MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Tungsten limiter start-up experiments in different boronization states in support of ITER

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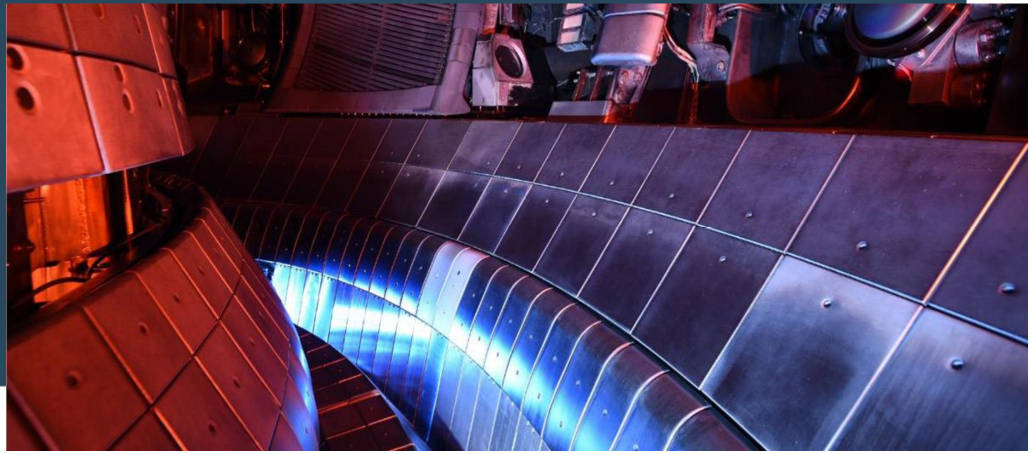

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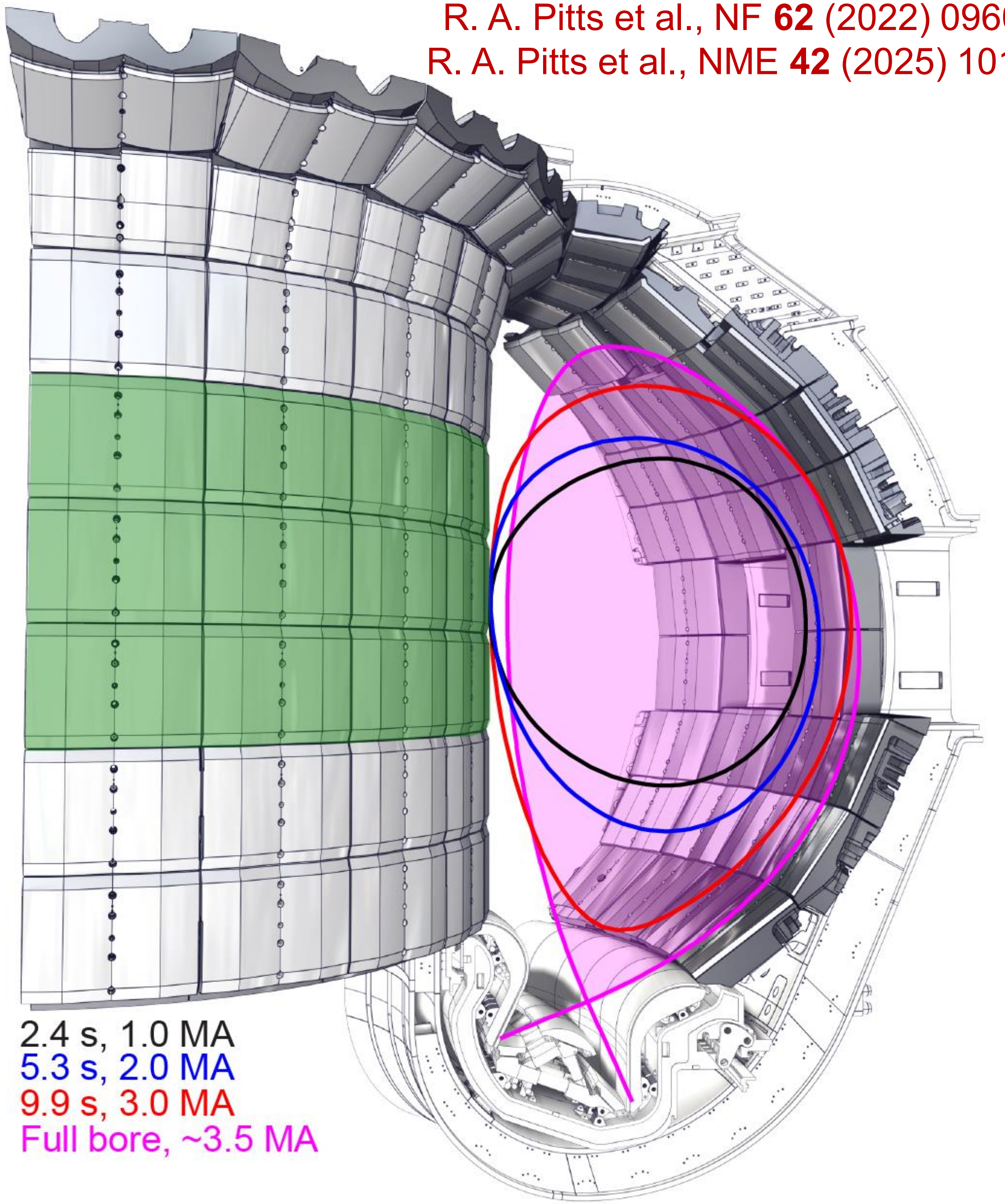
Outline

- Introduction
- Startup on outboard limiter, unboronized wall, ASDEX Upgrade
- Startup on inboard limiter, unboronized and transition to non-uniform boronized wall, WEST
- W sources in outboard limiter plasmas on ASDEX Upgrade
- SOLPS-ITER calculations for ASDEX Upgrade
- Summary and Conclusion

Limiter start-up on W – an issue or not?

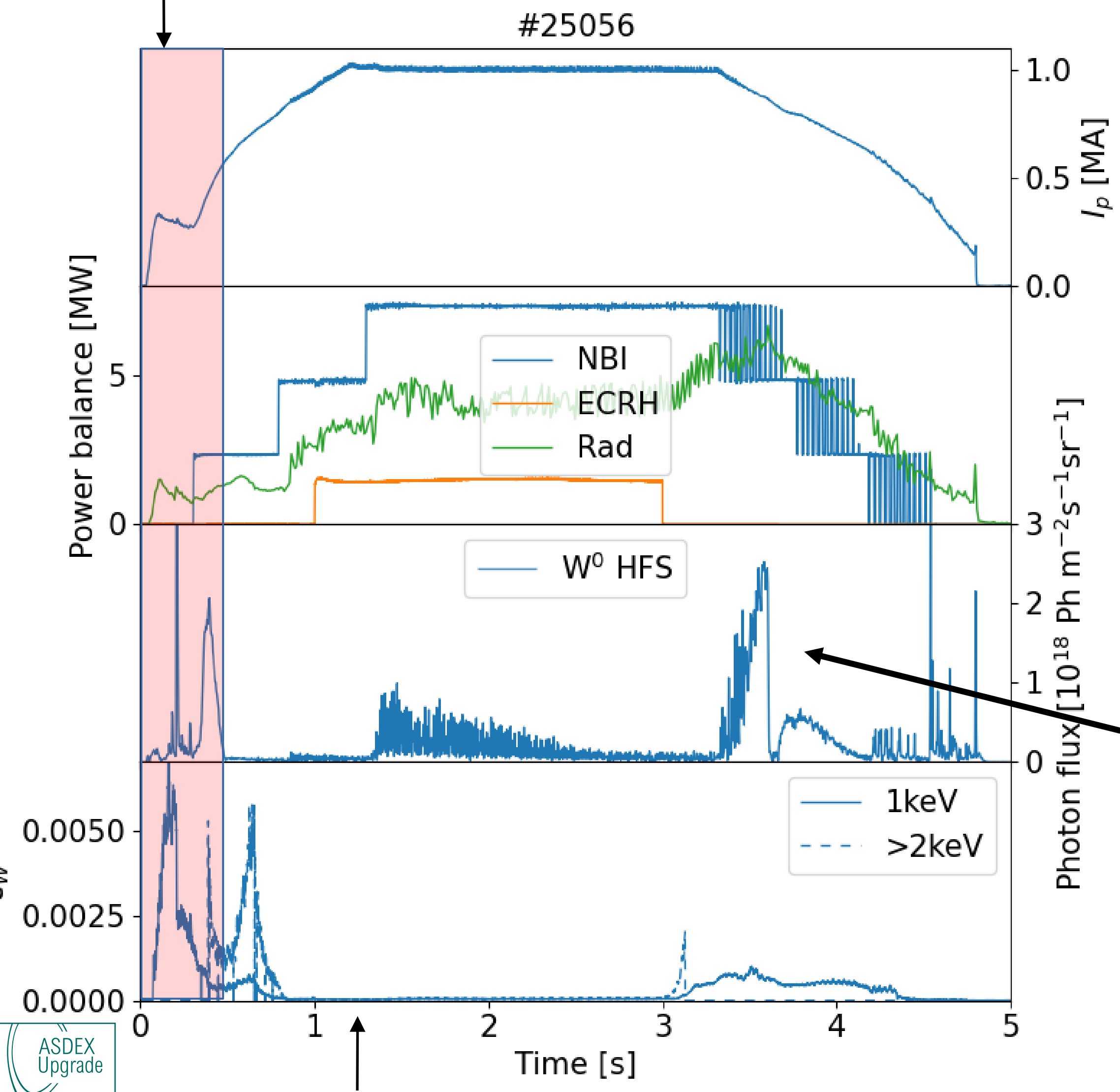
- Like many tokamaks, ITER plasmas will start up on the central column
- Switch from Be → W can have strong potential impact ($P_{RAD,W}$ >> $P_{RAD,Be}$)
- Limiter phase is rather long (~10 s) on ITER cf. current devices
- Very little detailed attention paid to this early phase
  - New expts. on ASDEX Upgrade, WEST, and EAST
  - New modelling for ITER
- Related: Is machine conditioning (boronization) necessary to start the machine?

