Tokamak operation with high-Z plasma facing components

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Outline

"high-Z plasma facing components are mandatory for a fusion reactor"[*]

how to understand, predict and control radiative losses ?

- basic high-Z sputtering mechanisms
- a simple model for the core high-Z concentration
- restrictions in operation
- prospects for ITER / reactor

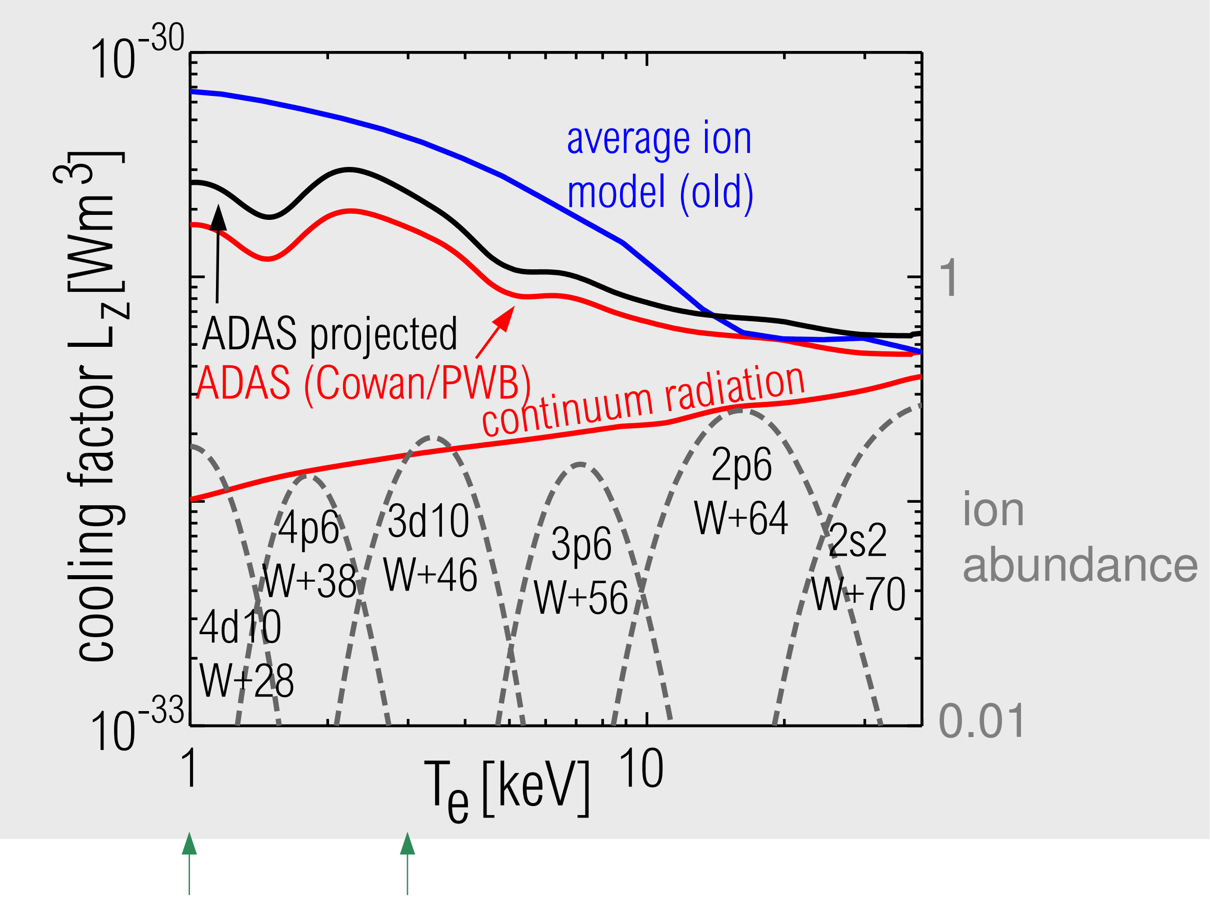
carbon to be exchanged by argon as main radiator

[*] G. Janeschitz, ITER JCT and HTs, J. Nucl. Mat. **290-293** (2001) 1

main concern of high-Z walls: central radiative losses

\+ high-Z metals like tungsten have a very low sputtering yield → long PFC lifetime

\- main disadvantage is the high radiative loss rate of not fully stripped ions
expected maximum allowed c_W in ITER ~ $5 \bullet 10^{-5}$



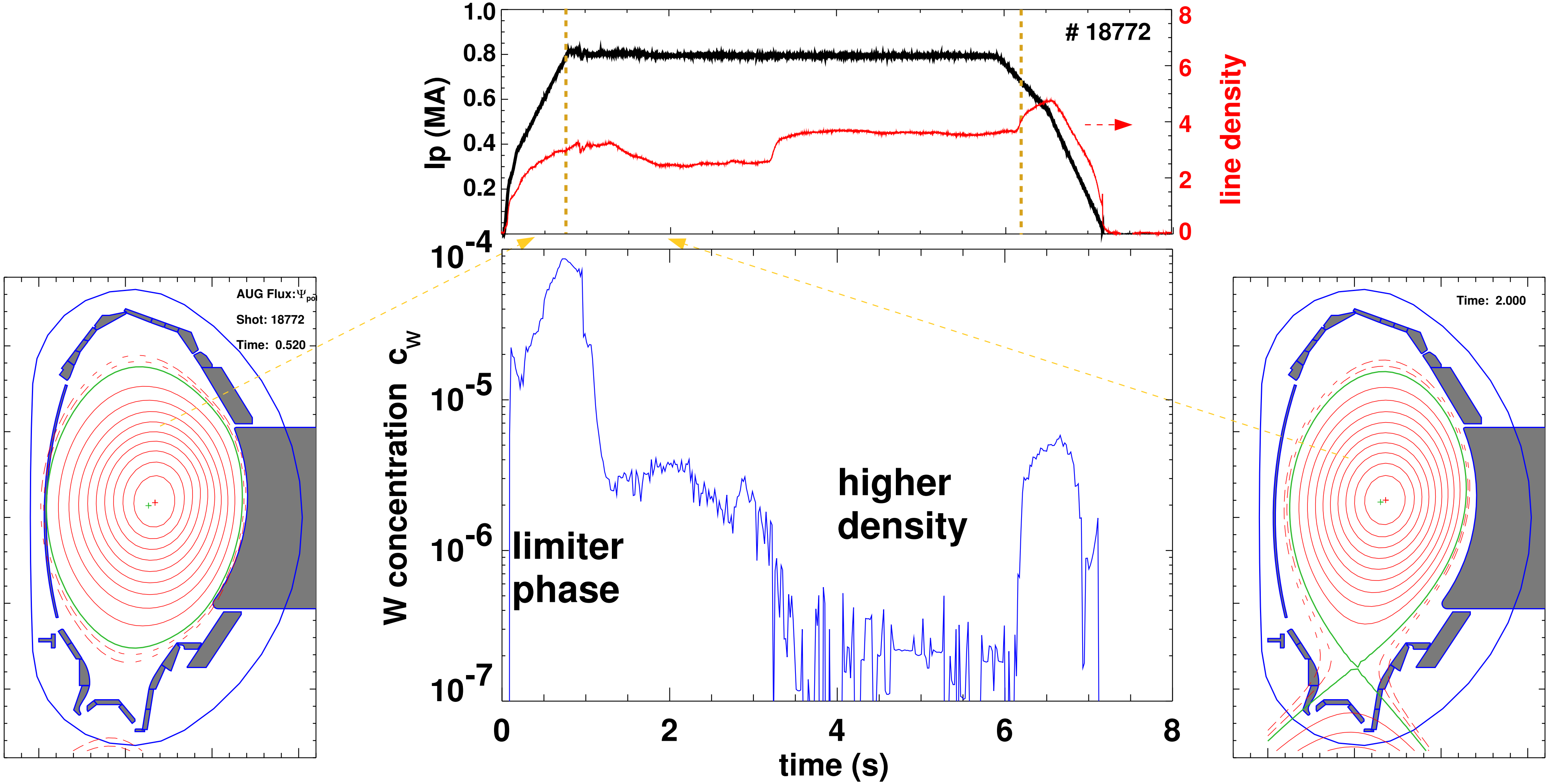
$$P_{cool} = n_e^2 \, c_z \, L_z$$

tungsten concentration c_W
measured @ T_e =1 and 3 keV

R. Neu et al., NF **45** (2005) 209

Tungsten behaviour in "standard" Ohmic discharge

- OH discharge not affected by fast ions, ELMs etc., repeated each day
- wide variation of c_W demonstrates sensitive dependencies



similar behaviour in C-Mod and FTU: M. May et al., PPCF **41** (1999) 45.

