Tungsten: An option for divertor and main chamber PFCs in future fusion devices


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• Motivation

• Status of W-Coverage

• Recent Results:
  Diagnostic / W-Divertor / W-limiter / Impurity Control

• Conclusions & Outlook
Motivation

ITER: tungsten baffles in the first operation phase
probably full W wall in its reactor like operation phase

ASDEX Upgrade: transformation into a full tungsten-coated tokamak

Several issues are addressed:

- operation must be compatible to W PFCs
- high performance scenario development along W compliant route
- investigation of W sputtering and migration
- C transport in a mixed material environment (see M. Mayer, EX/P5-24)
- seed impurity scenarios to replace intrinsic C radiation
- W diagnostics (spectroscopy)
Tungsten plasma facing components in ASDEX Upgrade

Full W-divertor during ’95/96 campaign

Step by step increase of W-coated plasma facing components (since 1999) towards a full W device

rationals: - risk minimisation
- partitioning of installation time
- production capacity

2003/2004 campaign:

65% of total area (24.8 m²) of plasma facing surfaces is covered by W-coatings:

'old' components: 1 µm PVD (on graphite)
'new' components: 4 µm PVD (on graphite & CFC)
Tungsten plasma facing components in ASDEX Upgrade

new components for the 2004 campaign:

- complete upper divertor
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• complete upper divertor
• outer baffle of lower divertor
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- complete upper divertor
- outer baffle of lower divertor
- 6 tiles of one guard limiter

lower 3 tiles of guard limiter Sec8
W Diagnostic

- successful simulation of VUV and SXR spectra within ADAS framework
- large number of spectral lines arising from different ionisation states ⇒ radial reconstruction of $c_W$

### VUV

- Measurement
- Modelled Spectrum

### SXR

- $T_{e0} \approx 2$ keV
- $W^{+45} \rightarrow W^{+40}$ (Cu $\rightarrow$ As)
- $W^{+35} \rightarrow W^{+27}$ (QC)
- $W^{+46}$ (Ni)

### ADAS

- $T_{e,\text{cntr}} = 3.9$ keV
- $^{74}W$ - measurement
- $W^{+38} \rightarrow W^{+48}$

### Brightness

- $10^5 W/m^2/sr/nm$
W Diagnostic

- Successful simulation of VUV and SXR spectra within ADAS framework

- Large number of spectral lines arising from different ionisation states
  \[ \Rightarrow \] radial reconstruction of \( c_\text{W} \)

- Consistent treatment of atomic data within ADAS
  \[ \Rightarrow \] refinement of cooling factor
Operation with W divertor

H-mode with $P_{\text{heat}} \approx 7.5\text{MW}$

configuration scan:
   Upper SN→LSN→USN→inner lim.

no remarkable difference of $W$-content between USN (W) / LSN (C)
first USN phase at low density has increased $n_W$ (hot divertor?)
limiter phase uses W-coated inner column as limiter
   $\Rightarrow$ strong rise of $n_W$

similar to W Div I experiment: divertor is not a strong tungsten source unless $T_e$ is too high
Operation with W divertor

high performance discharge $\beta_N = 2.8$, $H_{98y2} = 0.95$, $n_e/n_{gr} = 0.75$

in upper SNU feasible at low $c_W$

power load in between ELMs
W erosion by thermal and fast particles

Erosion at guard limiter:

- particle fluxes from spectroscopic measurements
- energy deposition from thermocouples in 3 tiles

- post mortem analysis (X-ray fluorescence): max. erosion ≈ 1 μm, (> 10 x larger than measured at other main chamber components)
W erosion by thermal and fast particles

Erosion at guard limiter:

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- energy deposition from thermocouples in 3 tiles
- post mortem analysis (X-ray fluorescence): max. erosion ≈ 1 μm, (> 10 x larger than measured at other main chamber components)
- same range of W influx densities and effective sputtering yields as in W Div I
W erosion by thermal and fast particles

W erosion at guard limiters depends strongly on:

- plasma parameter
- distance of observed limiter region to separatrix
- localized ion load if plasma does not fit limiter shape
- shielding of limiter by other limiters

W influx density follows roughly:

\[ \Gamma_W \propto \exp \left[ - \frac{x}{\lambda} \right] \]

\( x = \) separatrix distance, \( \lambda = 1.5 \text{ cm} \)

Power decay lengths: 0.8 cm

(see A. Herrmann, EX/2-4Rb)
**W erosion by thermal and fast particles**

### Theoretical estimate for erosion yield

thermal ion load with 1% C\(^4\+)
assuming equilibrated carbon coverage:

- \( Y_{\text{eff}} = \frac{W}{\Gamma D} \)

  - explains range of effective sputtering yield
  - does not explain large deposited energy per D

- fast ions contribute strongly to energy deposition
- less sputtered particles per deposited energy!