R. A. Pitts et al., NF **62** (2022) 096022
R. A. Pitts et al., NME **42** (2025) 101854



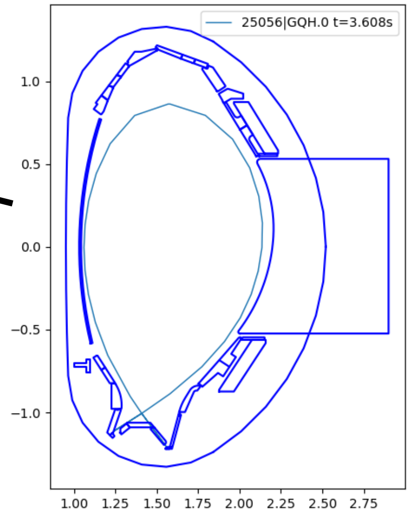
W radiation in AUG *inboard* limiter plasmas higher than in divertor plasmas

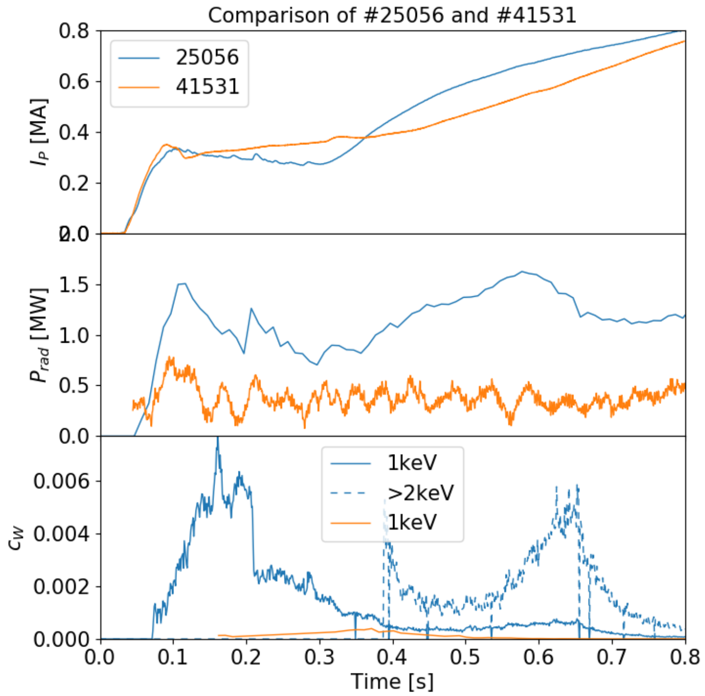
Limiter 2009, 2nd day after summer break, non boronised



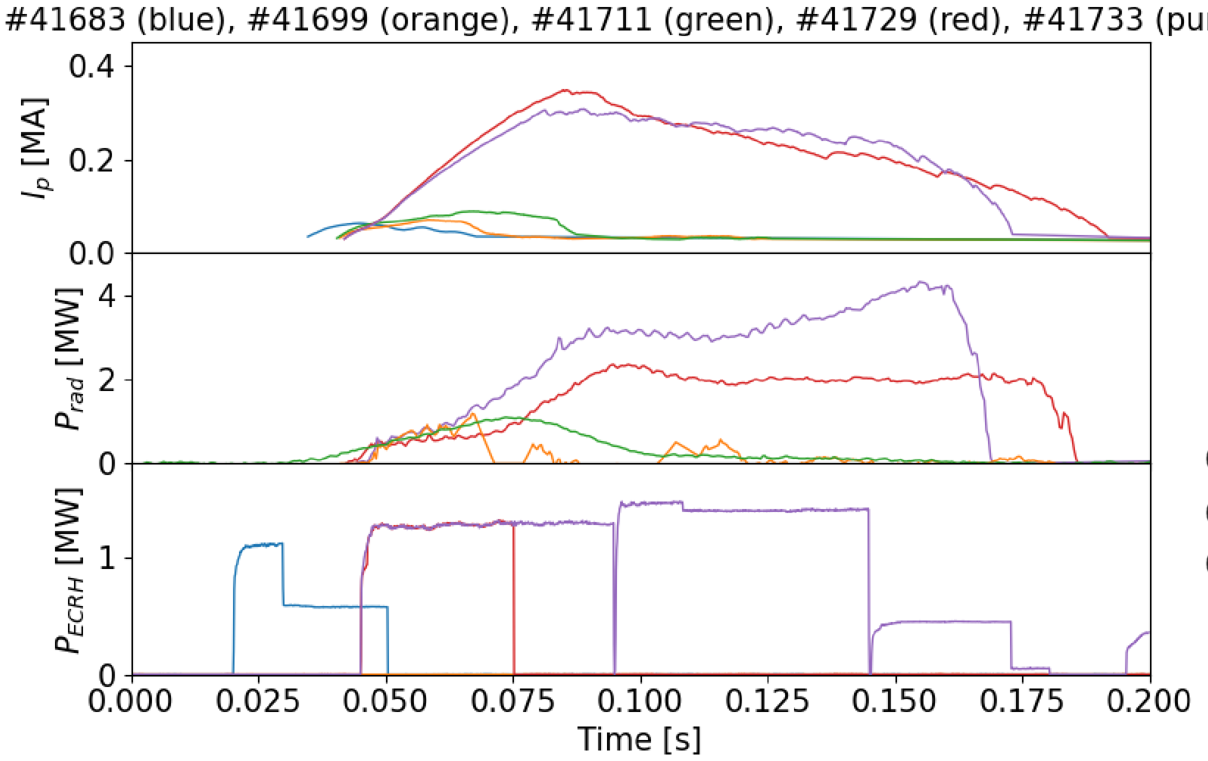
healthy W concentration

- W source from inner heat shield higher than in divertor H-mode
- Radiation losses can lead to very low electron temperatures
- Boronised and optimised pulses have a **factor 10** lower concentrations





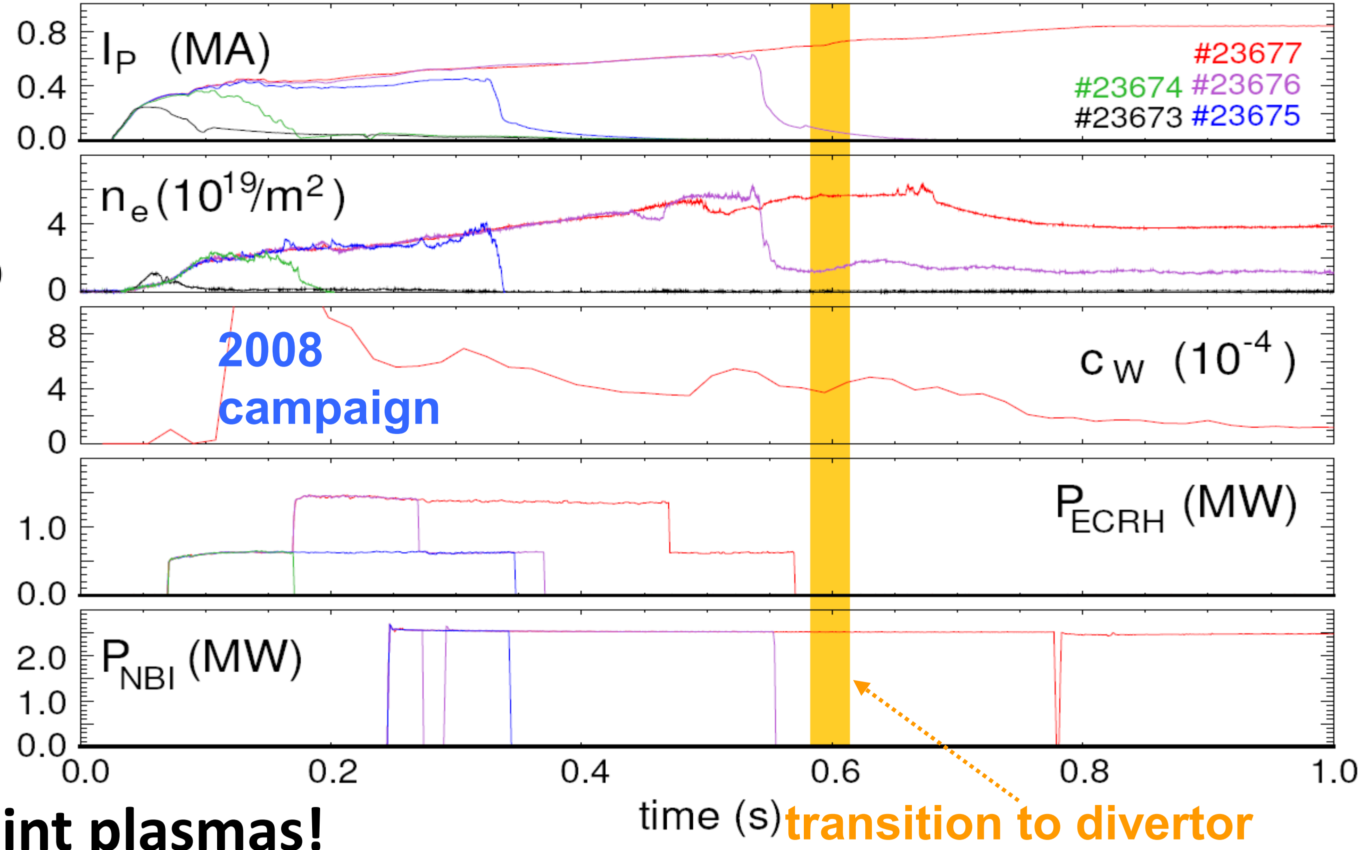
Non boronized restart on *outboard* limiter not successful



