ASDEX Upgrade

IPP

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

R. Neu, R. Dux, A. Kallenbach, C.F. Maggi, T. Pütterich, M. Balden, T. Eich, J.C. Fuchs, O. Gruber, A. Herrmann, H. Maier, H.W. Müller, M. O'Mullane*, R. Pugno, I. Radivojevic, V. Rohde, A.C.C. Sips, W. Suttrop, A. Whiteford*, M.Y. Ye, ASDEX Upgrade Team

MPI für Plasmaphysik, Euratom Association, Garching, Germany
*University of Strathclyde, Glasgow, United Kingdom

- **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

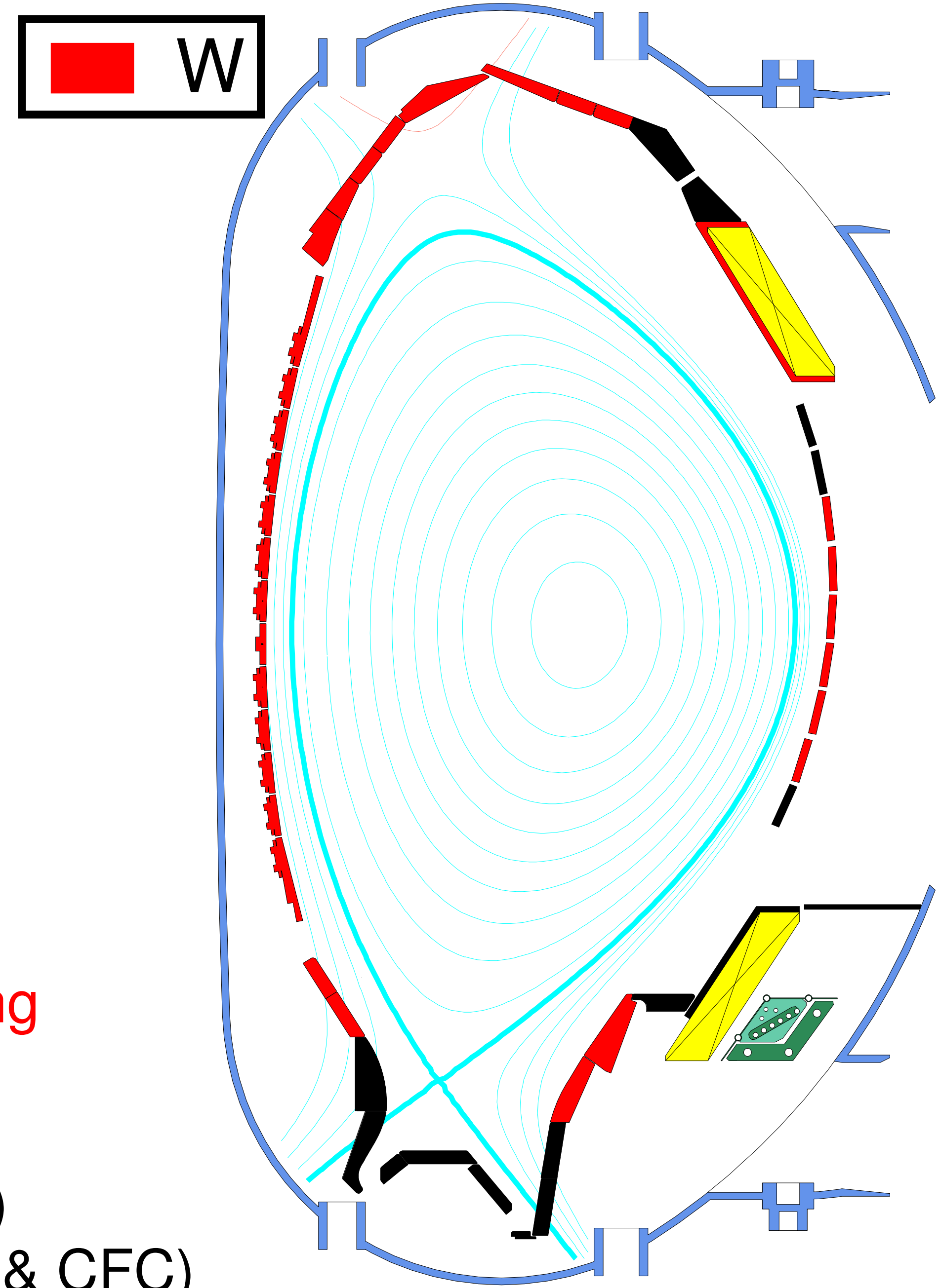
Step by step increase of W-coated plasma facing components (since 1999) towards a full W device

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

2003/2004 campaign:

65% of total area (24.8 m^2) of plasma facing surfaces is covered by W-coatings:

'old' components: 1 μm PVD (on graphite)
'new' components: 4 μm PVD (on graphite & CFC)

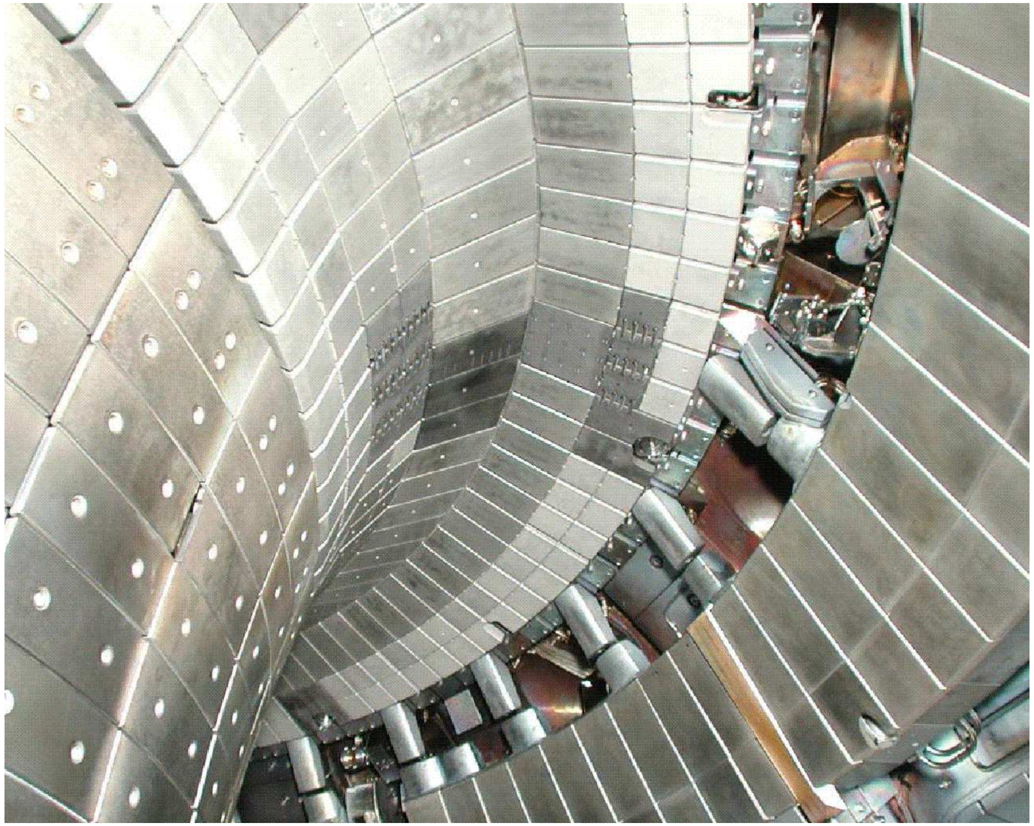


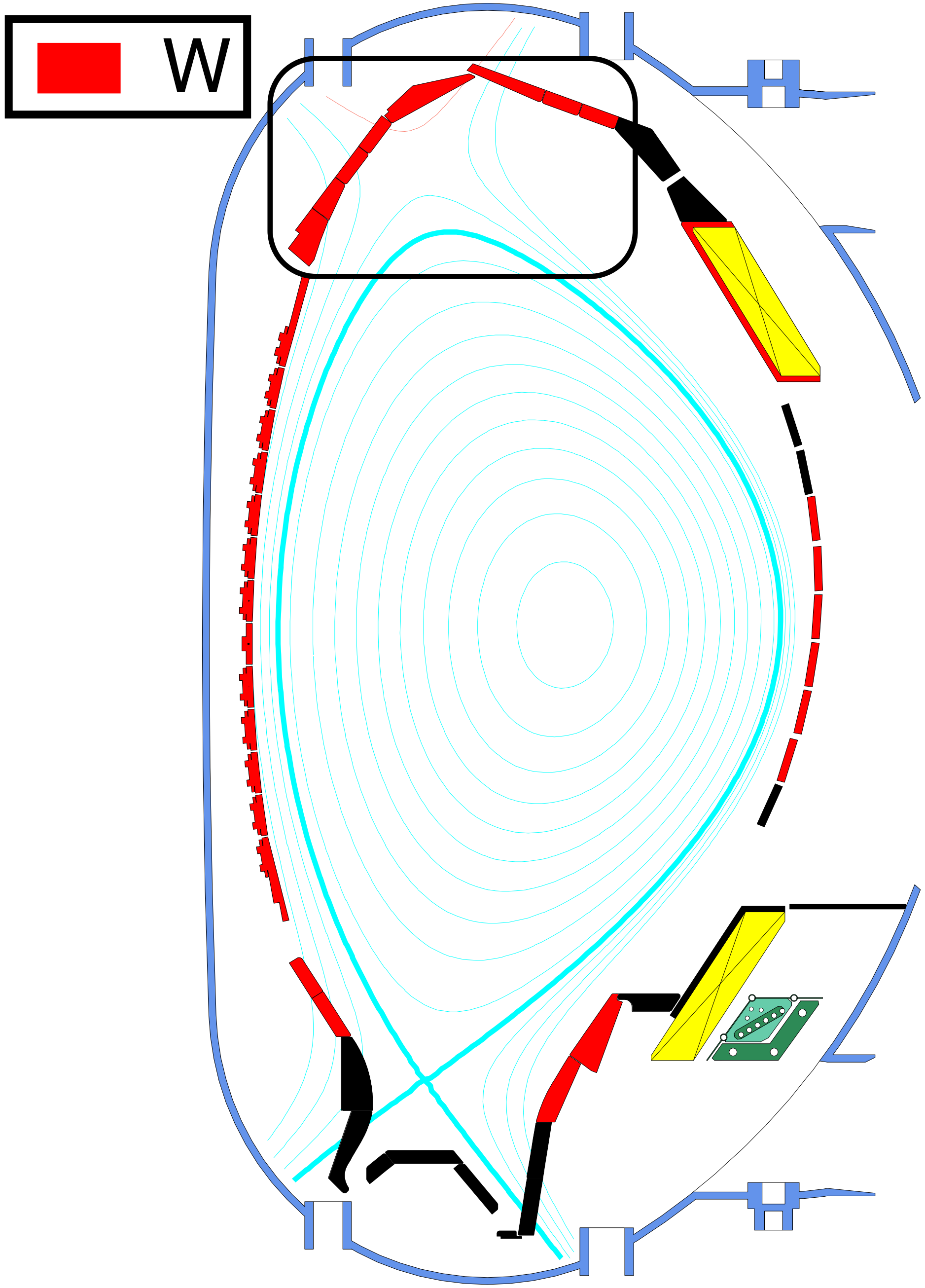
Tungsten plasma facing components in ASDEX Upgrade

new components for the 2004 campaign:

- **complete upper divertor**

upper divertor



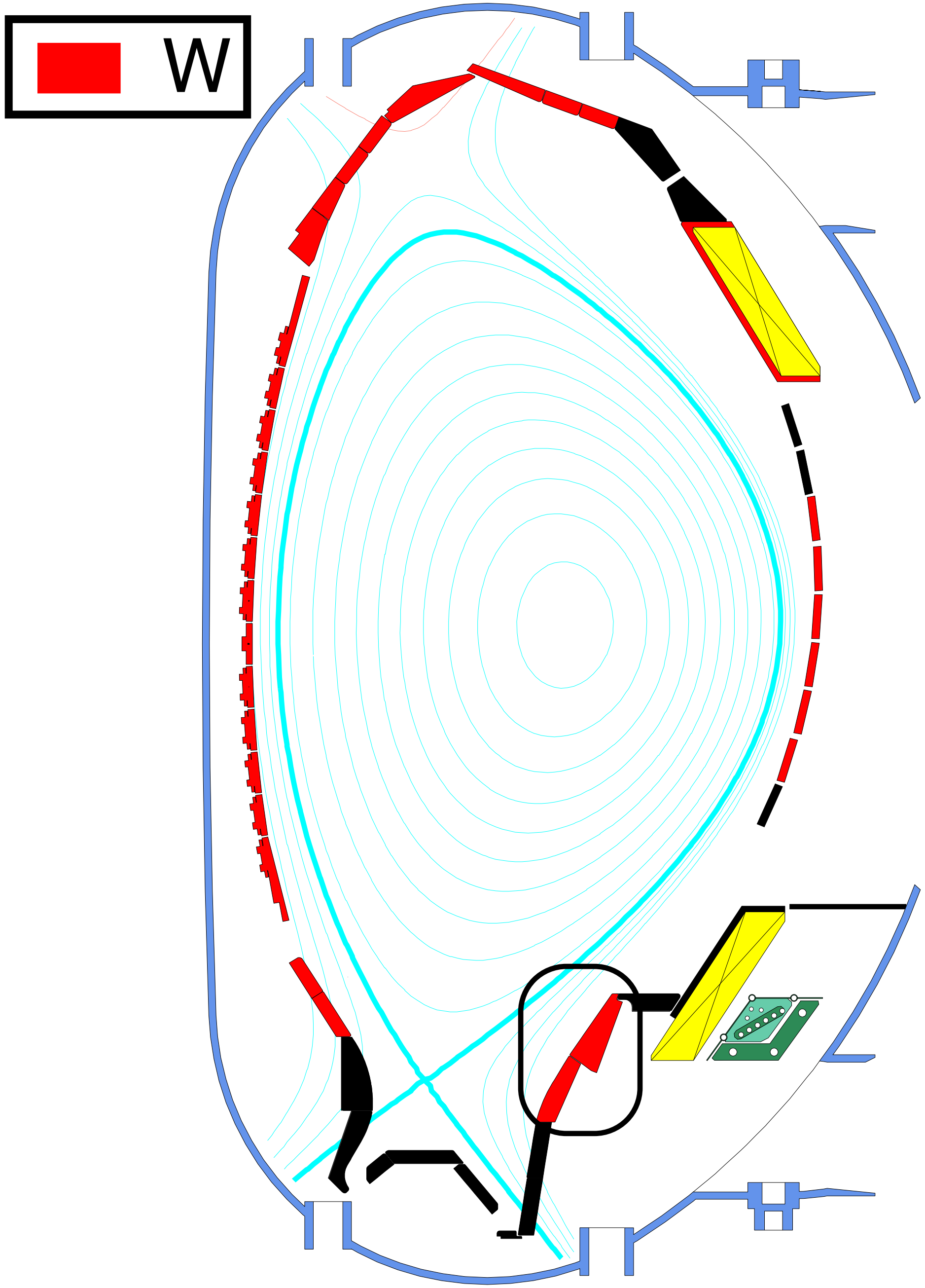


Tungsten plasma facing components in ASDEX Upgrade

new components for the 2004 campaign:

- **complete upper divertor**
- **outer baffle of lower divertor**

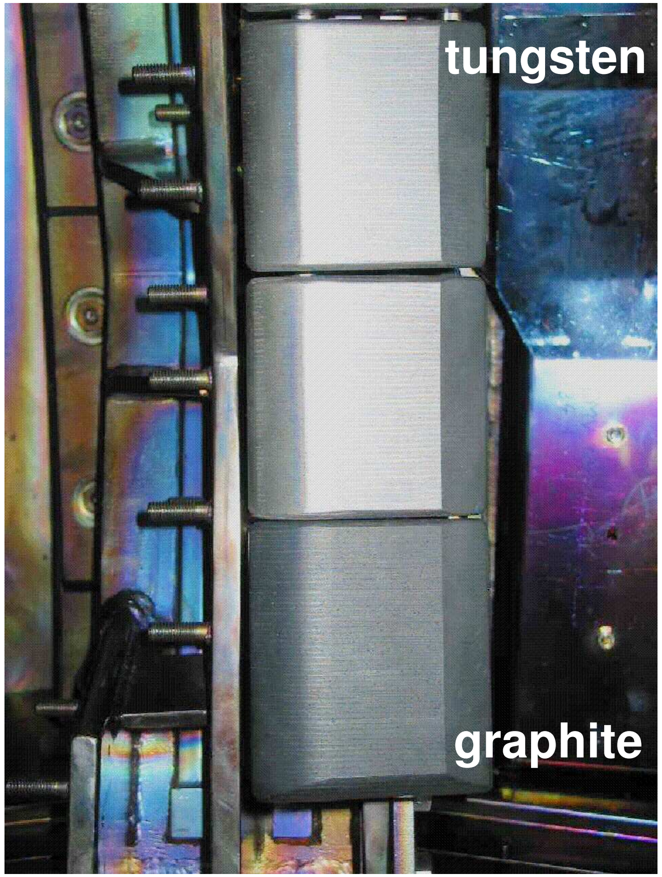
lower divertor

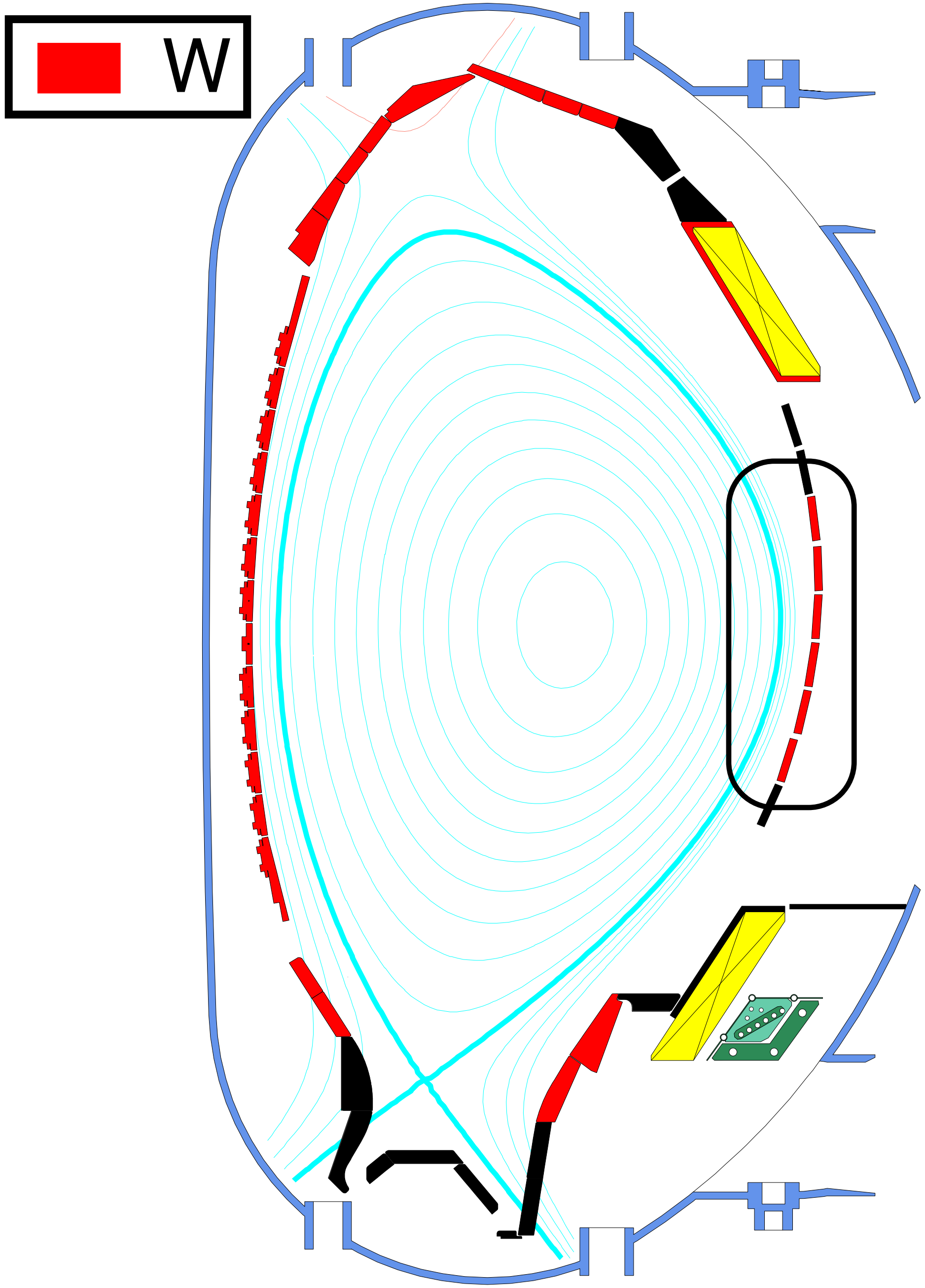


Tungsten plasma facing components in ASDEX Upgrade

new components for the 2004 campaign:
- **complete upper divertor**
- **outer baffle of lower divertor**
- **6 tiles of one guard limiter**

