Max-Planck-Institut für Plasmaphysik

CONTROL OF THE X-POINT RADIATOR IN FULLY-DETACHED ASDEX UPGRADE H-MODE PLASMAS

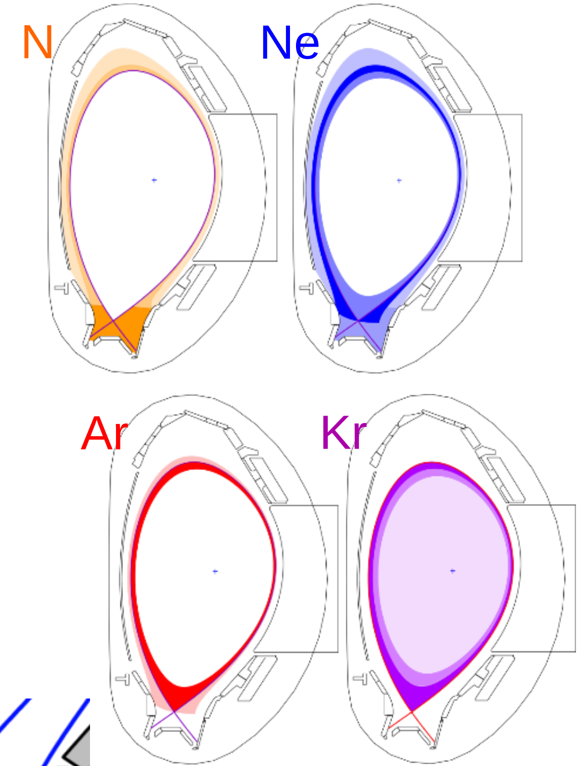
M. Bernert, F. Janky, B. Sieglin, A. Kallenbach, B. Lipschultz[1], O.Pan, F. Reimold[2], S. Wiesen[3], M. Wischmeier, O. Kudlacek, M. Cavedon, P. David, M.G. Dunne, B. Kurzan, R.M. McDermott, W. Treutterer, E. Wolfrum, D. Brida, O. Février[4], S. Henderson[5], M. Komm[6], the EUROfusion MST1 team* and the ASDEX Upgrade Team**

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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Max Planck Institute for Plasma Physics, Garching, Germany
[1]University of York, York Plasma Institute, York, United Kingdom
[2]Max Planck Institute for Plasma Physics, Greifswald, Germany
[3]Forschungszentrum Jülich Gmbh, IEK, Jülich, Germany
[4]EPFL, Swiss Plasma Center (SPC), Lausanne, Switzerland
[5]CCFE, Culham Science Centre, Abingdon, United Kingdom
[6]Institute of Plasma Physics of the CAS, Prague, Czech Rep.
*See: B. Labit et al 2019 Nucl. Fusion 59 086020
**See: H. Meyer et al 2019 Nucl. Fusion 59 112014

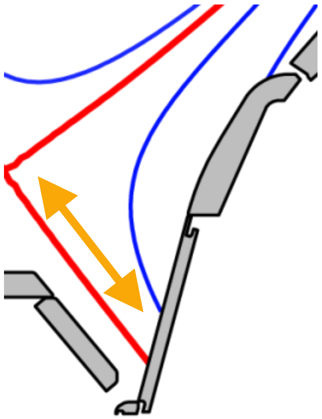
Motivation

- **Detachment is essential for ITER & DEMO**
  - Dissipated power fraction $f_{diss} \geq 95\%$
  - Partial to pronounced detachment



- **Induced by impurity seeding**
  - Reattachment ↔ Radiative collapse

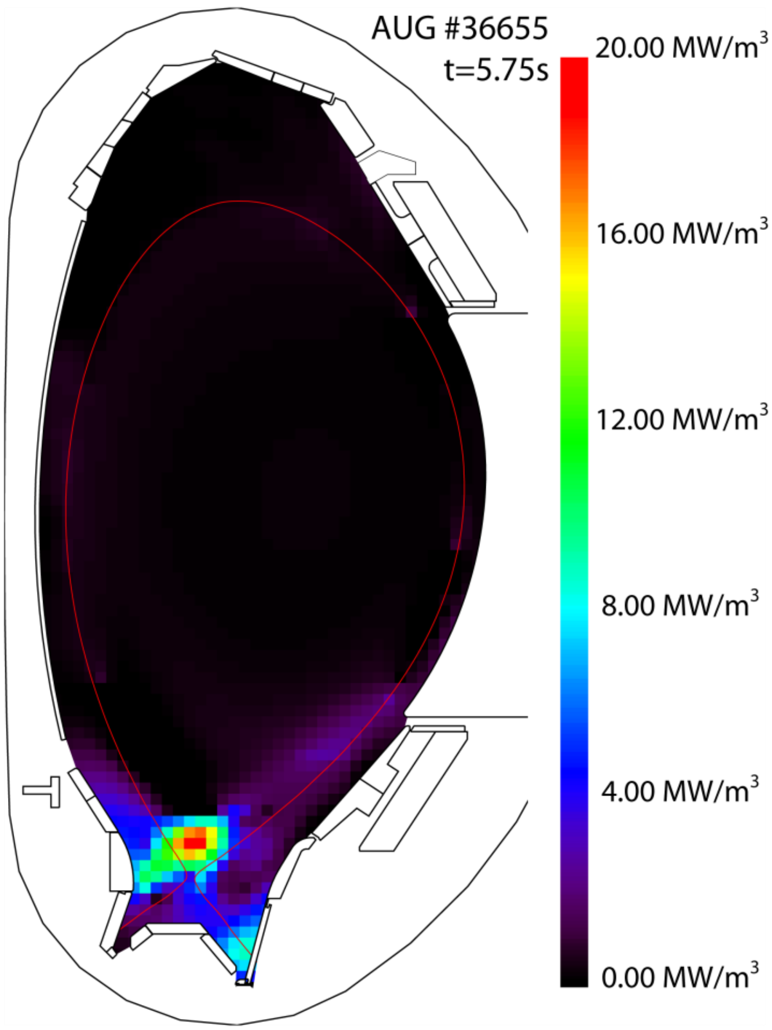
➡ **Control is crucial**
- Still requires a stable scenario
- ELMs lead to transient reattachment
  → can they be avoided?