- ECRH pre-ionisation successful but not long enough
- Later (and well aimed) ECRH allows plasma current ramp up
- After ECRH switch off plasma can't be sustained → too high (low Z, O) radiation

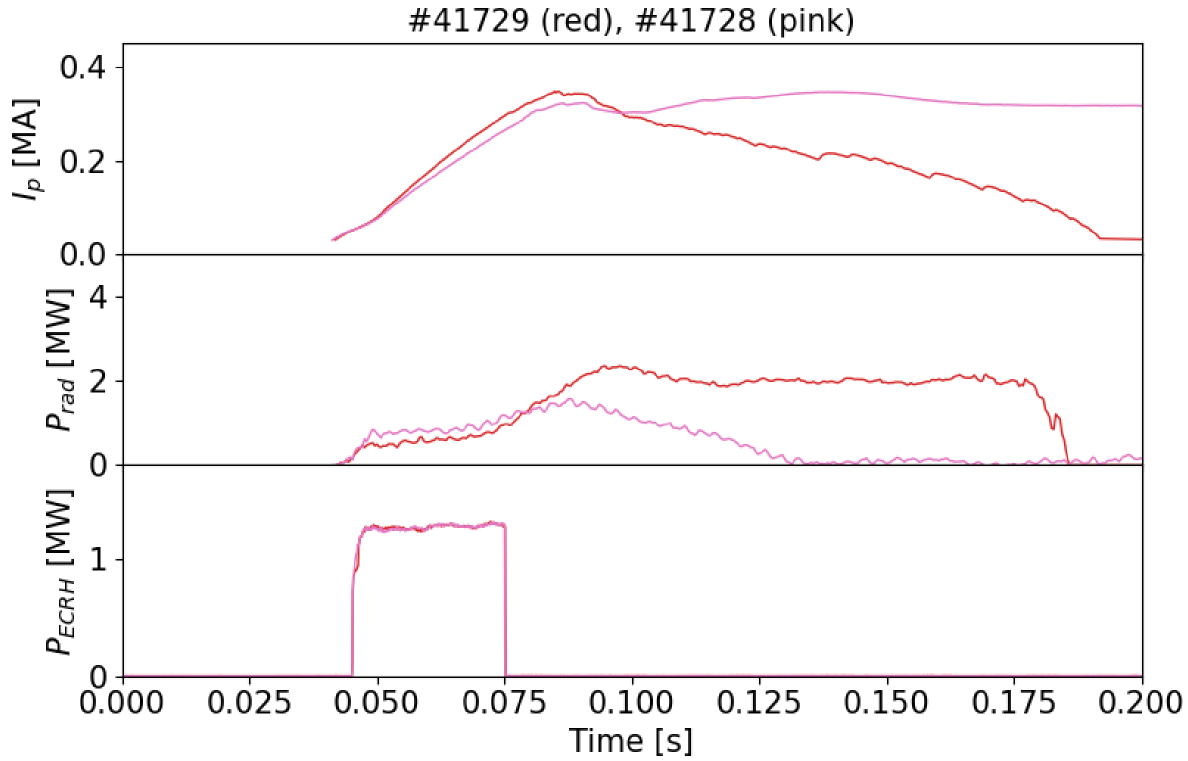
- Quite a few technical problems delaying progress (2 days too late prefill, no DCN → **very short ECRH (40ms)**, real time equilibrium wrong, right plasma position for ECRH had to be found)

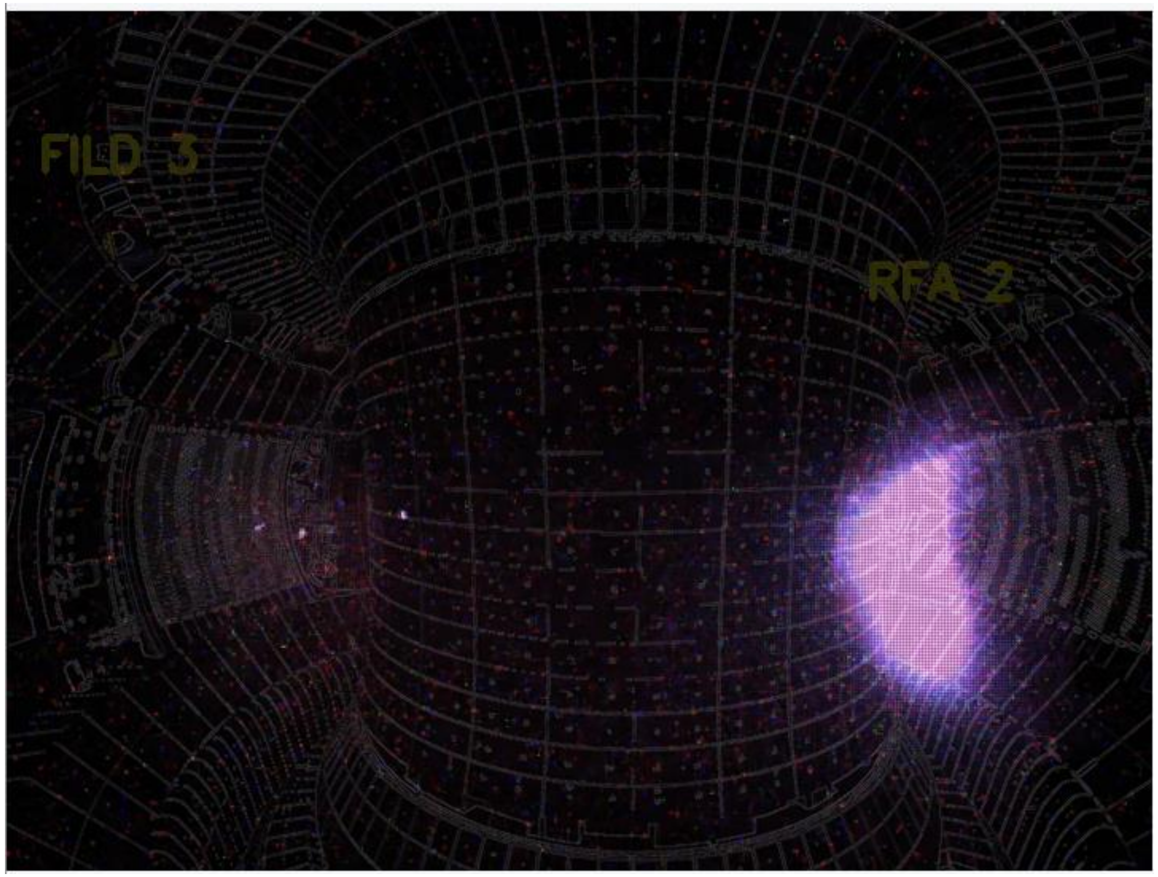
R. Neu *et al*, Phys. Scr., 014038, (2009)



Last slide with X-point plasmas!