Simple model for high-Z core concentration

$$c_Z = \mathbf{Yield} \otimes \mathbf{flux} \otimes \eta_Z^{\mathbf{pen}} \otimes \tau_Z^{\mathbf{conf}} \otimes \frac{1}{\mathbf{Vol}} \otimes \frac{1}{n_e}$$

better relate c_Z to differences between Z and D for dimensionless parameters:
replace n_e by $\Gamma_D\, A\, \eta_D^{pen}\, \tau_D\, /\, \mathrm{Vol}$, yield → R=1

$$c_Z = Y_{eff} \otimes \frac{\eta_Z^{pen}}{\bar{\eta}_D^{pen}} \otimes \frac{\tau_Z}{\tau_D}$$

impact energy, low-Z conc.

neutral and edge transport

neoclassical core transport

$$Y_{eff} = \frac{1}{A} \sum_{i,s} c_{i,s}\, a_s\, Y_i\, (E_{i,s})$$

$$a_s = \frac{\Gamma_s\, A_s}{\Gamma_D\, A} \qquad \sum_s A_s = A$$

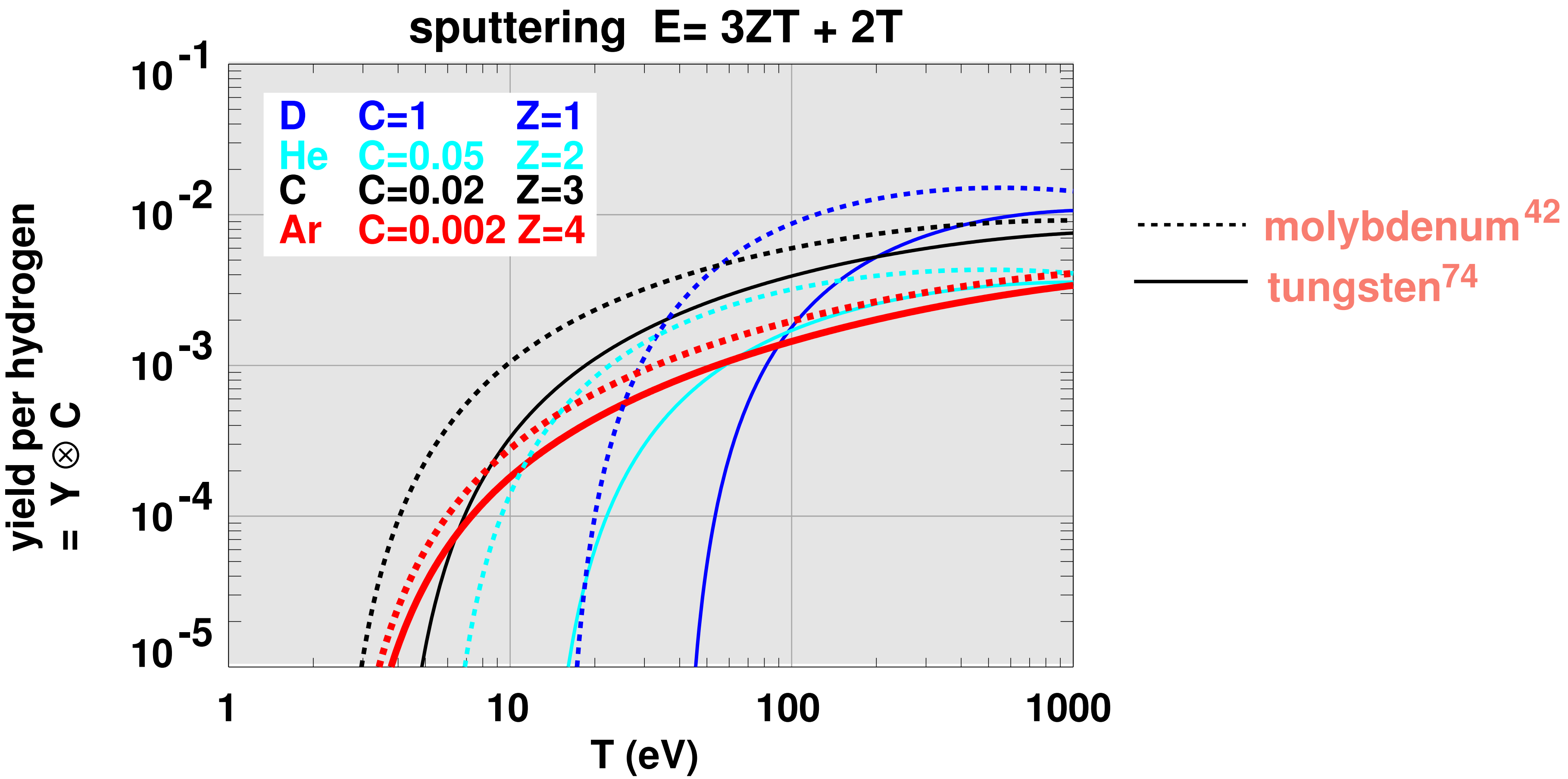
species i, wall element s with area A_s

key elements for high-Z performance

! caution - physics highly simplified !

K. Behringer, JNM 145-147 (1987) 145

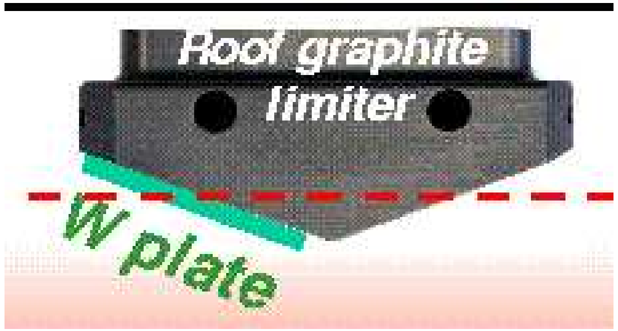
W an Mo sputtering yields: sensitive dependence on impact energy and impurity composition

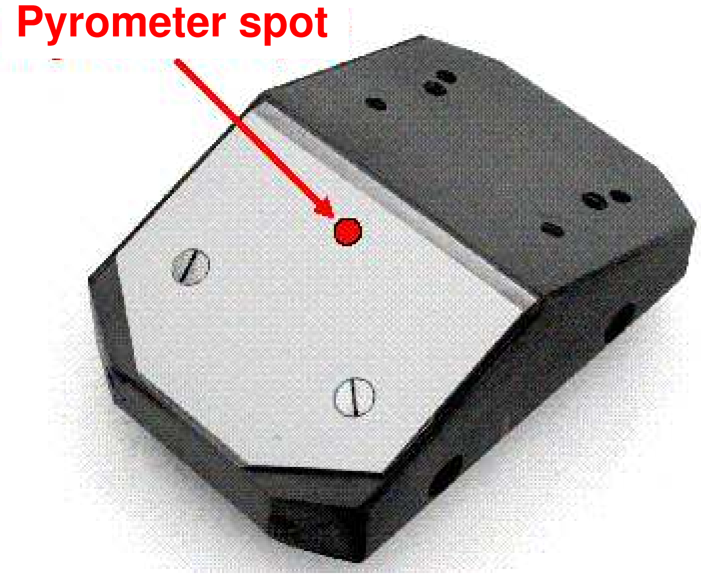


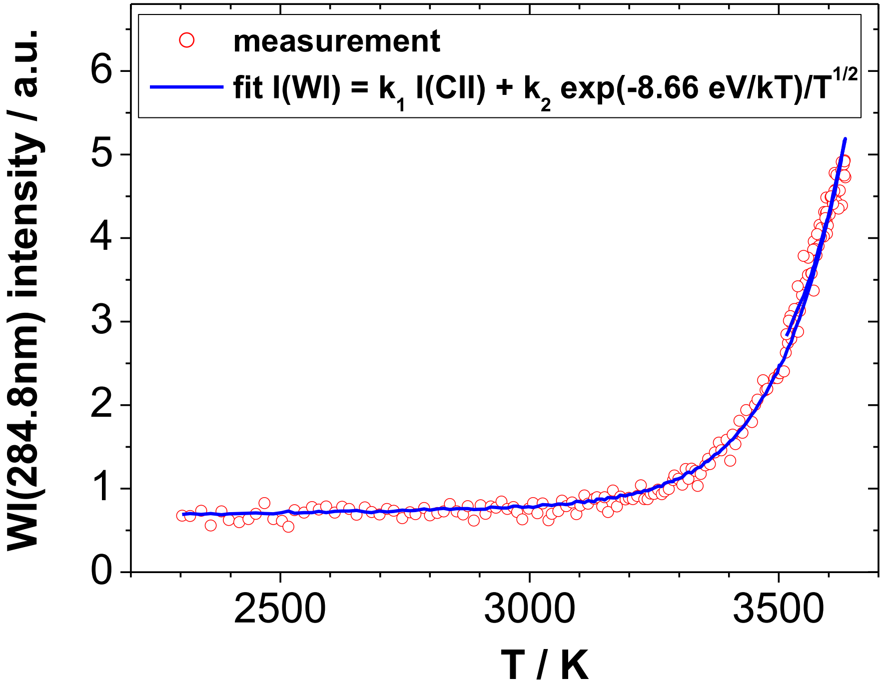
- impurities dominate yields at low temperatures/energies
- no W sputtering by edge-thermal D ions
- Ar takes over from C as main radiating / sputtering species in a reactor

