phase has been investigated, following the picture of modes generated by changes in the current density profile reflecting changes in the electron temperature profile.
- Two experimental parameters have been introduced, starting from ECE radiometry, to highlight the occurrence of TH and EC, highlighting that pulses with TH or EC develop 2/1 TM leading to disruption in different characteristic times (1 s for TH, 100 ms for EC).
- Fast initial mode rotations are observed in pulses with TH only, whilst spontaneous or triggered onsets. Only a few rotations before locking are observed when the mode onset is associated to EC, whilst a saturation of the mode amplitude for peaked temperature profiles, whilst an explosive behavior can be observed for hollow temperature profiles.
- TRANSP simulations have highlighted changes in current density profile reflecting changes in the electron temperature profile in relatively fast resistive time scales, as a consequence of an increased radiation emission in core or edge plasma.
- Linear stability analysis will be performed to confirm the picture of tearing modes generated by a continuous increase of the current density gradient near the mode resonant surface.



- The role of impurity accumulation and edge cooling in plasma termination at JET  
[https://users.euro-fusion.org/tfwiki/images/f/f6/Pucella\\_M18\\_02\\_meeting\\_20Mar2020.pdf](https://users.euro-fusion.org/tfwiki/images/f/f6/Pucella_M18_02_meeting_20Mar2020.pdf)
- Disruption precursors from ECE radiometry  
[https://users.euro-fusion.org/tfwiki/images/4/4f/Pucella-M18-04\\_24Apr2020\\_IA\\_and\\_EC.pdf](https://users.euro-fusion.org/tfwiki/images/4/4f/Pucella-M18-04_24Apr2020_IA_and_EC.pdf)
- Termination of neon seeded pulses  
[https://users.euro-fusion.org/tfwiki/images/c/c5/2020\\_06\\_12\\_Pucella-M18-04\\_Termination\\_neon.pdf](https://users.euro-fusion.org/tfwiki/images/c/c5/2020_06_12_Pucella-M18-04_Termination_neon.pdf)
- Tearing modes in the termination phase: experimental session 07/07/2020  
[https://users.euro-fusion.org/tfwiki/images/1/10/2020\\_07\\_10\\_Pucella-M18-01-04\\_TH\\_EC\\_termination\\_C38C.pdf](https://users.euro-fusion.org/tfwiki/images/1/10/2020_07_10_Pucella-M18-01-04_TH_EC_termination_C38C.pdf)