# Overview of ASDEX Upgrade results

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*see appendix of H. Meyer et al., (OV/P-12) Proc. 26th IAEA Fusion Energy Conf., Kyoto, Japan

the 2014-2016 AUG programme is a joint venture of IPP and EUROfusion

CN-234 OV/2-1

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# Outline

- Recent hardware upgrades
- Non-inductive operation
- ELM suppression with magnetic perturbations
- Pedestal stability and confinement
- Power exhaust
- Scenario integration and extrapolation to large devices

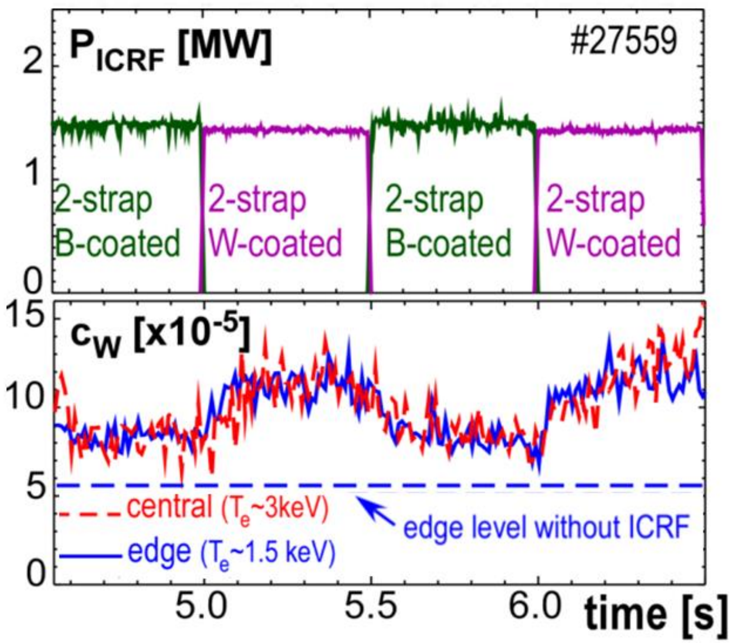
**Special emphasis is placed on the presence of tungsten (W) plasma facing components**

for ELM heat load studies and integrated edge/wall solutions see: **H. Meyer OV/P-12** later today
for disruption physics, mitigation and runaways, see **Martin EX/P6-23, Papp EX/9-4, Pautasso EX/P6-38 Plyusnin EX/P6-33**

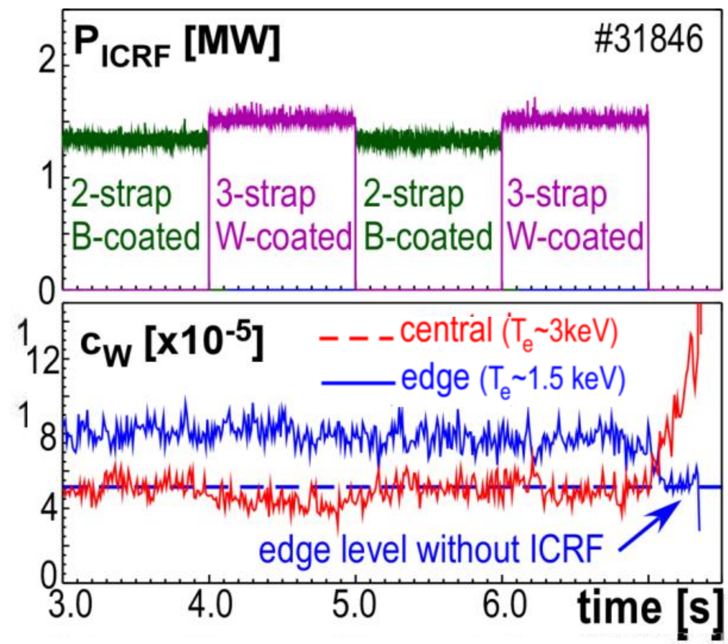
# New 3-strap ICRF antenna pair for reduced W release

- performs as predicted, factor 2 reduced W release as for 2-strap antenna with B limiters

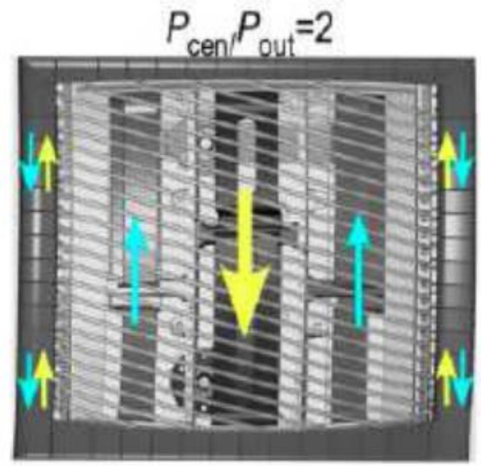
2-strap antenna




new 3-strap antenna




compensation of image currents in antenna frame

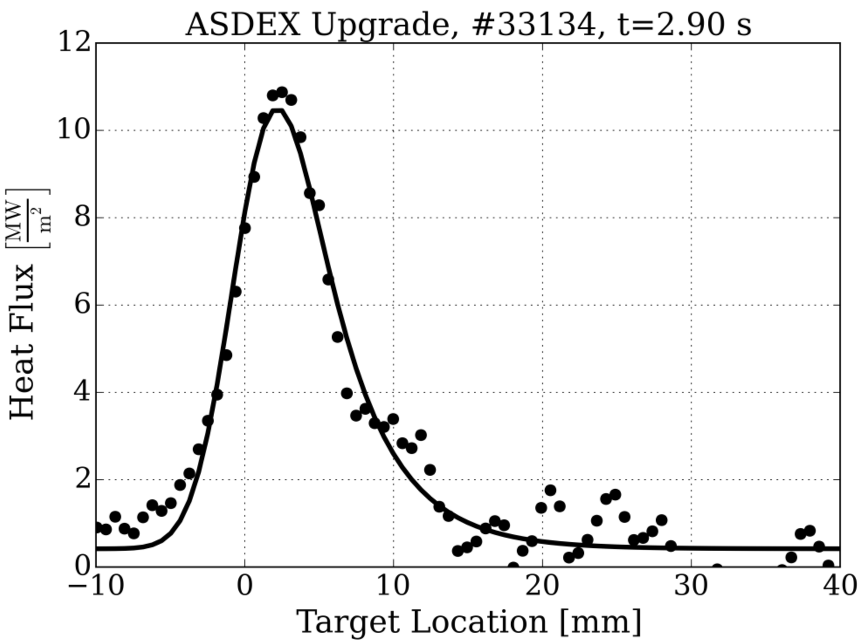



the success of the 3-strap antennas and its model validation paves the way for future ICRF in DEMO

