EUROfusion

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

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JET ENEA

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Outline

Termination phase

- Disruptions: operation safety & scenario development
- Tearing modes in termination: experimental observations

Destabilization of tearing modes

- The role of current density gradient
- Interpretative TRANSP simulations
- Linear stability analysis in toroidal geometry

Temperature hollowing and edge cooling

- Parameters characterizing the shape of Te profile
- Empirical stability diagram
- Characteristic time scales
- Lock modes alerts for avoidance & mitigation actions

Termination phase

- The capability to terminate plasma pulses safely is an important goal towards the optimization of an operating scenario in a tokamak.

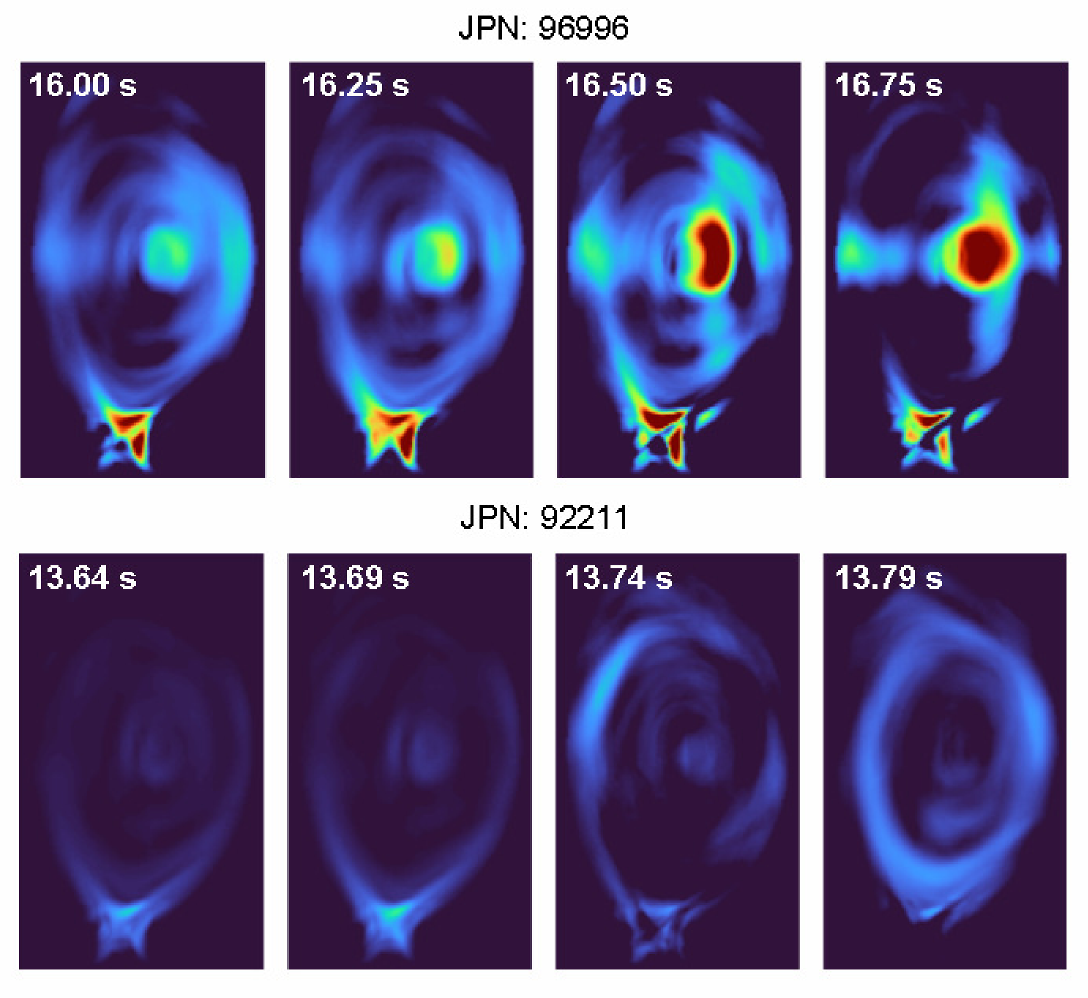
Disruption
- **safety** → thermal and electromagnetic loads on plasma facing components
- **scenario** → limits to the range of accessible plasma parameters

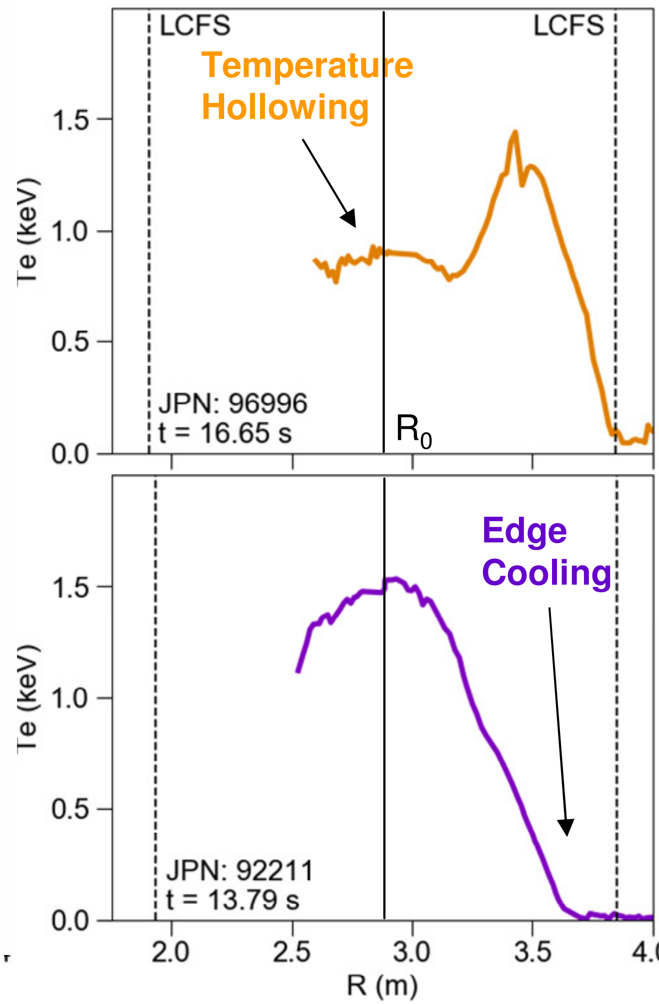
- It is of great importance to study the physical phenomena involved in the disruptions and to develop disruption precursors for avoidance or mitigation actions.

Tearing modes
- **flat-top** → TM (m/n) triggered by sawtooth crashes, fishbone activity and perturbations associated to ELMs
- **termination** → TM (2/1) in presence of an increased radiation emission in core or edge plasma, leading to temperature hollowing and edge cooling, respectively

