# Development of an integrated plasma scenario with high-Z PFCs

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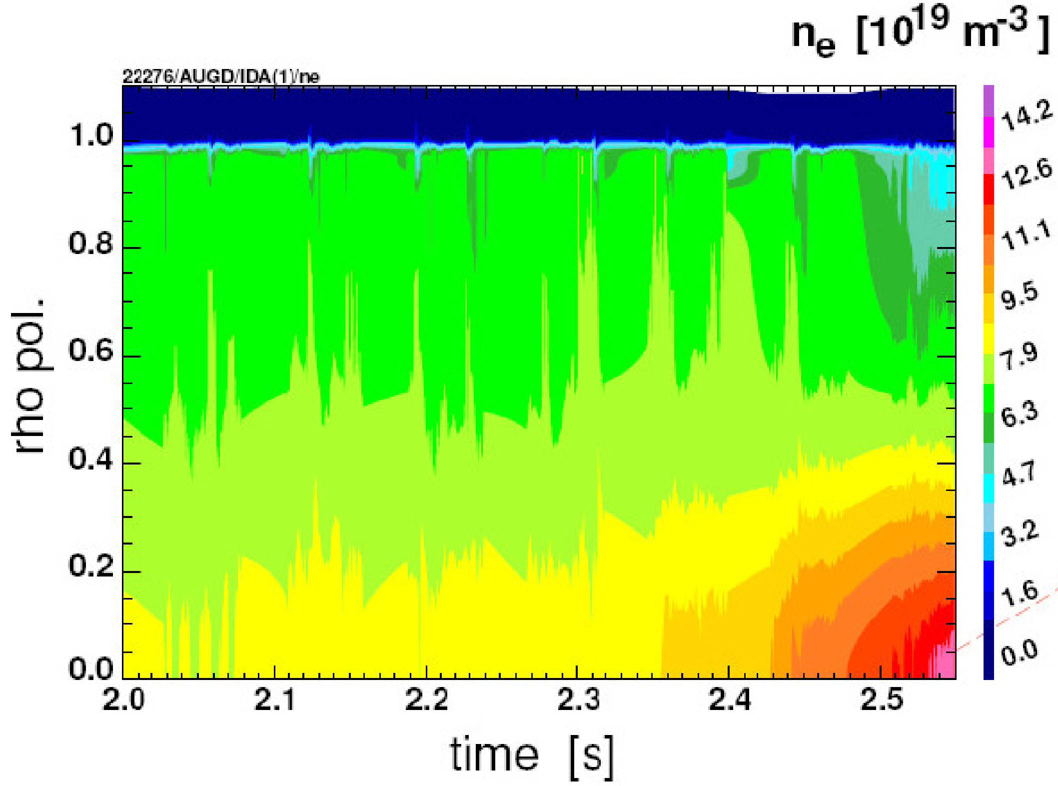
# Introduction

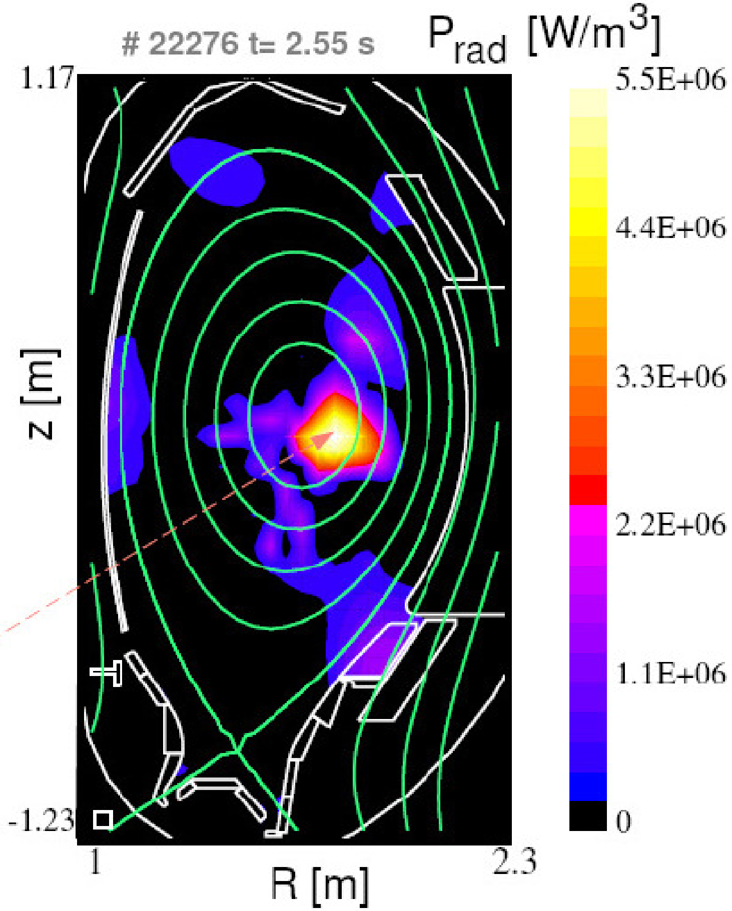
Operation with high-Z PFCs is restricted in comparison to low-Z PFCs

- Low sputtering rates and sufficient impurity sceening have to be maintained
- Scenarios prone to central impurity accumulation (like ITBs) have to be omitted
- Wall pumping (which is used to lower the plasma density by using depleted carbon PFCs) does not work with tungsten
- ELM control (high frequency, small ELMs) is very helpful, while ELM-free H-modes without edge MHD like EHO are no-go’s

On the bottom line, the restrictions force operation towards ITER/DEMO relevant edge parameter domains – with the exception of low $\nu^*$ plasmas, which are hard to achieve

## Central W accumulation and radiation is the limitation for operation of a high-Z device




peaked electron density profiles in particular at low collisionality

# In a no-carbon PFC machine with high power, impurity seeding is a must rather than nice-to-have

AUG 2008: divertor power load must be limited to < 10 $MW/m^2$
to avoid delamination of thick VPS coatings

JET-ILW, ITER, DEMO …
will require strong seeded radiative power dissipation

# Elements of an integrated high-Z scenario

Impurity seeding feedback system for low divertor heat flux
sensor: radiated power or divertor heat flux / temperature

Sufficient deuterium puffing (to keep high-Z sputtering and core $Z_{eff}$ low)

ELM control (for seeding species radiating inside pedestal like Ne, Ar)
high frequency pellets (f > 80 Hz needed in AUG)
RMP coils, plasma kicks

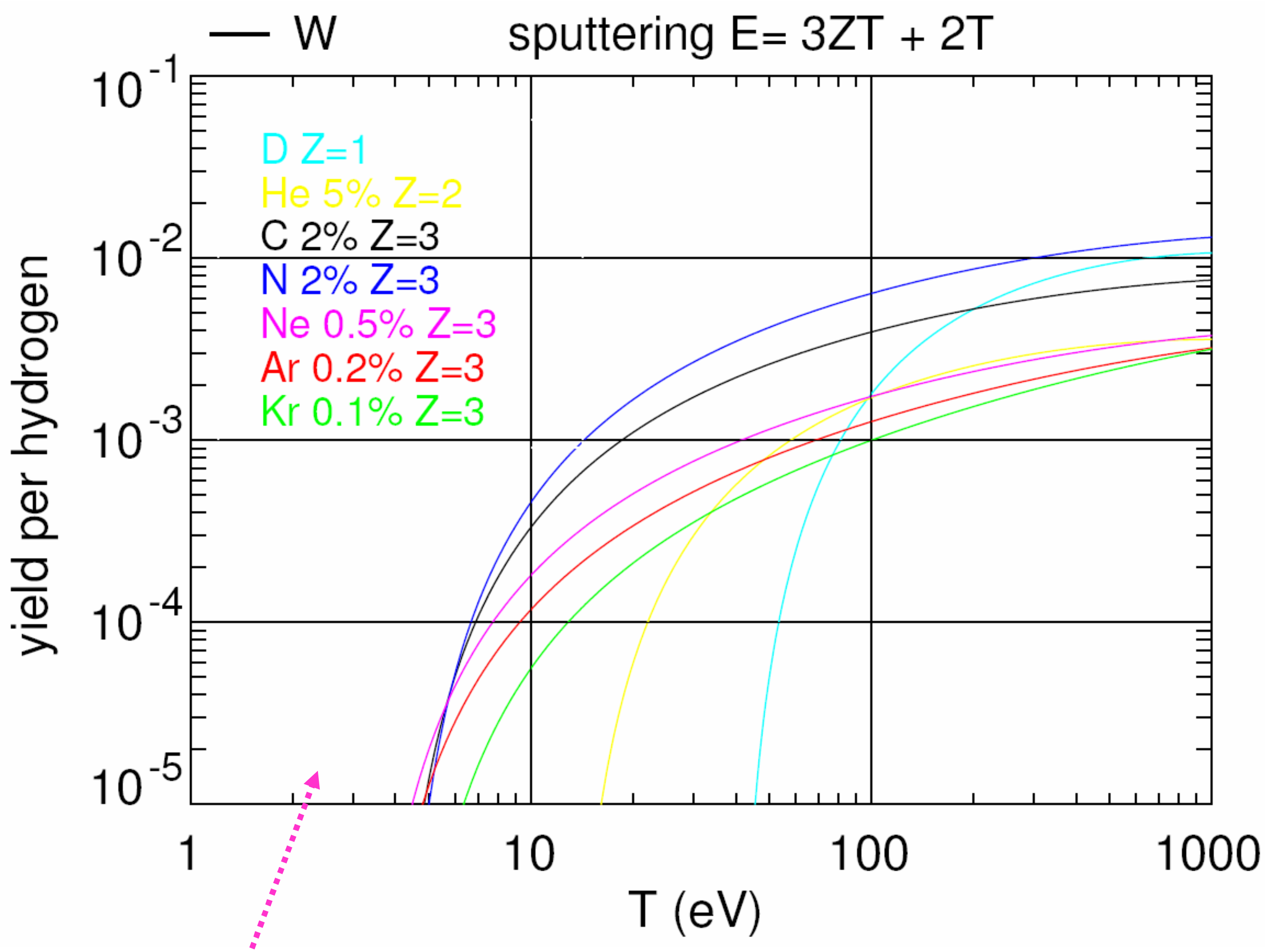
For really high power (> 15 MW in AUG) and good performance,
consider double-impurity seeding

