# Integrated power and particle exhaust scenarios

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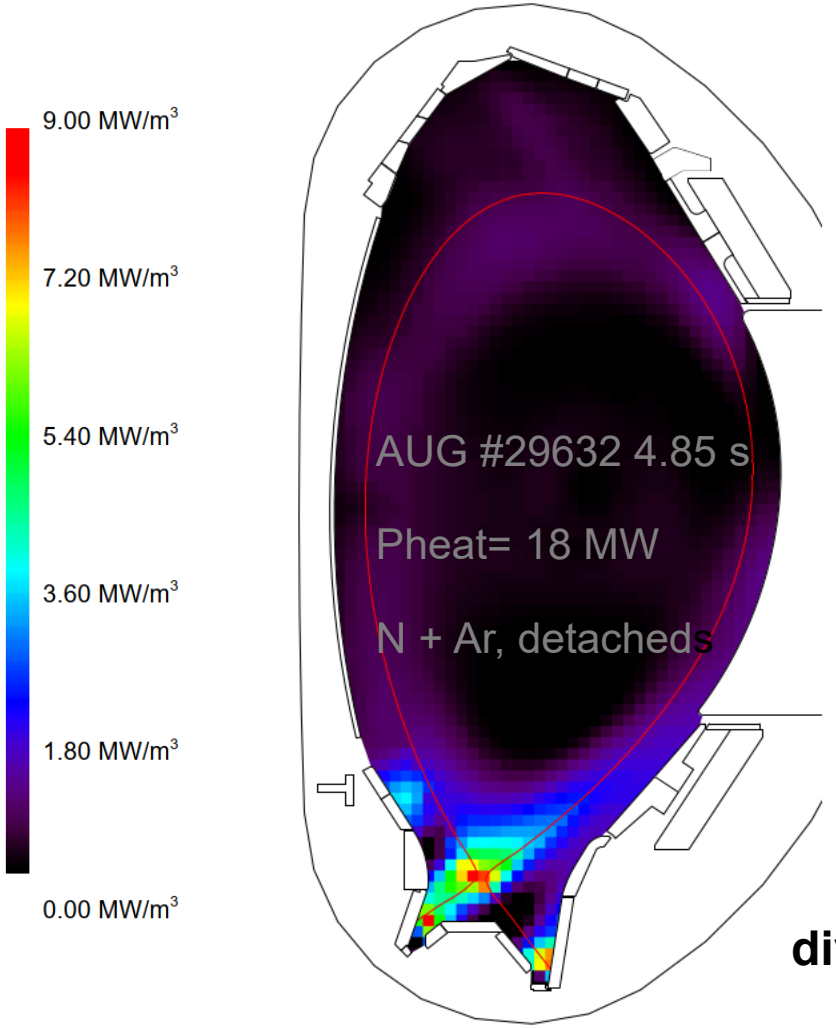
# Introduction: Elements of an integrated scenario

2 GW fusion power, 400 MW $\alpha$ power + 100 MW heating and current drive

[Federici, Nuclear Fusion (2019)]

[Day, FED (2022)]




**350 MW (outer) core radiation**

**no-ELM pedestal scenario**

**sufficient energy confinement, low dilution, non-inductive (?)**

**100 MW divertor radiation**

**divertor T at target < 3 eV to avoid tungsten sputtering**

7 $10^{20}$ He atoms / s pumped - max 7 % He in core plasma, ~ max. 3.5 % He in divertor → minimum 2 $10^{22}$ D+T at pumped