W. Eckstein et al., Rep. IPP 9/82 (1993)

do the low sputtering yields prevail under high heat flux conditions* ? - W limiter experiments in TEXTOR







Result:

Observed W atom flux is well described by sum of

- **flux of atoms sputtered by carbon ions**
- **flux of evaporated atoms**

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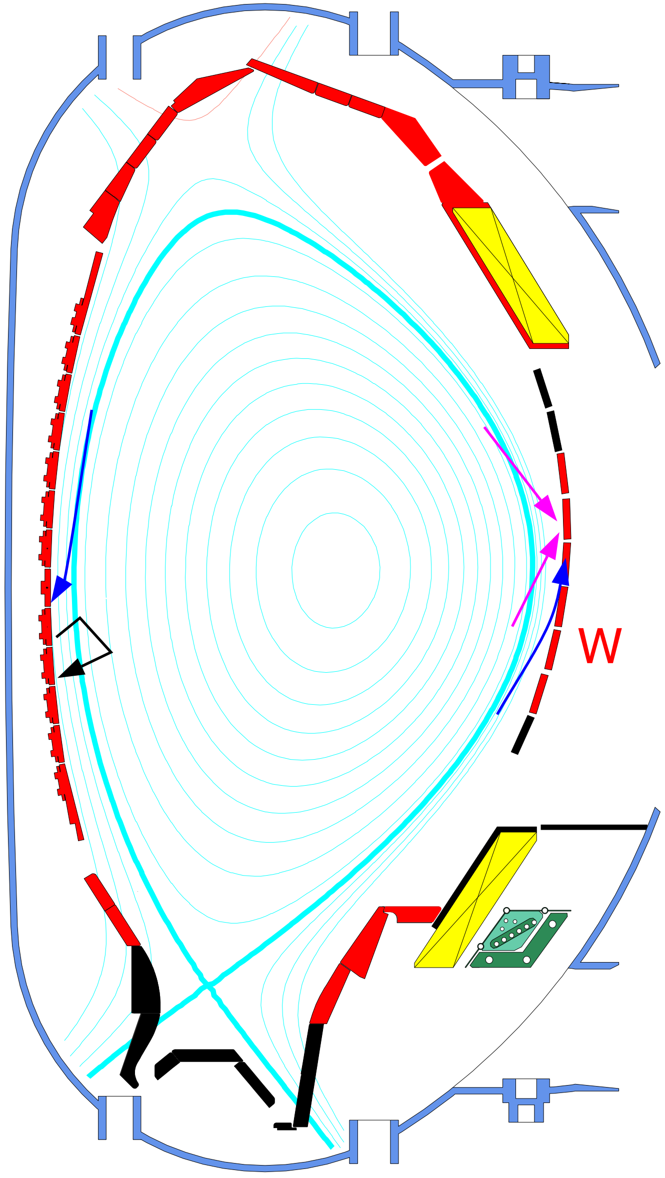
* enhanced sputtering rates reported for Be and Li due to creation of surface adatoms [Doerner et al., J. Appl. Phys. (2004)]

G. Sergienko et al., P 1.018, this conference

main high-Z sputtering species

impurity ions
mid-charged ion is
accelerated in sheath

charge exchange neutrals
thermal neutral makes CX
reaction with ~ keV pedestal ion



fast deuterons and imp.
NBI loss orbits
ICRH sheath accelerated

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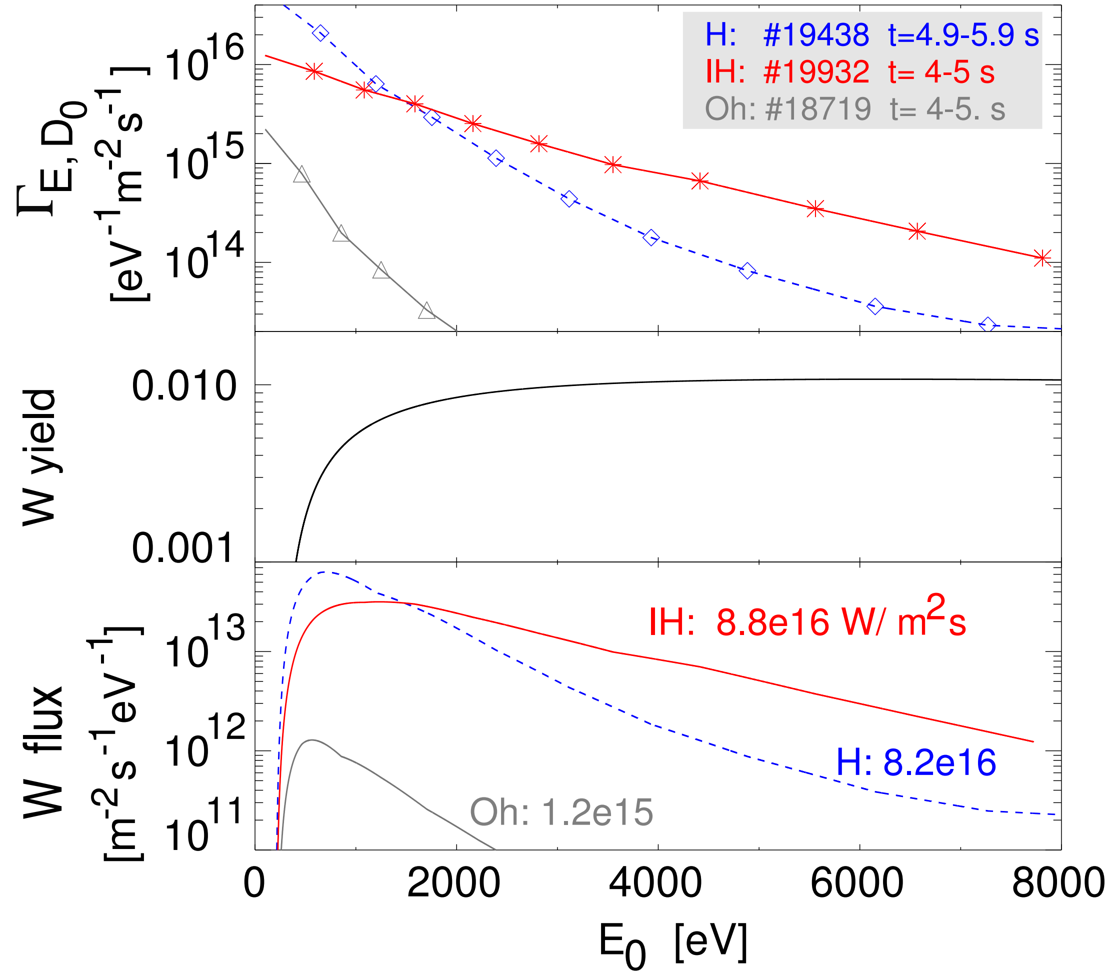
tungsten sputtering by charge exhange neutrals

