EUROfusion

MHD activity in DT (and isotopic) experiments on JET
Baseline and Hybrid scenarios

G. Pucella, P. Buratti, E. Giovannozzi,
E. Alessi, F. Auriemma, D. Brunetti, S. Nowak and JET Contributors

JET ENEA

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Outline

DTE2 experimental campaign

- Experimental programs and pulses
- Baseline vs. Hybrid scenario

Baseline scenario

- High plasma current
- Plasma termination: temperature hollowing and edge cooling
- Plasma termination: outboard radiative blob
- Neon seeding experiments

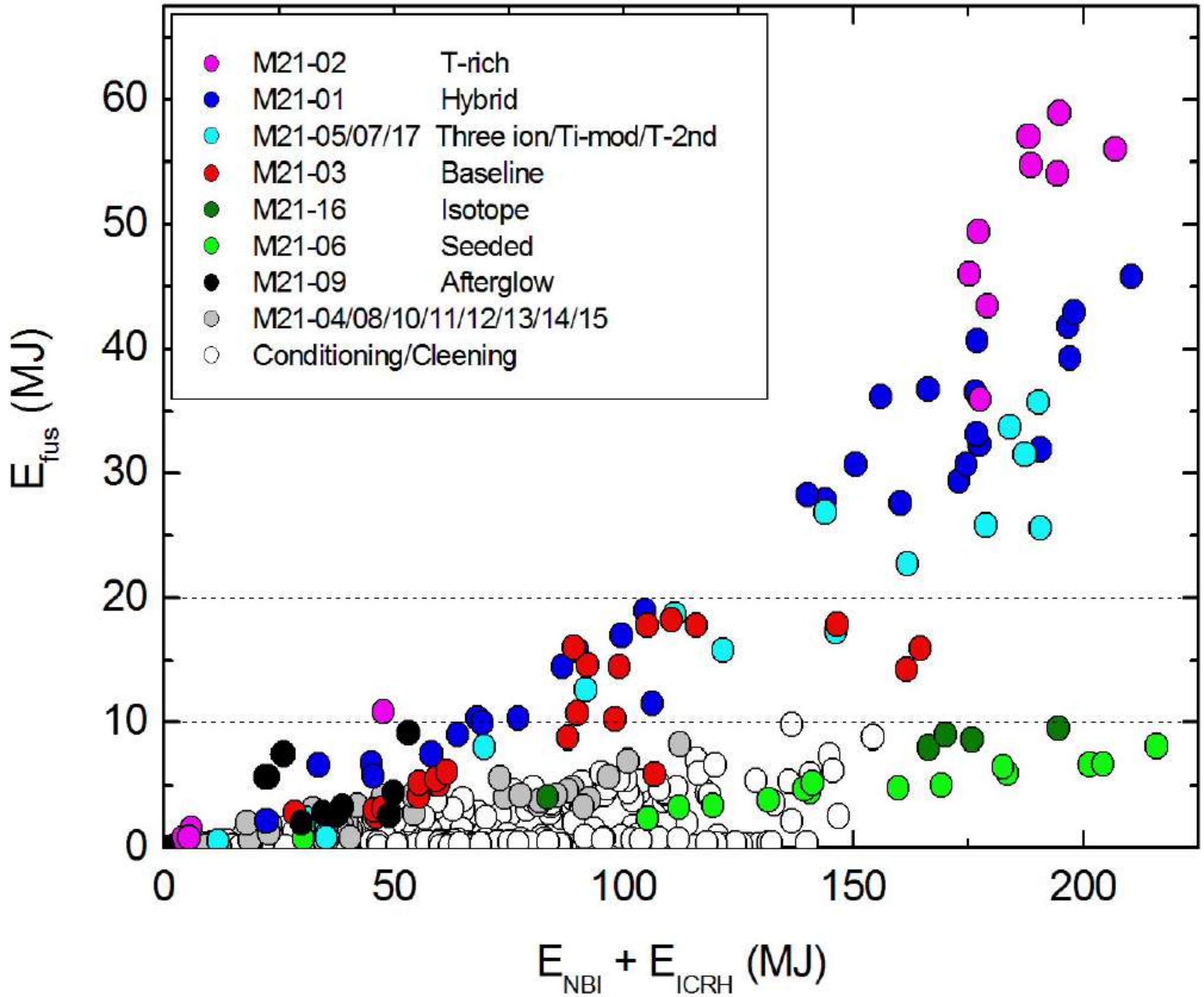
Hybrid scenario

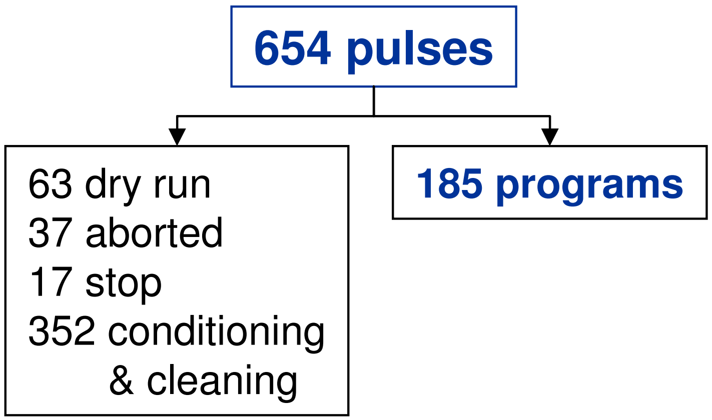
- Double tearing modes
- q = 1 arrival time
- TAE and early n = 3 TM
- 3/2 TM at relatively high β_N and low internal inductance
- Fishbones vs. (1,1) continuous modes
- Chain of TM in pulses with core impurity accumulation

DT scenario with optimized non-thermal fusion

DTE2 experimental campaign

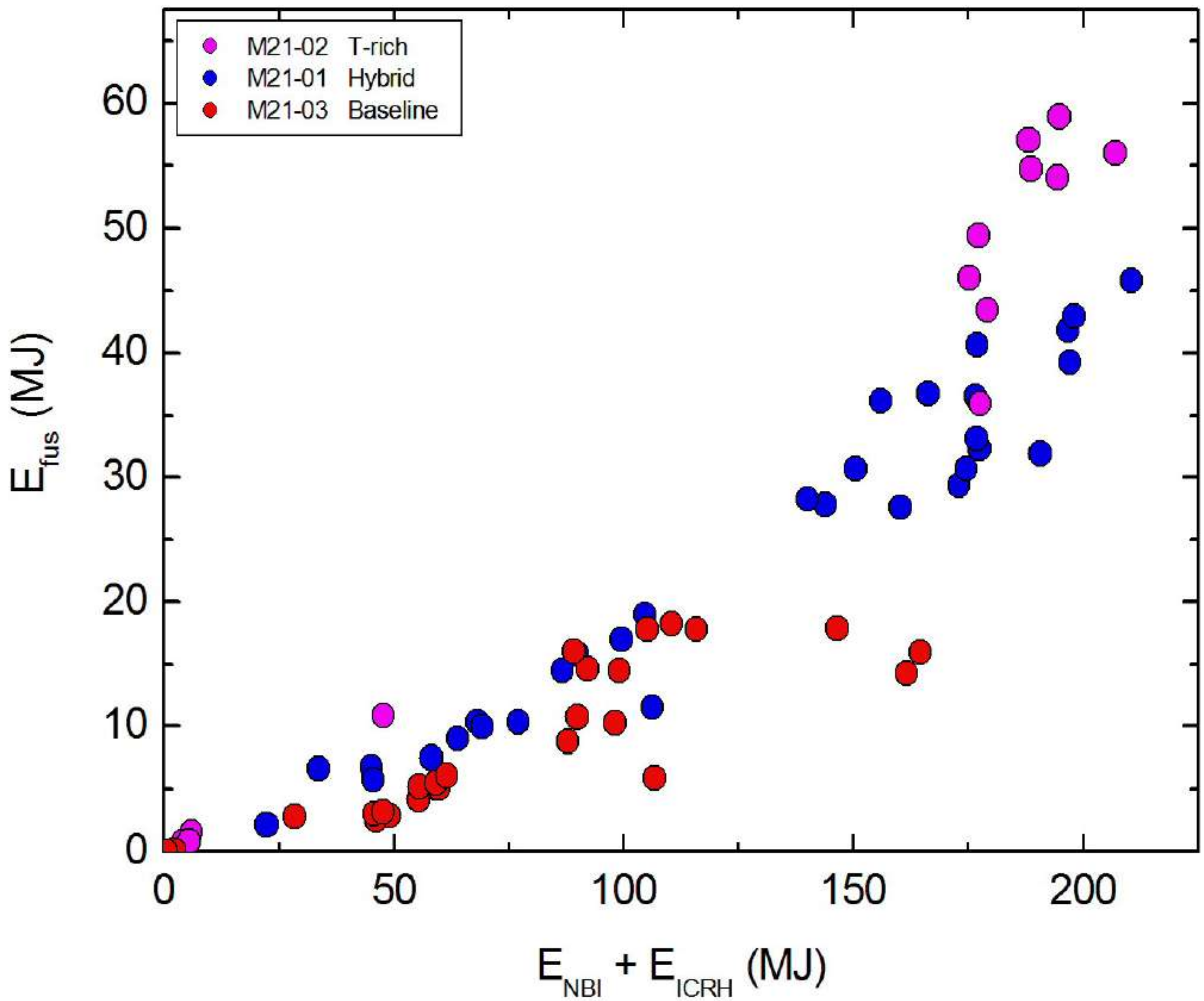
- Plasma operation from August to December 2021
- 17 main experiments





DTE2 experimental campaign

- Plasma operation from August to December 2021
- 17 main experiments



654 pulses

- 63 dry run
- 37 aborted
- 17 stop
- 352 conditioning & cleaning

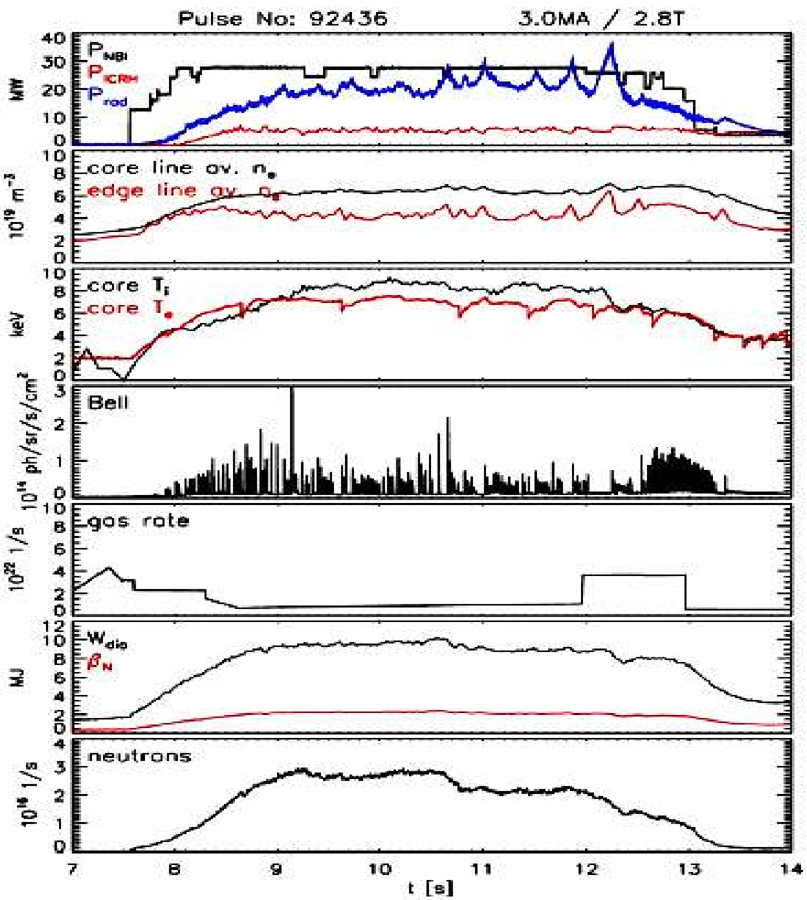
185 programs

- M21-01 38
- M21-02 14
- M21-03 26
- …

Baseline vs. Hybrid scenario

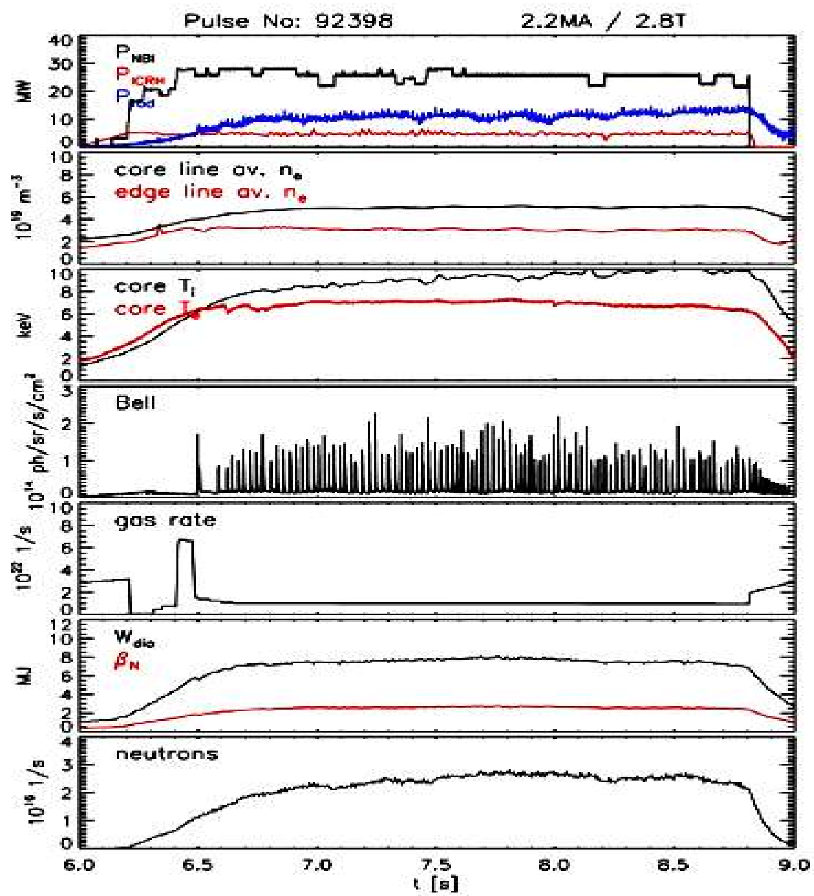
Baseline

The baseline activity concentrates mainly on pushing the operation towards the high current and field limits with a relaxed current profile (β_N **~ 1.8**, q_{95} **~ 3**, **higher** n_e).