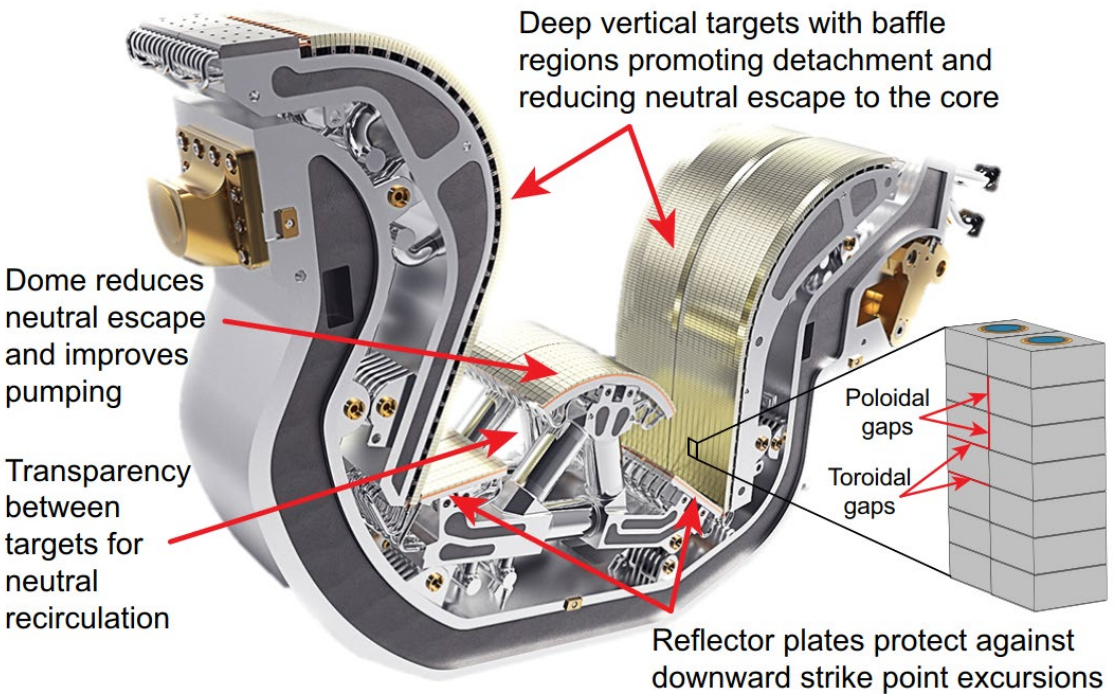
# Outline

- Divertor geometry
- Radiating species portfolio for divertor and outer core plasma
- Limits on core impurity concentrations
- Integration with no-ELM scenario
- impurity doped pellet fueling for shorter cooling timescale
- Outlook

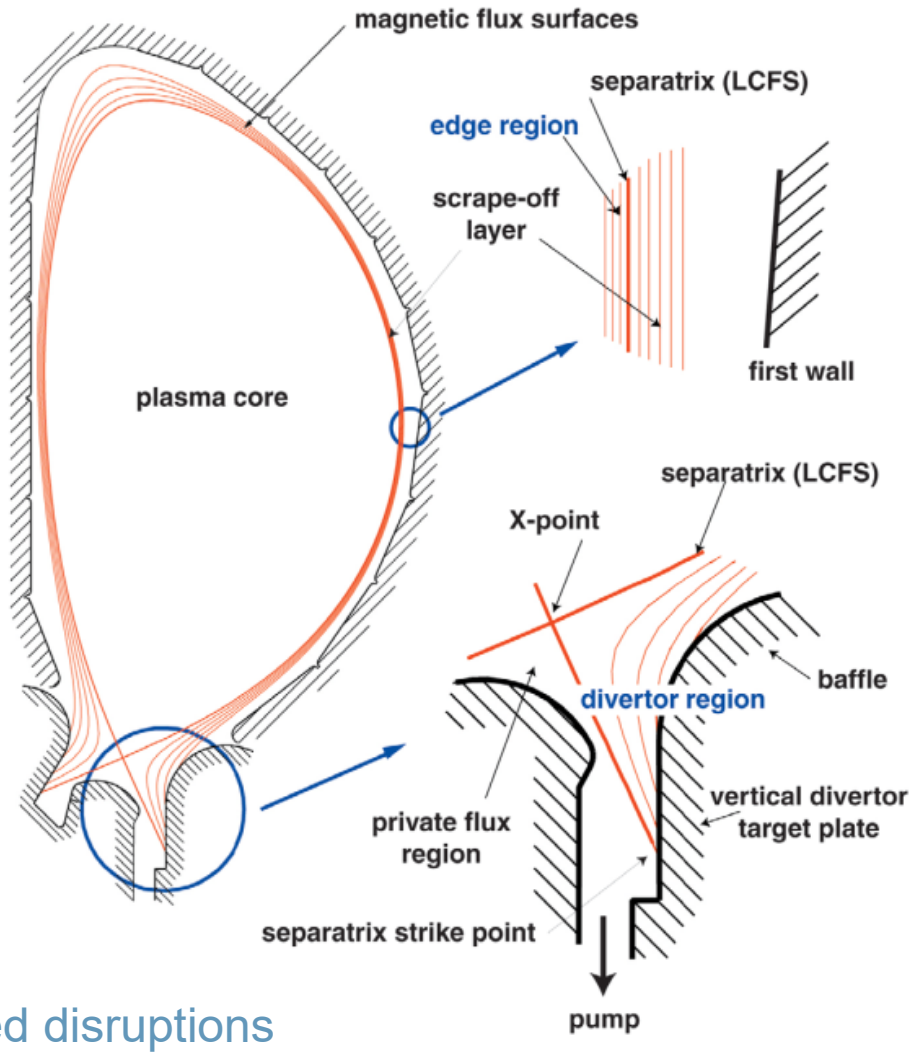
The talk will address the different elements / parameters which determine an integrated scenario

