MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

# Entry to and exit from ELM suppressed H-mode in detached conditions

ASDEX Upgrade

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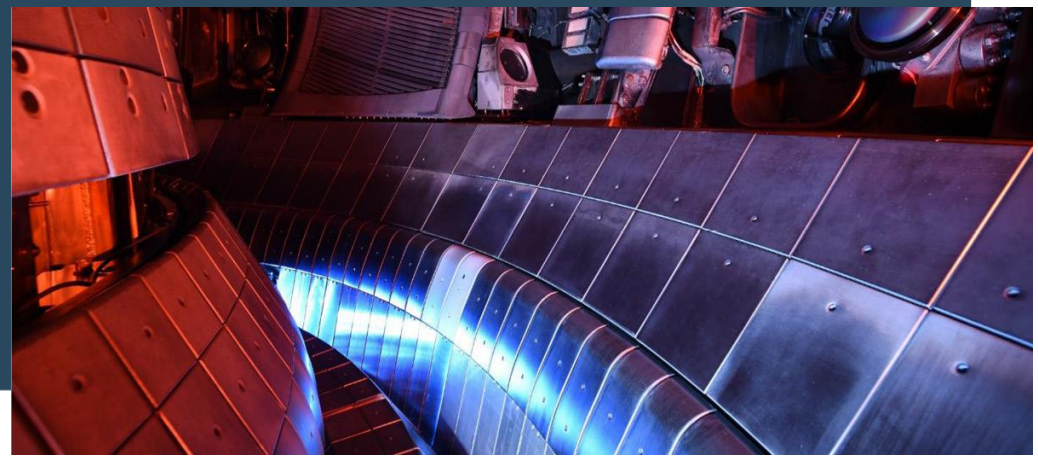

EUROfusion

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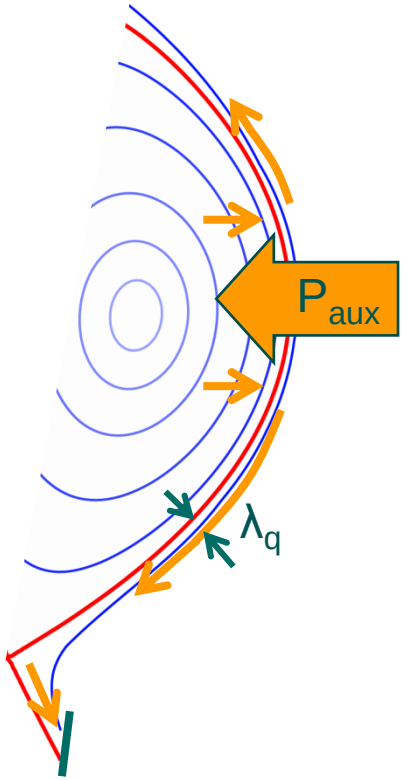
# Motivation

- Detachment mandatory for power exhaust in DEMO
  - Steady state solutions exist
- Also the ramp up must be detached

$\lambda_q \searrow$

  - This includes power ramp up and the LH transition

$\Delta P_{heat}$ $\partial W_{MHD}/_{\partial t}$




Can all these changes be balanced avoiding a disruption?

… and we also need to remain detachment during ramp down

# Outline

- **Motivation ✓**
- **The XPR & its control**
- **Discharge 40333**
  - Path through the discharge
  - ELM suppression
- **Repeatability**
- **How about a reactor?**

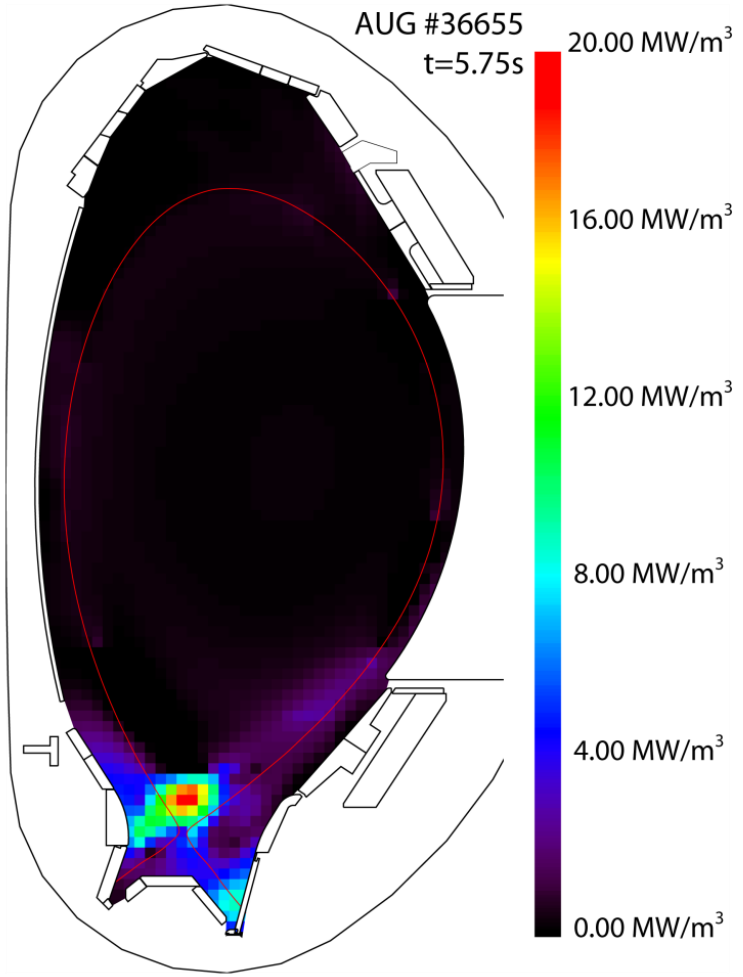
# The X-point radiation regime

With the pronounced detachment of the outer divertor, an intense, localized radiator evolves close to the X-point.

Radiated power fraction close to 100%

The X-point radiator (XPR) is:

- ➔ A stable scenario
- ➔ Existing with N or Ar seeding and at JET
- ➔ **Radiating up to 1/3 of the heating power**
- ➔ Existing in the full (high density) operational range at AUG



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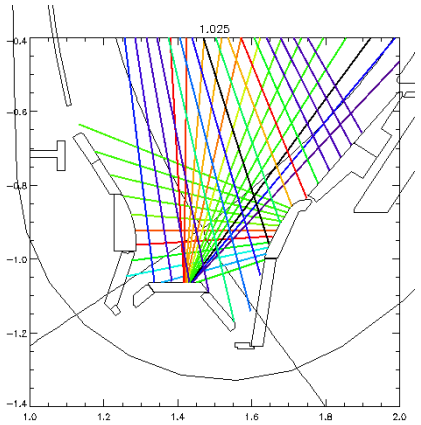
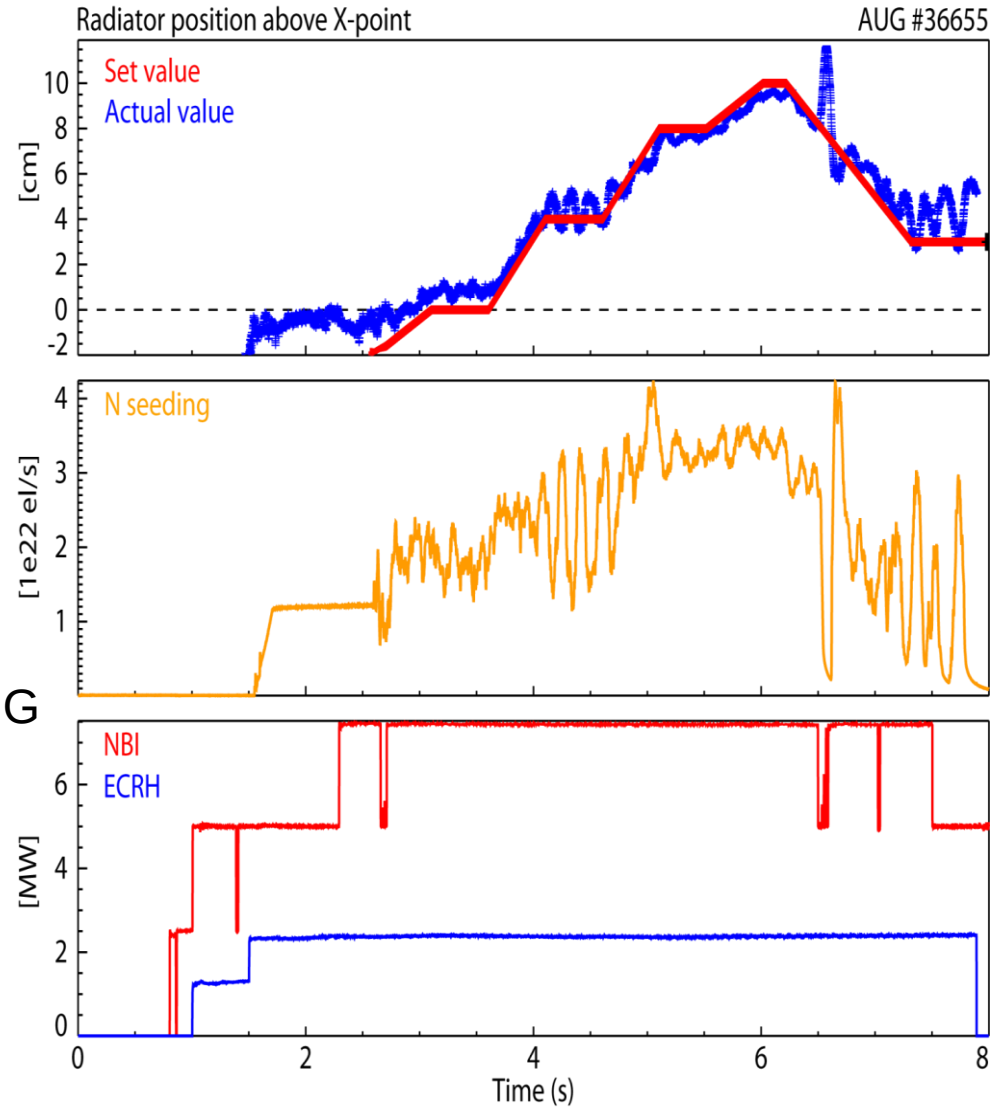
**The XPR moves into the confined region**