Outline

- **The X-point radiator (XPR)**
  - Movement of the XPR
- **Real-time Control of the XPR position**
- **An ELM-suppressed regime**

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%

  XPR radiates up to 1/3 of the heating power

- X-point radiation is:

  ➔ Stable scenario

  ➔ Existing with N or Ar seeding (at AUG)

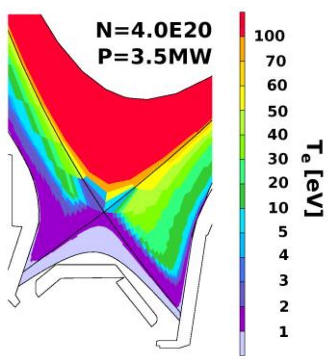
  ➔ Existing in a wide range of heating power: P_{heat} [MW] = 2.5 – 20

  P_{heat}/P_{LH} = 1 – 5

The X-point radiation regime

- Radiator reproduced by SOLPS [Reimold, NF 2015]
- Temperature reduction within confined region
  - D line radiation observed → efficient recombination
  - T_e = 1-2 eV, $n_e \geq 3 \cdot 10^{20}$ m^{-3}
    → **Parallel temperature gradients inside confined region!**

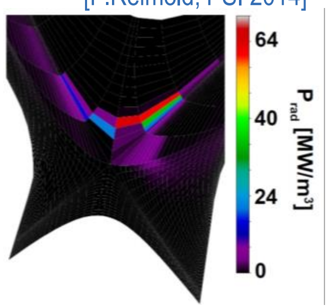
[I.Senichenkov, PPCF 2021]



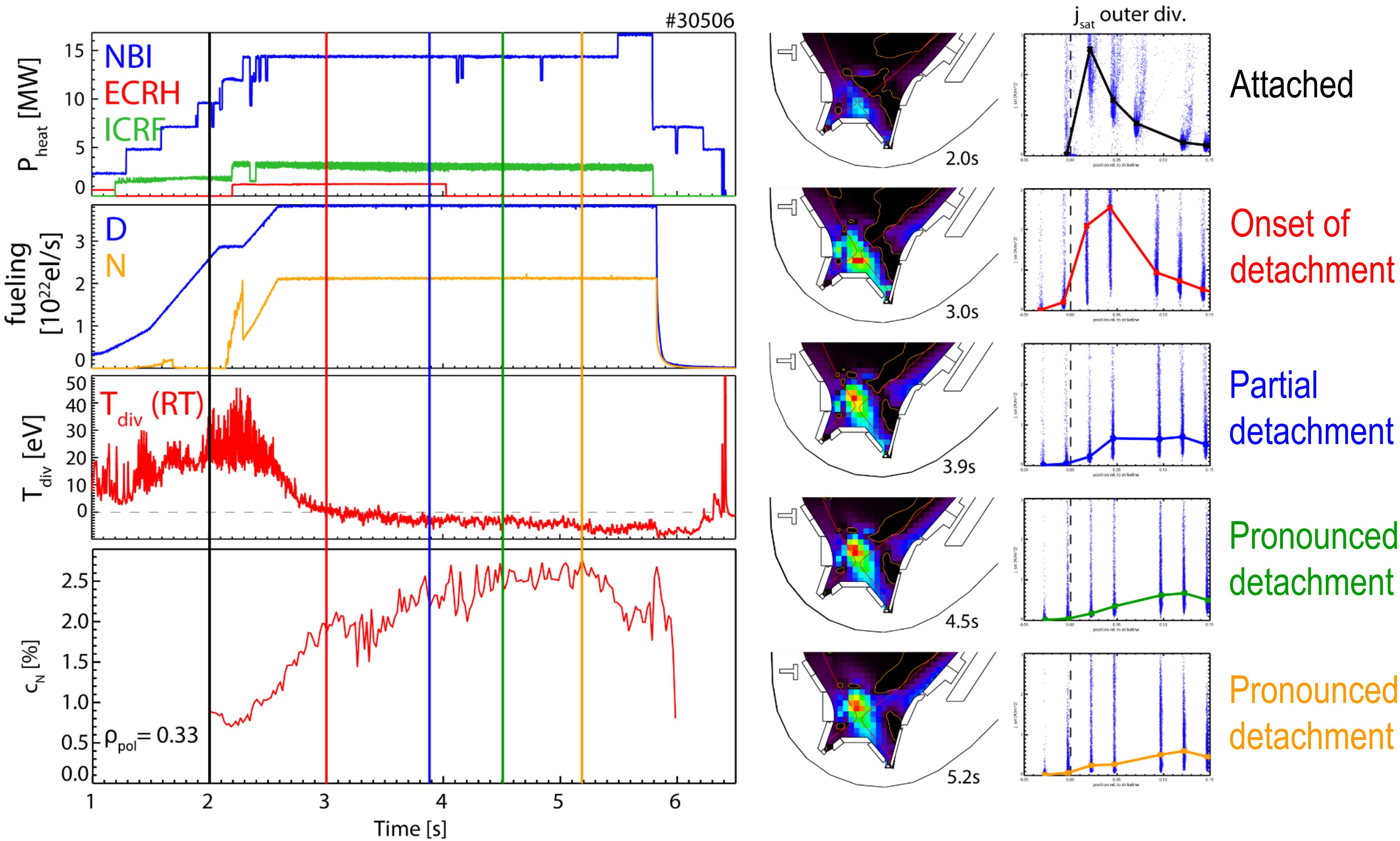
Why is it stable? Hypotheses:

- 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
- Influence of near divertor (neutral & impurity penetration for local cooling)

[F.Reimold, PSI 2014]



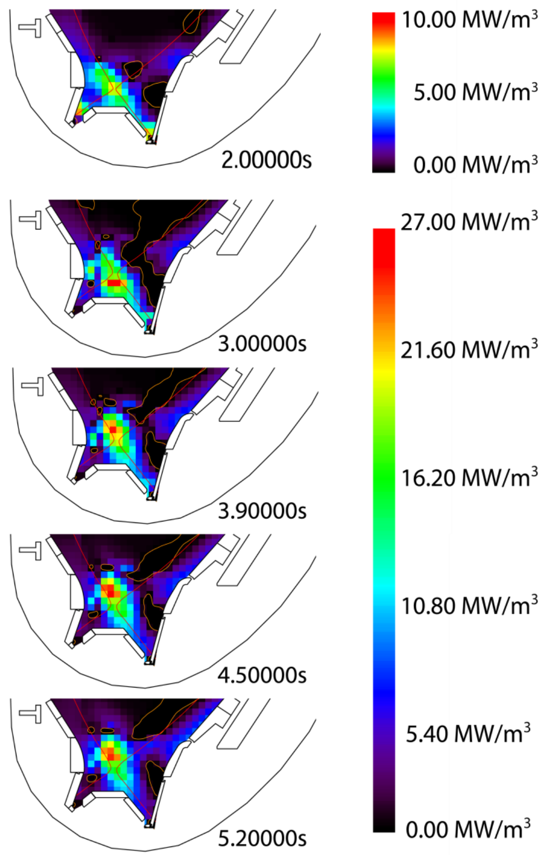
Overview of an XPR discharge



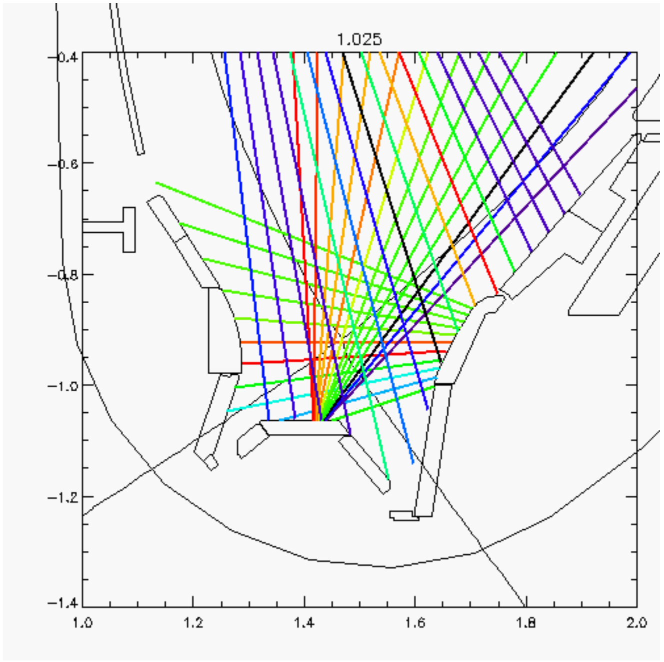
Movement of the X-Point radiation peak

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

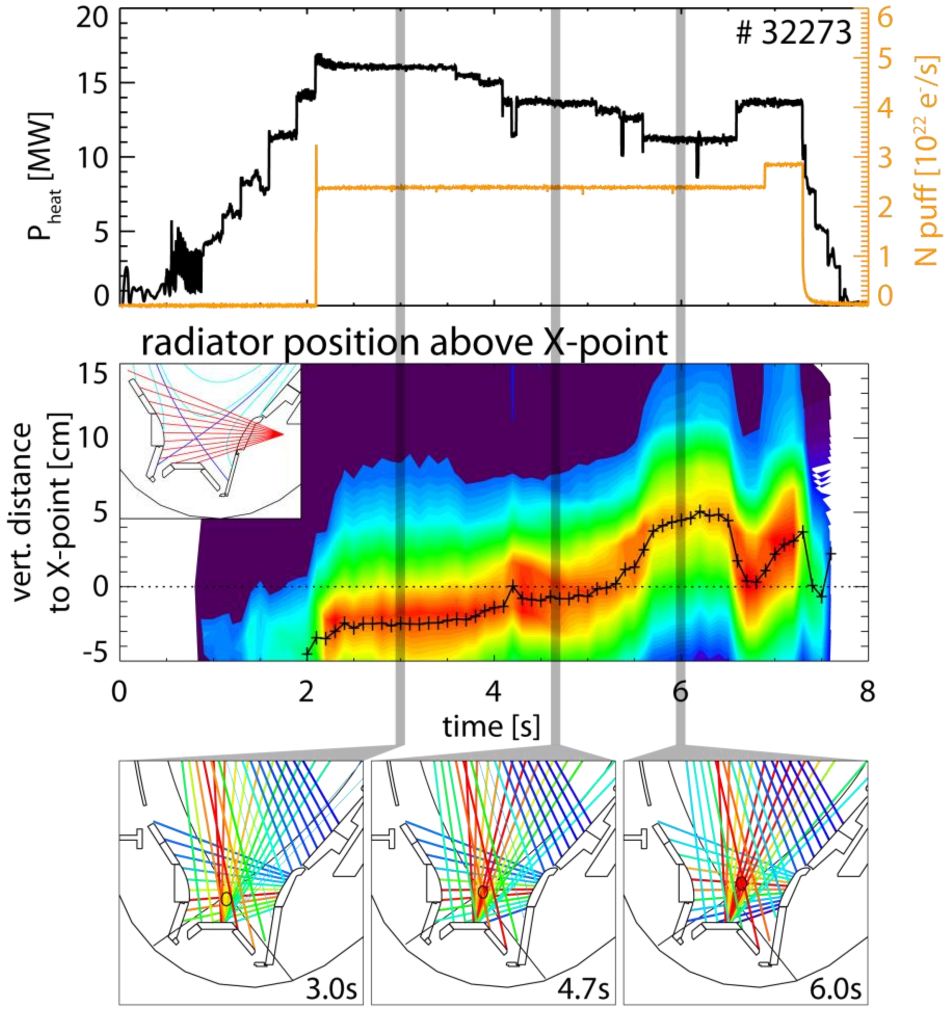
- Radiator forms close to X-point
- Moves further inside
- Up to 15 cm inside confined region ($\rho_{pol} \approx 0.99$) observed



Tracking using AXUV diodes (#32273, N seeding)



Actively influencing the location



- Location can be influenced by heating power or nitrogen seeding level
  - No clear scaling of position with c_N or Γ_N (& P_{heat})