## Sputtering of PFCs by seed impurities

## - an issue for high-Z PFCs

# Sputtering of high-Z PFCs by seed impurities

## - has to be limited due to central radiation limit and target lifetime

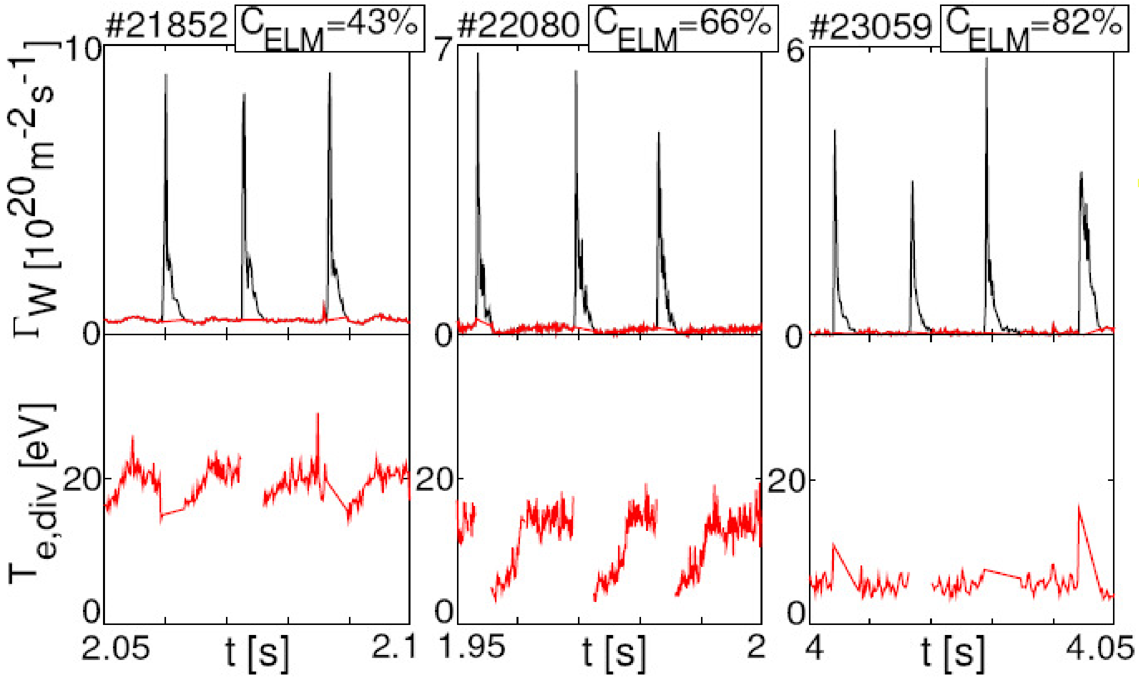


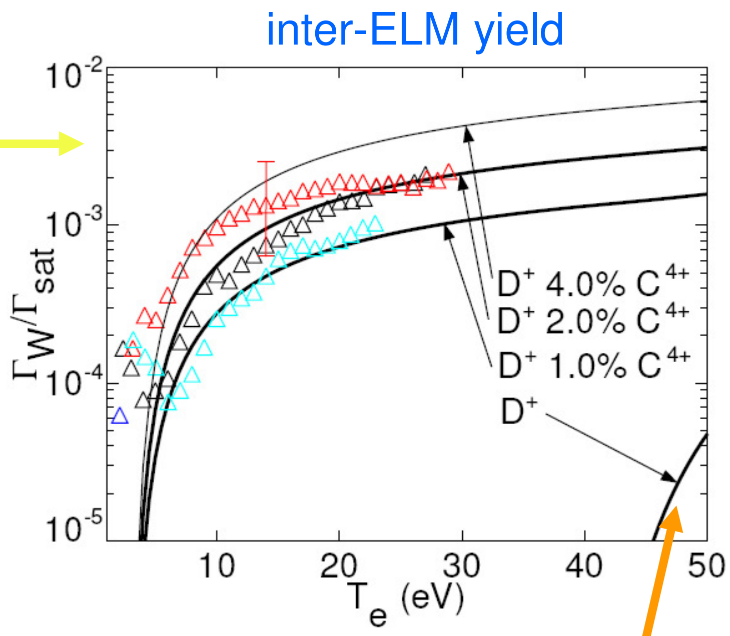

$T_e$ has to be limited below 5-10 eV

Eckstein 1993 Report IPP 9/82

# Experimental test of inter-ELM W sputtering: variation of divertor $T_e$ in ASDEX Upgrade

R. Dux, PSI 2008




D sputtering of W far too low

20 or 5 eV divertor temperature make a big difference !
ELMs dominate W erosion for cold conditions

# Radiative cooling to achieve partial detachment

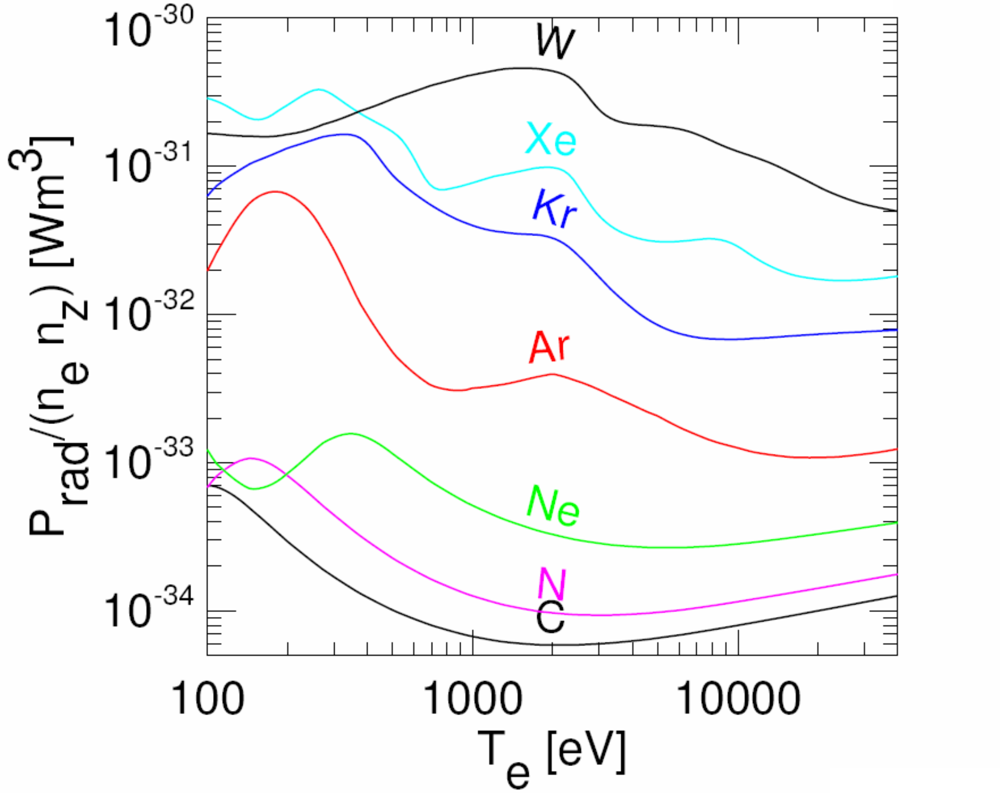
# Radiative cooling can be regarded as 3-stage process (but their coupling leads to non-linearities)

1) reduce power flux by core radiation as far as confinement permits ($P_{sep}$ ~ $2P_{H-L}$)

↓

**reduce power flow over separatrix**

# Core radiative losses (Corona equilibrium) ∝ $Z^3$




ADAS $n_e$=1.0 $10^{20}$ $m^{-3}$

around $T_e$~ 1 keV:

radiation per ion ∝ $Z^3$
$dP_{rad}/dZ_{eff}$ ∝ Z

large Z gives most efficient core radiation,
**but:**
danger of central accumulation,
energy confinement degradation

# Radiative cooling can be regarded as 3-stage process (but their coupling leads to non-linearities)

1) reduce power flux by core radiation as far as confinement permits ($P_{sep}$ ~ $2P_{H\text{-}L}$)

↓

**reduce power flow over separatrix**

↓

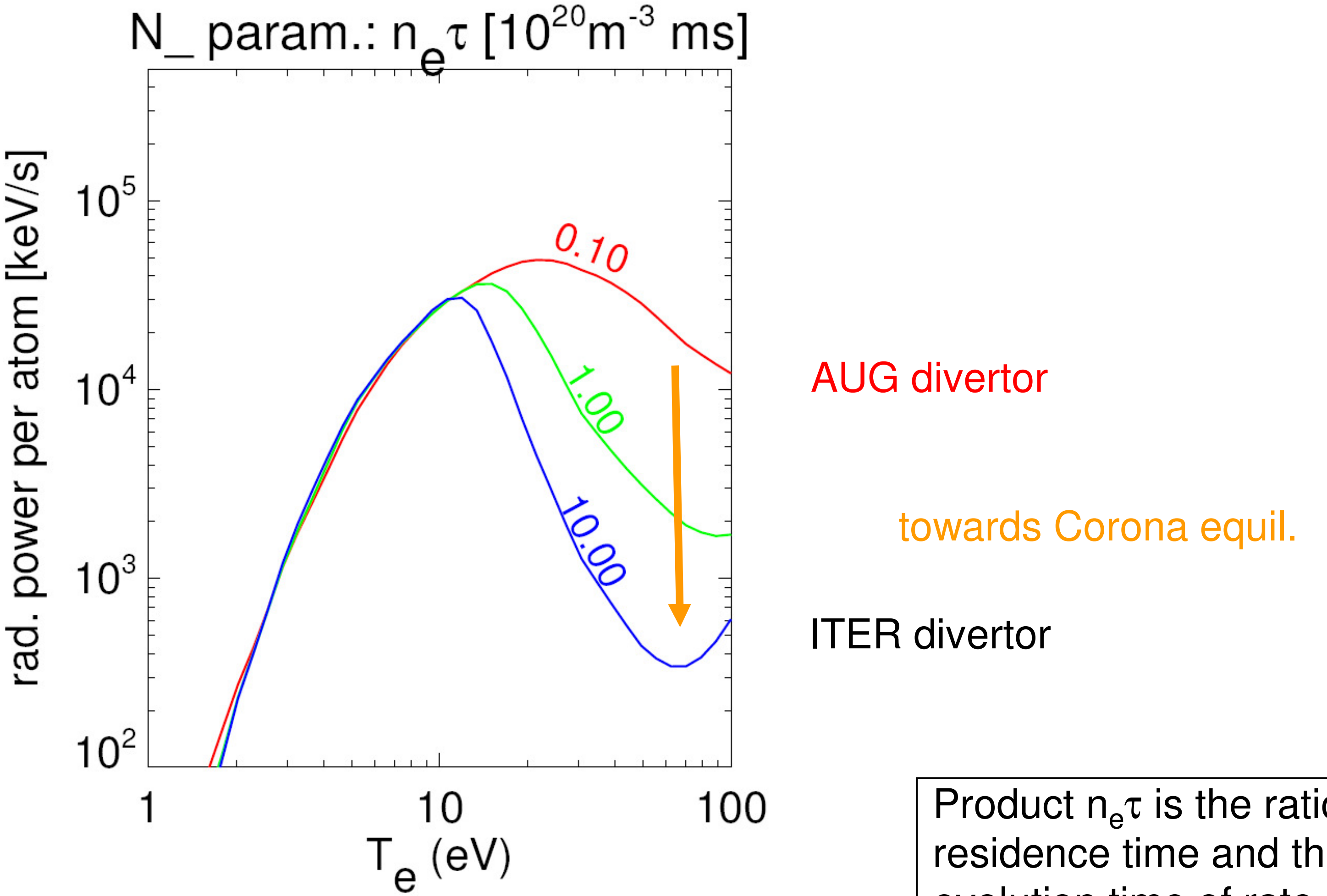
2) edge and divertor power dissipation and radiative cooling to $T_e$ ~ 5 eV