Non boronized restart can lead to runaways

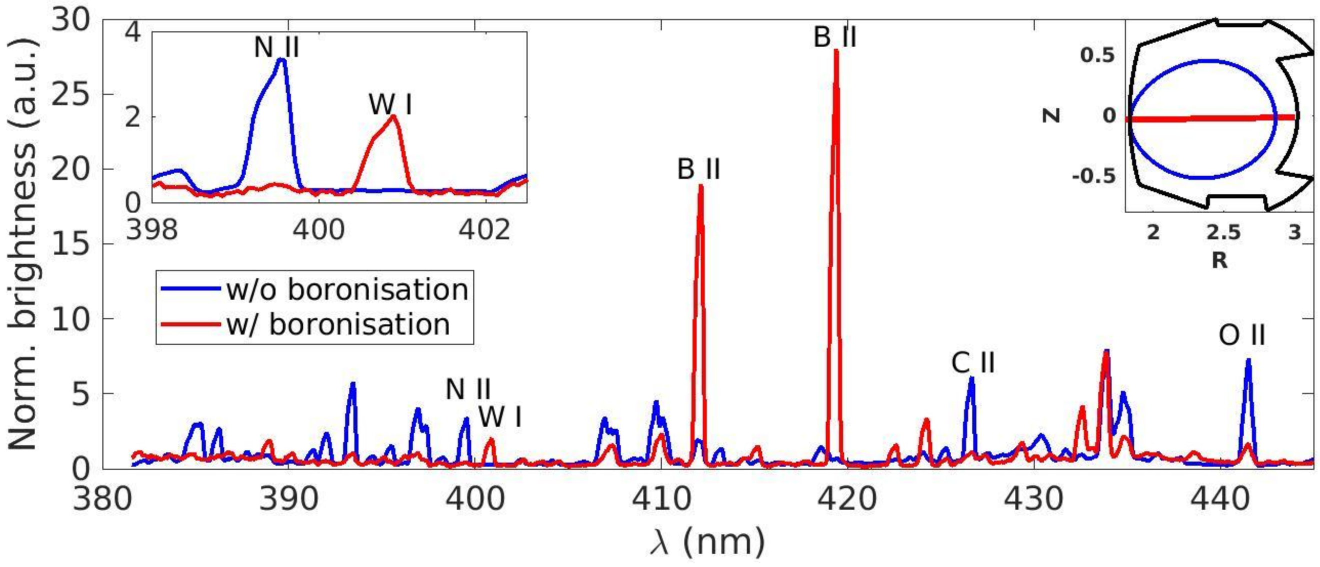


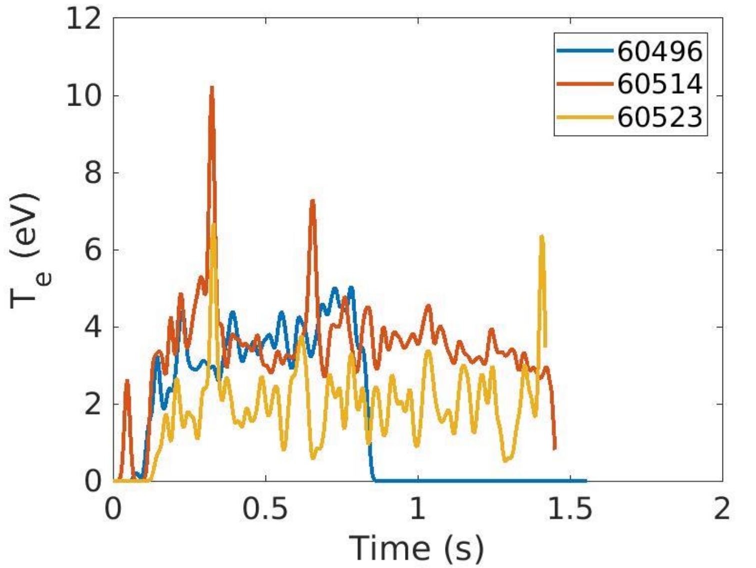


- High loop voltage and low density can lead to sustained runaway beams

WEST plasma restart on *inboard* limiter without boronisation

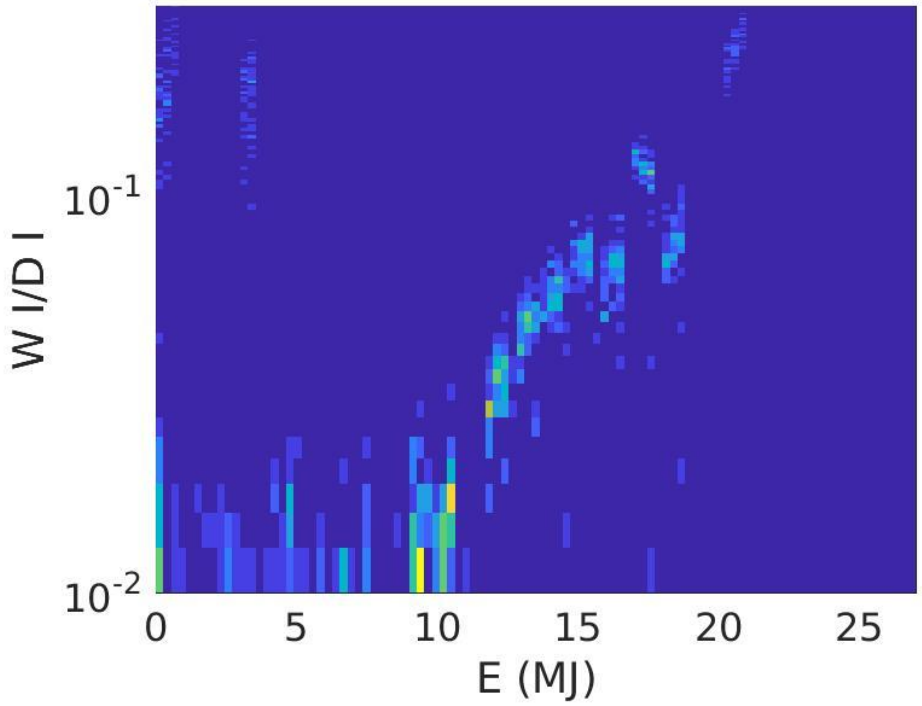
- Startup on bulk W inner limiter
- Density uncontrolled (strong outgassing from wall) but progressive conditioning
- RGA shows dominant mass 3 (HD) over 4 (D2) and isotopic ratio increasing during discharge (no D2 injection)
- Most plasmas cold and dense and do not attach on inner limiter (increase in density and P_{rad}) < 0.8 s
- Several “long pulses” obtained (~1.5 s) and up to 600 kA!
- Sawteeth observed and low loop voltages (~1 V)
- Visible spectroscopy shows dominant presence of oxygen carbon, nitrogen (also from UV) but no tungsten
- Newly installed Langmuir probes on inner limiter providing data (Tantalum probes embedded in tungsten tiles in the lower half of the limiter) with T_e < 10 eV

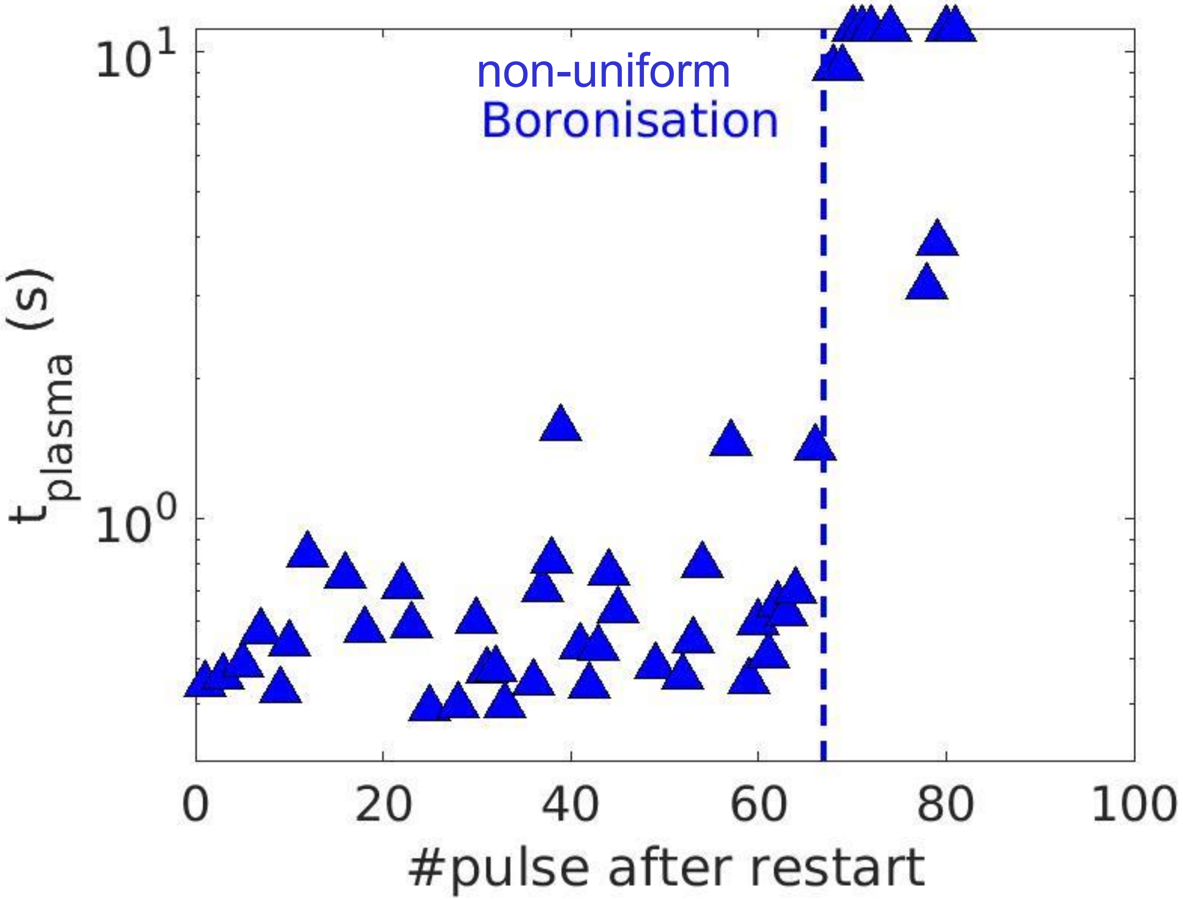




WEST plasma restart after non-uniform boronisation

- **First plasmas after non-uniform boronisation**
  - Startup on W inner limiter (ohmic pulses)





