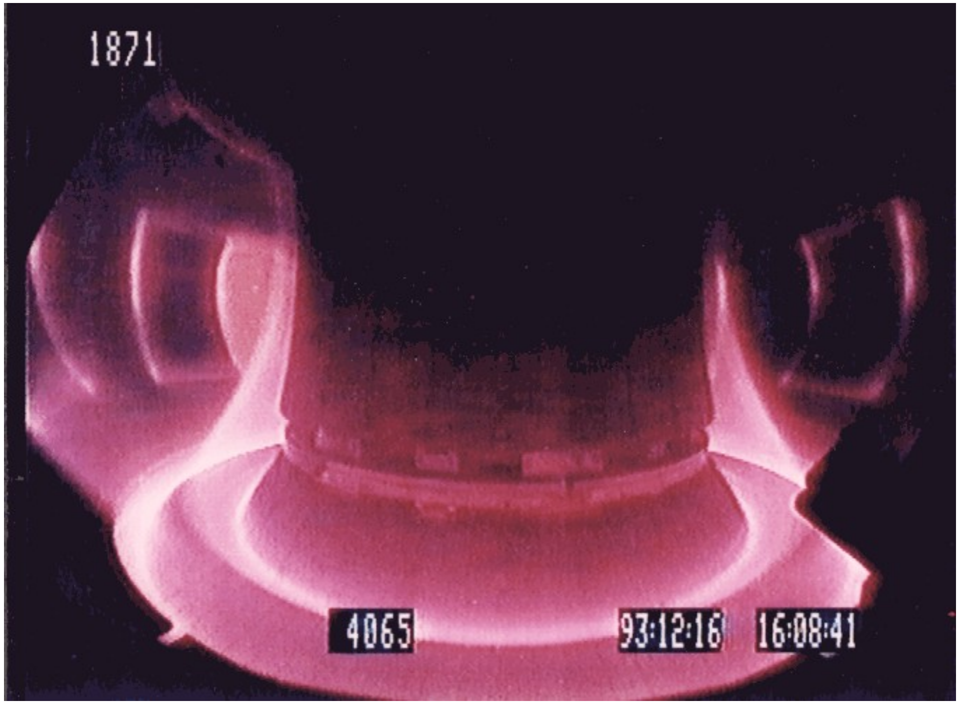
Fusion Research at the ASDEX Upgrade Tokamak – Experiences with Tungsten Plasma Facing Components

- Magnetically Confined Fusion
- Towards ITER
- Results with Tungsten PFCs in ASDEX Upgrade



R. Neu and ASDEX Upgrade Team

Thanks to:
Th. Pütterich, R. Dux, A. Kallenbach

Colloquium Dept. of Phys. Electronics, Czech Technical University, Prague

Magnetically Confined Fusion
Energy from the fusion of light elements

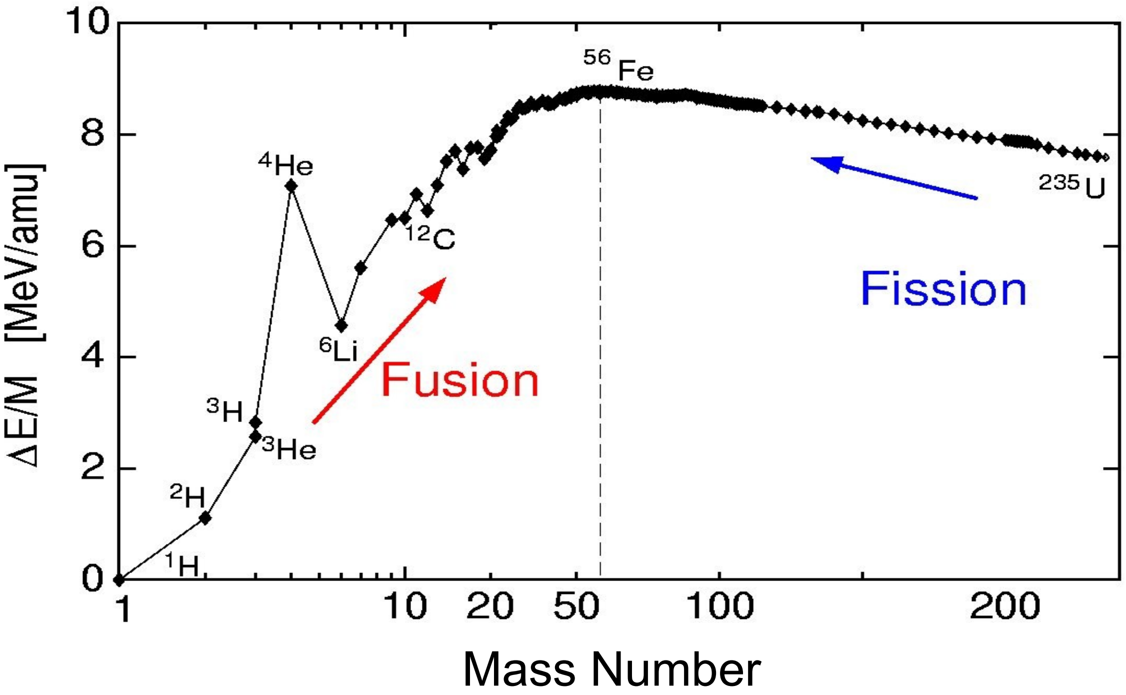
Sun: *pp*-cycle

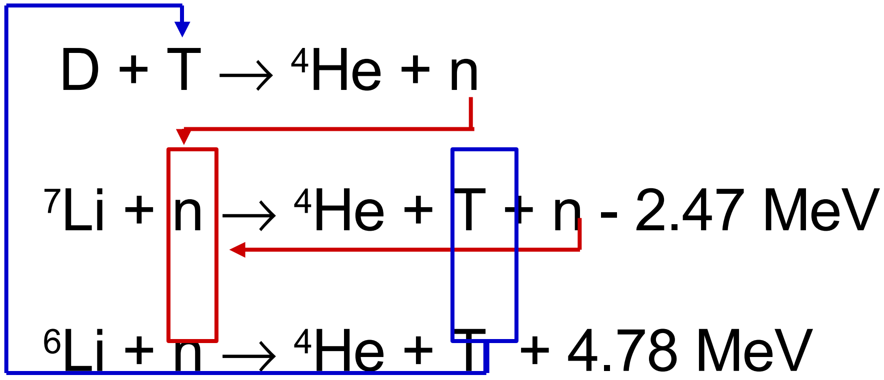
$$4\,H \rightarrow {}^{4}He + 2\,e^{+} + 2\,\nu_e + 26.7\ \text{MeV}$$

Fusion Reactor:

$$D + T \rightarrow {}^{4}He + n + 17.6\ \text{MeV}$$

D from water (0.02% D)
T from Li (92.5% ^{6}Li, 7.5% ^{7}Li)





$$D + T \rightarrow {}^{4}He + n$$

$${}^{7}Li + n \rightarrow {}^{4}He + T + n - 2.47\ \text{MeV}$$

$${}^{6}Li + n \rightarrow {}^{4}He + T + 4.78\ \text{MeV}$$

Energy Release:

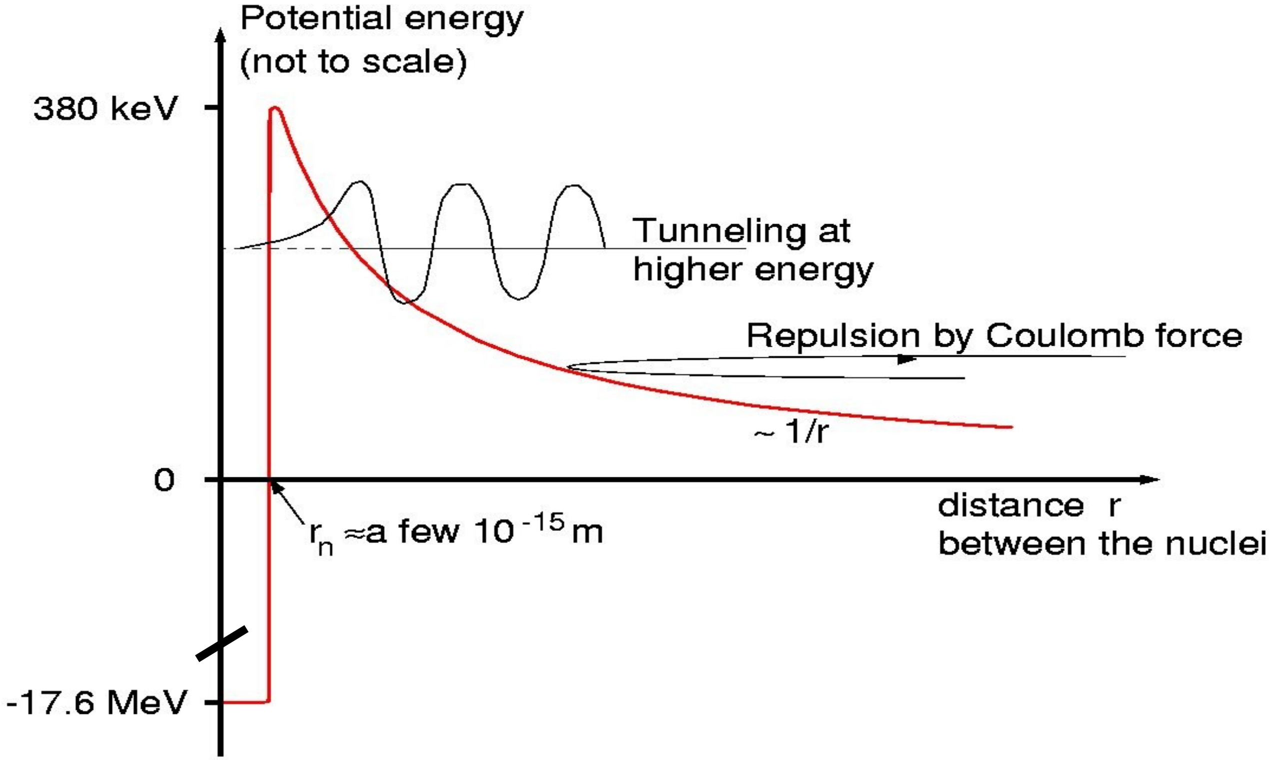
Fusion	(D+T)	≈ $3\cdot10^{14}$ J/kg
Fission	(U)	≈ $8\cdot10^{13}$ J/kg
Chem. Reaction	(C)	≈ $3\cdot10^{7}$ J/kg

Magnetically Confined Fusion

Tunnel effect allows sub-threshold reactions

fusion reaction only at high kinetic energy:
coulomb well
⇔ tunneling

DT:
σ_{DT} max. at
$E_{rel} = 64$ keV
($^5He^*$ - resonance)

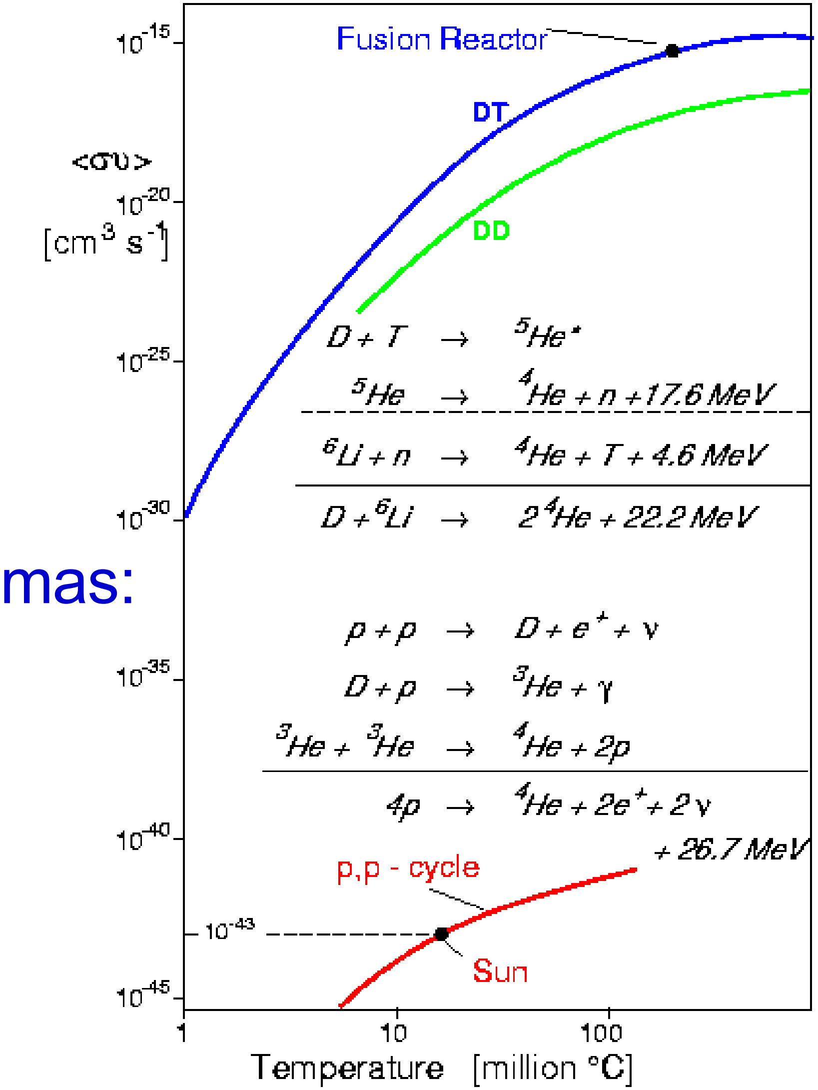


Magnetically Confined Fusion

Typical parameters

crossed beams or beam target reaction
not suited because σ_{coul} much too high

⇒ (magn.) confinement of a thermal
plasma at $T \approx 20$ keV
($T = 11600K \rightarrow kT = 1eV$)



typ. values for magnetically confined plasmas:

$T = 20$ keV $\quad n_e = 2n_D = 2n_T = 10^{20}\ m^{-3}$

$p = (n_e + n_D + n_T)\,kT = 2\,n_e kT = 6 \cdot 10^5$ Pa

$P_\alpha / V = 1\ MW\ m^{-3}$

typ. values for the centre of the sun:

$T = 1.5$ keV $\quad n_e = 5 \cdot 10^{31}\ m^{-3}$

$p = 2.5 \cdot 10^{16}$ Pa $\qquad P_\alpha / V = 0.3\ kW\ m^{-3}$

Magnetically Confined Fusion

Criterion for ignition

Ignition condition: fusion power $\ge$ power loss

$$\frac{n_e^{\,2}}{4}\langle\sigma v\rangle E_\alpha \ge c_{Br}\, n_e^{\,2}\sqrt{kT} + 3\,\frac{nkT}{\tau_E}$$

α-particle heating

radiation loss (Bremsstrahlung)

thermal convection

(τ_E: energy confinement time)

leads to

$$n_e\tau_E \ge \frac{3kT}{{}^{1}\!/_{4}\langle\sigma v\rangle E_\alpha - c_{Br}\sqrt{kT}} = f(T)$$

minumum @ T=20 keV (200 Mill. K) : $n\tau_E = 2 \times 10^{20}\ \mathrm{m^{-3}\ s}$

Magnetically Confined Fusion

Principle of magnetic confinement

- Lorentz force:

$$\boldsymbol{F}_L = q \cdot \boldsymbol{v} \times \boldsymbol{B}$$

particles move on spiral paths around the magnetic field lines

- movement parallel to ***B*** is unhindered

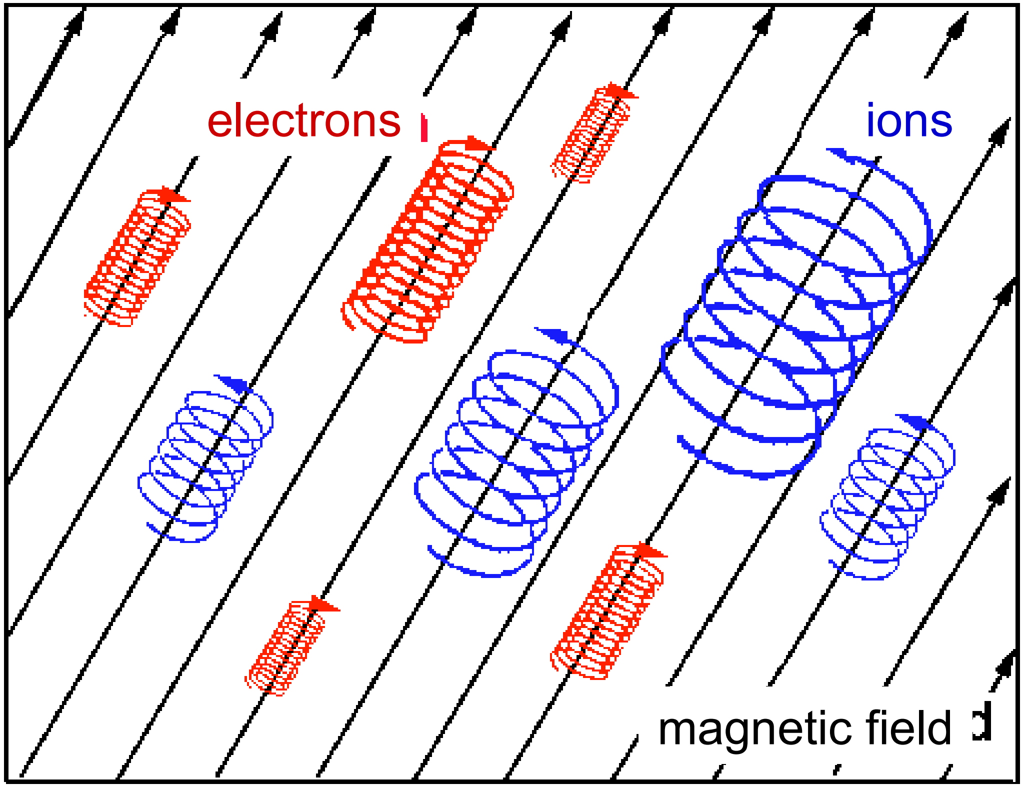
- huge transport along field lines:

  electrical cond.: $\sim T^{3/2}$

  thermal cond.: $\sim T^{5/2}$

⇒ field lines have to be closed

⇒ torus



- transport ⊥**B** only by collisons and drifts

Magnetically Confined Fusion

Drifts in a toroidal field

Toroidal magnetic field: $|B|=B_0\cdot R_0/R$ ⇒

Particles drifts:

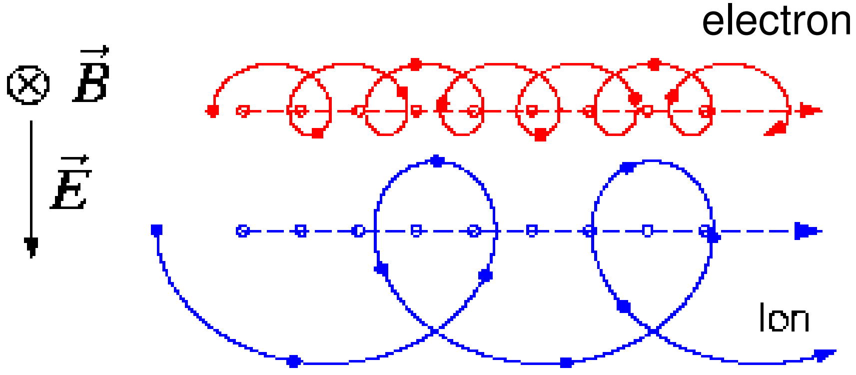
$$\vec{v}_D = \frac{\vec{F} \times \vec{B}}{q\,B^2}$$

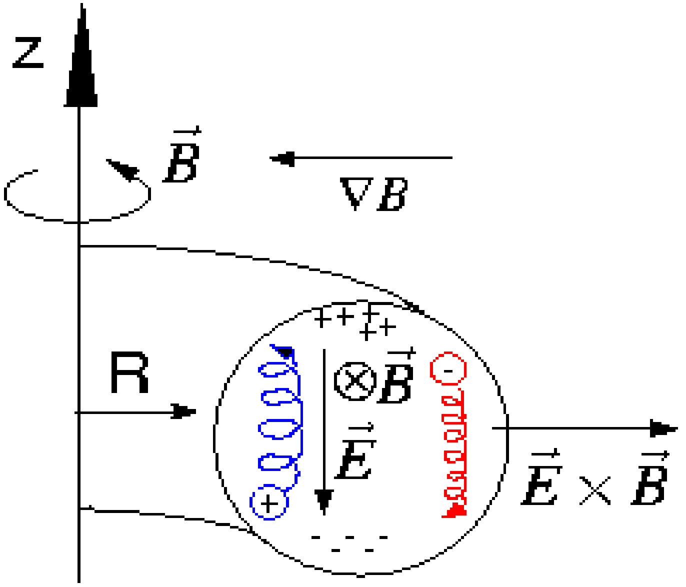
perpendicular to external force and field lines ($v_\perp \approx 10^{-3}\, v_\parallel$)

$\vec{F}_E = q\,\vec{E}$ electr. force

$\vec{F}_B \approx E_{kin}\, \nabla|B|/B$ grad. force, centrif. force

Example: E-field drift



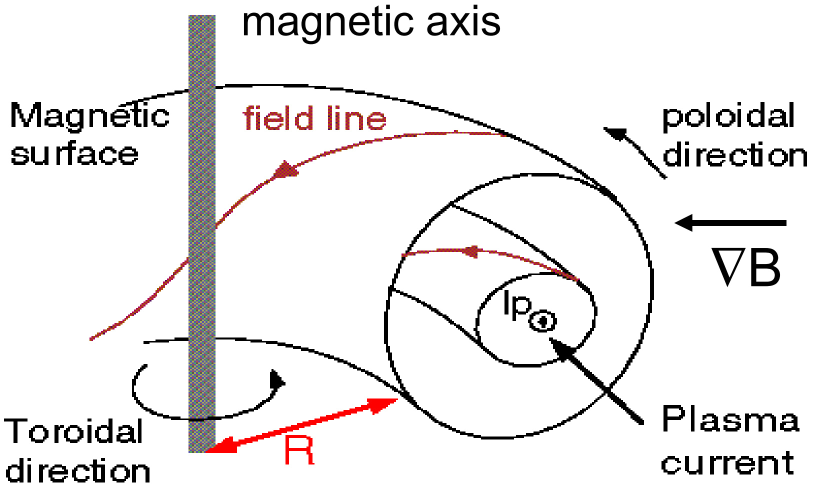


⇒ No confiment in a purely toroidal device!

Magnetically Confined Fusion

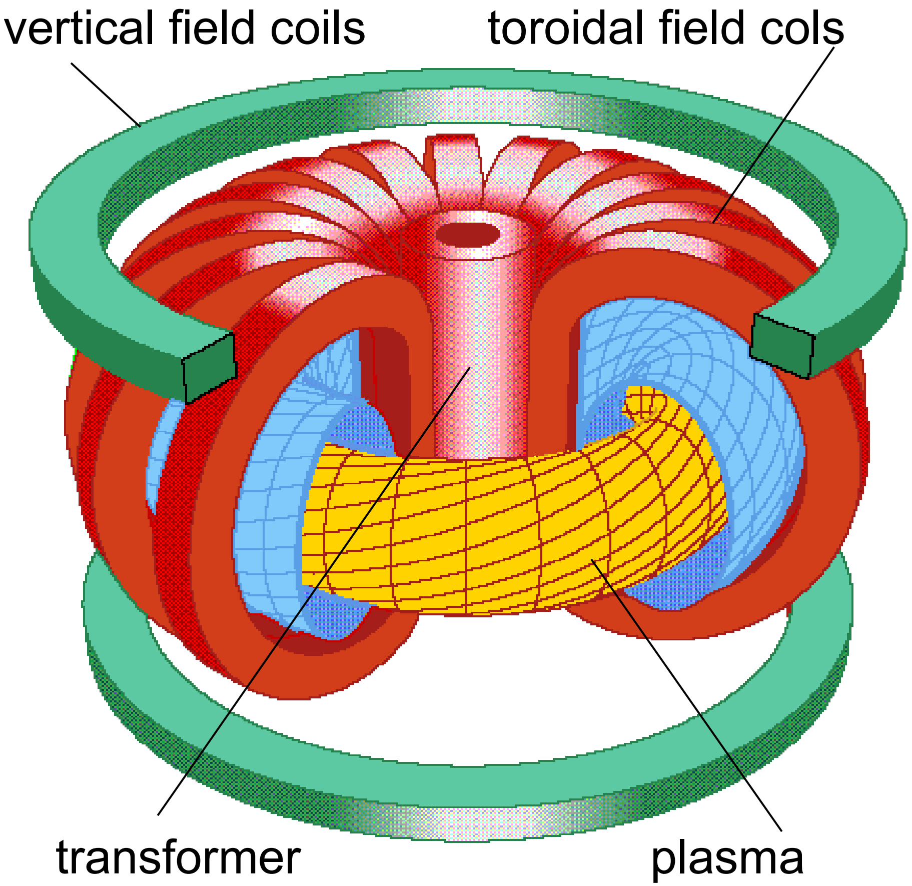
Compensation of drift by a helical field

- additional poloidal component yields helical magnetic field
- current can short cut E-field alternatively: compensation of inward and outward drift



Tokamak

poloidal field by plasma current



Magnetically Confined Fusion

Radial transport anomalously increased

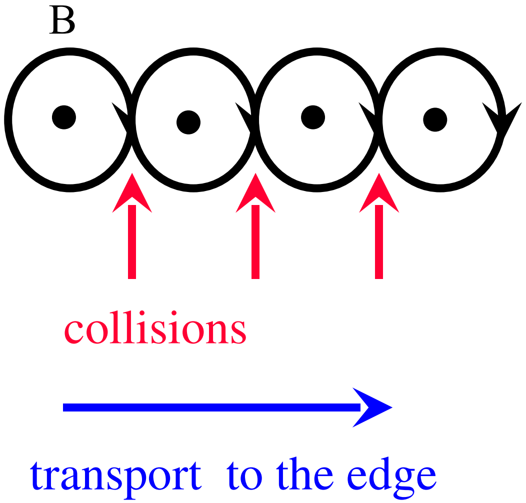
Simplest ansatz for heat transport:

- diffusion due to collisions

$\chi \approx r_L^2 / \tau_c \approx 0.005\ m^2/s$

$\tau_E \approx a^2/(4\chi)$

- table top experiment ($a \approx 0.2$ m, $R \approx 0.6$ m) should ignite!

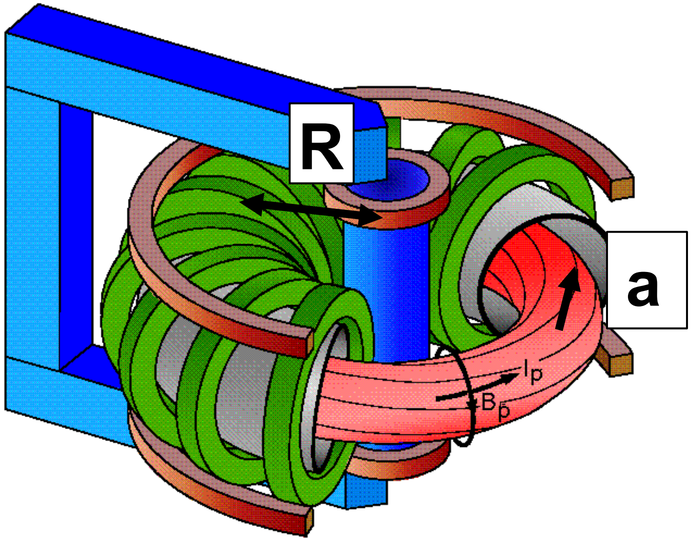


Experimental result:

- Anomalous transport (turbulence):
  $\chi, D \approx$ a few m^2/s

(note: $\lambda_\perp = 0.001$ W/mK, $\lambda_{air} = 0.026$ W/mK)

- Tokamaks: Ignition expected for R = 8 m!

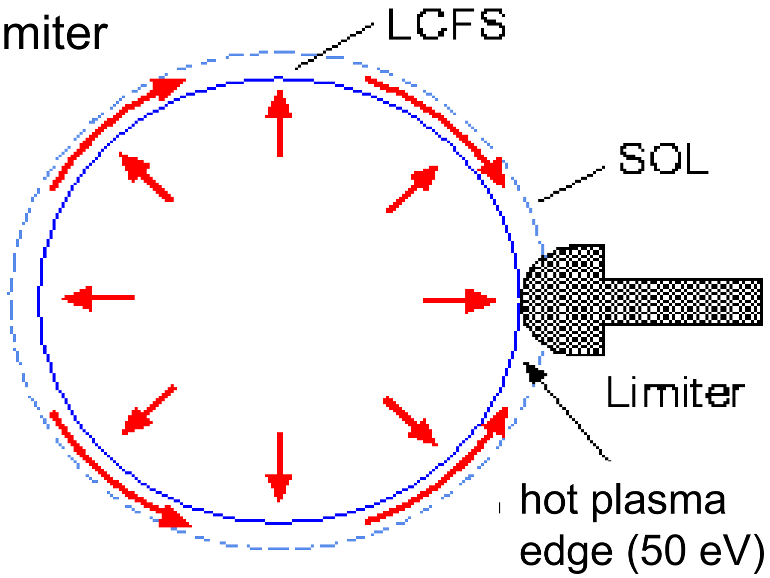


Magnetically Confined Fusion

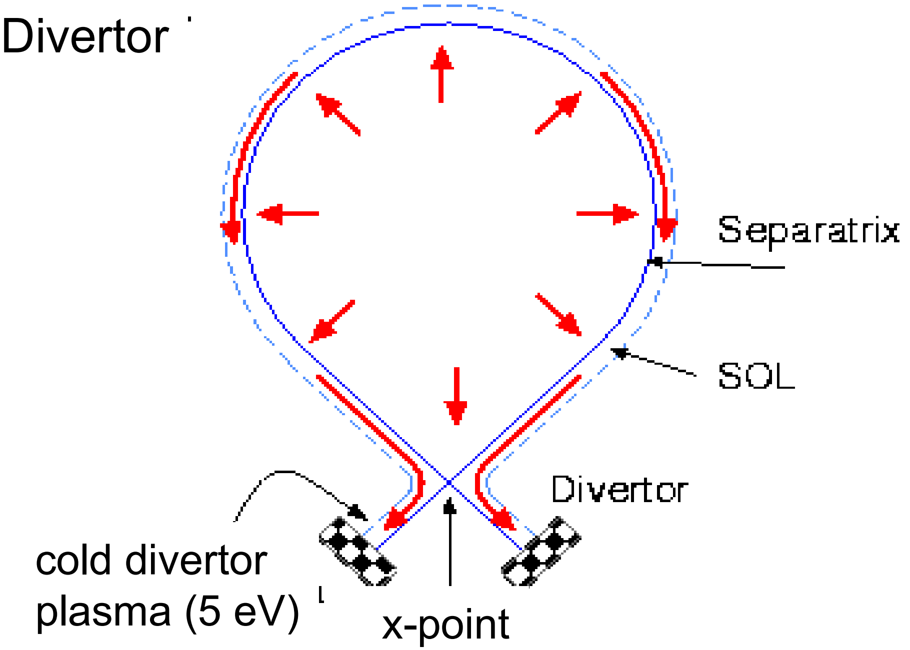
Limiter / Divertor Concept

width of scrape-off layer (SOL) given by ratio of ⊥ to || transport
⇒ very small radial extension ⇒ very large power loads

