X-point radiation and detachment control at ASDEX Upgrade

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See author lists of [6]B. Labit et al 2019 Nucl. Fusion 59 086020 and [7]H. Meyer et al 2019 Nucl. Fusion 59 112014

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Overview

1. **The X-point radiation regime**

2. **Real-time control of the radiator position**

   - An ELM-mitigated scenario

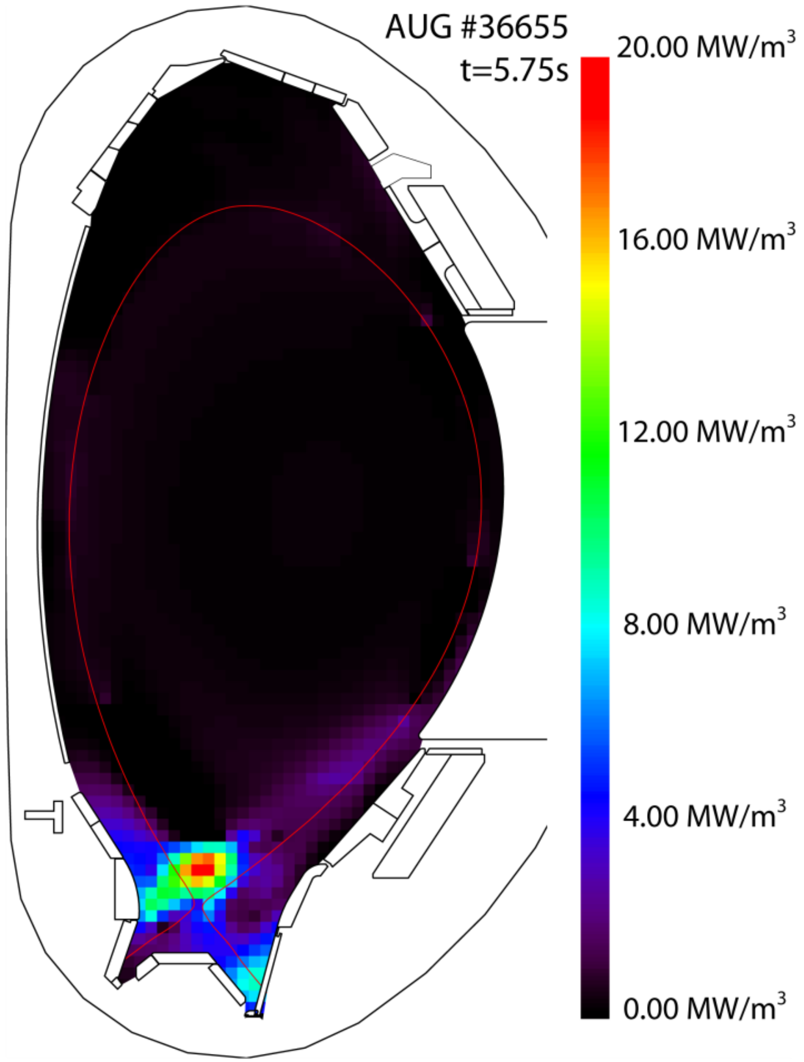
3. **Other Control at AUG, TCV & DIII-D**

4. **Feasibility for future reactors?**

5. **Summary**

The X-point radiation regime

- Detachment in metal machines achieved with seeding
- With the pronounced detachment of the outer divertor, an intense, localized radiator evolves close to the X-point.
- Most likely radiation condensation (MARFE-like)
- Radiated power fraction close to 100%



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- X-point radiation is:

➔ Stable scenario

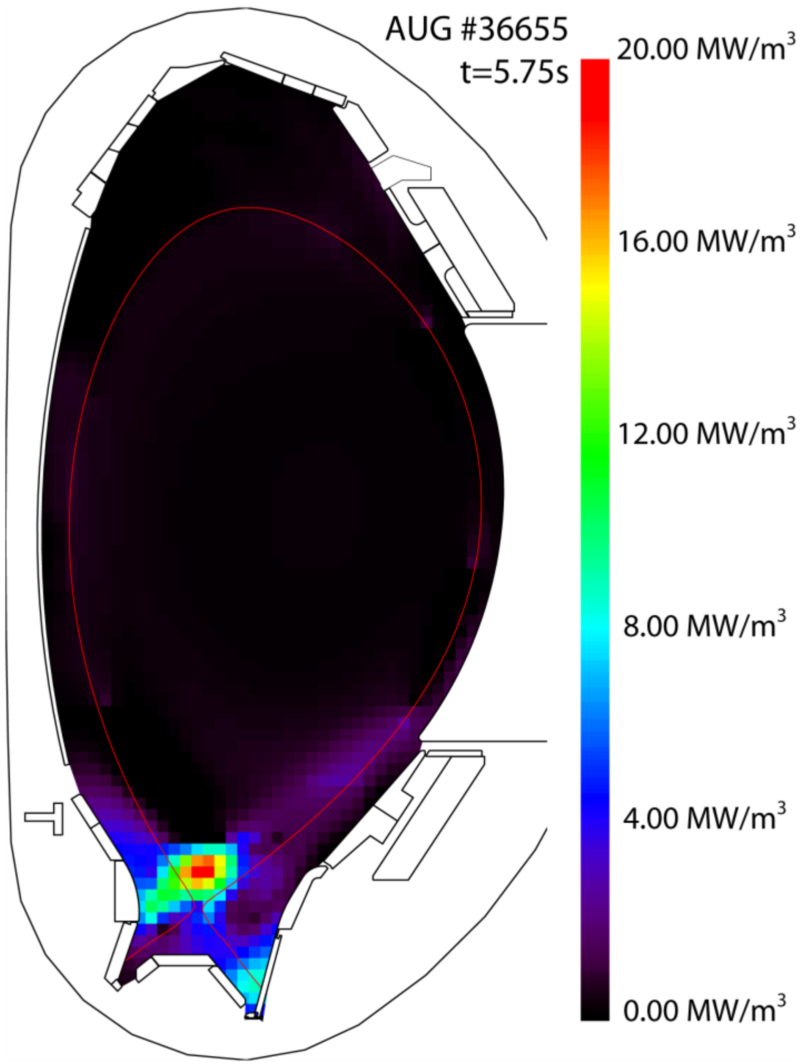
➔ Existing with N or Ar seeding

➔ Radiates up to 1/3 of the heating power

➔ Existing in a wide range of heating power:

P_{heat} [MW] = 2.5 – 20

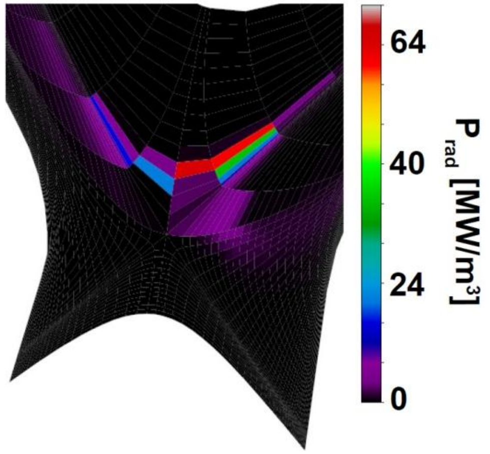
P_{heat}/P_{LH} = 1 – 5

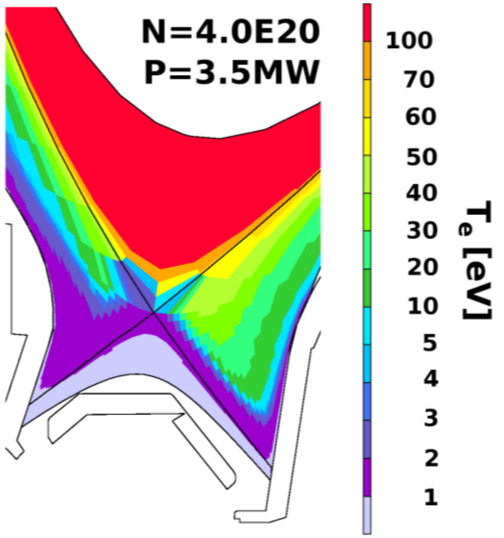


The X-point radiation regime

- Radiator reproduced by SOLPS [Reimold, NF 2015]
- Temperature reduction within confined region
  - $T_e < 5$eV
  - D line radiation observed
  - → Parallel temperature gradients inside confined region!