- **Up to 15cm above X-point**
- **Location determined by seeding level & heating power**
- **Location controlled in real-time**



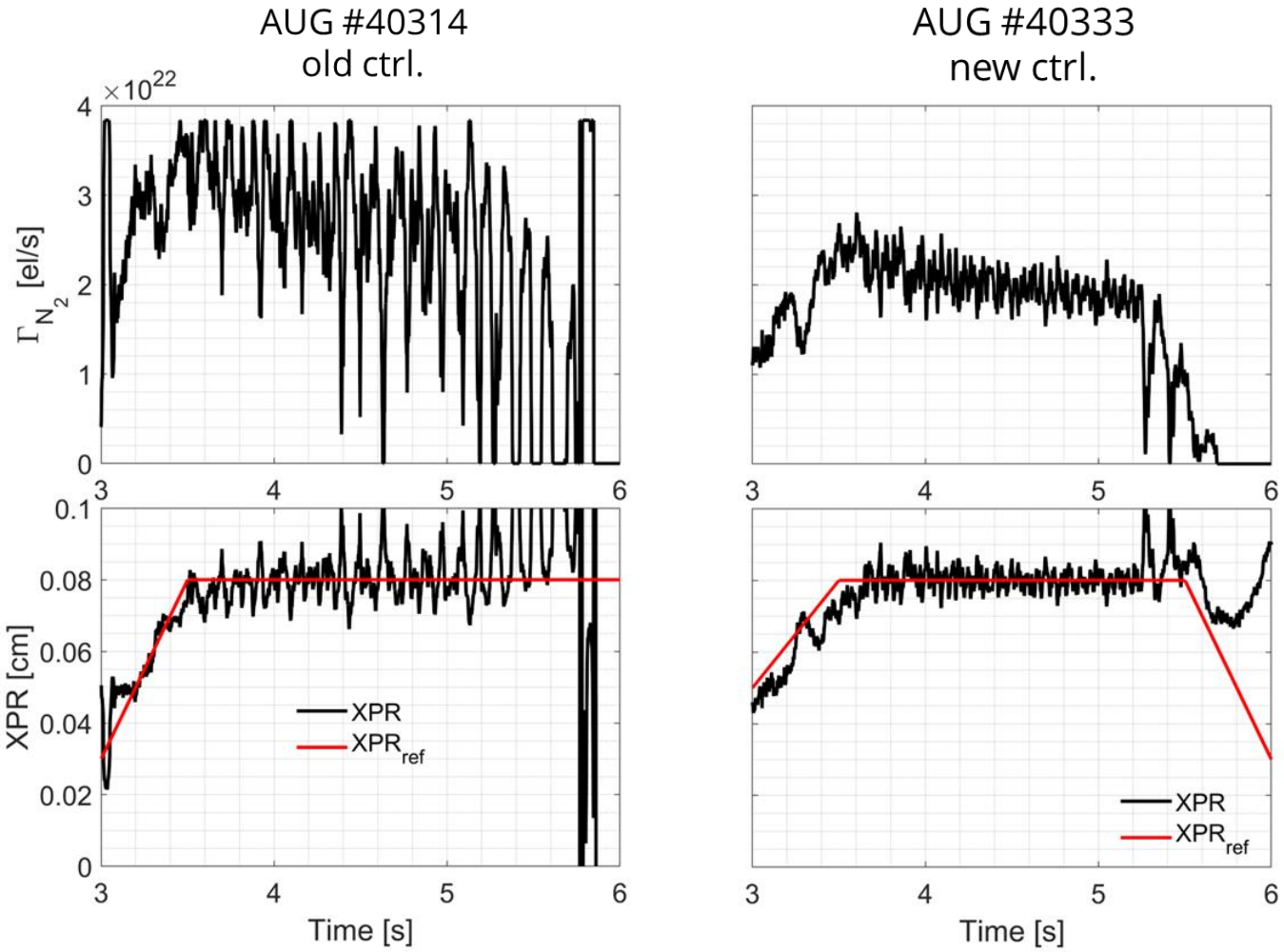


# Improved control

System identification used to improve XPR controller:

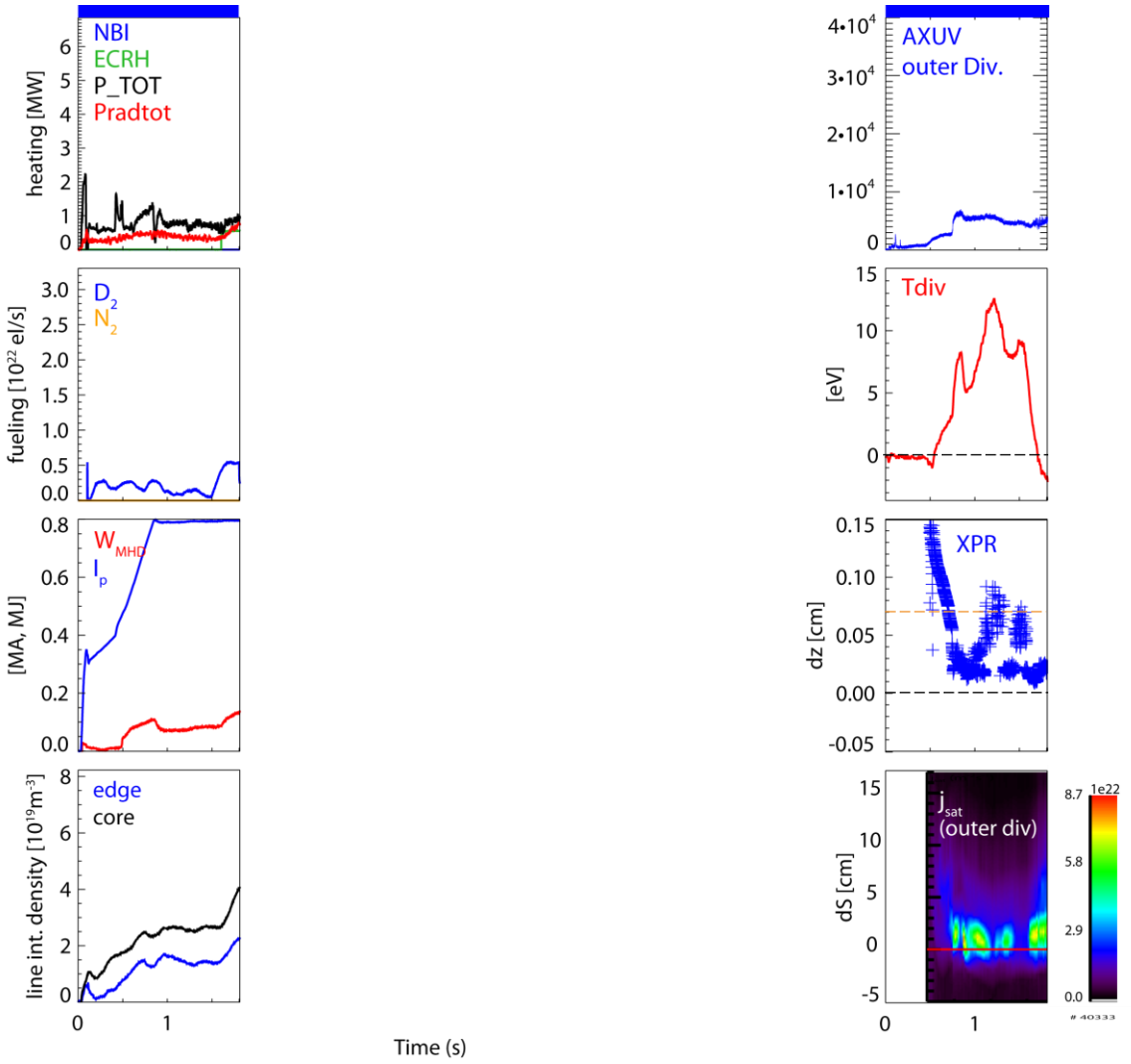
- Perturbation signal to identify response function
- Control model adjusted and gains for PI controller optimized