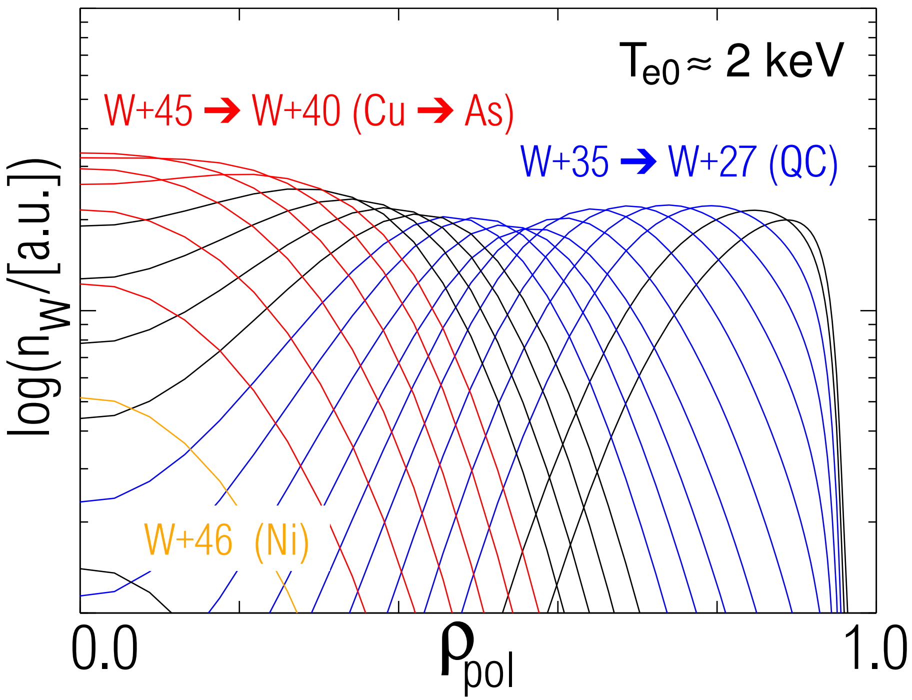
lower 3 tiles of guard limiter Sec8

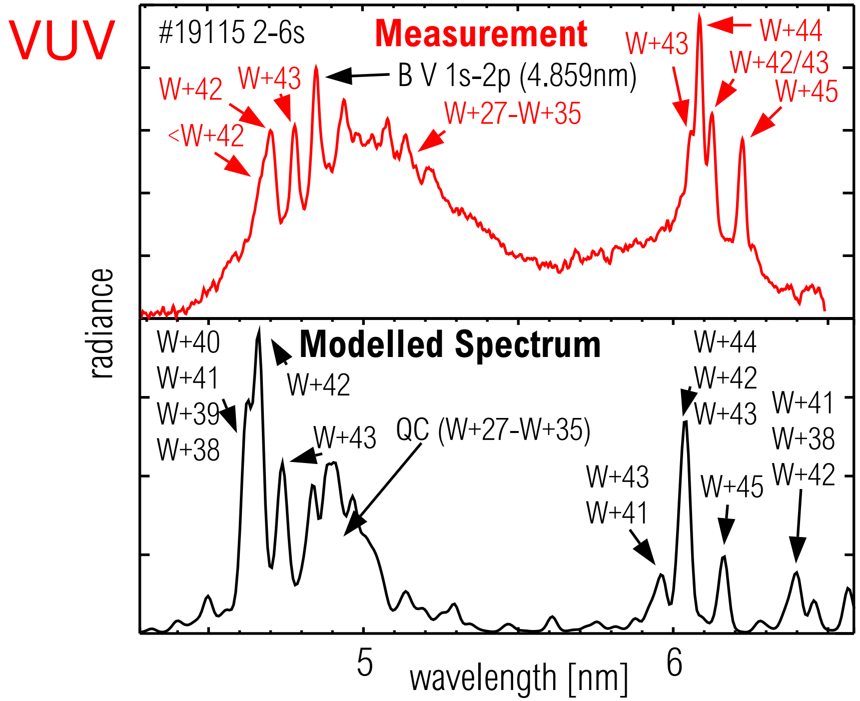


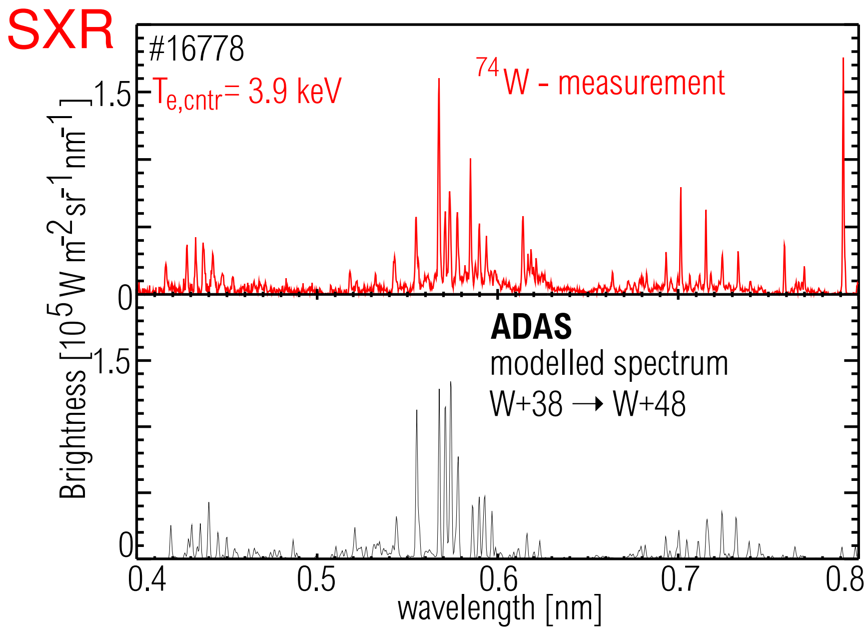


W Diagnostic

- 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

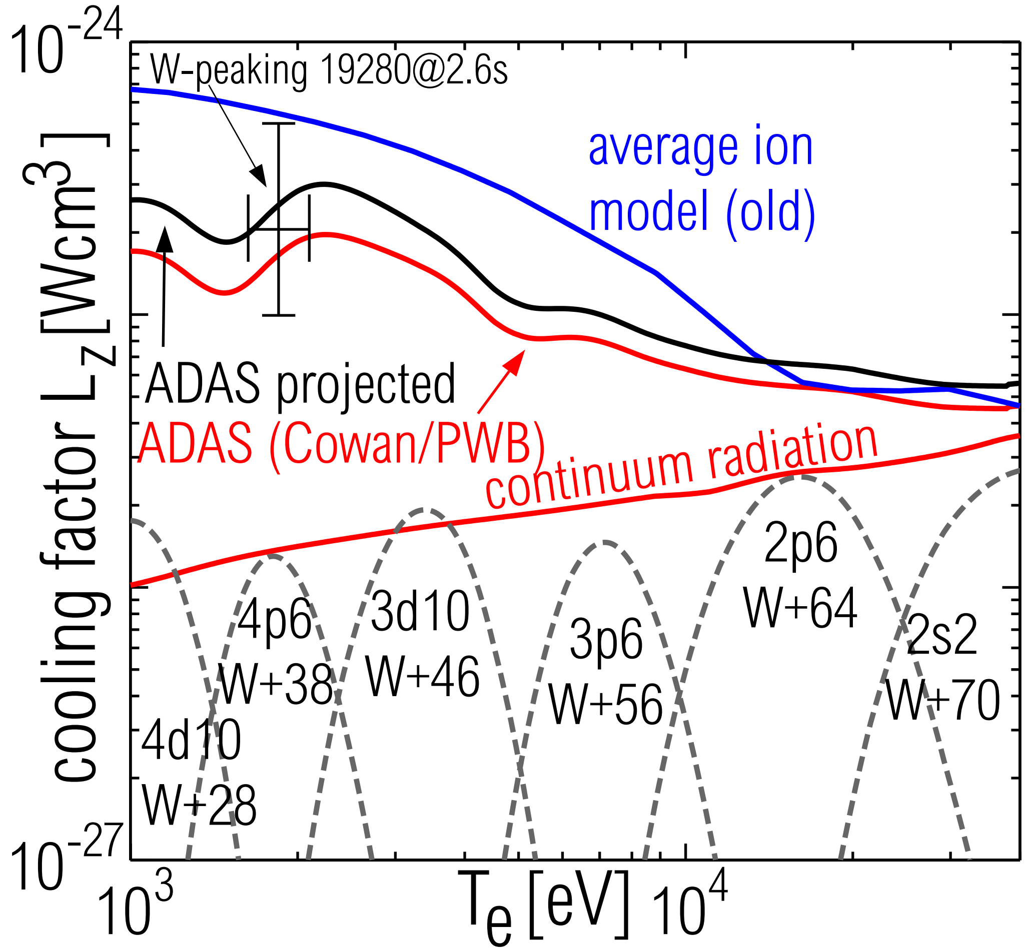






W Diagnostic

- 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
- consistent treatment of atomic data within ADAS
  ⇒ refinement of cooling factor