[F.Reimold, PSI 2014]





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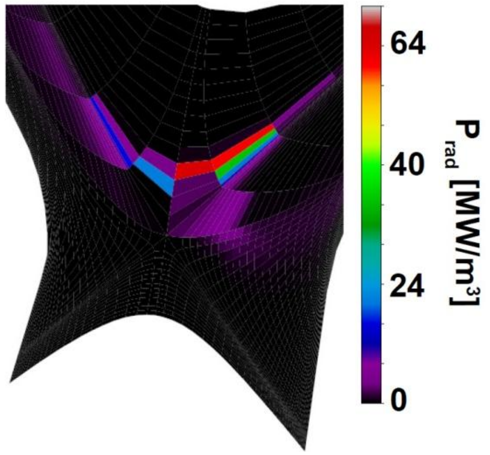
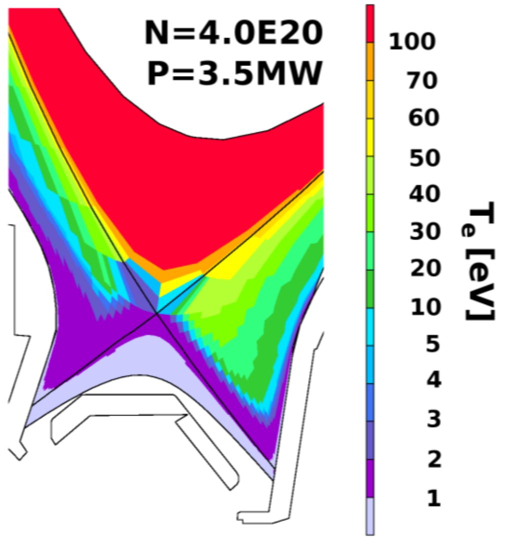
Why is it stable here?

- Highest flux expansion ↔ longest connection length to midplane
  - → Low, sustainable parallel temperature gradients
  - → Power flux driven parallel to magn. field
  - → Radiator acts as heat sink

Moves inside confined region with higher impurity concentration

[F.Reimold, PSI 2014]

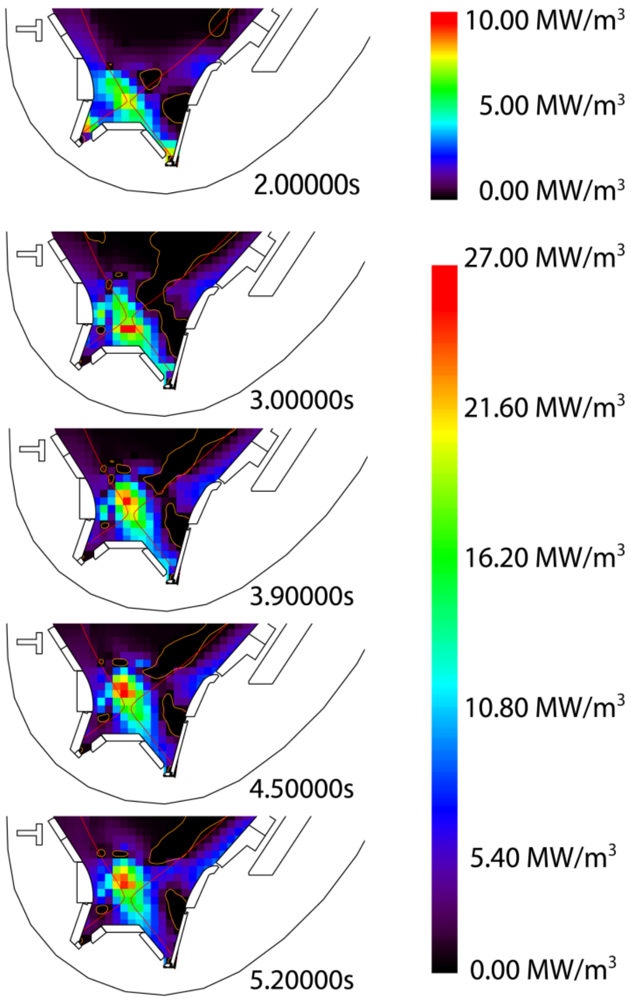




Movement of the X-Point radiation peak

Tomographic reconstruction of X-point radiation movement (#30506, N seeding)

- Radiator forms close to X-point
- Moves further inside
- Up to 15cm inside confined region ($\varrho_{pol} \approx 0.99$) observed