Increased radiation emission in core or edge plasma

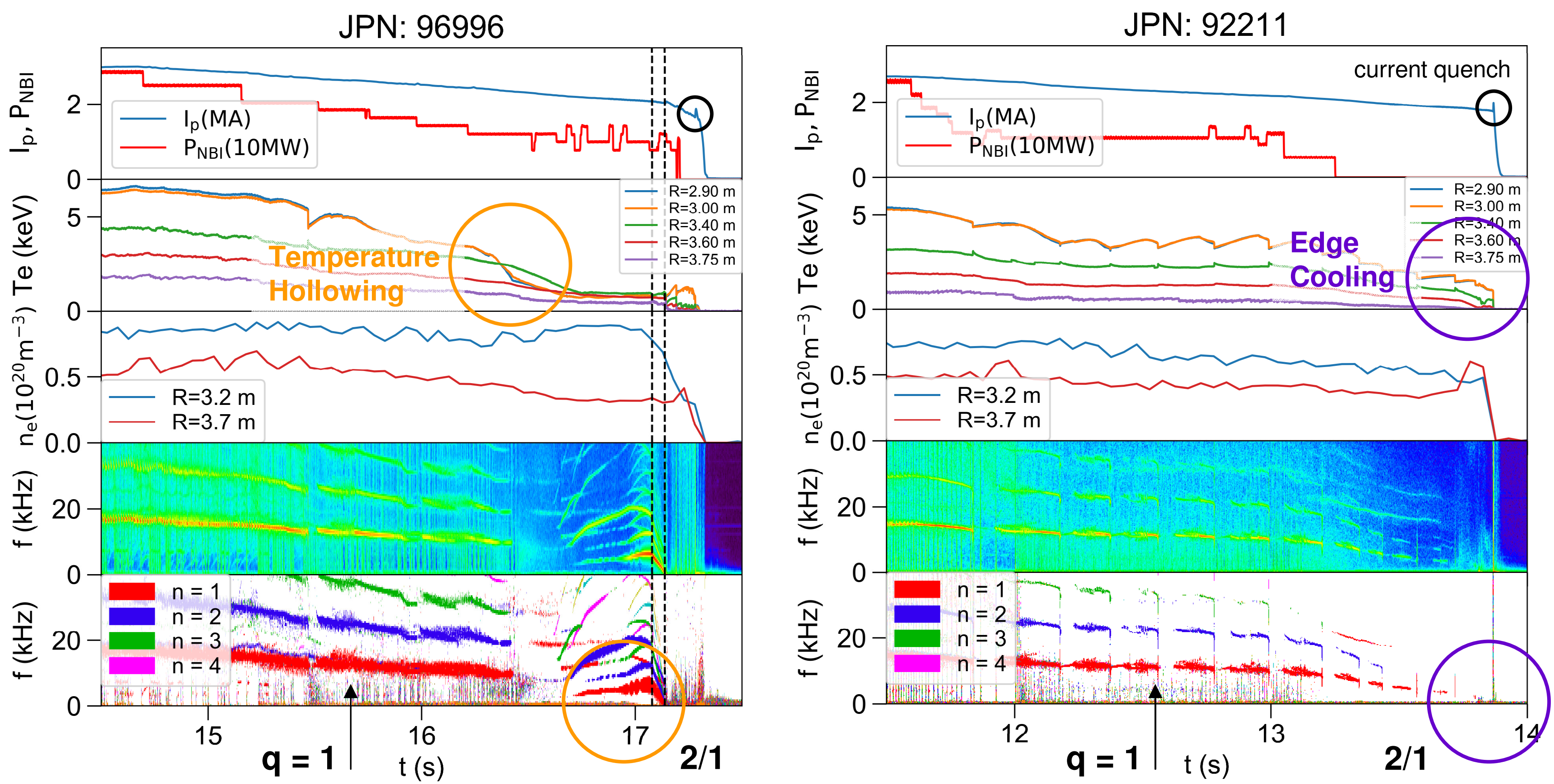
- Tomographic reconstructions of the plasma radiation profile and electron temperature profiles from ECE radiometry for two pulses characterized by an increased radiation emission in **core** (JPN 96996, top) and **edge** (JPN 92211, bottom) plasma, respectively.



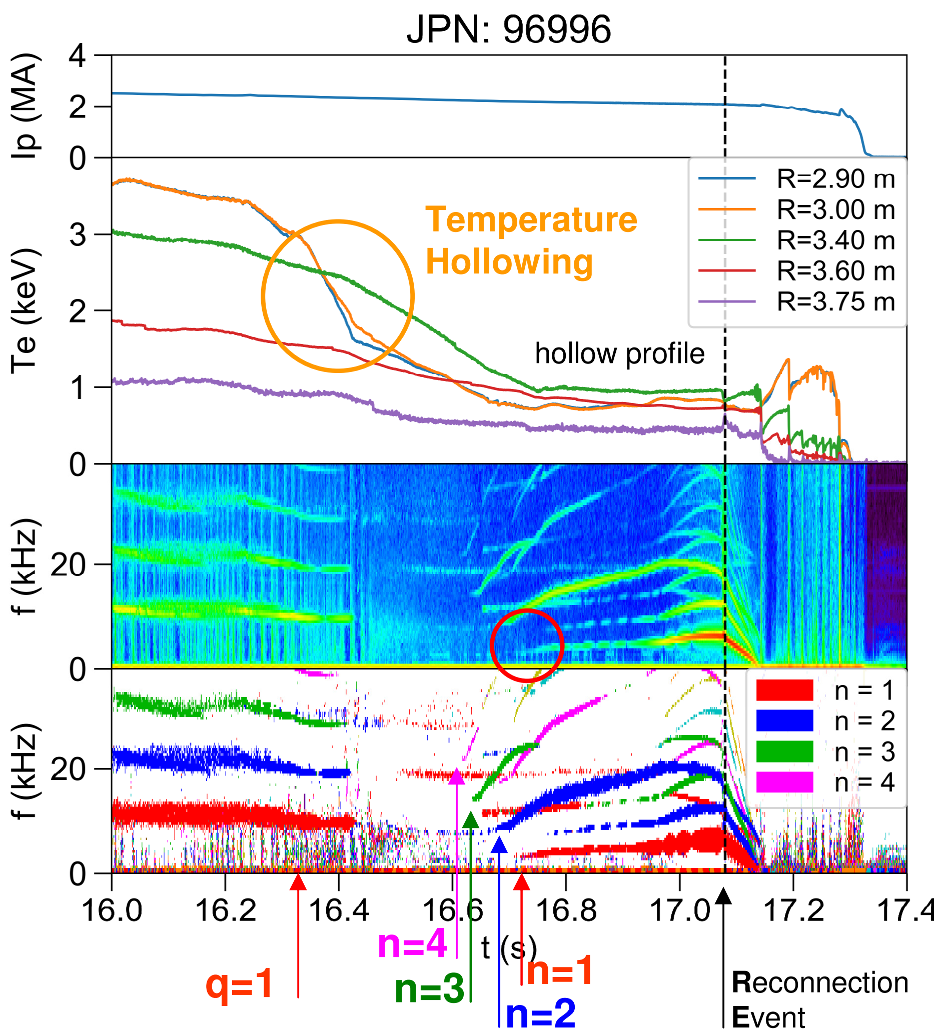


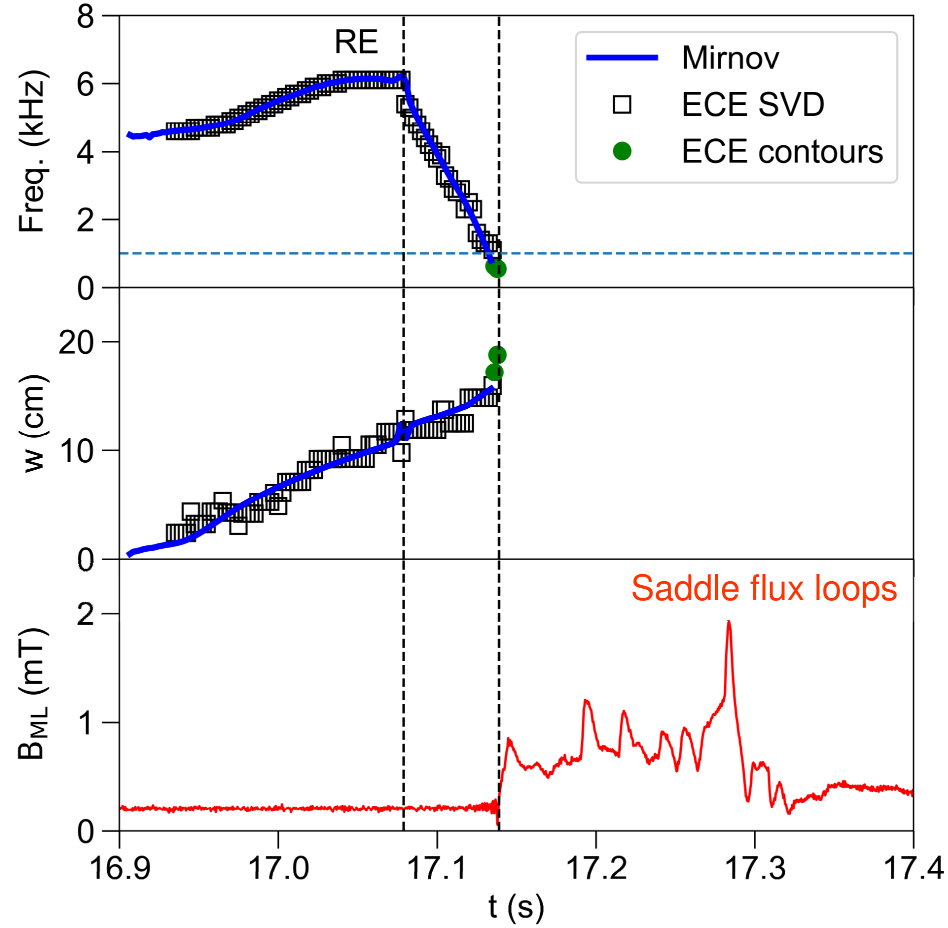
Tearing modes

- Tearing modes (**2/1**) 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** and **edge cooling**, respectively.