Limiter



Divertor



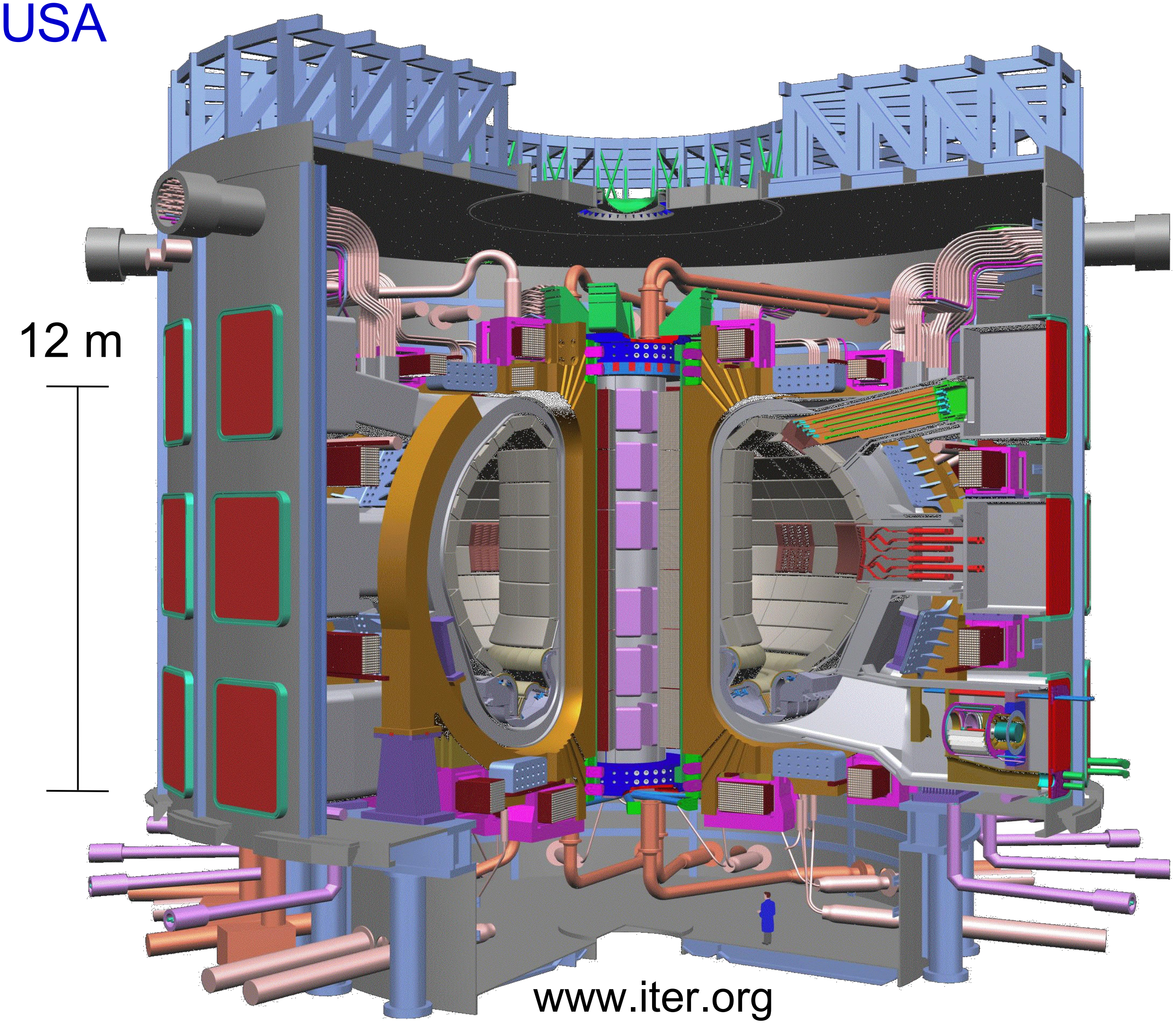
simple configuration
direct contact of last closed
flux surface (LCFS) with limiter

needs additional coils
decoupling of plasma wall
interaction and central plasma

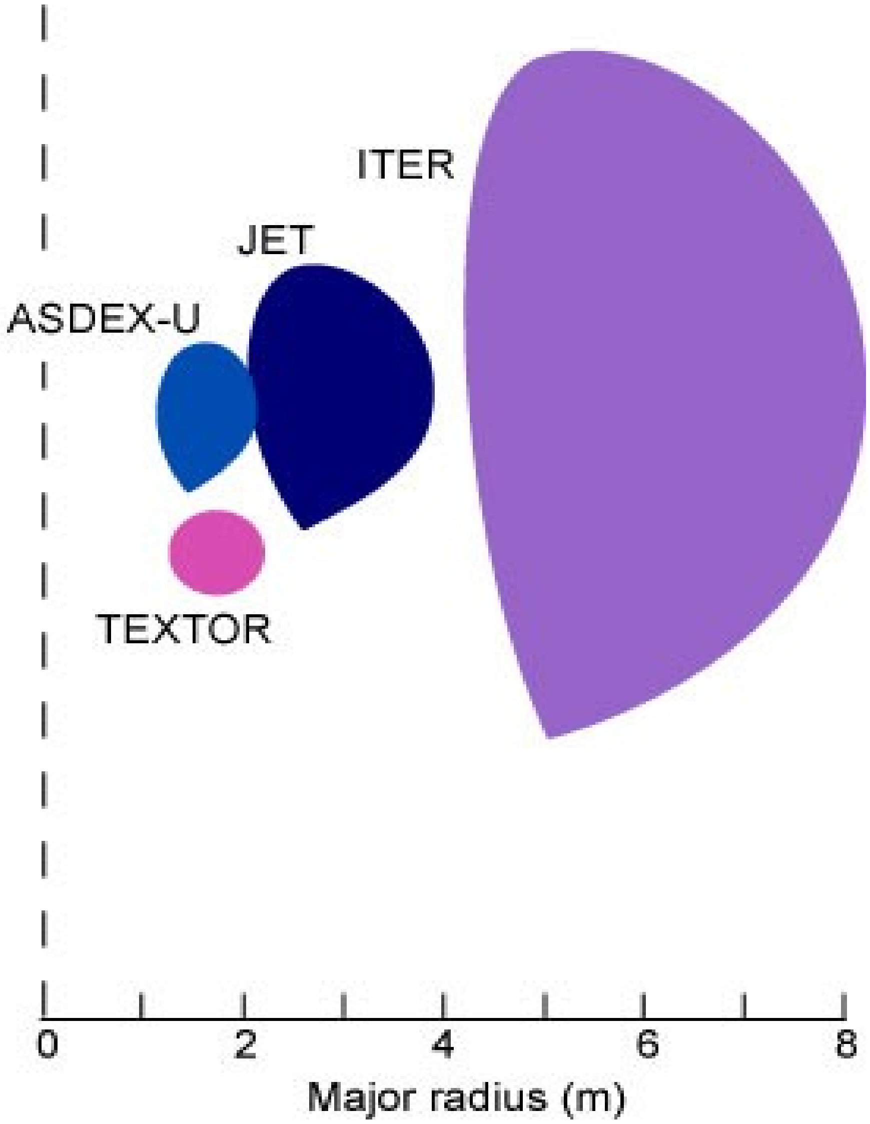
Magnetically Confined Fusion
ITER

Joint project of EU, Russia, USA
Japan, China, South Korea

large radius	6.2 m
minor radius	2.0 m
elongation	1.9
volume	$837\ m^2$
tor. field	5.3 T
plasma	
current	15 MA
density	$10^{20}\ m^3$
temperature	20 keV
aux. power	73 MW
fusion power	500 MW
pulse length	500 s



Towards ITER
Scaling of Confinement



Diffusive process:

confinement time $\tau_E \propto a^2/\kappa$

(a = small plasma radius,
κ = thermal conductivity)

larger a $\Rightarrow$ higher τ_E

ASDEX Upgrade, TEXTOR (D):
$a = 0.5$ m, $\tau_E = 100$ ms

JET (GB):
$a = 1$ m, $\tau_E = 500$ ms

ITER (F):
$a = 2$ m, $\tau_E = 3$ s (?)

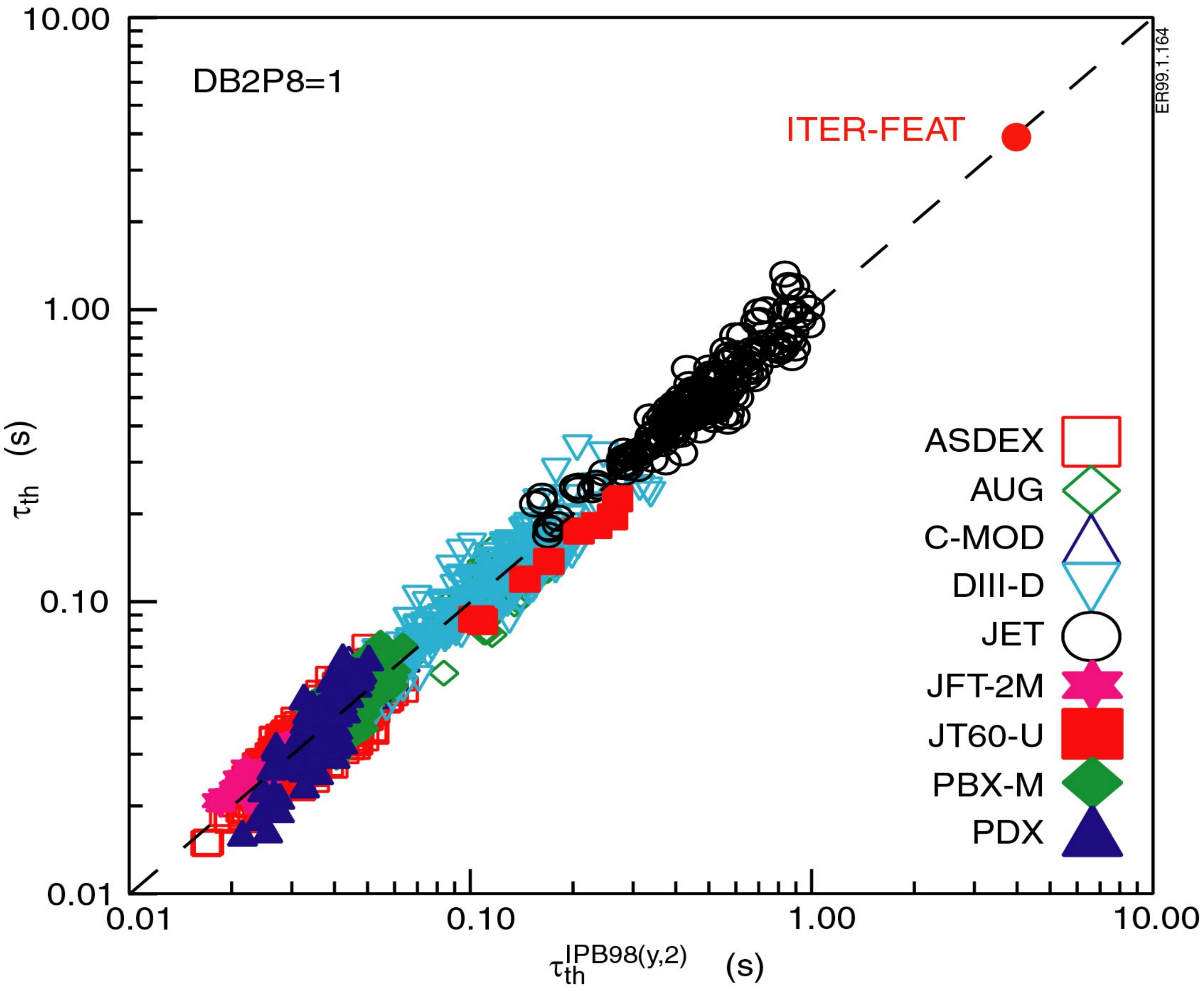
Towards ITER
Scaling of Confinement

$$\tau_E \sim I^{0.93} n^{0.41} B^{0.15} P^{-0.67} R^{1.49} a^{0.58} m^{0.19} \kappa^{0.78}$$

- „wind tunnel experiments“
- used for extrapolation to ITER

- scaling laws

- being tested by turbulence calculations

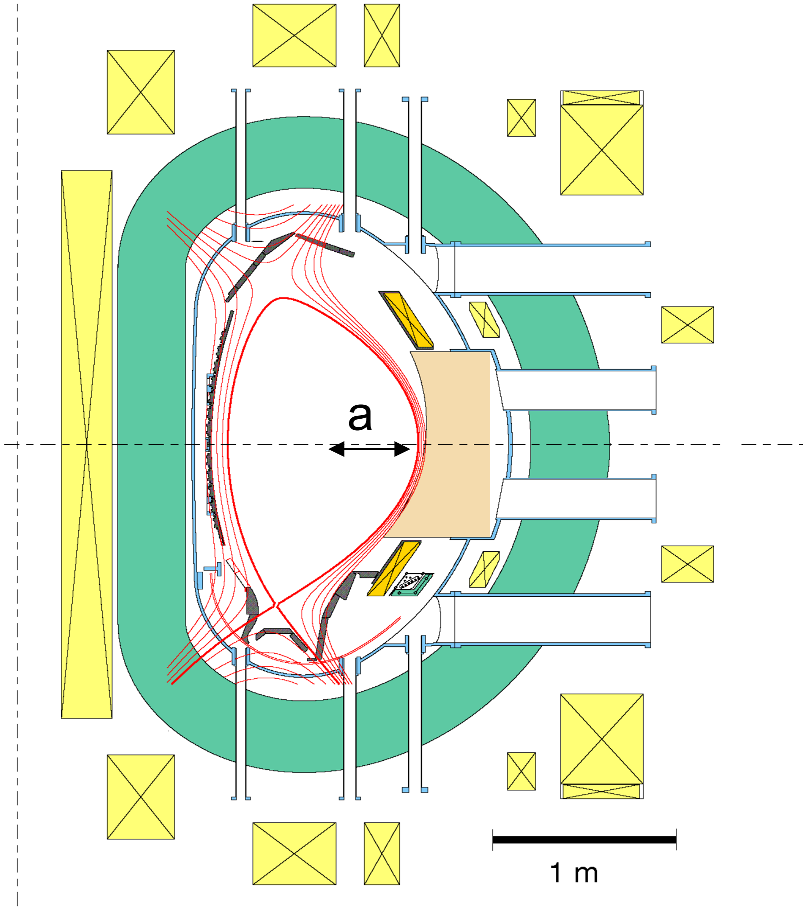


Towards ITER

Scaling using existing devices / ASDEX Upgrade

ASDEX Upgrade

R = 1.65m



Parameters:

R_0=1.65 m

a=0.5 m

I_p= 0.4-1.4 MA

$B_T \leq 3$ T

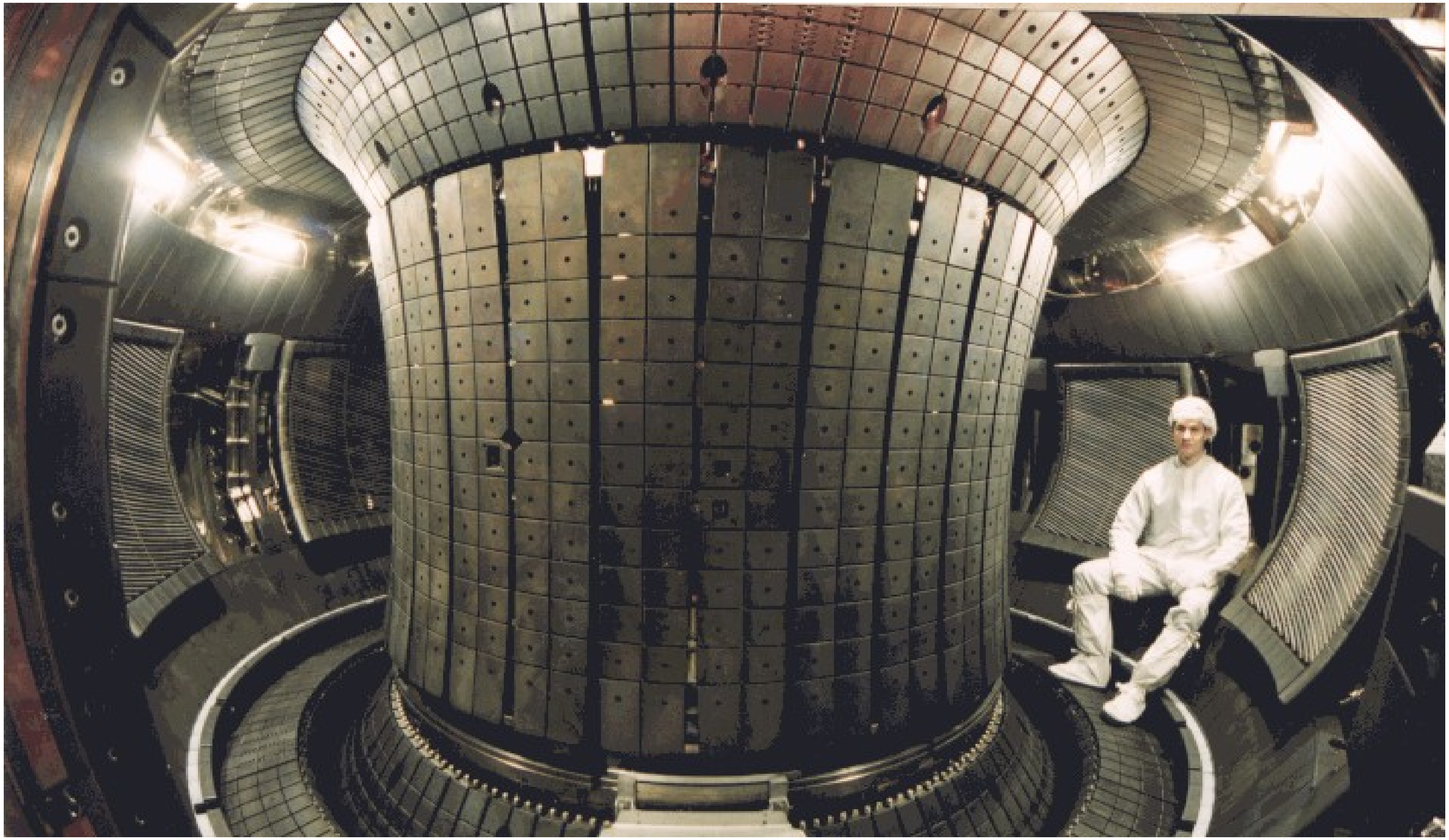
Auxiliary heating:

20 MW NBI

7 MW ICRH

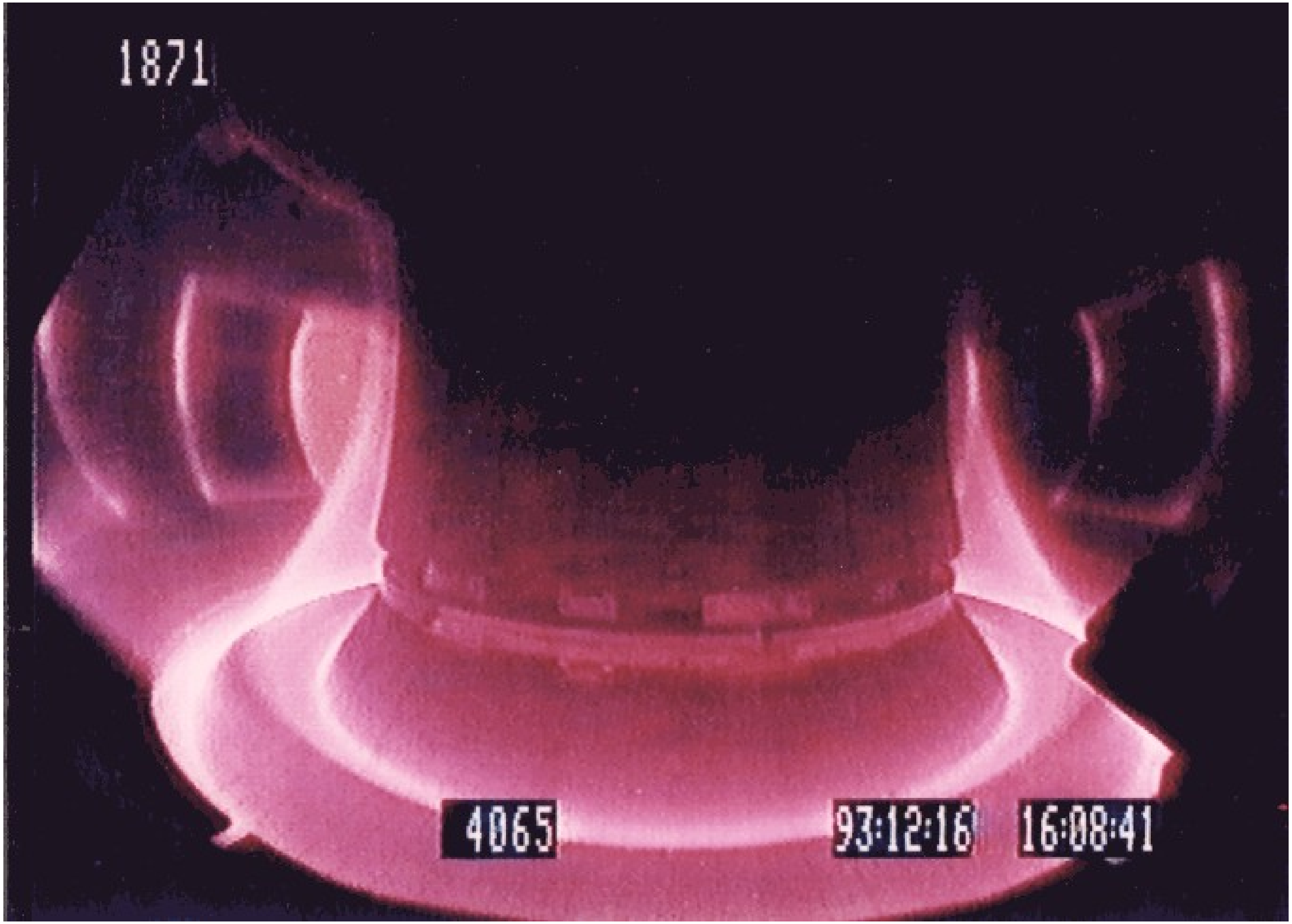
2 MW ECRH

Towards ITER
View into the ASDEX Upgrade Tokamak



Towards ITER

Plasma discharge in ASDEX Upgrade



Towards ITER
T codeposition with C can limit operation

Carbon (CFC) as Plasma Facing Material (PFM):

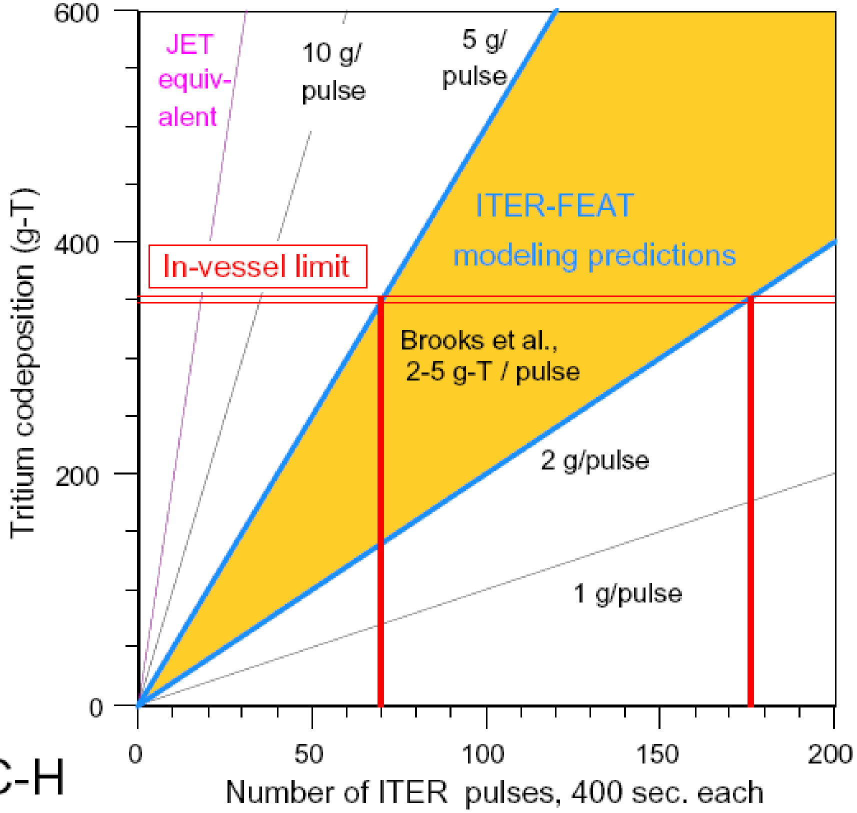
- low-Z
- high thermal conductance,
- sublimation
- low electrical conductance
- good machinability
- low activation

⇒ all major divertor devices used/use C

however: very complex chemistry with hydrogen

- high (chemical) erosion already at low impact energies
- strong codeposition of hydrogen (tritium) in a:C-H layers

→ 'infinite' accumulation of T in a reactor, not permitted due to radiation safety



Federici et al, PSI 2002

⇒ a future fusion device needs alternatives to carbon based PFCs!

Towards ITER

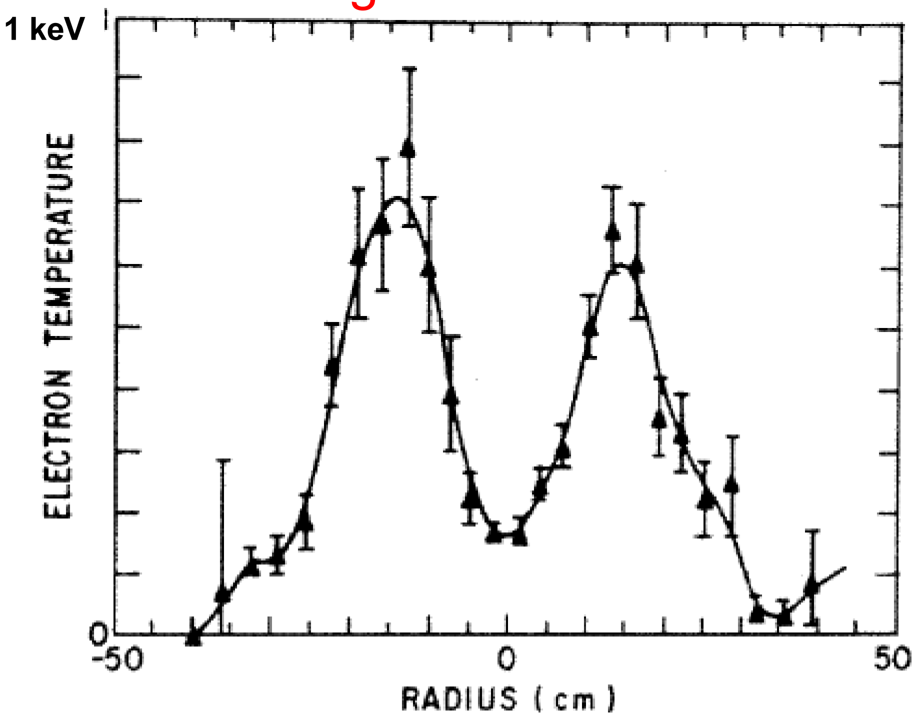
High-Z PFCs in early devices

Most of the fusion devices in the 70‘ties started with high-Z PFCs (limiters):

Alcator A,C
FT
ORMAK
PLT

DIVA

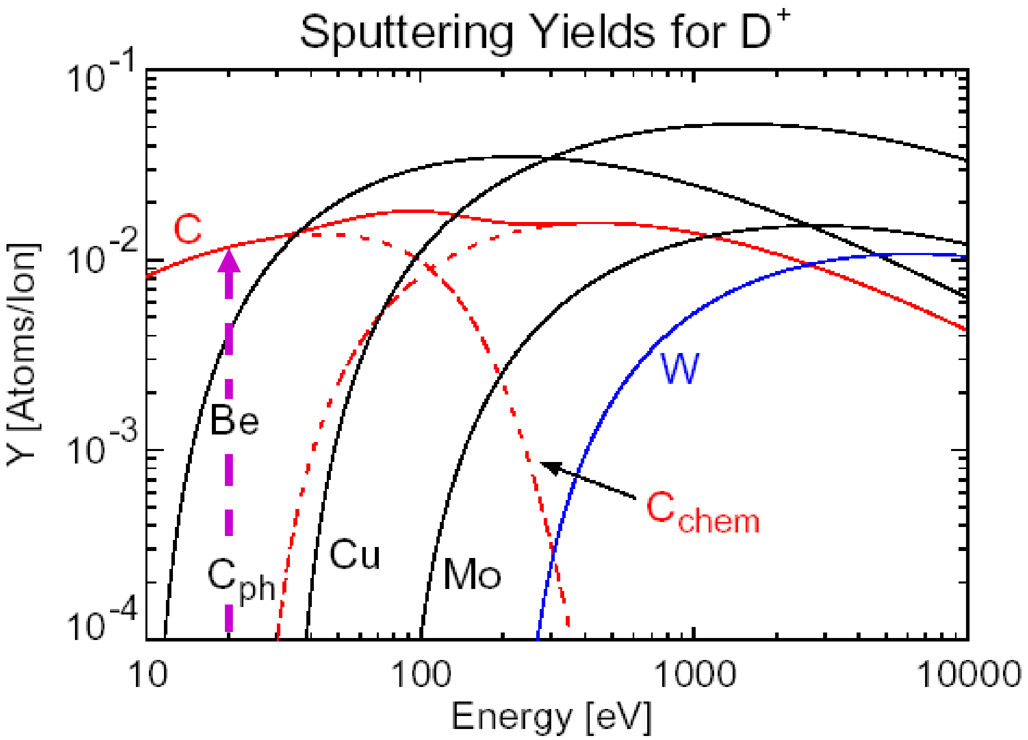
temperature profile in PLT during W accumulation

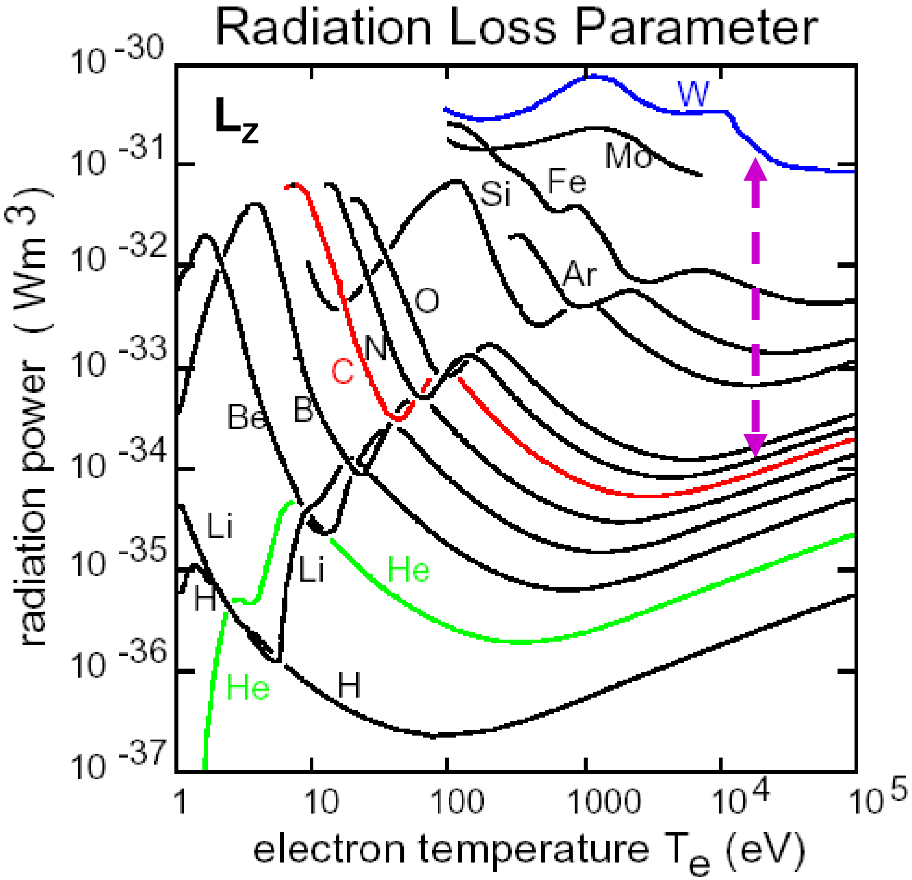


high-Z contamination / accumulations
strongly deteriorated performance
⇒ all devices with moderate current densities changed to low-Z PFCs

Towards ITER

Choice of PFM / Source Rate versus Radiation Losses





Impurities lead to central power losses

by

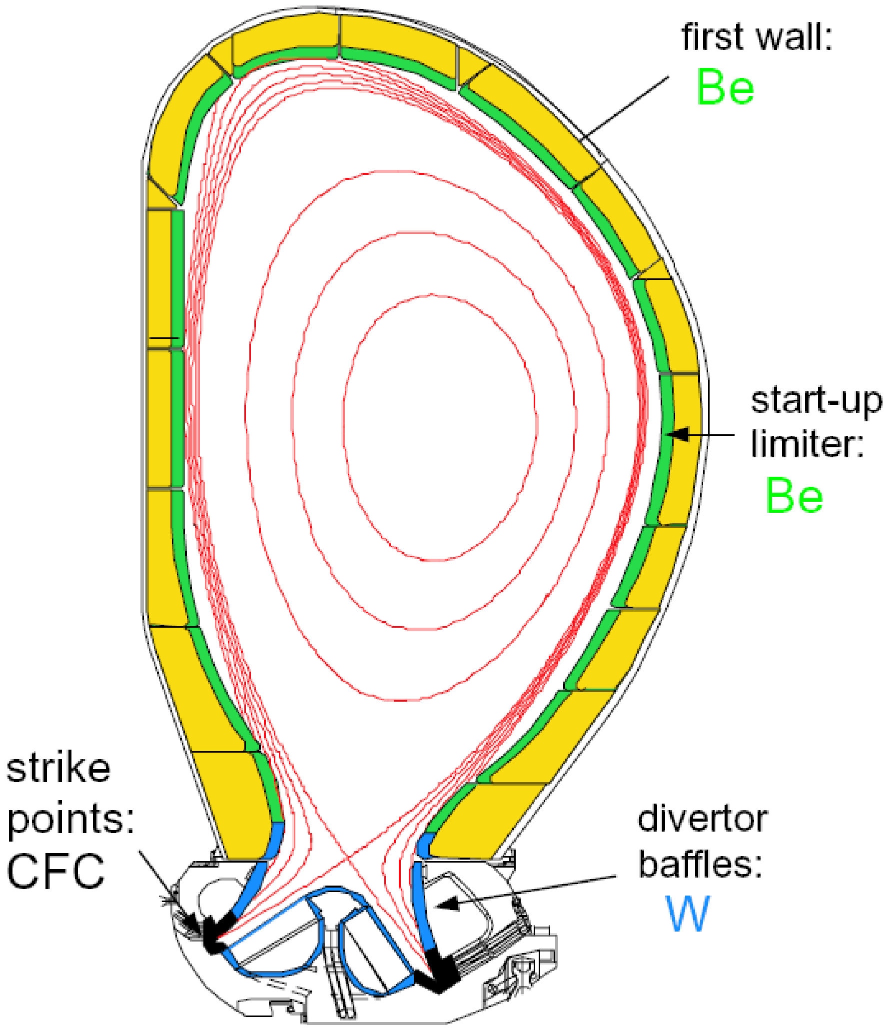
dilution of fuel (low-Z) : $n_{DT} = n_e(1 - Zn_Z)$

radiation (high-Z) : $P_{rad} / V = L_Z \, n_Z \, n_e$

maximum concentrations (ITER):