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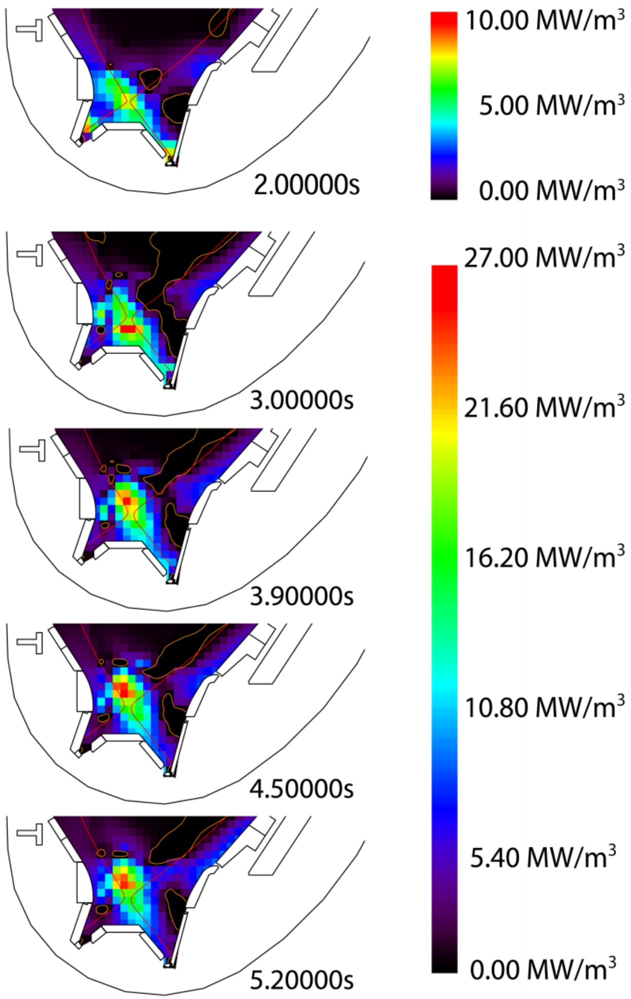
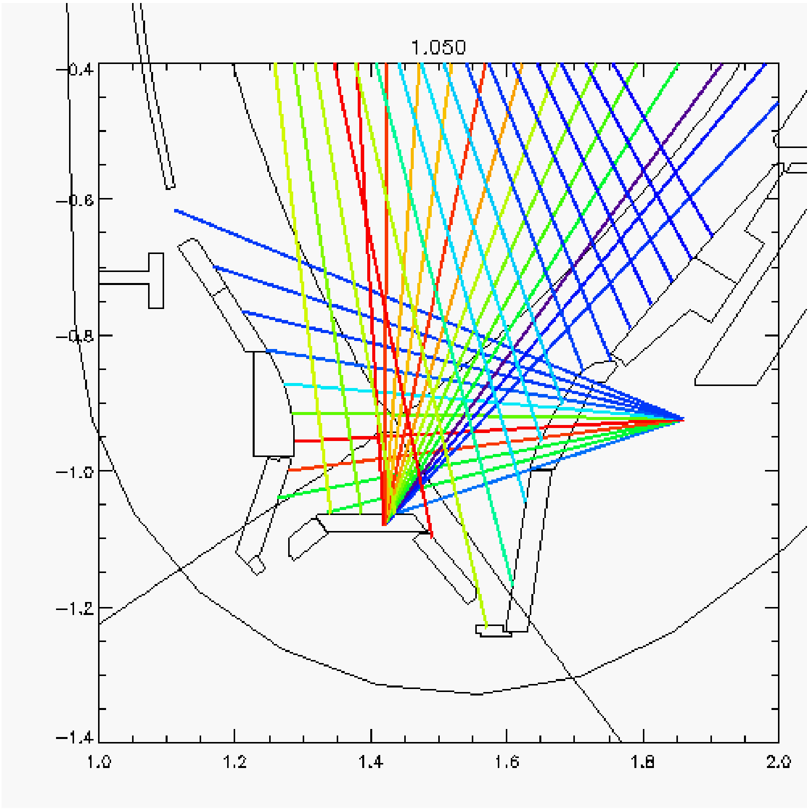
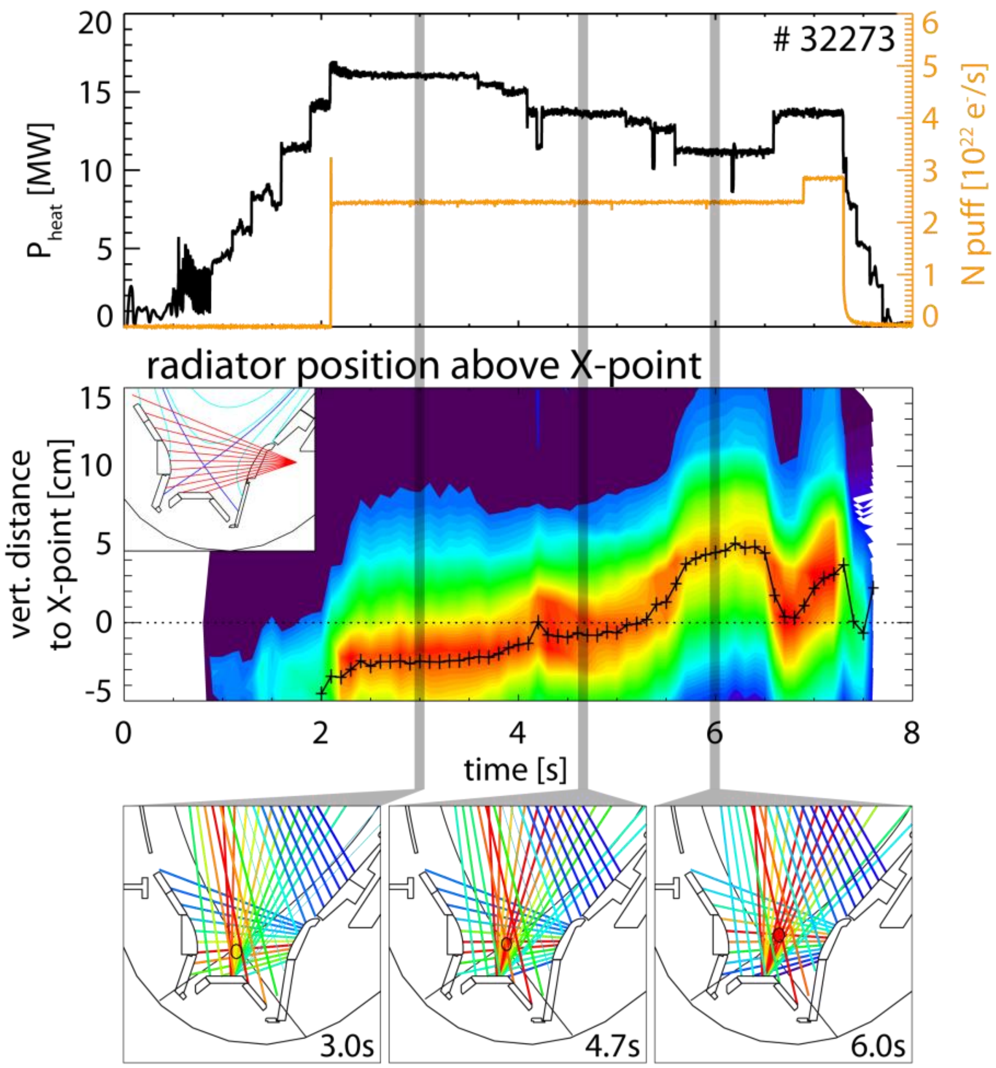


Tracking using AXUV diodes (#32273, N seeding)



Actively influencing the location

- Location can be influenced by heating power or nitrogen seeding level →



Implemented real time control

Sensor: AXUV diodes

- SIO2 real time data acquisition
- 20ms median filtered data → ELM filter

Actively influencing the location

- Location can be influenced by heating power or nitrogen seeding level

Implemented real time control

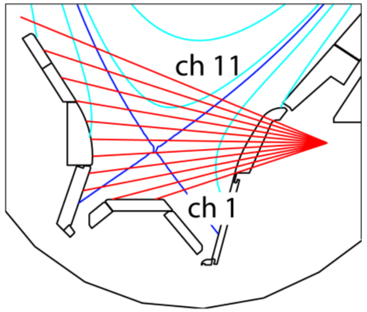
Sensor: AXUV diodes

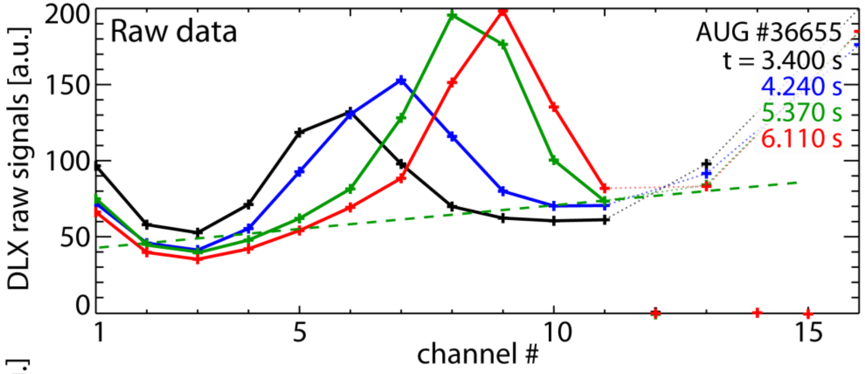
- SIO2 real time data acquisition
- 20ms median filtered data → ELM filter
- Peak detection by calculation of 1st moment →