Temperature hollowing

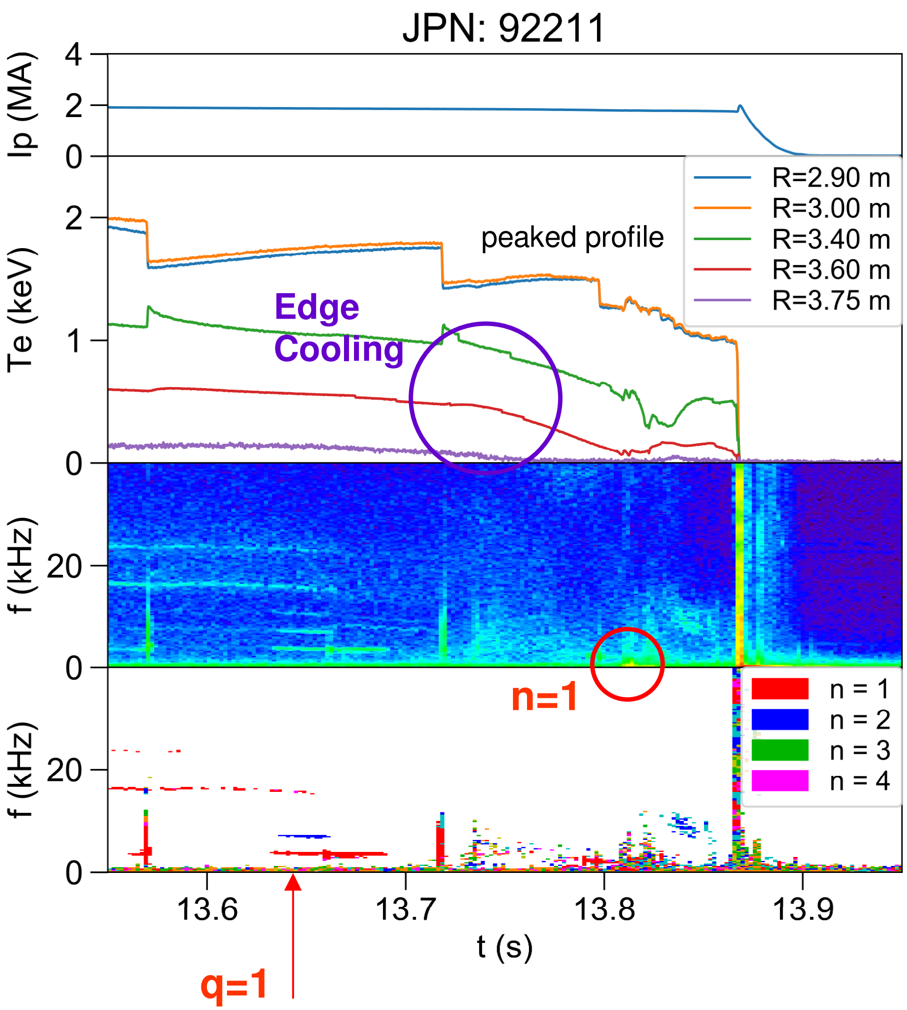


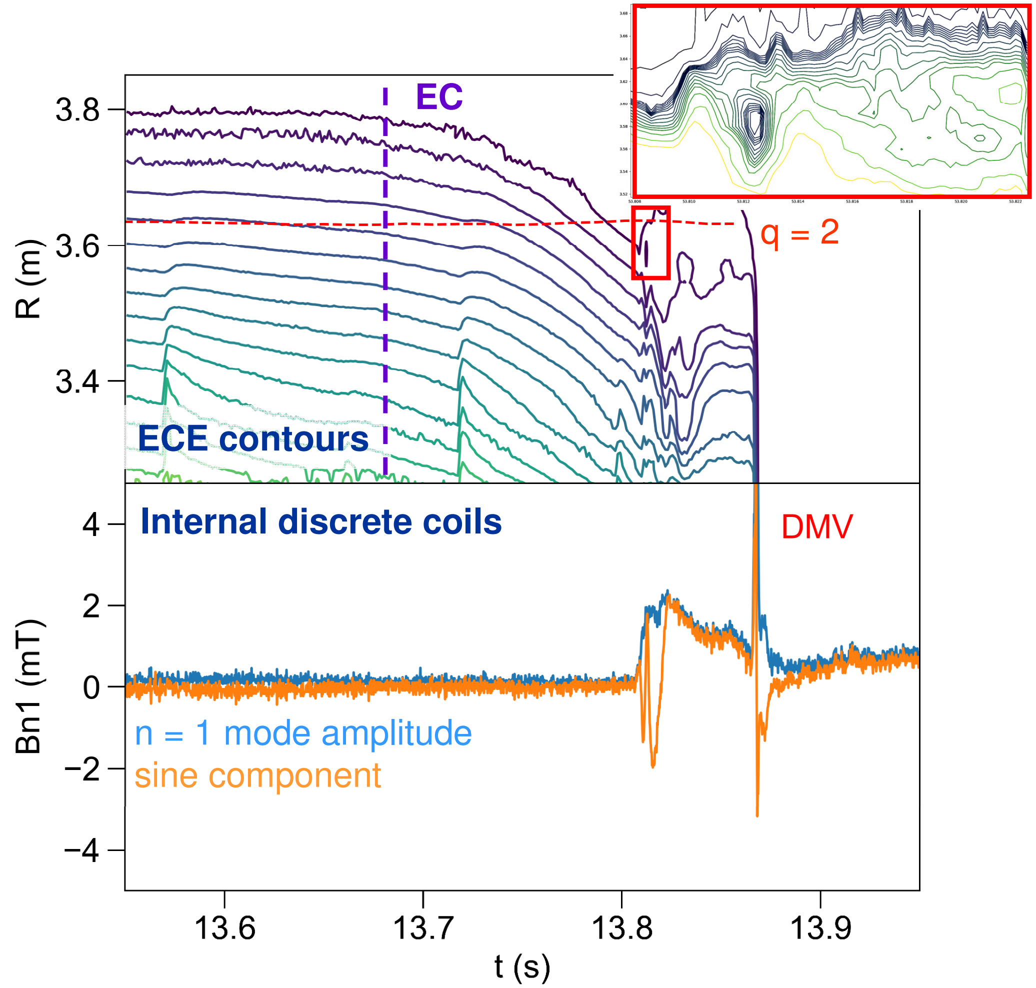


Hollowing of Te profile
Disappearance of q = 1 activity
Sequence of modes with decreasing n

2/1 mode characterized by a fast initial mode rotation

Edge cooling





Rapidly increasing variations on ECE contours when edge cooling affects the region of the q = 2 surface

2/1 mode usually makes only a few turns before locking

Destabilization mechanism

- The destabilization of a classical tearing mode is driven by the radial gradient of the toroidal current density profile:

$$\frac{d}{dr}\left[\left\langle\frac{g_{\theta\theta}}{\sqrt{g}}\right\rangle\frac{d}{dr}\left(rB_{r1}\right)\right]=\left[\left\langle\frac{g_{rr}}{\sqrt{g}}\right\rangle m^2+\frac{\mu_0 q}{\left(1-nq/m\right)}\frac{d}{dr}\left\langle\frac{j_{tor}}{B_{tor}}\right\rangle\right]\left(rB_{r1}\right)$$

zero pressure limit

Cylindrical limit:

$g_{rr}=1\,;\,g_{\theta\theta}=r^2\,;\,g_{\phi\phi}=R_0^2$

$\sqrt{g}=rR_0$

  - In the termination phase the current profile is dominated by the ohmic contribution and **the resistivity is high** due to the low temperature:

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

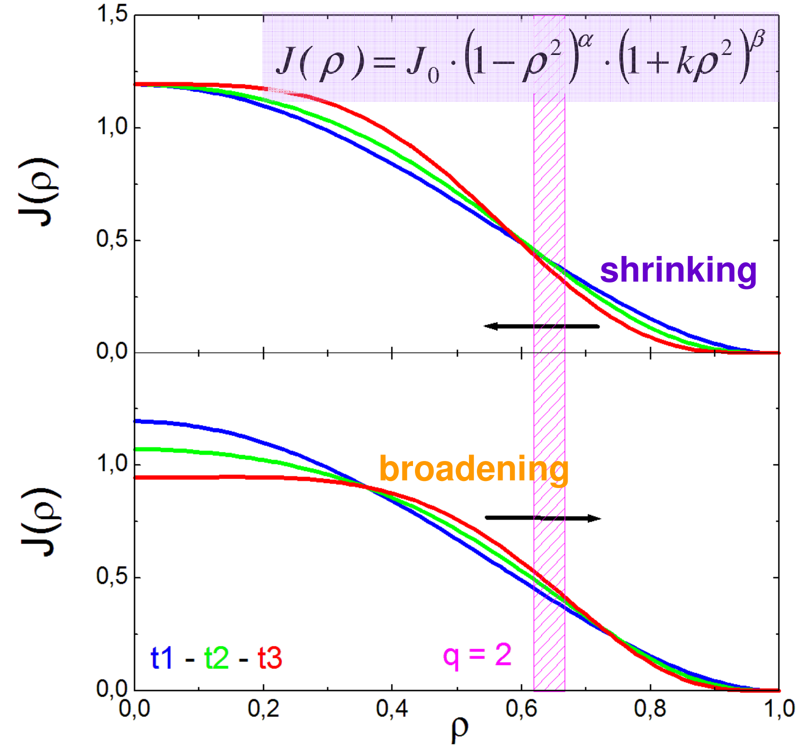
  - The current profile changes on a relatively **short resistive diffusion time scale** reflecting the changes in the electron temperature profile:

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

  - The possibility of **2/1 tearing modes** linearly destabilized by changes in the current density profile has been explored.

Broadening and shrinking of current density profile

- Qualitatively, both **temperature hollowing** and **edge cooling** can destabilize a 2/1 tearing mode as a consequence of an increase of the current density gradient near the mode resonant surface:
  - **broadening** of the current density profile from inside in case of temperature hollowing
  - **shrinking** of the current density profile from outside in the case of edge cooling

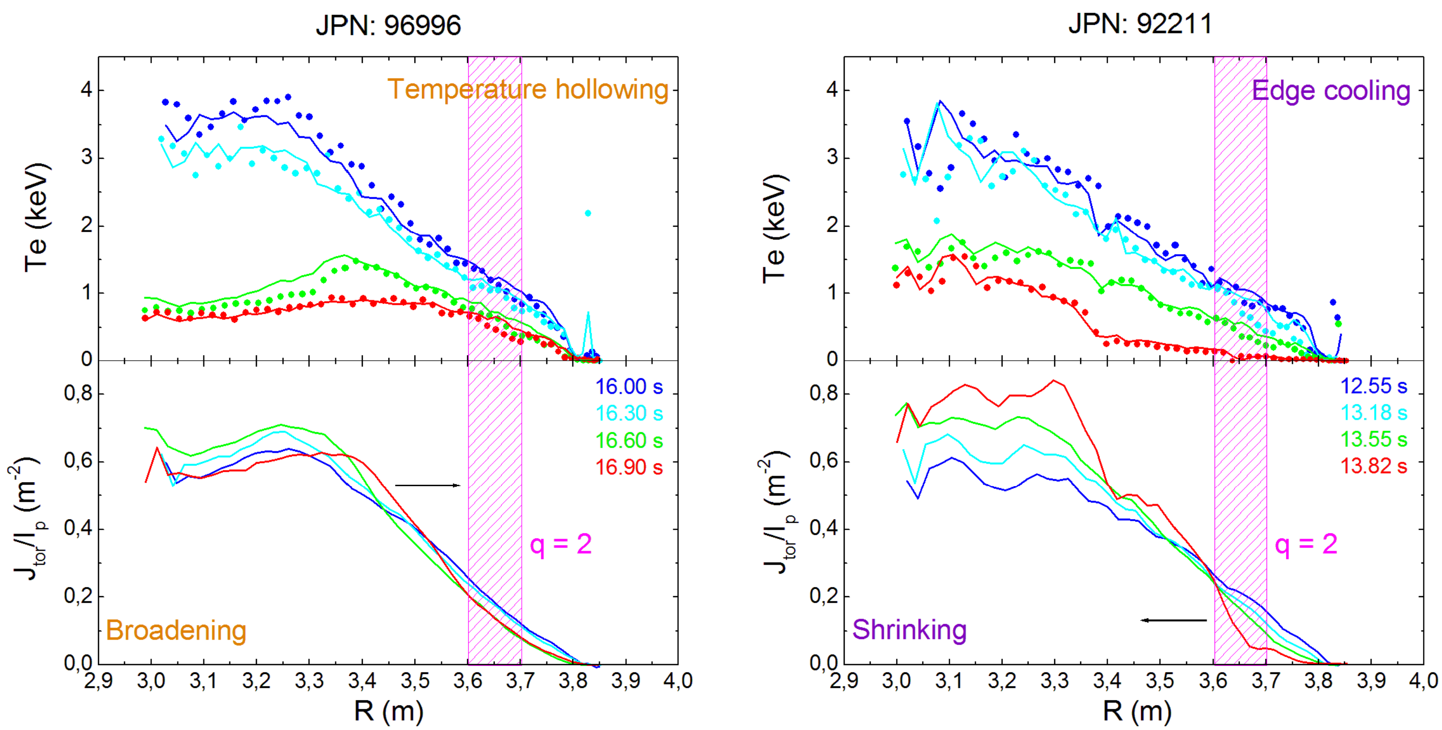


Open questions

- Is the current density profile changing before the mode onset ? → TRANSP simulations
- Do profile changes lead to an unstable scenario ? → Linear stability analysis

TRANSP simulations

- Interpretative TRANSP simulations carried out for the two pulses mentioned before: **JPN 96996** (**temperature hollowing**) and **JPN 92211** (**edge cooling**).
  - Electron temperature and density profiles as measured by high resolution Thomson scattering, plasma equilibrium evolved by the internal inverse solver and current density profiles calculated according to the poloidal field diffusion equation, with classical Spitzer resistivity.



Stored energy and total neutrons within 10% of the corresponding experimental values.

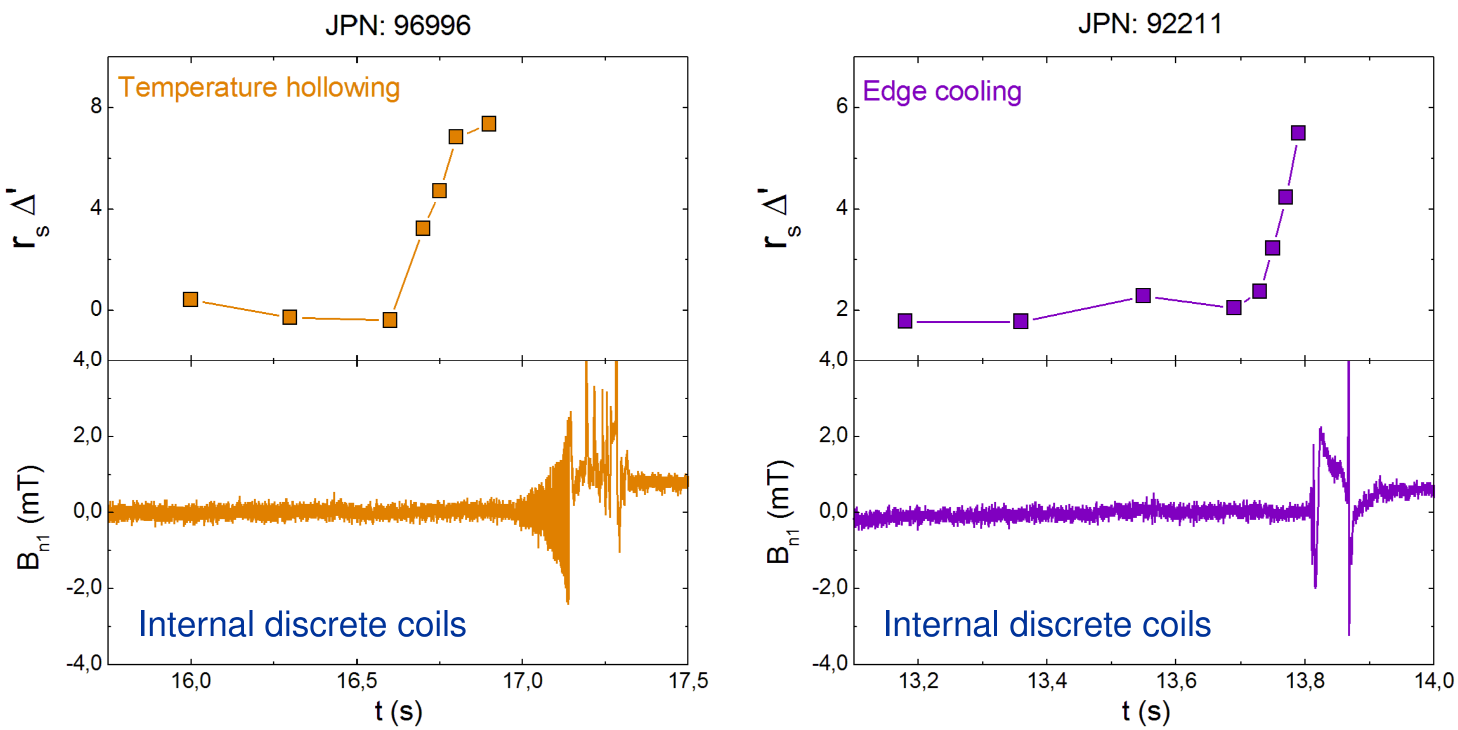
  - Changes in current density profile reflect the expected evolution following changes in the electron temperature profile, with time delays associated with the effective resistive diffusion time: **0.3-0.5 s** for JPN 96996, **50-100 ms** for JPN 92211.