CX spectra from neutral particle analyser

for
standard H-mode
Improved H-mode
Oh plasma



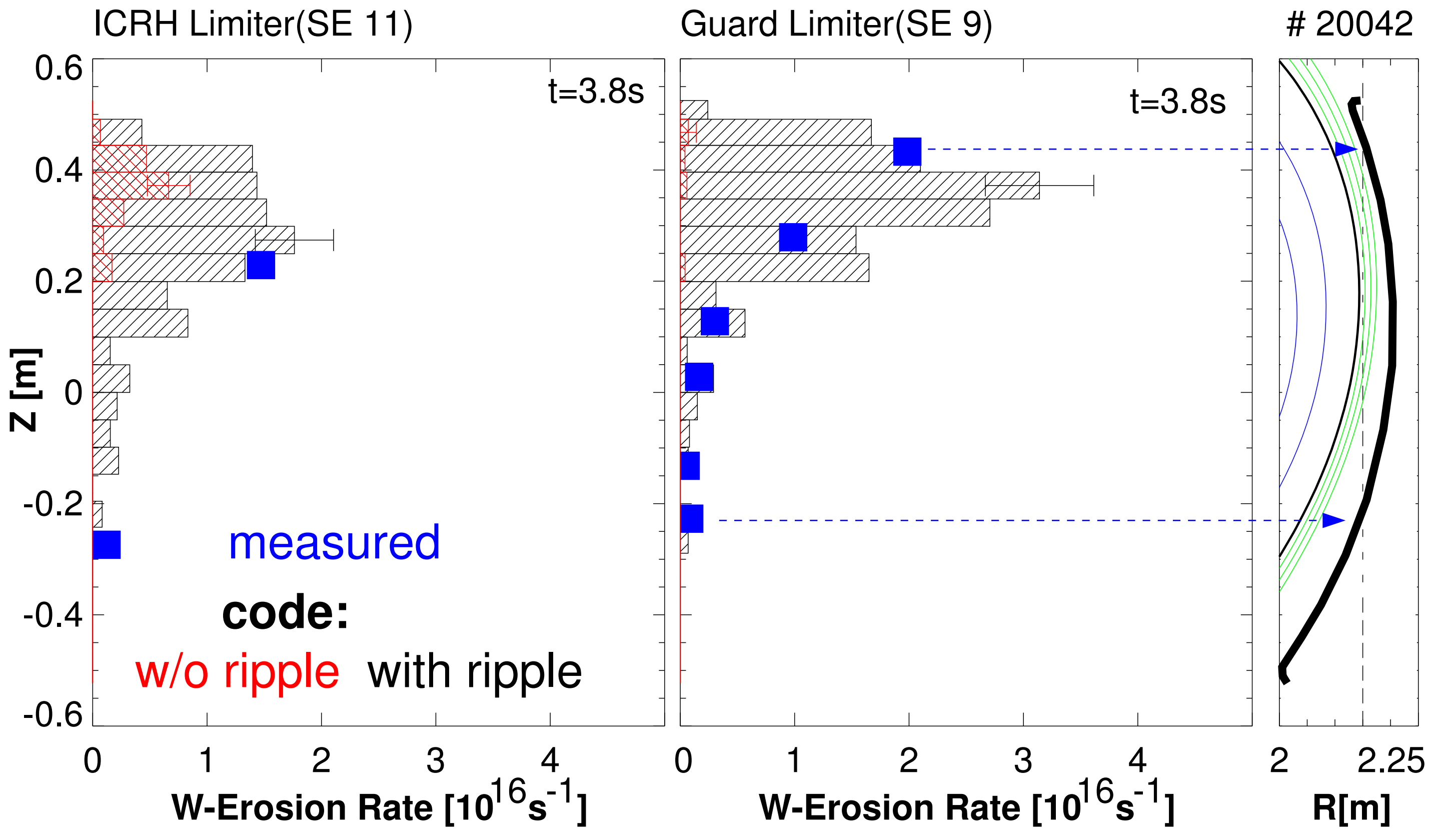
almost 2 orders of magnitude variation
energies around 0.5-2 keV contribute most

CX sputtering yield: $\mathbf{Y_{CX}} = \Gamma W / \Gamma D$

OH	H-mode	improved H
10^{-5}	$7\,10^{-5}$	$4\,10^{-4}$

tungsten erosion due to NBI fast ions

considerable erosion of W observed on l.f.s. limiters - attributed to fast NBI ions
fast ion birth rate from full geometry Monte Carlo NBI deposition code (FAFNER) → orbit following



$\Sigma=(1.1+-0.1)10^{17}$
$\Sigma=(1.7+-0.3)10^{16}$

$\Sigma=(1.5+-0.1)10^{17}$
$\Sigma=(2.1+-1.1)10^{15}$

- good agreement code vs. exp. in absolute fluxes
- ripple banana transport dominates

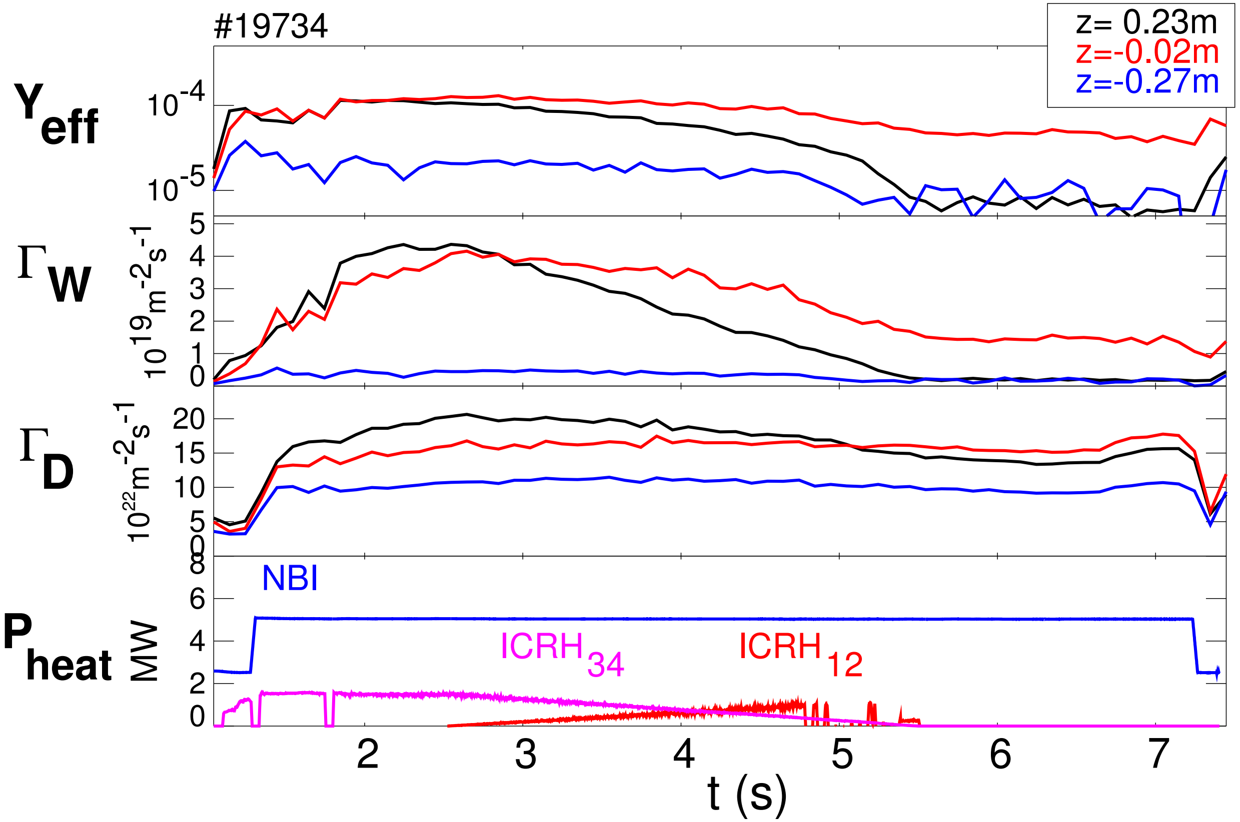
R. Dux et al., P 1.010

tungsten erosion during ICRH operation

spectroscopic measurement of D and W influx from l.f.s limiters:

enhanced W sputtering during ICRH operation

additional Yield depends on distance   limiter - antenna
→ not fast ion sputtering, but sheath accelerated ions