Hybrid

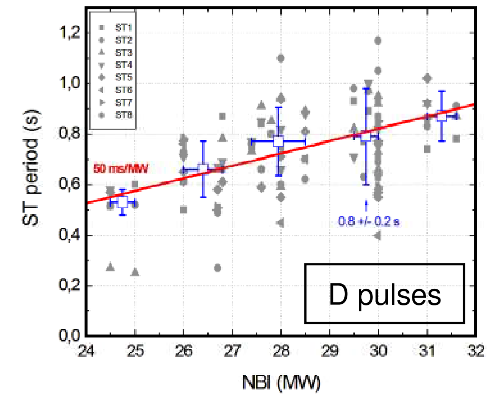
Hybrid experiments addresses with more emphasis the advantages of operating at high β_N with a shaped current profile and $q_0 > 1$ (β_N **~ 2÷3**, q_{95} **~ 4**, **lower** n_e).



L. Garzotti *et al* 2019, Scenario development for DT operation at JET, Nucl. Fusion **59** 076037

Baseline: high plasma current

- **Incidence of high-n tearing modes**

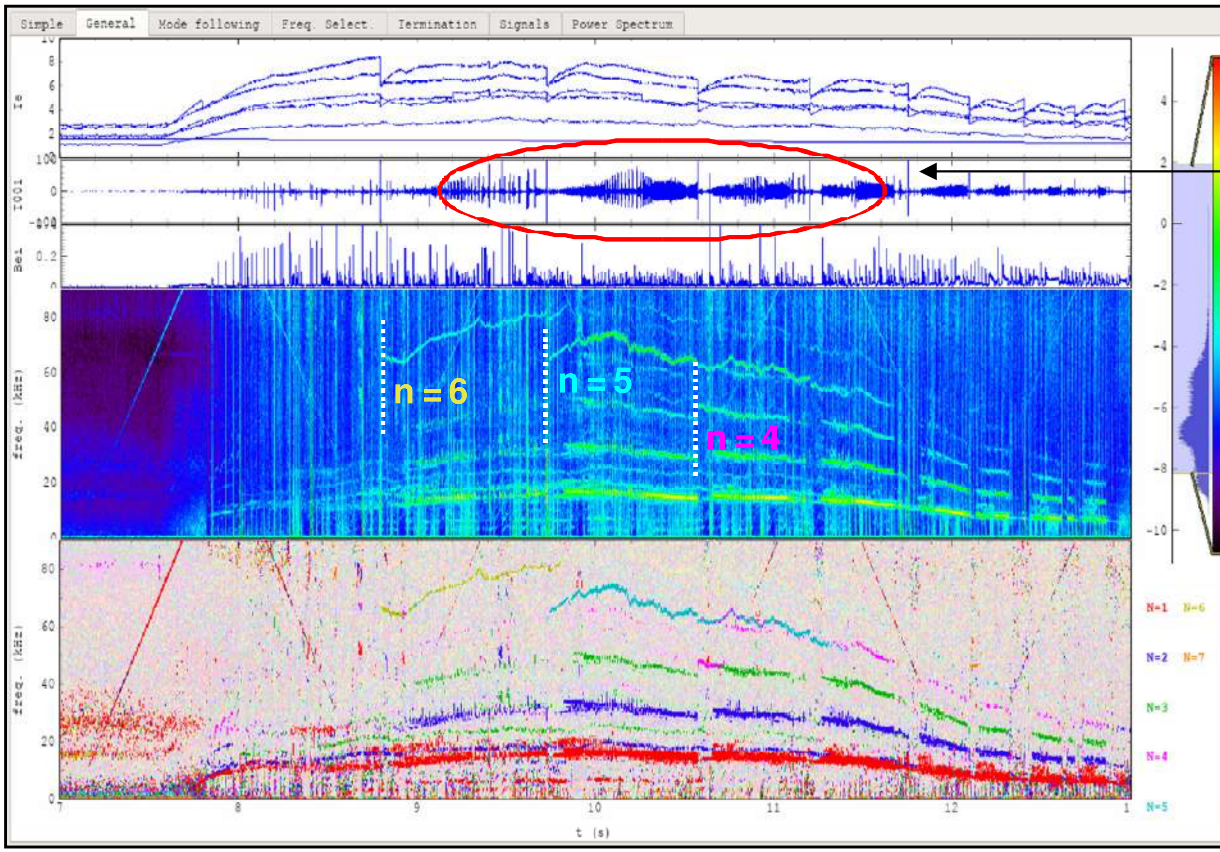


8 T pulses
24 DT pulses

→ Only q = 1 activity for low NBI power

→ High-n tearing modes for higher NBI power, mostly triggered by long period sawtooth crashes

JPN: 99523 (Ip = 3.5 MA, Bt = 3.3 T)



- n = 1 + harmonics
- Fishbones
- ST-triggered Tearing Modes:

  n = 6 @ 8.80 s

  n = 5 @ 9.73 s

  n = 4 @ 10.57 s (short lived)

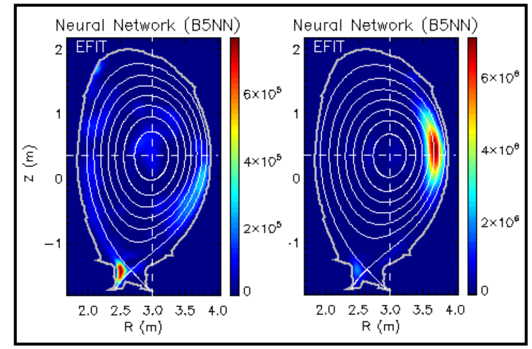
E_{fus} ≈ 14.2 MJ

$P_{NBI,max}$ ≈ 25.3 MW

Baseline: high plasma current

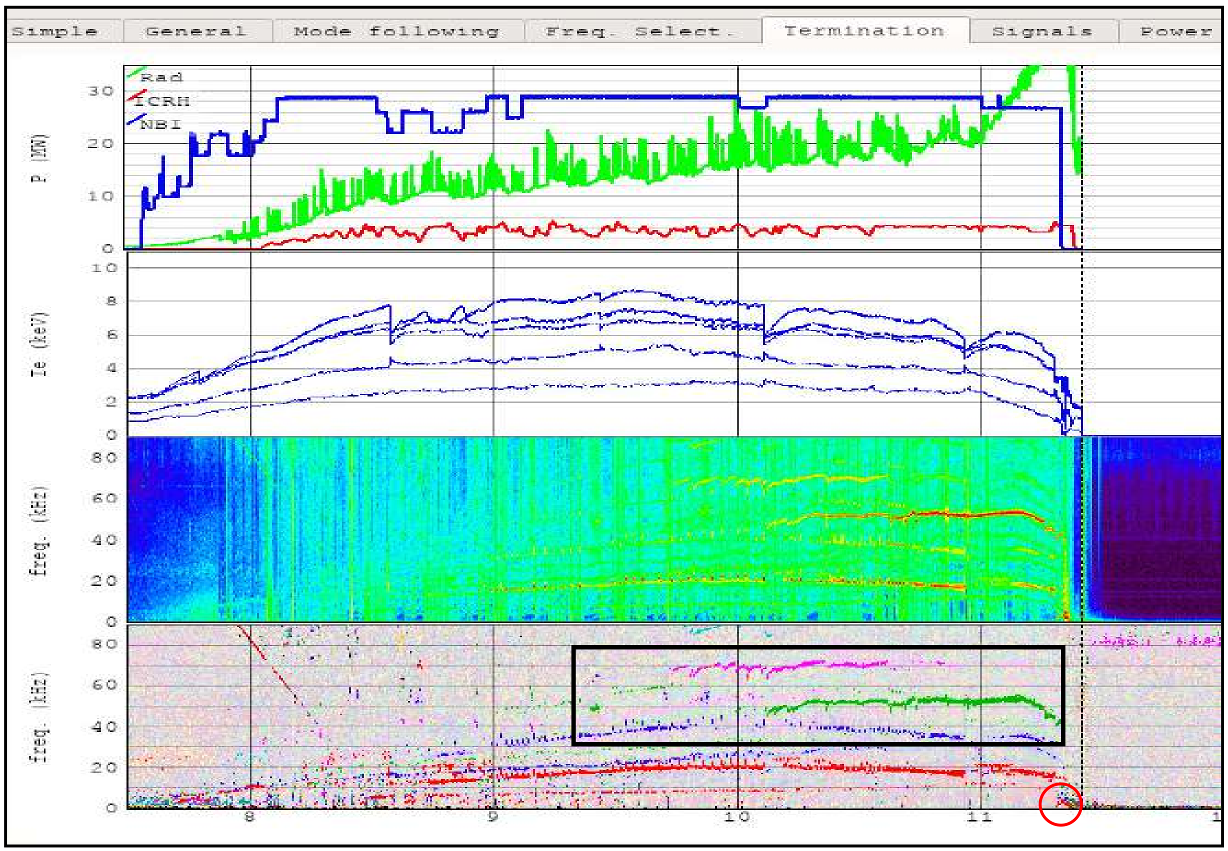
Radiation increase at high-power and high-current

Progressive increase in the radiated power, due to heavy impurities accumulated in the low field side, in pulses at higher power, limiting the pulse length and the possibility to achieve higher fusion energy values.

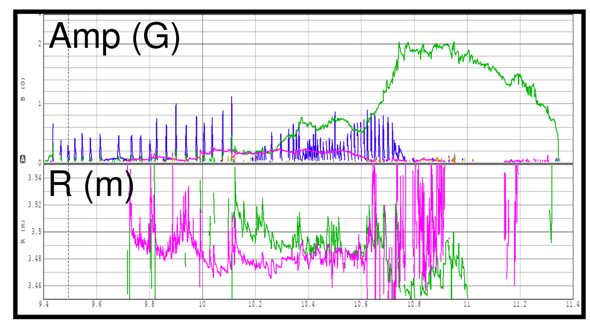


8.1 s   11.2 s

JPN: 99948 (Ip = 3.5 MA, Bt = 3.35 T)



- n = 1 + harmonics
- Fishbones
- **n = 4** from 49.72 s (ELM-triggered)
  n = 3 from 50.11 s (ST-triggered)
  high amplitude from 50.6 s



E_{fus} ≈ 18.2 MJ
$P_{NBI,max}$ ≈ 29.4 MW

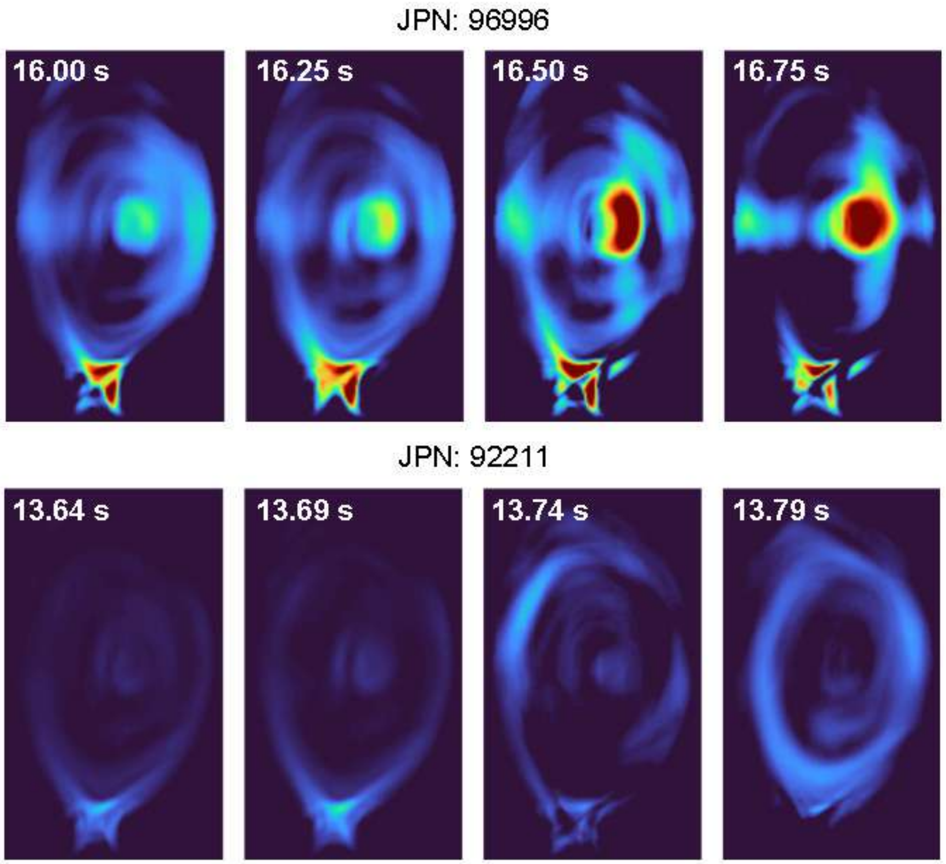
Baseline: high plasma current

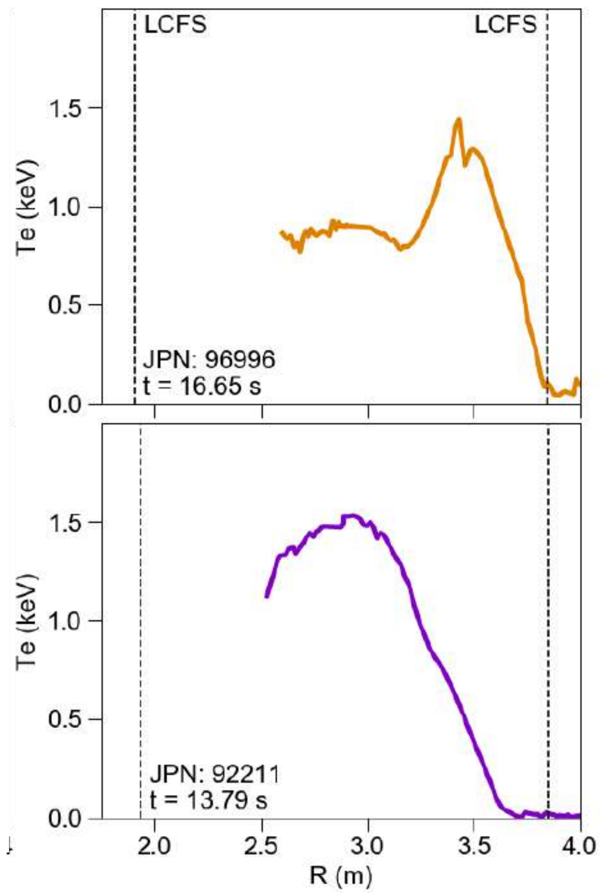
Plasma termination: temperature hollowing and edge cooling

Higher level of disruptivity with respect to the lower-current hybrid scenario. Two main “disruption paths”, connected with an increased radiation emission in core or edge plasma:

- Core accumulation of high-Z impurities → Temperature Hollowing → j_ϕ broadening
- Influx of low-Z impurities → Edge Cooling → j_ϕ shrinking

2/1 TM destabilization
(Δ' increase)



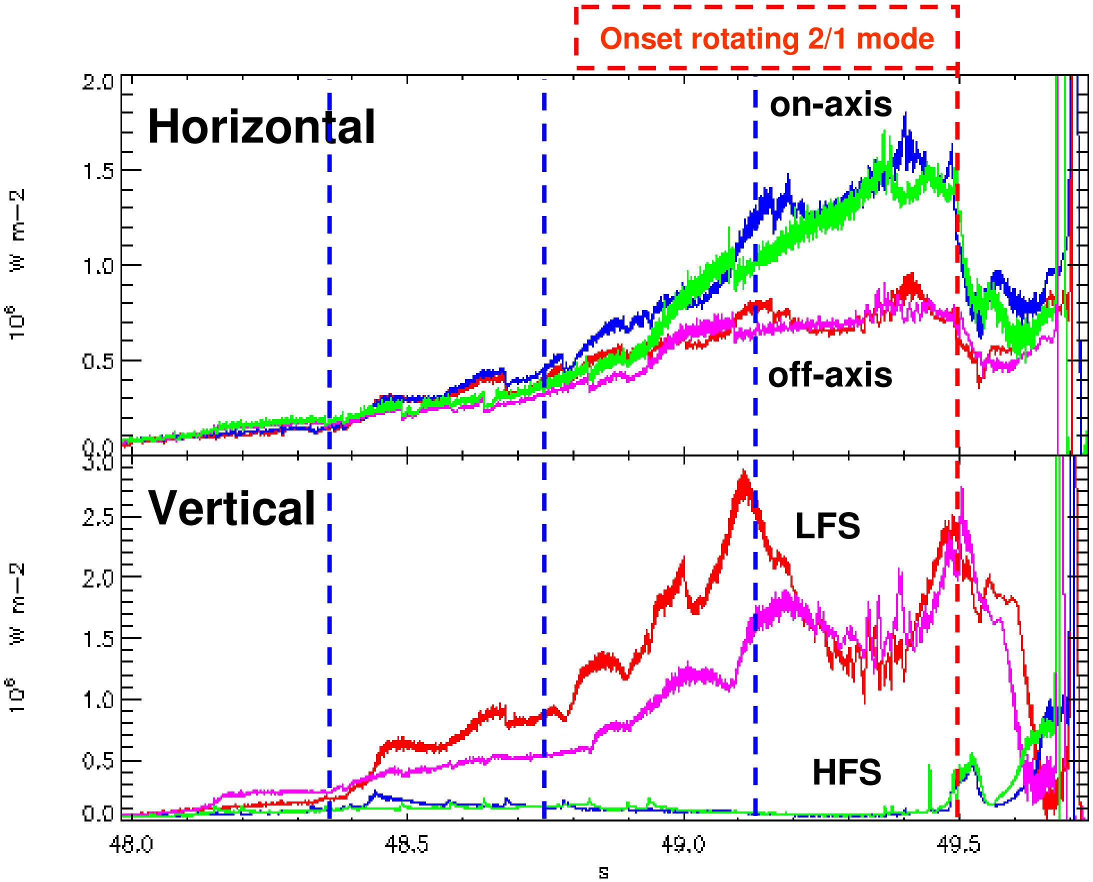


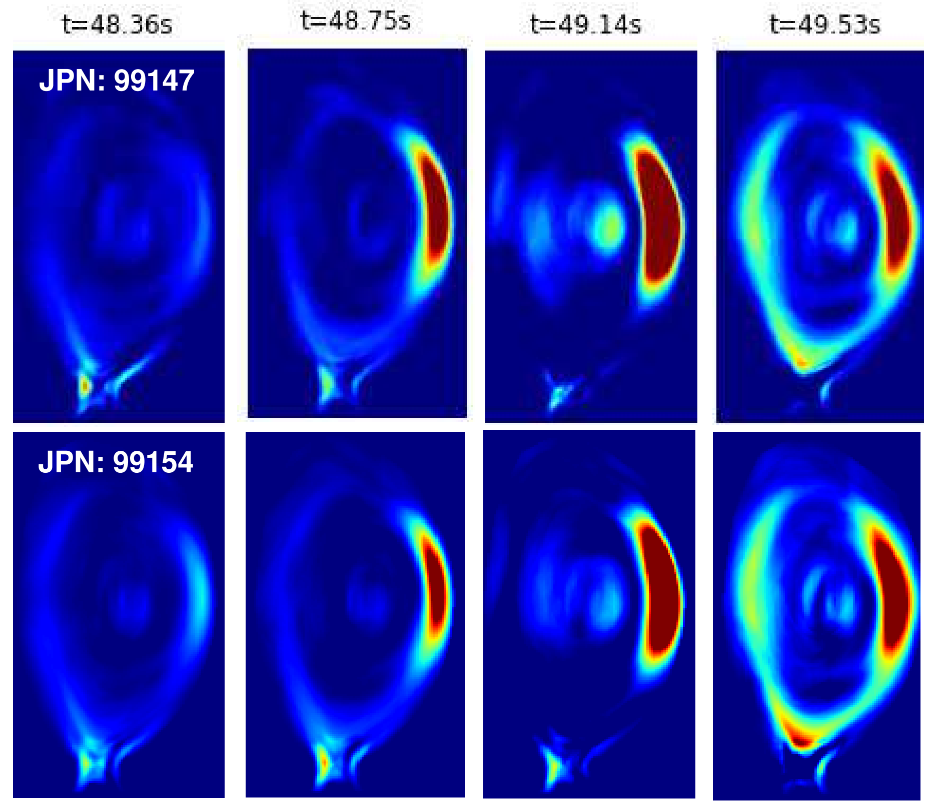
D pulses

Baseline: high plasma current

Plasma termination: outboard radiative blob

An outboard radiating blob due to heavy impurities accumulated in the low field side can also lead to **edge cooling** and to the destabilization of a 2/1 TM, possibly locking and triggering the DMV intervention.





T pulses

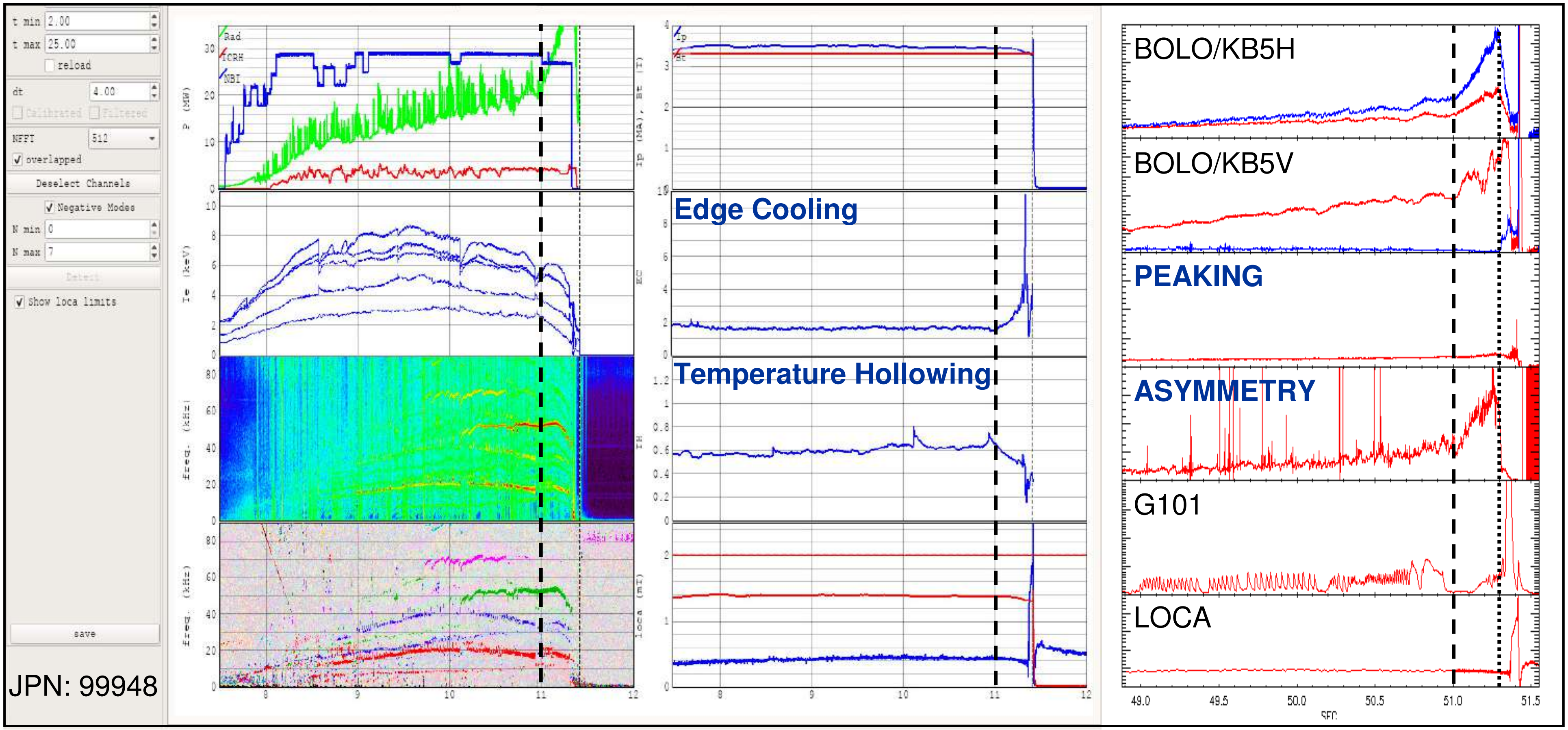
Signals from bolometer cameras:

Horizontal: BOLO/KB5H
Vertical: BOLO/KB5V

Peaking from Horizontal camera:	$\frac{BOLO/KB5H/ch14}{BOLO/KB5H/ch12}$	Core impurity accumulation
Asymmetry from Vertical camera:	$\frac{BOLO/KB5V/ch03}{BOLO/KB5V/ch18}$	Outboard blob

Baseline: high plasma current

Disruption alerts from temperature and radiation profiles

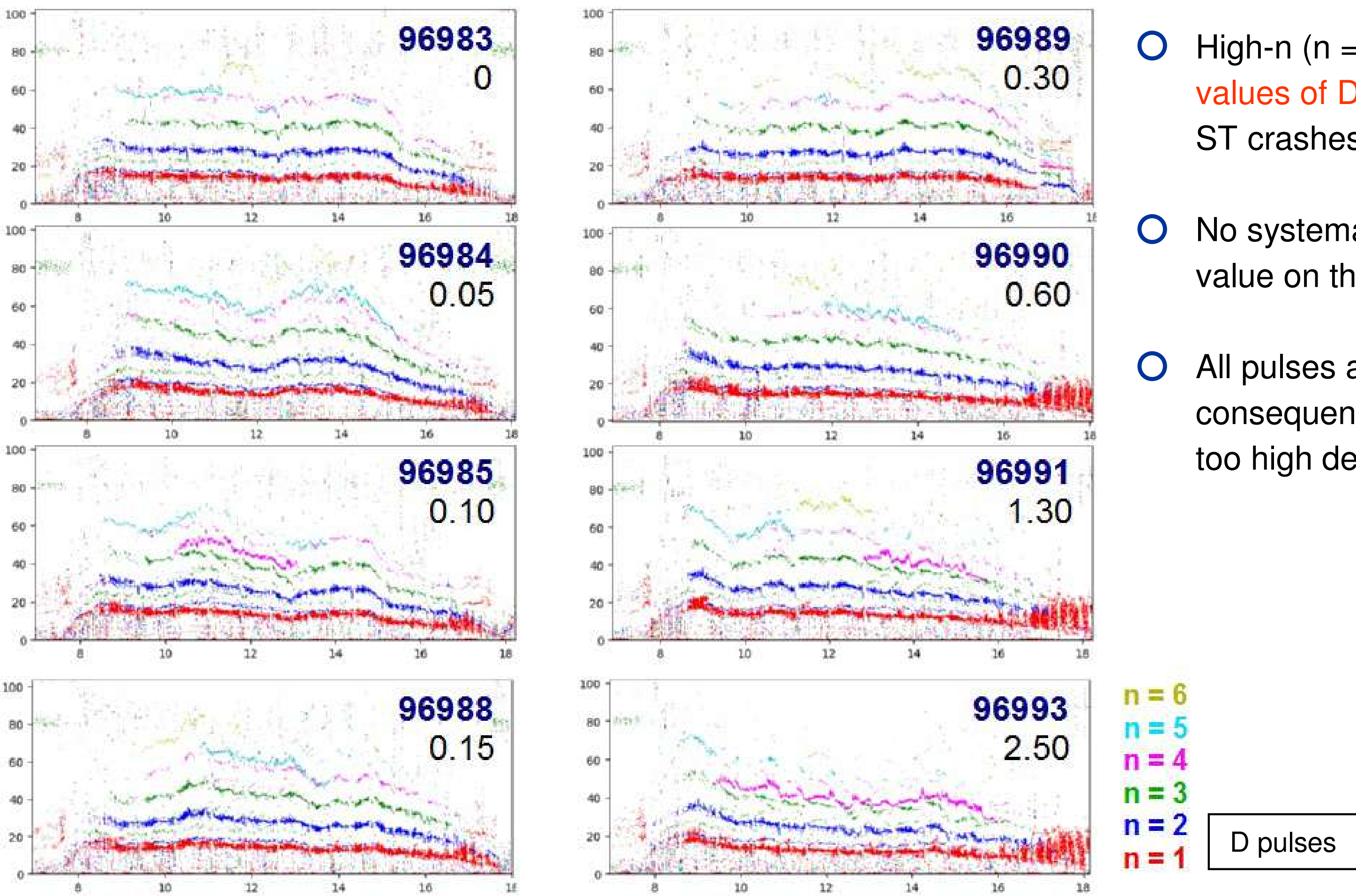


	Light impurities at the edge	Core impurity accumulation	Outboard radiative blob
Temperature Hollowing	- - -	AVOIDANCE	- - -
Edge Cooling	MITIGATION	- - -	MITIGATION
Radiation Asymmetry	- - -	- - -	AVOIDANCE
Radiation Peaking	- - -	AVOIDANCE	- - -

Baseline: neon seeding experiments

High D flow-rate

13 pulses performed in D plasmas at 3 MA, with two different deuterium flow-rate values (**1.8×10^{22} el/s**, and **0.4×10^{22} el/s**), to study the influence of Neon seeding on main parameters and MHD activity.