Linear stability analysis

- Linear stability criterion in the zero pressure approximation:

$$\Delta' \equiv \left.\frac{d\,\ln B_{r1}}{dr}\right|_{s+} - \left.\frac{d\,\ln B_{r1}}{dr}\right|_{s-} \propto -\delta W_{mag} \quad ; \quad \Delta' < 0 \xrightarrow{pressure,\quad curvature} \Delta' < K(\beta, 1/\eta)$$

  - Time evolution of the **linear stability parameter Δ'** calculated by solving the equation for the perturbed radial magnetic field in toroidal geometry neglecting pressure effects.



A high-resolution toroidal equilibrium has been computed by CHEASE code based on TRANSP outputs.

  - An increase of Δ' is obtained. Assuming the neglected stabilizing contributions to be not increasing, being proportional to β and $1/\eta$, an ongoing destabilization process can be claimed.

Recurrent paths

- Although a rigorous classification of all possible paths leading to the onset of 2/1 tearing modes is not the goal of this work, some recurrent typologies can be identified:

Temperature hollowing

Edge cooling

<u>Spontaneous onset</u>

Reconnection event

Hollowing, but final collapse from edge

<u>Onset with peaked temperature profile</u>

Broadening of the current density profile

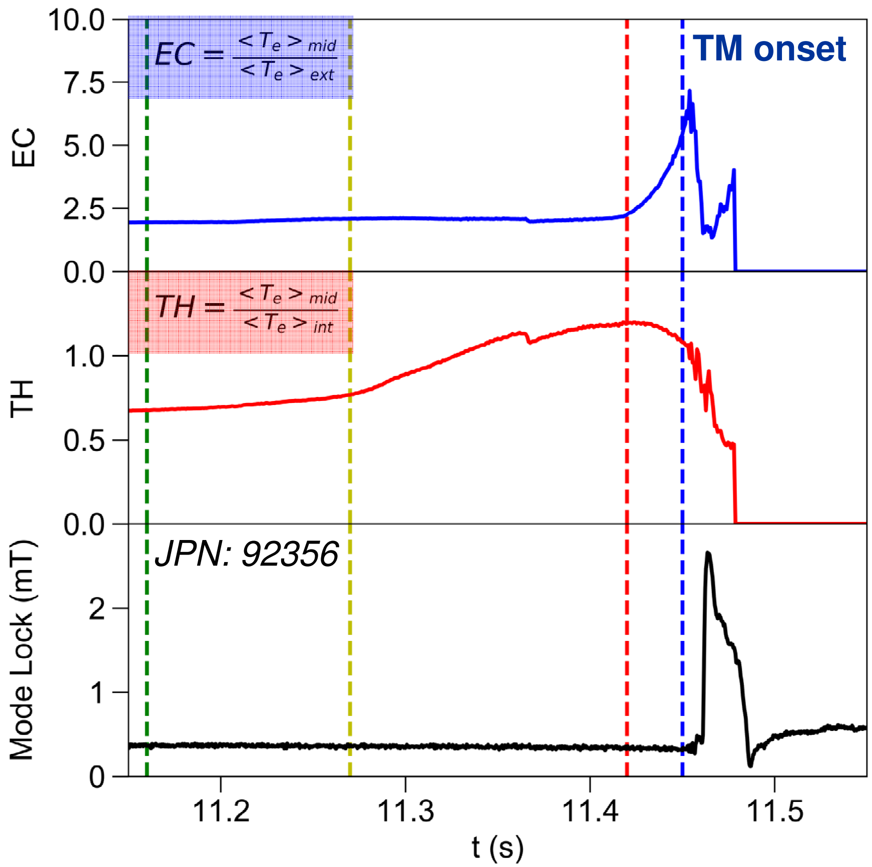
Shrinking of the current density profile

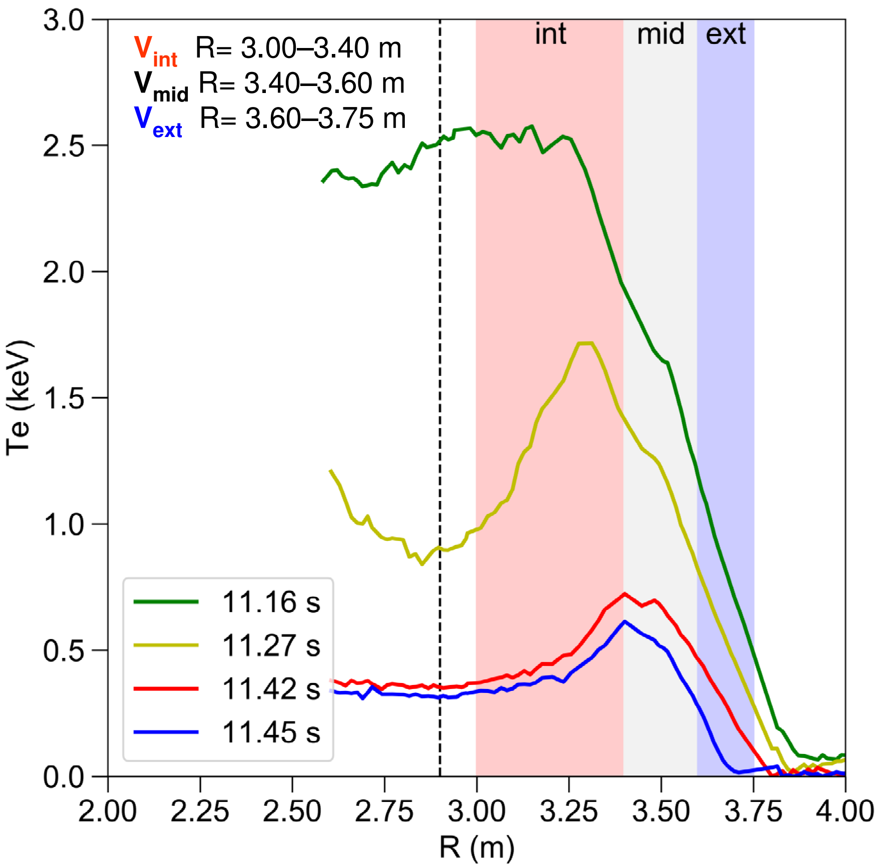
  - The formation of an **outer radiating blob** due to impurities accumulated in the low filed side can also be responsible for an edge cooling.