J.M Noterdaeme, EX/P6-26, Thu

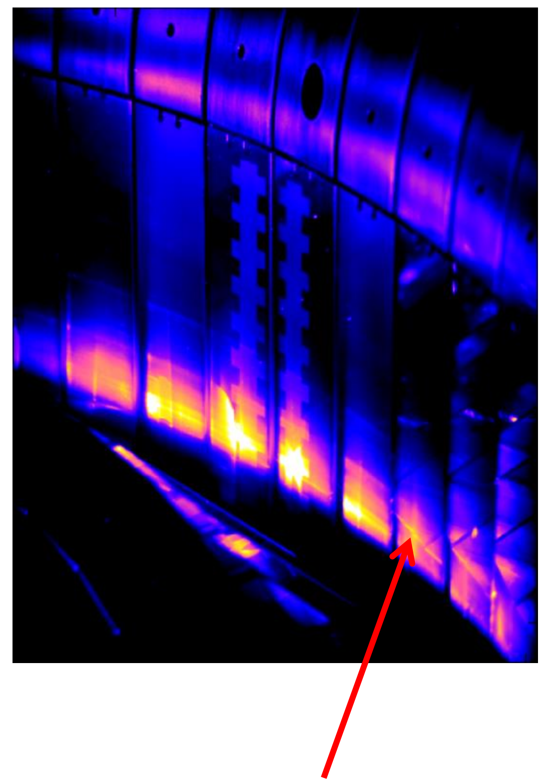
# Massive tungsten divertor performed well in operation

more than 10 MW/m² inter ELM peak load for 5 s measured by IR in low density, medium power H-mode




stripe view for profiles

full IR view (33303, less power, more gas)



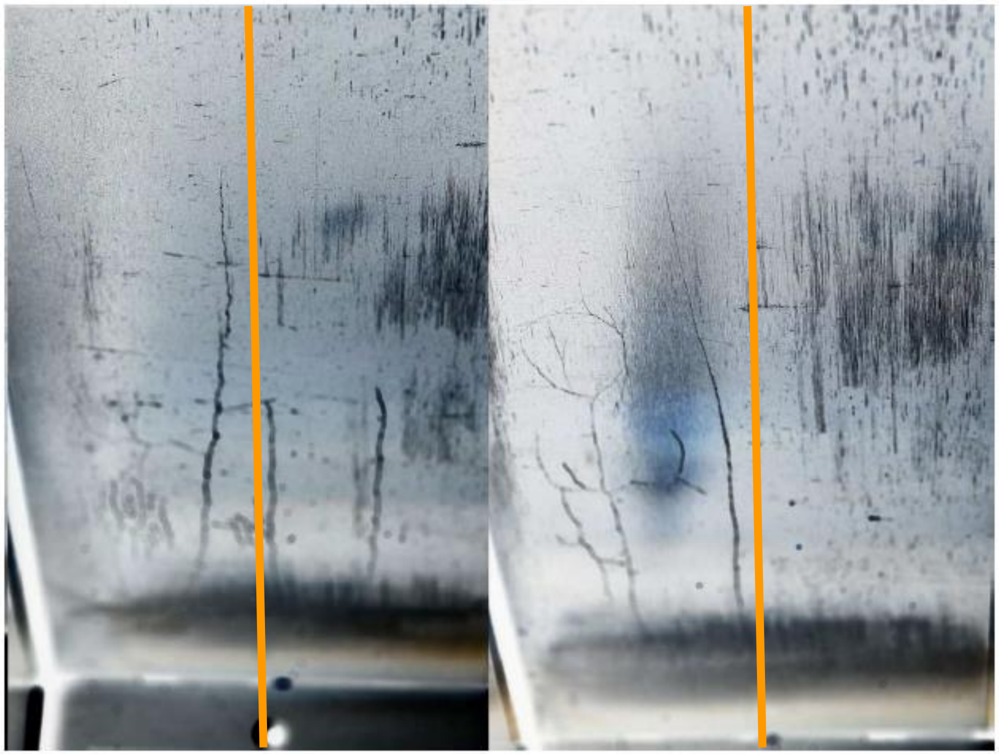
more on IR and heat flux: B. Sieglin, EX/7-3R, Fri | H. Meyer, OV/P12 Mon

reliable divertor operation (apart from some Langmuir probe melting), but cracks observed

# Cracks formed – through tile and at the surface

- cracks not observed  in high heat flux tests in GLADIS before
- forces during disruption in addition to thermo-mechanical stresses

A. Herrmann, PSI 2016



PWI (mainly He)

A. Hakola, EX/P6-22 Thu

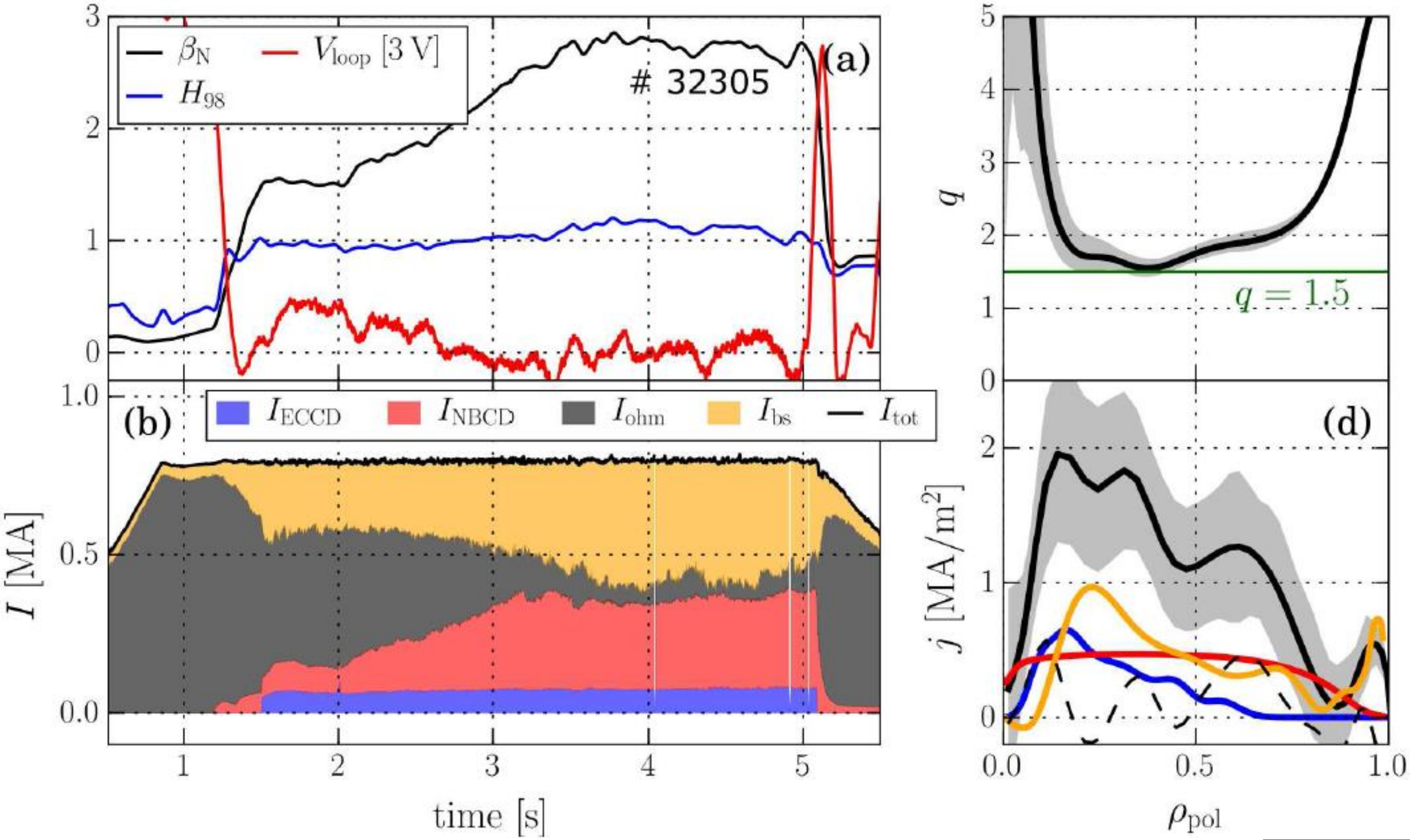
FEM calculations suggest vertical tile splitting for crack avoidance (done in current AUG vent)
¼ of tiles will be made from more ductile material 97 % W, 2 % Ni, 1 % Fe (magnetic)

# Scenario development

- Non-inductive operation
- ELM suppression

# Fully non-inductive operation at $I_p$= 0.8 MA

- about 40 % of $I_p$ driven by NBCD (11 MW NBI), 50 % bootstrap, 10 % ECCD (2.7 MW)
- ECCD used to tailor current profile for optimum stability and $q_{min}$ > 1.5




- fresh boronization

J.Stober, PostDeadline, Sat.