He ≈ 10^{-1} C ≈ 5×10^{-3} W ≈ 2×10^{-5}

Towards ITER
ITER tries to minimize use of C (and W)



Material selection in ITER:

- minimize use of C !
- low-Z main chamber wall
  ⇒ Be
- high heat flux / high erosion zones
  ⇒ W
- regions with strong transients (ELMs)
  ⇒ CFC (C)

If transients can be avoided (before DT operation?):
⇒ W for complete divertor

Material selection in DEMO (H. Bolt ICFRM-10, 2001):

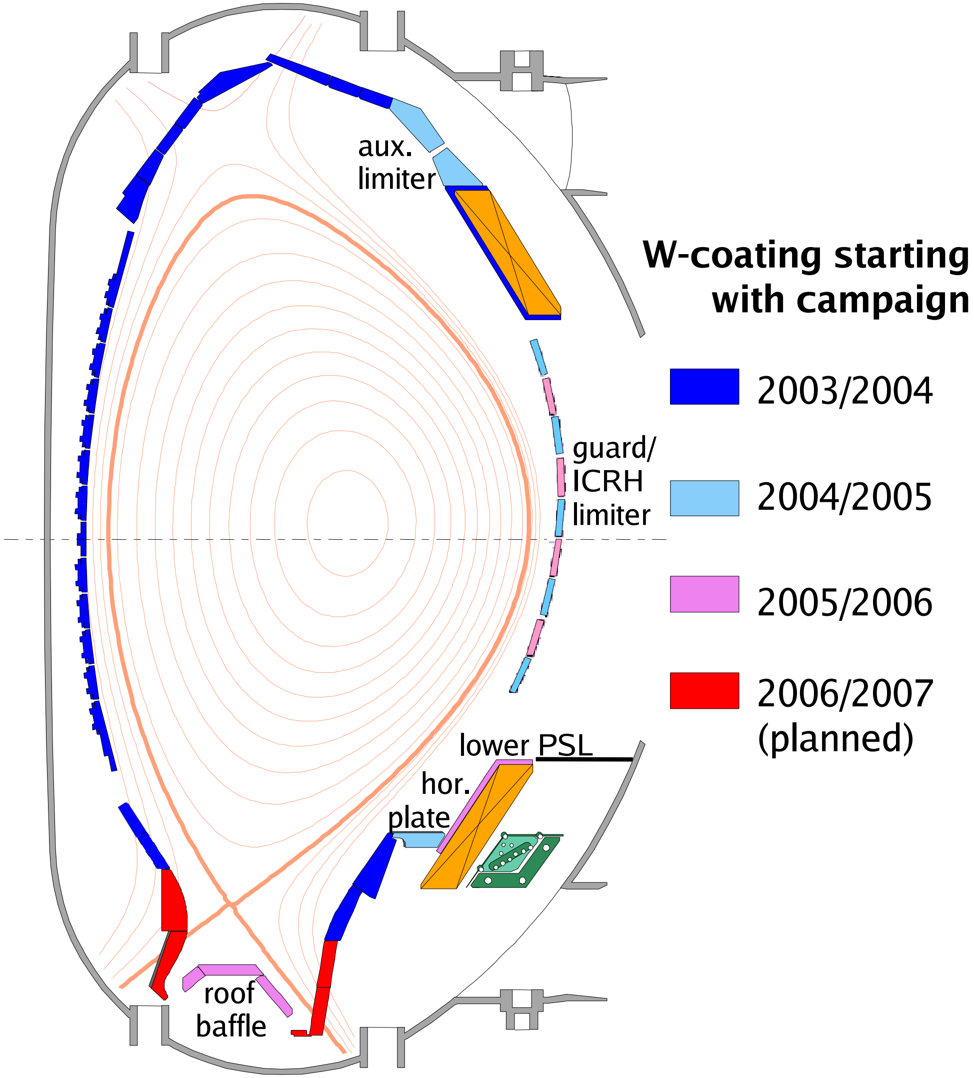
- (W coated) steel in main chamber
- W in divertor

All major design studies plan to use W as PFM!

Results with W PFCs in ASDEX Upgrade

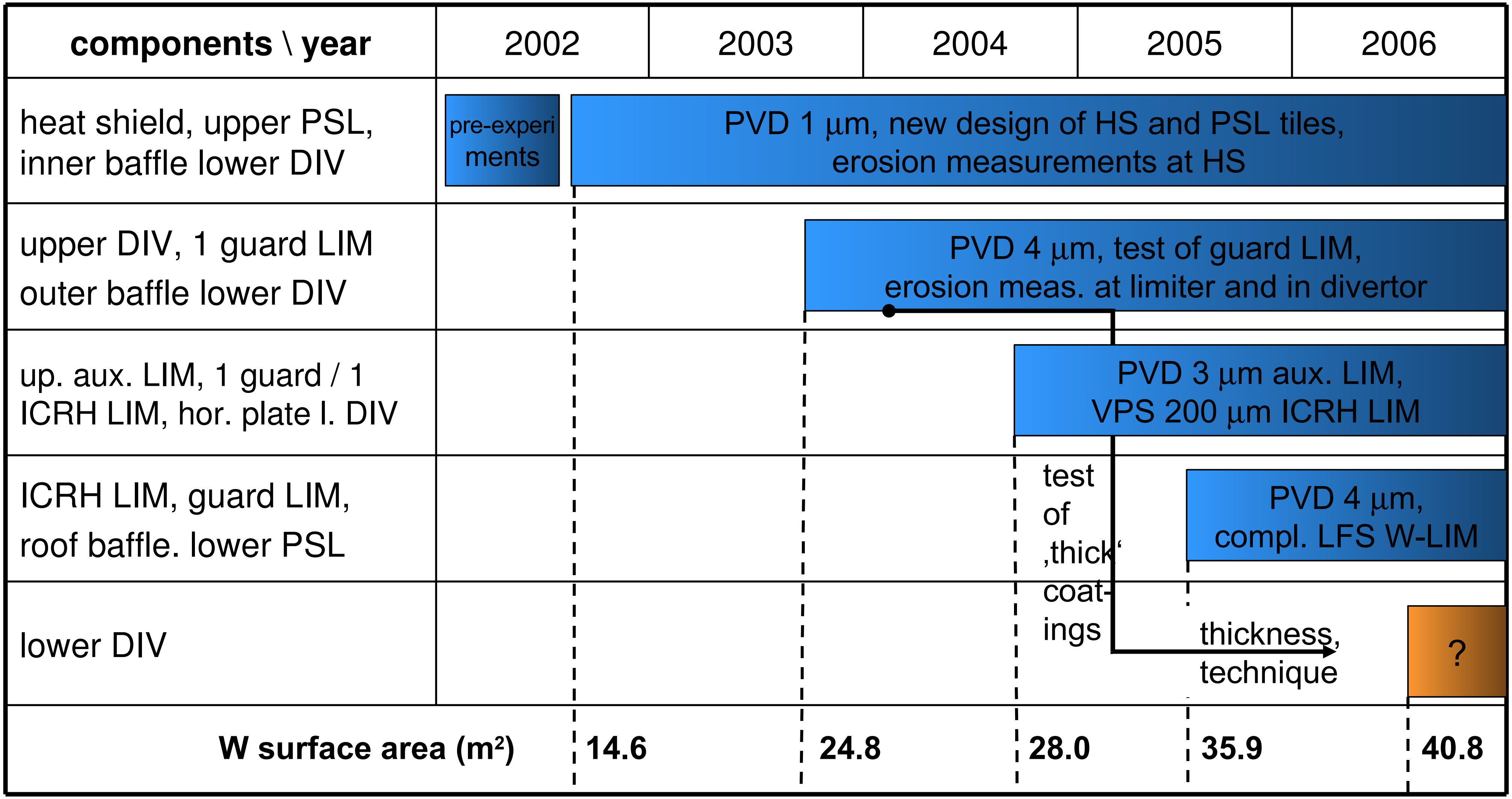
History / Schematic view

- 1995/1996 W-divertor:
  W is feasible in divertor tokamak
  main chamber is strong source of C
- 1999/2000 W-tiles in main chamber:
  no impact on plasma performance
- 2001/2003 W centr. col. (start-up lim.):
  start-up possible, strong reduction
  of W inventory after x-point formation,
  erosion mainly by ions
- 2003/2005 W divertor, LFS limiter:
  confirmation of '96 divertor results,
  erosion at LFS limiter dominated
  by fast ions (NBI) and accelerated ions (ICRH)



Results with W PFCs in ASDEX Upgrade

Implementation of W coatings

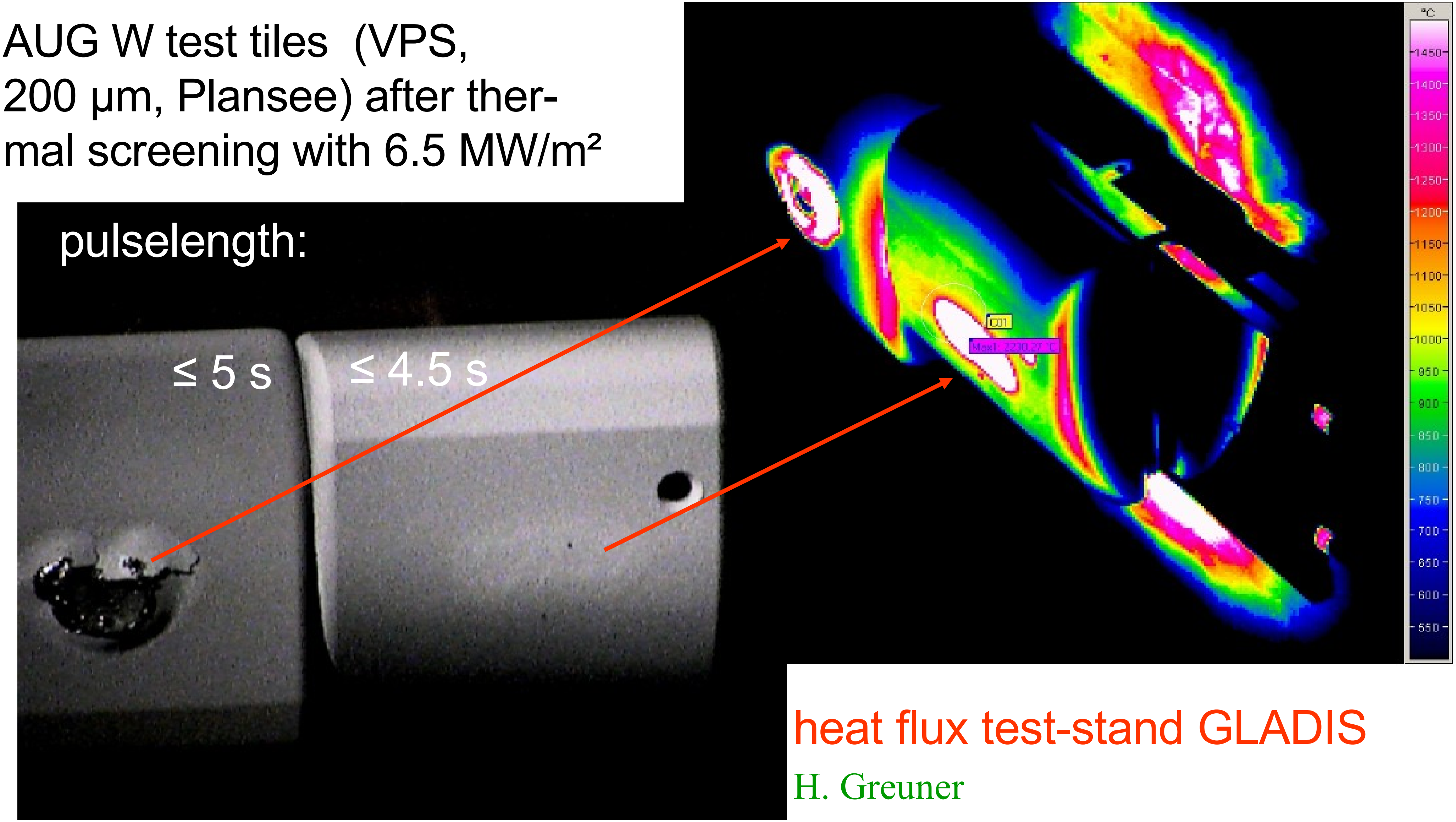


components \ year	2002	2003	2004	2005	2006
heat shield, upper PSL, inner baffle lower DIV	pre-experiments PVD 1 μm, new design of HS and PSL tiles, erosion measurements at HS				
upper DIV, 1 guard LIM outer baffle lower DIV		PVD 4 μm, test of guard LIM, erosion meas. at limiter and in divertor			
up. aux. LIM, 1 guard / 1 ICRH LIM, hor. plate l. DIV			PVD 3 μm aux. LIM, VPS 200 μm ICRH LIM		
ICRH LIM, guard LIM, roof baffle. lower PSL			test of ‚thick' coat-ings	PVD 4 μm, compl. LFS W-LIM	
lower DIV				thickness, technique	?
W surface area (m²)	**14.6**	**24.8**	**28.0**	**35.9**	**40.8**

Results with W PFCs in ASDEX Upgrade

Test of W-coatings

AUG W test tiles (VPS, 200 µm, Plansee) after thermal screening with 6.5 MW/m²



heat flux test-stand GLADIS

H. Greuner

Results with W PFCs in ASDEX Upgrade

Test of W-coatings

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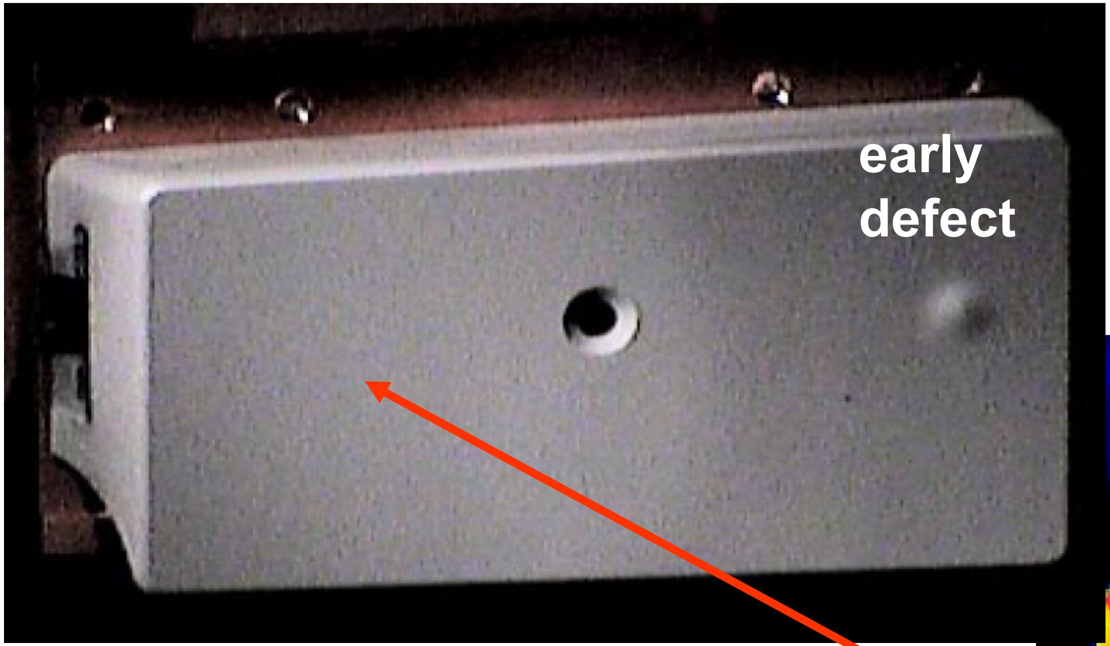
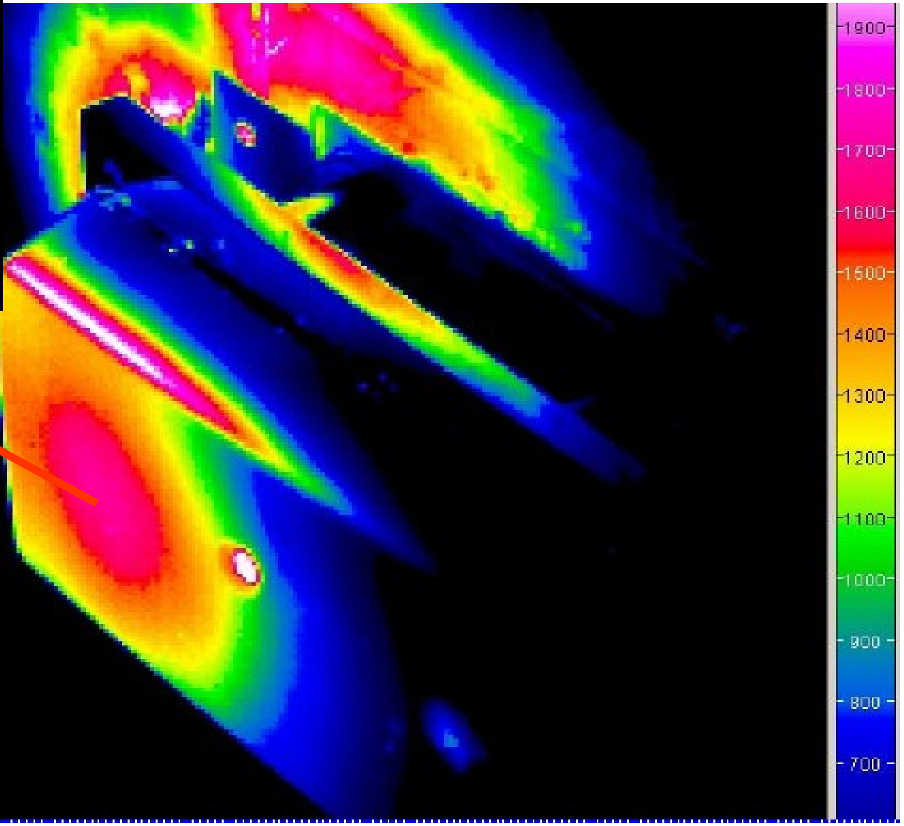