Temperature hollowing and edge cooling parameters

- Following the picture of tearing modes generated by changes in the current density profile reflecting the changes in the electron temperature profile, two parameters are defined, from **ECE radiometry**, to highlight the occurrence of edge cooling or temperature hollowing:

$$EC \equiv \frac{\langle Te \rangle_{Vmid}}{\langle Te \rangle_{Vext}}$$ **Edge cooling** ; $$TH \equiv \frac{\langle Te \rangle_{Vmid}}{\langle Te \rangle_{Vint}}$$ **Temperature hollowing**

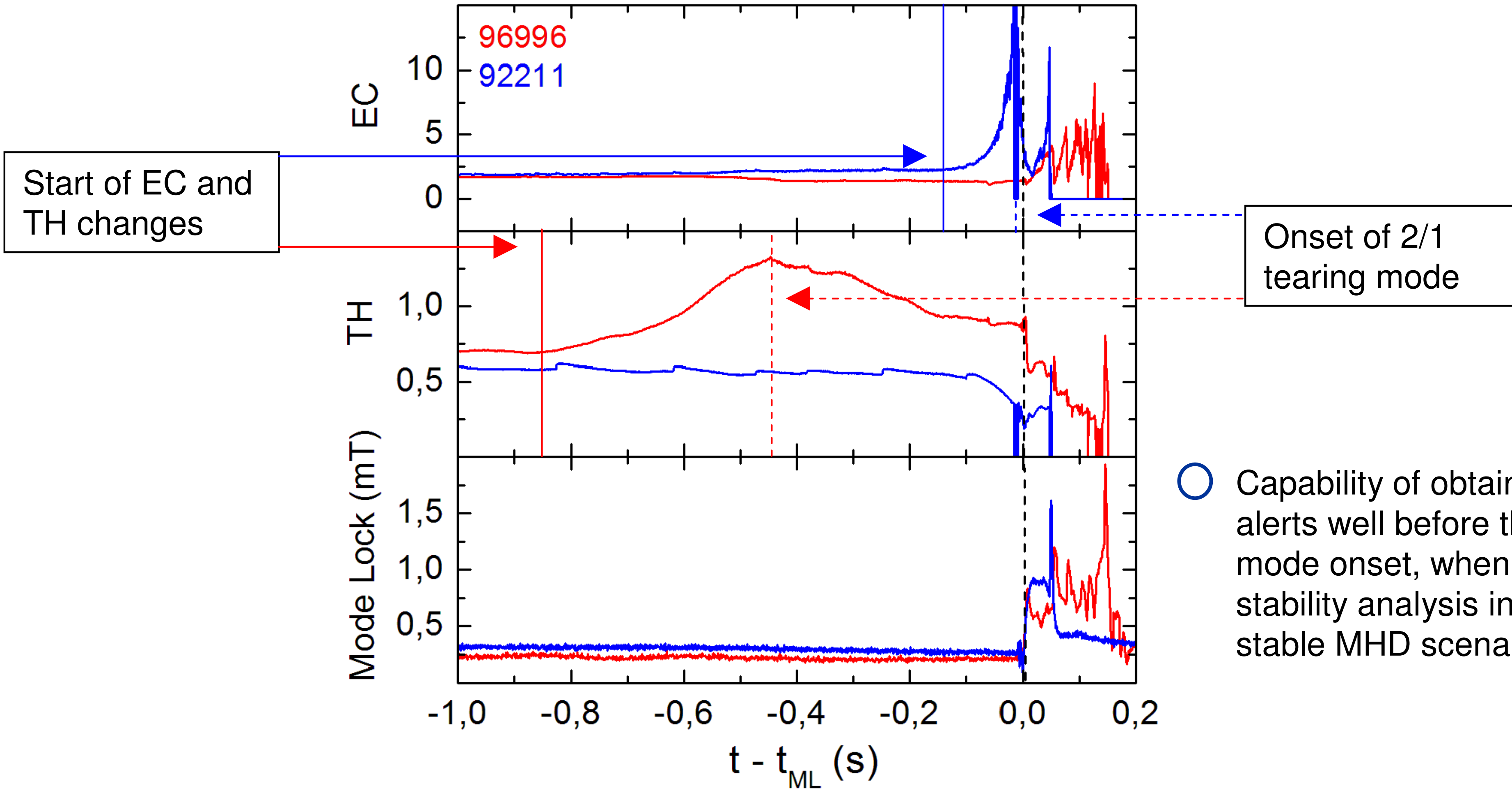




Temperature hollowing and edge cooling parameters

- TH and EC parameters for the two pulses mentioned before:

  JPN 96996 pulse characterized by temperature hollowing
  JPN 92211 pulse characterized by edge cooling

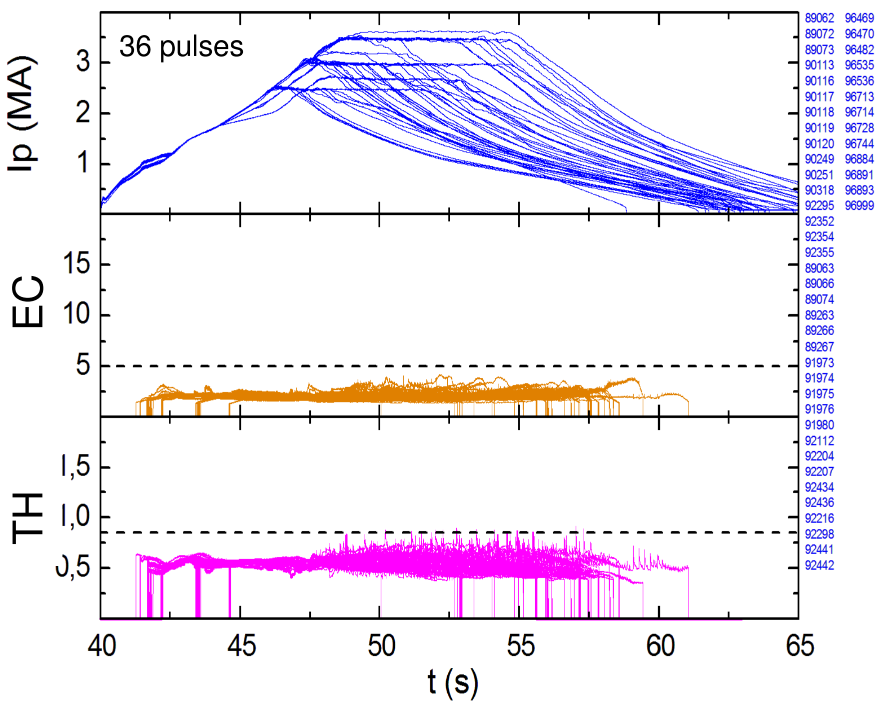


- Capability of obtaining alerts well before the mode onset, when stability analysis indicate stable MHD scenario.

Non-disruptive and disruptive pulses

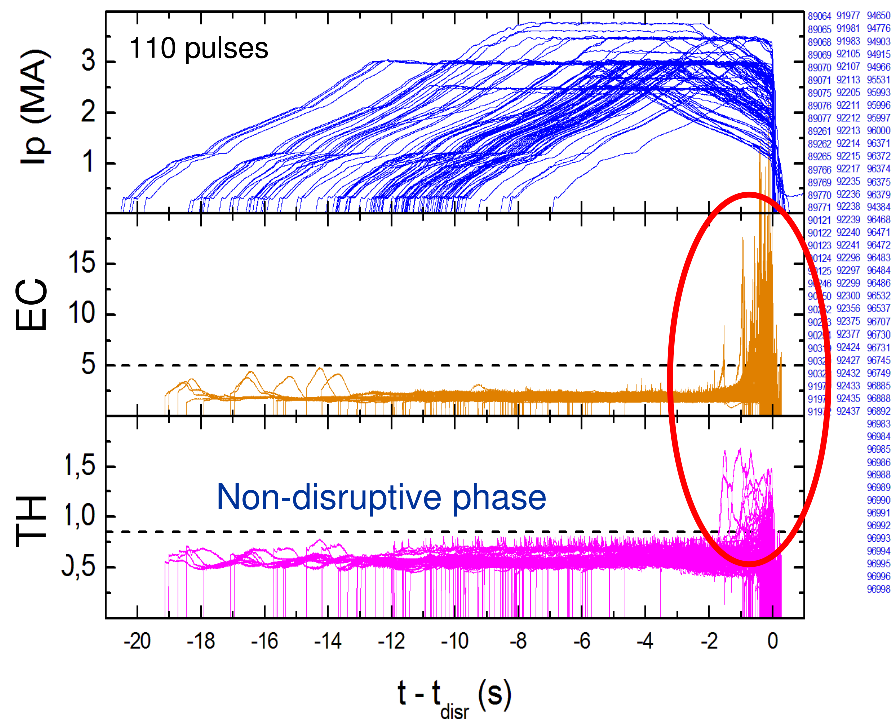
- Time evolution of EC and TH parameters for a dataset of 268 pulses (136 non-disruptive, 132 disruptive) carried out at different plasma current values (2.5 – 3.7 MA) in the baseline scenario at JET in the period 2016-2020.