Operation with W divertor

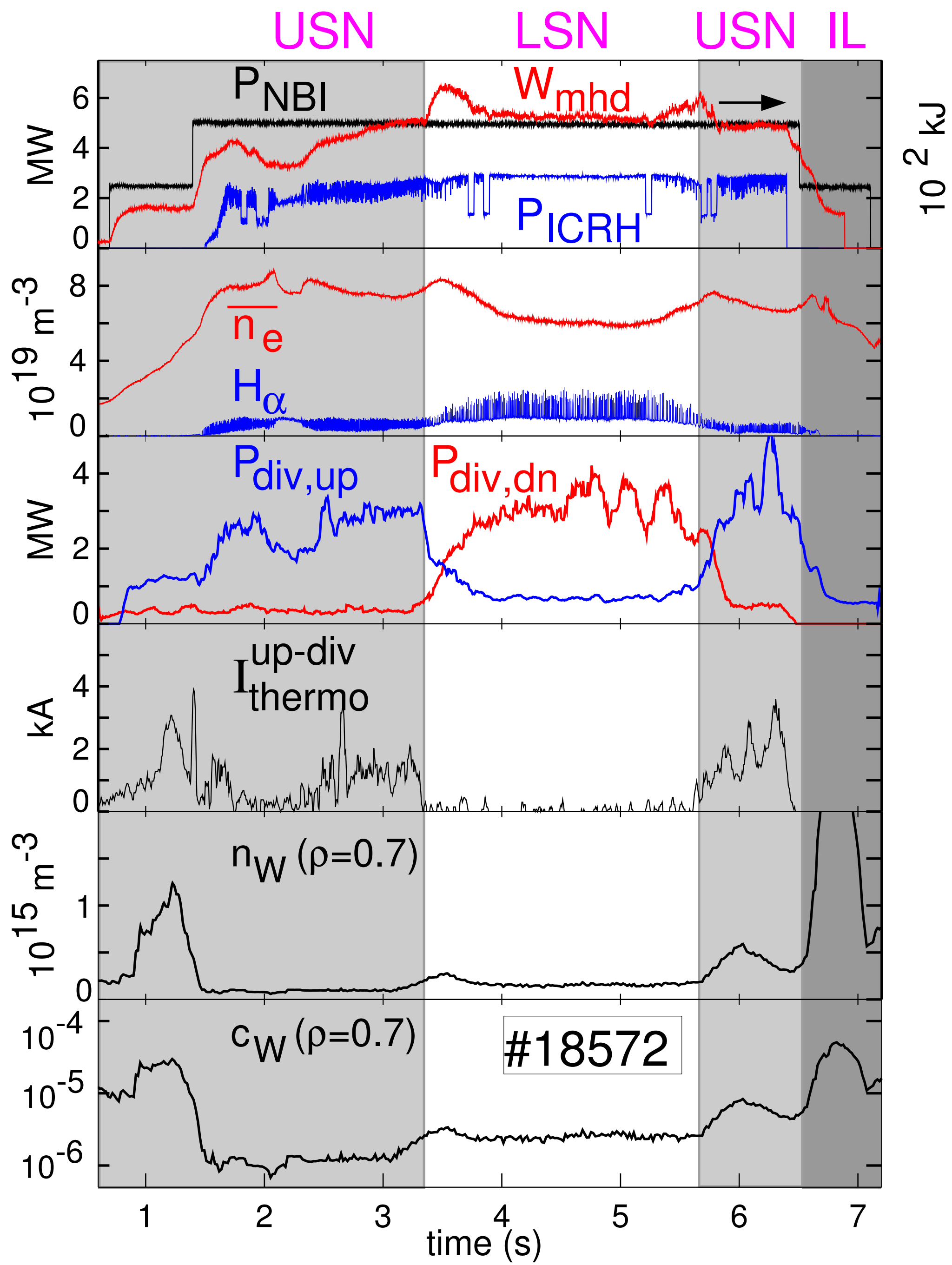
H-mode with $P_{heat} \approx 7.5$MW

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

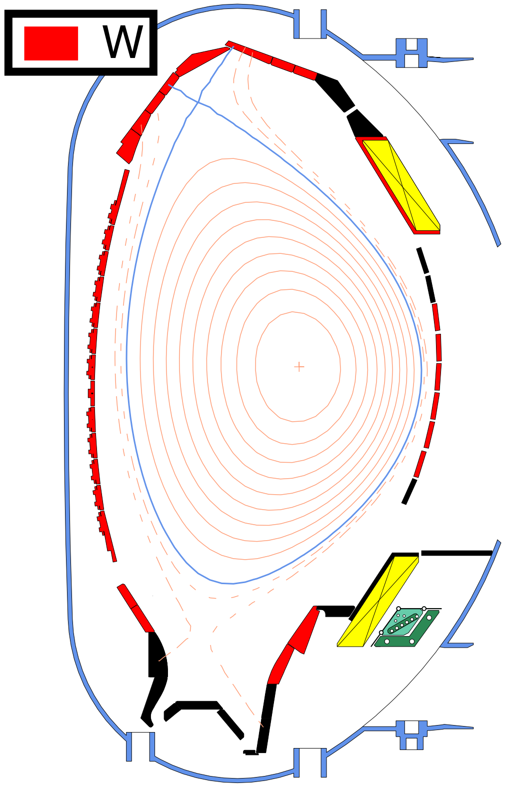
no remarkable difference of
W-content between USN (W) / LSN (C)
first USN phase at low density
has increased n_W (hot divertor?)

limiter phase uses W-coated
inner column as limiter
⇒ strong rise of n_W

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

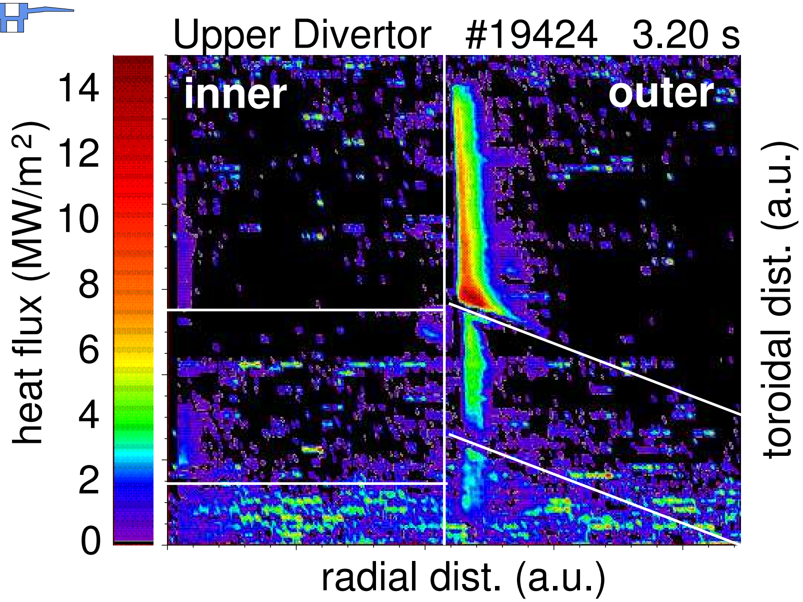


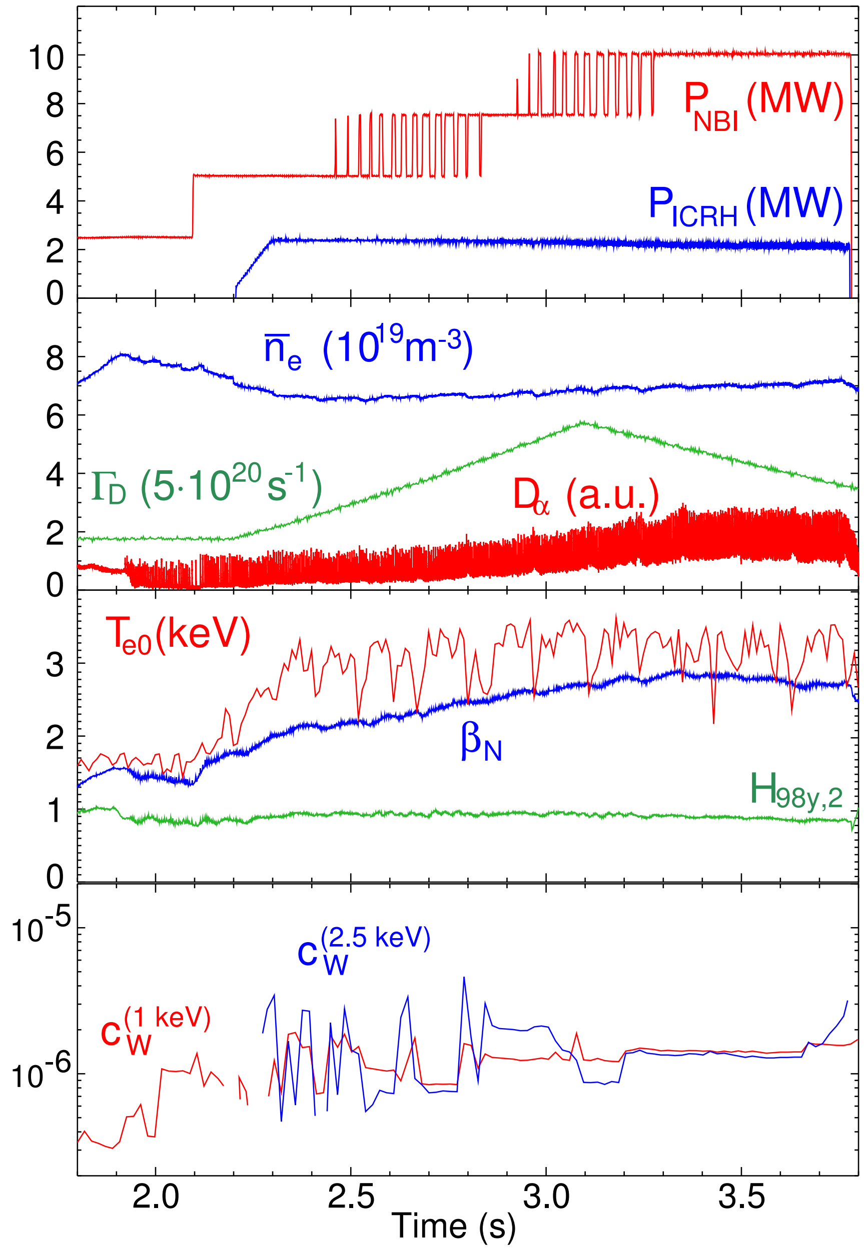
Operation with W divertor



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



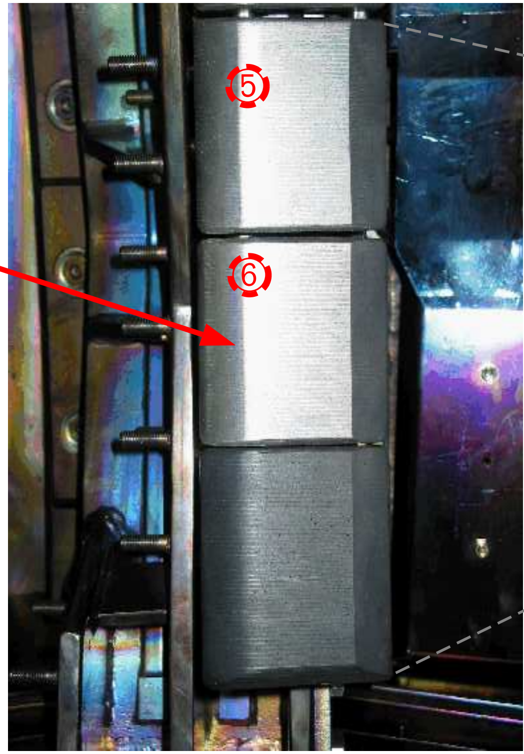


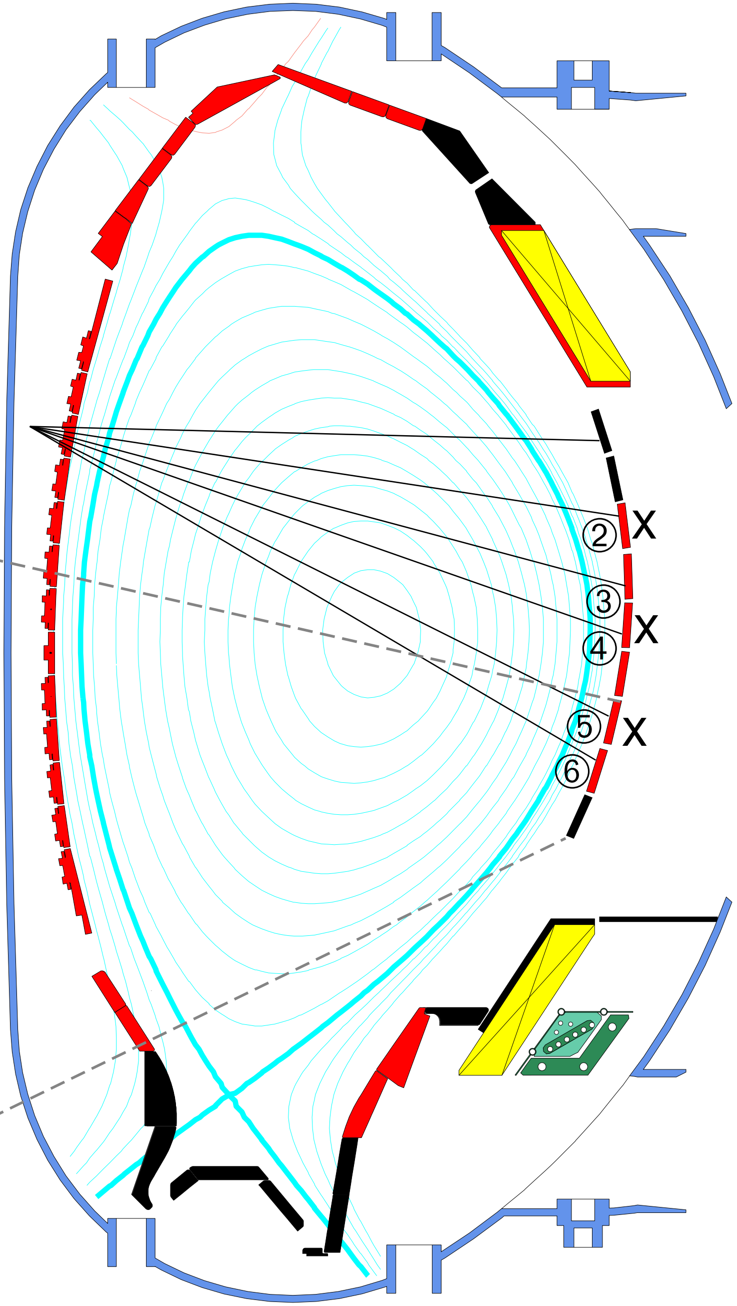
W erosion by thermal and fast particles

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)





