Non-Boronized Operation of ASDEX Upgrade with Full-Tungsten Plasma Facing Components


MPI für Plasmaphysik, EURATOM Assoziation, Garching bei München
Main physics questions related to an all-tungsten tokamak
- to be answered without compromise by un-boronized operation

Is the hydrogen retention problem of a carbon machine relaxed/solved by using plasma facing components (PFCs) made of tungsten?

Is it possible to have plasmas with low W-concentration and good H-mode confinement?

• tungsten sources
  - spatial distribution over PFCs
  - contribution of ELMs

• tungsten transport and impact of sources on concentrations
  - edge transport barrier, edge and core inward pinch
  - W source and W removal by ELMs

What are the operational restrictions due to tungsten?
Step-wise tungsten coating of PFCs finished in 2007

Step by step replacement of C tiles by W coated tiles

• 3 – 4 µm W-PVD on most tiles
• 200 µm plasma-sprayed W at outer strike point

First 1.5 experimental campaigns with full-W done without boronisation for uncompromised results
AUG inner divertor: deposition of B + C

Total amount deposited

- C: 14.6 g
- B: 2.8 g
- C: 2.2 g
- B: 2.3 g
- C: 1.0 g
- B: < 0.1 g

Reduction of deposited impurity layers by factor 15

W coating of outer limiters

W divertor

No boronization

All numbers normalized to 3000 s discharge time
In 2008 shiny metallic plasma facing components

no color filter trick: uncleaned edge
AUG divertor: Evolution D inventory

Carbon dominated machine
• total D-inventory dominated by inner divertor and remote areas

All-W machine
• boronizations result in high D-inventory, co-deposition with B (2005/2006)
• D-inventory dominated by trapping in VPS-layers at outer strike point
• decrease of total D-inventory by factor 5 – 10 from C-dominated to unboronized all-W
• fuel storage in W expected less than linear with flux

combined effect of reduced B and C codep
Deuterium inventory from gas balance

D retention 30 s after discharge:

3.6 ± 2.7 %

Compare: long-term D retention in full-W AUG is 0.4-0.6 % of gas input
Full-W operation without boronization: higher impurity level

overall, medium term reduction of $Z_{eff}^{-1}$ due to boronisation by 20-30 %
Restrictions of the operational space
Understanding the operational range of an all-W tokamak

- no influence of tungsten PFCs with and without boronisation on Ohmic and L-mode plasmas (except slightly reduced density limit without boron)

- no negative effect on plasma startup (after learning phase)

- in 2008 unboronised startup after summer vent:
  5th discharge reached current flattop, 8th discharge H-mode

- restrictions in H-mode operation by central radiative losses
Understanding the operational range of an all-W tokamak

central density peaking, in combination with W accumulation, sets central power operational limit in H-mode
Dedicated experiments to define the operational range

central W accumulation connected to electron density peaking - clearly controlled by gas puff and central heating
Understanding the operational range of an all-W tokamak

Operational space
with and without boronization
Relaxed restrictions on gas feed and ECRH with high heating power

- At high power, operation with small (no-boron) or zero (boron) gas puff possible.
- Anomalous transport beats neoclassical inward drift at high power flux.
- With boron (lower $P_{\text{rad}}$), divertor power density limit reached (thick coatings, $\approx 10 \text{ MW/m}^2$) $\Rightarrow$ nitrogen seeding.
Understanding the operational range of an all-W tokamak

Tungsten sources and their impact on the central W concentration / radiation
Time resolved tungsten erosion profiles in the outer divertor

in H-mode plasmas:

- modulation of erosion profiles with arrival of energy bursts due to type-I ELMs
- time resolution (3ms) sufficient to measure erosion between ELMs

W sputtered almost exclusively by impurity ions

Tungsten spectroscopy using 400.9 nm WI line evaluated with S/XB=20

\[
\Gamma_W \quad [m^2 s^{-1}] \quad 10^{18} \quad 10^{19} \quad 10^{20}
\]

\[
t(s) \quad 4.50 \quad 4.55 \quad 4.60 \quad 4.65 \quad 4.70
\]

\[
[\mu] \quad 1.1 \quad 1.2 \quad 1.3 \quad 1.4 \quad 1.5
\]
W main chamber erosion well documented

similar total sources on HFS and LFS – details depend on plasma alignment
Limiter sources increase strongly during ICRH

- ICRF heating causes strong increase of limiter erosion and tungsten concentration
- Effect is due to increase of sheath potential drop causing an increase of the W sputtering yield
- Optimization of ICRF antennas needed - and under way

ICRH W sputtering is one tool to

outer limiters most important W source
Detailed parameter scans for influence of ELMs and W sources

W source stays ~ constant with reduction of gas puff

W concentration rises strongly with reduced ELM frequency - attributed to neoclassical W inward drift over ETB

ELMs essential in W removal
Radiative cooling with N$_2$ to reduce divertor power load

for high power, boronized discharges N2 seeding is mandatory to protect thick W coatings
thick coatings to be exchanged by more robust, thinner coatings after this campaign
Conclusions

• fuel retention in unboronized tungsten machine is considerably reduced

• stable, high performance H-mode operation with low W-concentrations obtained, provided a sufficiently high central heating power and ELM frequency

• low heating power, low ELM frequency, off-axis heating are unfavourable conditions and may lead to central peaking an W accumulation

+ Nitrogen seeding used to replace missing intrinsic radiation in boronized W-AUG

+ ELM pacemaking by pellets, and by resonant magnetic perturbations in the future
Operational space of AUG with / without boronization

extended operational database → poster EX/9-2

\[ P_{\text{heat}} - P_{\text{rad}} \quad [\text{MW}] \]

- Divertor power load limit
- Type-III ELMs
- Reduced \( \tau_E \)
- Too low \( f_{\text{ELM}} \)
- Too low \( D_{\text{ano}} \)

\[ \text{divertor } n_0 \quad [\text{m}^{-3}] \sim \text{gas valve flux} \sim f_{\text{type-I ELM}} \]