Implemented real time control

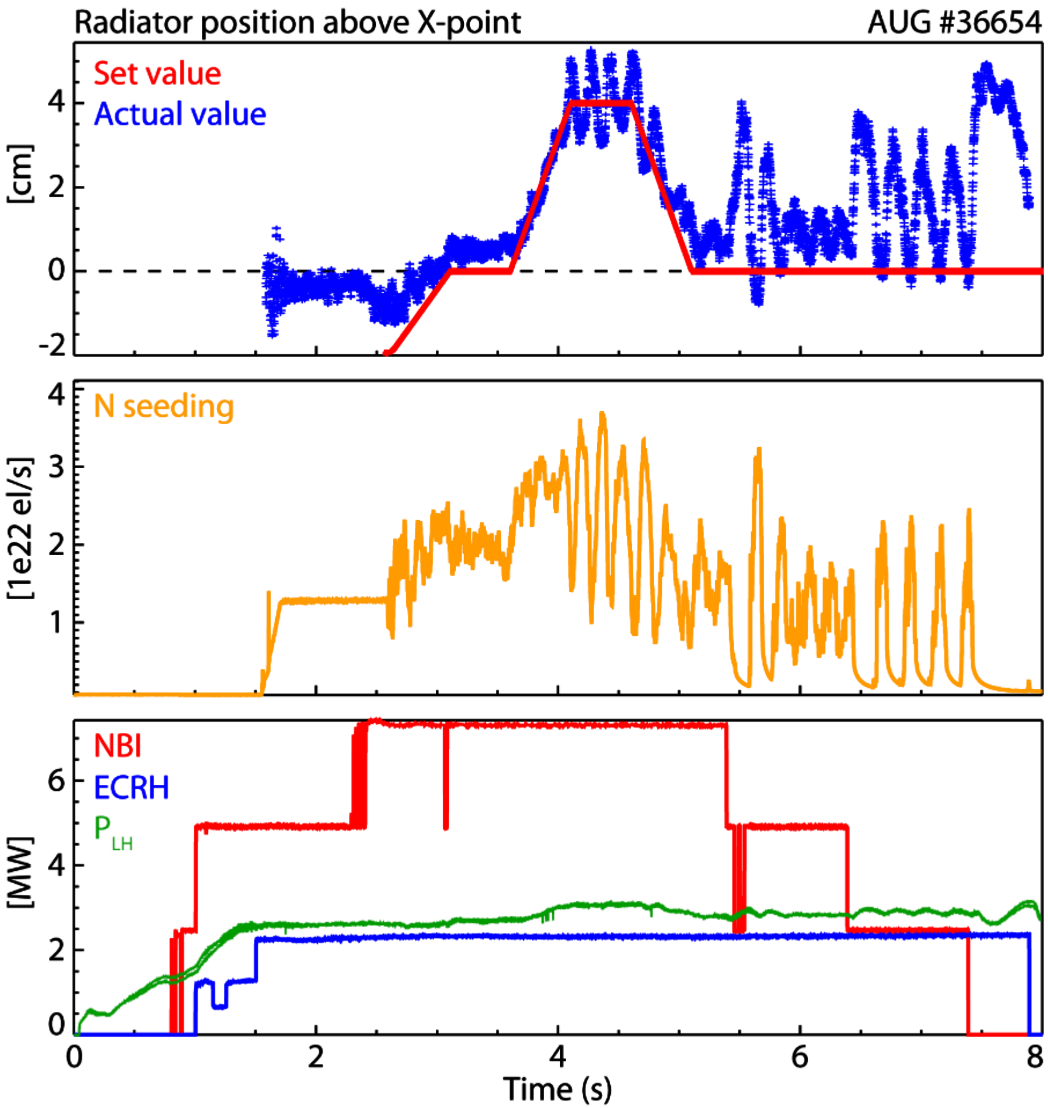
Sensor: AXUV diodes

- ELM filter & offset subtraction
- Peak defined by 1st moment