↓

**reduce power flow + $T_e$, increase divertor $n_e$**

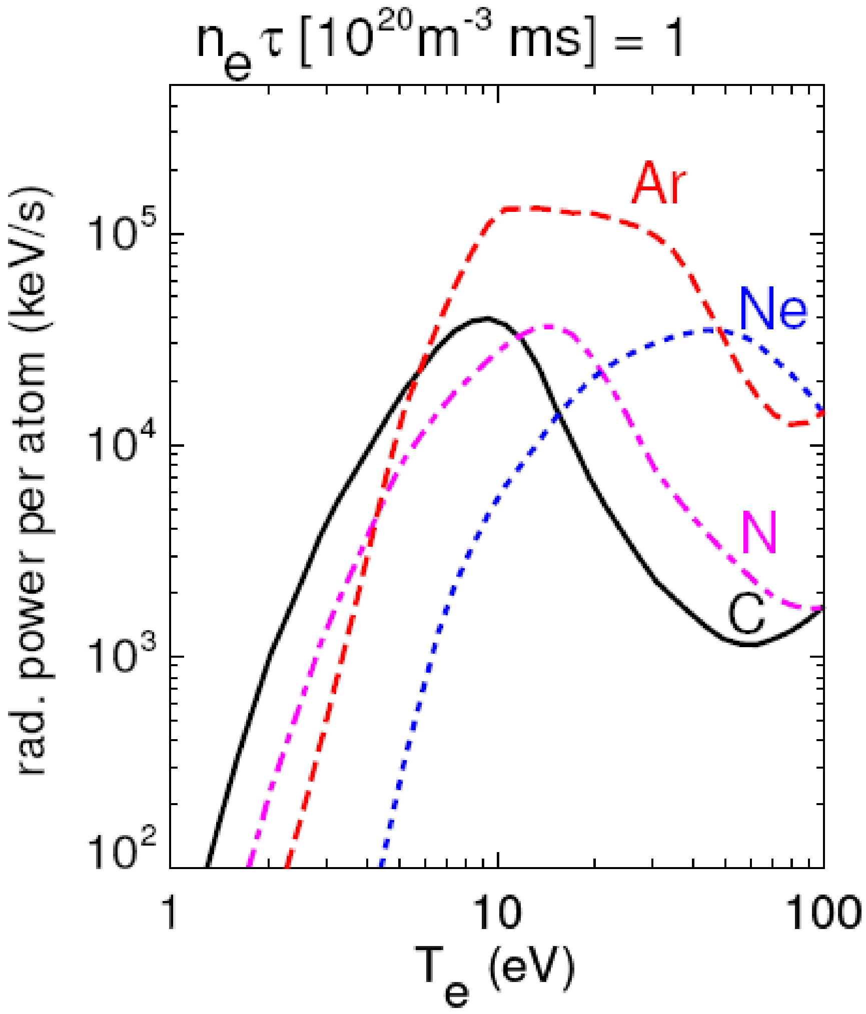
# Divertor radiation deviates from Corona equilibrium
# $\rightarrow$ calculation requires residence time $\tau$

impurities start as neutrals, emission power averaged over $\tau$ (similar radiation potential, Samm JNM 1990)
Atomic data taken from ADAS




Product $n_e\tau$ is the ratio of the residence time and the characteristic evolution time of rate system

# Carbon and nitrogen are best radiators below 10 eV - Ar performs good, but core concentration limit




Ar not feasible as divertor radiator except very high enrichment achieved
$\rightarrow$ DIII-D puff and pump scenario

# Radiative cooling can be regarded as 3-stage process (but their coupling leads to non-linearities)

1) reduce power flux by core radiation as far as confinement permits ($P_{sep}$ ~ $2P_{H\text{-}L}$)

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**reduce power flow over separatrix**

↓

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↓

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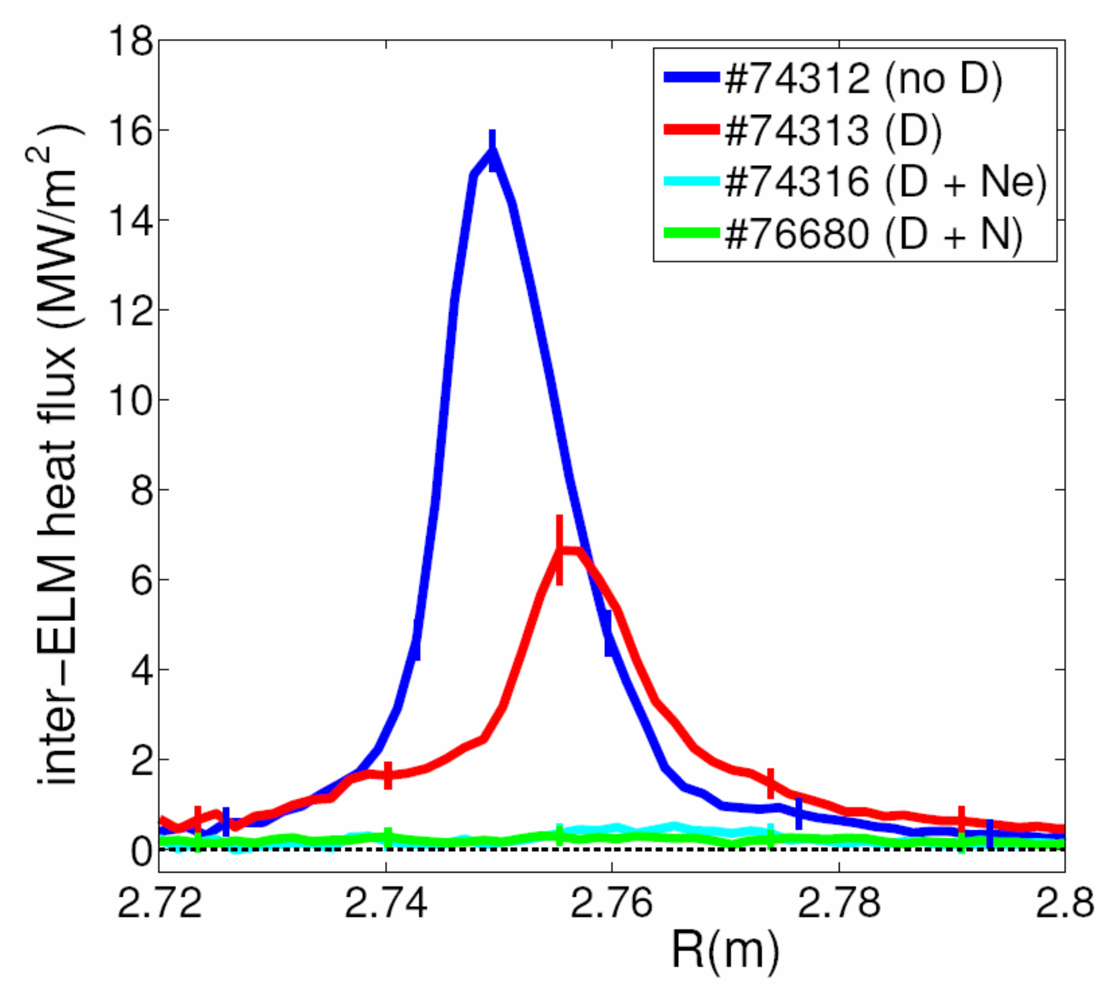
↓