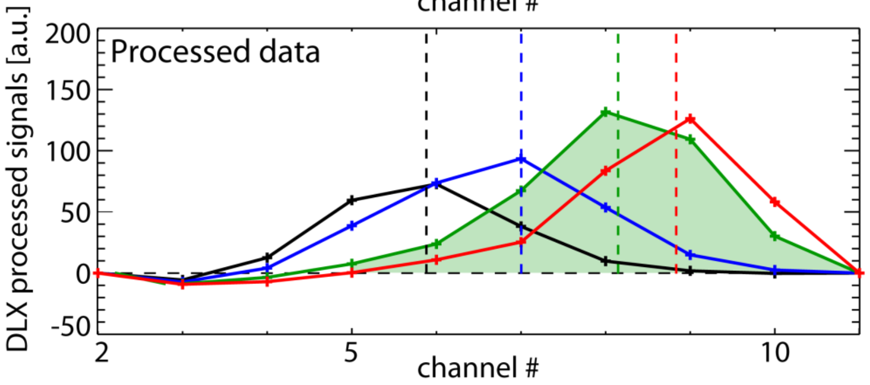
Actuator: N seeding

- PI controller
- Further possibilities: Ar seeding, Heating power

AXUV diodes, DLX camera







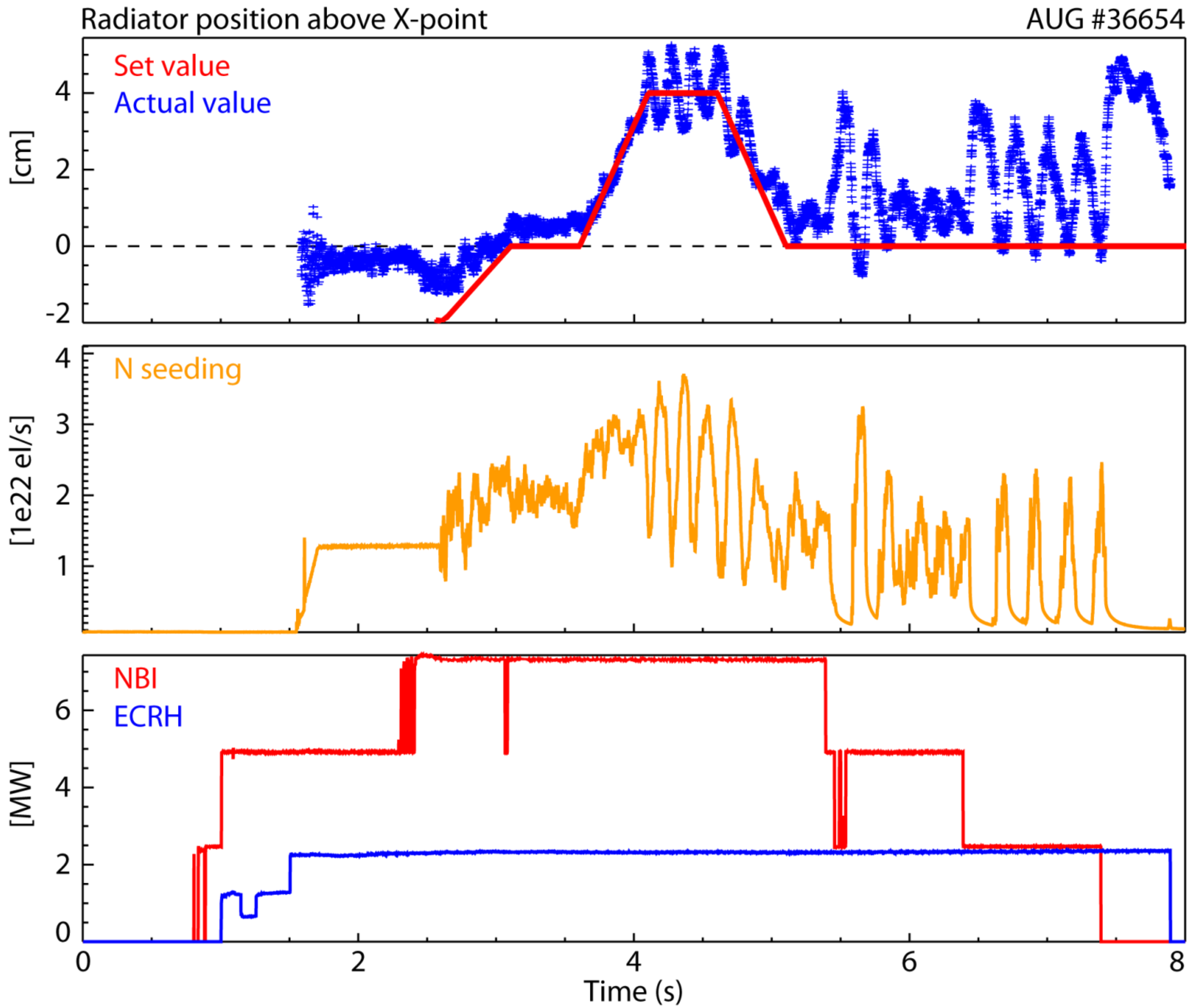
First application: Location & heating variation

- Detection within 5mm
- Power steps well compensated

- Controller unstable at:
  - Location around 4cm
  - Low heating power

  → Optimisation necessary

- Oscillation period (150-250ms) in time scale of seeding reaction time (~50ms)



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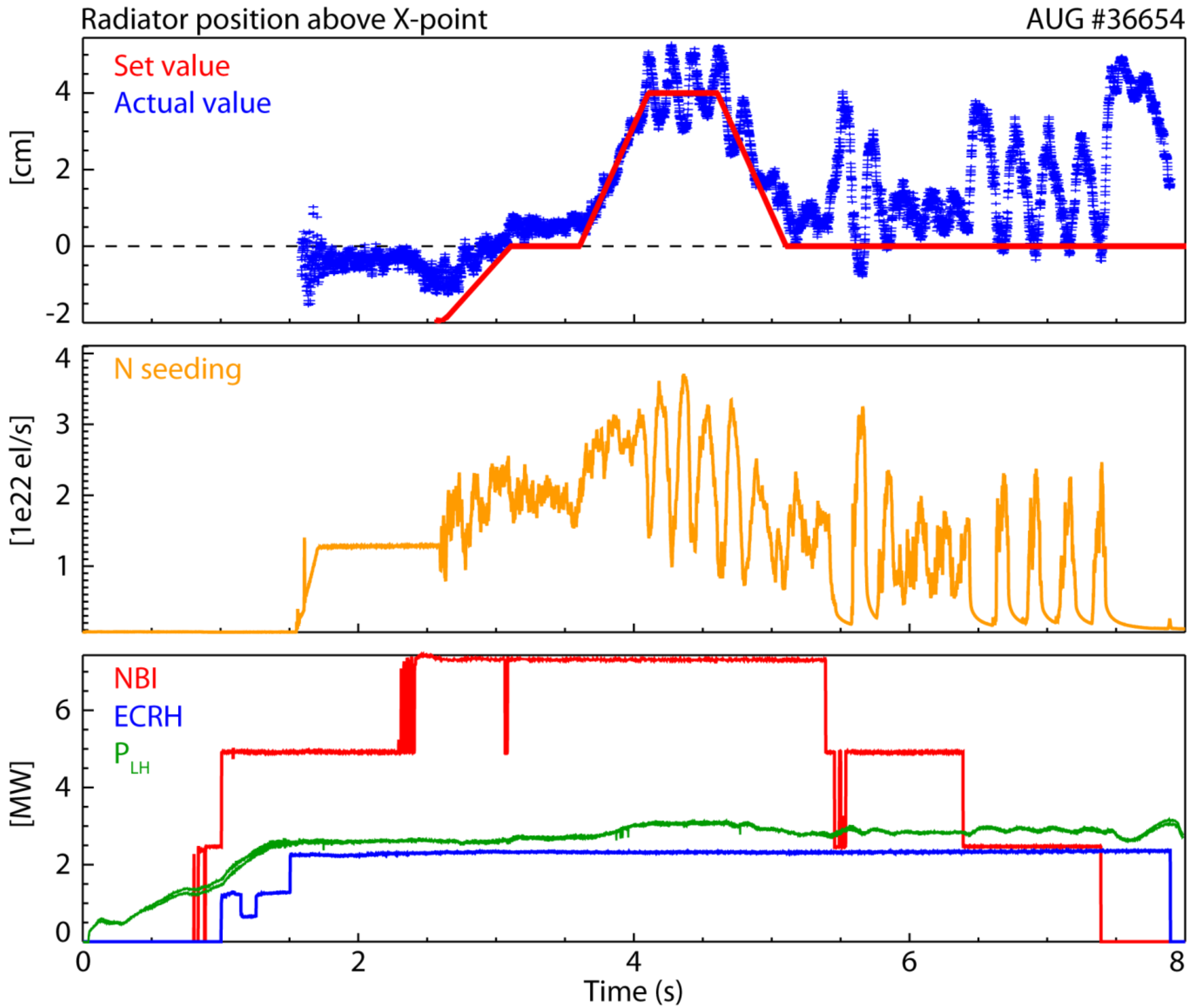
Scenario (in ELMy H-mode) stable for P_{heat} = 2.5MW ≈ P_{LH}