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- particle fluxes from spectroscopic measurements
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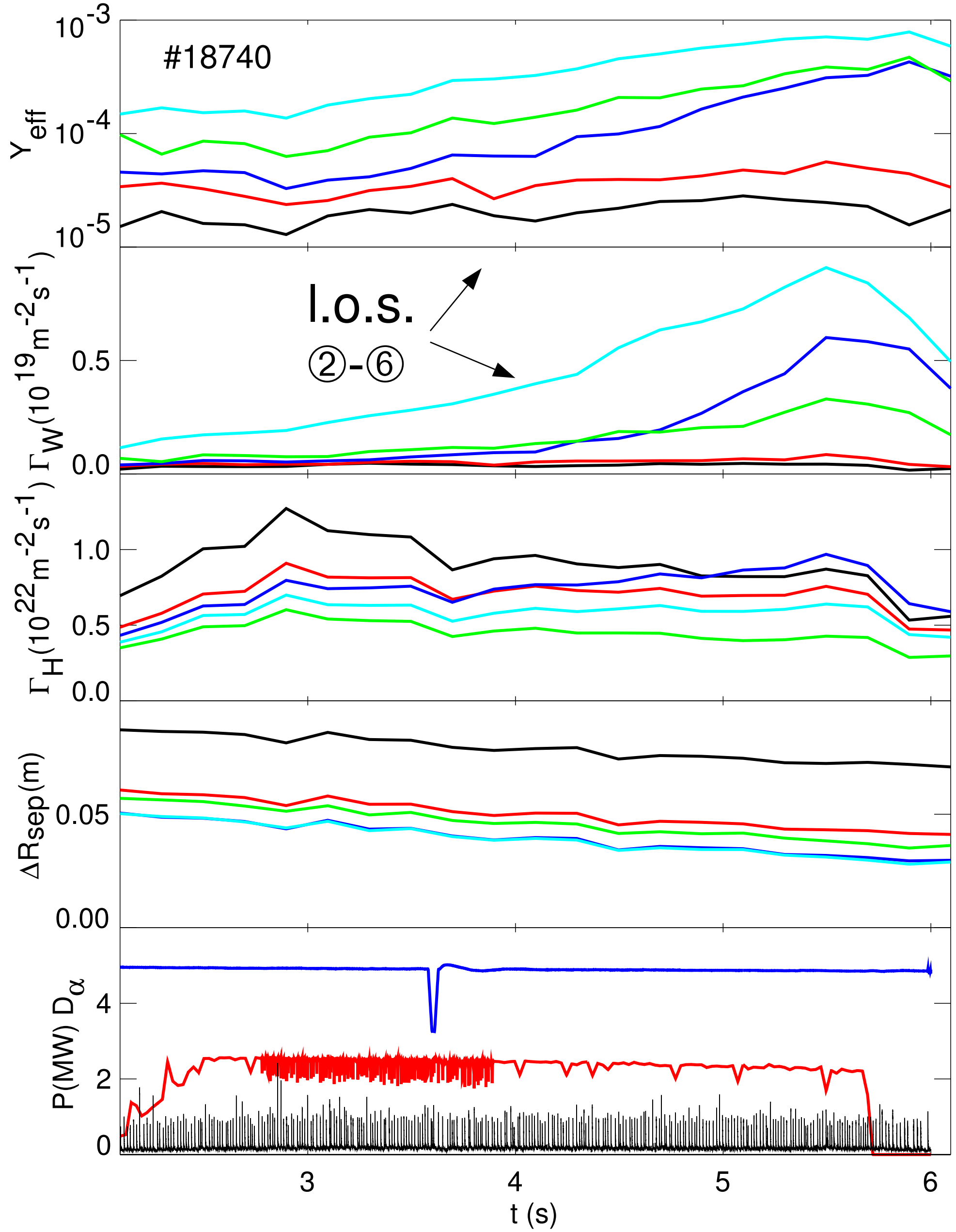
- same range of W influx densities and effective sputtering yields as in W Div I

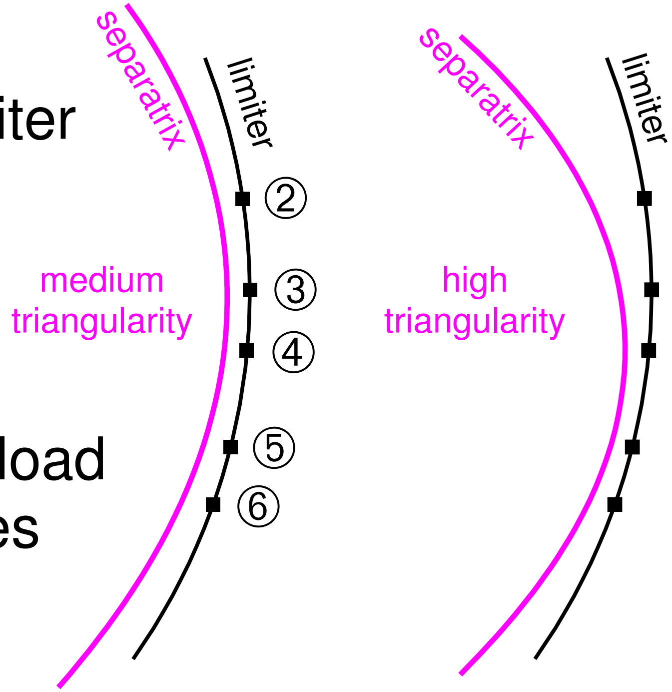
radial scan towards guard limiter



W erosion by thermal and fast particles

W erosion at guard limiters depends strongly on:

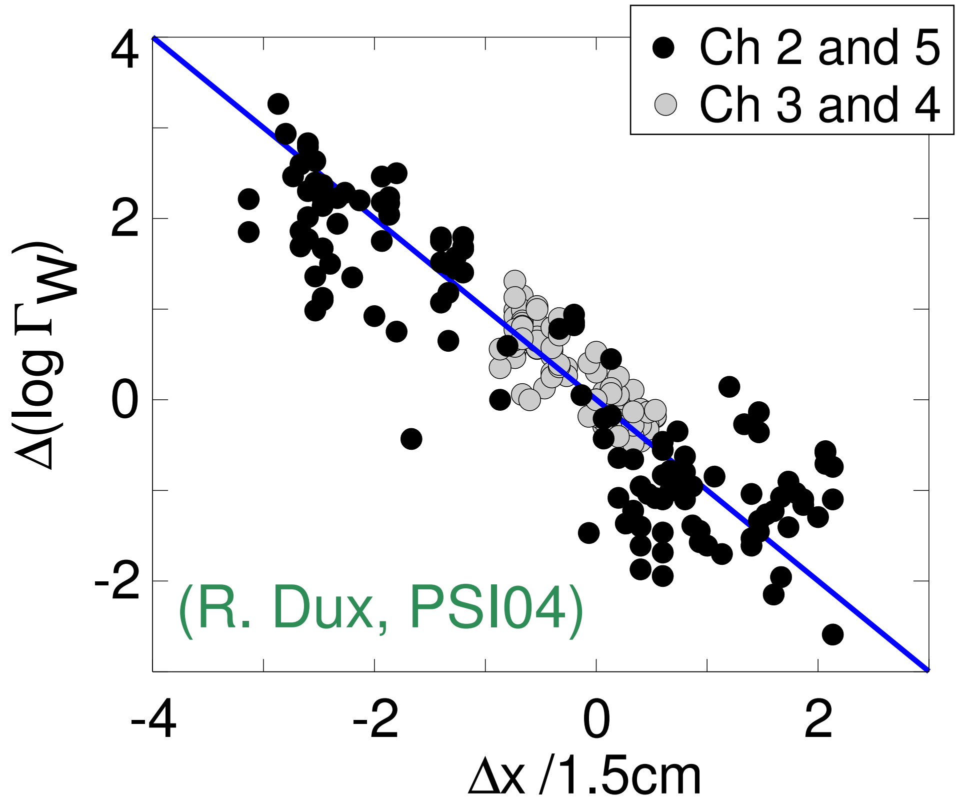
- plasma parameter
- distance of observed limiter region to separatrix
- localized ion load if plasma does not fit limiter shape
- shielding of limiter by other limiters



W influx density follows roughly:

$$\Gamma_W \propto \exp[-x/\lambda]$$

x = separatrix distance, λ = 1.5 cm



power decay lengths: 0.8 cm
(see A. Herrmann, EX/2-4Rb)

W erosion by thermal and fast particles

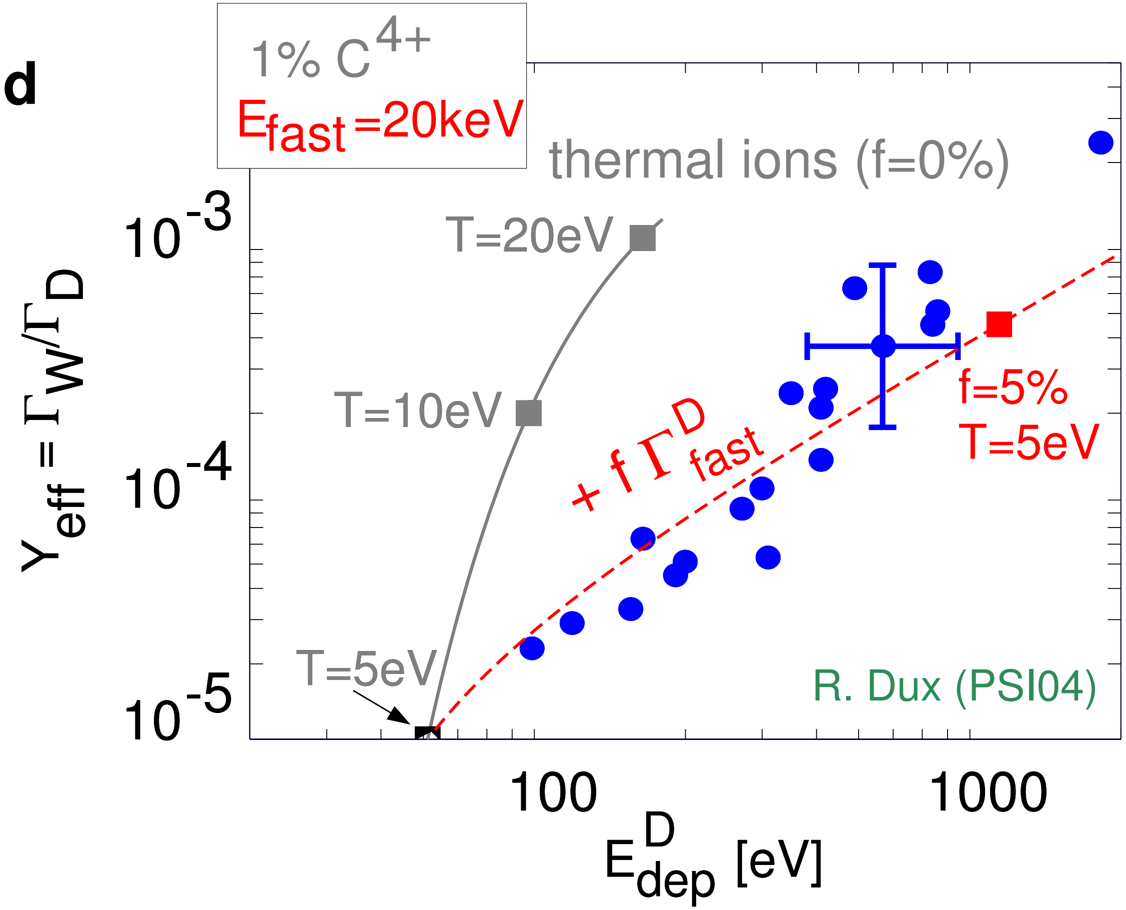
Theoretical estimate for erosion yield

thermal ion load with 1% C^{4+} assuming equilibrated carbon coverage:

⇒ 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 form code calculations (FAFNER, ASCOT) support picture



$$E^D_{dep} = \frac{\text{total deposited energy on tile}}{\text{shot integrated deuterium flux}}$$

$=$ average deposited energy per D

(discharges with dominant staedy state)

W behaviour / operational issues

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

- divertor configuration
- control impurity transport in plasma centre: (accumulation)

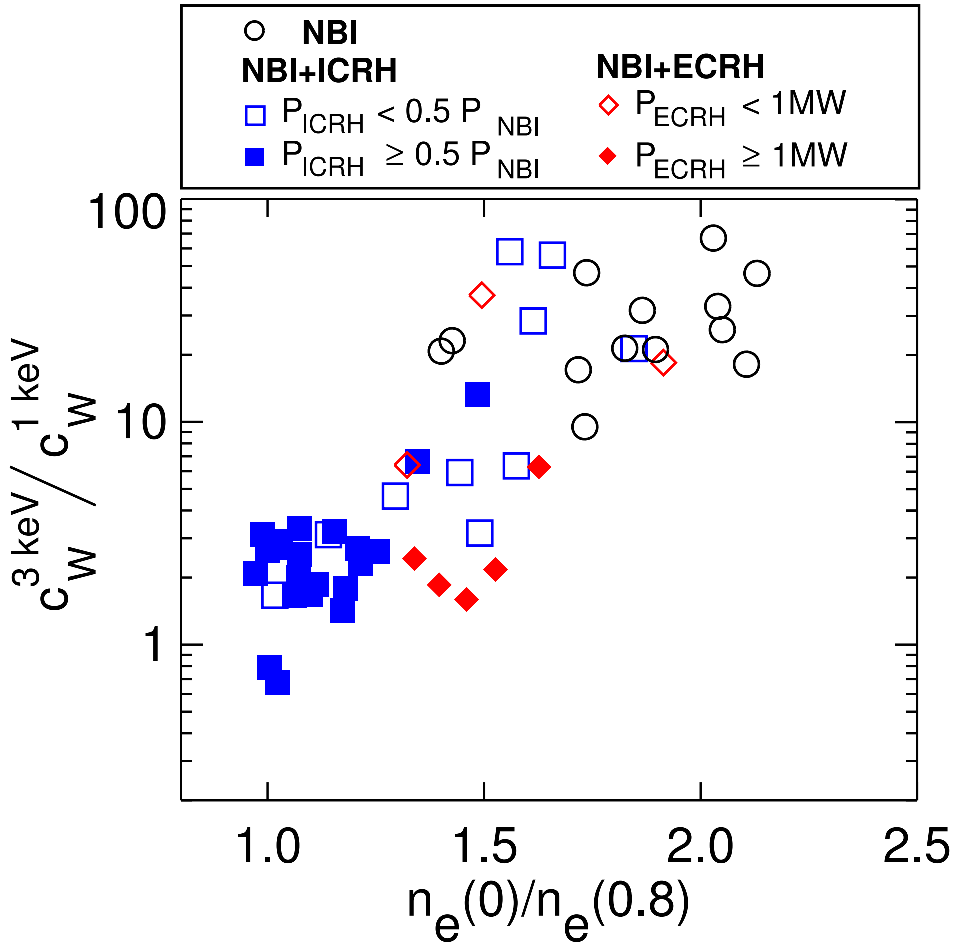
  avoid strongly peaked density profiles
  combined with low anomalous transport

  ⇒ central heating by ECRH/ICRH

  ⇒ small reduction of performance (≈10%)

  (see A. Stäbler, EX/4-5)

imp. transport from Si LBO:
strong increase of D_{an} for central heating



impurity control see: R. Dux, EX/P6-14

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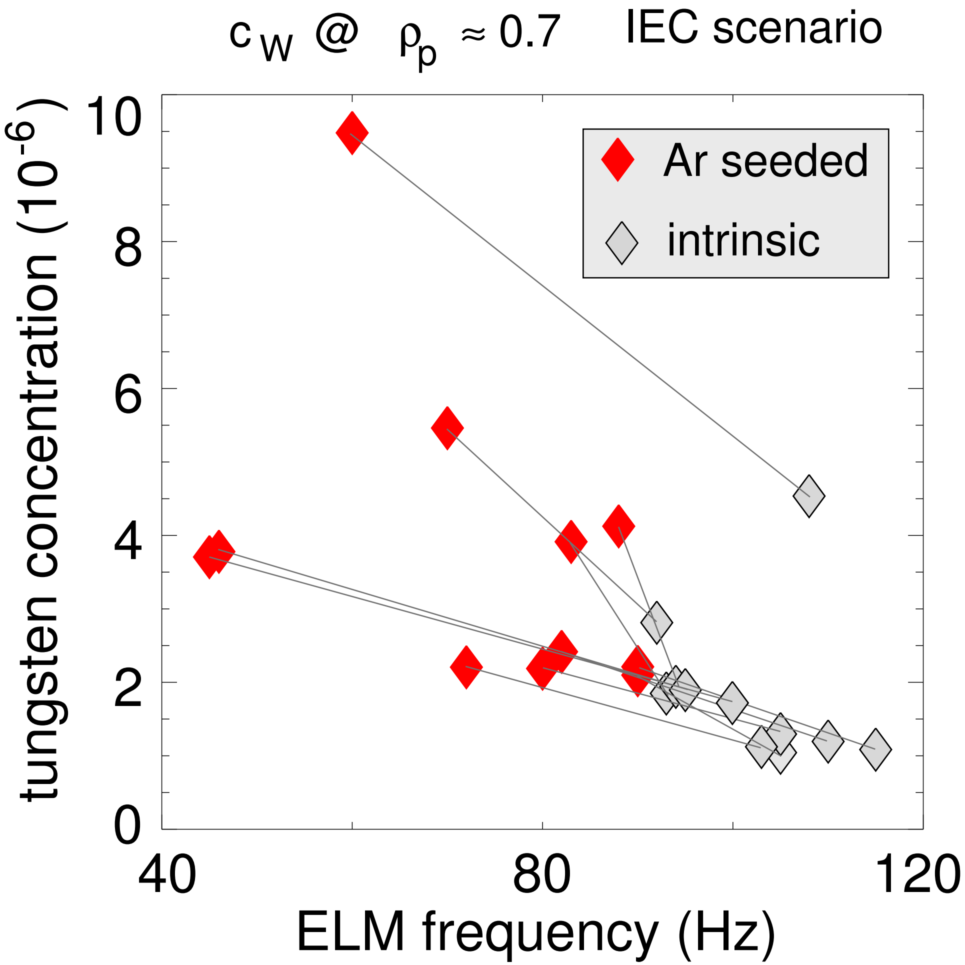
Conditions for low W-concentration ($c_W < 10^{-5}$)

- 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 (≈10%)
- control impurity transport in H-Mode edge transport barrier (impurity inventory):
  avoid long ELM free H-phases
  ⇒ stay away from H-L threshold
  ⇒ ELM pace-making



⇒ integrated scenario with:
central heating
ELM pace-making
radiation cooling by Ar seeding

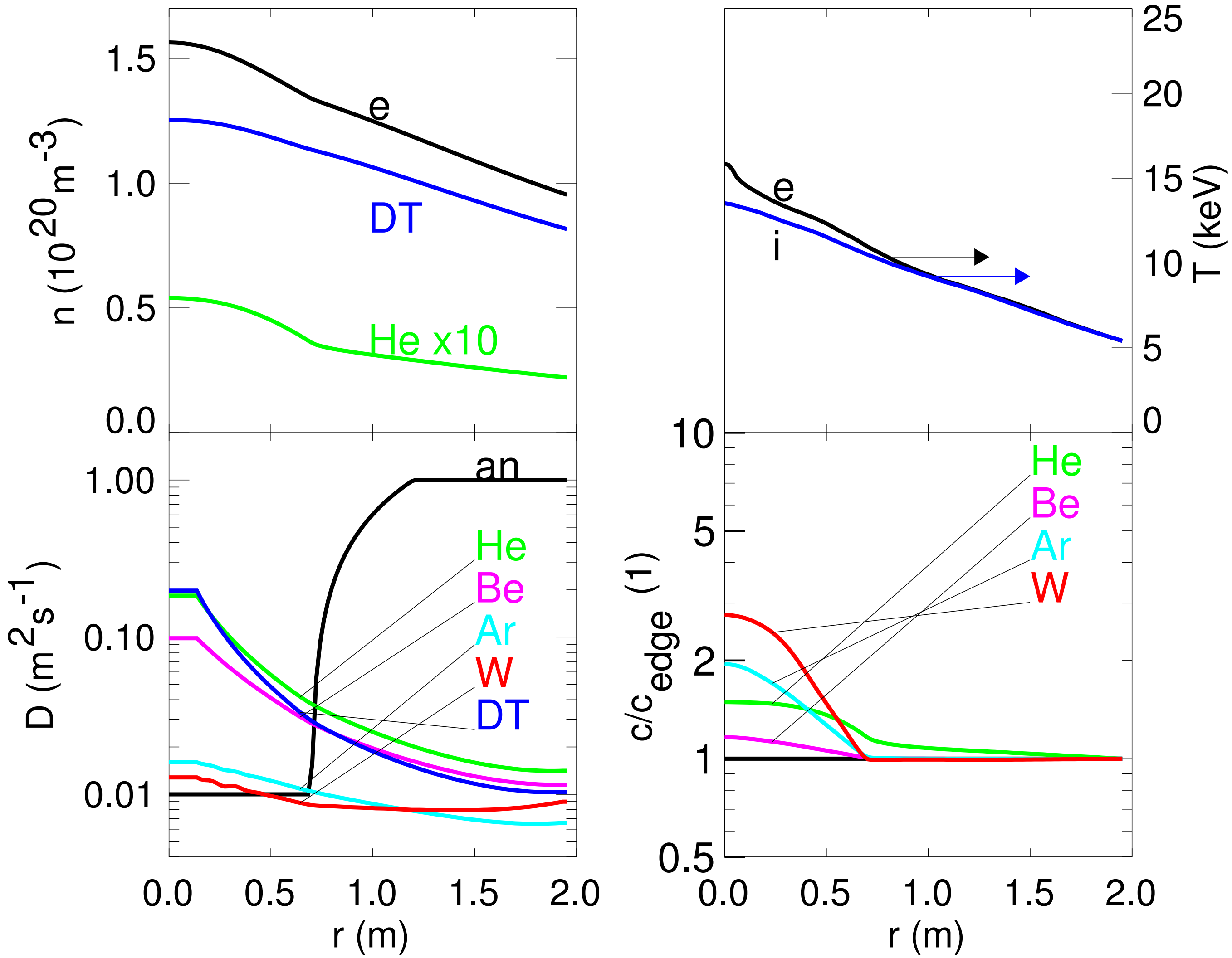
see P. Lang, EX/2-6

Prediction for ITER reference scenario (inductive operation)