3) Momentum losses: CX and recombination for strike-point detachment

# Target power load reduction by seeding works



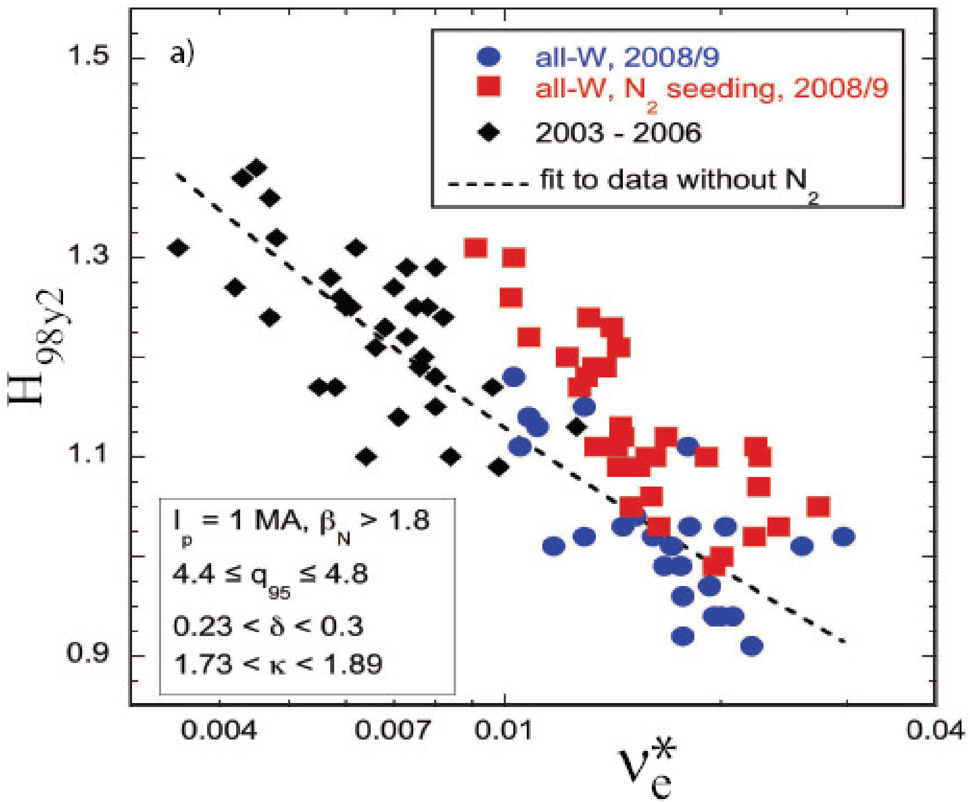

JET inter-ELM

T. Eich, PSI 2010, O-6
G. Maddison, PSI O-23

… but optimization required for confinement, sputtering, …

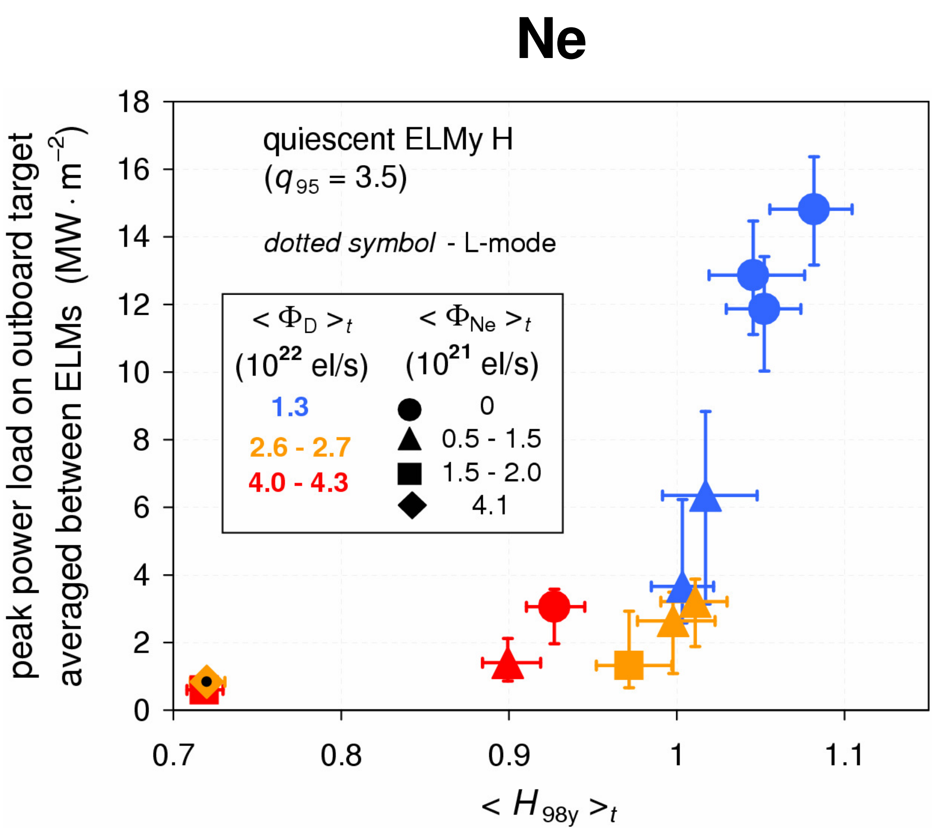
# In AUG, **energy confinement** improves with N seeding

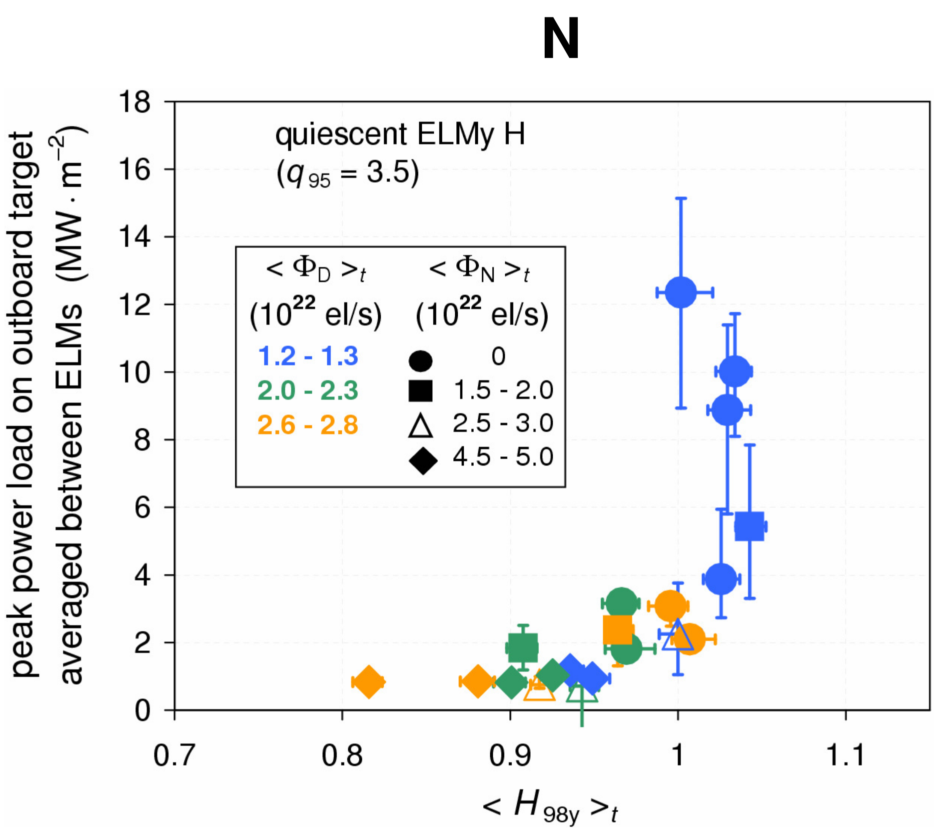
N seeding results in increased
pedestal and core temperatures and $\tau_E$




Schweinzer, EXC/P2-07

# JET: Optimization needed for confinement and heat flux



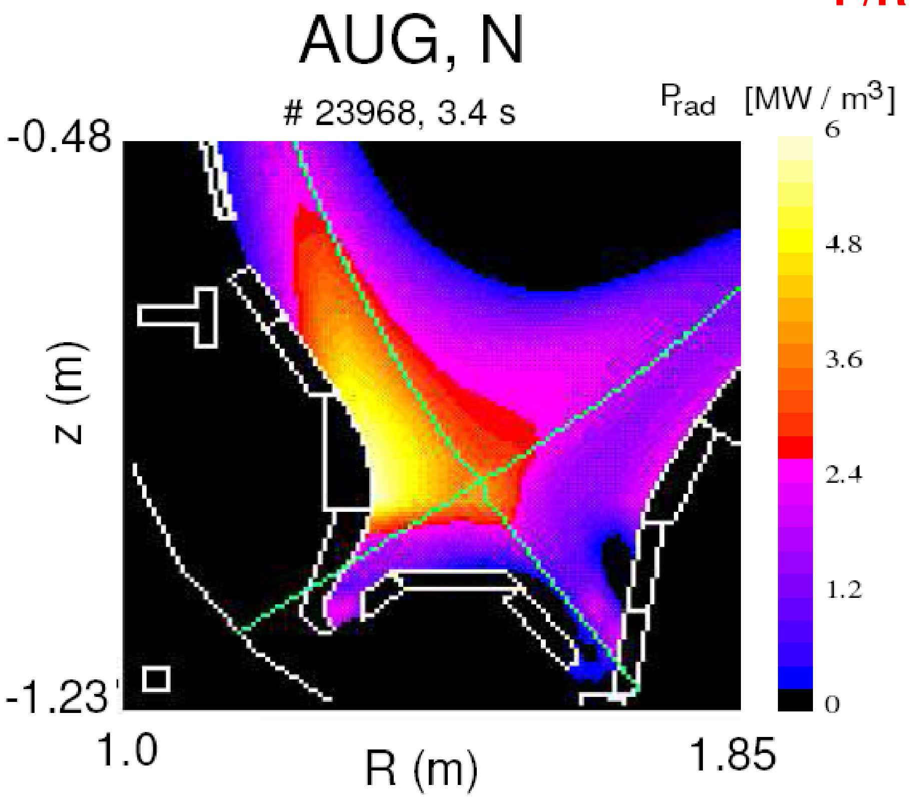



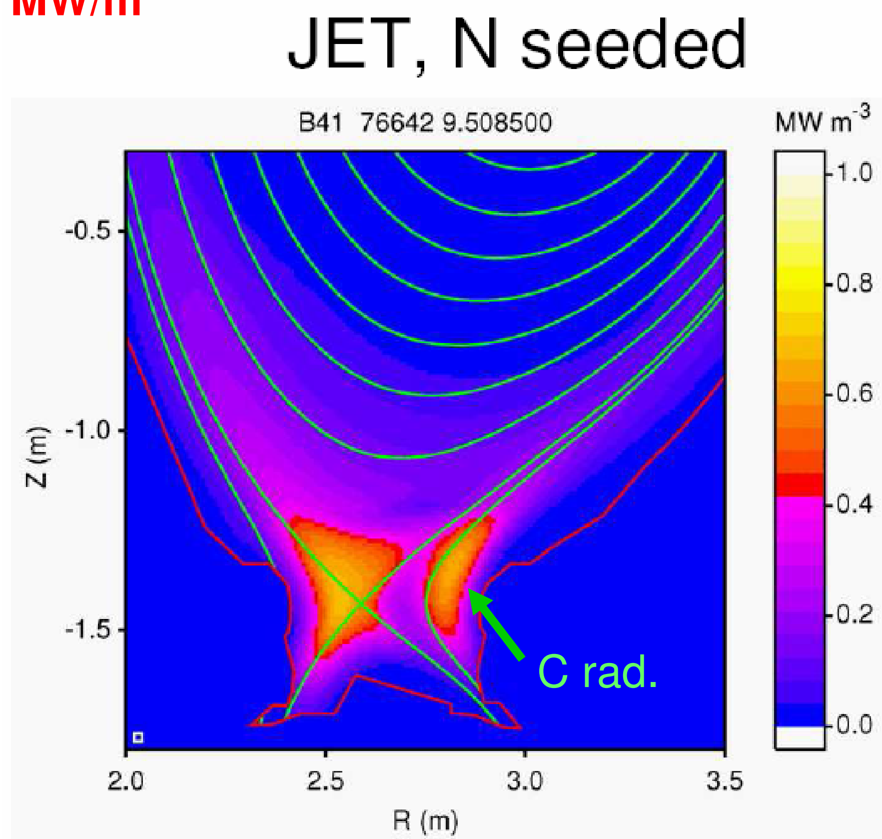

Reason for different confinement behaviour JET vs. AUG not known yet (pedestal is key player)