# Standard divertor geometry well developed

**ITER** [Pitts et al. NME (2019)]




**EU-DEMO** [Federici et al. NF (2017)]




- castellated tungsten monoblocks
- steady state heat load ≤ 10 MW/m$^2$, no ELMs, few and mitigated disruptions

# Particle exhaust

For fixed pumping speed, exhaust (particles/s, bar l / s) is proportional to divertor neutral pressure

Under this assumption, the neutral pressure is proportional to the total gas puff rate (valves + pellets)

The plasma density, and even the separatrix density, weakly react to increased gas puff rate

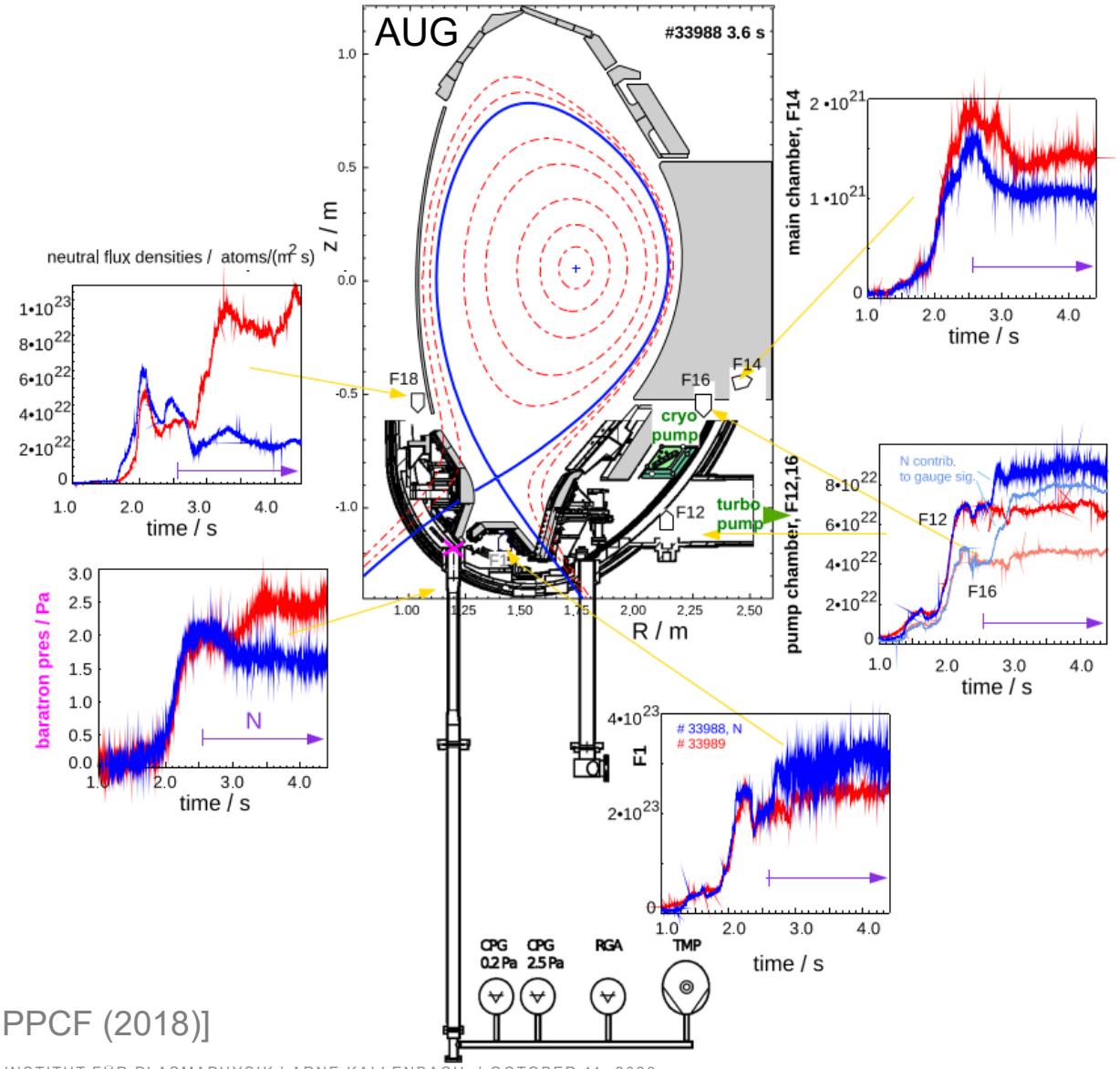
- SOL density profile broadens
- SOL gets more opaque for neutrals
- pellets required for fuelling