→ **Much better performance, also for low power**



# Discharge 40333

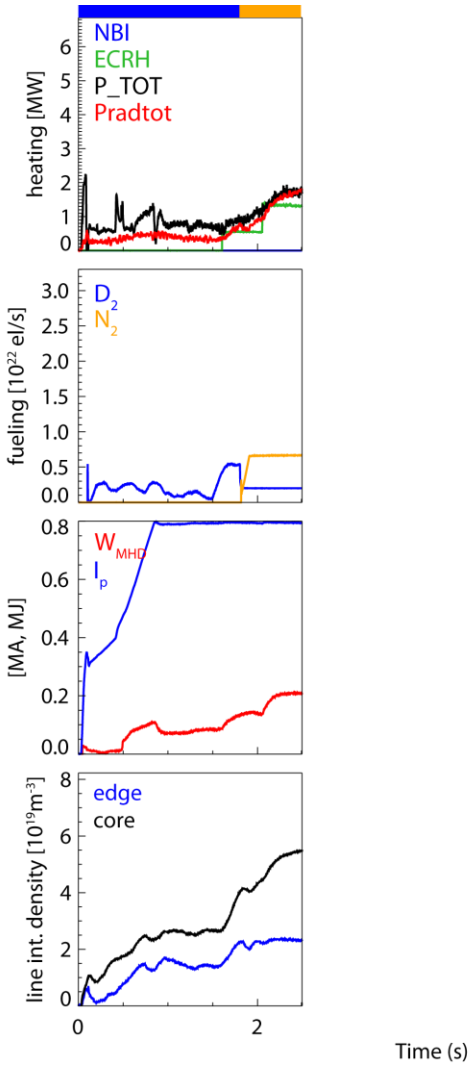
- Long L-mode reference phase:
  - Avoid LH transition before seeding

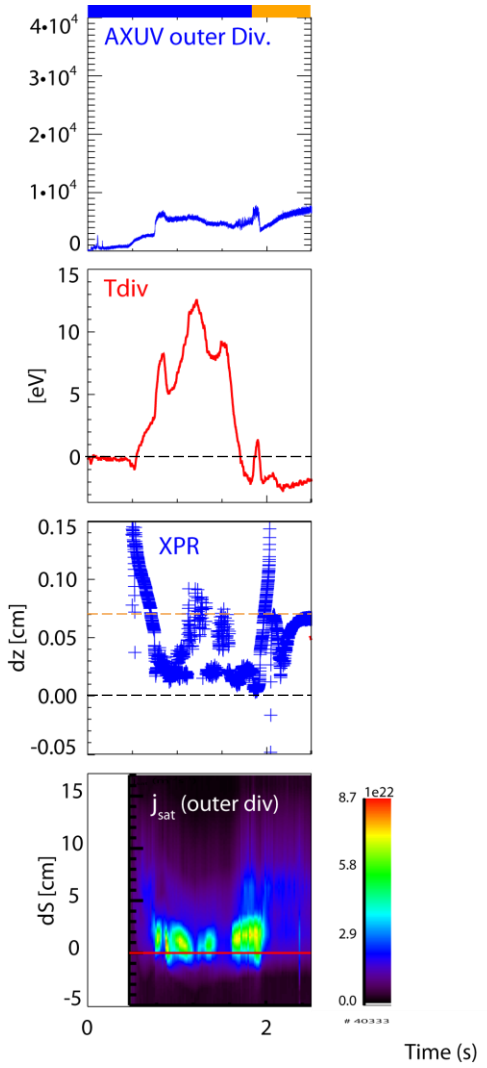


# Discharge 40333

- Long L-mode reference phase ✓
- Feed forward seeding of $N_2$:
  - Create XPR
  - Values based on reference discharge
  - Avoid over-seeding
  - Increase heating
  - Avoid H-mode

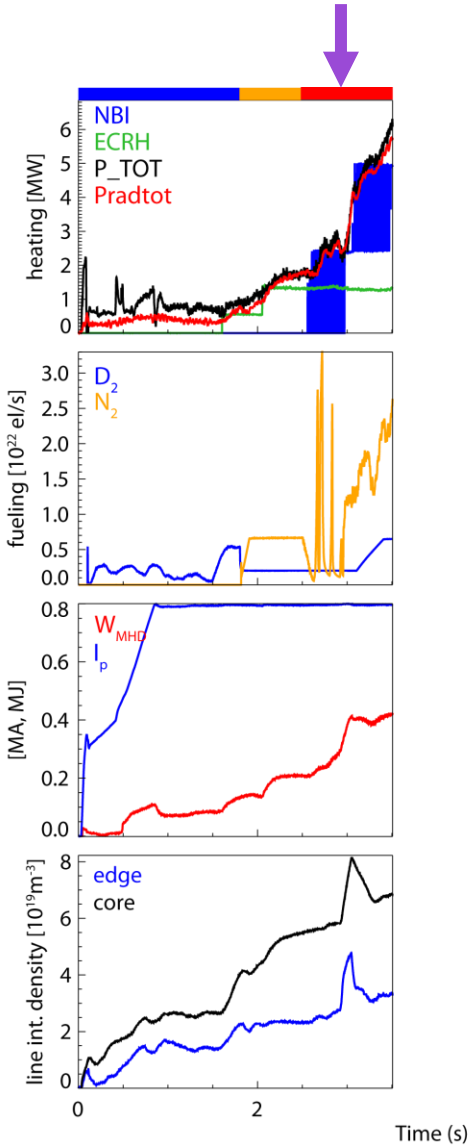
→ Required several tries to create & stabilize XPR in L-mode (5 shots)