G. Maddison, PSI 2010 O-23

# JET radiation more inside sep. / X-point region
# - reason for reduced confinement compared to AUG N

**P/R~ 6 MW/m**



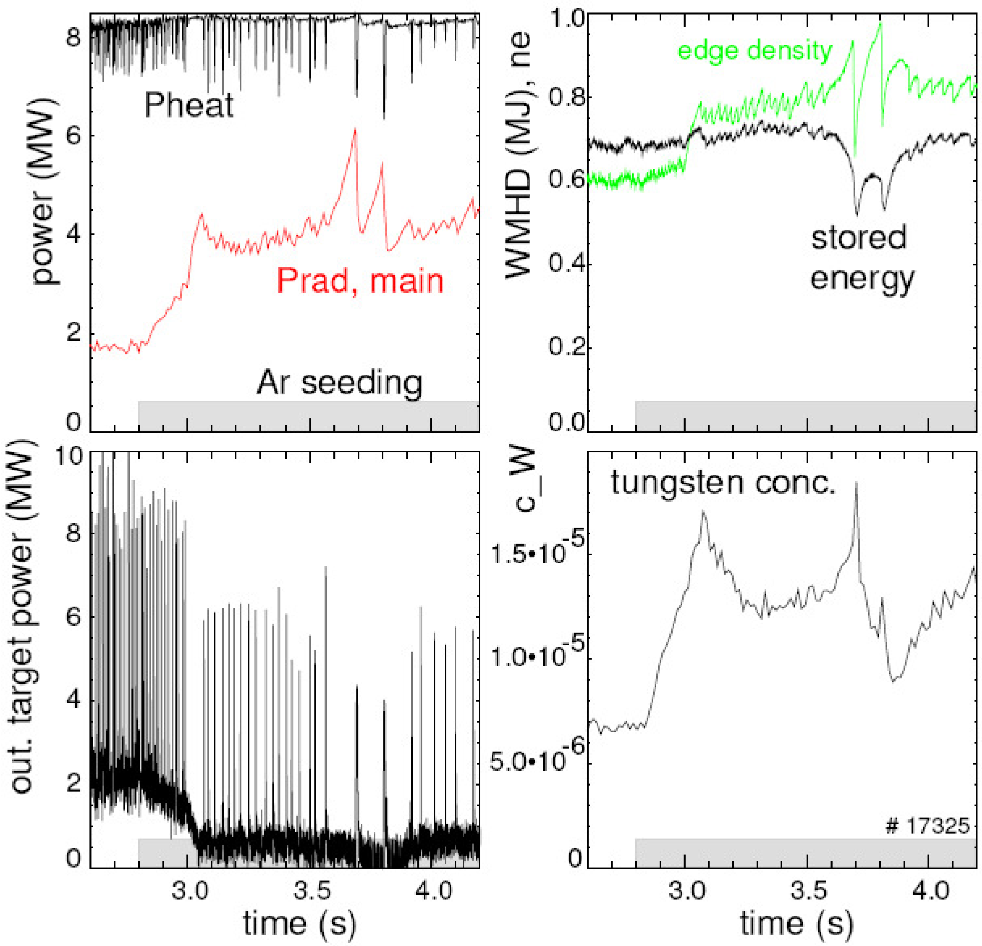

More open divertor reason for higher X-point radiation in JET ?

# Integration of seeding with small ELM scenarios

ELMs have to be limited to very small energies in ITER to avoid divertor damage ($\Delta W < 0.5$ MJ/m$^2$)

On the other hand, ELMs are required to flush high-Z impurities out of the pedestal

# Seeded core radiation leads to reduced ELM frequency and impurity accumulation problems

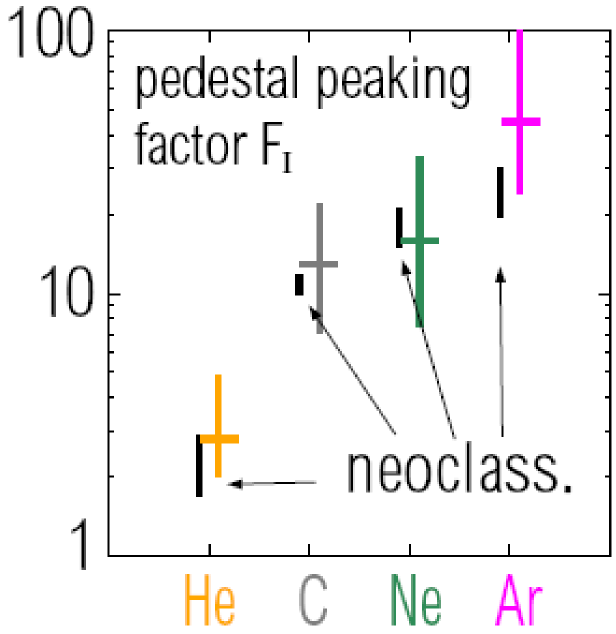



**no pellets**

- power flux over ETB reduces during H* phase due to increase in Prad, delaying next ELM
- effect more dominant for core-edge radiator compared to carbon

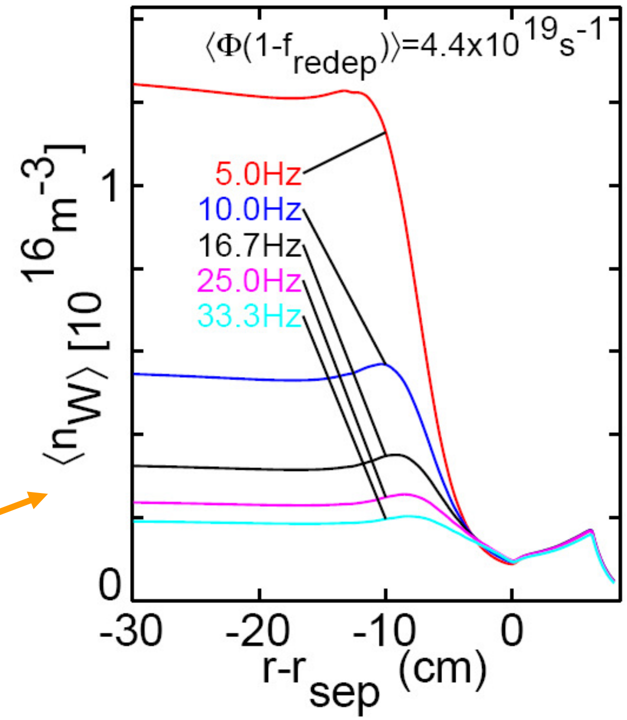
# Impurity ion transport in ETB is neoclassical
# → high frequency, small ELMs required

experimental D, v derived by STRAHL modelling/fit to edge CXRS measurements




ELM flushing required
in particular for high Z
- issue for ELM control
-techniques

Predicted W pedestal
Rise for ITER




See following talks
by R. Dux, and T. Pütterich

# Sensor for target heat flux required for feedback

**Bolometry** to derive $P_{target} = P_{heat} - P_{rad}$

problematic at high powers (difference of large numbers)

online deconvolution difficult

ELM subtraction not possible due to temporal resolution

**IR thermography** would be ideal

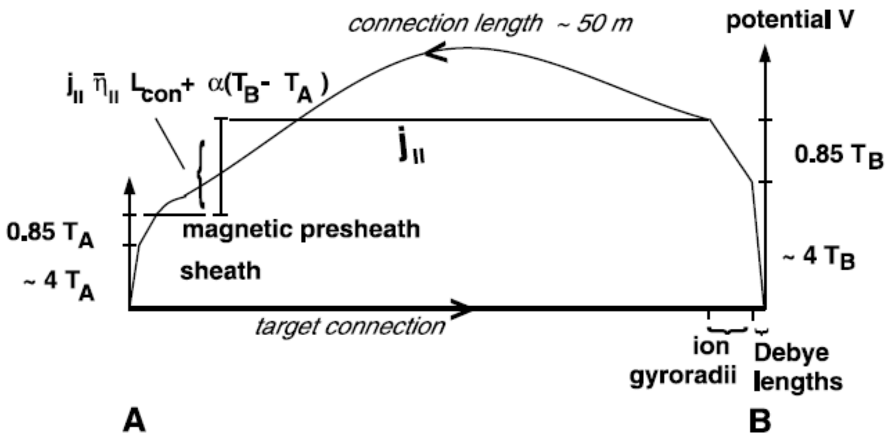
real time heat flux derivation difficult

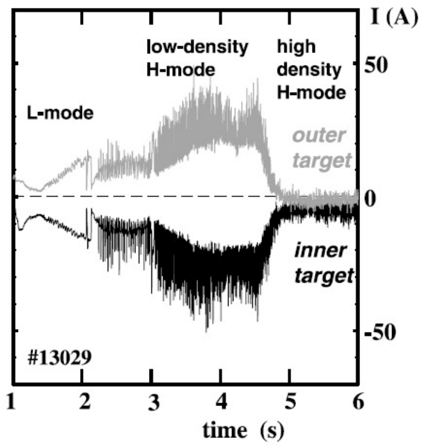
**Langmuir probes** – ok but real time is problematic