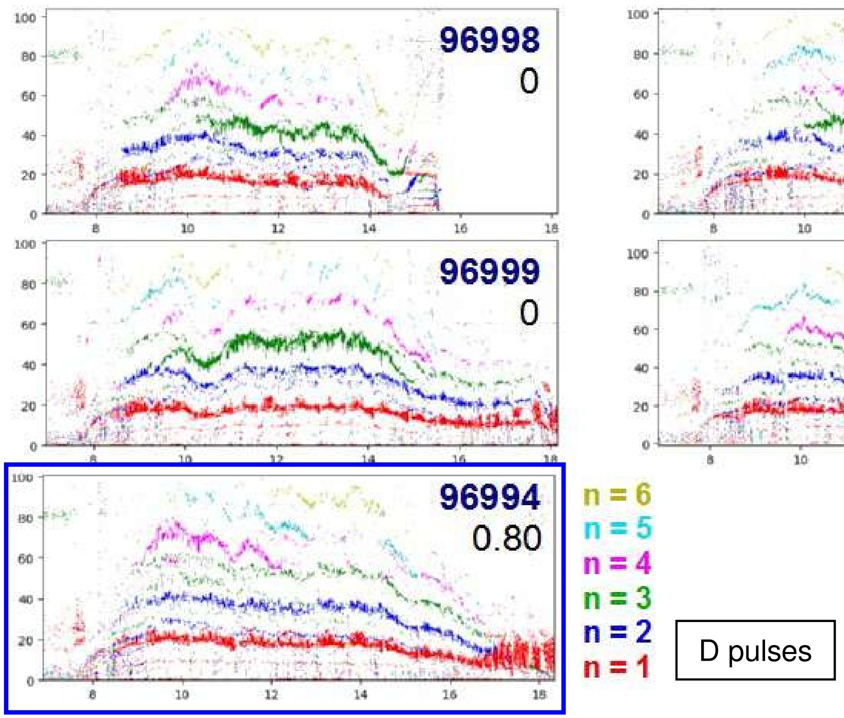


- High-n (n = 4,5,6) Tearing Modes for higher values of D flow-rate, mostly triggered by ST crashes.
- No systematic effect of Neon flow-rate value on the mode onset (Ne_{FR} / D_{FR} < 1.4).
- All pulses at high D flow-rate disrupt as a consequence of edge cooling, suggesting too high density for the residual Neon.

Baseline: neon seeding experiments

Low D flow-rate

13 pulses performed in D plasmas at 3 MA, with two different deuterium flow-rate values (**1.8 x 10^{22} el/s**, and **0.4 x 10^{22} el/s**), to study the influence of Neon seeding on main parameters and MHD activity.



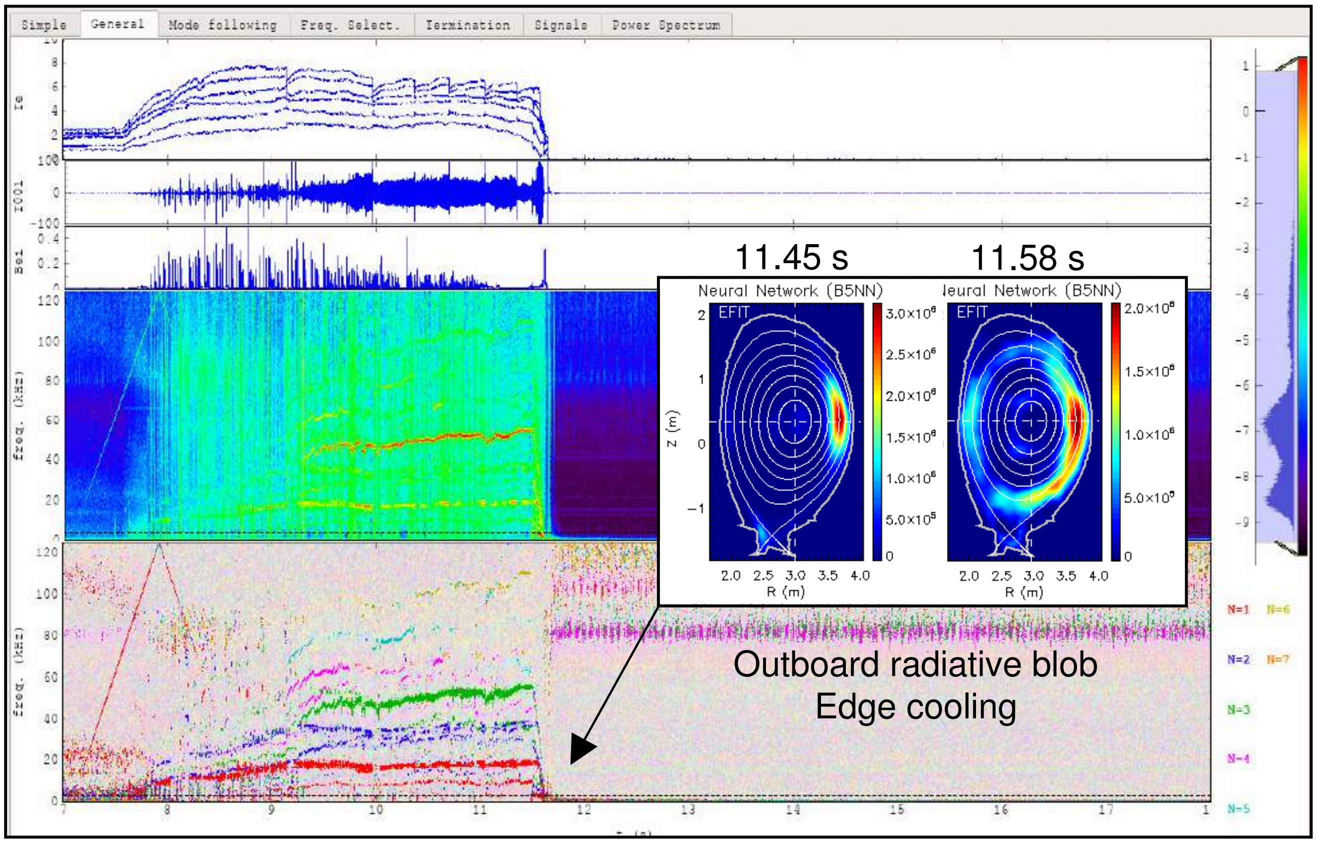
- High amplitude n = **3** Tearing Modes, coincident with a neutron rate decrease, for lower values of the D flow-rate, with different kind of trigger mechanisms.
- The possibility of a n = 3 avoidance for Ne_{FR} / D_{FR} > 2.0 has to be deeply investigated.
- An increase in impurity accumulation in the plasma termination is observed in pulses with reduced D flow rate.

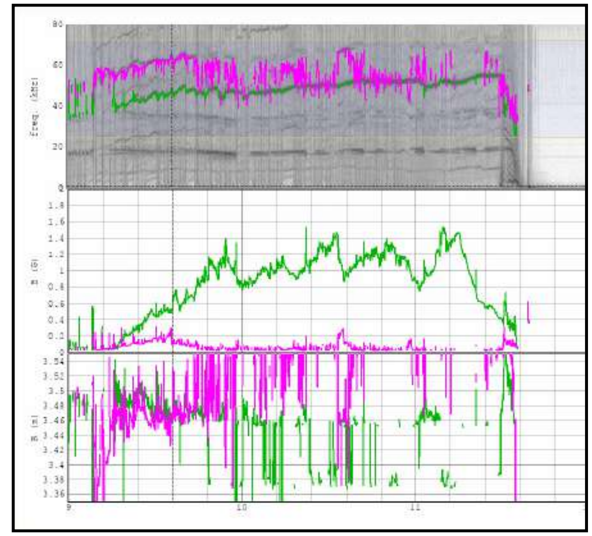
Baseline: neon seeding experiments

DT experimental campaign

Only 1 Neon seeded pulse during DT experimental campaign, at T dosing of **~ 0.5 x 10^{22} el/s**, with D pellets and Ne level as #96994.

JPN: 99513 (Ip = 3.0 MA, Bt = 2.85 T)





High amplitude **n = 3** tearing modes (up to 1.5 G)

Weak **n = 4** tearing mode

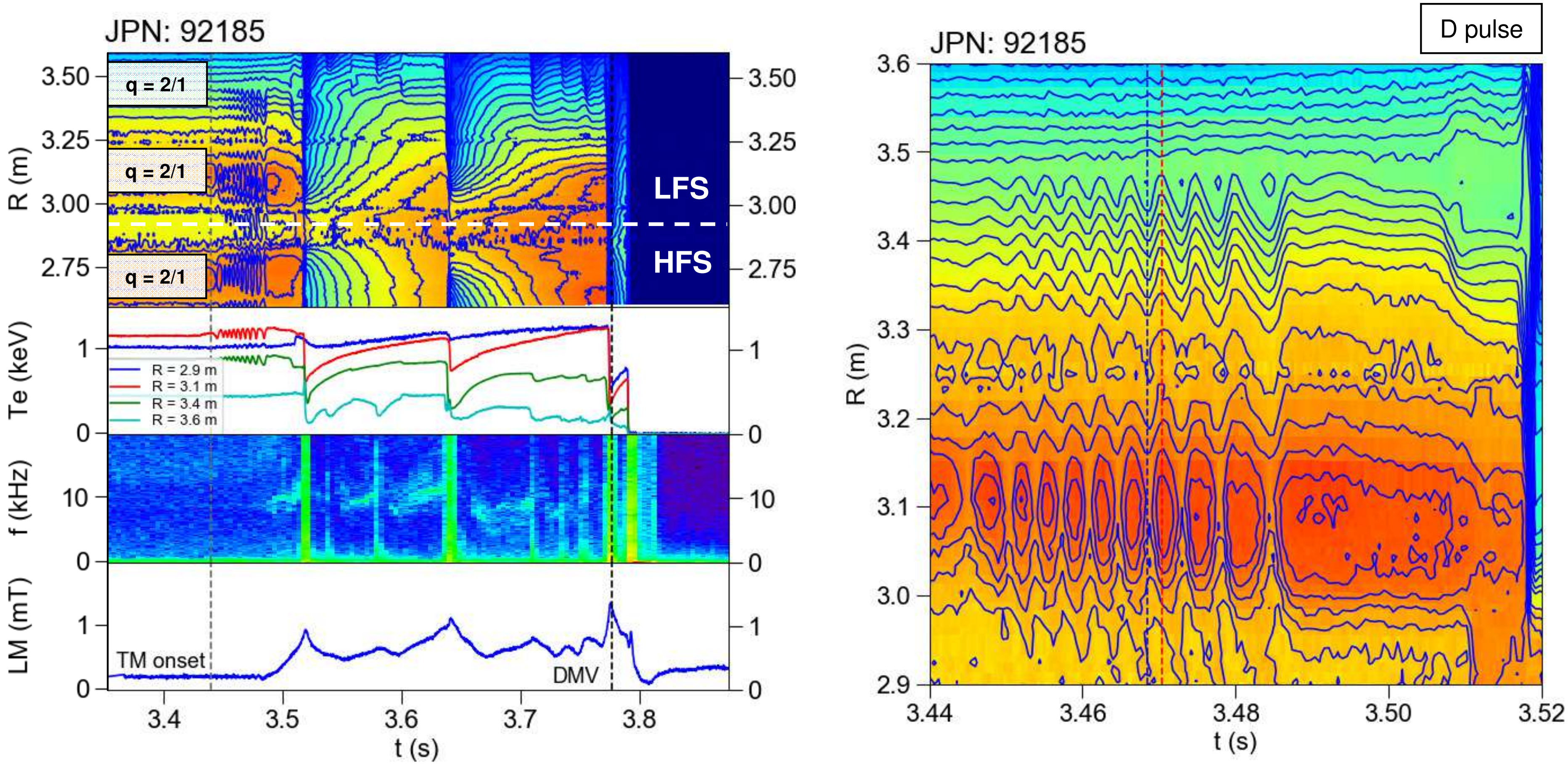
E_{fus} ≈ 10.2 MJ

$P_{NBI,max}$ ≈ 26.5 MW

Hybrid: current ramp-up

Double Tearing Modes

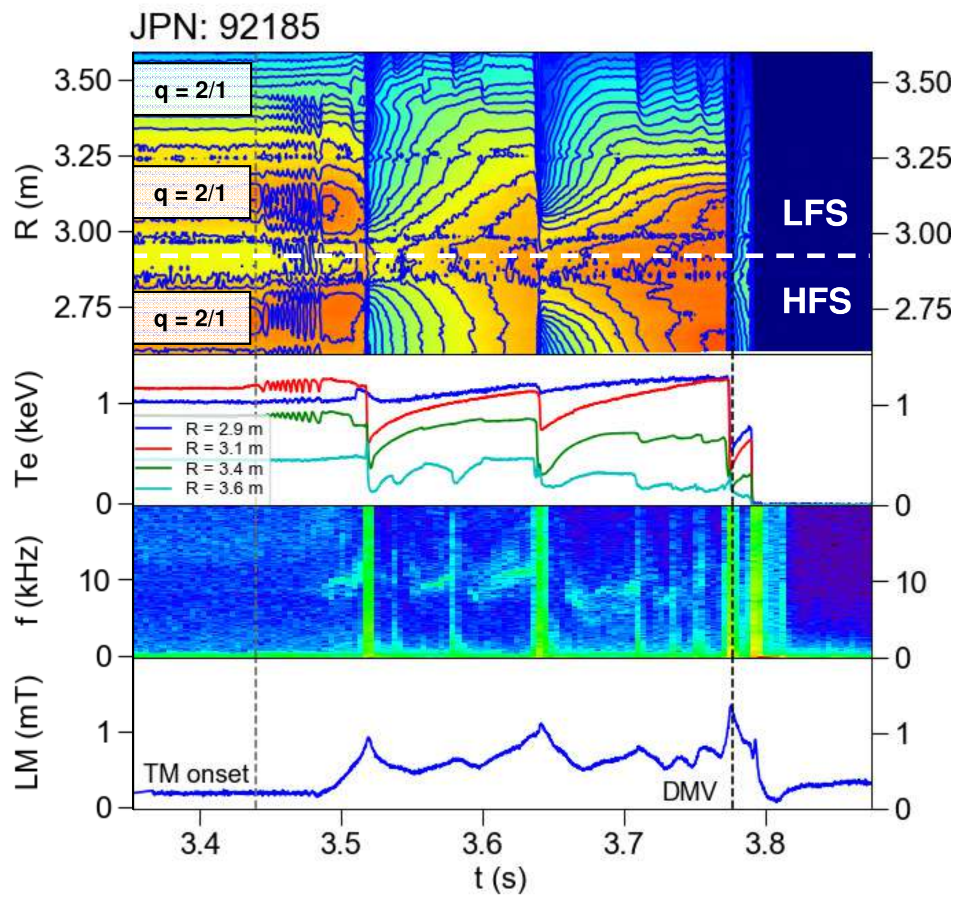
Double tearing modes during the current ramp-up of pulses with hollow electron temperature, mainly due to fast current ramp-rate and high-Z impurity influx at low density values.