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

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

- T_e, T_i fixed
- D_{an}
  at edge: 1m²/s
  in centre: varied
- v_{an} (fit to GLF23 profile)
- D_{neo}, v_{neo} from NEOART
- 6 components
  D,T,He,Be,Ar,W
- n_e from quasi neutrality
- edge densities fixed
  He(≈3%)   Be(2%)
  Ar(0.1%)   W(0.001%)



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 ⇒ 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
  ⇒ 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)

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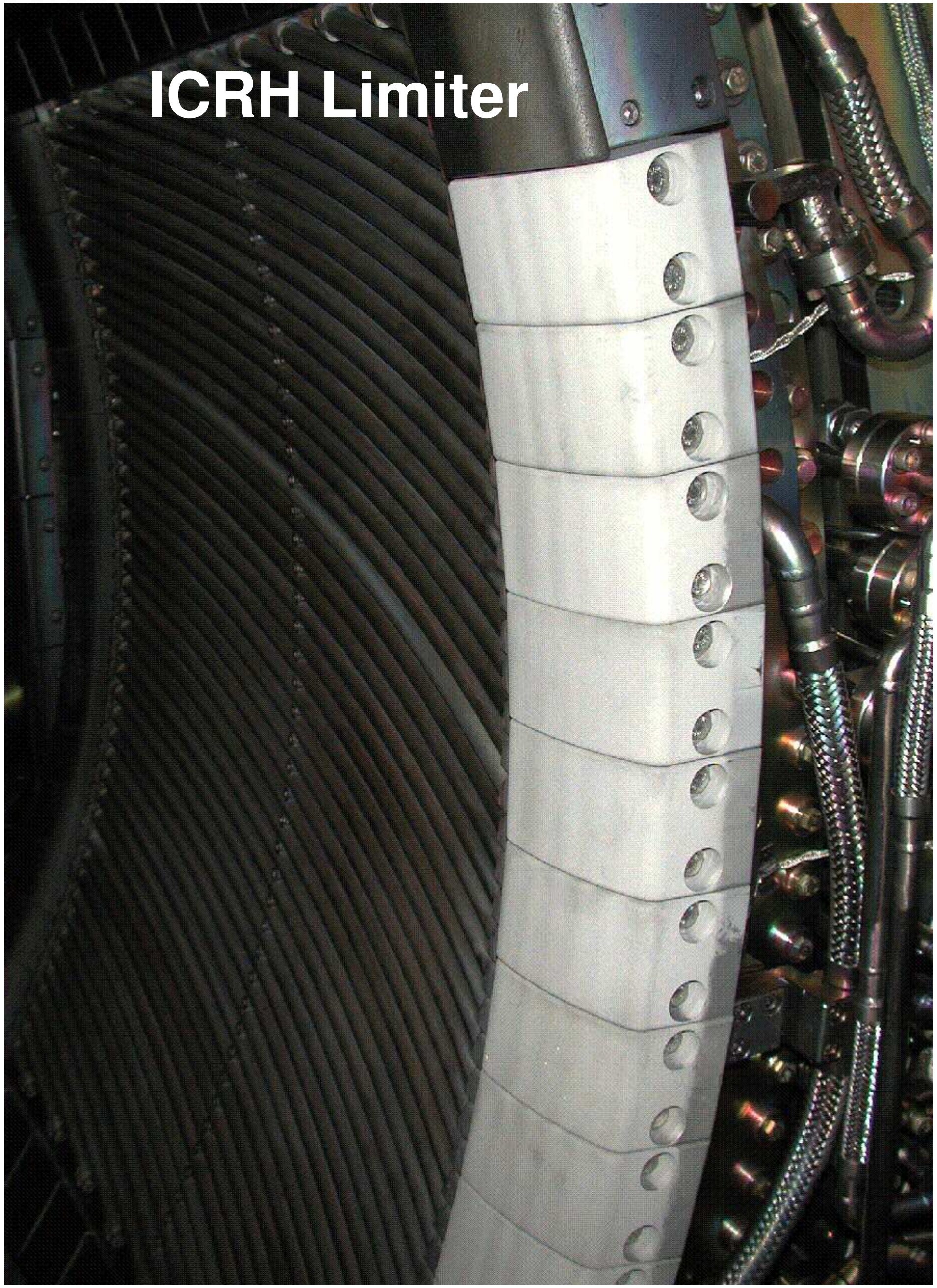
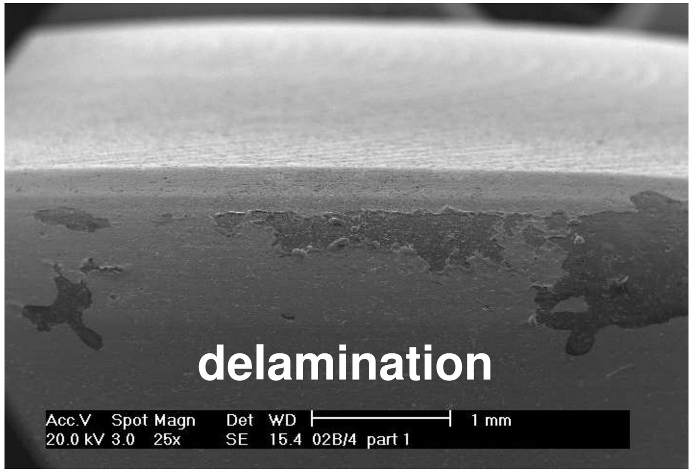
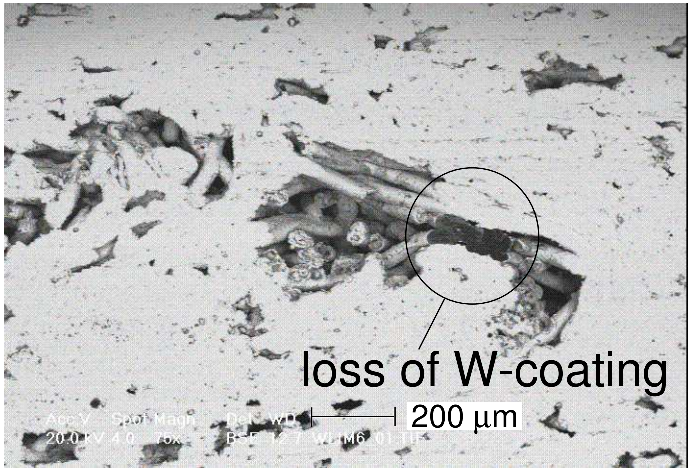


Performance of W tiles

divertor baffle (4 µm) power load:
coating problems



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



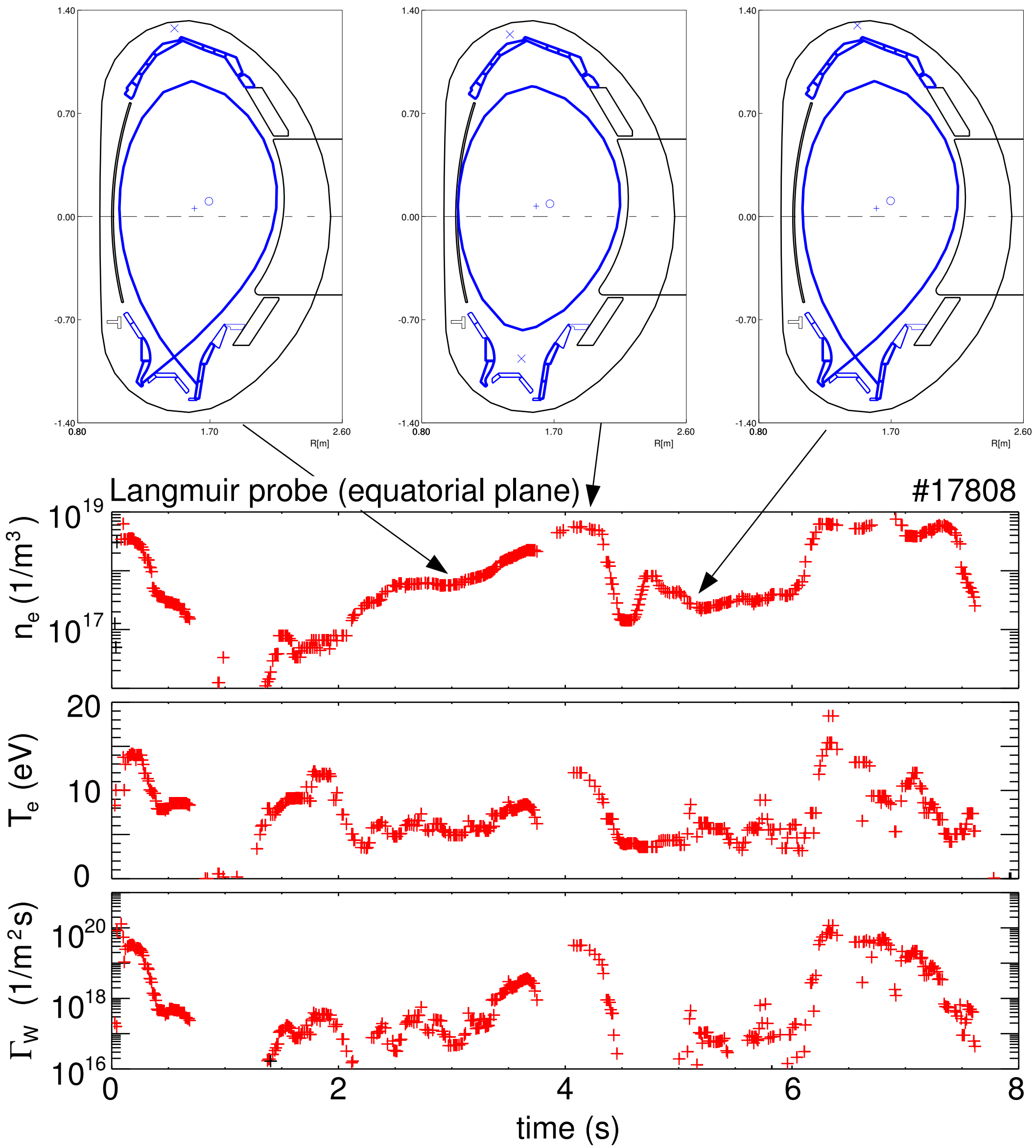
central column (ramp/down limiter)
beam dump (1 µm)
> 2000 discharged, no damage