Actuator: N or Ar seeding

- PI controller
- Further possibility: Heating power

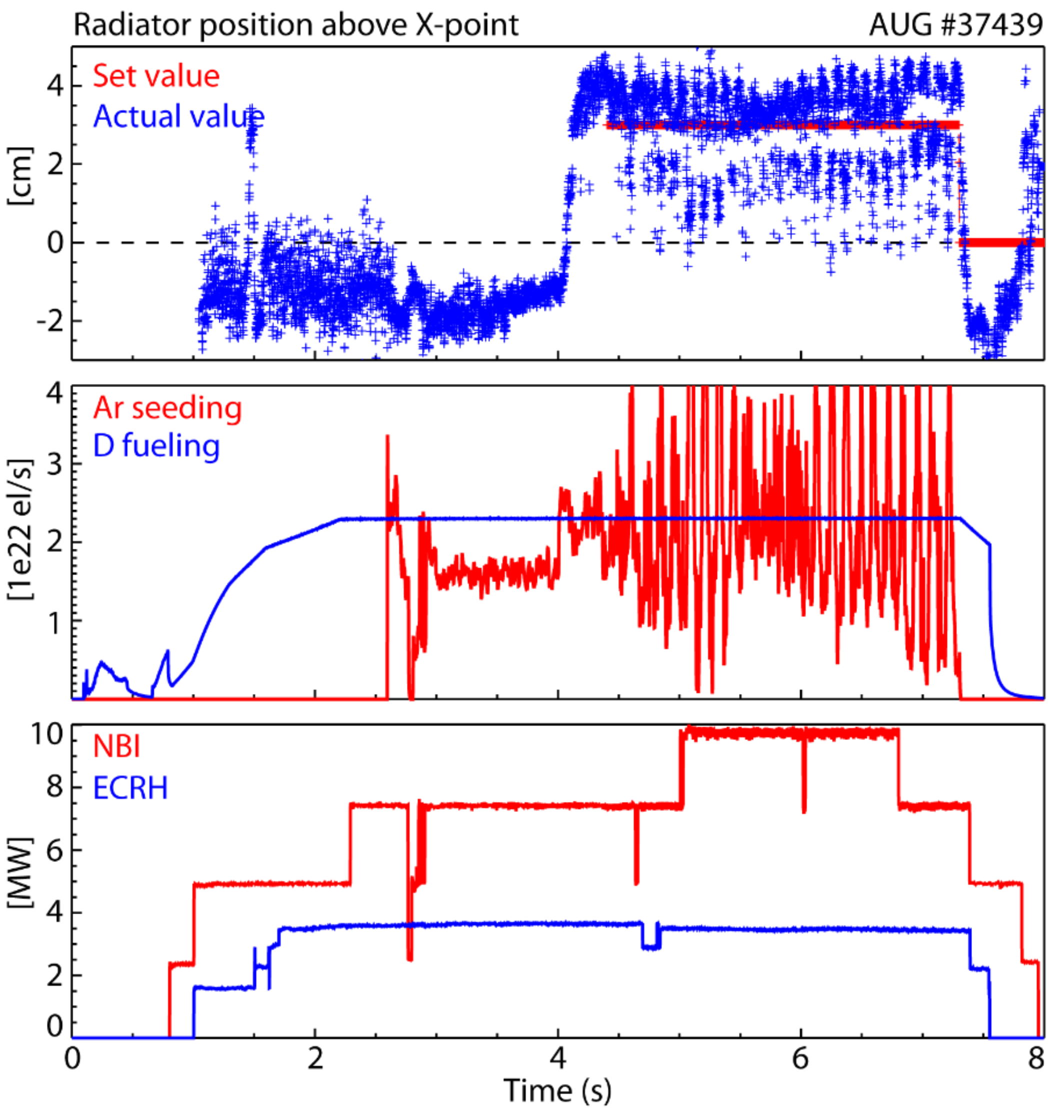
First application: Location & heating variation