10.5 MW/m² 5s, 17th pulse



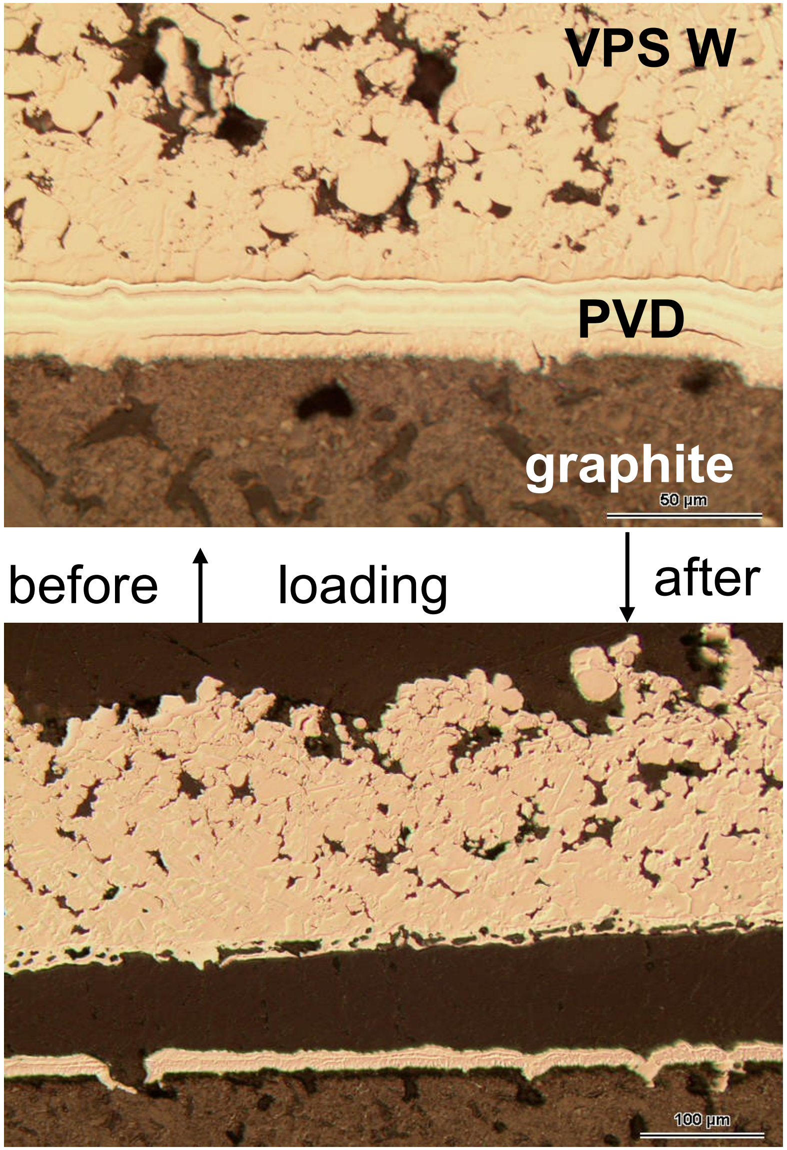
thermal screening on reference tile (DIV I (1995), 0.5 mm W VPS on W/Re interlayer):

coating survives 10.5 MW/m² for up to 5 s

Results with W PFCs in ASDEX Upgrade

Test of W-coatings

- reason for failure of W VPS coatings (Plansee, 200 µm) identified (wrong interlayer)
- new coatings produced and delivered (to be tested in GLADIS)
- additional test coatings ordered at Sulzer Metco (VPS: W 300µm, Re 20µm)
- and in collaboration with IPP Prag (PS: W 300µm) KFKI Budapest (PVD: 3µm)



H. Greuner

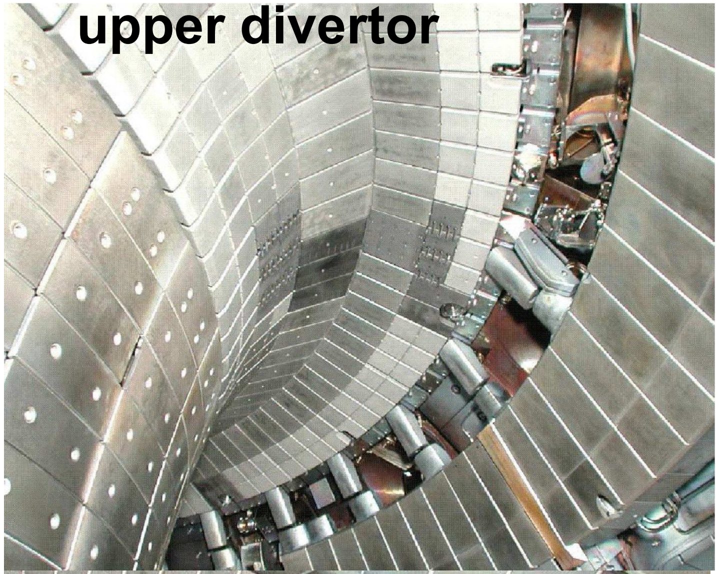
Results with W PFCs in ASDEX Upgrade

Spectroscopic investigations

- ASDEX Upgrade uses W-PFCs on a large scale

⇒ behaviour of W in plasma discharges

- spectrocopic measurements
  (visible - x-ray, absolute)
- ionisation equilibria: strong influence
  of exciation/autoinisation (EA)
- determination of total radiation
- comparison with EBIT:
  similar excitation, but lower densities
- benchmarking of codes
  (HULLAC, Cowan/ADAS)
- investigation of isoelectronic sequences


upper divertor

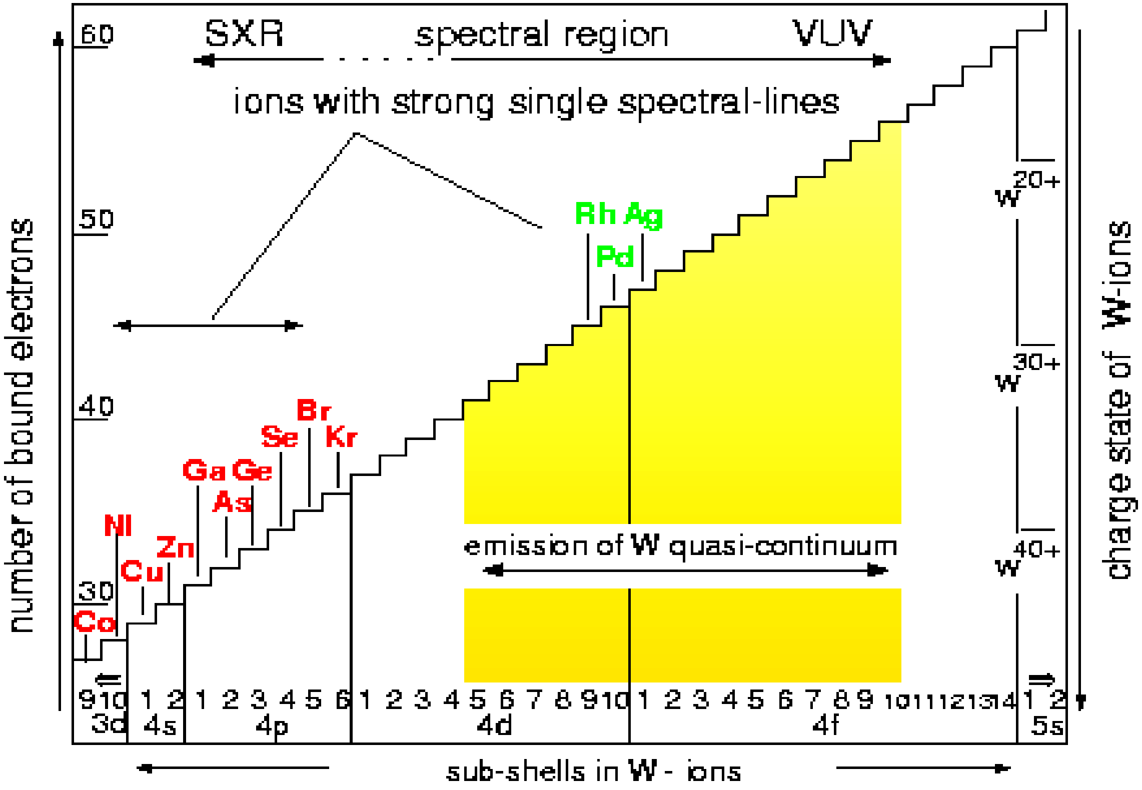

lower divertor

Results with W PFCs in ASDEX Upgrade

Investigated transitions

Accessible ionisations states in present day fusion devices

- Δn=0 transition observable in the VUV
- Δn=1 transition observable in the SXR
- quasi continuum emission from states around W^{30+}
- strong single line transitions observed for ionisation states around Ni-like W (W^{46+}, $3d^{10}$)

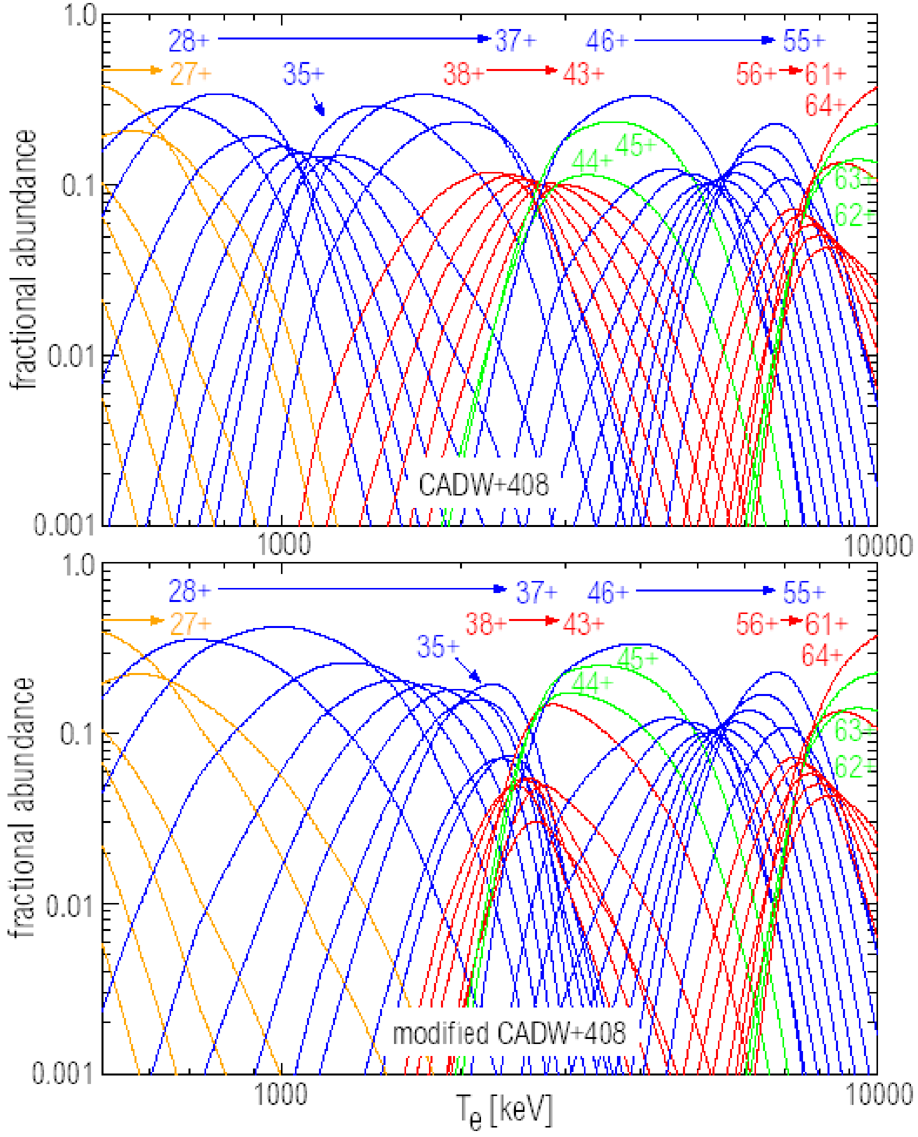


Results with W PFCs in ASDEX Upgrade

Revision of ionization equilibrium

Revision of W ionization equilibrium deduced from

- temperature dependence of spectral lines
- new theoretical ionization rate coefficienst



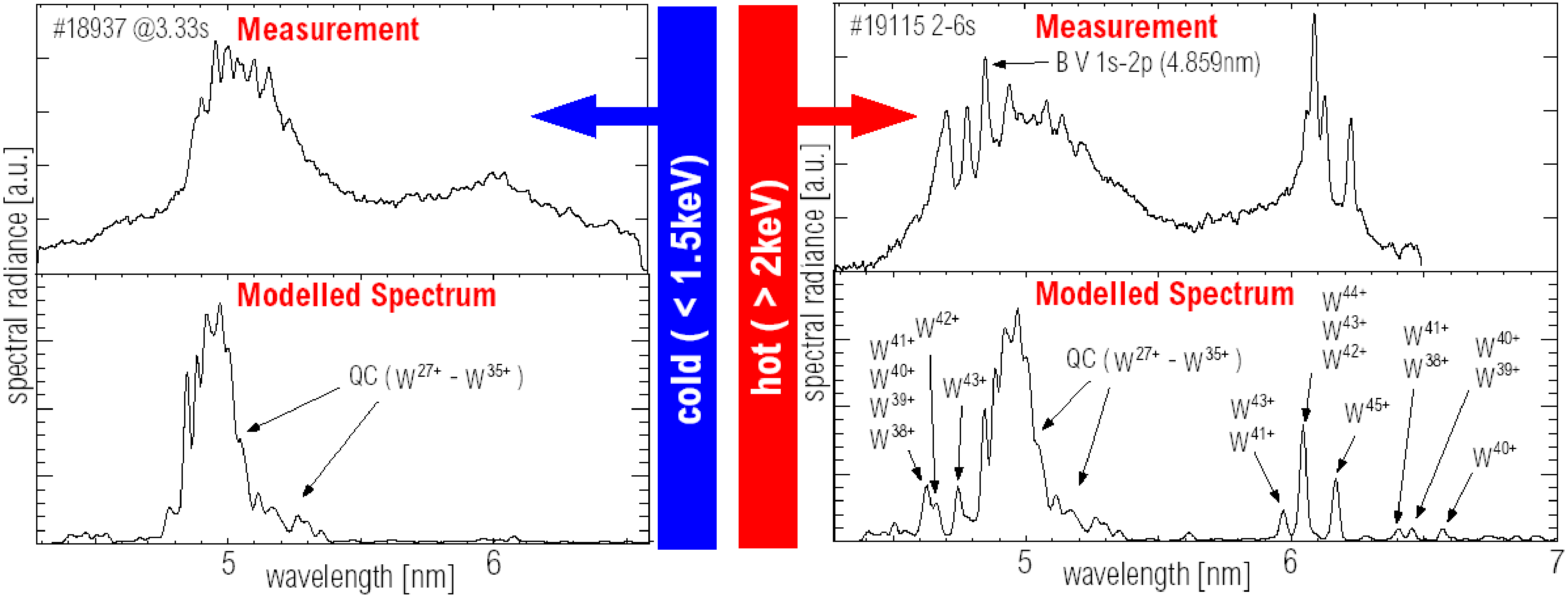
Th. Pütterich (PhD thesis)