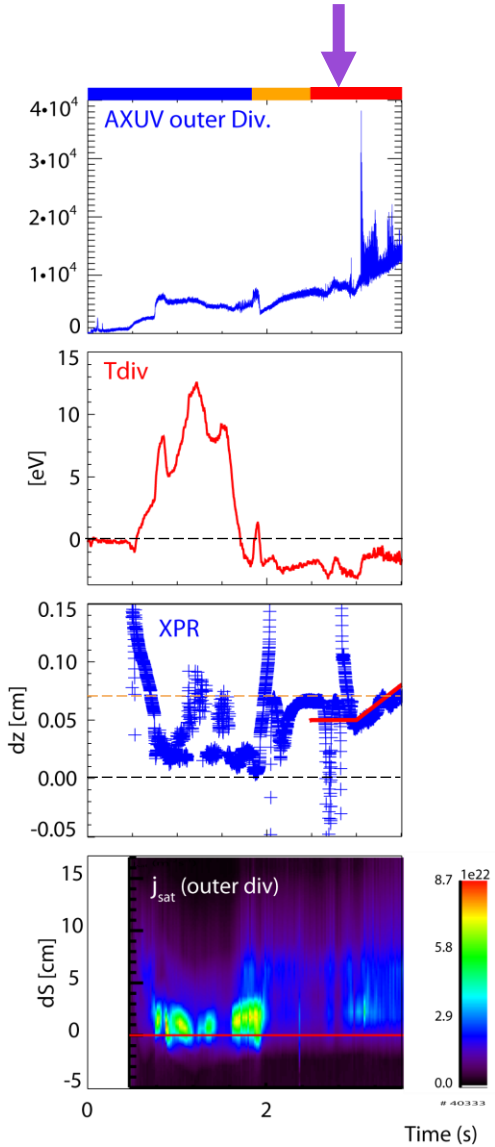


# Discharge 40333

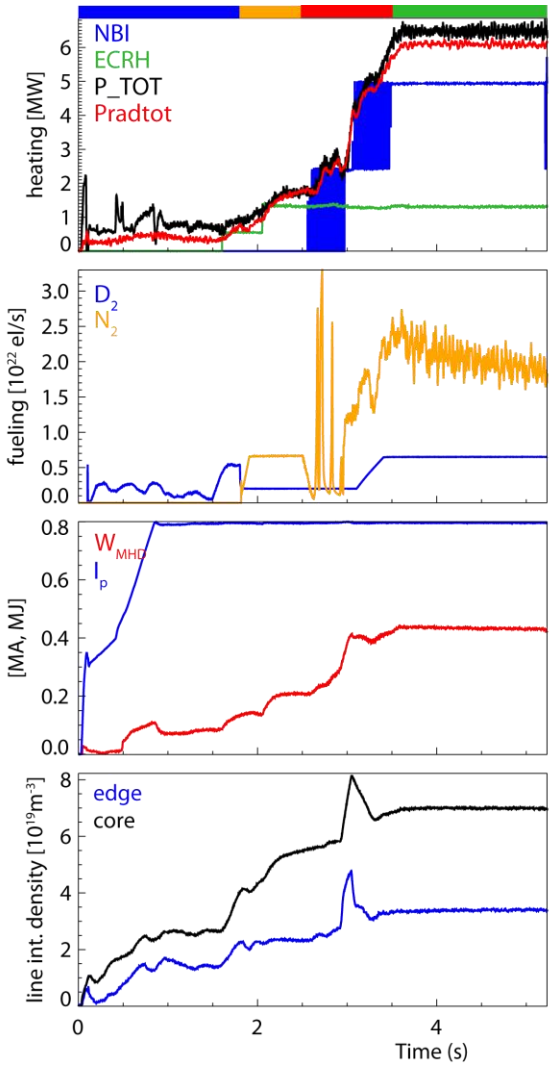
- Long L-mode reference phase ✓
- Feed forward seeding of $N_2$ ✓
- Activate XPR feedback and ramp power:
  - L-H transition
  - $P_{LH} \approx 3.3$ MW
    $P_{LH,scal} \approx 2.3$ MW
    $P_{rad\ (rho<0.97)} \approx 0.7$ MW
  - Significant excursions of XPR
  - Short ELM-free phase with density increase
  - Few benign ELMs ($^{\partial W_{MHD}}/_{\partial t} < 1\%$)

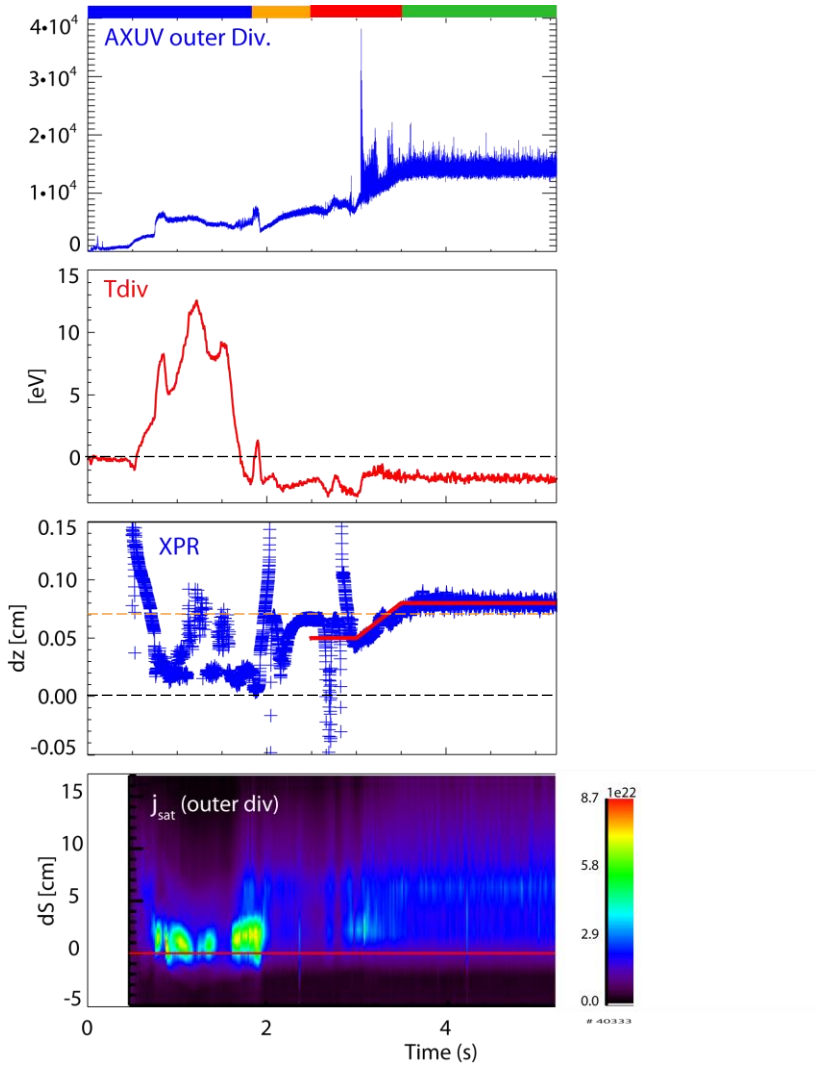


# Discharge 40333

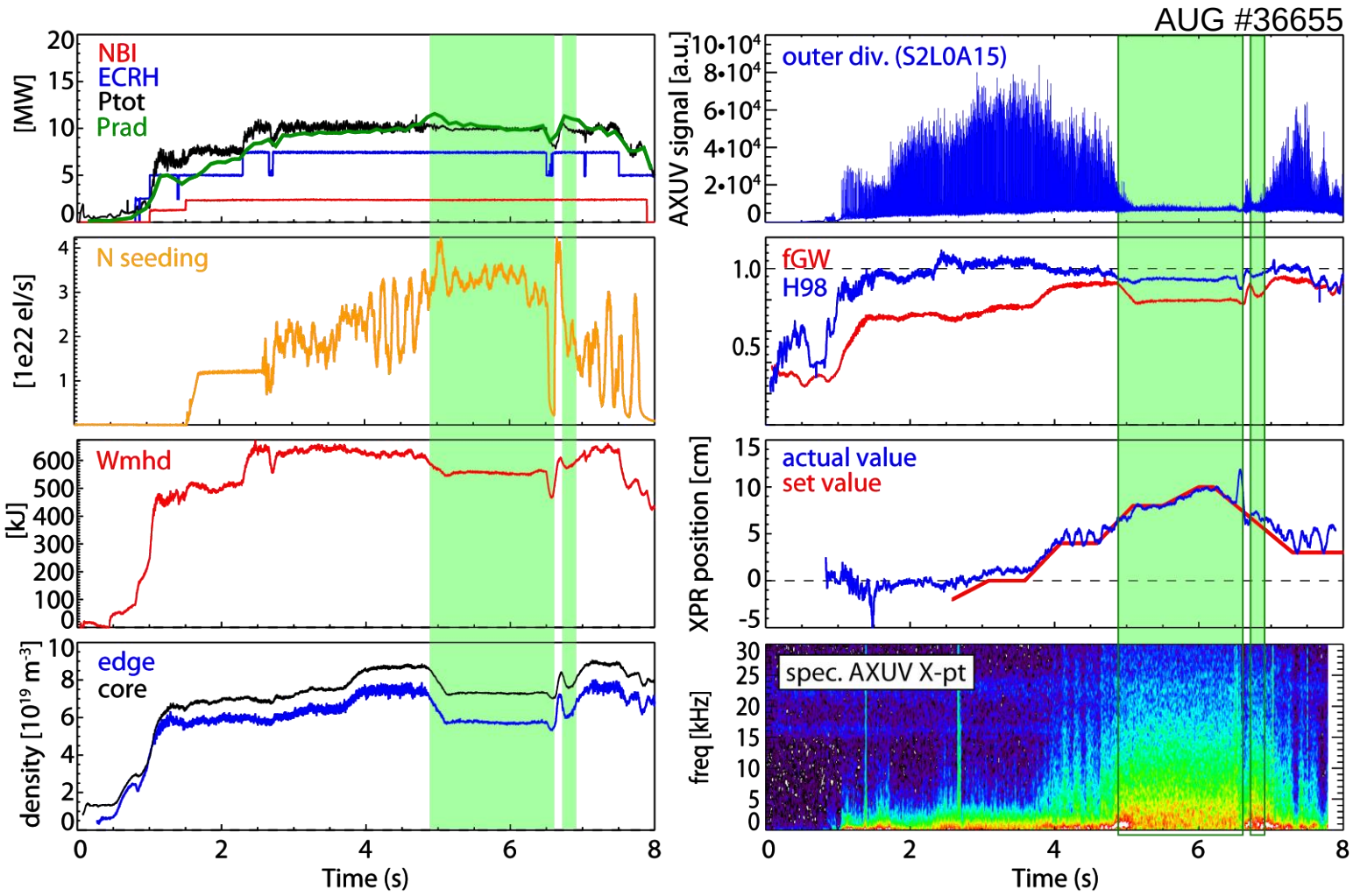
- Long L-mode reference phase ✓
- Feed forward seeding of $N_2$ ✓
- Activate XPR feedback and ramp power ✓
- ELM suppressed H-mode:



# Interlude: XPR ELM suppression

- Sudden change of characteristics:
  - + No clear ELM signature
    - → ELMs suppressed
  - - Density reduced by 15%
  - - $W_{MHD}$ reduced by ~10%
  - + Increased divertor neutral compression
  - + Reduced W content
- $H_{98} \approx 0.95$, $f_{GW} \approx 0.8$
- Characteristics between L- & H-mode:
  - $E_r$-well depth
  - Filament characteristics



# Interlude: XPR ELM suppression

- Observed at heating powers of 2-17.5MW
- Access condition:

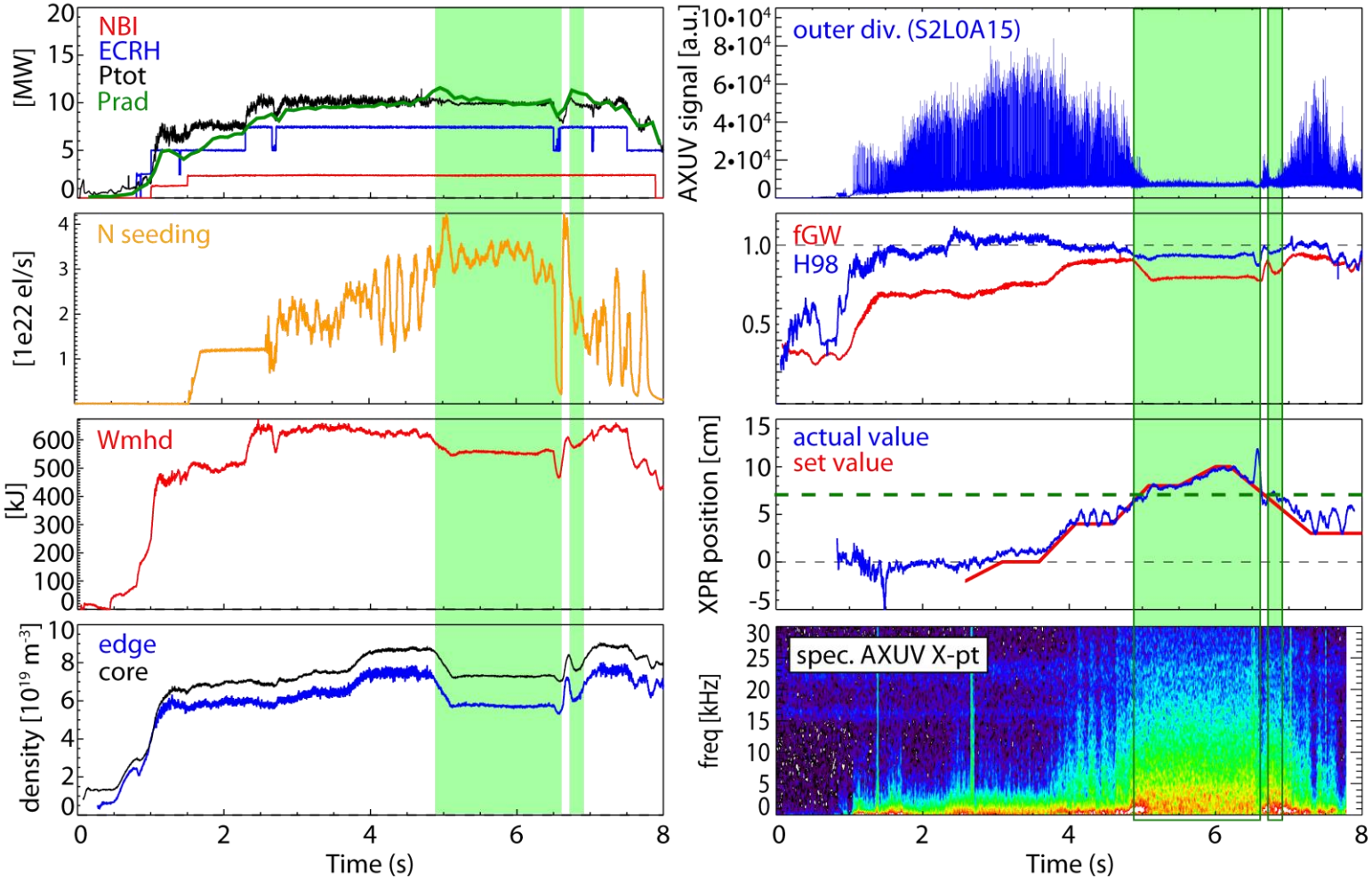
  **$dz_{XPR}$ > 7 cm**

  $dR_{midplane} \approx 2mm$

- Reduction in density and confinement reproduced
- N concentration between 2-4%

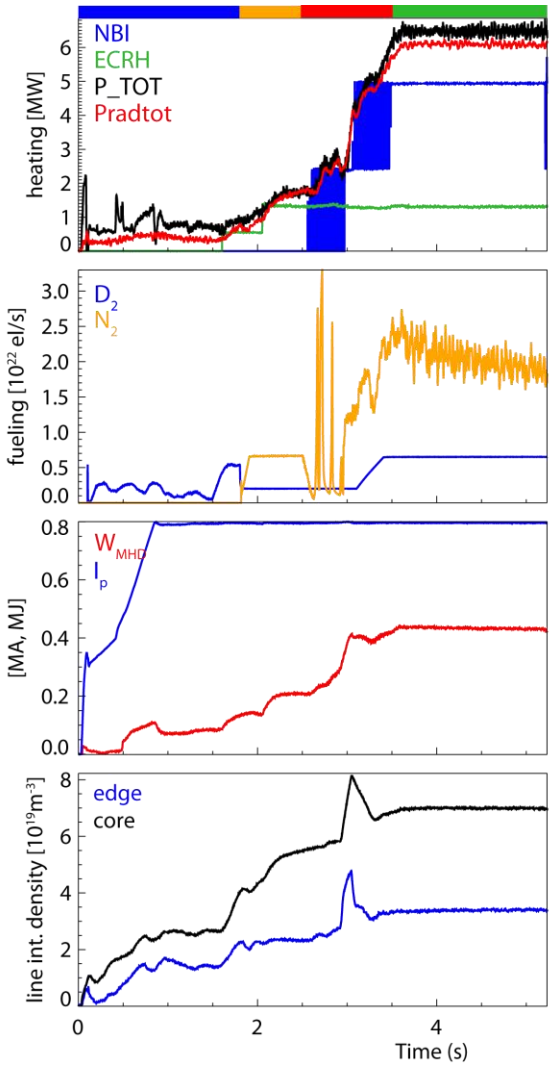
- Increase of fluctuation levels of radiation at XPR

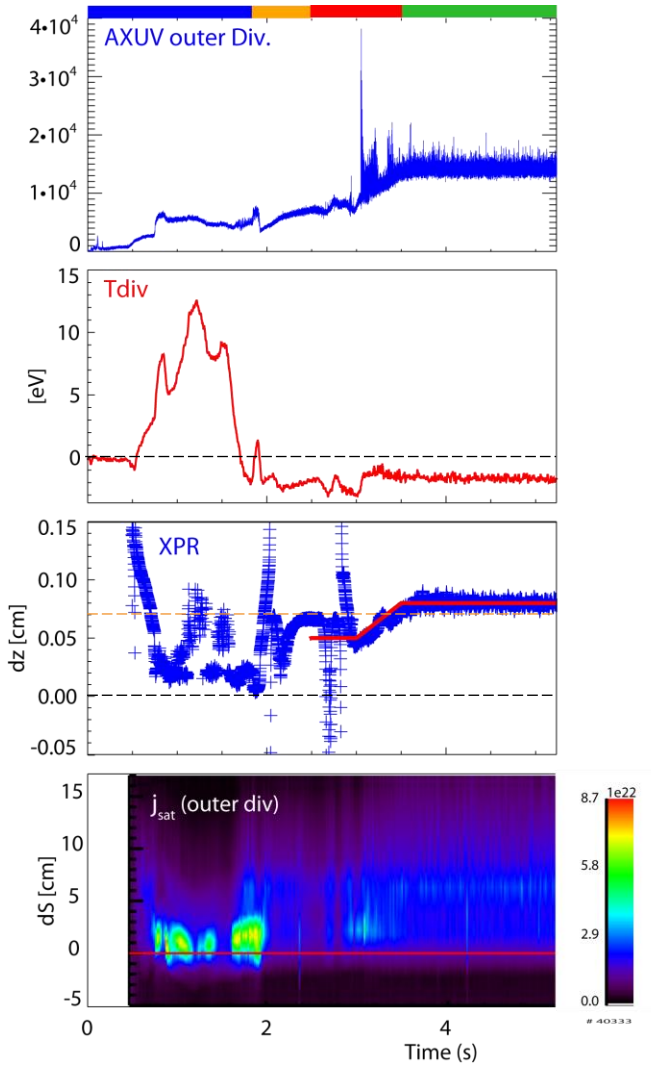
  → **new energy loss channel suppressing ELMs?**