Divertor impurity entrainment rises with neutral pressure

Divertor recycling and radiation rise with neutral pressure

Caveat: high $n_{e,sep}$ may degrade confinement and, consequently, current drive efficiency

# ASDEX Upgrade: Internal recycling pattern quite stiff (physics det.)




**un-seeded** versus **N-seeded**

1 Pa (mol.) ≅ 5 $10^{20}$ D/T atoms / $m^3$

S= 100 $m^3$/s: 5 $10^{22}$ atoms pumped per Pa

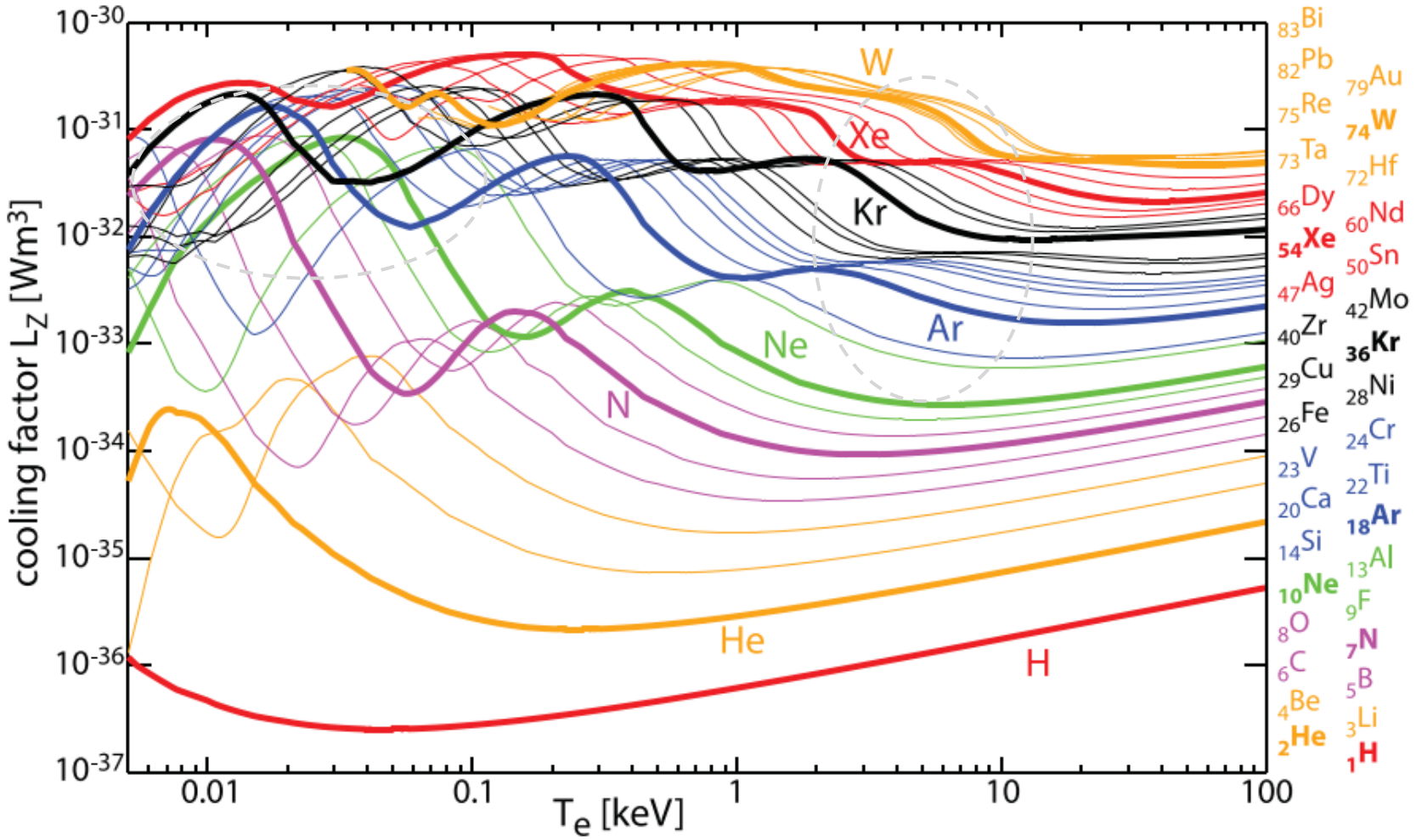
expect a throughput of ~ 5 $10^{23}$ at/s in DEMO

+ a few % N/Ne, a few per mille Ar

[Kallenbach, PPCF (2018)]

# Radiator portfolio (plasma enhancement gases)

[ Pütterich, Nucl. Fus. (2019) ]