Results with W PFCs in ASDEX Upgrade

Detailed investigations of W-spectra in VUV

- Around 5 nm: Features emitted at $T_e \approx 0.8 - 1.5$ keV and at $1.8 - 4.5$ keV
- Detailed EBIT measurements (Berlin, LLNL) available
- Disagreement in many details
- Rough structure of predictions is found in the spectrum

Th. Pütterich (PhD thesis)



Results with W PFCs in ASDEX Upgrade

Detailed investigations of W-spectra in VUV

Comparison with EBIT investigations

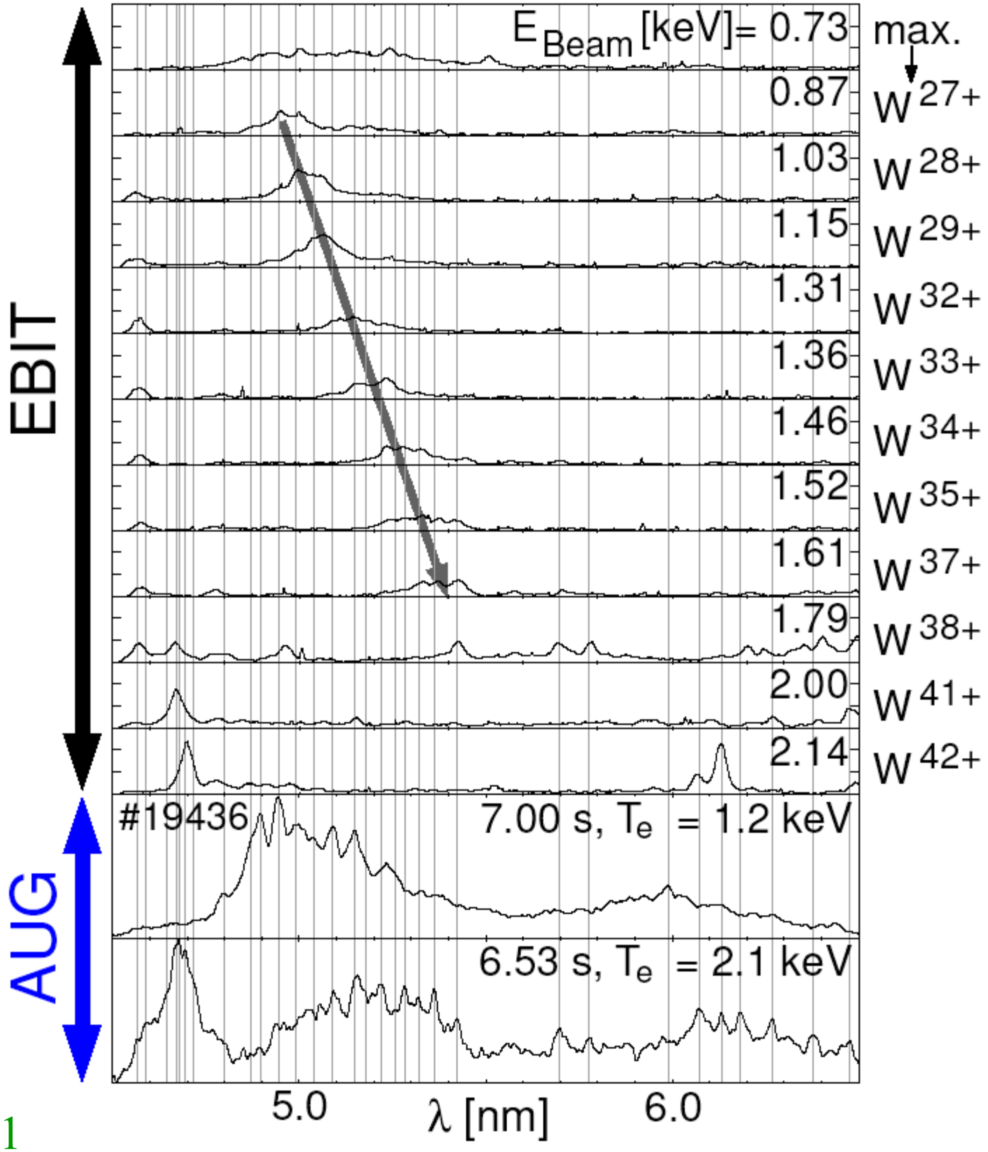
strong influence of transport (here: central accumulation) observed

→ locally higher W-density

→ emission mostly from a few ionisation states

⇒ situation resembling to EBIT

⇒ very similar single line spectra

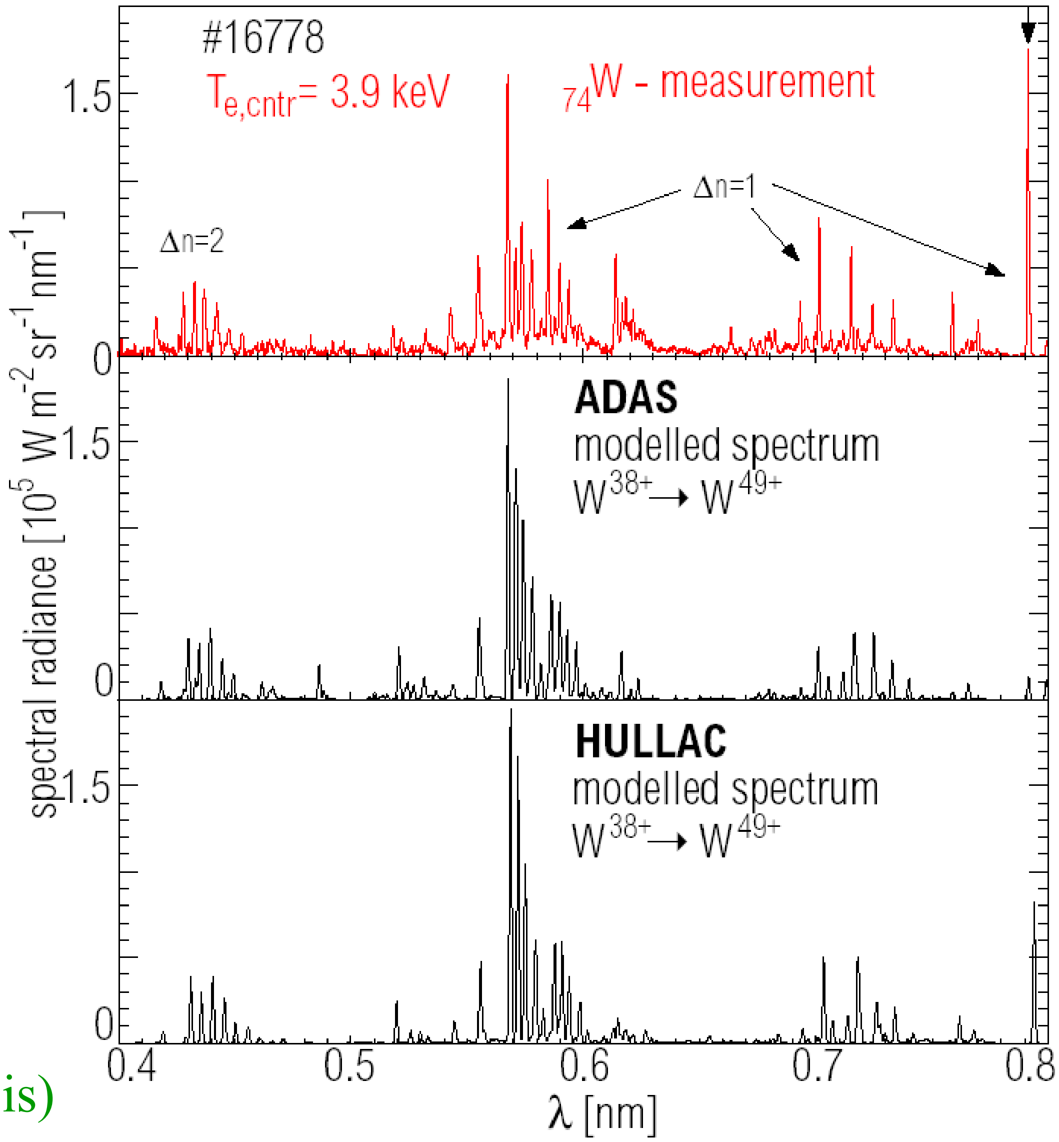


Th. Pütterich et al., J. Phys. B 38 (2005) 3071

Results with W PFCs in ASDEX Upgrade

Detailed investigations of W-spectra in SXR

- Spectral lines of Kr-like W^{38+} to about Mn-like W^{49+}
- Ni-like W^{46+} exhibits most intense spectral lines
- At ASDEX Upgrade the electric quadrupole line at 0.793 nm is monitored

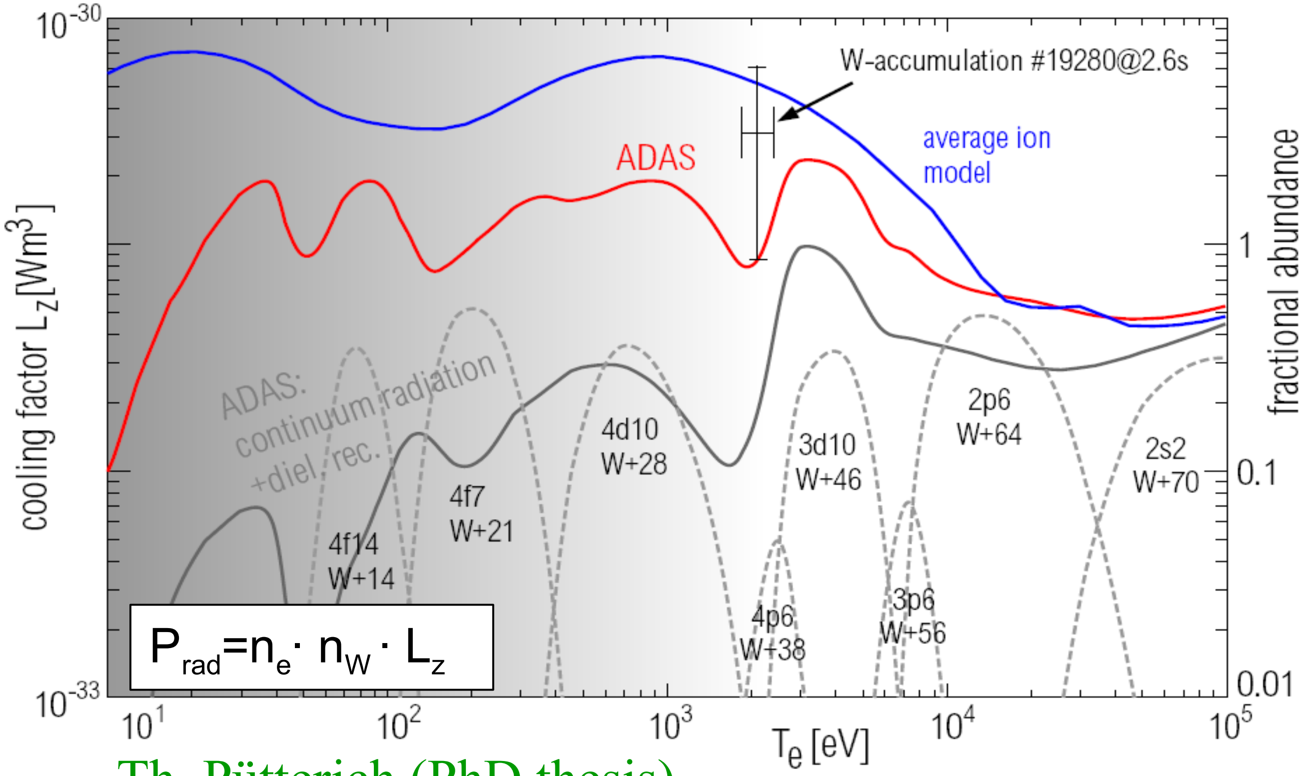


Th. Pütterich (PhD thesis)

Results with W PFCs in ASDEX Upgrade

Recalculation of cooling factor

Revised cooling factor from ADAS calculations benchmarked by spectroscopic measurements:



$P_{rad}=n_e \cdot n_W \cdot L_z$

Th. Pütterich (PhD thesis)

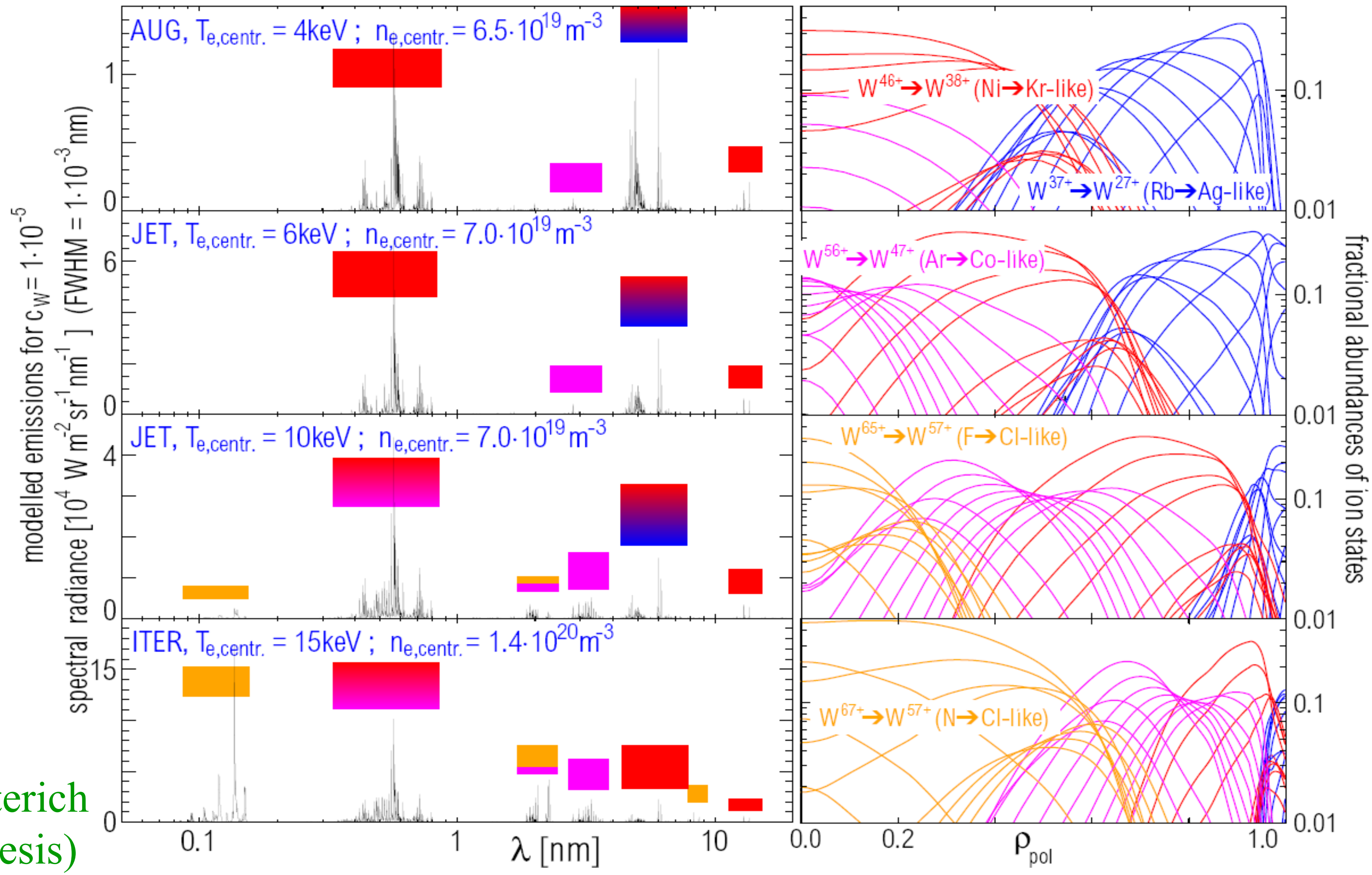
Large number of configurations at low temperature (lower ionisation states) results in lower credibility of calculations

⇒ detailed spectroscopic measurements at low temperature will be performed

Results with W PFCs in ASDEX Upgrade

Extrapolation to JET and ITER

Modelled W emission (ADAS) @ different temperatures



Th. Pütterich
(PhD thesis)