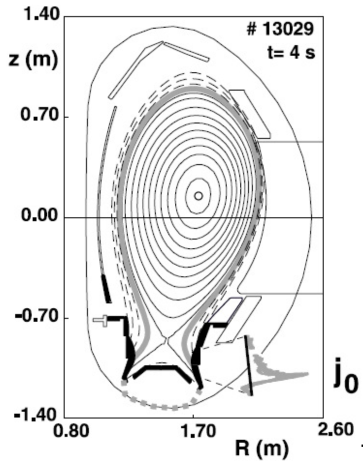
**Passive electric current measurement in the divertor**

easily measured by shunts, high S/N, fast enough for ELM subtraction

routinely used on AUG

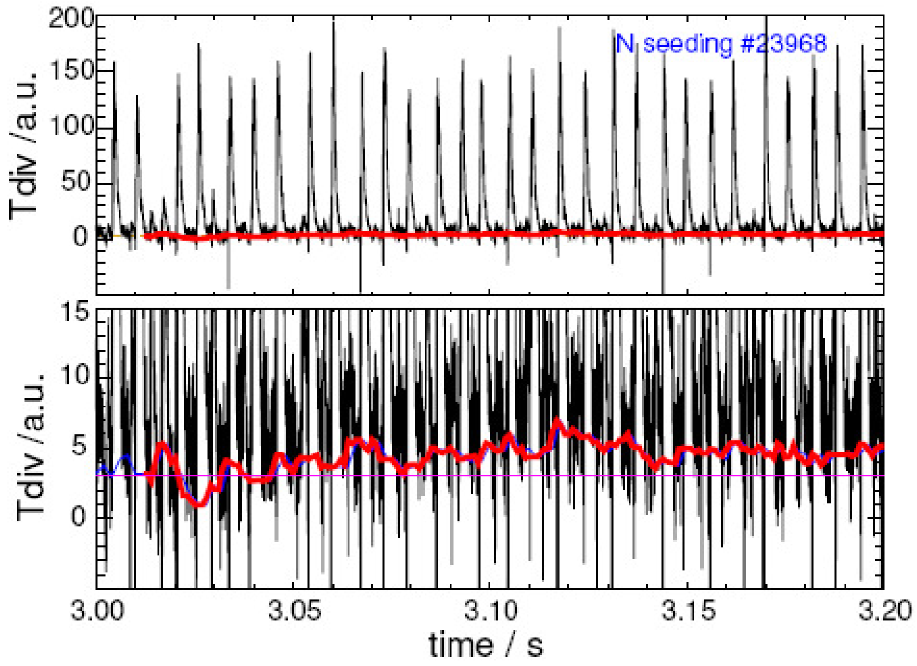


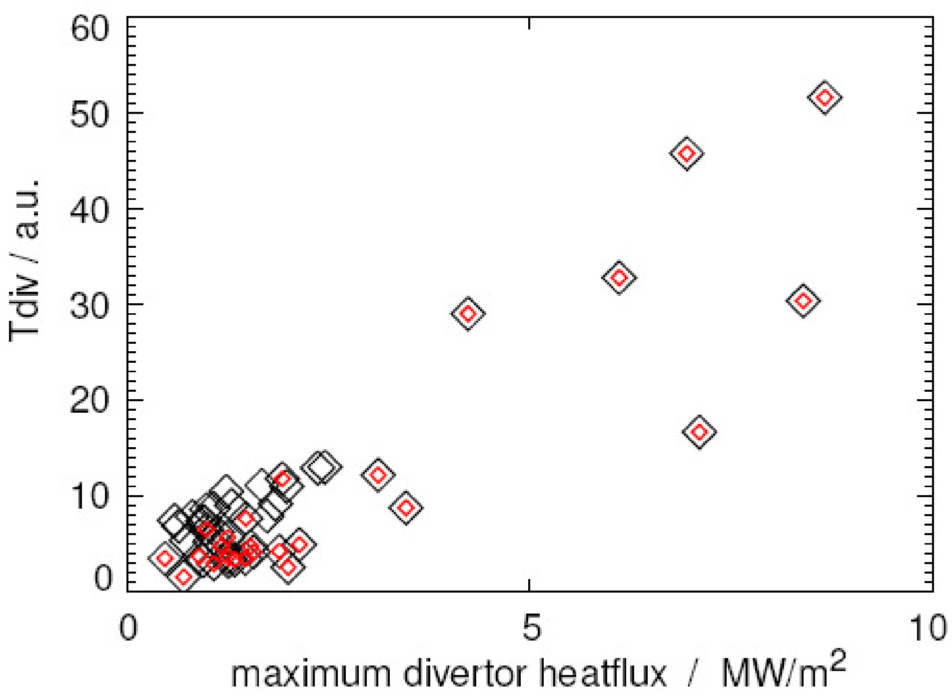



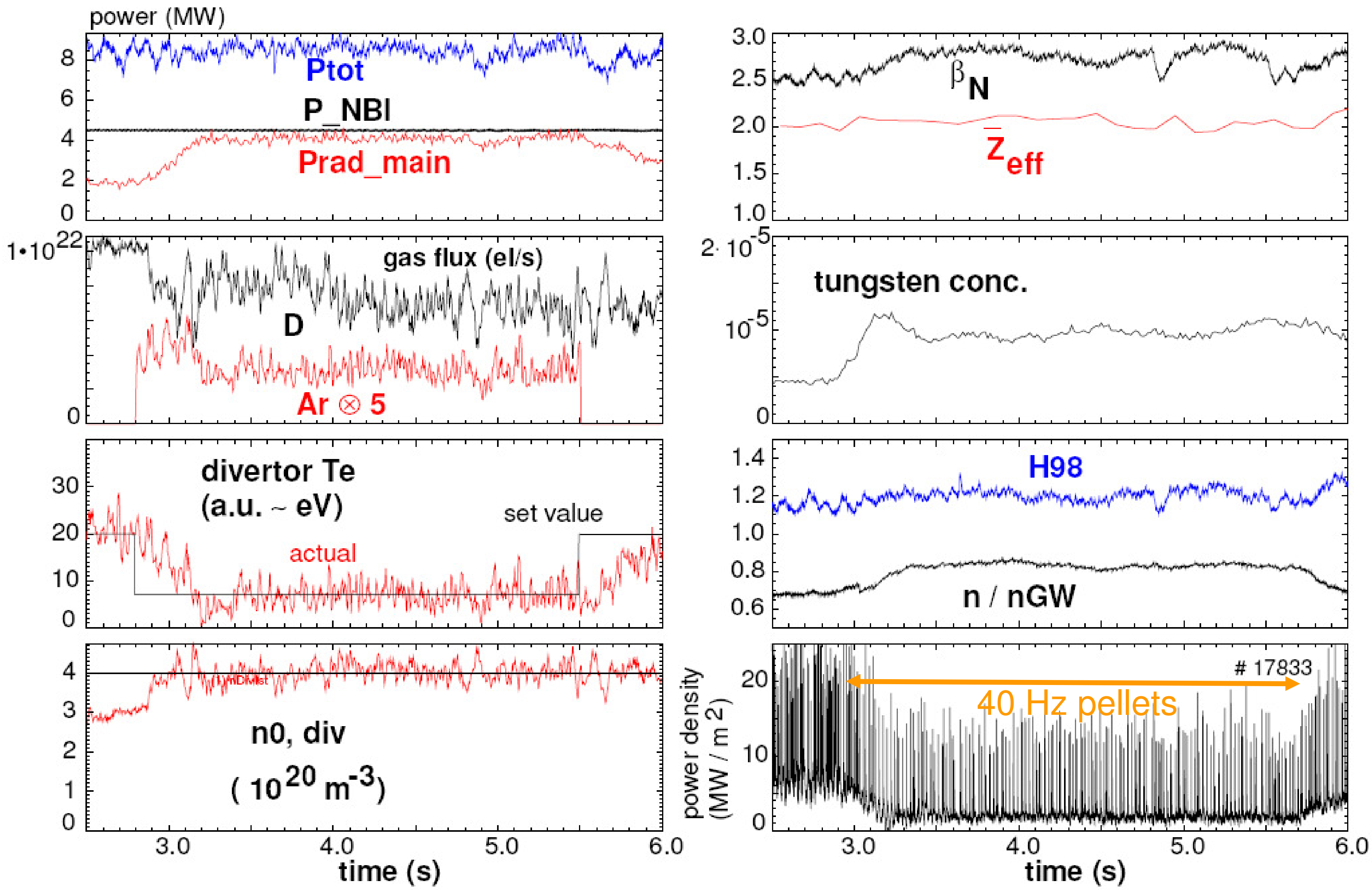
# Sensor for target heat flux required for feedback

AUG uses (thermo-) electric currents measured by divertor shunts
- roughly proportional to divertor $T_e$ and heat flux (for H-mode)



# Integrated scenario with feedback controlled Ar seeding and ELM pacemaking with pellets



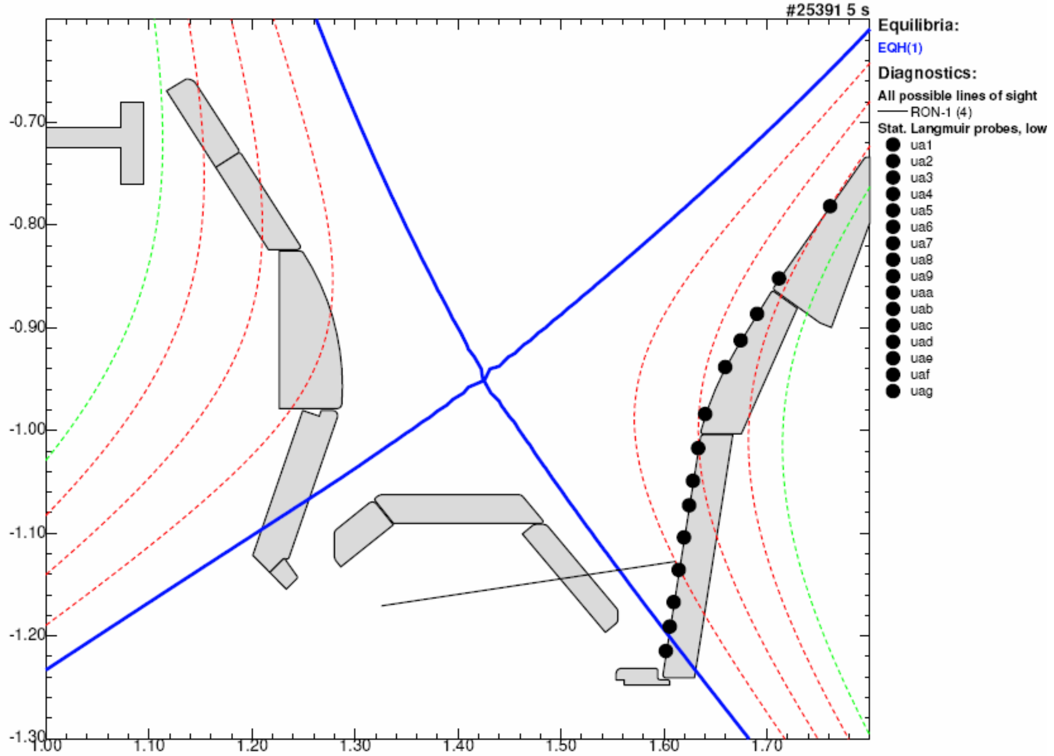
# Tungsten sputtering by nitrogen

Nitrogen is key to obtain low divertor temperature
- but it is also the dominant sputtering species