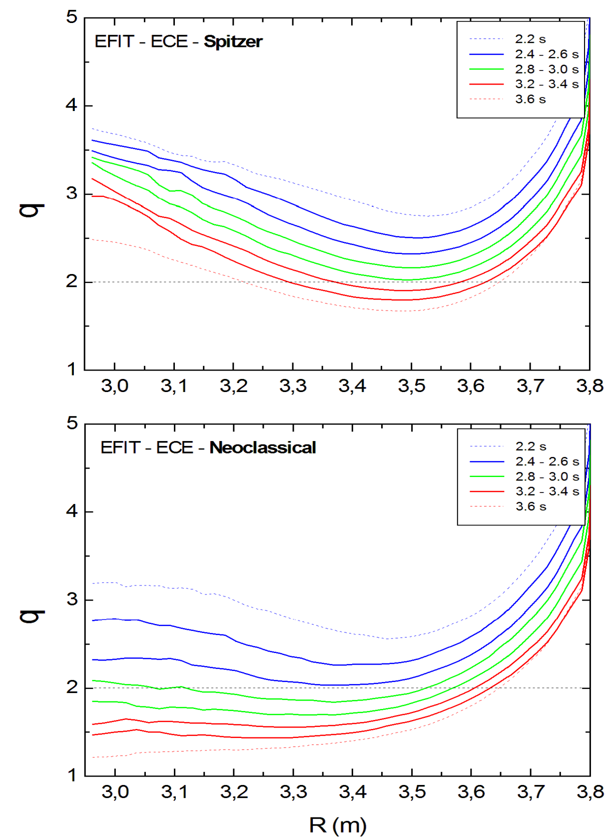


An electron temperature profile peaking factor has been included in the JET real-time control system, allowing an early pulse termination by rapidly ramping the plasma current down.

Double Tearing Modes

Interpretative TRANSP simulations have been carried out, with the current density profiles calculated at each time step by solving the poloidal field diffusion equation.



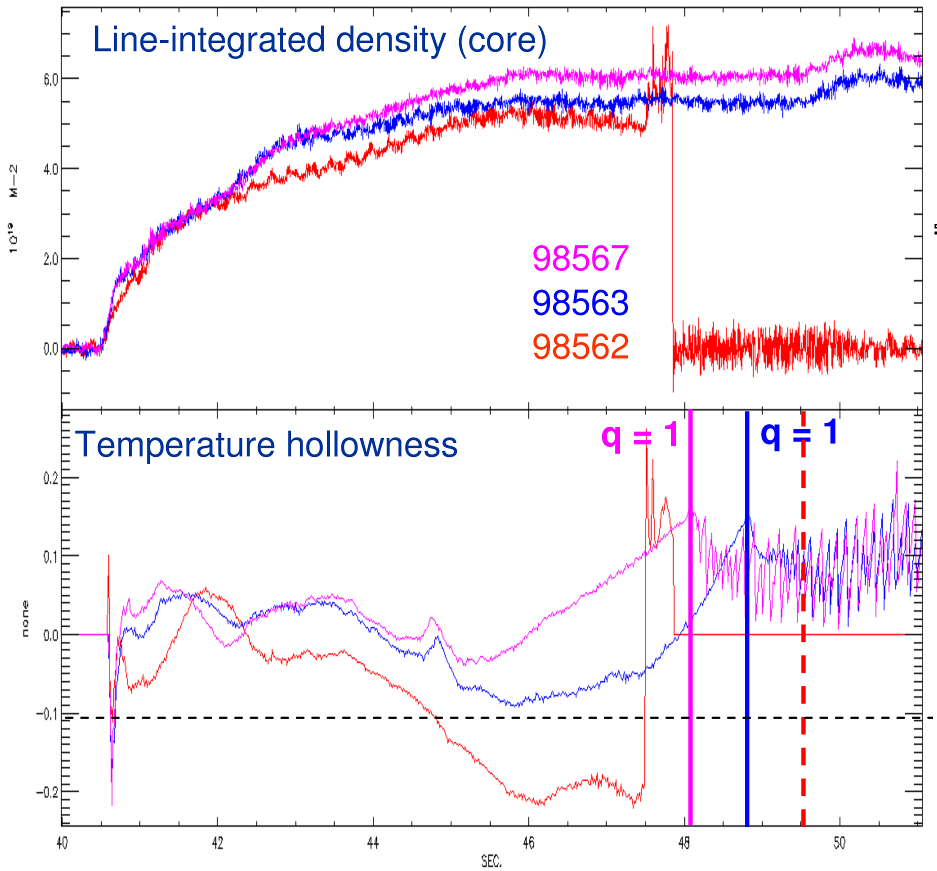


Linear stability analysis have been performed by solving the equation for the perturbed radial magnetic field in the zero pressure limit. Non-linear MHD simulation with JOREK code are planned.

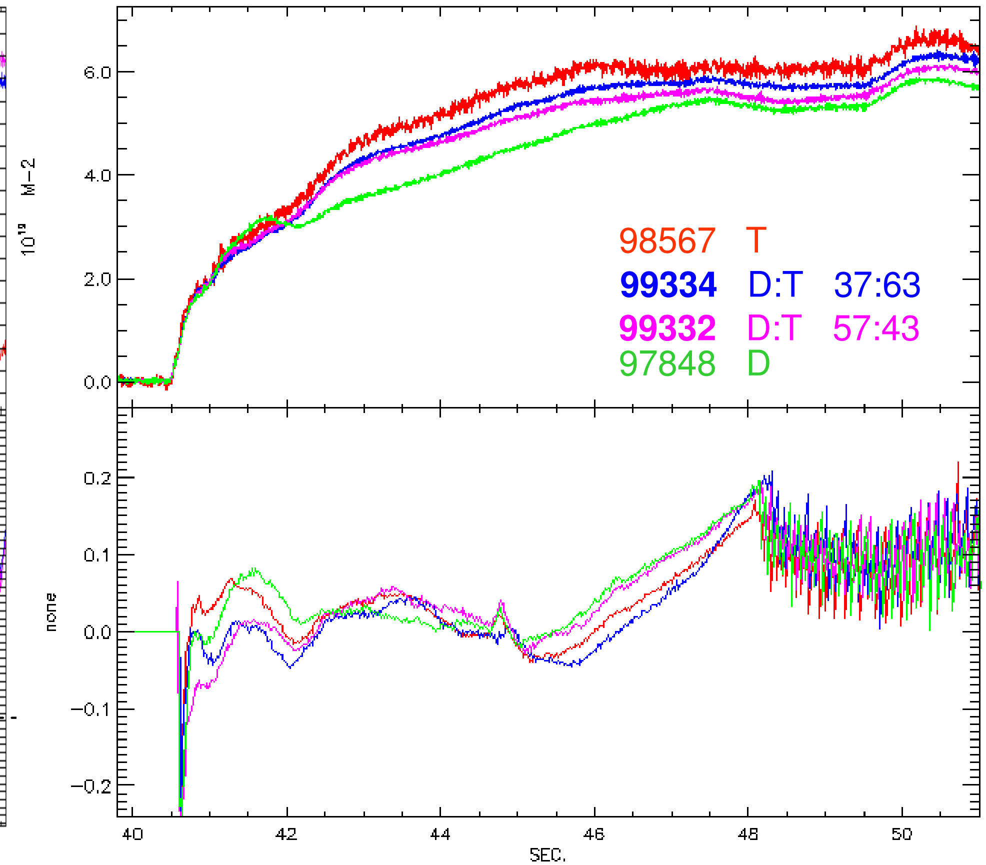
Hybrid: current ramp-up

q = 1 arrival time

The arrival time of the q = 1 magnetic surface into the plasma has been utilized to optimize the shape of the safety factor profile at the beginning of the main heating phase.



Density scan for T plasmas

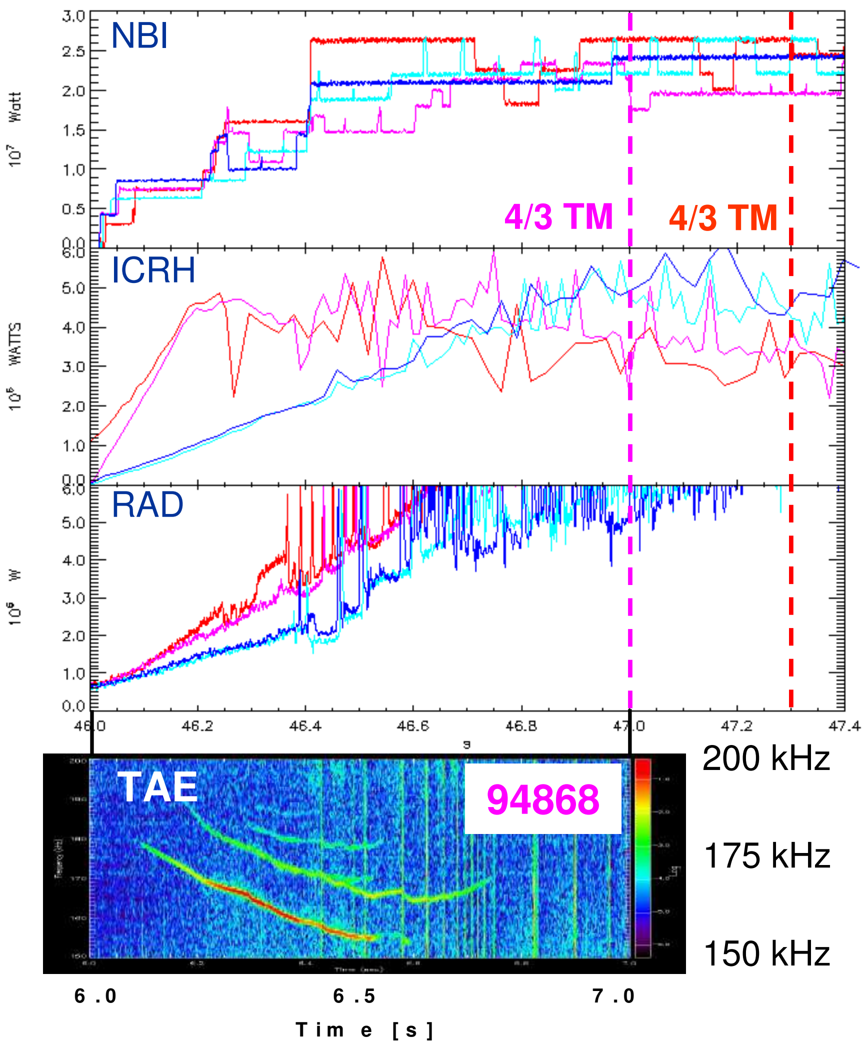


Isotope scan

Hybrid: beginning of the main heating phase

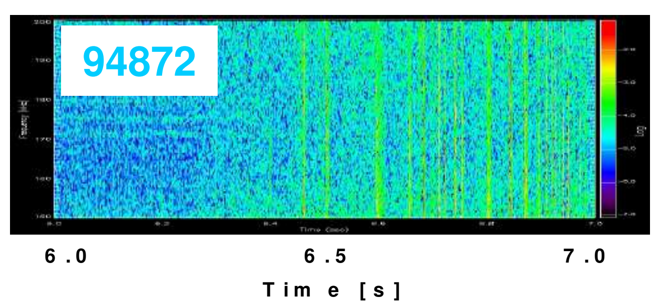
Toroidal Alfvén Eigenmodes and spontaneous 4/3 tearing modes

By reducing the slope of the ICRH ramp-up in the initial phase of hybrid pulses, TAE and spontaneous 4/3 TM are no longer observed.



- **Steeper ICRH ramps: 94867, 94868**
  - The ICRH power overcomes the radiated power
  - TAE activity is observed before the NBI flat-top phase
  - A spontaneous 4/3 TM is observed (the onset time is delayed for the pulse with more NBI power)

- **Slower ICRH ramps: 94872, 94874**
  - The ICRH and the radiated powers are balanced
  - No TAE activity is observed
  - No spontaneous 4/3 activity is observed (also for higher value of ICRH power on the flat-top)



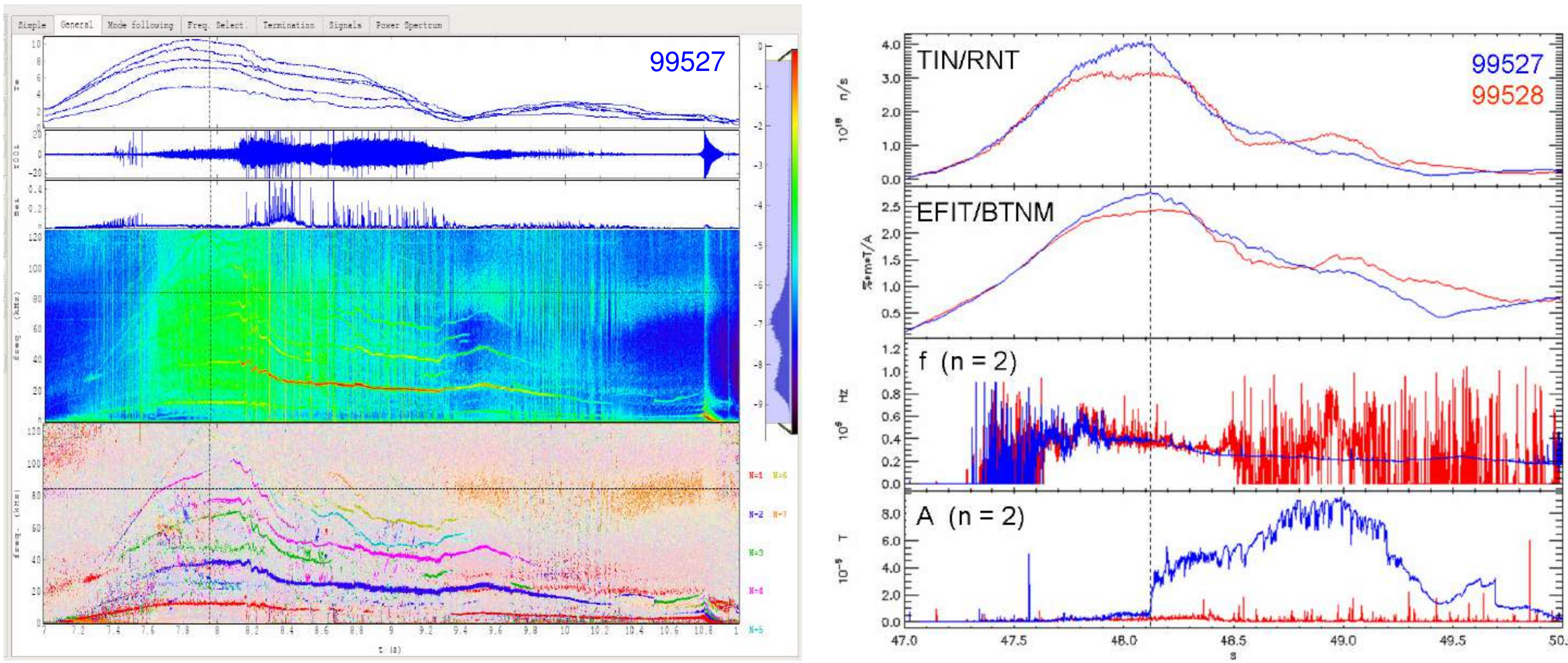
Scan for D plasmas

Hybrid: beginning of the main heating phase

Spontaneous 3/2 Tearing Modes

Early destabilization of spontaneous 3/2 tearing modes in pulses with relatively high β_N and low internal inductance.