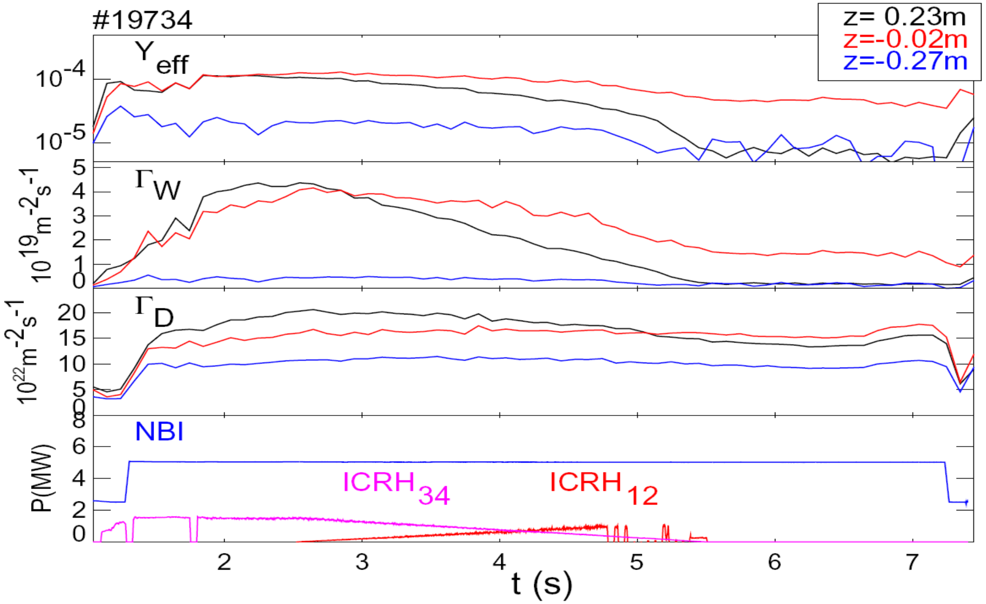
Results with W PFCs in ASDEX Upgrade

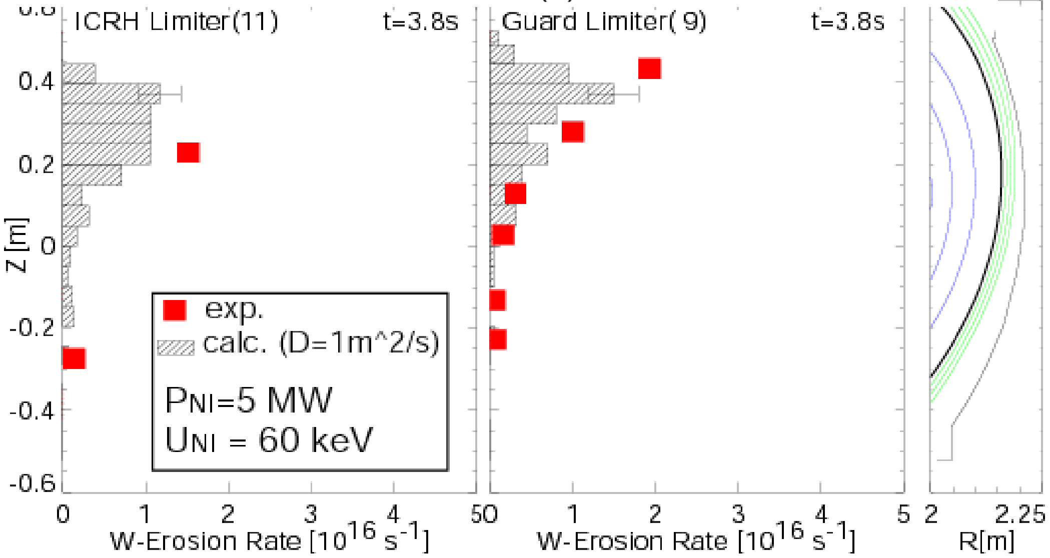
W erosion dominated by fast particles

W influx

- from HFS mostly below det. limit (except for very low distances)
- from LFS signicant
  - - for NBI (mostly fast ions)
  - - and ICR heating (acceleration in rectified sheath)

but still not dominant
W source
(small area ’04/‘05).

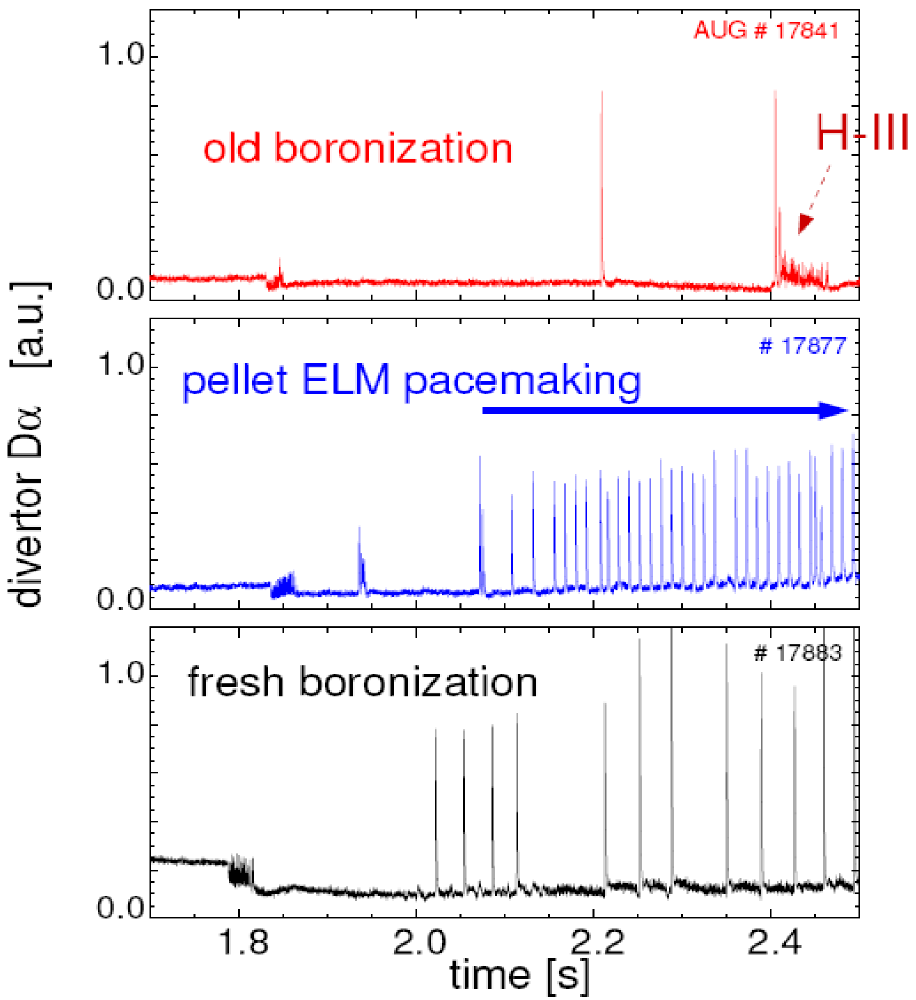


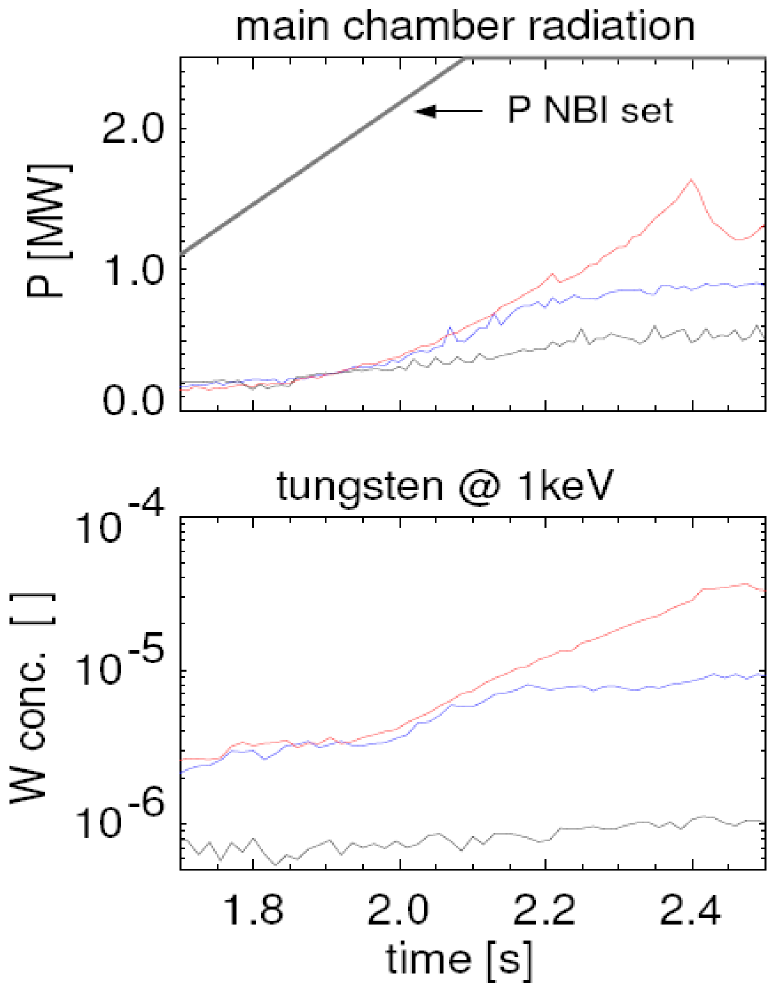


R.Dux, EPS05

Results with W PFCs in ASDEX Upgrade

Reduction of W content by increasing ELM frequency



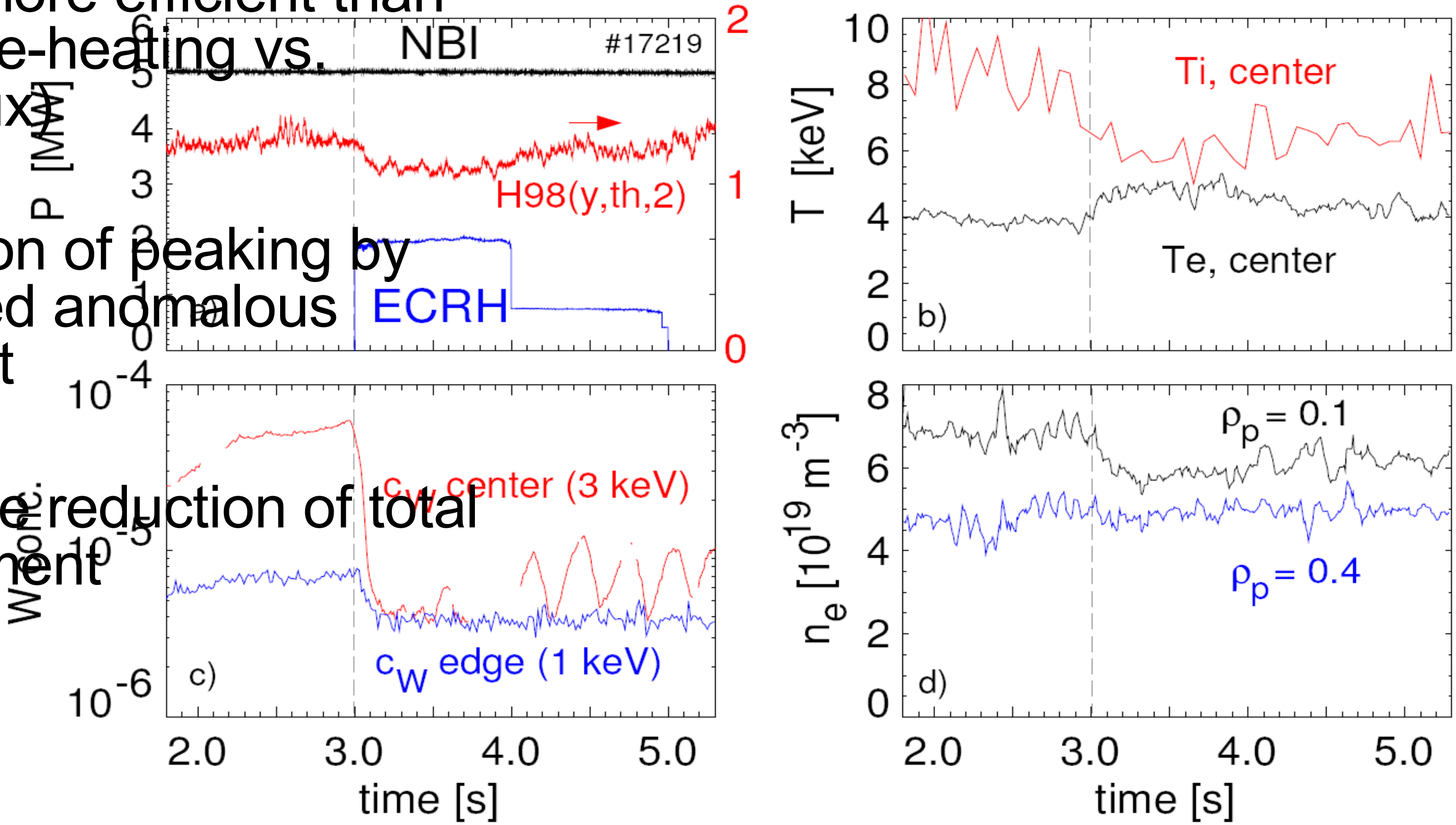


Results with W PFCs in ASDEX Upgrade

Suppression of central impurity peaking

Central wave heating strongly suppresses impurity peaking

- ECRH more efficient than ICRH (e-heating vs. powerflux)
- Reduction of peaking by increased anomalous transport
- Moderate reduction of total confinement

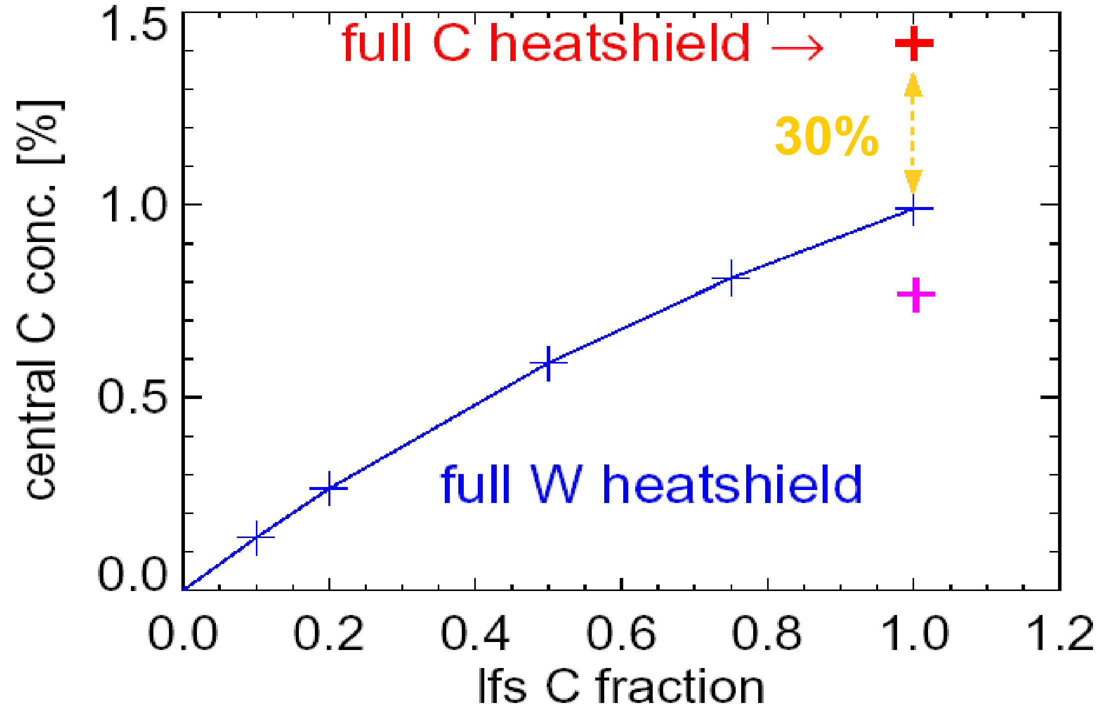


Results with W PFCs in ASDEX Upgrade
Marginal reduction of C content

Migration model
- core transport similar to STRAHL
- l.f.s. and h.f.s. SOLs as reservoir models
- wall fluxes according to empirical scale
- arbitrary drift from l.f.s. to h.f.s.
- transport parameters adjusted to exp.

Sputtering model
- inner div deposition zone
- outer div: out=in
- carbon balance for W surfaces
- sputtering yield ∝ f_monolayer

prediction for reduction of C content



C lost in inner div
C returns from outer div.

no C backflow
from outer div

A. Kallenbach

Summary and Outlook

W-Programme in ASDEX Upgrade

- Transition to W-device almost complete,

  W coating of lower divertor, propably next year depending on availability of technical solution (thick coating)

- C deposition on W rather small, but role of surface conditioning and C recycling not yet completely clear

- Restrictions of working space identified,

  but remedies developed

- W diagnostic capabilities strongly improved and further development in regard of JET and ITER

- Detailed investigations of W sources and their origin and sinks

- Testing of startup at W limiter as input for ITER design

- Preparation for C free device (diagnostic, scenarios)