NBCD:

C. Hopf, EX/P6-28, Thu

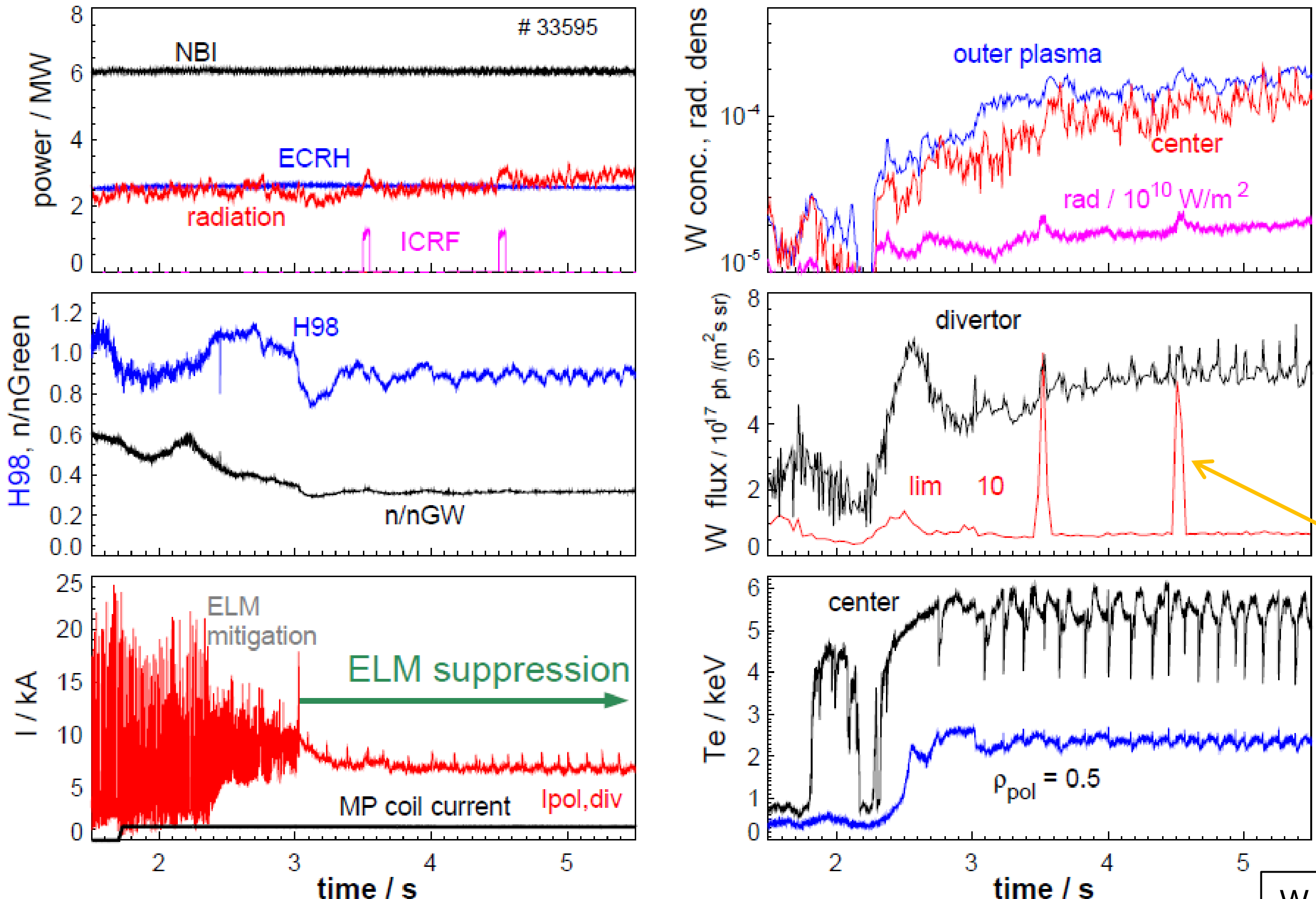
improved diagnostics: MSE, IMSE, polarimetry

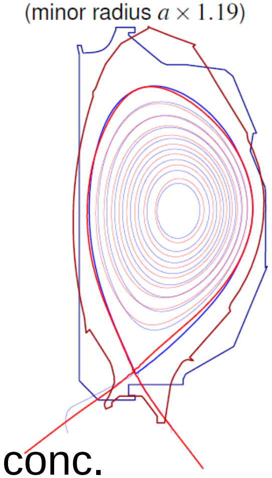
MHD at high β:

V. Igochine, EX/P6-24,Thu

# ELM suppression by RMPs obtained, finally

- full ELM suppression obtained in AUG. trick: δ-dependence of threshold as found in DIII-D
- no accumulation of W at pedestal top




quite high W conc. due to hot divertor

W blips from midplane limiter (ICRF detuned phasing) exhibit normal decay times

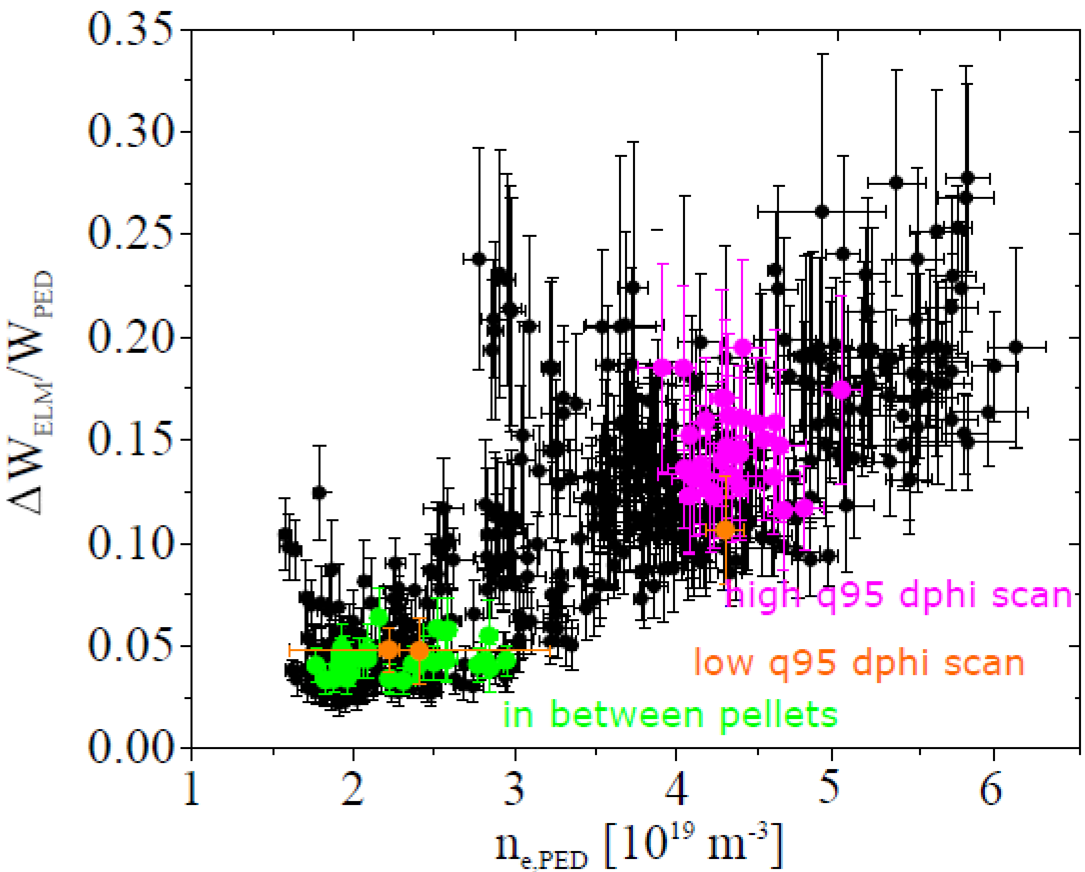
W. Suttrop, EPS 2016, R. Nazikian, PD, Sat