JPN: 99527 (Ip = 2.3 MA, Bt = 3.4 T)

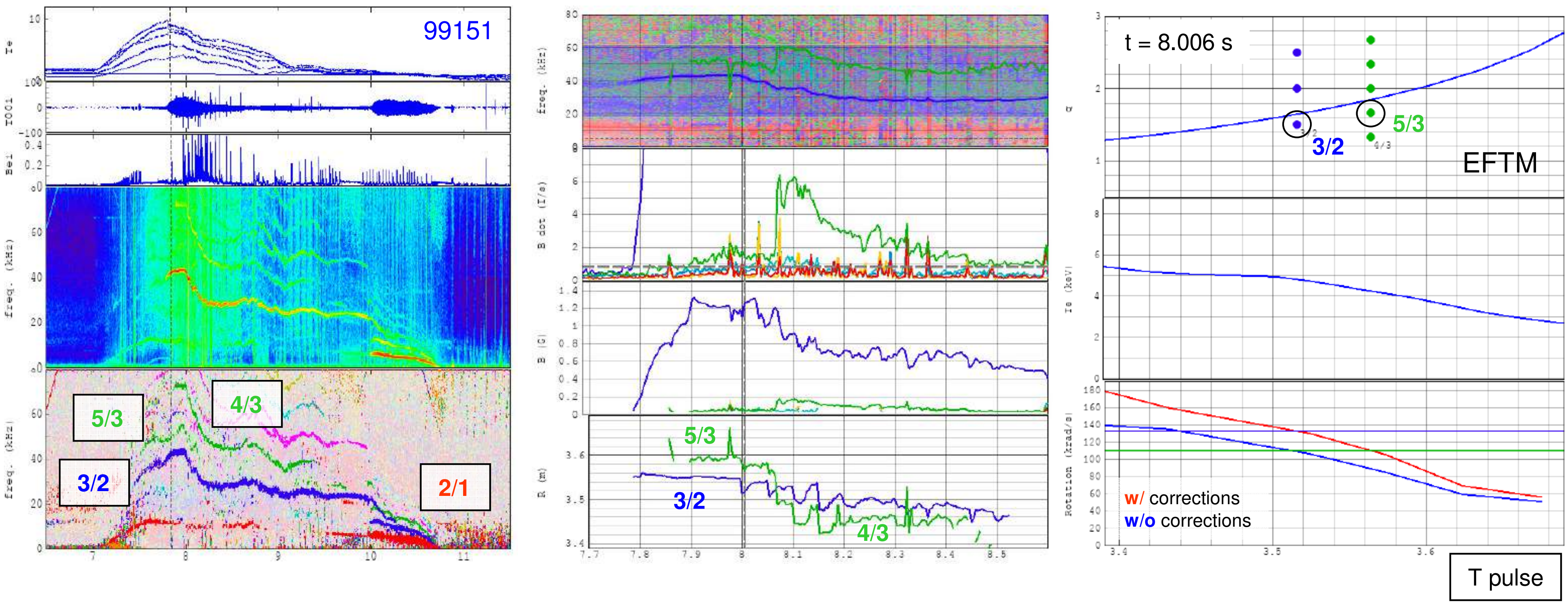


Strategies have been applied to avoid the early destabilization of 3/2 TM, acting on the waveforms of the additional heating and of the gas injection.

Hybrid: beginning of the main heating phase

Spontaneous 3/2 Tearing Modes

The simultaneous presence of different modes allows the identification of the poloidal mode number from CX rotation profile (with diamagnetic corrections).



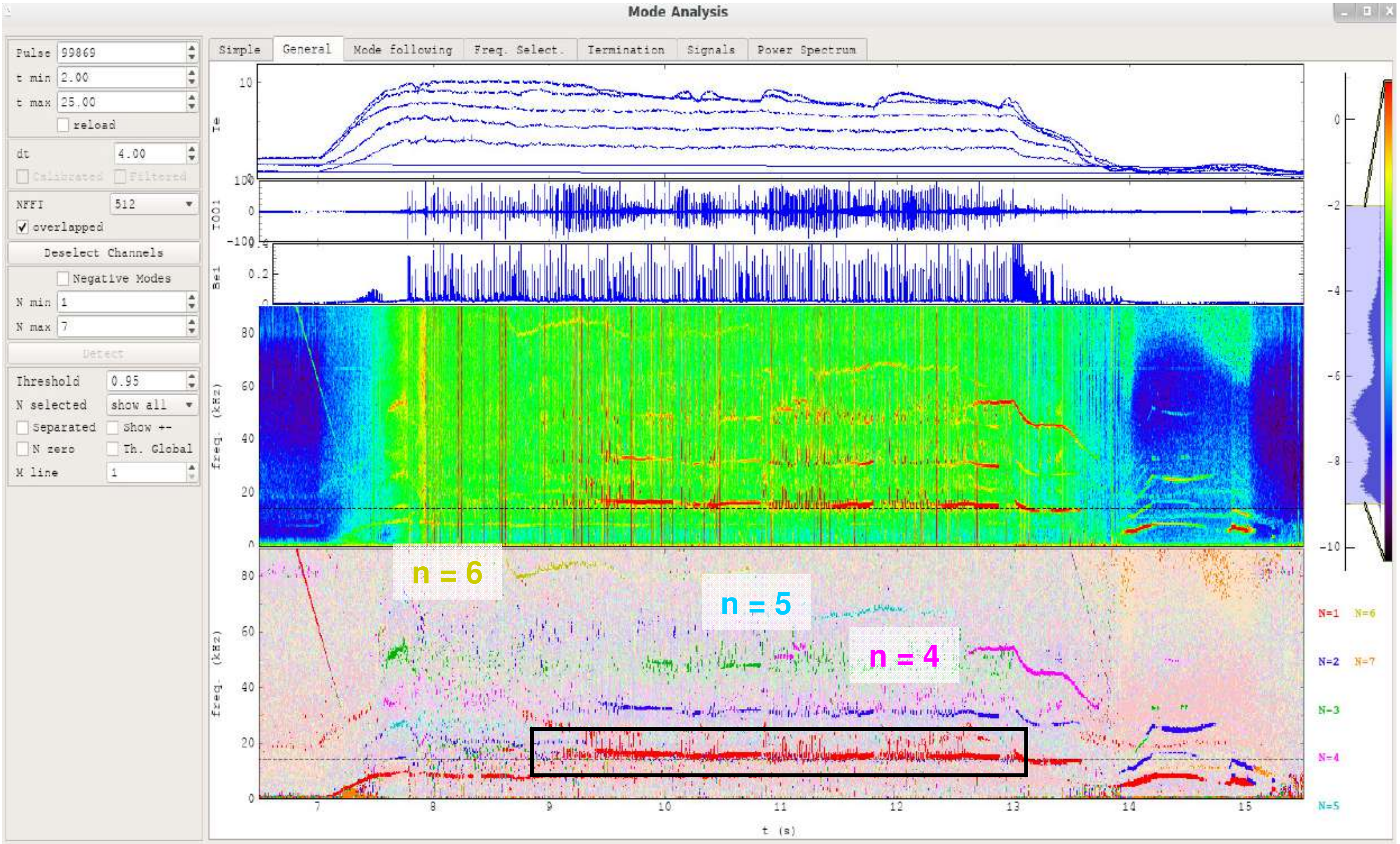
The equilibrium reconstruction (EFIT, EFTF, EFTP, EFTM) can be utilized for the estimation of poloidal mode number, starting from CX rotation profile.

Hybrid: flat-top

- **High-n Tearing Modes**

High-n Tearing Modes (n = 6, 5, 4) during the flat-top in pulses with low radiated power.

JPN: 99869 (Ip = 2.3 MA, Bt = 3.4 T)



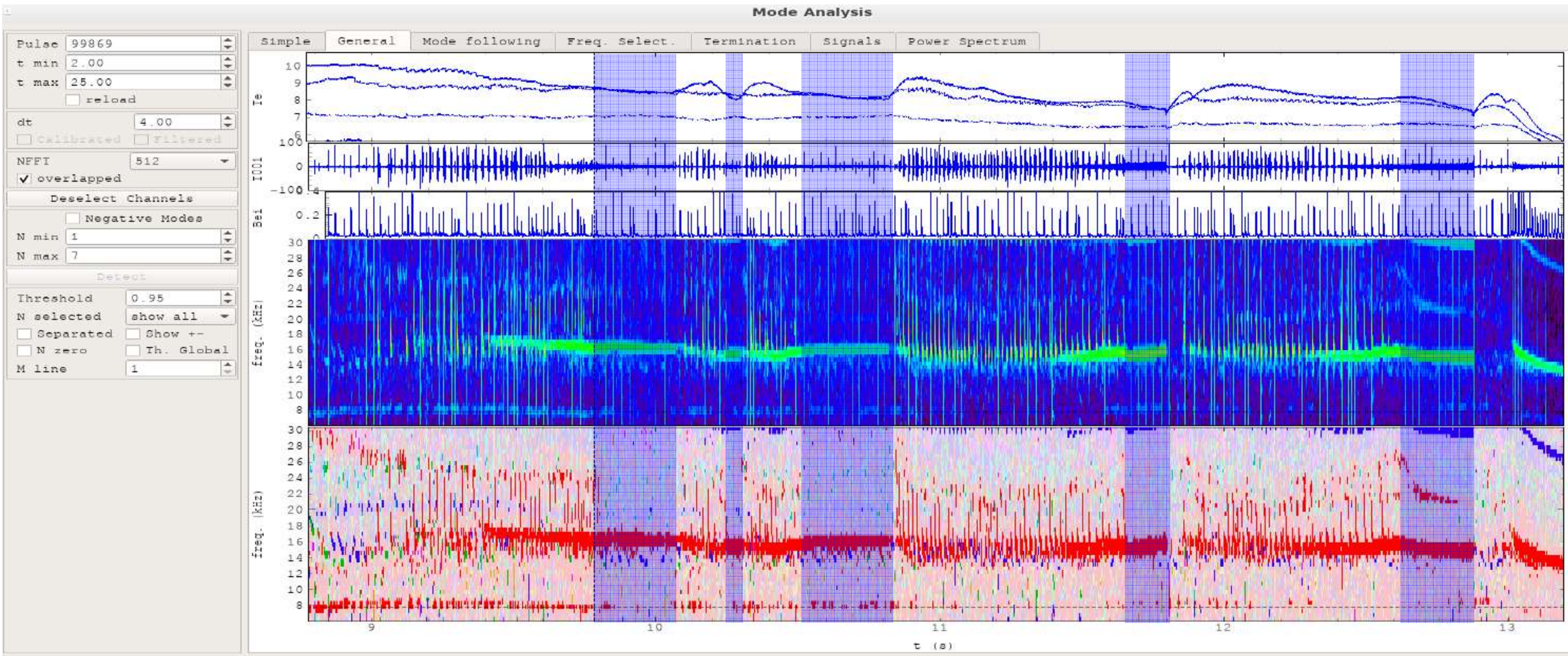
$E_{fus} \approx$ **41.8 MJ**

$P_{NBI,max} \approx 29.6$ MW

Hybrid: flat-top

Fishbones and continuous (1,1) mode

An interesting “competition” between fishbone activity and continuous 1/1 mode has been observed, with the dominant “character” of the n=1 activity which seems to depend on the shape of the electron temperature profile in the core region.