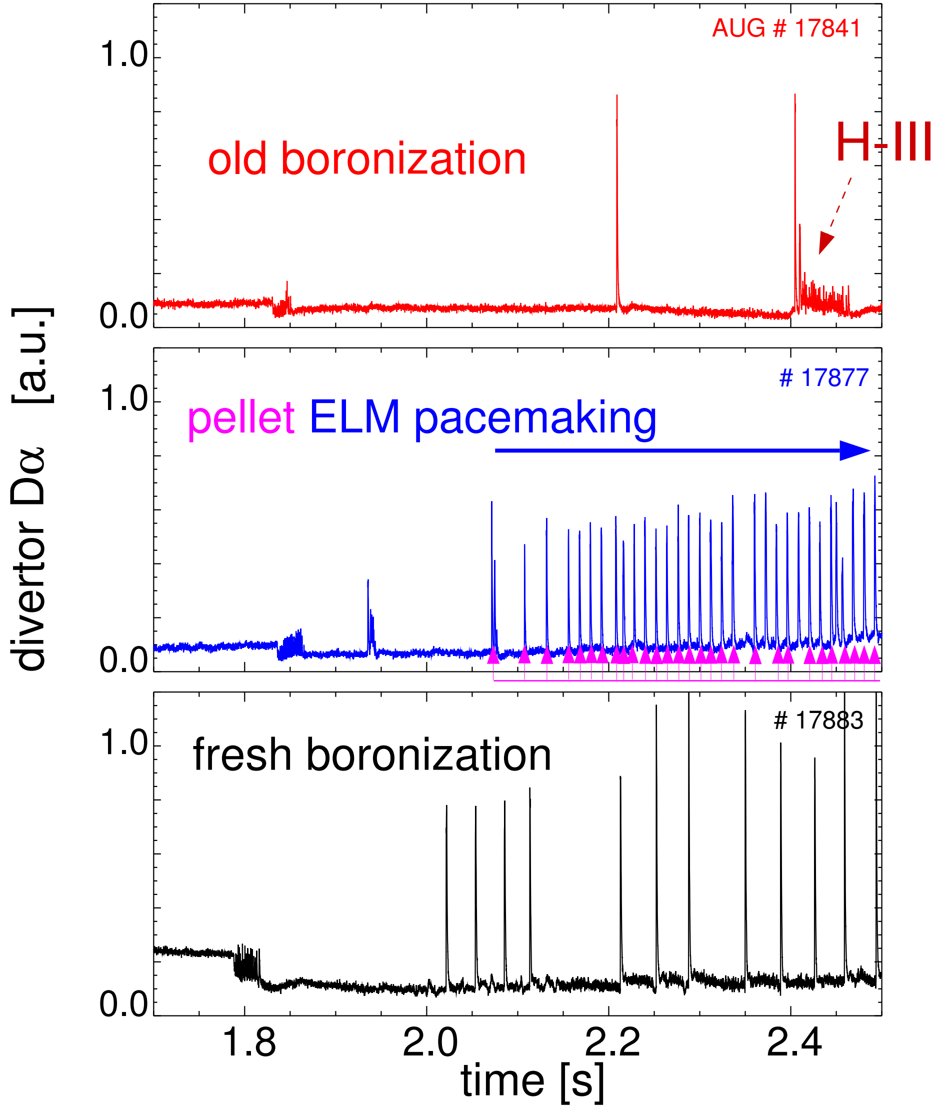


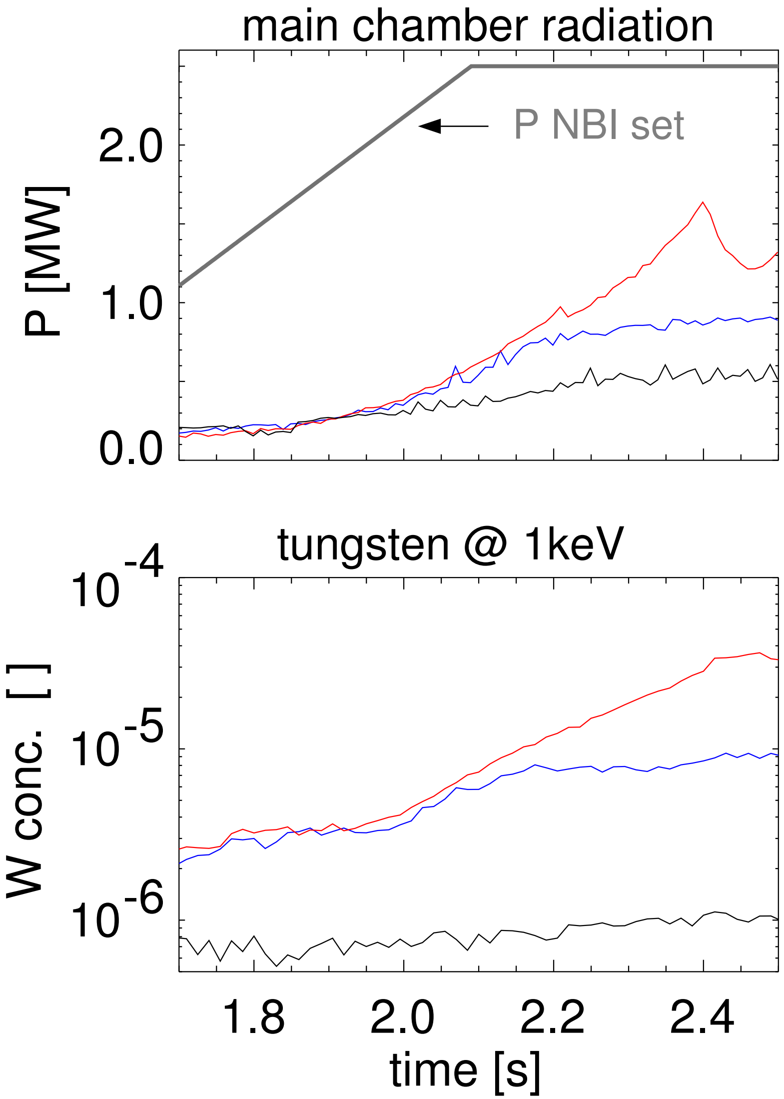
typical rise of sheat potential
at limiters from ΔY_{eff} :   10 V / MW

R. Dux et al., P 1.010

operational restrictions with a high-Z wall:
1) low ELM frequency and bad conditioning

- long H* phase at low power leads to excessive radiative losses
  - requires ELM pacemaking or fresh boronization

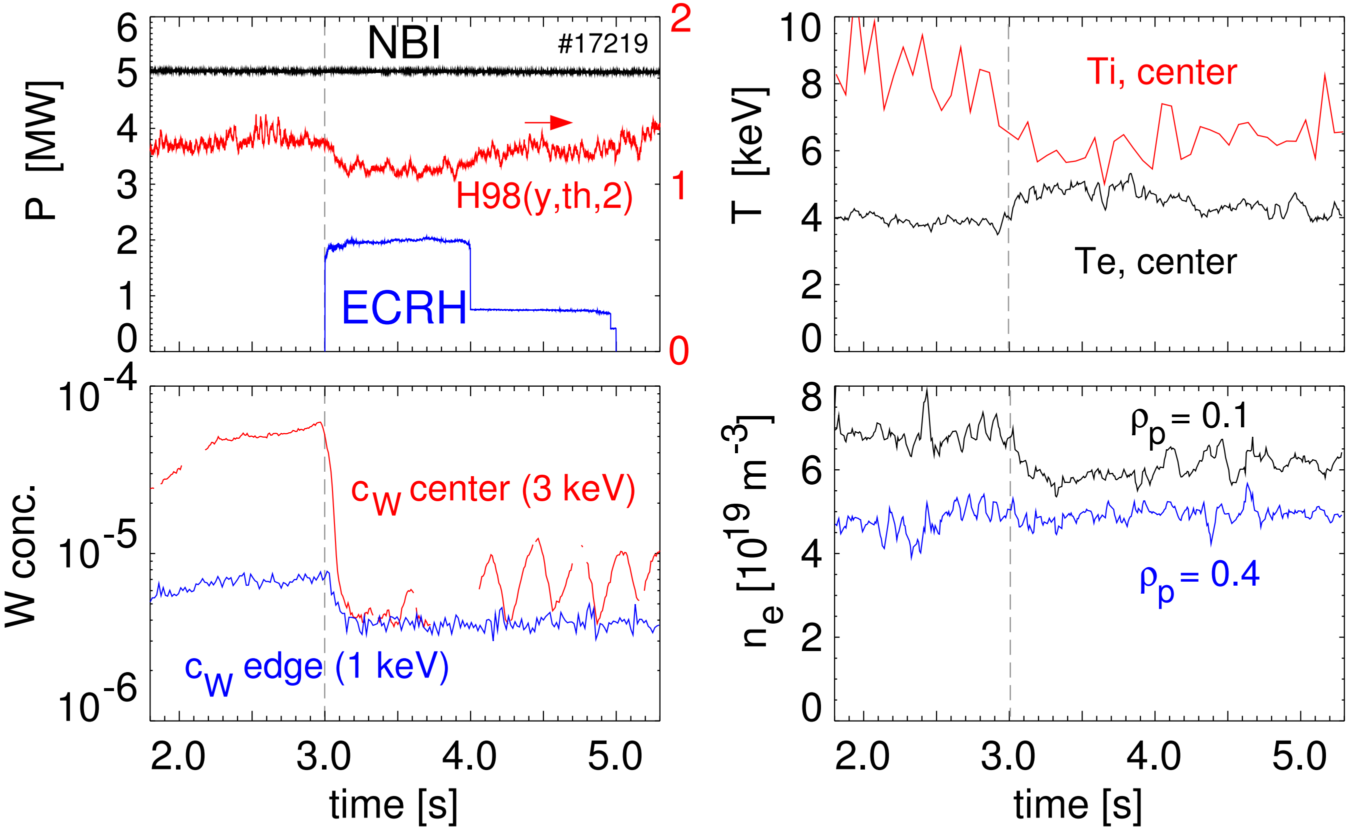




operational restrictions with a high-Z wall:
2) weak central heating and peaked density profiles