scenario can only be reached with prior ELM mitigation and fresh boronization

# Relative ELM size depends mainly on pedestal density w/wo MPs

- ELM mitigation closely connected to density pump-out

N. Leuthold, subm. PPCF




low collisionality $\nu^*_{ped} < 1$

edge plasma response to MPs:

M. Willensdorfer, EX/P6-25 Thu

non-linear JOREK modelling:

F. Orain, TH/P1-26, Tue

fast ion losses with MP:

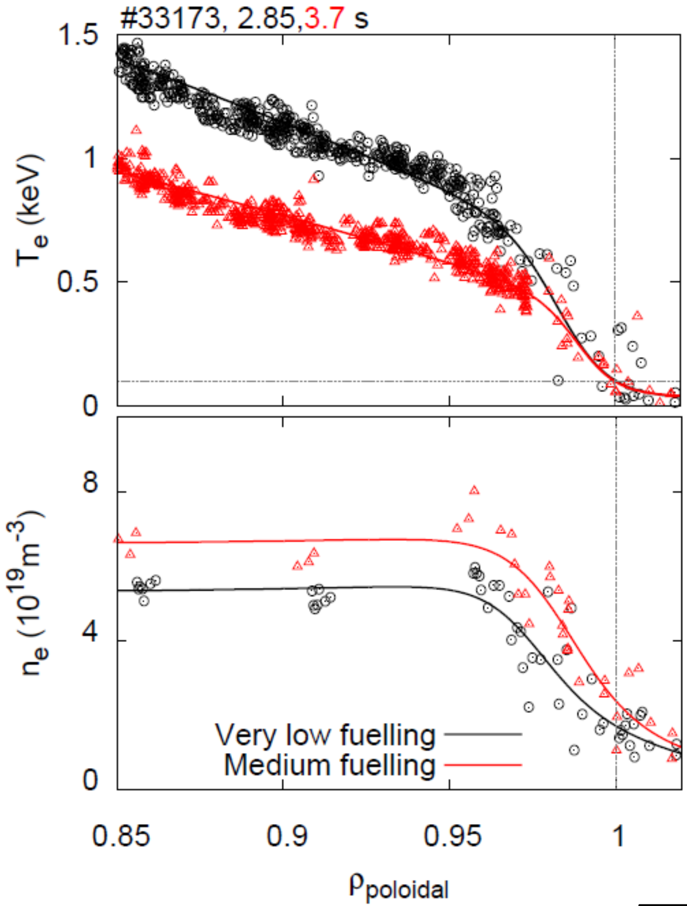
M. Garcia-Munoz, EX/6-1, Thu

$n_{e,ped}$ gives better correlation compared to $\nu^*$ or pedestal pressure

# Pedestal physics

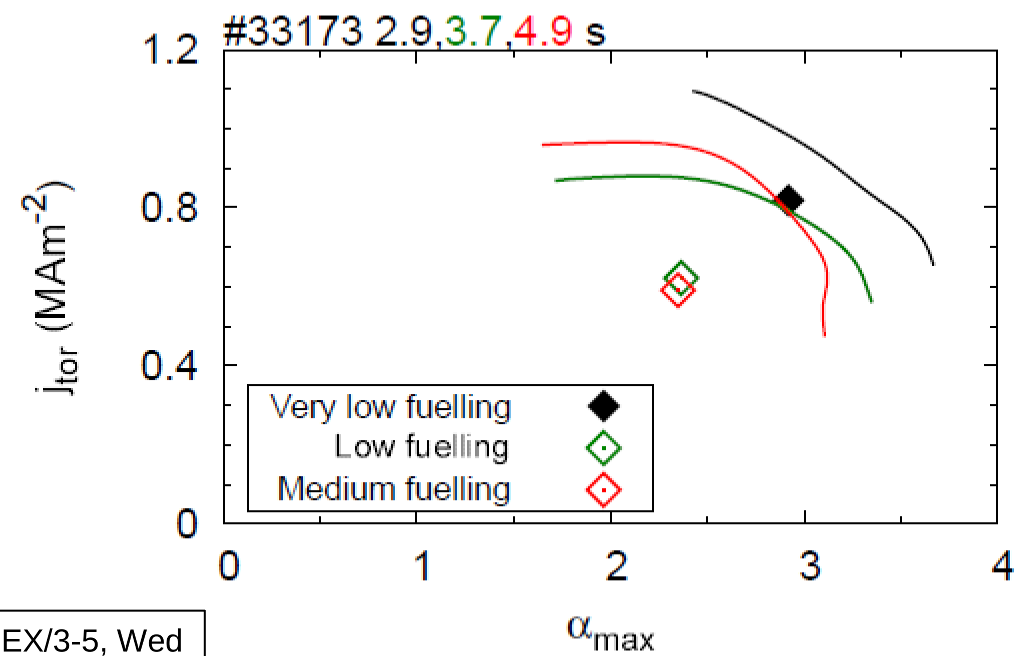
# Pedestal- and global energy confinement depend on edge density profile

- D fueling shifts density profile outward – T profile anchored at separatrix




Stability analysis:

- unfavourable alignment of shear and max. pressure gradient

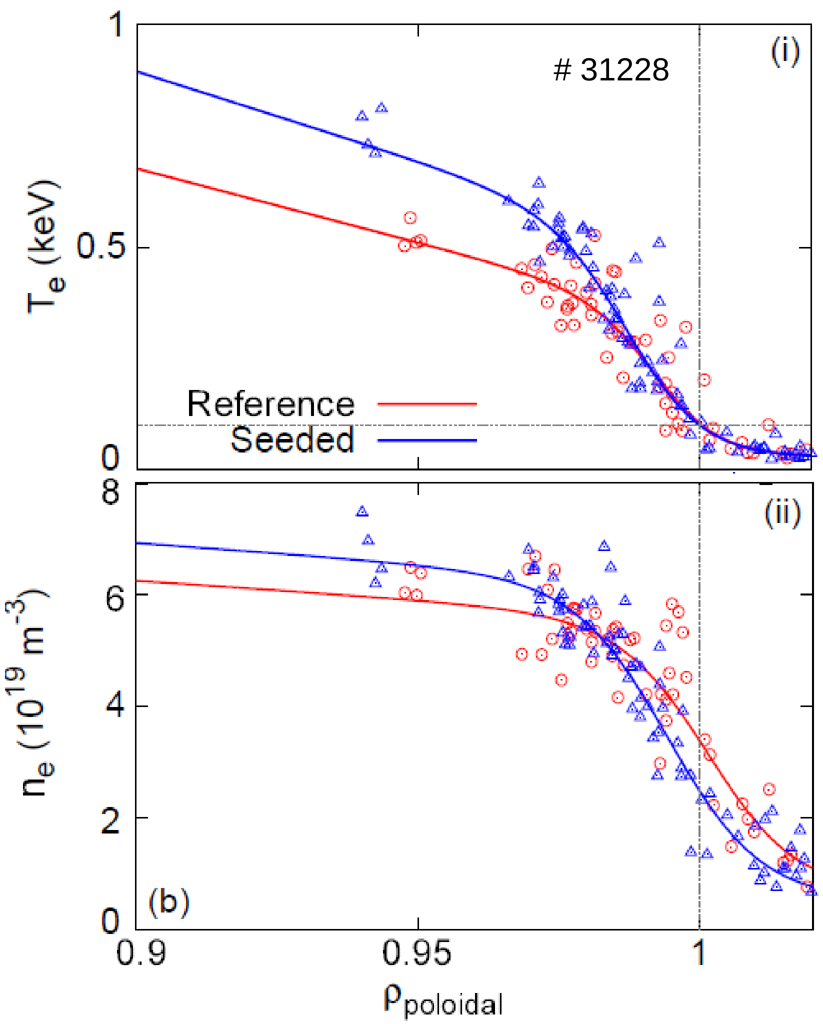


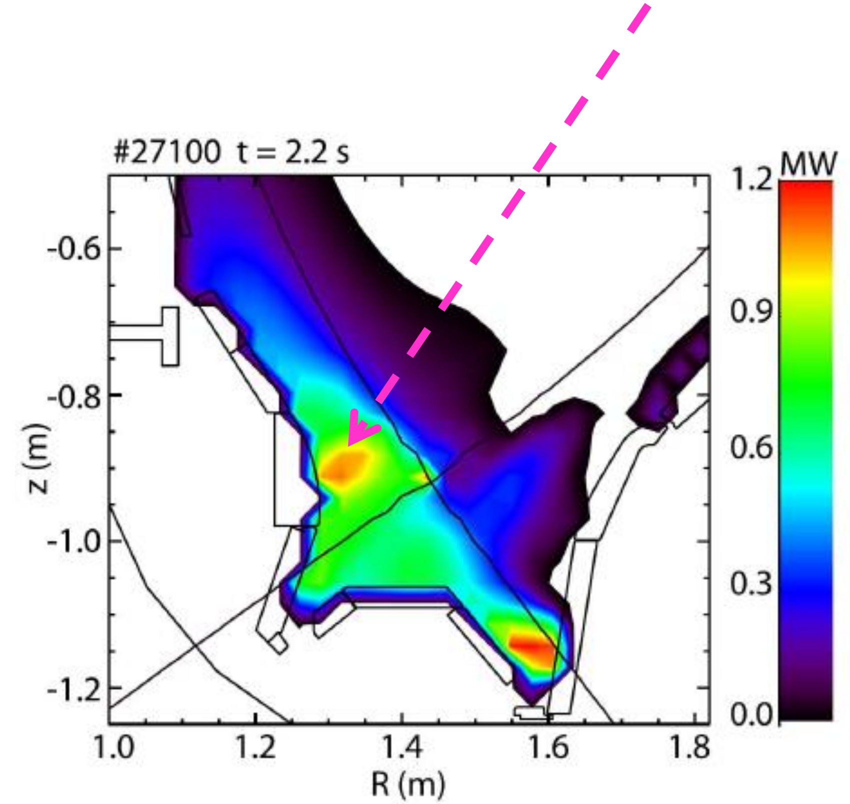

M. Dunne, EX/3-5, Wed

recall $\alpha \propto q^2\, dp/dr$

# Effect of N seeding via HFSHD as heating power reduction

- N seeding effects fueling via reduction of high field side high density (HFSHD)




HFSHD modelling: F. Reimold, EXS/P6-191, Thu

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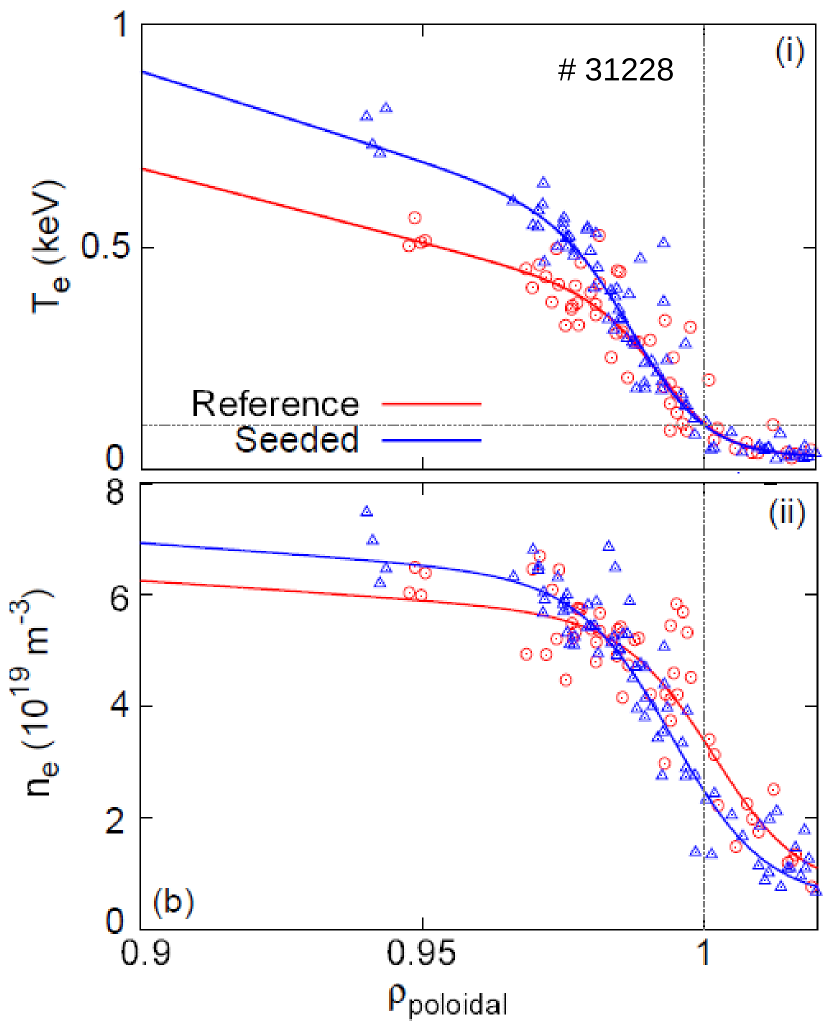
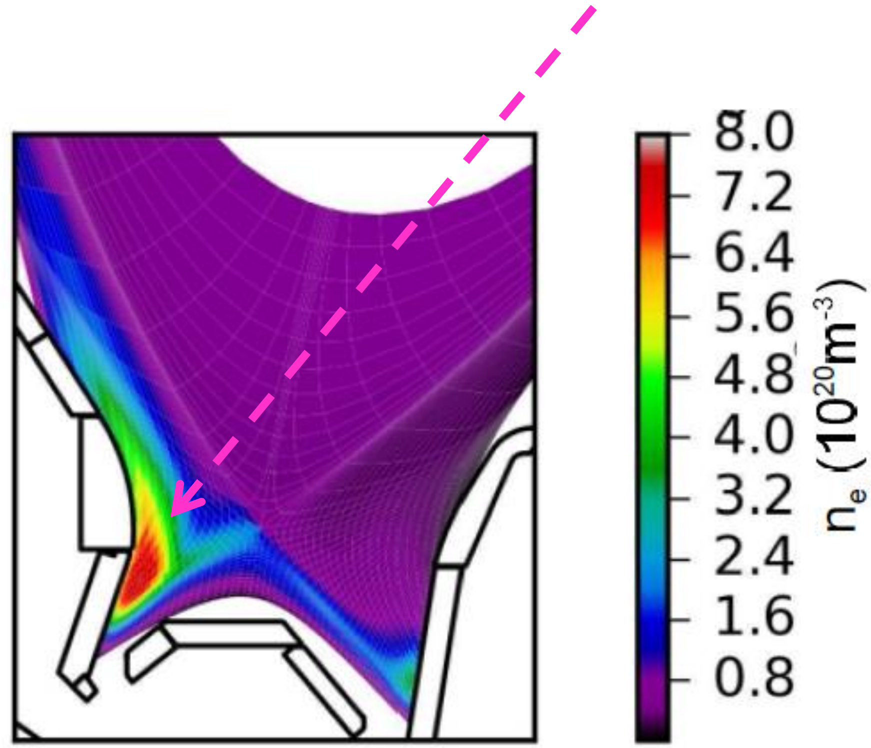