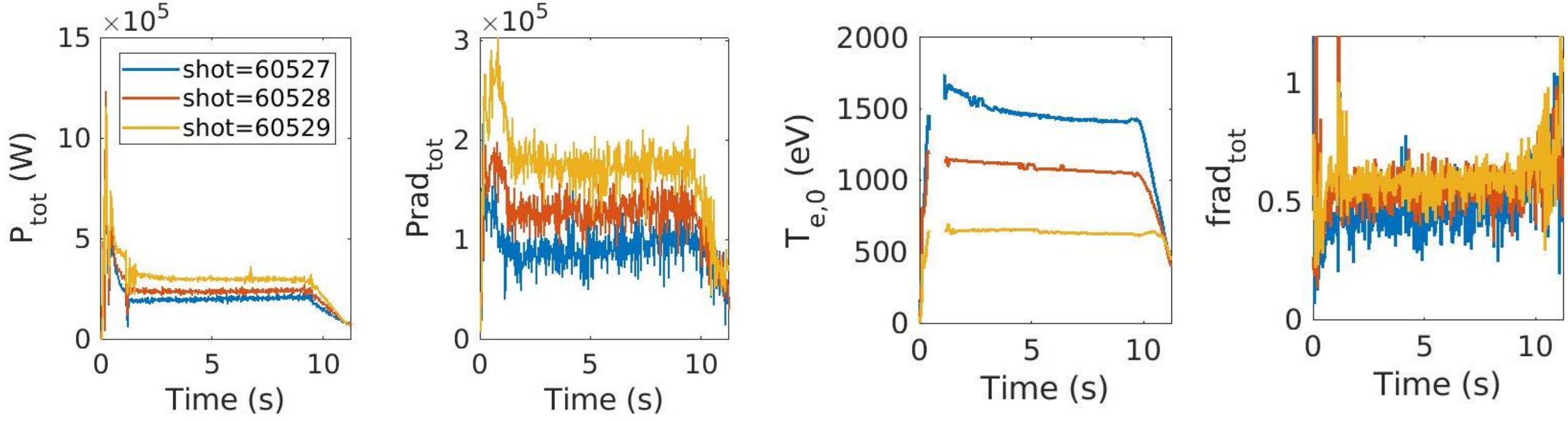
- First two shots with natural density (n ~ 0.5 x 10^{19}m^{-3})
- Increasing intensity of tungsten visible line during the first two shots without gas injection

- Long pulses only after boronization
- Small conditioning effect visible

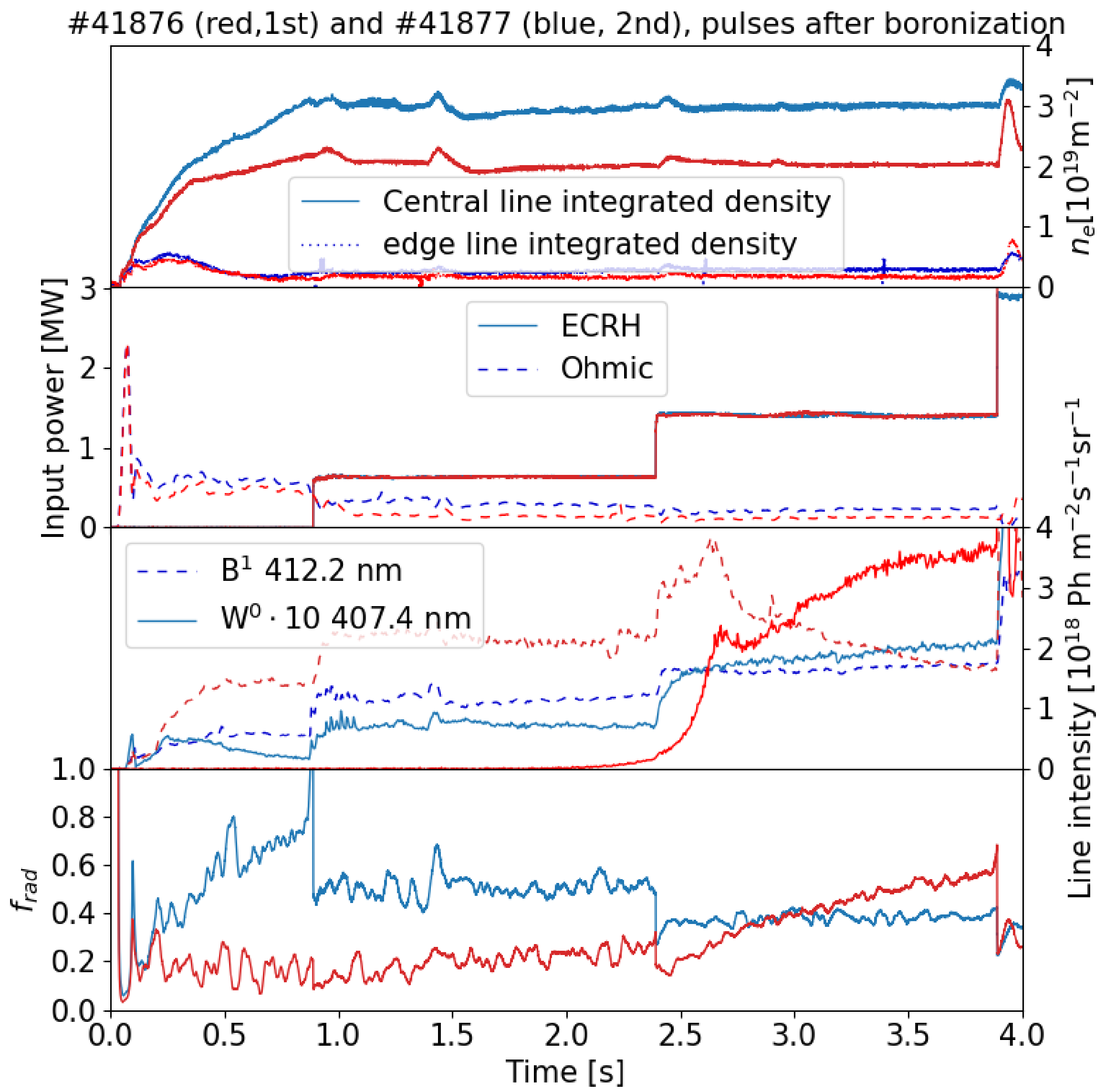
3 consecutive shots with increasing core W radiation

First cases with consecutive ohmic shots after boronisation:

- ❑ Central temperature decreasing from shot to shot
- ❑ Radiated power increasing together with ohmic power
- ❑ Lower frad for 60527 but similar between 60528 and 60529