Non-disruptive pulses



- Non-disruptive pulses are generally devoid of temperature hollowing and edge cooling, with stable values for both parameters TH and EC (**10% false positive**).

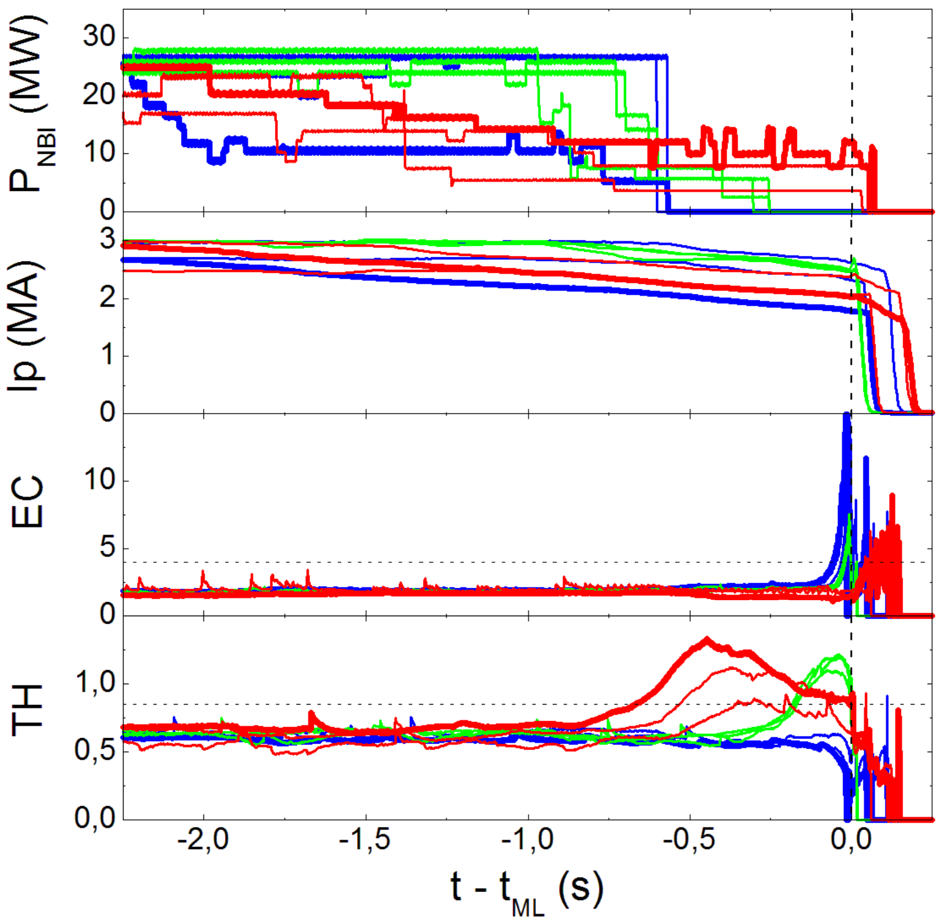
Disruptive pulses



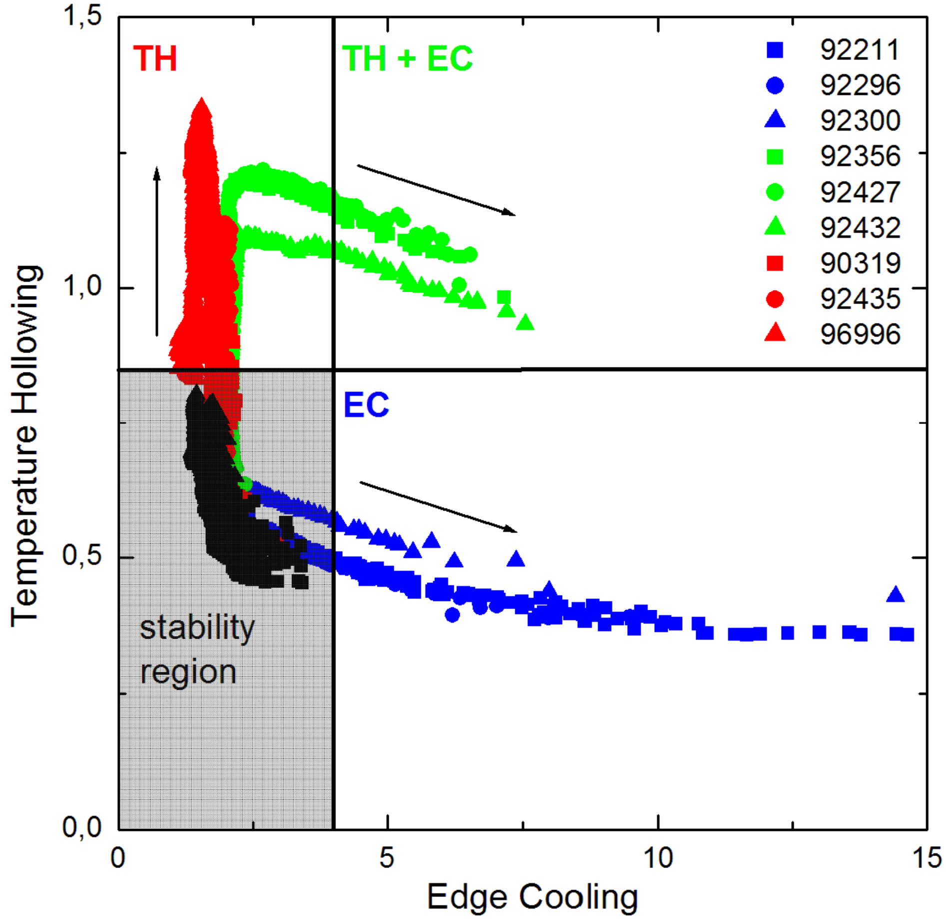
- Only in the last two seconds before the disruption an increase on one or both parameters TH and EC is observed in disruptive pulses (**90% right alerts**).

Empirical stability diagram

- Paths of representative pulses on an EC-TH plane.
  - Temperature hollowing only
  - Temperature hollowing and edge cooling
  - Edge cooling only