effect of HFSHD
meanwhile reproduced with SOLPS modelling

HFSHD modelling: F. Reimold, EXS/P6-191, Thu

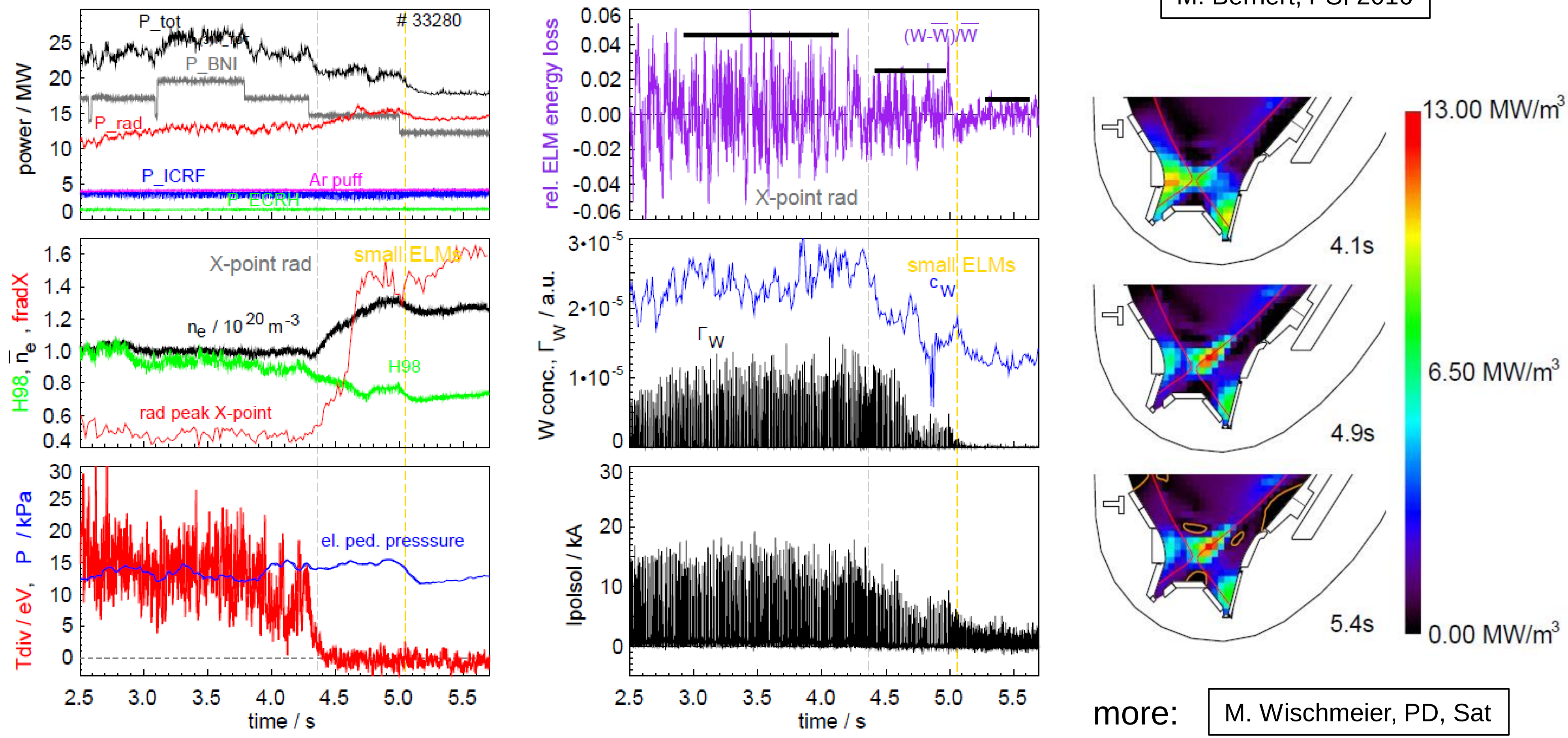
# Power exhaust

- X-point radiator
- Integration with pellet fueling
- Divertor impurity enrichment