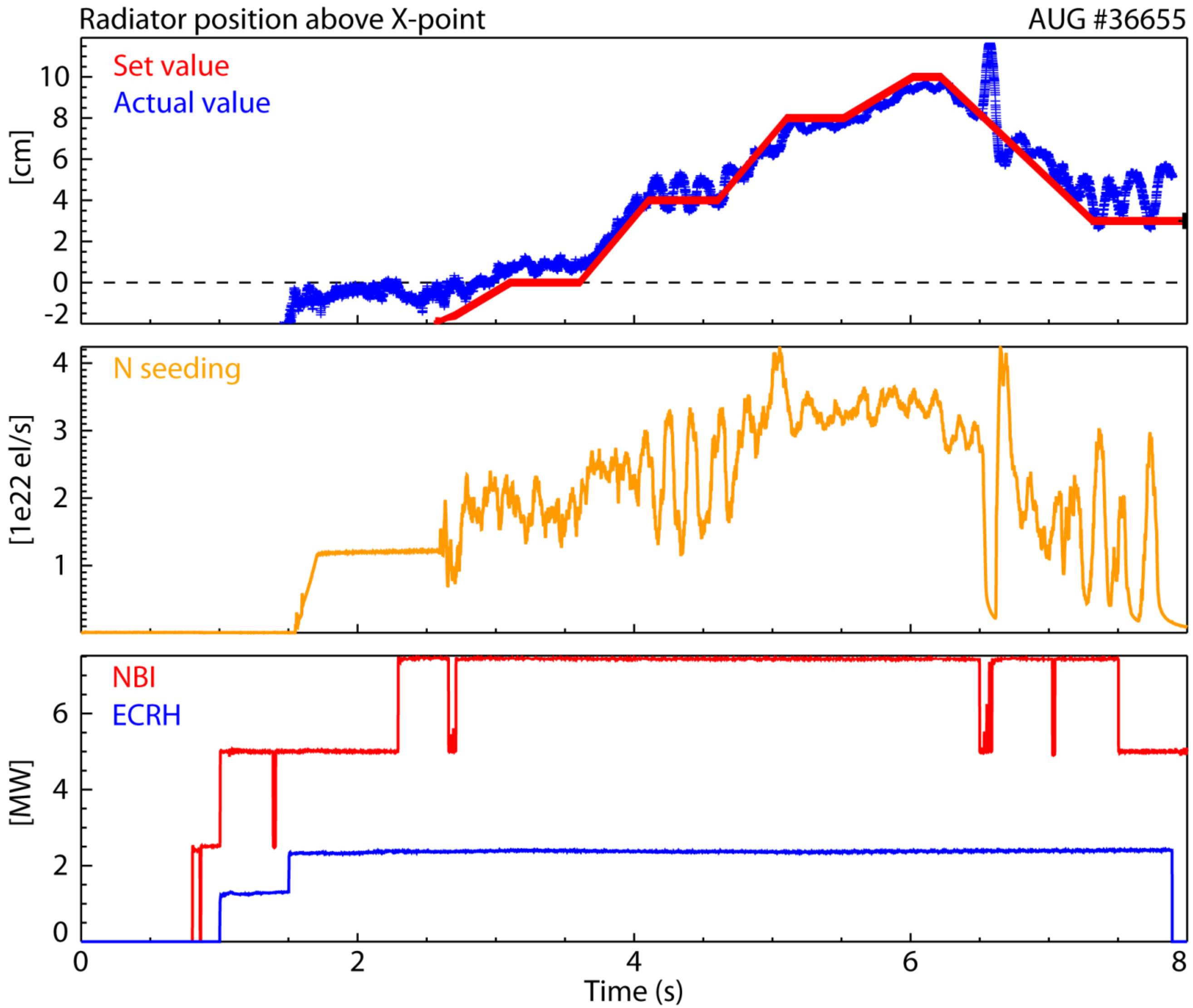


First application: Deep penetration

- Control up to 10cm above X-point (and higher)
- Power trips also far inside well compensated