# Discharge 40333

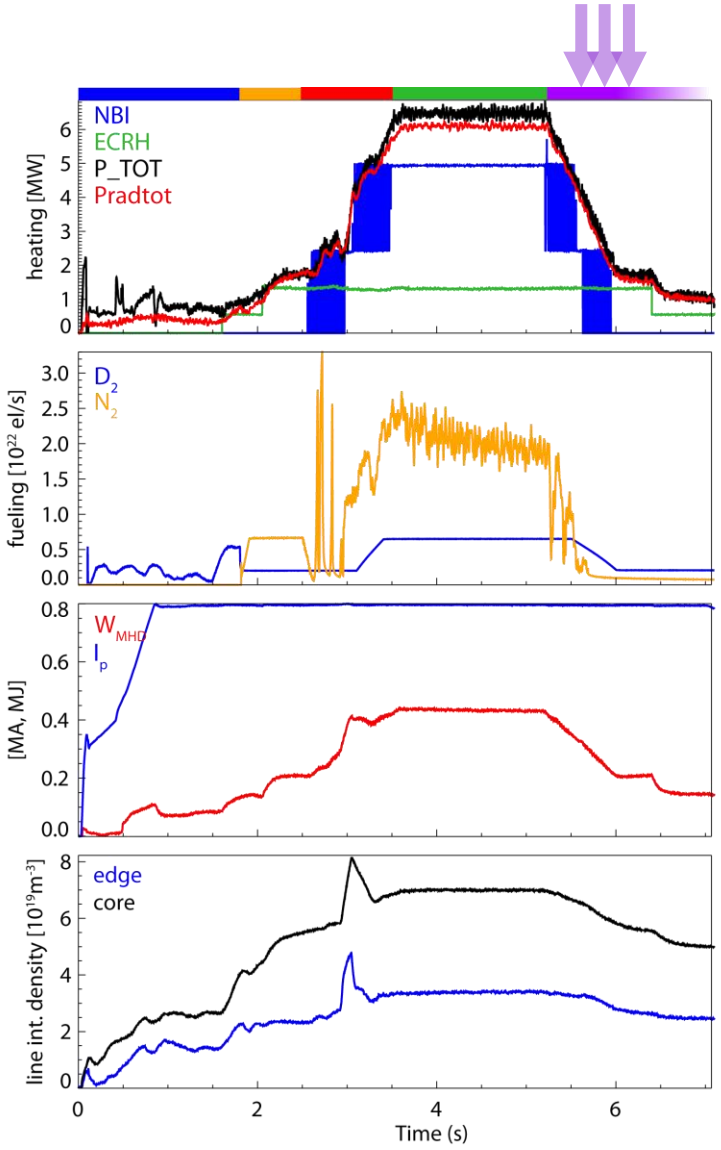
- Long L-mode reference phase ✓
- Feed forward seeding of $N_2$ ✓
- Activate XPR feedback and ramp power ✓
- ELM suppressed H-mode:
  - XPR request above 8cm
  - $H_{98} \approx 0.92$, $f_{GW} = 0.72$
  - Flat top could be extended or altered for any program
    - Incl. $I_P$ & shape ramps?

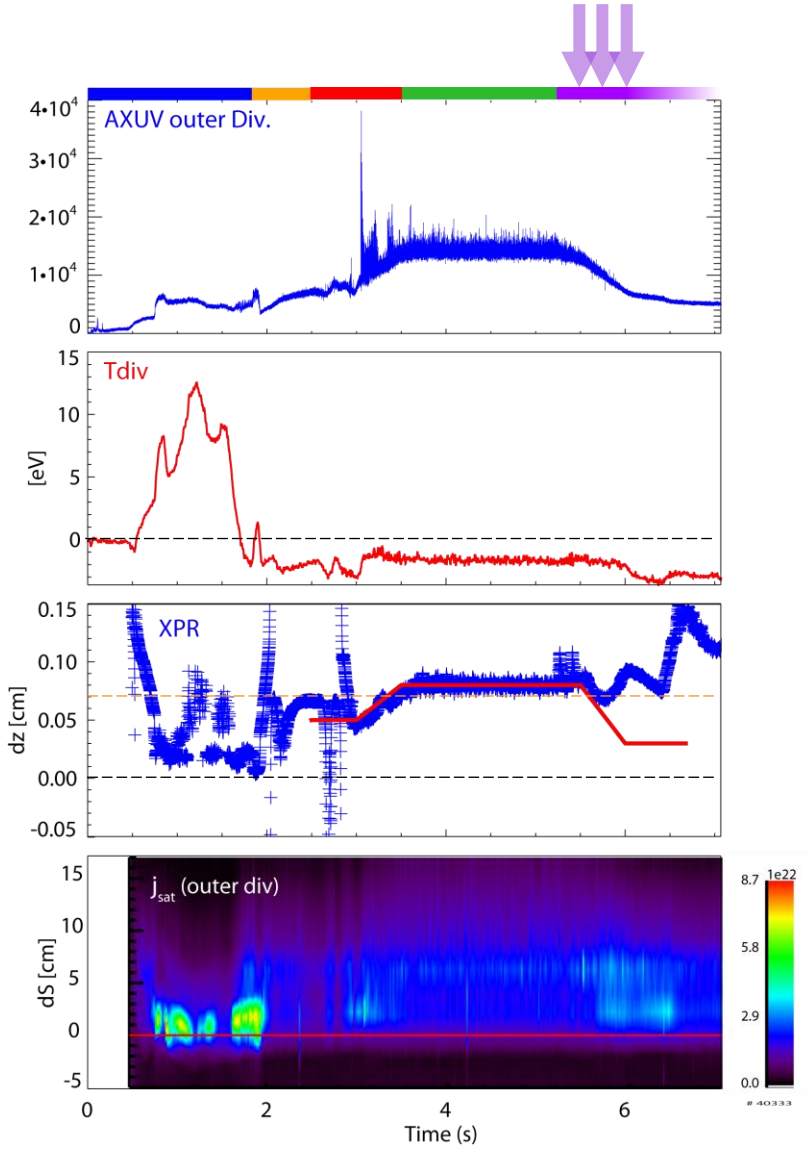


# Discharge 40333

- Long L-mode reference phase ✓
- Feed forward seeding of $N_2$ ✓
- Activate XPR feedback and ramp power ✓
- ELM suppressed H-mode ✓
- Power ramp down:
  - Slow power ramp
  - XPR control active, but limited
    - $N_2$ valves close fully
  - H-L transition not identifiable