Pulses directly after boronization work well

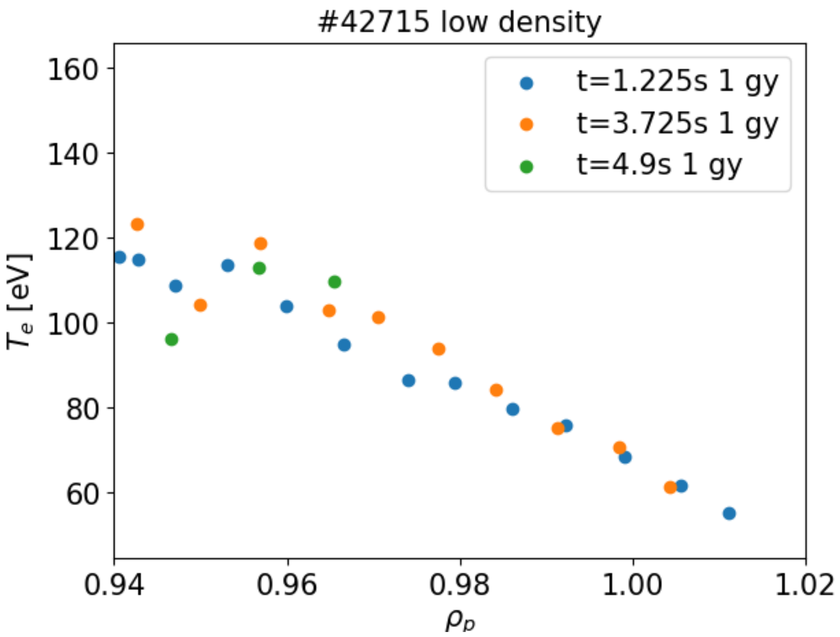


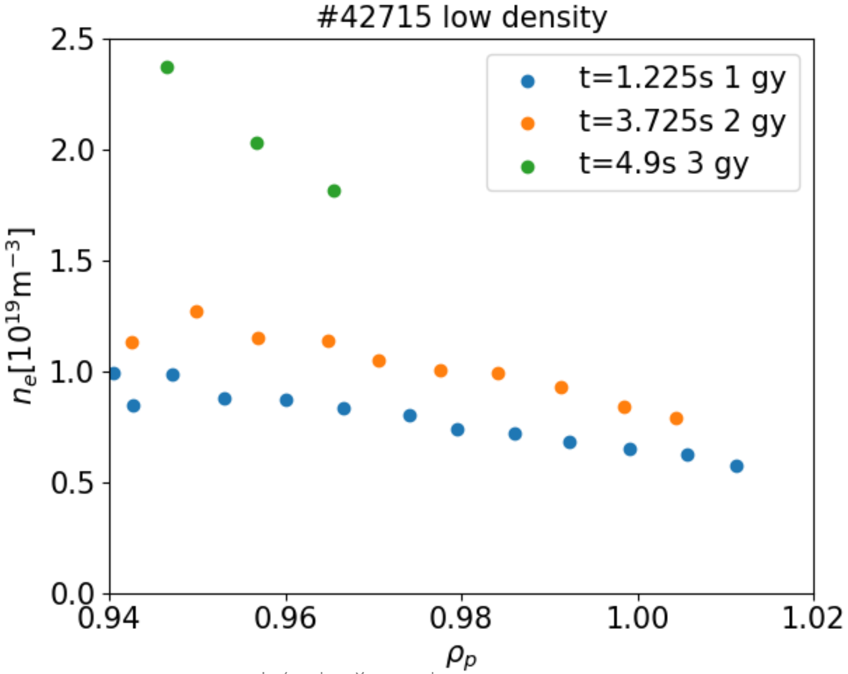
- 2 core densities on outboard limiter
- ECRH power scan 0.8MW and 1.5MW
- High heating power (5MW/3MW in 41876/41877) phase leads to melting and unstable plasmas
- Higher density pulse very stable in both heating phases
- W source and f_{rad} are increasing with time, even though background plasma stable. Max f_{rad}~57%, stronger visible at low density
- No W source in #41876 before 2 gyrotron phase

→ indication of B layer lifetime

- **Operation on outboard limiter not dependent on limiter surface B layer health**

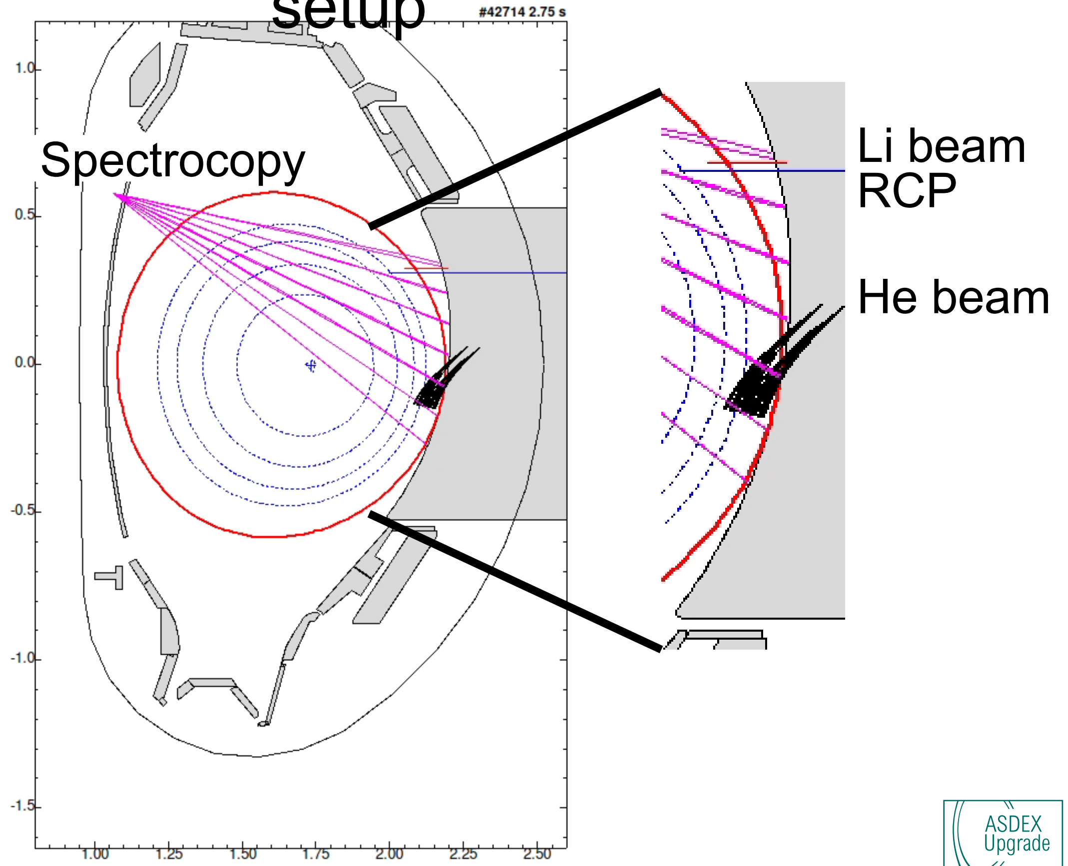
Profiles do not change with heating power, diagnostics agree



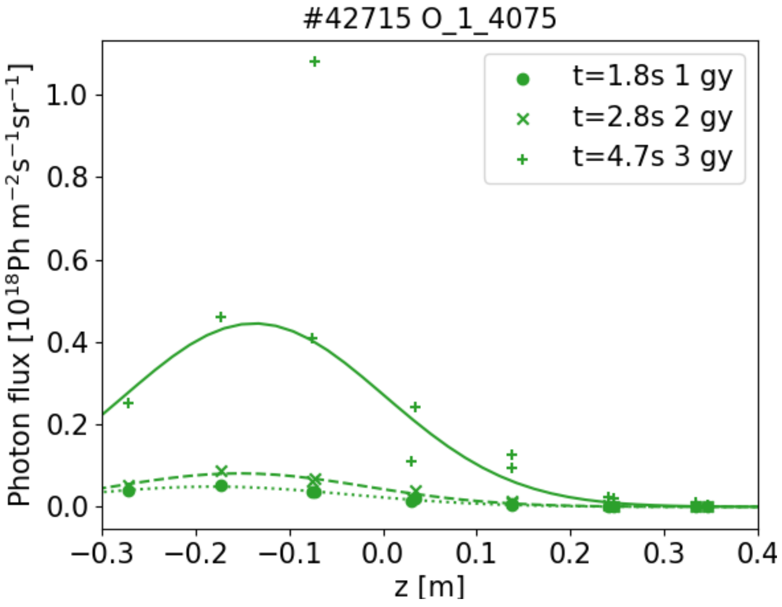


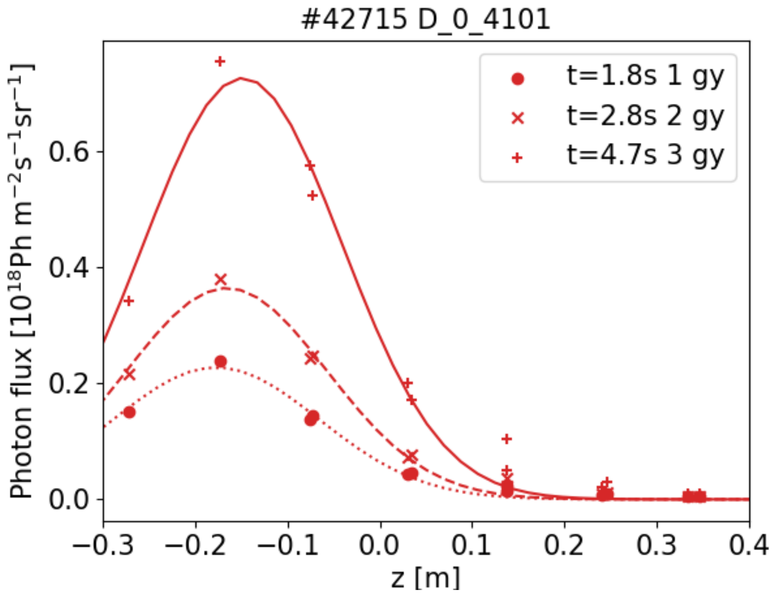
- Pulse with low density and 1.7MW ECRH
- n_e^{LCFS}~5-12·$10^{18}m^{-3}$
- T_e^{LCFS}~40-60eV
- LCFS electron temperature constant with input power
- LCFS density increasing