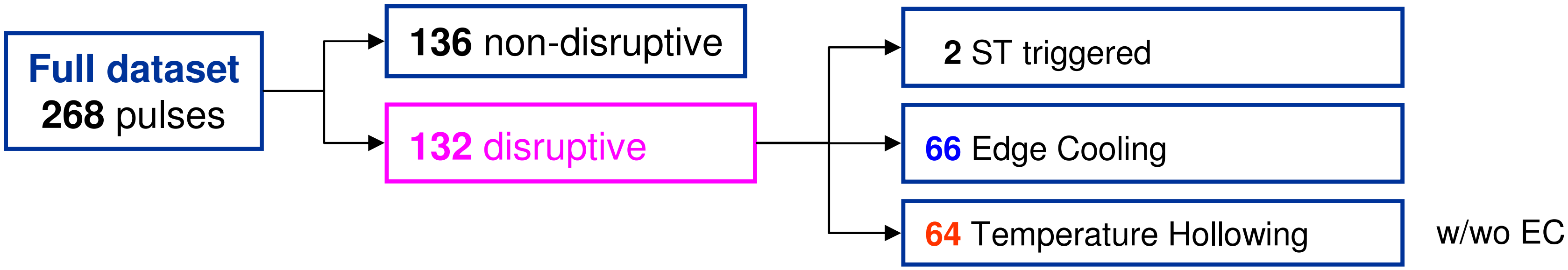


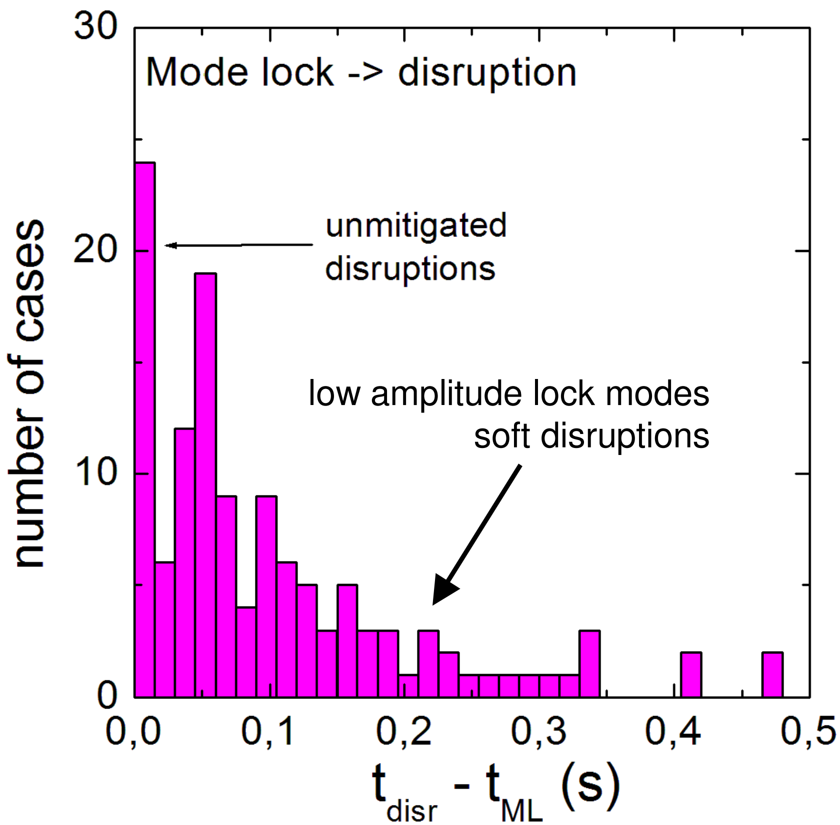
- For time interval between **5s and 1s to mode lock** the EC-TH pairs are located in a well defined quadrant, identifying the **stability region** for parameters EC and TH.



Characteristic time scales: mode lock and disruption

- The time corresponding to the mode lock has been used as a reference as it is related to the mode growth up to a given amplitude.

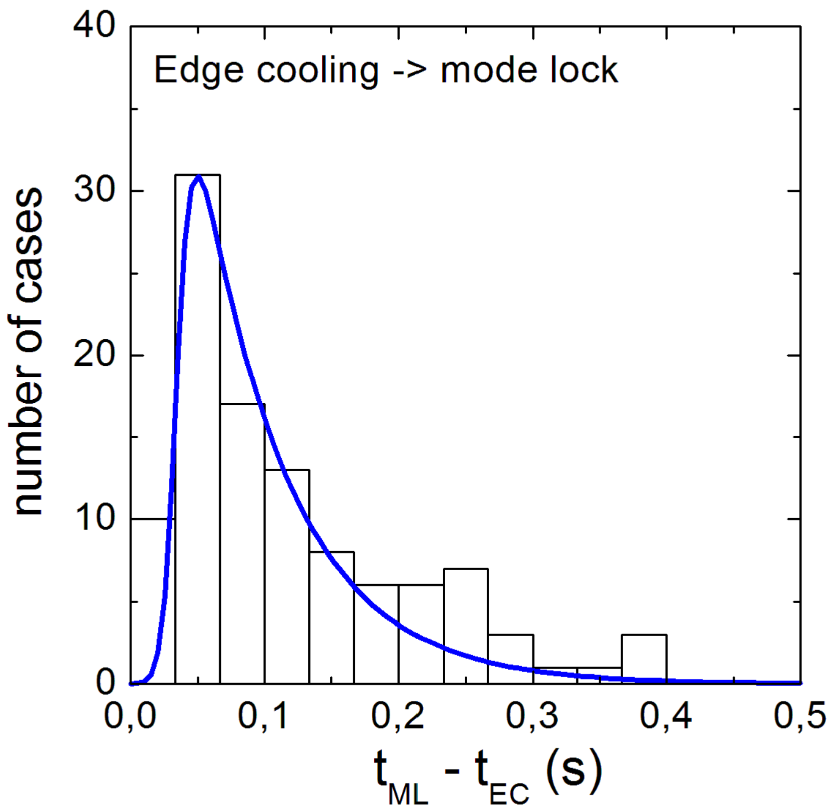


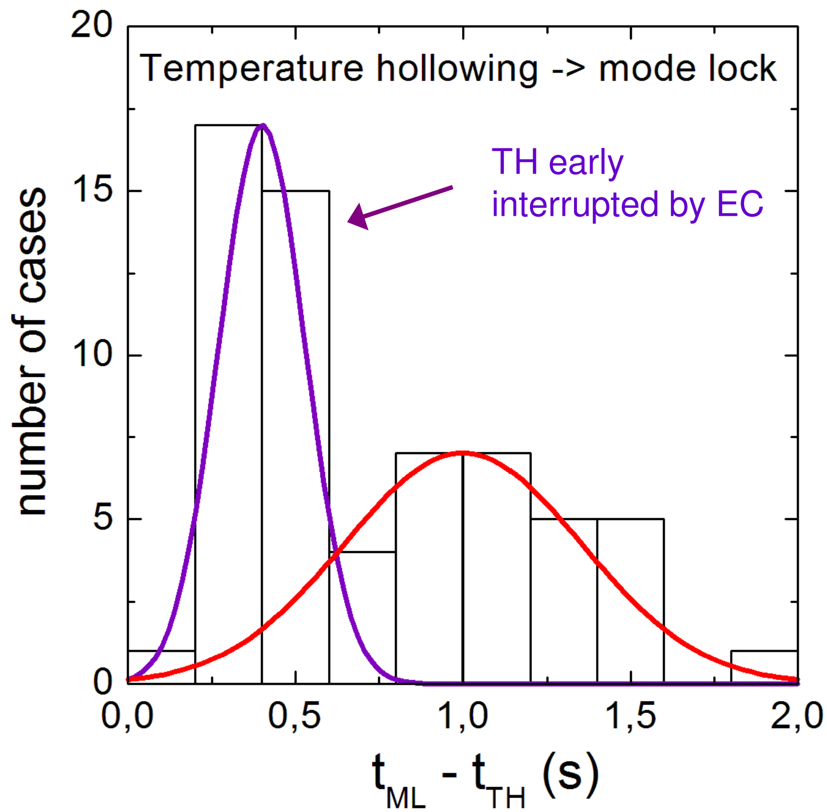


- The time from mode lock to disruption can vary from few milliseconds to hundreds, depending on the mode dynamics and on the logic of the mitigation actions.

Characteristic time scales: TH and EC

- The distributions of the time interval between the increase of the parameters **EC** and **TH** and the **mode lock** have been evaluated for the 132 disruptive pulses.





- The parameter **EC** could provide alerts falling within **200 ms** from the mode lock, 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 lock, so an attempt to correct the termination **avoiding** the disruption is possible.

Avoidance and mitigation actions

- Re-establishing temperature profiles peaked in case of core impurity accumulation, e.g. providing **central additional heating** to counteract the inward transport of high-Z impurities, is a strategy **to avoid disruptions** due to **temperature hollowing**.
  - The additional power has to be carefully calibrated to avoid the onset of tearing modes triggered by long-period sawtooth crashes.

- **Gas injection** into the tokamak, leading to a fast loss of thermal energy by photon radiation, is a strategy **to mitigate disruptions** due to **edge cooling**.
  - Mode saturation is quite general for EC in **peaked Te profile** and usually the thermal quench is induced by DMV intervention → not crucial to anticipate DMV
  - An explosive growth of the mode amplitude occurs for EC in **hollow Te profile**, leading in some cases to unmitigated thermal quenches → crucial to anticipate DMV

Conclusions

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

- Linear stability analysis have shown that both cases can lead to the destabilization of a 2/1 tearing mode, as a consequence of an increase of the current density gradient near the mode resonant surface, due to a **broadening** of the current density profile in the case of temperature hollowing and to a **shrinking** in the case of edge cooling.

- Two parameters have been defined, from ECE radiometry, to highlight the occurrence of temperature hollowing (**TH**) and edge cooling (**EC**) and the time evolution of such parameters has been studied for a large dataset of pulses, to highlight the correlation with mode onset in plasma termination and to evaluate the characteristic times interval between the increase of such parameters and the mode lock in disruptive pulses (~ 1 s for TH, ~ 100 ms for EC).

- The possibility to obtain **lock mode precursors** based on the two parameters TH and EC has been preliminary explored, showing that the parameter related to the temperature hollowing could provide alerts useful to attempt to correct the termination avoiding the disruption, whilst the parameter related to the edge cooling could provide alerts useful to anticipate mitigation actions.