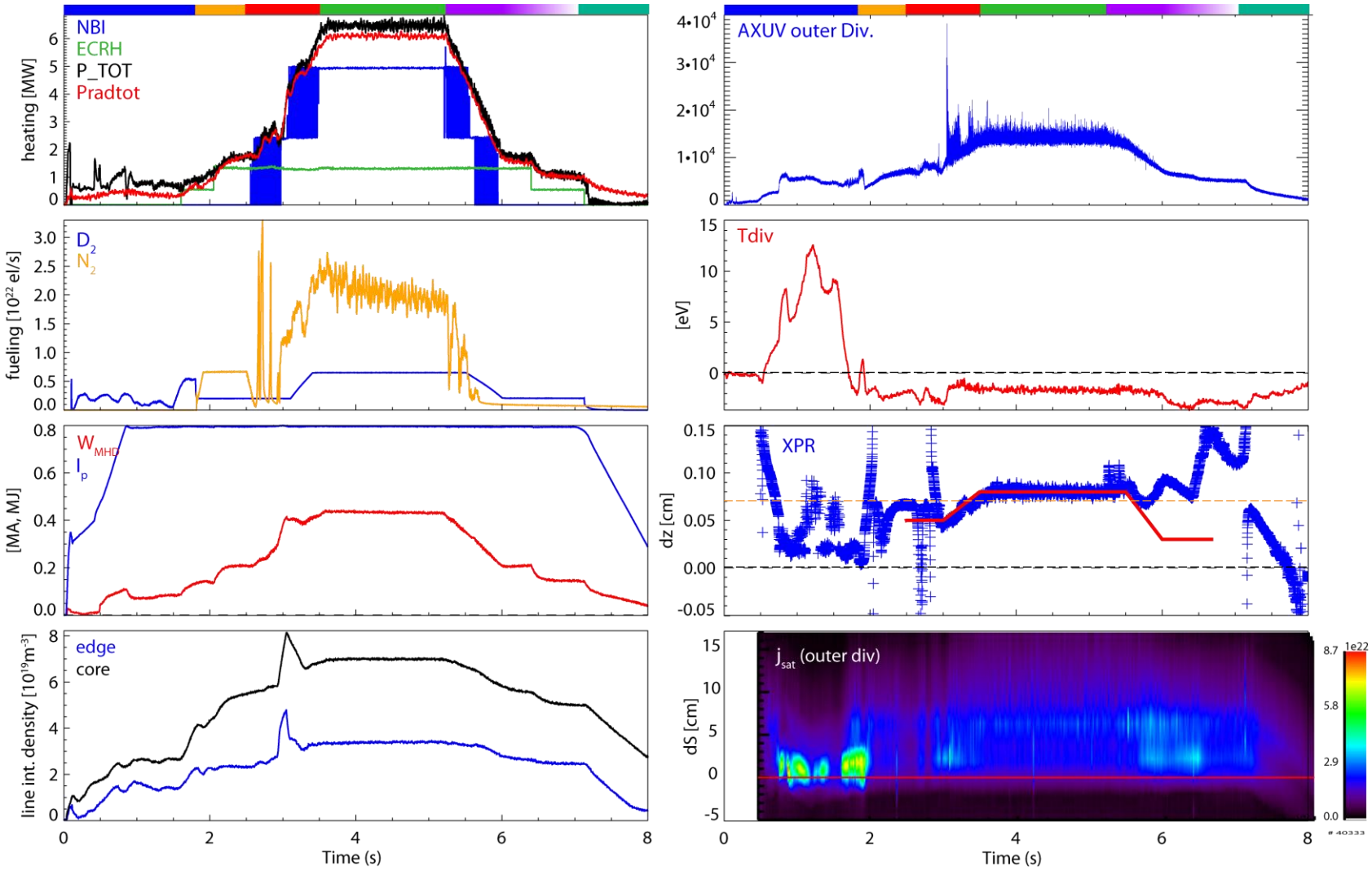


# Discharge 40333

- Long L-mode reference phase ✓
- Feed forward seeding of $N_2$ ✓
- Activate XPR feedback and ramp power ✓
- ELM suppressed H-mode ✓
- Power ramp down ✓
- Current ramp down
  - Shape ramp towards end
  - Detachment remained throughout

→ Lucky that pumping times of N are fast enough ☺



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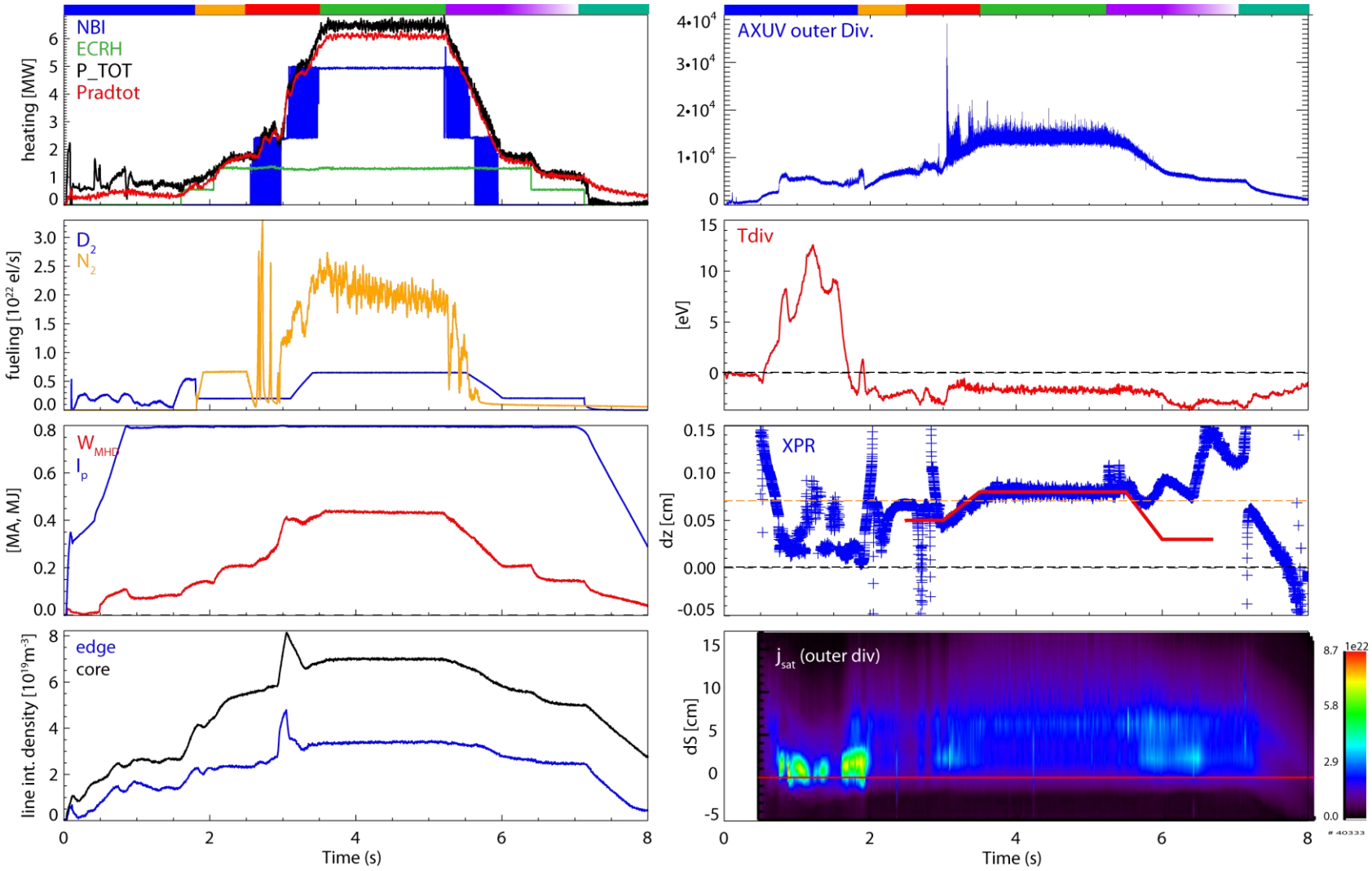
- Long L-mode reference phase ✓
- Feed forward seeding of $N_2$ ✓
- Activate XPR feedback and ramp power ✓
- ELM suppressed H-mode ✓
- Power ramp down ✓
- Current ramp down ✓