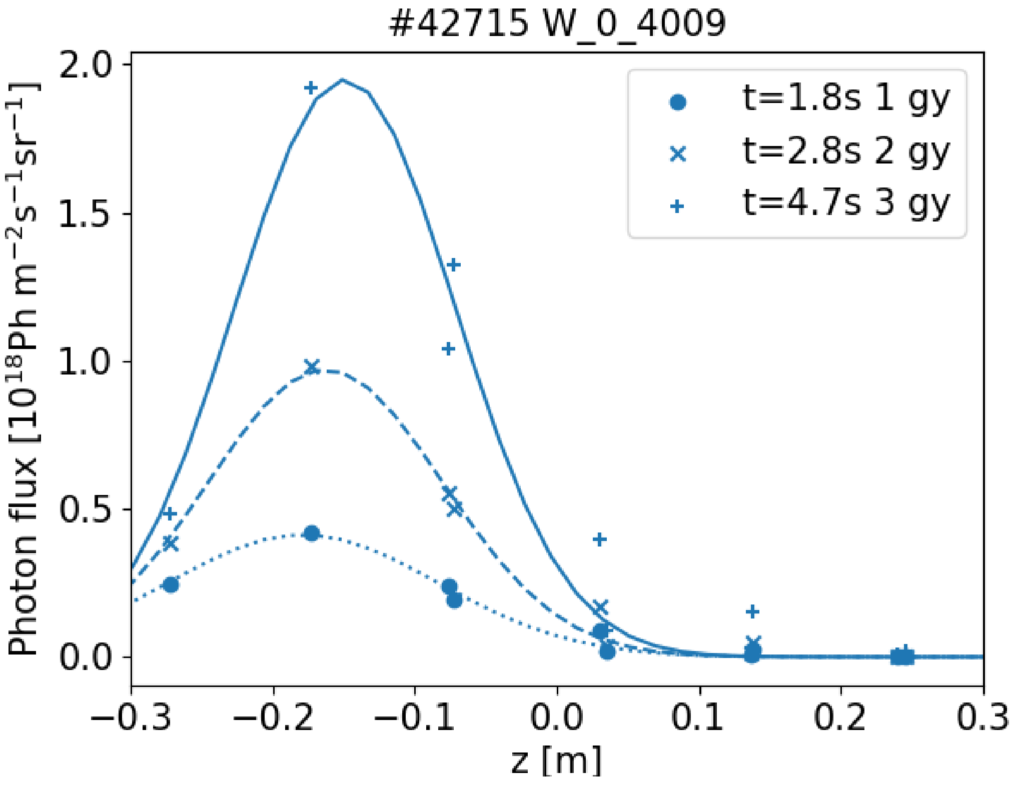
Diagnostic setup



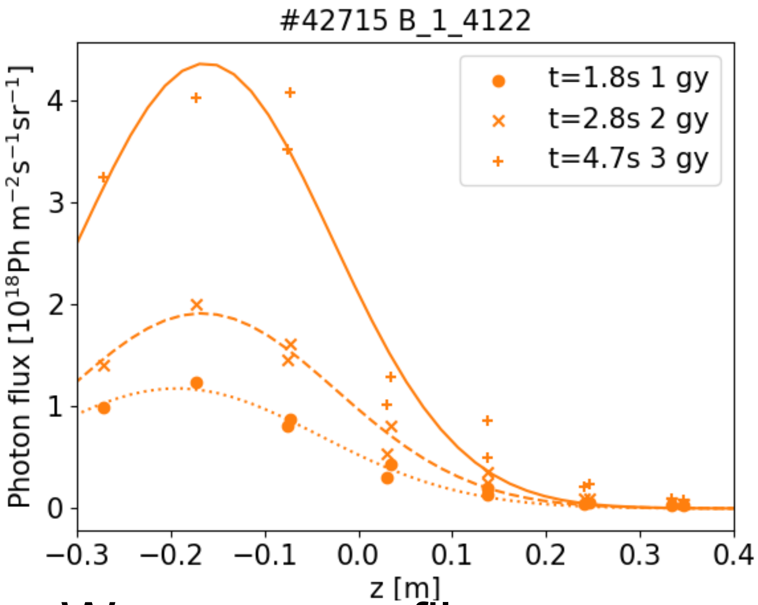
At constant density impurity sources increase with input power





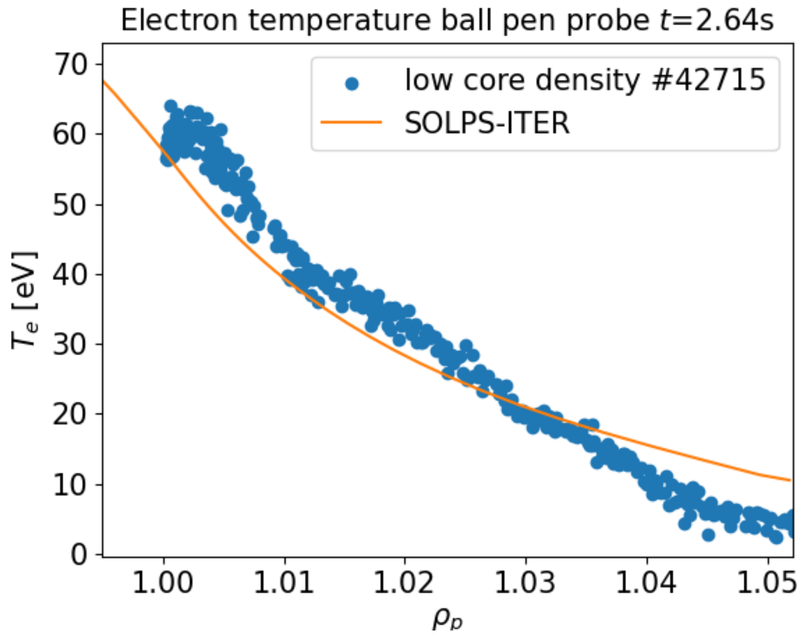


W source profile for 3 different heating phases, similar pulse to shown before, low density

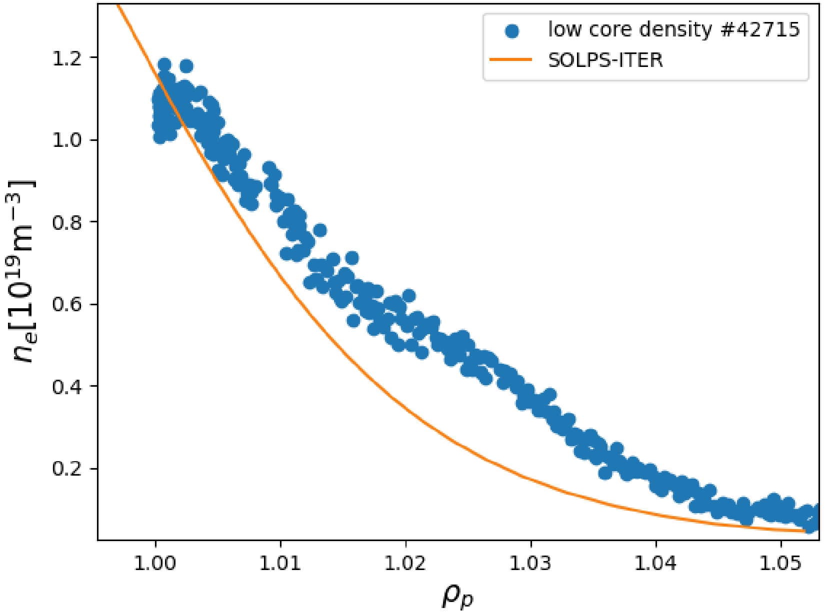


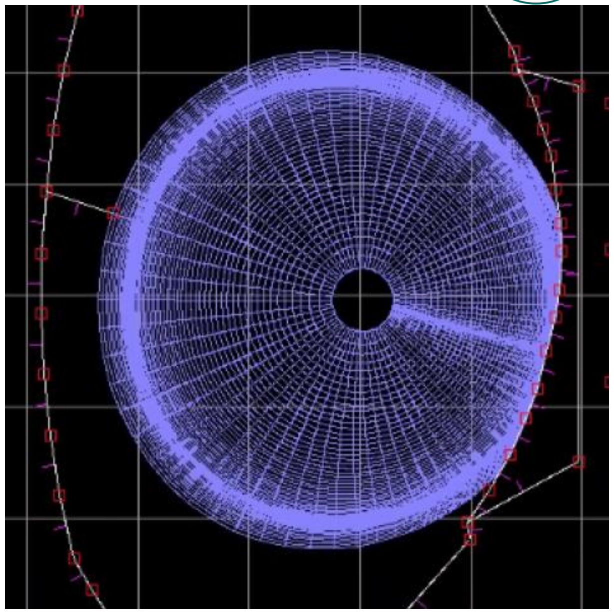
- W source profile narrow
- Other profiles wider
- W source proportional to input power
- Oxygen only increases at highest power