- Detection within 5mm
- Power steps well compensated
- Controller unstable at:
  - Location around 4 cm
  - Low heating power

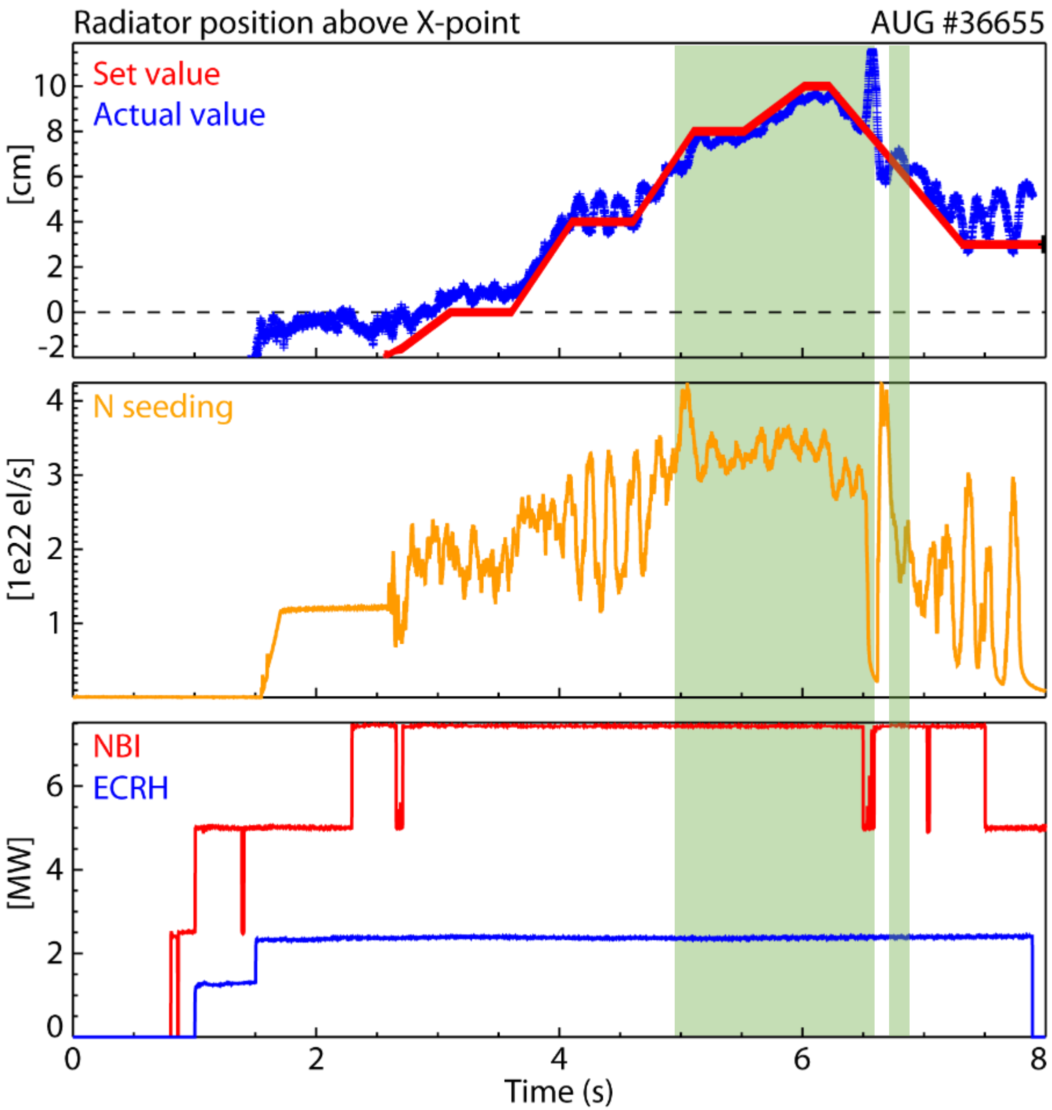
Scenario (in ELMy H-mode) stable for P_{heat} = 2.5 MW ≈ P_{LH}