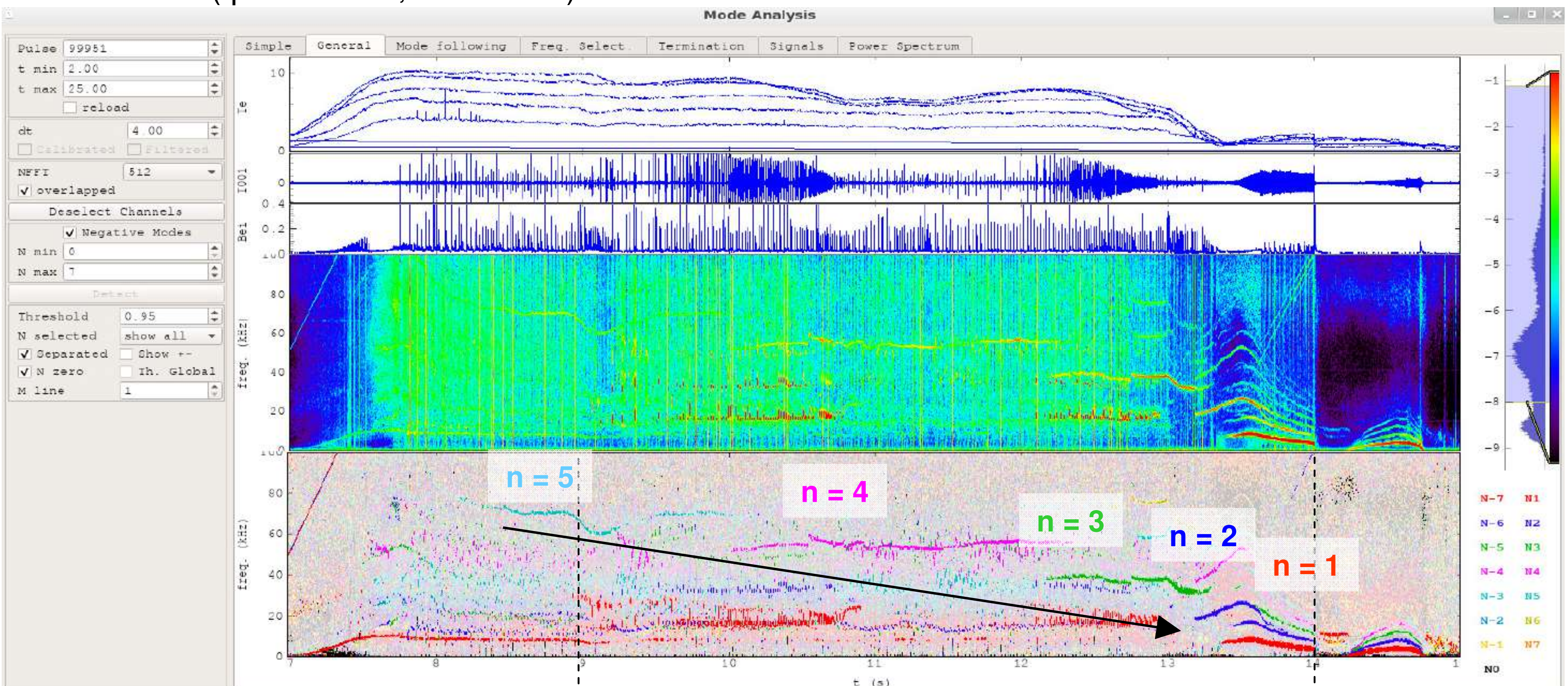
- total
- fishbone
- 1/1

Hybrid: core impurity accumulation

Chain of Tearing Modes

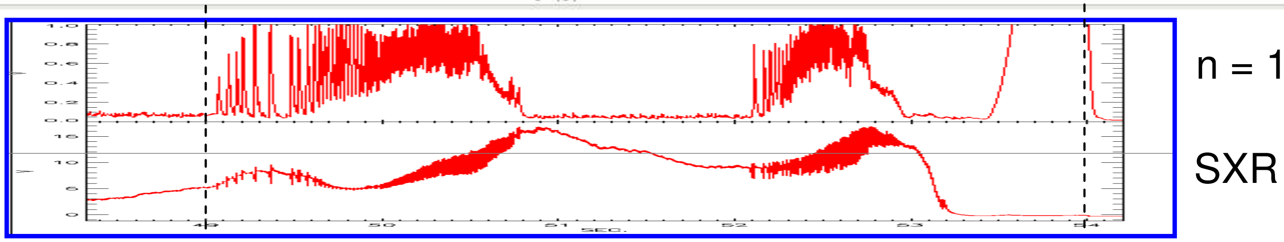
Chain of Tearing Modes associated with the increasing radiated power due to core impurity accumulation.

JPN: 99951 (Ip = 2.3 MA, Bt = 3.4 T)



$E_{fus} \approx$ **42.9 MJ**

$P_{NBI,max} \approx 29.4$ MW

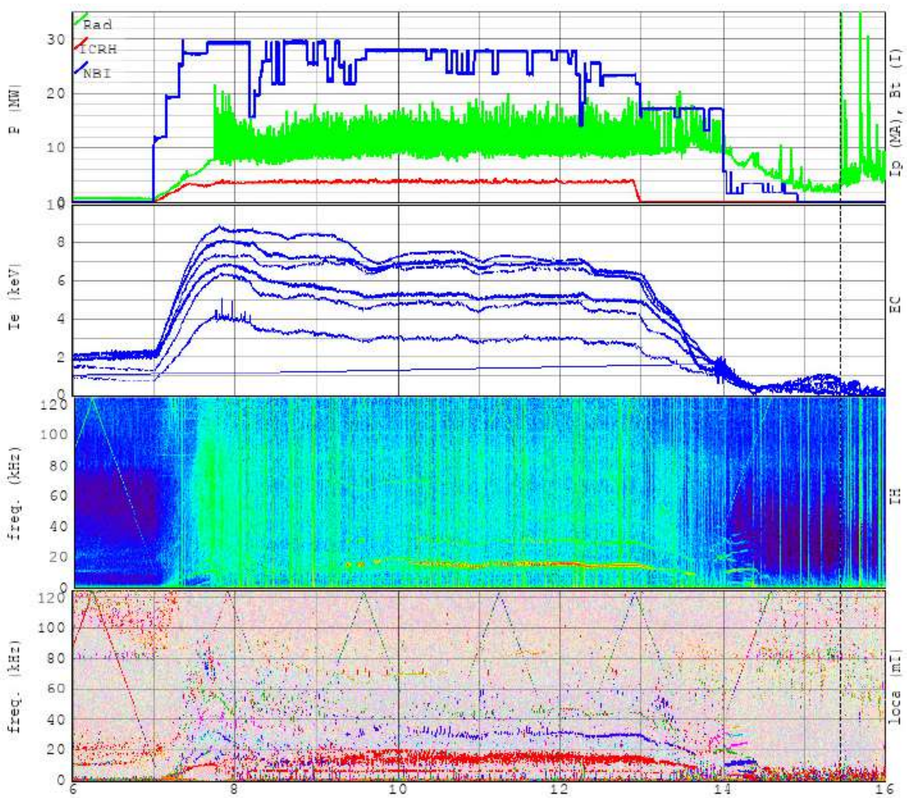


DT scenario with optimized non-thermal fusion

Optimized non-thermal fusion

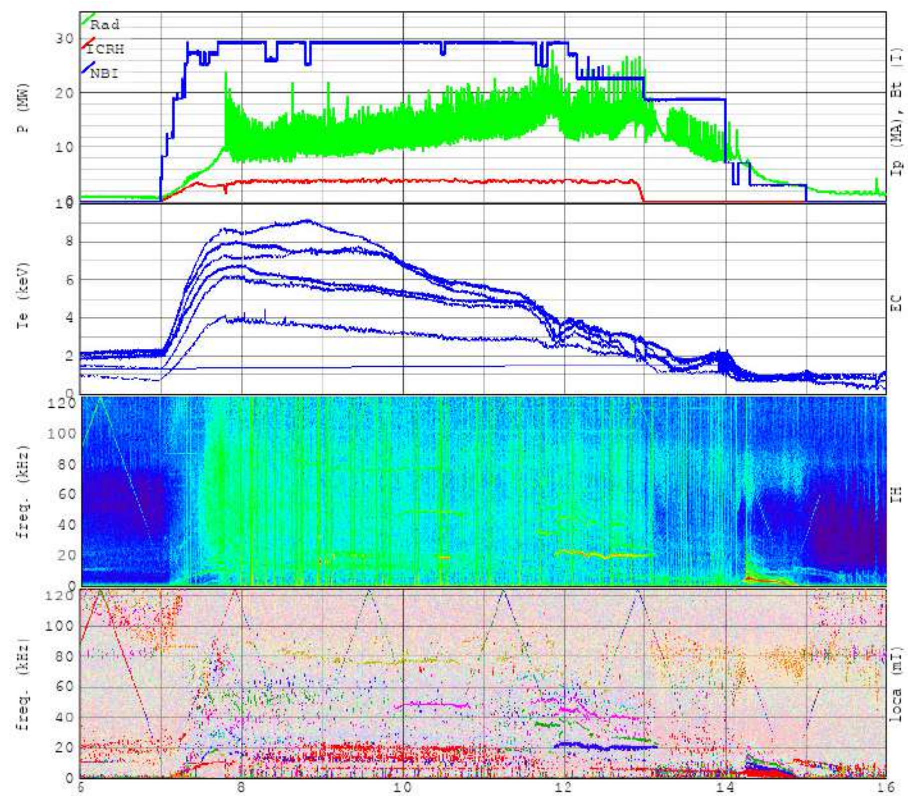
Achieve highest Pfus sustained for ~ 5 s, by optimizing the number of NBI beam-target fusion reactions: T-rich H-mode, D-NBI (D:T 20:80), with appropriate ICRH scheme (N=1 D ICRH)

JPN: 99971 (Ip = 2.5 MA, Bt = 3.85 T)



E_{fus} ≈ 58.9 MJ

JPN: 99972 (Ip = 2.5 MA, Bt = 3.85 T)

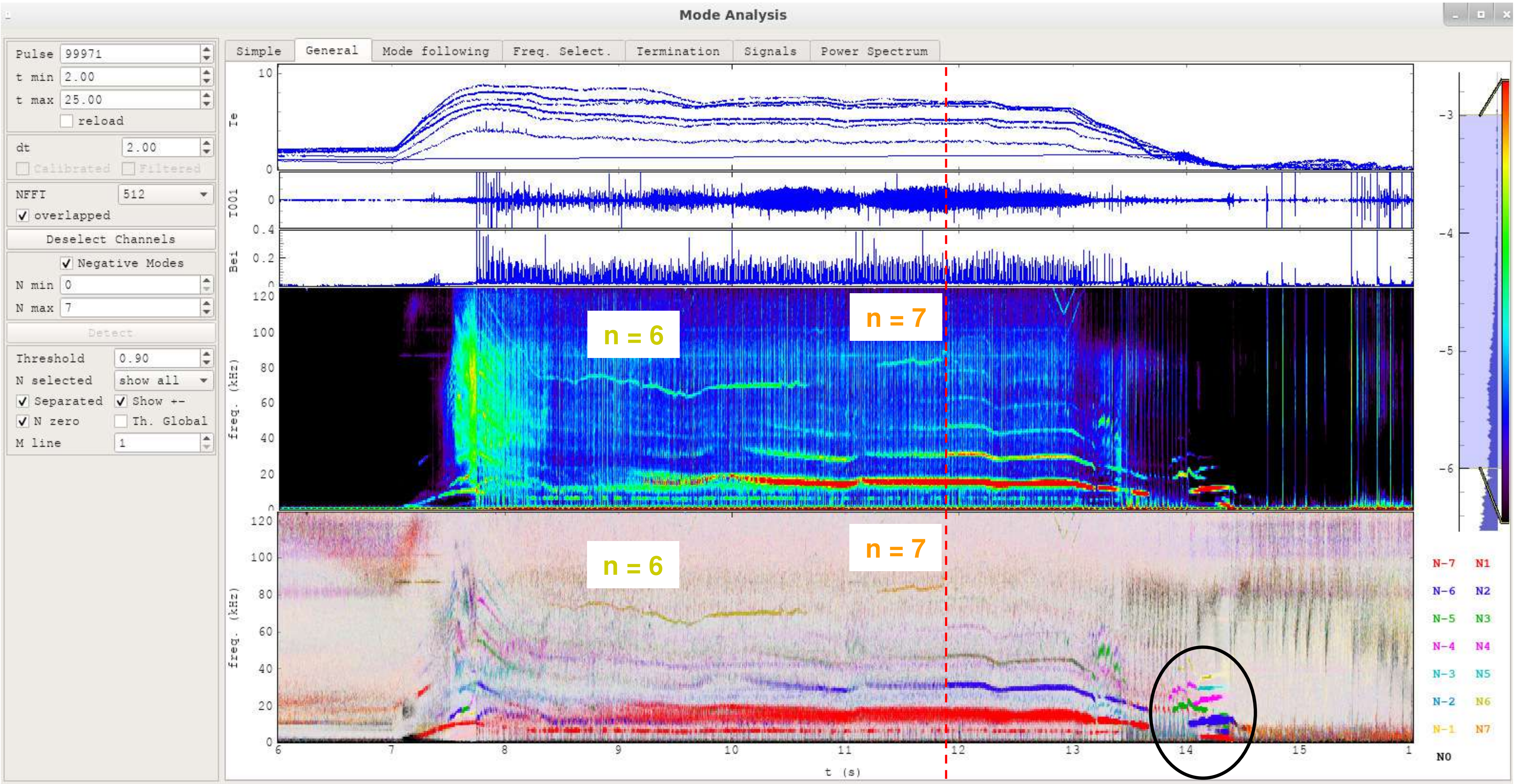


E_{fus} ≈ 56.0 MJ

Interpretative TRANSP simulations are carrying out, with current density profiles calculated solving to the poloidal field diffusion equation, to perform linear stability analyses for tearing modes.

DT scenario with optimized non-thermal fusion

JPN 99971: MHD activity

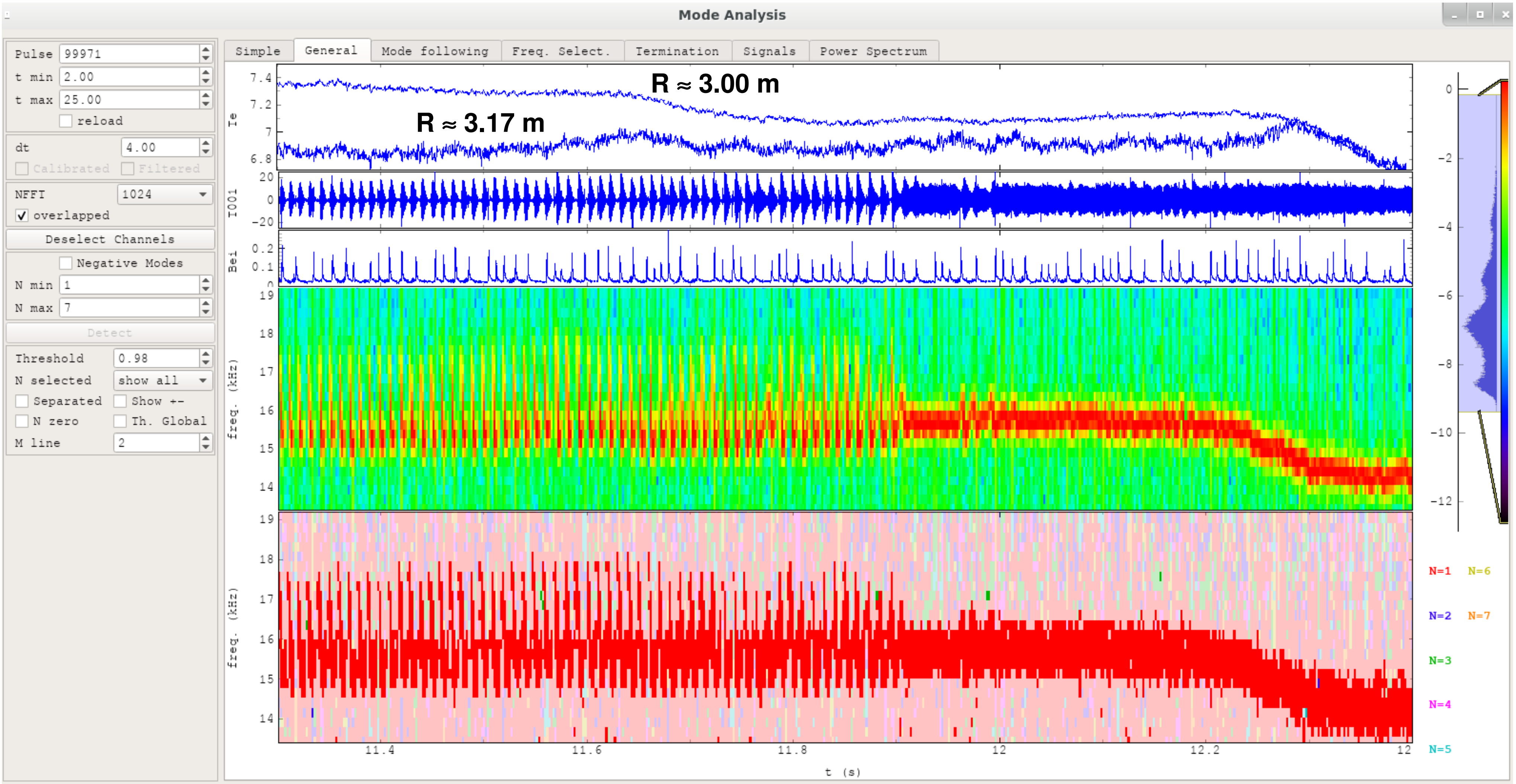


Fishbones	9.2-11.9 s
Continuous n=1	11.9-13.7 s

Chain n = 4, 3, 2 13.8-14.0 s
n = 1 @ 14.1 s (hollow Te)