- Improved H-mode without central heating shows high central tungsten conc.
- additional ECRH reduces density peaking and increases D_{ano} → c_W reduced

moderate penalty in terms of confinement reduction



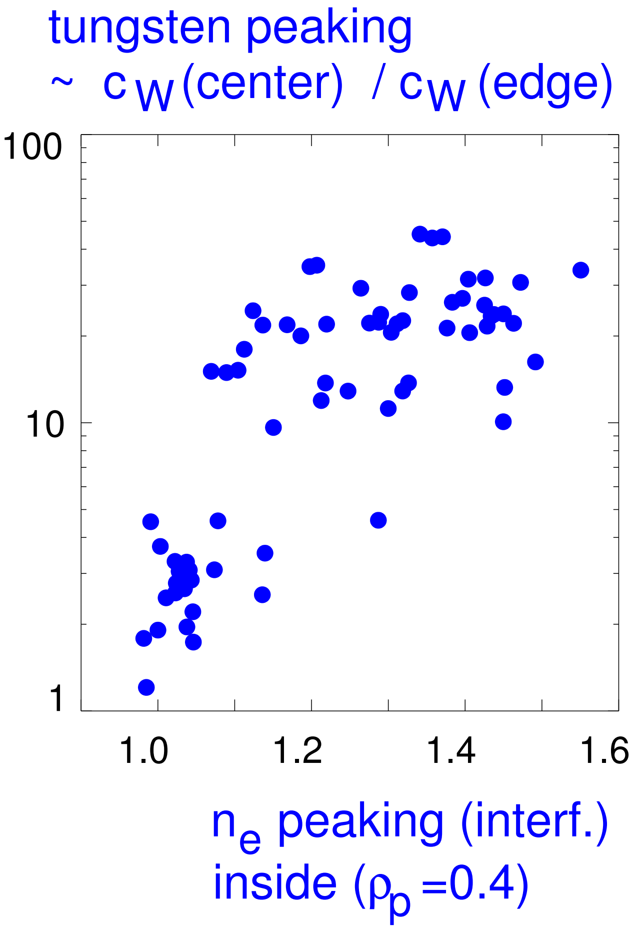
R. Neu et al., PPCF **44** (2002) 811

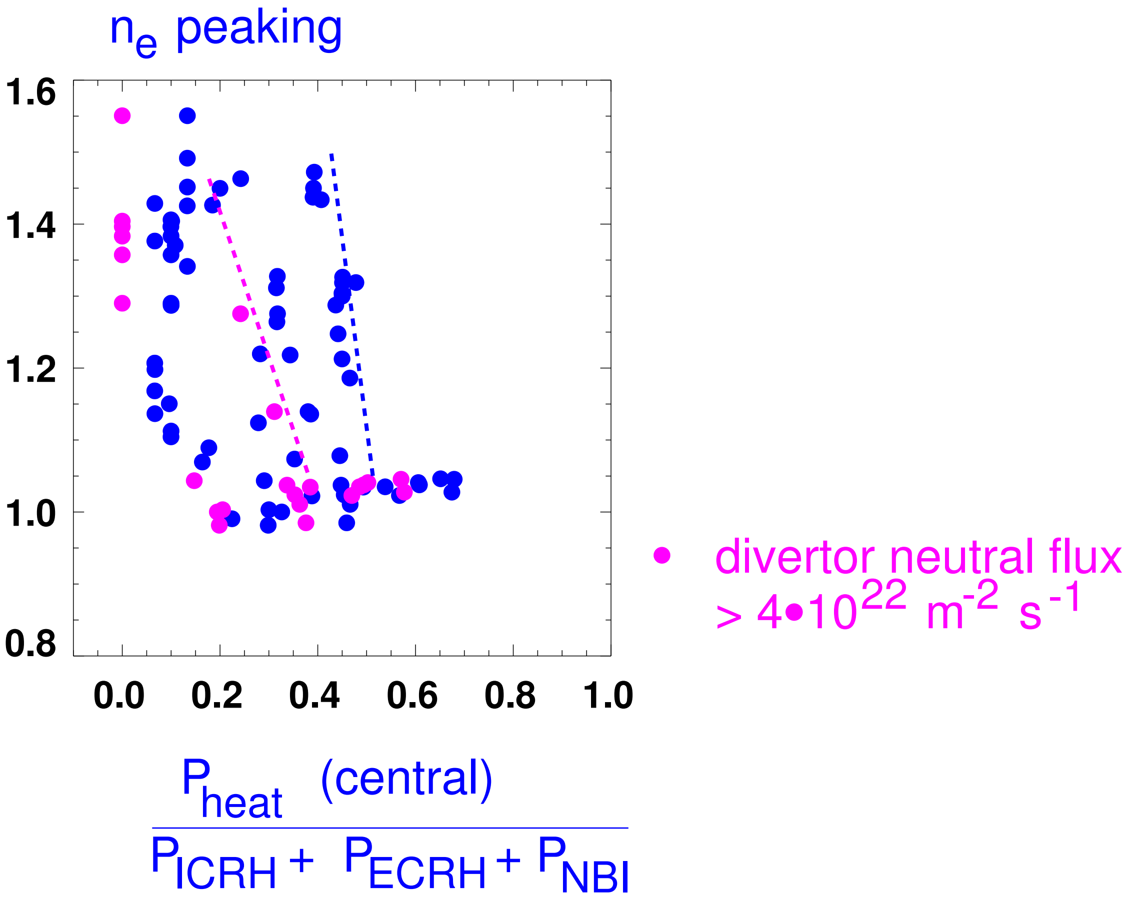
high central (neoclassical) W enhancement factor τ_z / τ_D : density peaking during improved H-mode

- peaking of tungsten in plasma center caused by central density peaking

- central density peaking controlled by central heating or neutral gas flux

  threshold for profile flattening by central heating decreases for higher neutral gas flux