  → **stable!**

- Oscillations only around 4-6cm



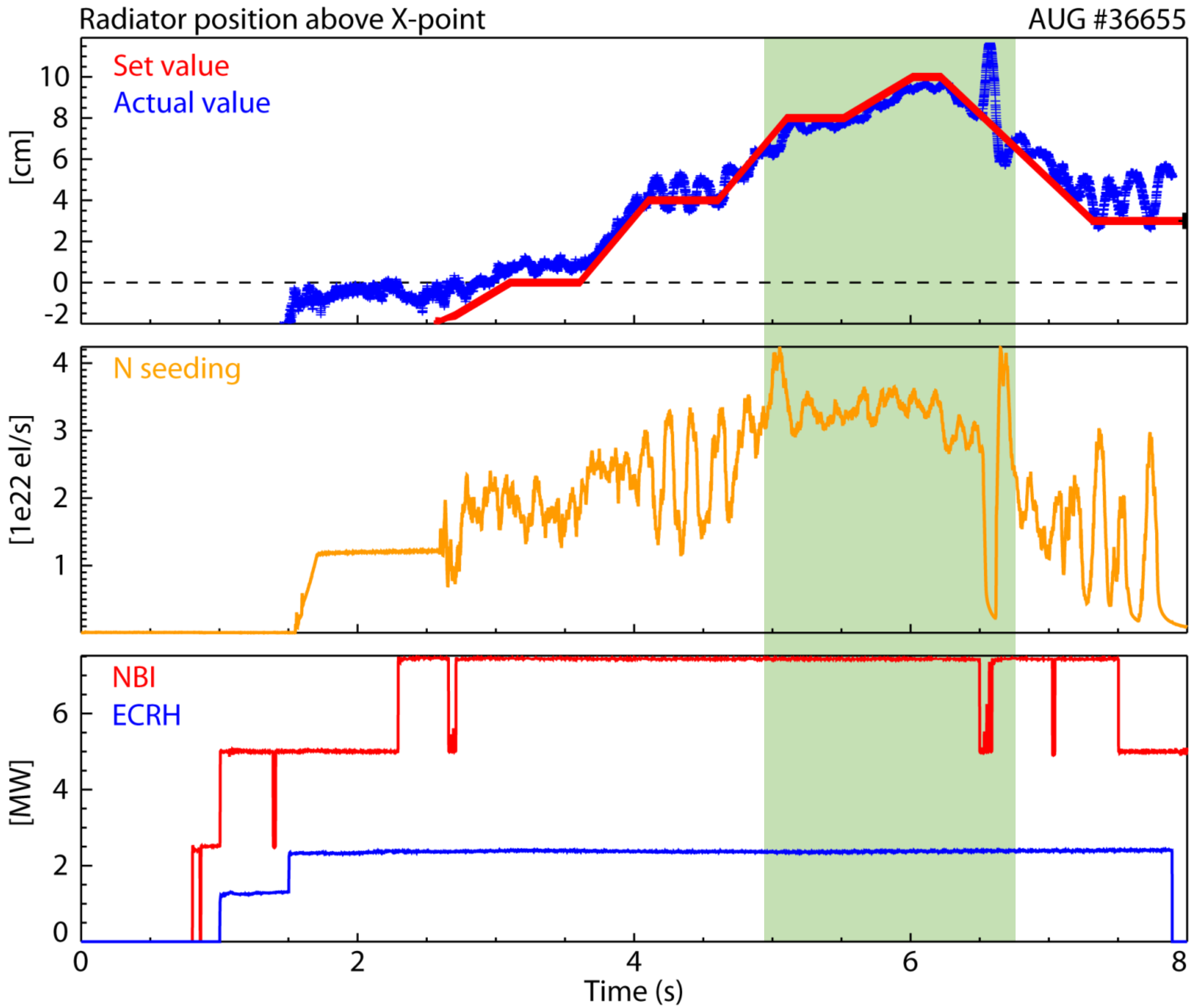
First application: Deep penetration

- Control up to 10cm above X-point (and higher)
- Power trips also far inside well compensated

→ **stable!**

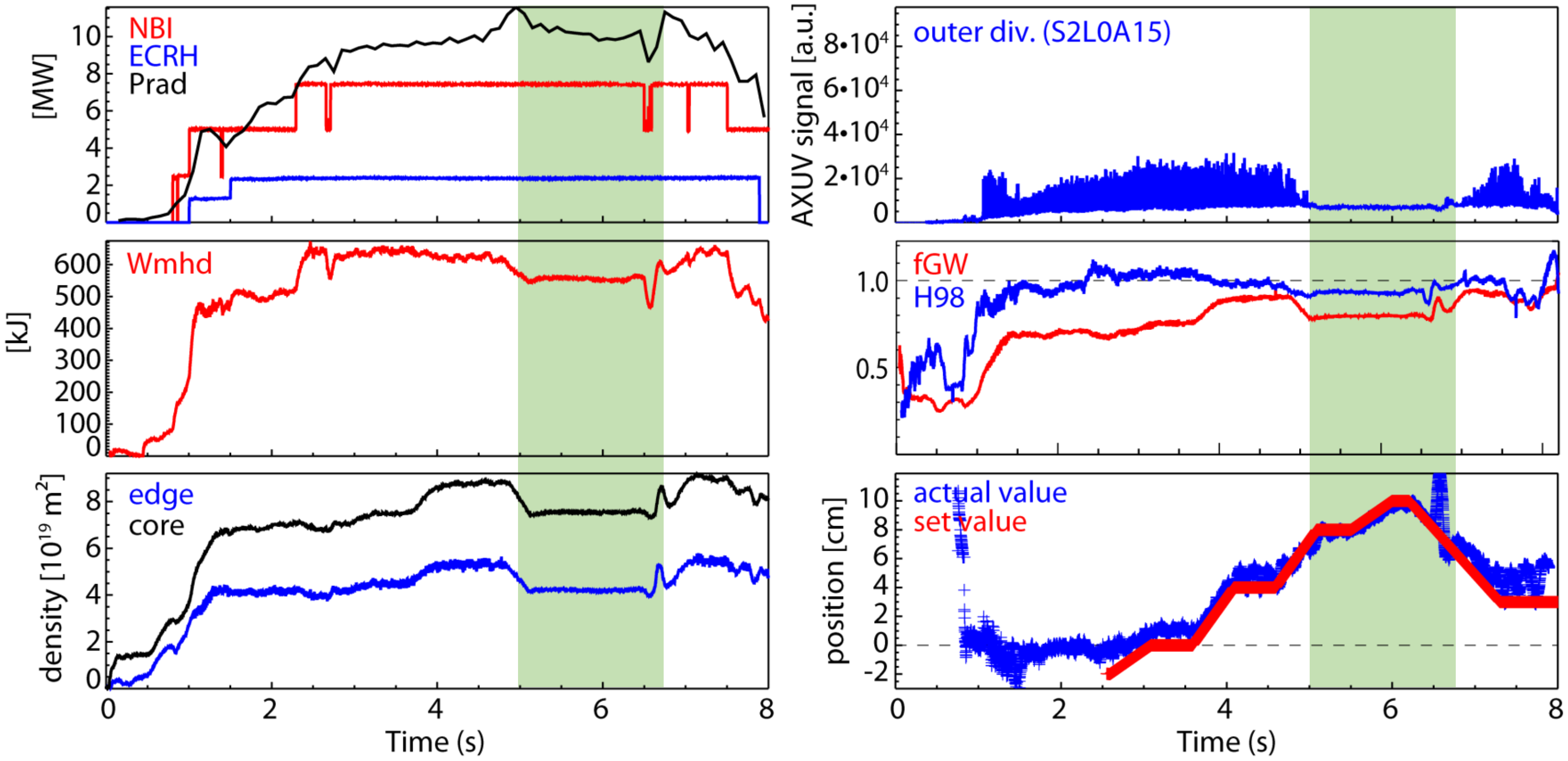
- Oscillations only around 4-6cm
- ELMs disappear for location higher than 7cm

- reappear for lower locations



An ELM-free regime?

- Reproducible in other shots
  e.g. [Reimold, NF 2015]
  - Though without control less stable



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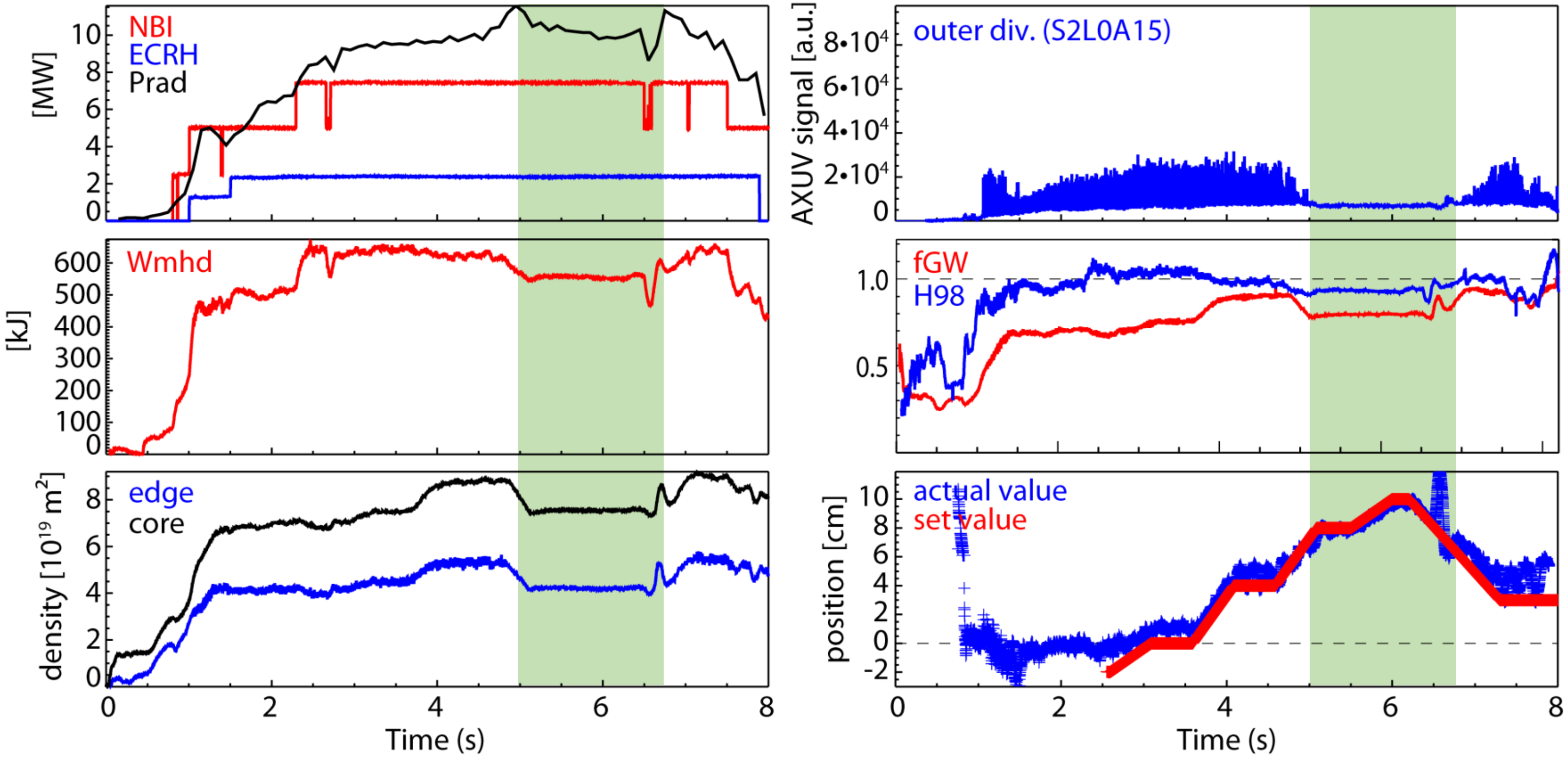