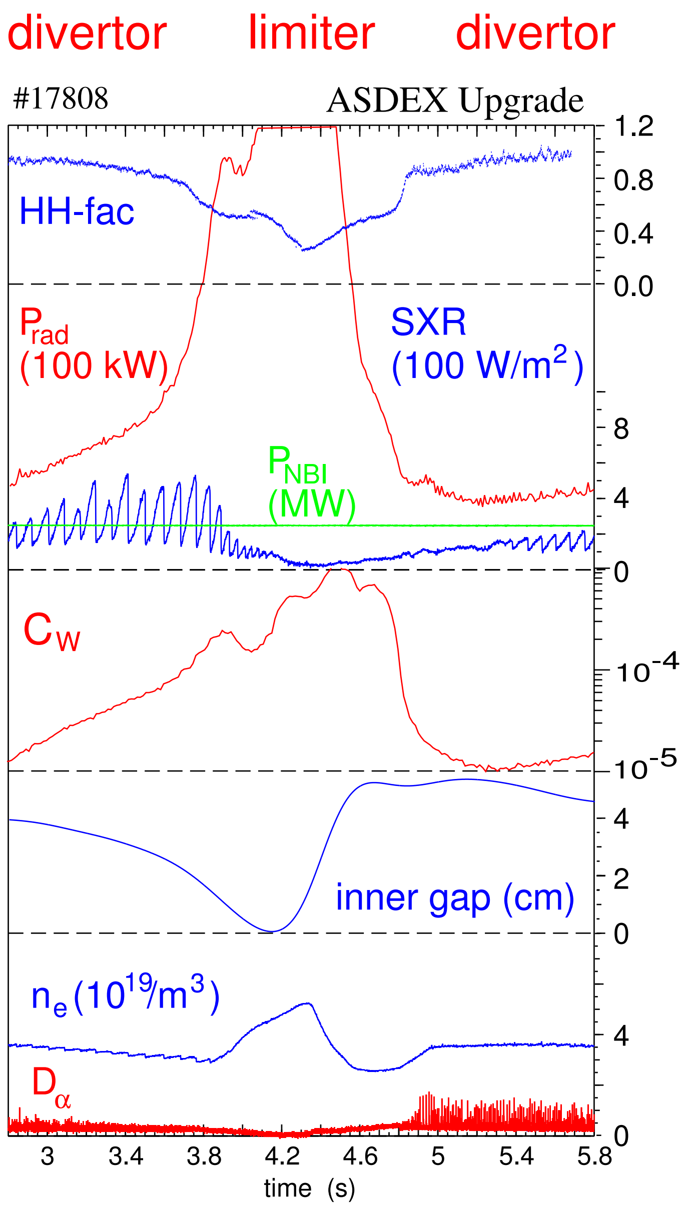
upper divertor (4 µm)
$P_{avg} \leq 10$ MW/m^2
melting at edges:
estim. power > 20 MW/m^2

no strong degradation during
second half of campaign

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

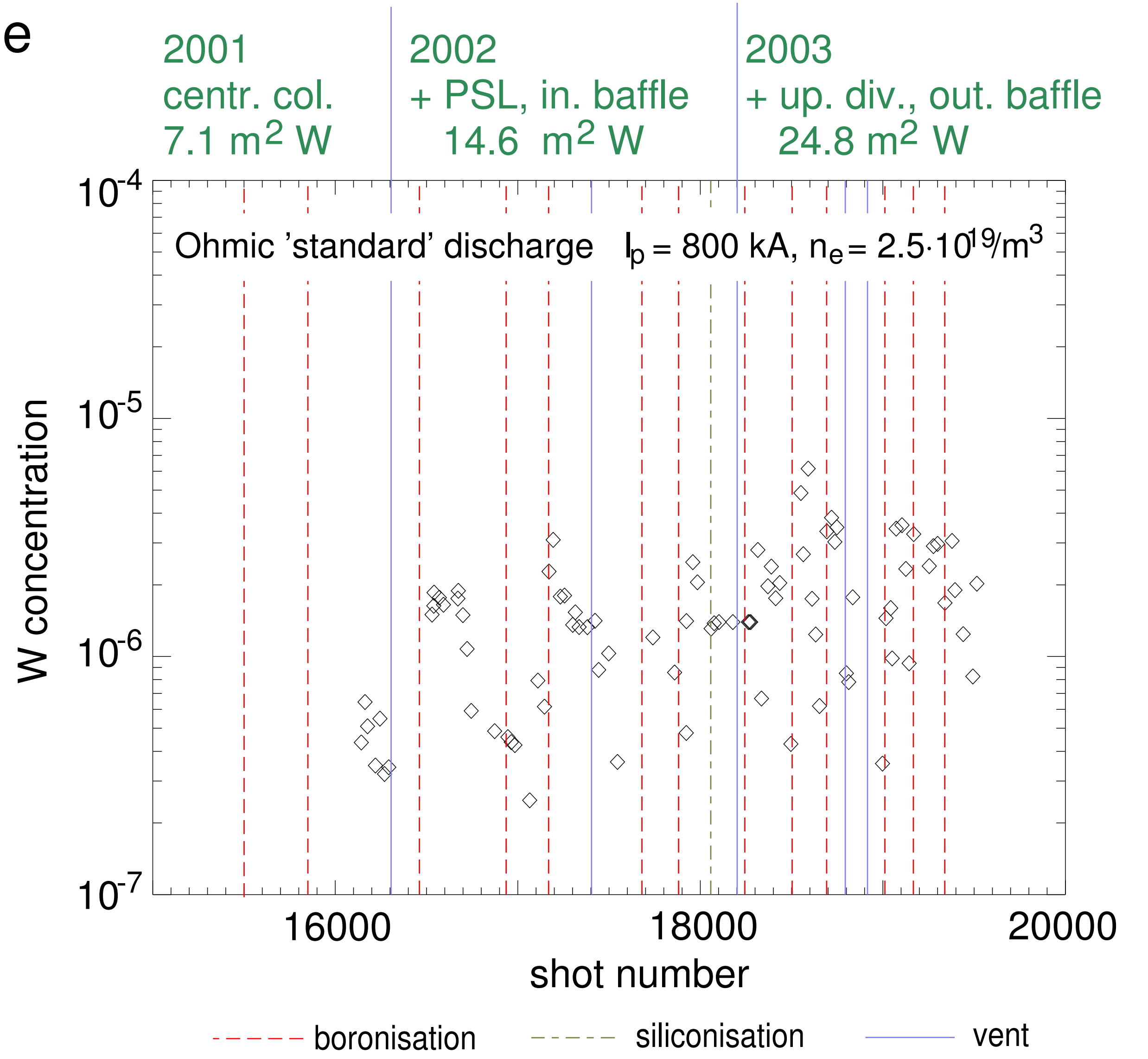
- divertor configuration





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:

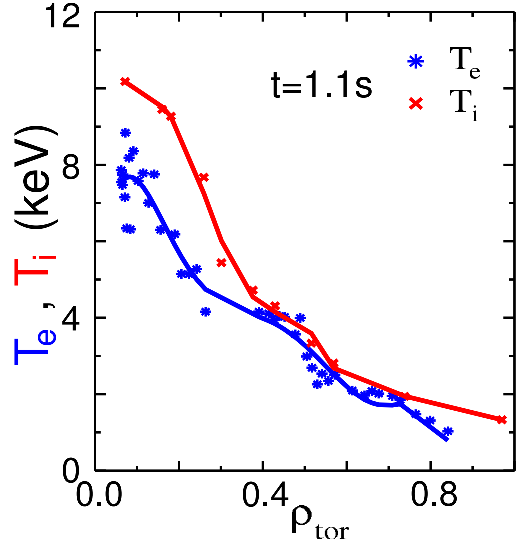
→ high central W-content

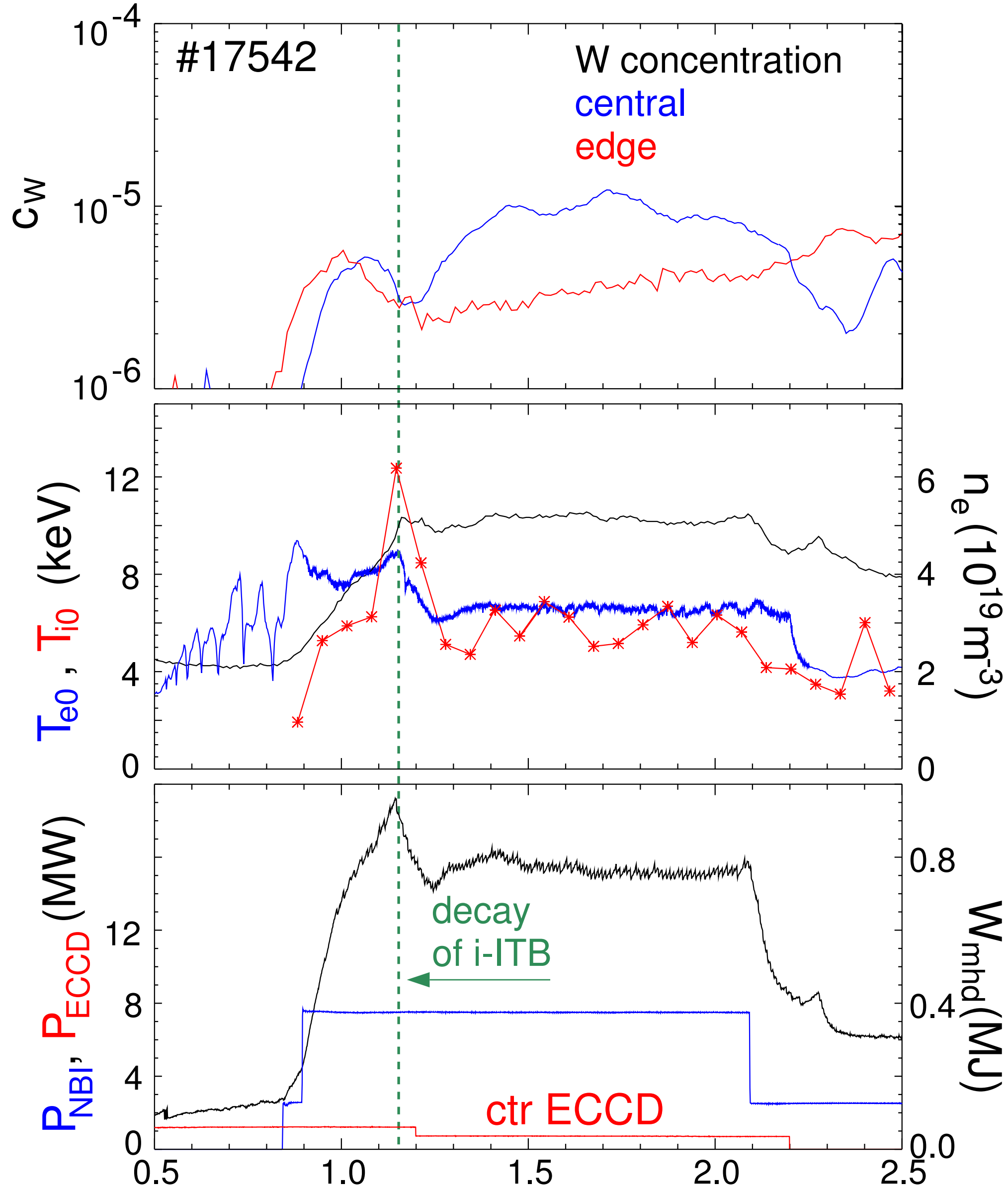
- divertor ITBs

→ 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

Distribution of lost ions from NBI (beam 2+3)