Applicability to other scenarios



- Tested for N seeding with 2-18 MW
- Applicable also to Ar seeding
  - Adjusted gains
  - ➔ noisy signal and noisy feedback

First application: High location



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

→ stable regime!

ELMs disappear for location higher than 7 cm!

An ELM-suppressed regime

Sudden change of characteristics:

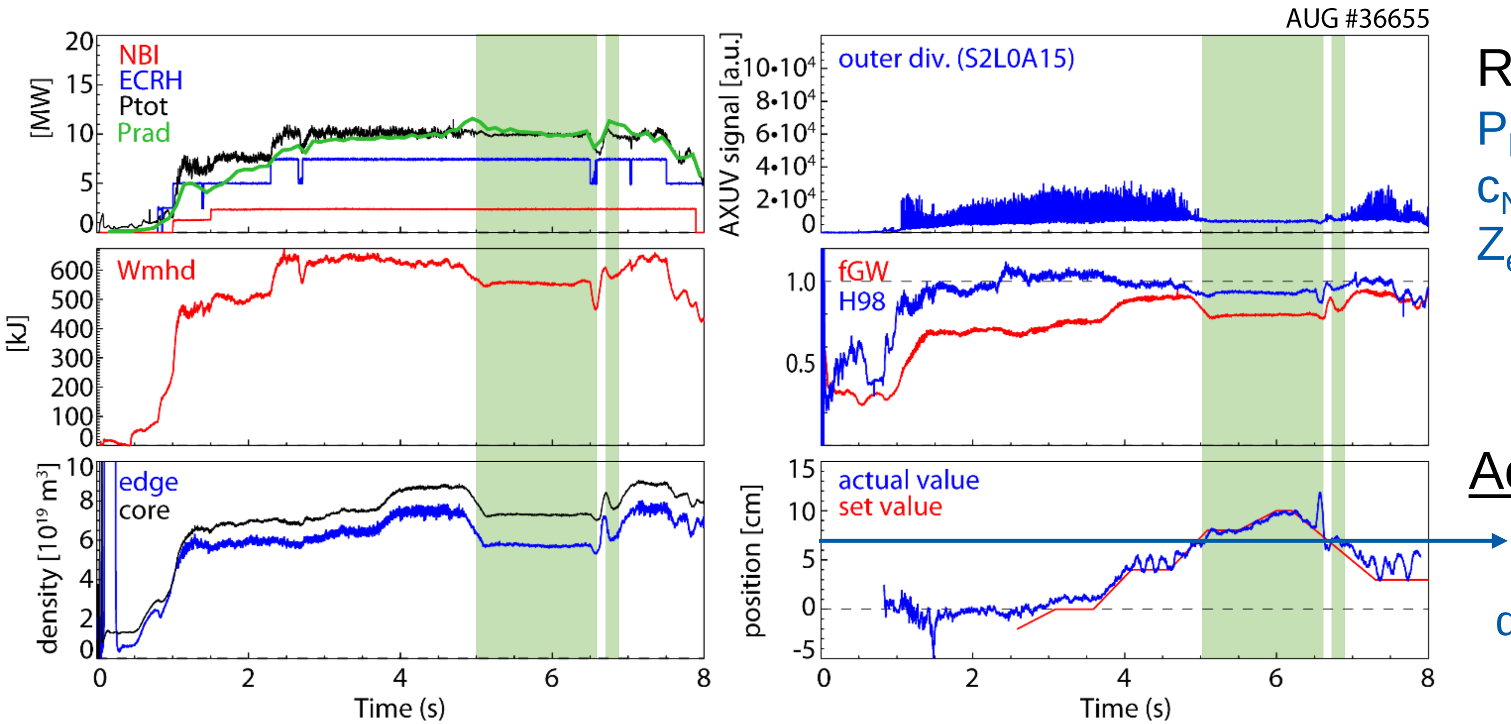
+ No ELM signatures
- Density reduced by 15%
- W_{MHD} reduced by ~10%

+ Increased divertor neutral compression
+ Reduced W content

$H_{98} \approx 0.95$

$f_{GW} \approx 0.8$

$f_{GW,\ sep} \approx 0.2$



Reproducible:

P_{heat} = 2-18 MW

$c_N \approx$ 2-3.5%

$Z_{eff} \leq$ 2.5

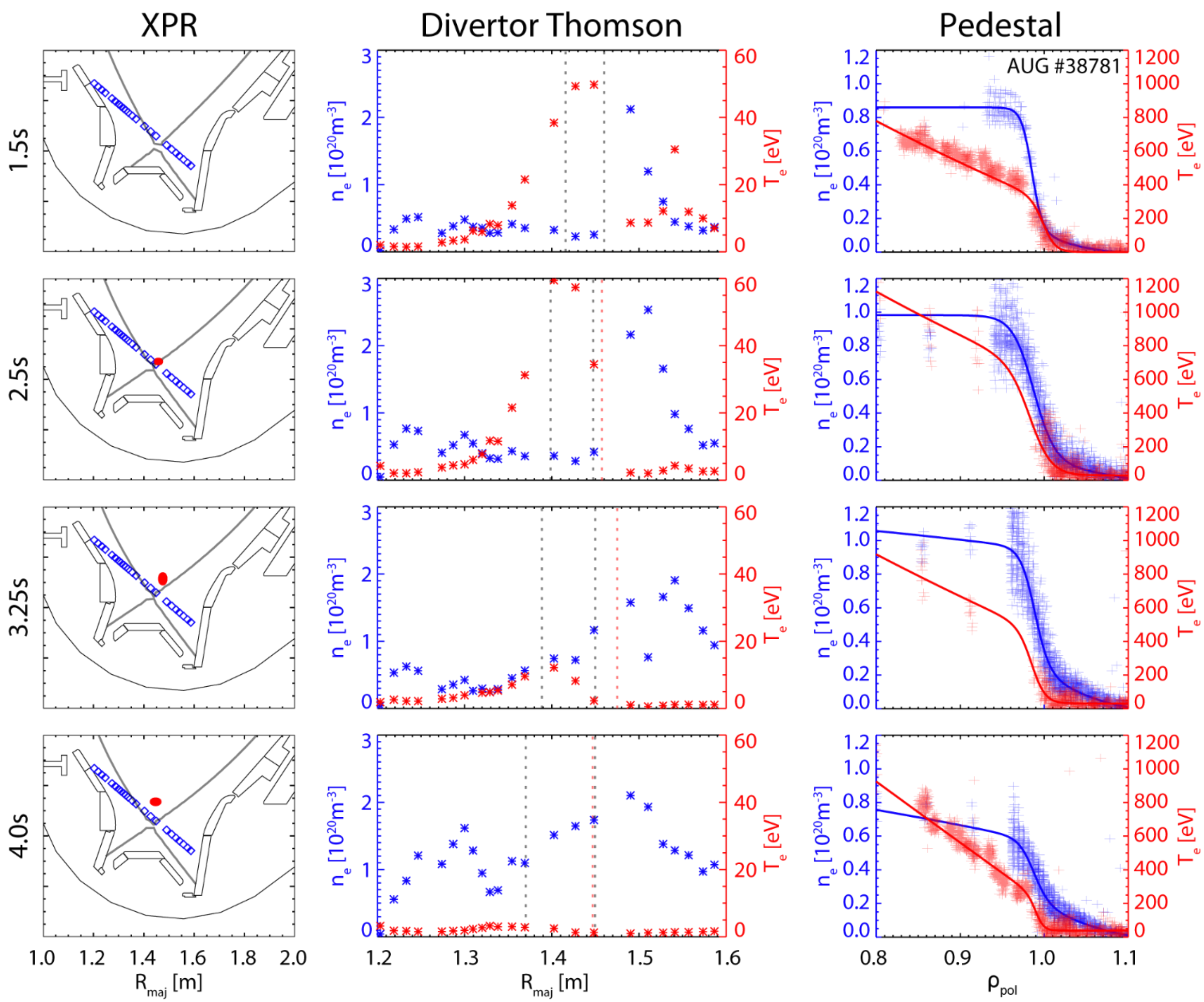
Access condition:

dz_{XPR} > 7 cm

$dR_{midplane}$ = 2 mm

T_e & n_e evolution – divertor vs midplane

- Pedestal changes further inside than radiator
  - Pedestal stability changed by XPR
- Div. Temperature reduces only ‘behind’ XPR
  - $T_e \approx$ 1-2 eV
  - $n_e \leq 2 \cdot 10^{20}\, m^{-3}$
- Pedestal gradients reduce at last step
  - Core T_e persists (higher core ∇T_e)



Summary

- **X-point radiation is a stable regime, shown in AUG & JET**
- **The X-point radiator moves inside the confined region**
- **The movement can be actively controlled**
- **First time control of full detachment!**
- **A high location of the radiator leads to ELM suppression**

Promising regime for a future reactor:

- ✓ Operational window between detachment and radiative collapse
- ✓ Simple observer
- ✓ ELM suppression

➡ Applicability for a future reactor to be investigated