DT scenario with optimized non-thermal fusion

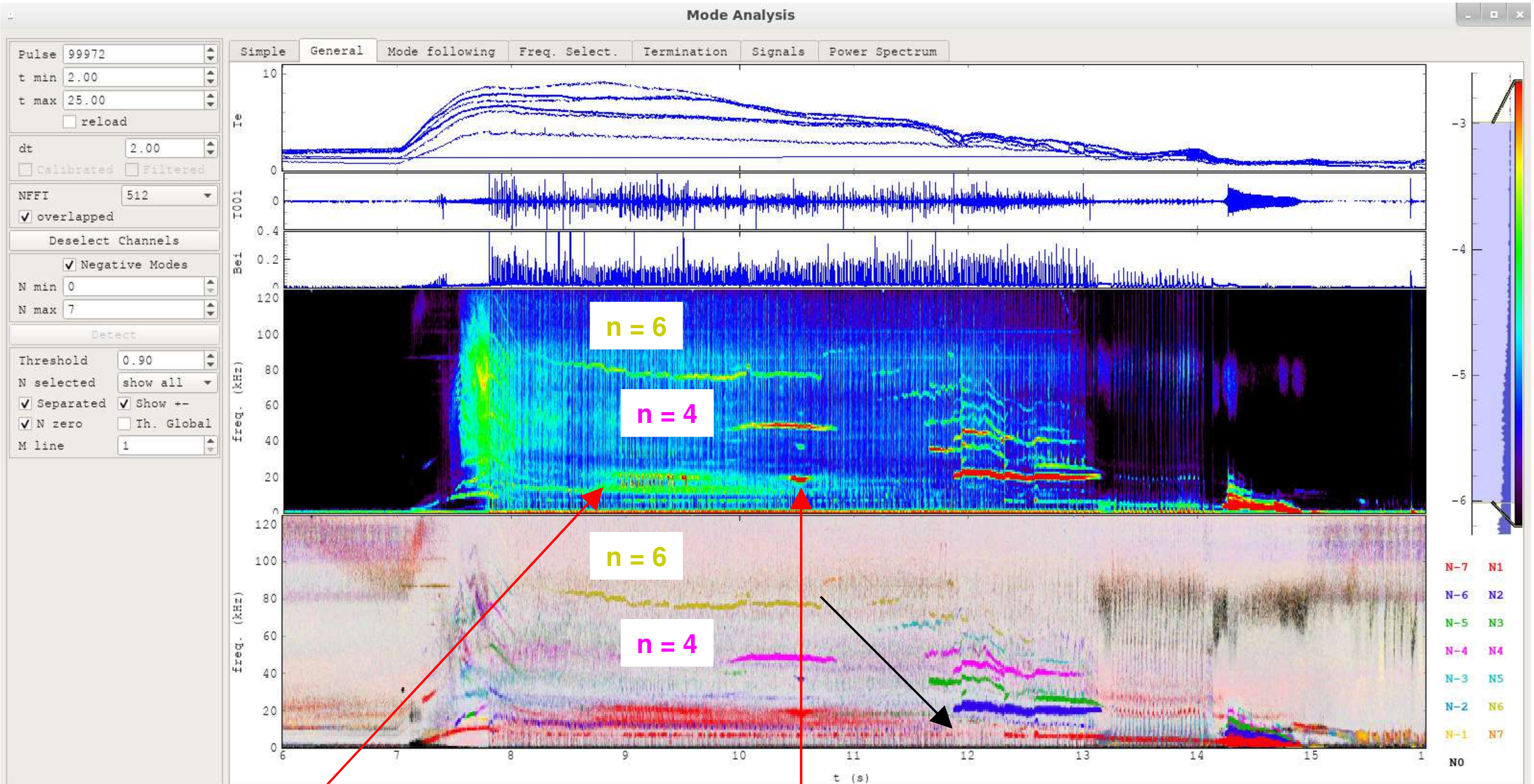
JPN 99971: fishbone vs. continuous mode



Character of the **n = 1** activity → fishbone for “peaked” profile → continuous mode for more “flat” profile

DT scenario with optimized non-thermal fusion

- **JPN 99972: MHD activity**



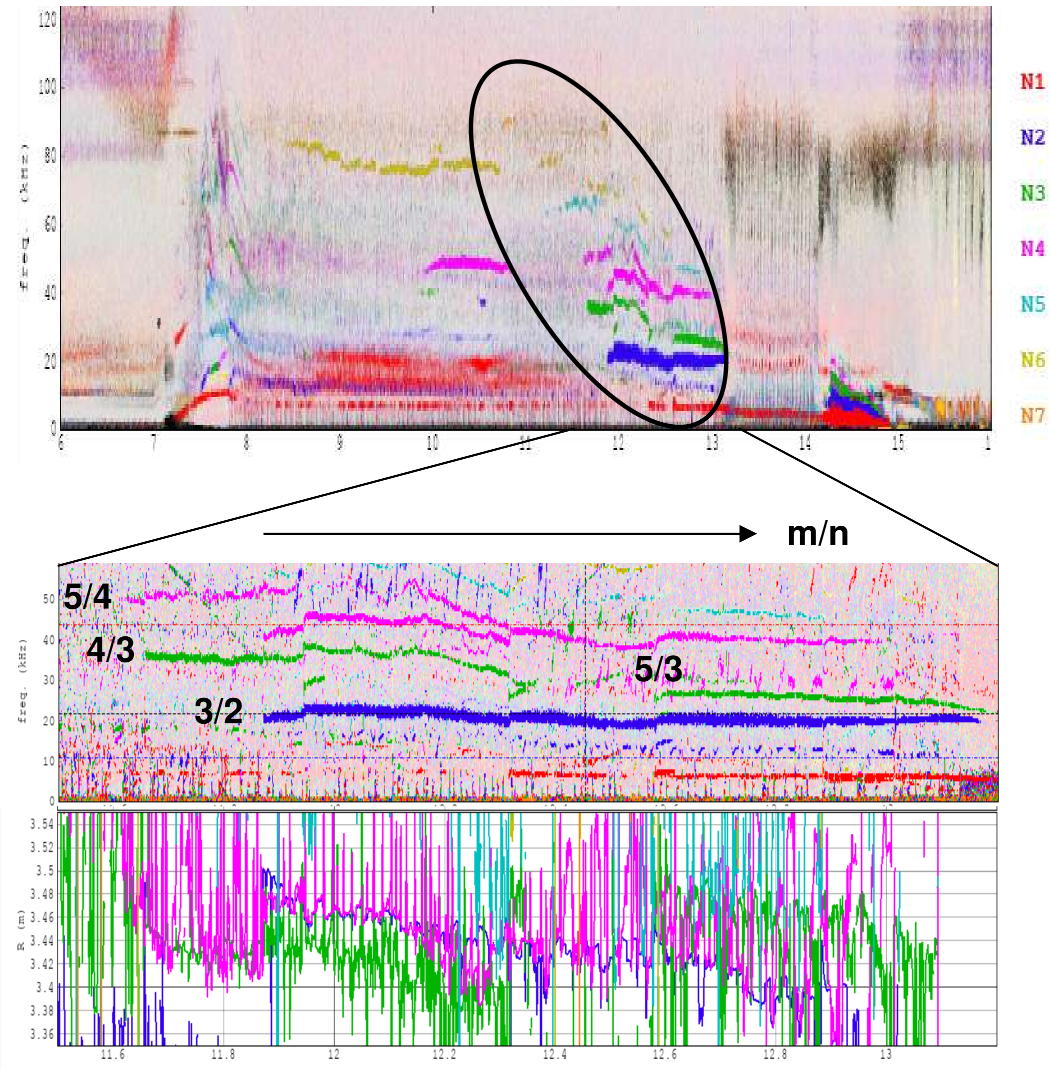
Fishbones

Continuous n=1

Chain n = 7, 6, 5, 4, 3, 2   10.7-11.9 s
n = 1   @ 14.3 s (hollow Te)

DT scenario with optimized non-thermal fusion

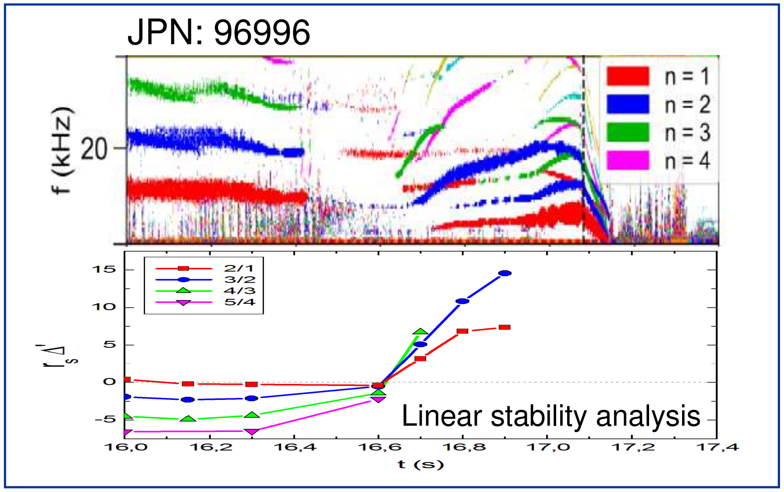
- **JPN 99972: sequence of Tearing Modes**



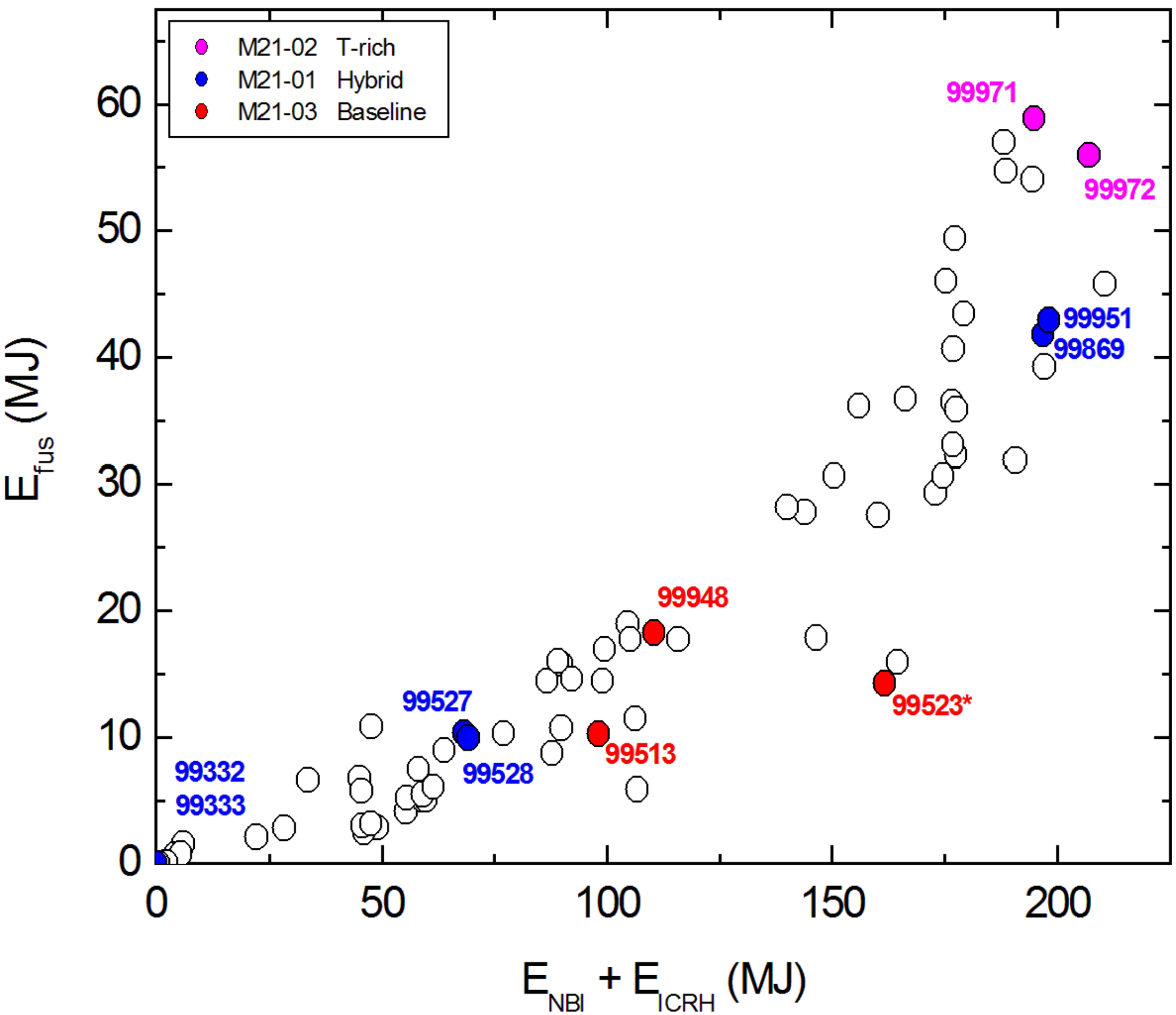
Destabilization from inside:

n = 7 → 6 → 5 → 4 → 3 → 2 → …

- Hollowing of the temperature profile
- Broadening of the current density profile
- Higher gradient near the mode resonant surfaces



Conclusions



Baseline scenario

- High-n tearing modes for higher NBI power, triggered by long period sawtooth crashes
- Heavy impurities accumulated in the low field side, limiting the pulse length
- Possibility of higher performances with neon injection (*) to be deeply investigated

Hybrid scenario

- Systematic investigation to reduce the risk of DTM and optimize the shape of the q-profile
- Early destabilization of spontaneous 3/2 TM in pulses with high β_N and low l_i
- Different character of n=1 activity: fishbone and continuous mode
- Chain of TM associated with core impurity accumulation