# Detachment studies with X-point radiator

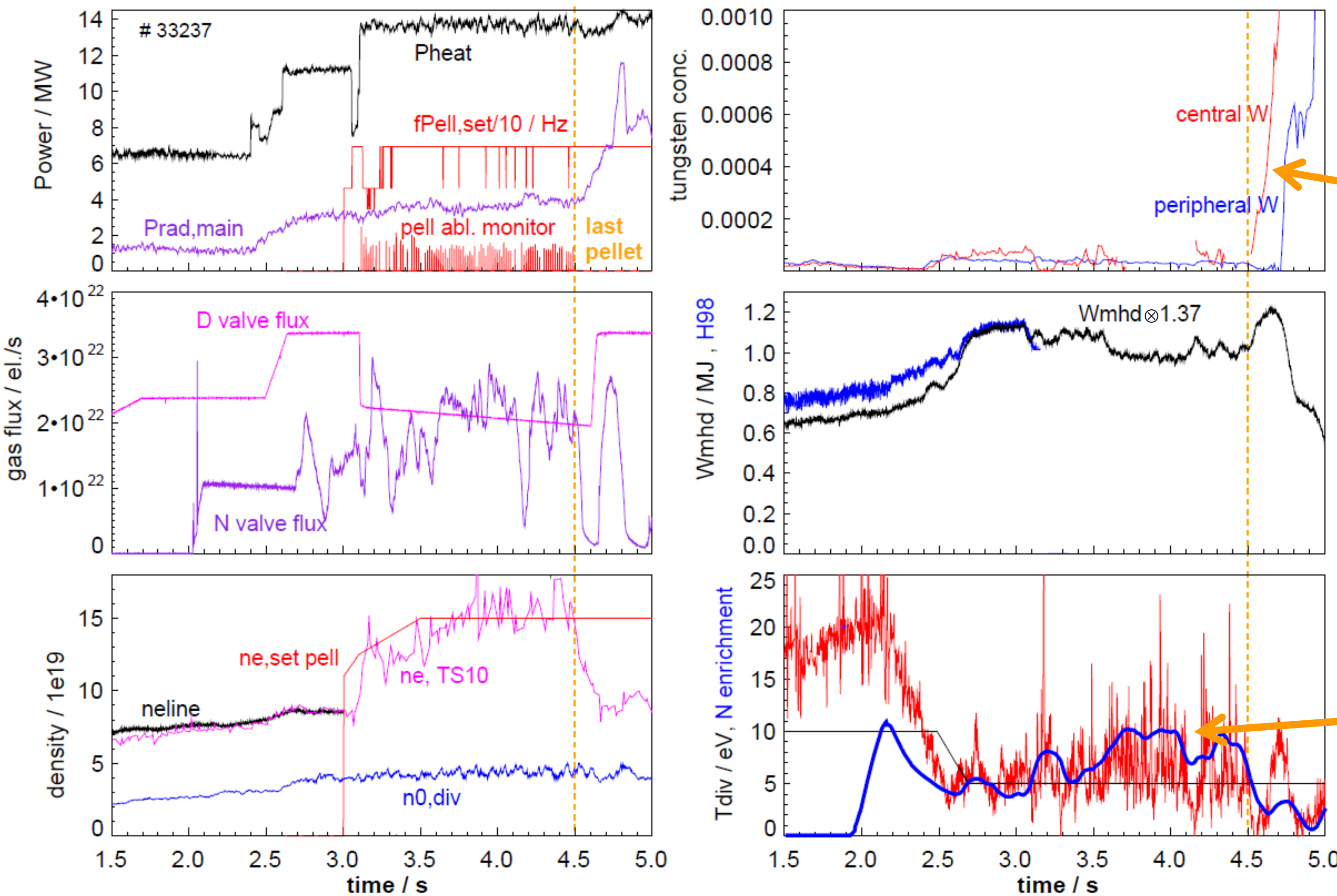
- X-point radiator at pronounced detachment with N and Ar seeding
- favourable properties: cold divertor with low power load, no W sputtering, smaller ELMs
- expected to be feedback-controllable

M. Bernert, PSI 2016




more: M. Wischmeier, PD, Sat

# Integration of Tdiv feedback control and pellet density control




W accum. after last pellet: $n_e$ peaking

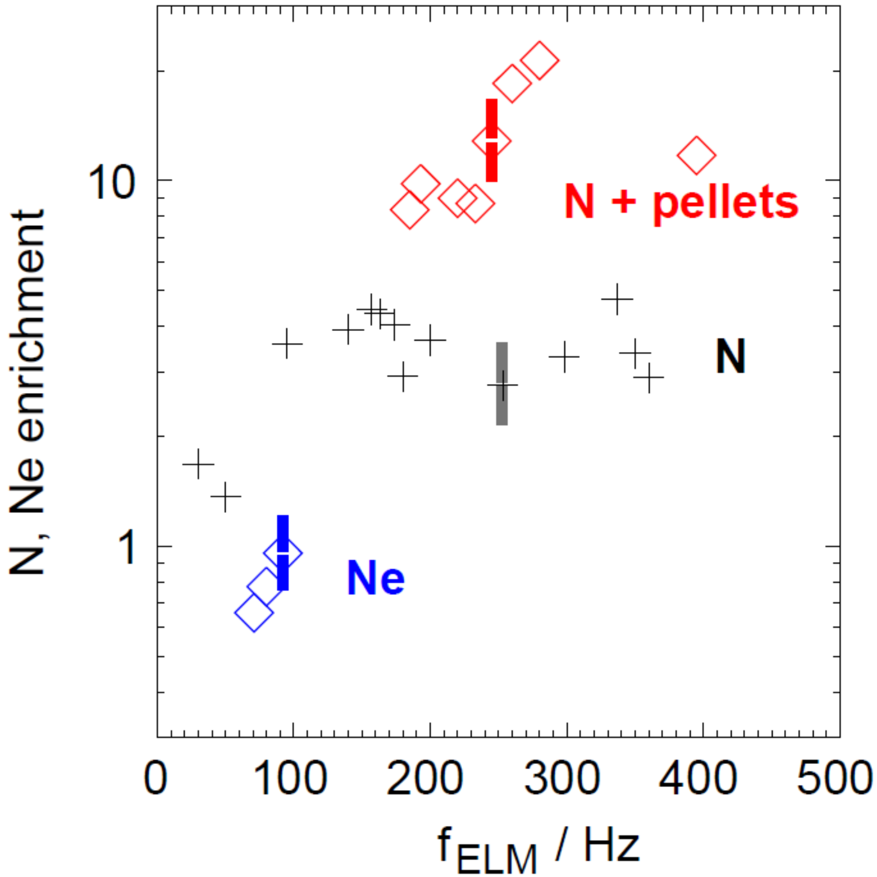
density control to $1.2 \otimes n_{Greenwald}$

high nitrogen divertor enrichment during pellets

# ELM frequency is important for enrichment, but not exclusively

impurity divertor enrichment

$$E = \frac{\Gamma_Z}{Z\,\Gamma_D} / \frac{n_Z}{n_e}$$




ELMs enhance E via impurity flushing, reducing $c_{z,core}$

**other effects**:

- impurity ionization length
- neoclassical pedestal inward drift

N, Ne enrichment modelling: F. Reimold, EXS/P6-191, Thu

a high divertor enrichent E is key for efficient power exhaust with low core impurity content

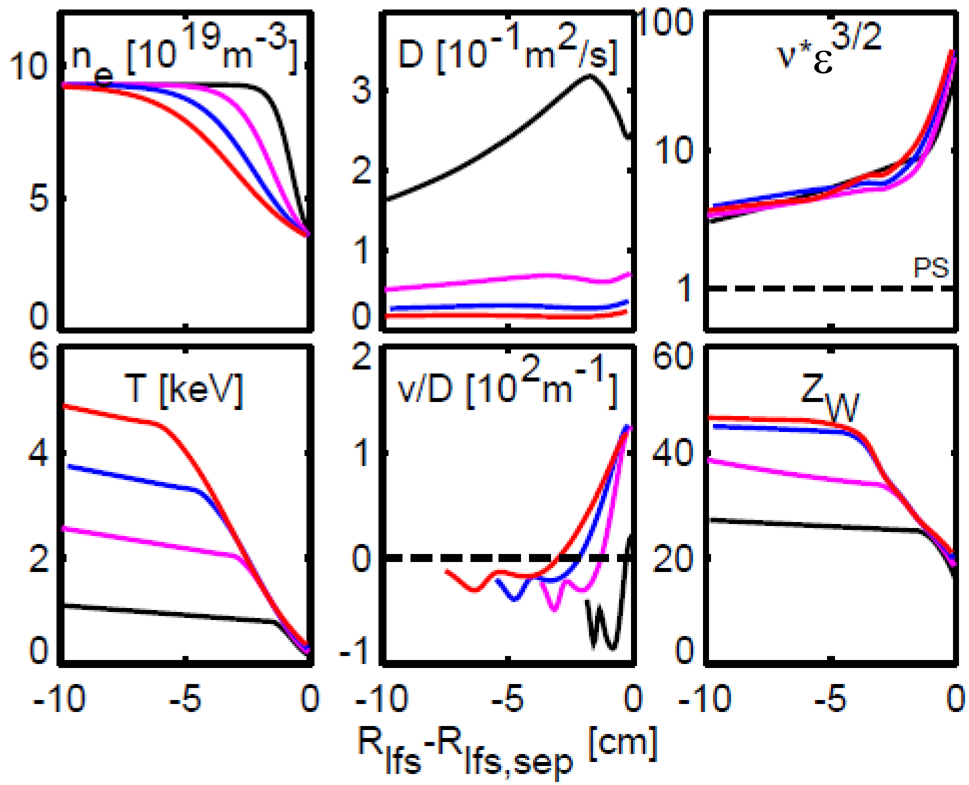
# Challenges caused by tungsten PFCs.