ELMs turn out to dominate sputtered W fluxes

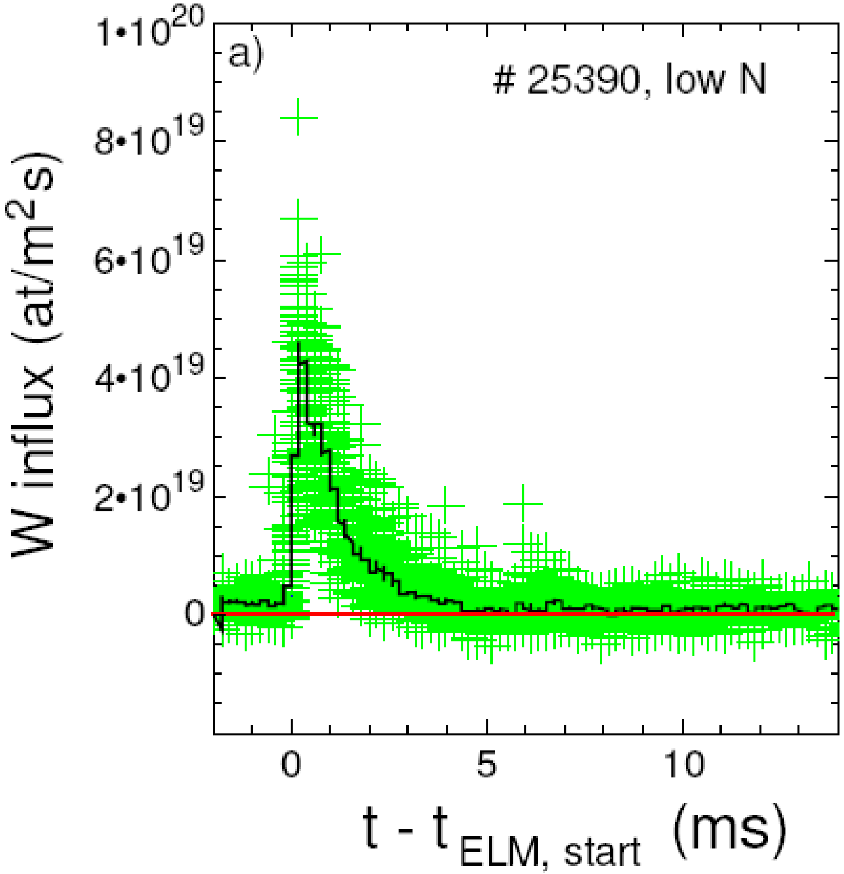
# Tungsten sputtering by nitrogen: experimental setup

fast spectroscopic measurement of WI and NII lines (0.2 ms)
plasma parameters obtained from triple Langmuir probe

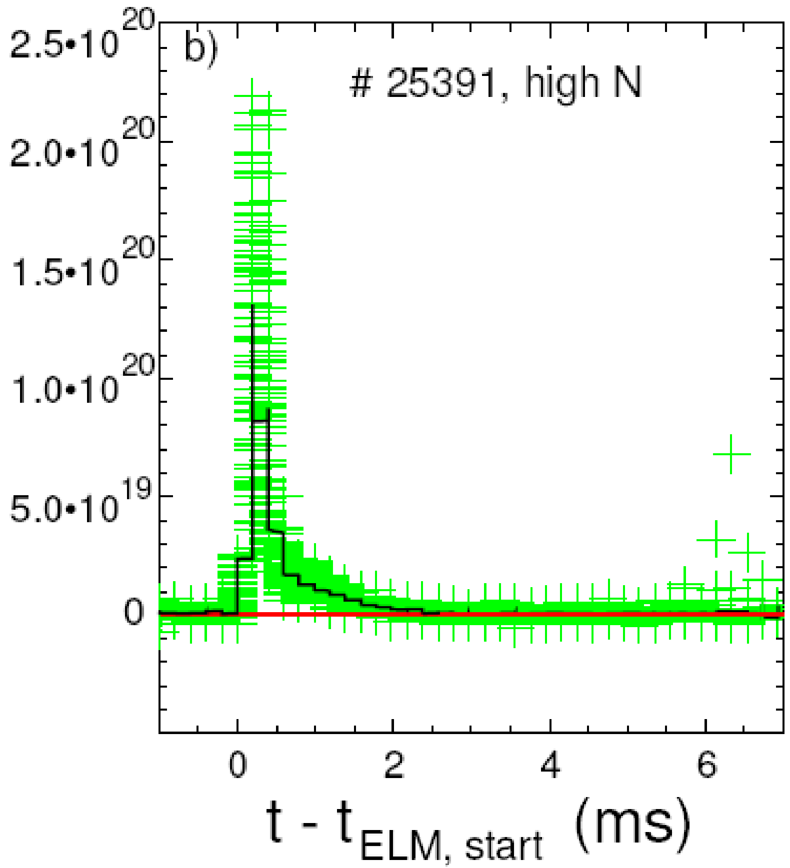



divertor profiles from strike point sweep
nitrogen concentration in ion flux from core data assuming enrichment $\eta$=2