Preliminary results from code calculations (FAFNER, ASCOT) support picture:

\[ E_{\text{dep}}^D = \frac{\text{total deposited energy on tile}}{\text{shot integrated deuterium flux}} \]

\[ = \text{average deposited energy per D} \]

(discharges with dominant steady state)
W behaviour / operational issues

Conditions for low W-concentration \((c_W < 10^{-5})\)
- divertor configuration
- control impurity transport in plasma centre: (accumulation)
  - avoid strongly peaked density profiles combined with low anomalous transport
  - ⇒ central heating by ECRH/ICRH
  - ⇒ small reduction of performance \(\approx 10\%\)
  - (see A. Stäbler, EX/4-5)

![Graph showing impurity transport from Si LBO and performance implications.](graph)

impurity transport from Si LBO:
strong increase of \(D_{an}\) for central heating

![Graph showing ne(0)/ne(0.8) vs. \(c_W/3\) keV.](graph)

impurity control see: R. Dux, EX/P6-14
W behaviour / operational issues

Conditions for low W-concentration \( (c_W < 10^{-5}) \)

- divertor configuration
- control impurity transport in plasma centre (accumulation):
  avoid strongly peaked density profiles combined with low anomalous transport
  \( \Rightarrow \) central heating by ECRH/ICRH
  \( \Rightarrow \) small reduction of performance \( (\approx 10\%) \)
- control impurity transport in H-Mode edge transport barrier (impurity inventory):
  avoid long ELM free H-phases
  \( \Rightarrow \) stay away from H-L threshold
  \( \Rightarrow \) ELM pace-making

\( \Rightarrow \) integrated scenario with:
- central heating
- ELM pace-making
- radiation cooling by Ar seeding

see P. Lang, EX/2-6
Prediction for ITER reference scenario (inductive operation)

Q=10  P(NBI)=40MW  \(U_{loop} \approx 75\text{mV}\)

- \(T_e, T_i\) fixed

- \(D_{an}\)
  - at edge: 1m\(^2/\text{s}\)
  - in centre: varied

- \(v_{an}\) (fit to GLF23 profile)

- \(D_{neo}, v_{neo}\) from NEOART

- 6 components
  - \(D, T, \text{He, Be, Ar, W}\)

- \(n_e\) from quasi neutrality

- edge densities fixed
  - \(\text{He}(\approx 3\%)\)
  - \(\text{Be}(2\%)\)
  - \(\text{Ar}(0.1\%)\)
  - \(\text{W}(0.001\%)\)

no strong W accumulation expected as long as 
\(D_{an} \approx D_{neo}\) and \((v/D)_{an}\) not increasing with Z

see R. Dux, EX/P6-14
Summary

- progressive increase of W coated PFCs towards a full tungsten based ASDEX Upgrade

- W diagnostic well established and ready for extrapolation

- typ. $c_W$ increased with W area $\Rightarrow$ more demanding plasma operation: equilibria, heating profile, ELM activity

- USN and LSN discharges have similar W content, divertor W source is not dominant

- fast particle play important role for low field side W erosion

- impurity seeding compatible with W-PFCs $\Rightarrow$ stable integrated scenario available

- no W accumulation expected for ITER reference scenario

further extension of W surfaces under way, full W device first possible in ’06/07
Extension of W surface / main investigations 2004/2005

W extensions:

- newly designed guard limiter
- vertical plate between lower divertor and PSL
- aux. limiter between upper PSL and divertor
- ICRH antenna limiter

Investigations will be concentrated on:

- performance of coatings
- parameter dependance of W influx from ICRH and guard limiter
- interconnection of W content and discharge conditions / plasma parameters
- behaviour with seeded impurities

⇒ provide information for full W device (first possible in 2006/2007)
Extension of W surface / main investigations 2004/2005

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Performance of W tiles

divertor baffle (4 μm) power load:
coating problems

central column (ramp/down limiter)
beam dump (1 μm)
> 2000 discharged, no damage

upper divertor (4 μm)
$P_{avg} \leq 10 \text{ MW/m}^2$
melting at edges:
estim. power > 20 MW/m$^2$

no strong degradation during second half of campaign

at test limiter (4 μm):
CFC surface very inhomogeneous

loss of W-coating
W behaviour / operational issues

Conditions for low W-concentration ($c_W < 10^{-5}$)

- divertor configuration
Long term evolution of $W$ concentration

- gradual increase of $W$ concentration (5 -10 x) for increasing $W$ coverage (2001 → 2003)

- ohmic discharge: good measure for $W$ source

- similar increase for H-Mode discharges, partly obscured by transport

- effect of boronisation not very pronounced

- $C$ content in main plasma barely changed

- first hints for increased divertor electron temperatures
W behaviour / operational issues

- limiter ITBs:
  → high central W-content

- divertor ITBs
  → $c_W$ strongly reduced compared to limiter operation
  → ITB formation and decay usually not influenced

↔ long term evolution of $c_W$ not clear
W erosion by thermal and fast particles

**FAFNER**
start distribution of fast beam ions

**ASCOT** (Helsinki University)
fast ion orbits + collisions

First (preliminary) simulations support assumption of considerable fast ion contribution to limiter load