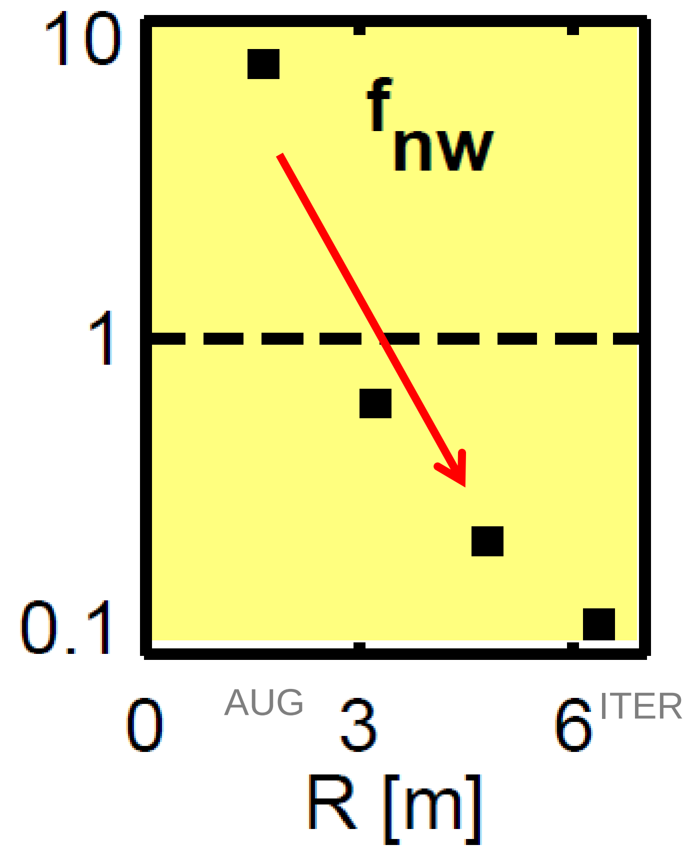
- favourable prospects for larger devices

# Favourable tungsten behaviour expected in a large device

neoclassical W transport to predict pedestal scaling $n_{W,ped}/n_{W,sep}$

R. Dux, PSI 2016




**higher temperature screening causes decrease of W density at pedestal top vs. separatrix**

# Main conclusions

- successful ICRF antenna development (3-straps) for operation with tungsten PFCs
- massive W divertor performs well in high power – W released at crack edges not critical

despite challenges caused by high W concentrations with low gas input:

- fully non-inductive operation up to $I_p$= 0.8 MA
- ELM suppression with RMPs

achieved with the help of boronization in AUG

- favourable scaling of W transport for larger machines predicted

**relative position of edge density and temperature profiles:**

- important for confinement improvement by low-Z species
- subject for future optimization with tailored pellet injection

- high divertor N enrichment in integrated divertor cooling scenario with pellets
  $\rightarrow$ pure core plasma with high divertor radiation and detachment

# The ASDEX Upgrade team

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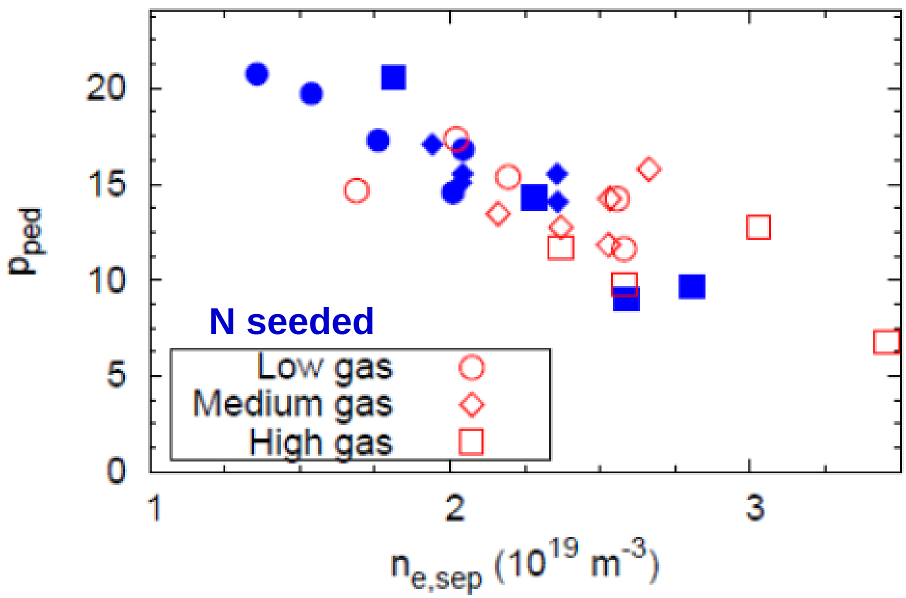
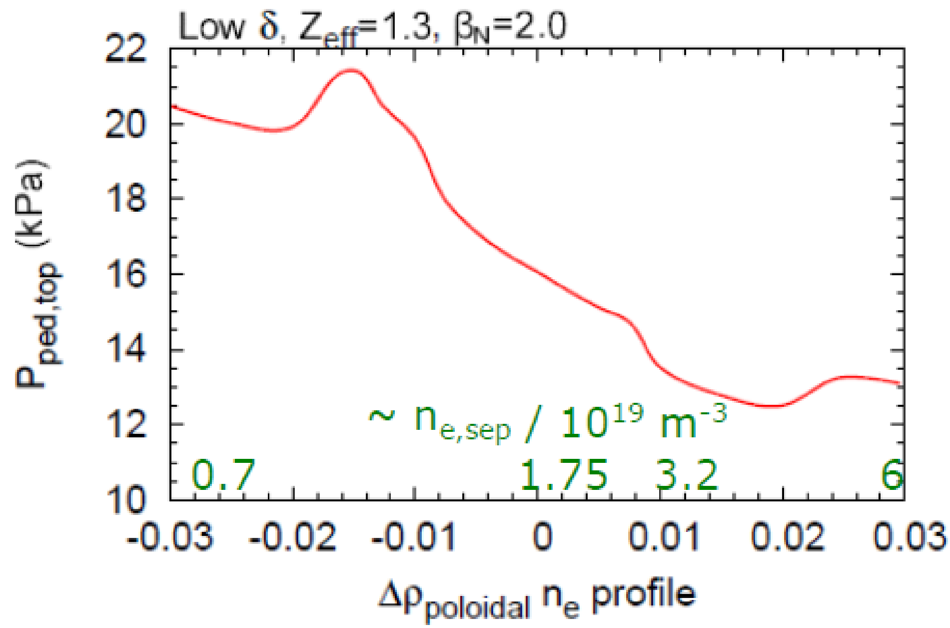
# Reserve slide

# Stability calculations confirm effect of $n_e$ profile location on pedestal top pressure

- pedestal top pressure closely linked to density at separatrix
- further effects, like amplification of β increase by effect on shear




M. Dunne, EX/3-5, Wed

more on the AUG pedestal: E. Viezzer, EX/P6-30, Thu T. Pütterich, EX/P6-29, Thu