- Sudden change of charateristics:
  - No clear ELM signature
    → ELM mitigated
  - Density reduced by 15%
  - W_{MHD} reducted by ~10%
  - Characteristics between L- & H-mode (E_r well, filament characteristics)
  - Increased divertor compression
  - Reduced W content

How is the pedestal affected?

Attached → partially detached:

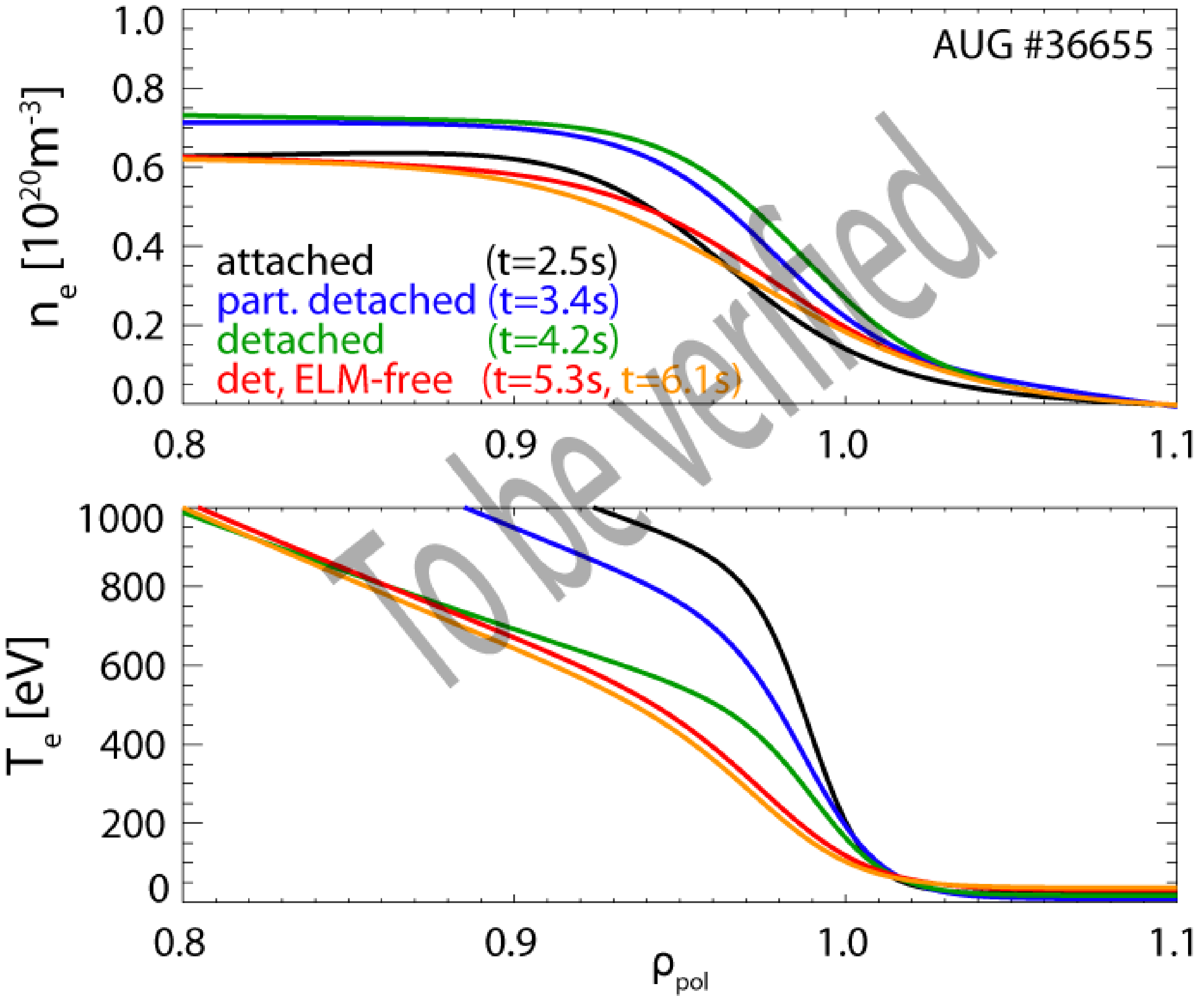
- Temperature ↘
- Density ↗

Partially detached → detached:

- Temperature ↘
- Density ↗

Detached → ELM-free:

- Density ↘
- Temperature gradient ↘
  → Temperature recovered further inwards



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Partially detached → detached:
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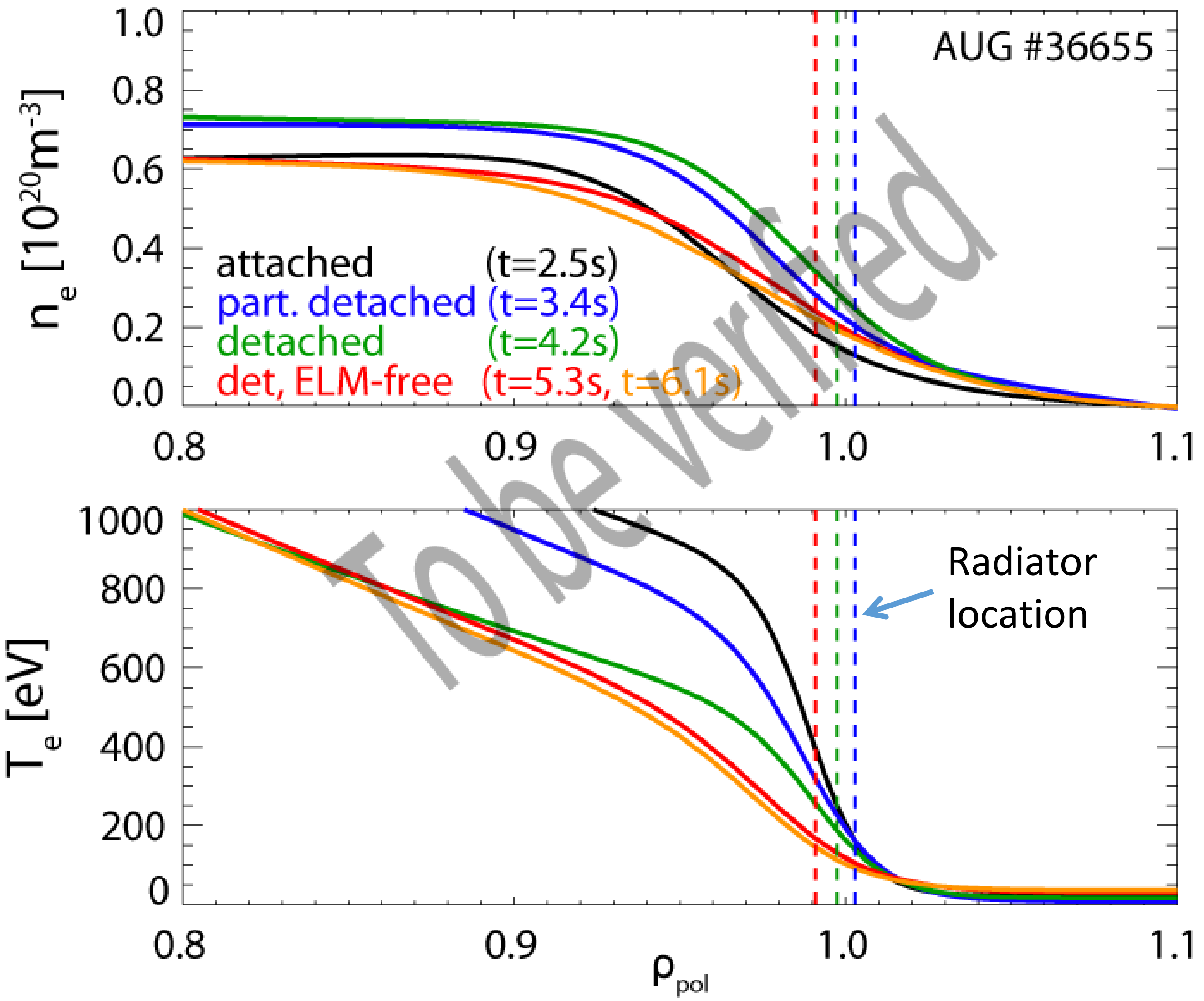
- Temperature gradient ↘
  → Temperature recovered further inwards

All changed further inside than radiator
→ Pedestal stability is affected



How is the pedestal affected?

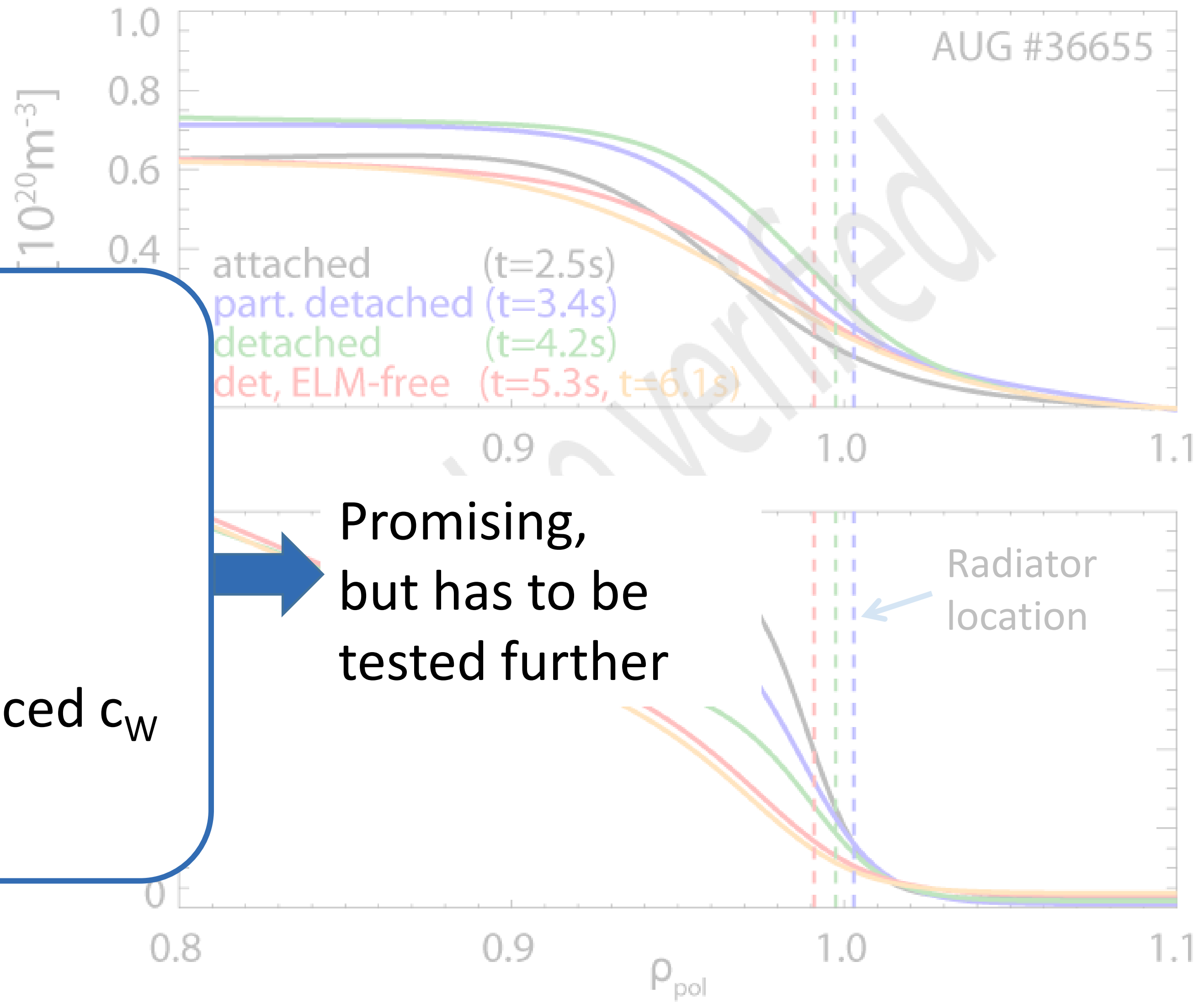
Attached → partially detached:

- Temperature ↘
- Density ↗

Parti…

Det…

- $H_{98} \approx 0.95$
- fGW ≈ 0.8
- Full detachment
- ELM mitigated
- Increased compression & reduced c_W
- $c_{N,core} \approx$ 2-2.5%



Promising, but has to be tested further

All c… radiator

→ Pedestal stability is affected

Comparison to existing detachment control

Detachment control…

… exists at:
- AUG
- DIII-D
- TCV
- JET
- EAST
- C-Mod

… sensors are:
- Divertor Thomson Scattering
- Shunt currents
- Bolometry
- Langmuir probes
- Thermocouples
- Filt. Cameras

… controls with:
- N seeding
- Ar seeding
- D fuelling

… controlled state:
- L-mode **- onset of detachment**
- H-mode **- partial detachment**

Where does the new control set in?

Detachment control…

… exists at:
- **AUG**
- DIII-D
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… controlled state:
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X-point radiator control allows for:
- Control of full detachment
- Buffer between re-attachment and radiative collapse

Summary

- X-Point radiating regime promising candidate for heat exhaust
  - Stable & controllable
  - Large buffer
  - Good performance
  - ELM mitigated

- Different paths of detachment control exist
  - X-Point radiator control first to control full detachment
  - Offers operational buffer between re-attachment and radiative collapse

→ Applicable for detachment control in reactors