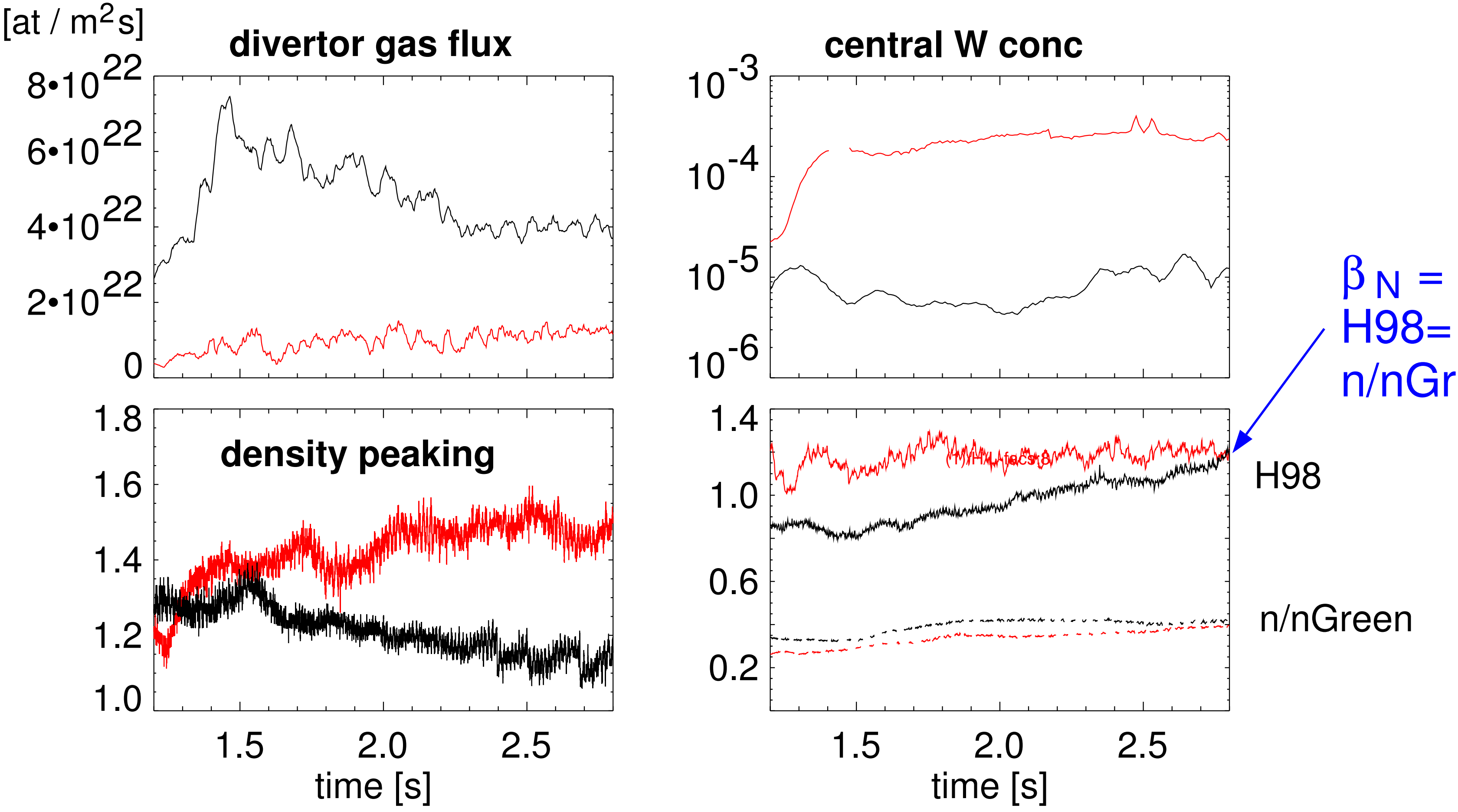




higher divertor gas flux: favourable W behaviour in improved H-mode

example: improved H-modes with 2 MW ICRH andNBI power ramps to 6 MW
variation of divertor neutral flux

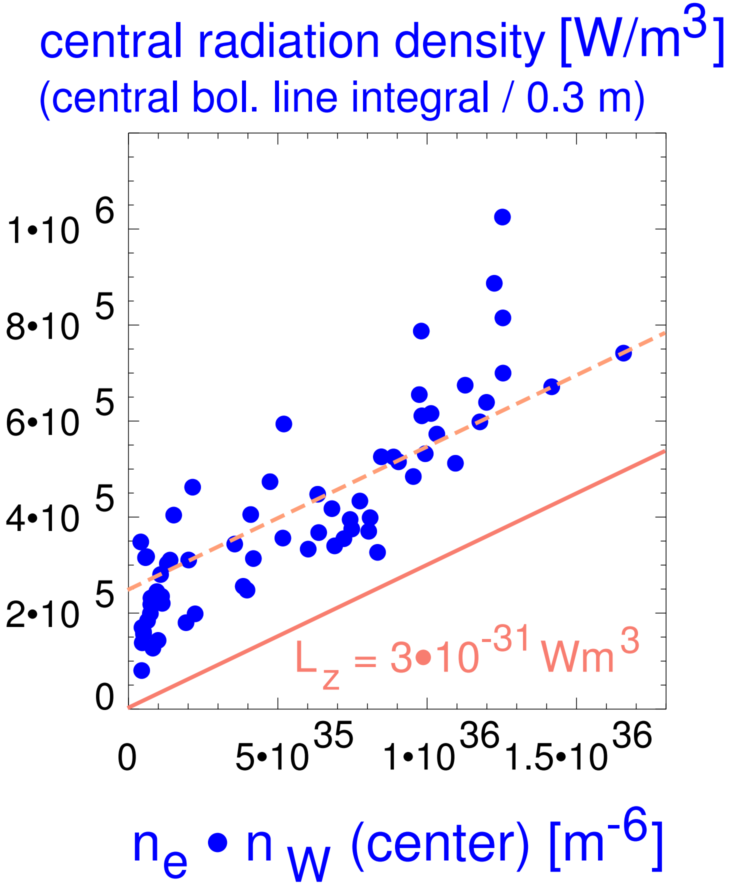
flatter density profiles and much lower W conc. and radiation with higher gas flux

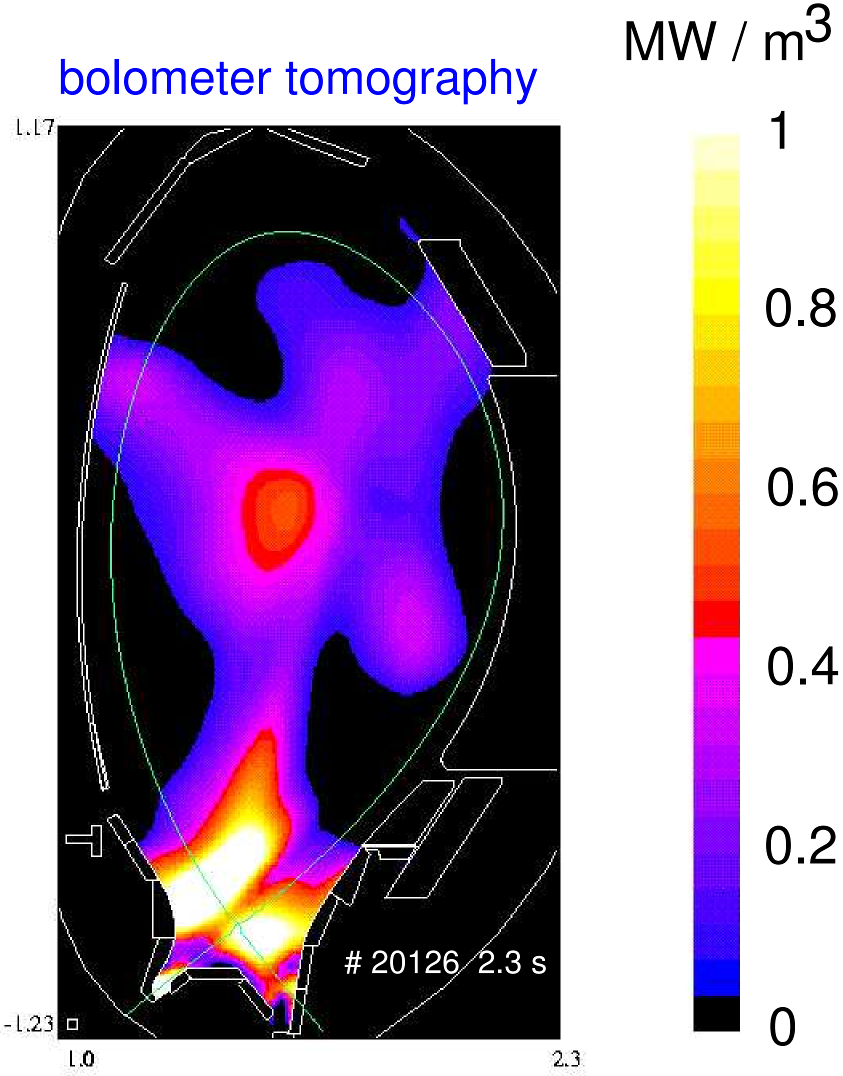


β_N = 2.5
H98= 1.2
n/nGreen= 0.5

tungsten radiative losses concentrated in the plasma center - fully dominant for peaked fuel density profiles