# Tungsten sputtering by nitrogen: ELM resolved divertor fluxes

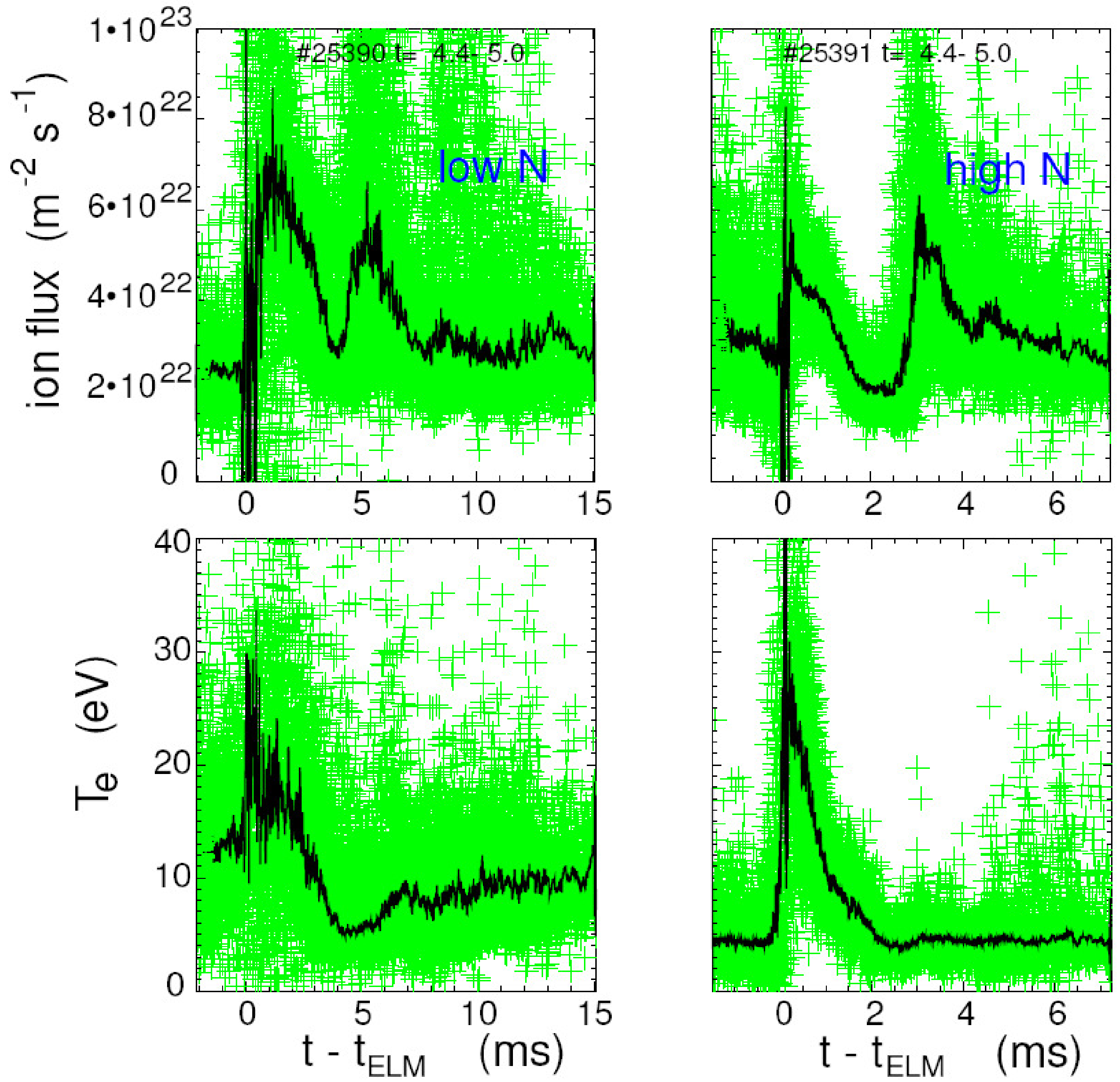



**0.5 % N, H98= 0.9**

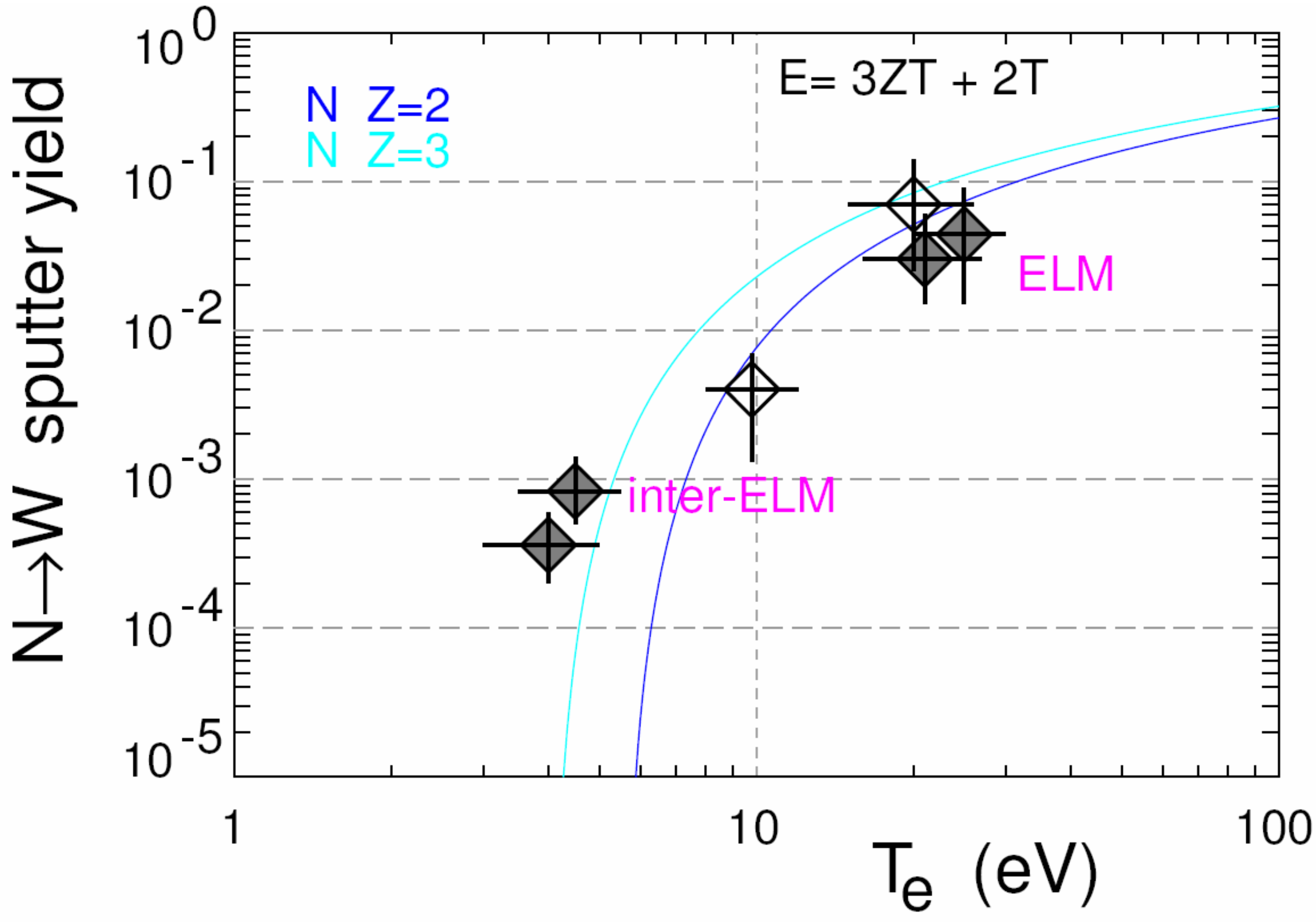



**2% N, H98= 1.1**

# Tungsten sputtering by nitrogen
# - ELM resolved divertor parameters



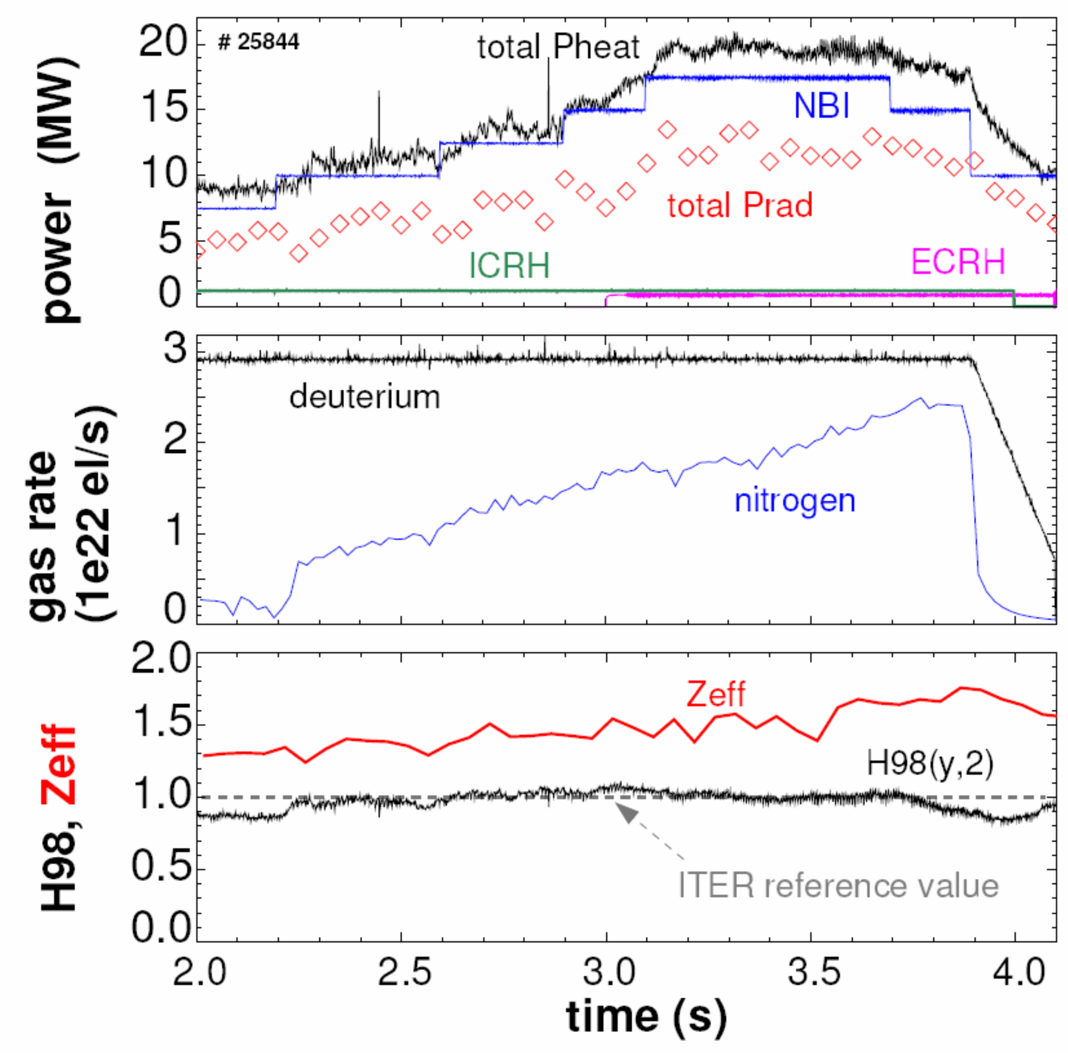
# Tungsten sputtering by nitrogen
# - experimental yields in AUG versus simplest expectations




full symbols:
N saturated W

# High power integrated seeding scenario in ASDEX Upgrade: high N + D puff, feedback-controlled Tdiv

20 MW AUG discharge with strong D + N seeding




just above type III – type I threshold

moderate inter-ELM divertor conditions (considering 20 MW heating):

$T_{e,div} \leq 10$ eV, heatflux $\leq 5$ MW/m$^2$

ELM size again 4 % of stored energy (was 2 % with type III at 12 MW)

# Conclusions

- prerequisite for seeding scenaruo is a good sensor, fast gas puff system and sufficient pumping

- multi-species seeding will be required in future high P/R devices

- the low-Z species used for divertor radiation has the highest wall fluxes and is therefore most critical for PWI issues

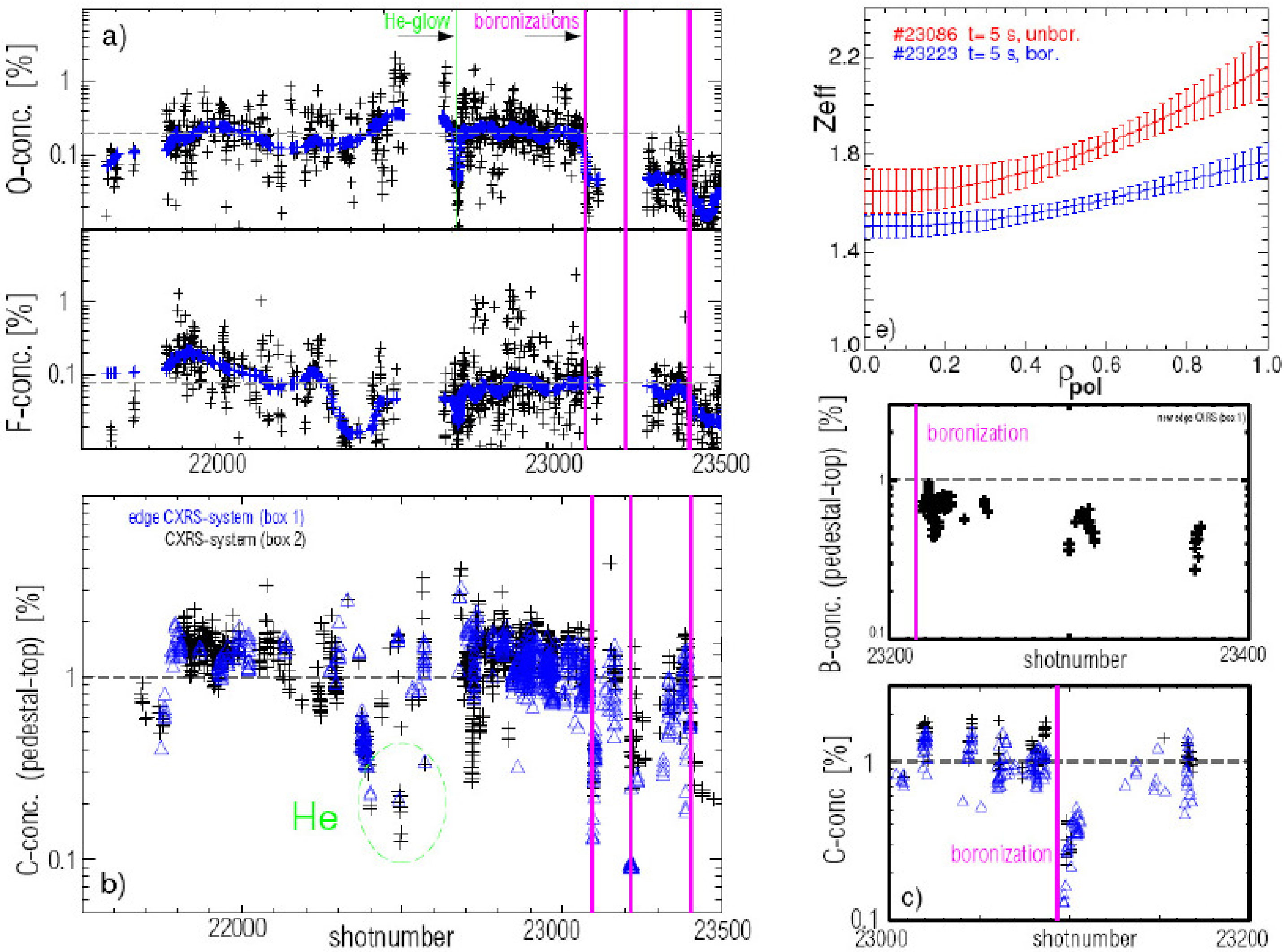
- nitrogen comes closest to good radiative characteristics of carbon

- nitrogen exhibits best performance as radiator in AUG
  - other low divertor compression machines undecided

- integration of seeding with mitigated ELM scenarios required
  - work has started, but needs to be extended to high P/R

Reserve slides …

# Intrinsic Zeff level is reduced in a boronized high-Z device




overall, medium term reduction of $Z_{eff}$ -1 due to boronisation by 20-30 %