# Global parameters of the discharge

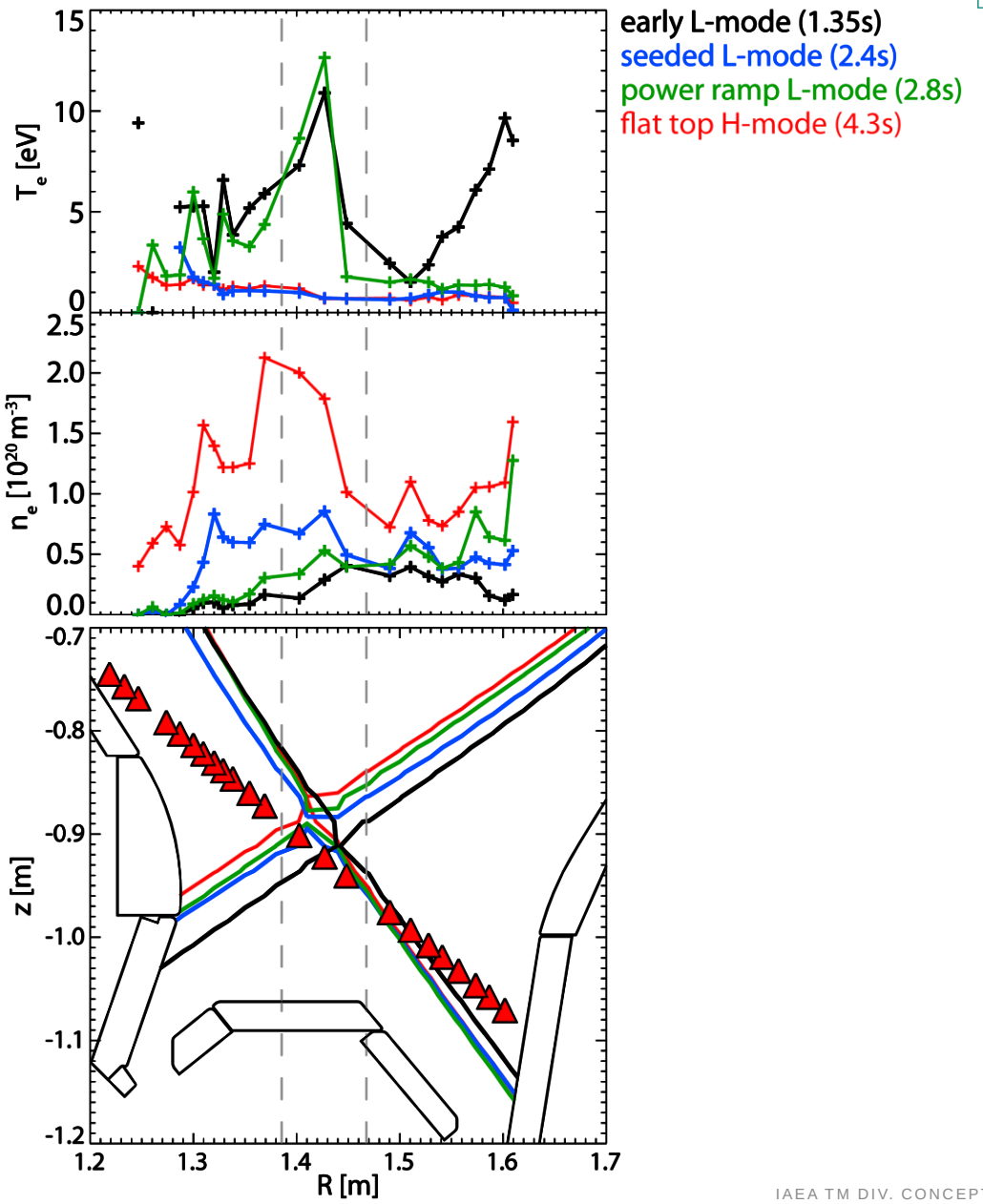
- High nitrogen concentration
  - $c_N \approx 2.5\%$ still allows ignition [Pütterich, EPS 2015]
  - Pedestal impurity transport might become better for a reactor [Dux, PSI 2016]
- Tungsten and other impurities not an issue
- High neutral compression of divertor maintained!

| | **L-mode** (2-3s) | **H-mode** (3.5-5.5s) |
|---|---|---|
| Nitrogen core concentration | 1-2 % | 3 % |
| Tungsten concentration | $< 2 \cdot 10^{-6}$ | $< 5 \cdot 10^{-6}$ |
| $Z_{eff}$ | 1.9 | 2.5 |
| Neutral compression $n_{0,div}/n_{0,main}$ | ~100 | >>100 |

# DTS measurements

Divertor Thomson scattering confirms observation:

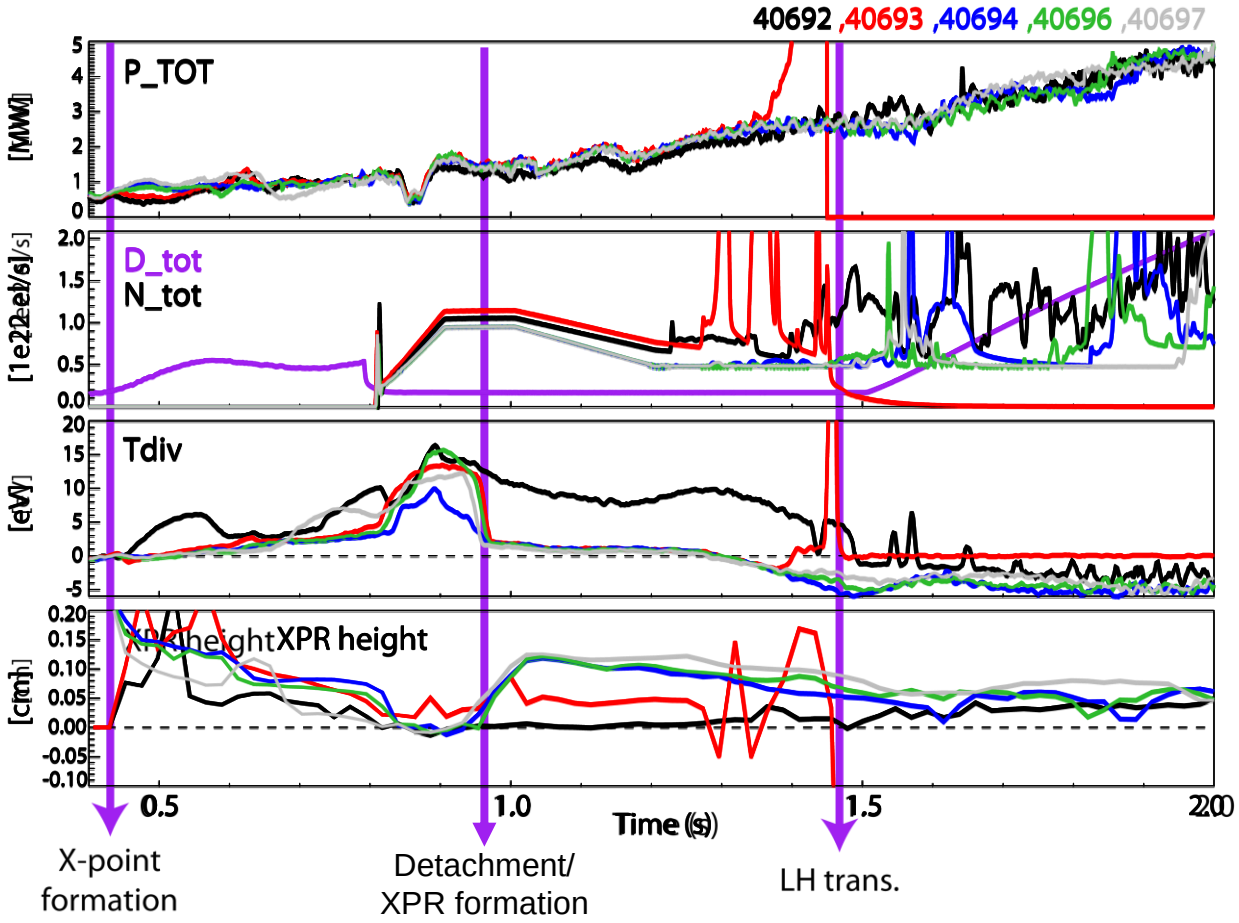
- Outer divertor remains cold with start of seeding
- Heat increase seen in PFR & inner divertor
- Whole divertor remains below 2eV in H-mode



# Reproducibility

- Reproducible in other scenarios (5 shots)
- N2 FF seeding has to be adapted to machine/wall conditions

- Further work for fully automated detached L-H transition possible, but necessary?
- Ramp up combinable with other scenarios (if they tolerate some N2 present)
  - $H_{98}$≈1 achievable



# Possible improvements at AUG

Slow access to H-mode
Only small optimization possible, ramp-up takes at least 2s

Ramp up fully controlled
Requires further development for the controller

Your input?!

Fixed seeding & fueling
More flexibility would require many more experiments

Avoiding first ELMs
To be tested

Detachment access during $I_P$ ramp
Reactor-like ramp up experiments might be possible, but costly

# How about a reactor?

Detachment control during $I_P$ & $P_{heat}$ ramp up
- After limiter phase
- Required start point defined by:

  $\lambda_q$, $P_{SOL}$ → Material limit (10-20 MW/m² cw)
- Potentially after LH transition?

Do the time scales allow an active control?
- Time dependent full scale simulations required
- (virtual) System identification powerful tool for preparation

Reduced Sensors
- XPR radiates >>100MW
  → easy to detect ☺
- Redundancy essential

After L-H transition
- Does $\partial W_{MHD}/\partial t$ or $\Delta P_{heat}$ dominate detachment behaviour?

  → use AUG for investigations, XPR position as very sensitive sensor

Many more aspects of reactor ramp up not covered here

# Summary

- **First demonstration of detached L-H transition**

  **→ physical possibility proven**

- Detachment maintained throughout whole discharge
- X-point radiator buffers power transients
- ELM suppression can directly be accessed

➔ Possible ramp up solution for a reactor

What can we learn for ITER and future reactors with nowadays machines?