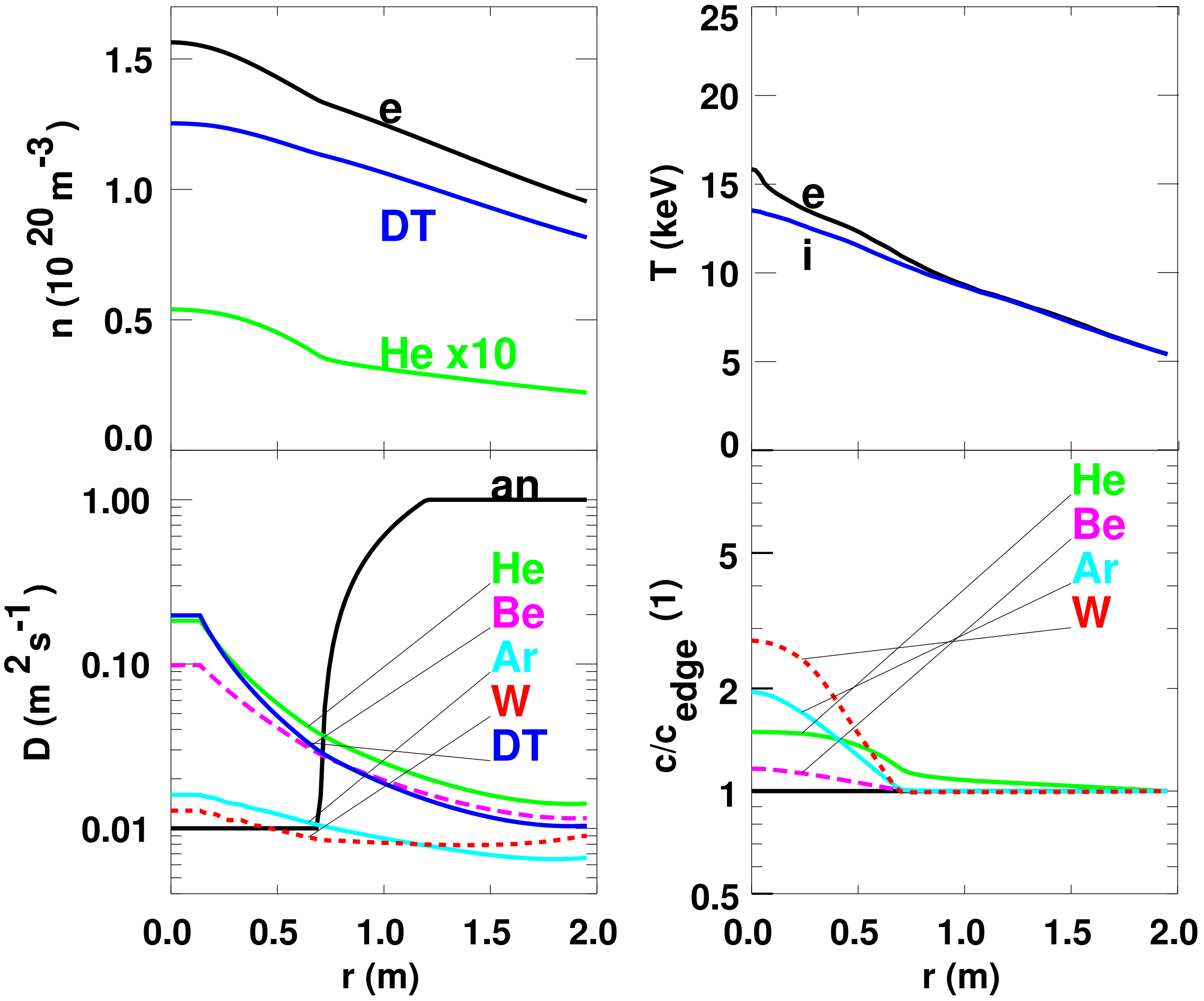
- central radiation dominated by tungsten
  - ◊ can approach local heating
  - ◊ compatible to cooling factor $L_Z = 3 \bullet 10^{-31}$ Wm^3





is high-Z peaking expected under reactor conditions ?

- transport model well calibrated against AUG data



⇒ only moderate peaking of W expected in ITER, even with peaked density profiles

R. Dux, R. Neu et al.,
NF **45** (2005) 209

summary of W erosion and transport parameters in AUG and extrapolation to ITER

and critical parameters for different scenario restrictions

	n/n_{GW}	c_W (1 keV)	c_W (3 keV)	f_τ -	Γ_{main} m^{-2} s^{-1}	Y_{CX}	C_cY_c	T_{PWI} eV	C_c	$\gamma_{WD} = \frac{f^W_{pen}}{f^D_{pen}}$
Ohmic	0.36	3×10^{-7}	-	-	1.2×10^{20}	1×10^{-5}	1×10^{-5}	5	0.015	0.05
high n_e H	0.75	1×10^{-6}	1×10^{-6}	1	3.2×10^{21}	6×10^{-5}	1×10^{-5}	5	0.015	0.04
H-mode	0.6	5×10^{-6}	8×10^{-6}	2	1.2×10^{21}	7×10^{-5}	2×10^{-4}	8	0.02	0.06
ELM free H	0.54	3×10^{-5}	-	-	2.4×10^{20}	2×10^{-5}	2×10^{-4}	8	0.02	0.4
Improved H	0.38	6×10^{-6}	10^{-4}	16	2×10^{20}	4×10^{-4}	5×10^{-4}	10	0.03	0.02

what is expected for ITER in case of a W main chamber wall ?

assuming $\gamma_{W\text{-}D}$ =0.025 (neg. size scaling), C_{Ar} = 0.002, T_e = 15 eV, f_τ = 2

→ c_W = 1.6 •10^{-5} (CX and fast ions not included)

→ compatible to limit of 5•10^{-5}, but careful tailoring of discharges will be required

Conclusions

"high-Z plasma facing components are mandatory for a tokamak reactor"

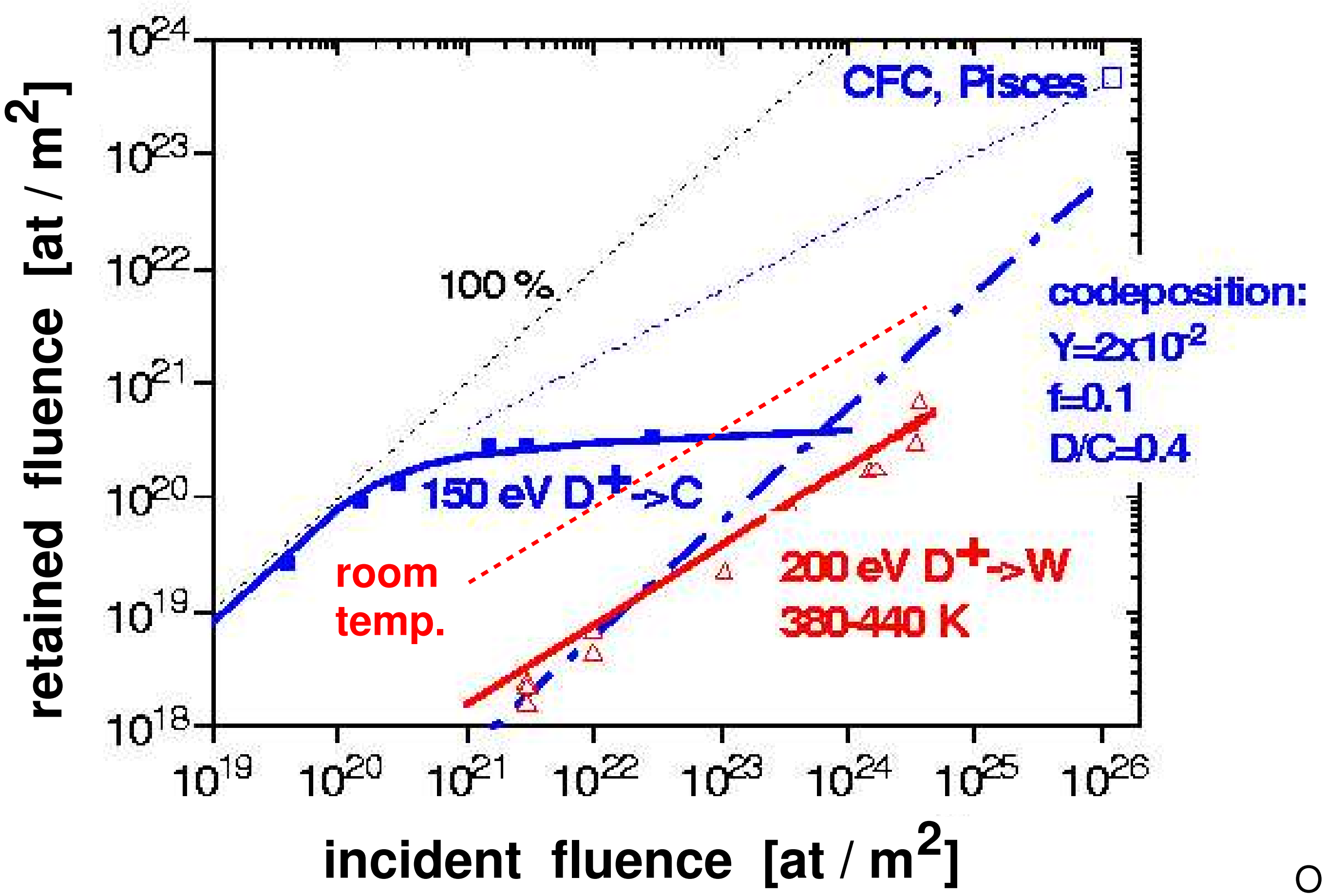
current tokamak operation suggests that high-Z PFCs are **feasible** for a reactor
- tungsten currently regarded as most suitable

restrictions to operational scenarios have to be expected:

- no strongly peaked density profiles with low central transport
- edge temperatures should not exceed ~ 15 eV
- ELM frequency should not fall below critical value (pace-making)
- argon seeding to substitute carbon radiation to be embedded into operation
- impact of NBI and ICRH heating on low field side limiters to be checked

W hydrogen retention favourable compared to carbon

- carbon/graphite hydrogen retention dominated by co-deposition at high fluences
- CFC much higher retention due to material structure
- tungsten retention by diffusion into bulk - favourable behaviour at elevated temperatures



O. Ogorodnikova et al.
JNM **313-316** (2003) 469