SOLPS-ITER run matches experimental profiles well



Courtesy A. Pshenov





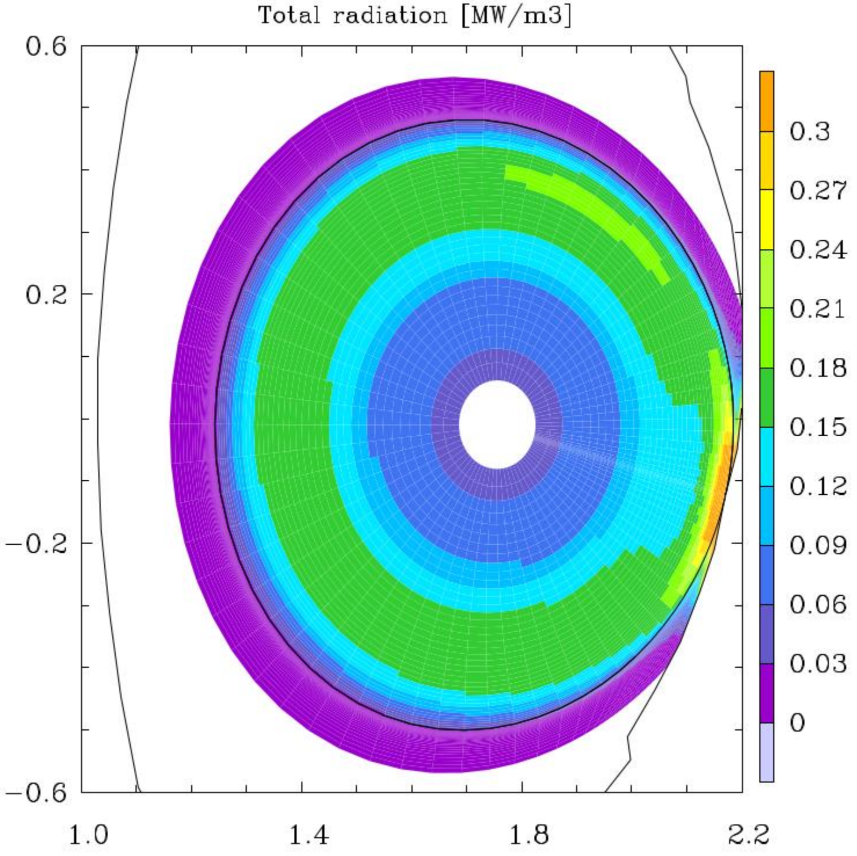
- SOLPS has been run to match the ASDEX Upgrade parameters.
- Uniform transport assumed
- W self consistently calculated (source ↔ radiation balance)
- Impurities (B,O) have little impact on result!
- W source in SOLPS mainly by W self sputtering
- Main “tuning” parameter r_{prompt} roughly consistent with publications* and ERO calculations for ITER

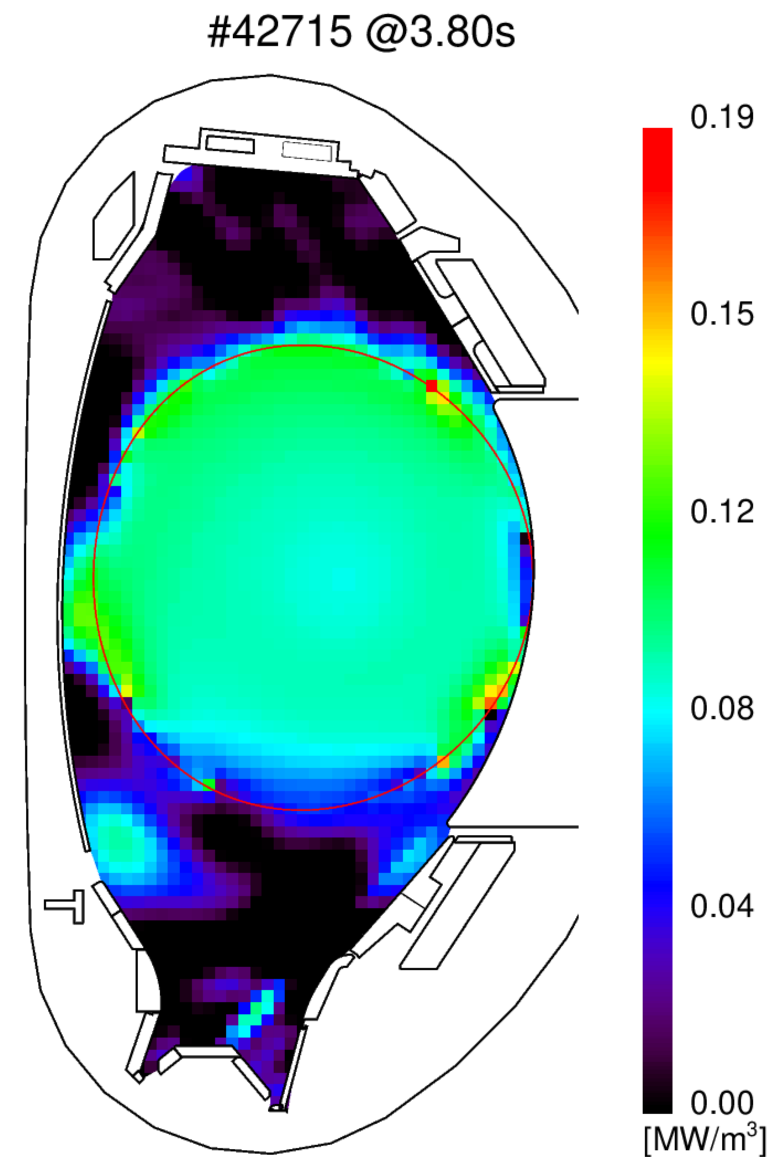
Used parameters:
$D=0.5m^2/s$
$\chi_{e,i}=1m^2/s$
$v_{pinch}=2m/s$ (only W)
$P_{heat}=1.7MW$ 2:1 e:i
$c_B=2\%$
$c_O=0.5\%$
W up to W40+
$r_{prompt}=0.6$
$n_{e,sep}=6\cdot10^{18}m^{-3}$

* S. Brezinsek et al, Phys. Scripta, T145 (2011) 014016

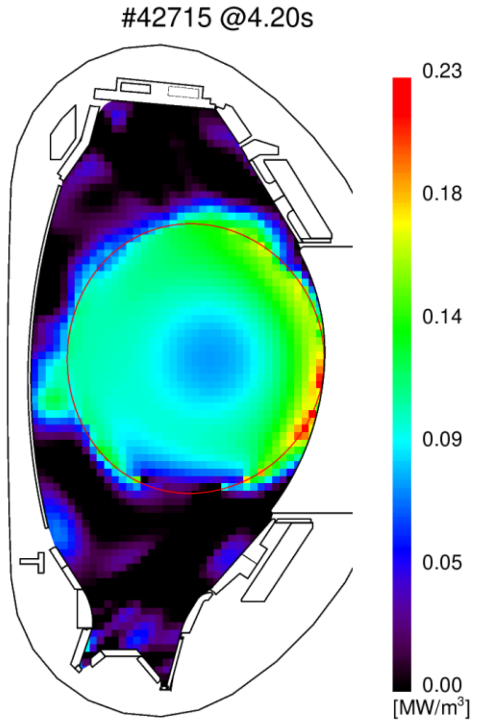
SOLPS-ITER calculation gives a very similar radiation pattern

SOLPS-ITER





- Radiation pattern from SOLPS-ITER very similar to experimental one
- Profile very flat – no peaking
- Higher radiation at interaction point



Courtesy A. Pshenov

Summary and conclusions

- “Multi-machine” experiment conducted (AUG, EAST, WEST) in support of ITER
- AUG and WEST have tried a non boronized startup
- Both experiments show difficulties to control the (low Z) radiation and to produce long flattop plasmas without boronization
- more runtime and/or heating power could have allowed longer pulses
- Non-uniform boronization allows “normal” startup
- Detailed impurity source and plasma data has been collected
- Preliminary SOLPS-ITER runs show very good agreement with AUG data
- These AUG and WEST experiments clearly indicate that ITER's decision to include a diborane boronization system is an important risk mitigation measure!

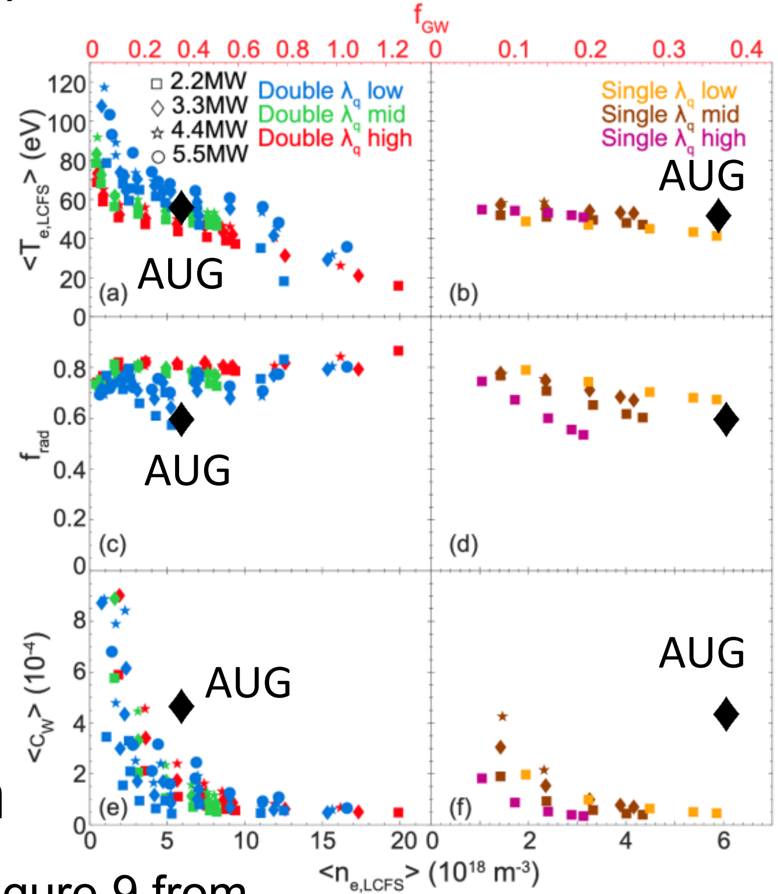


Figure 9 from
Y. Zhang, NF **65** (2025), 056035