**Most suitable species**

Divertor: (**N**), **Ne**, **Ar**

Pedestal: **Ar**, **Kr**

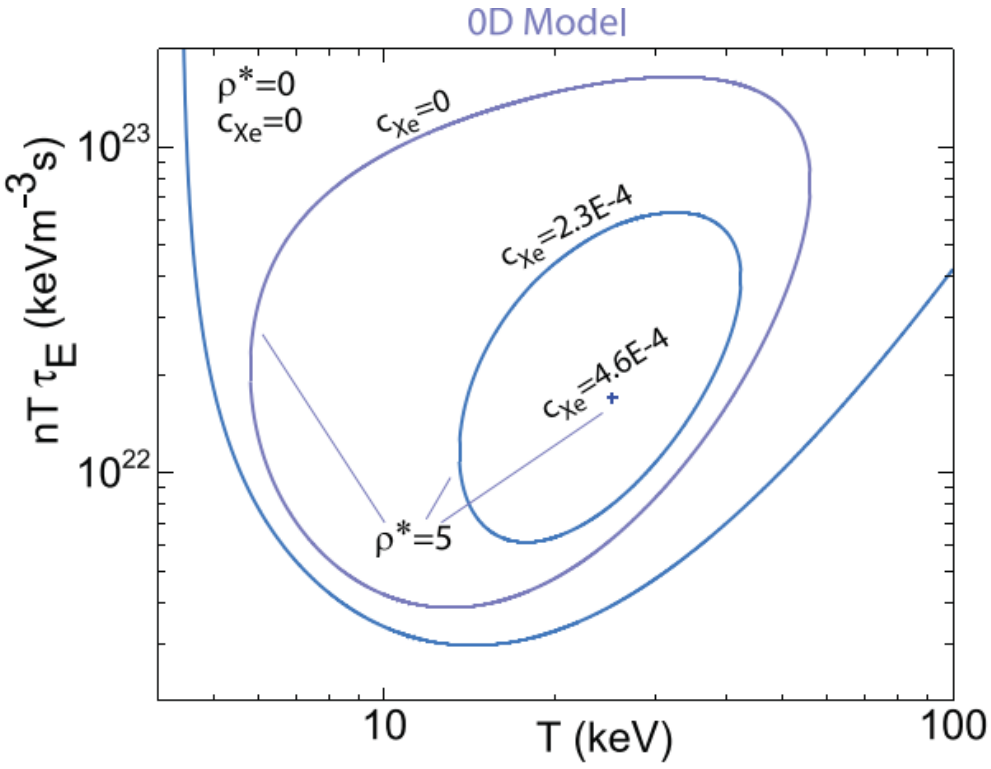
Core: **Xe**

Note: enhanced cooling rates in divertor and pedestal due to non-Corona effect and charge exchange with $H^0$

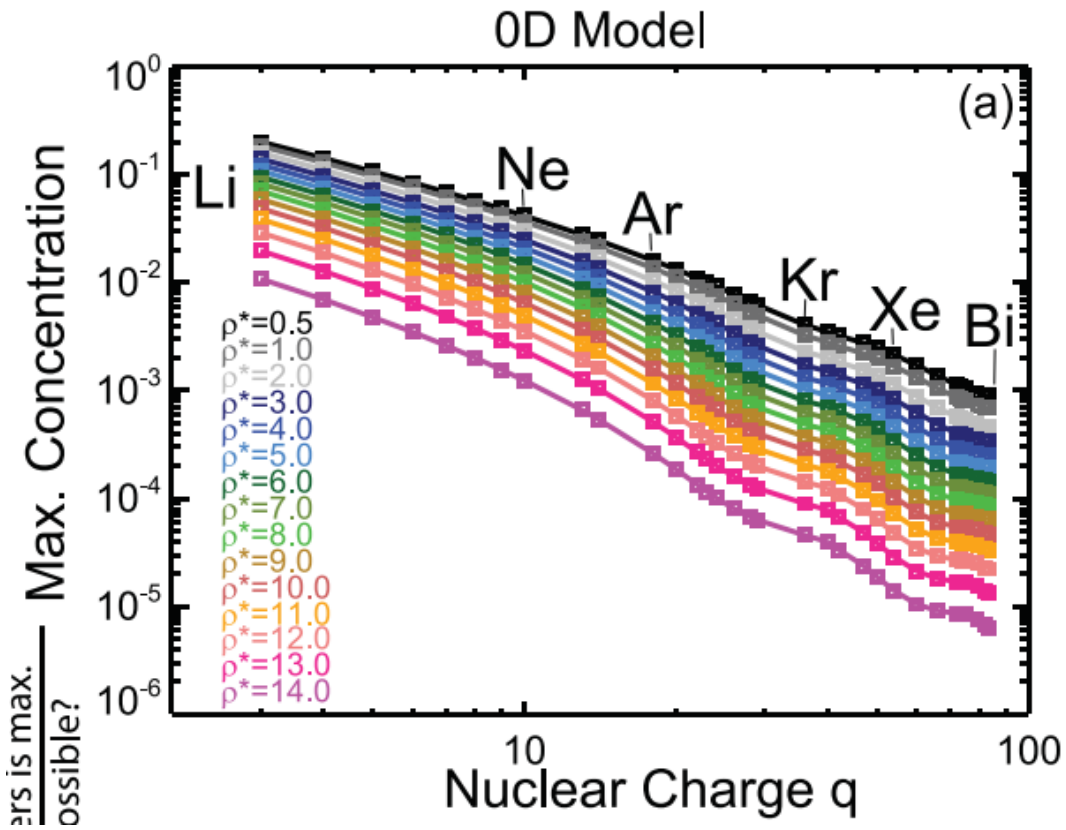
Applicability of nitrogen is questionable due to formation of Tritium containing molecules like ammonia

# Limits on core impurity concentrations

- 0D model, supported by ASTRA calculations




$$\rho^* = \tau^*_{\mathrm{He}}/\tau_E$$




[Pütterich, Nucl. Fus. **59** (2019)]

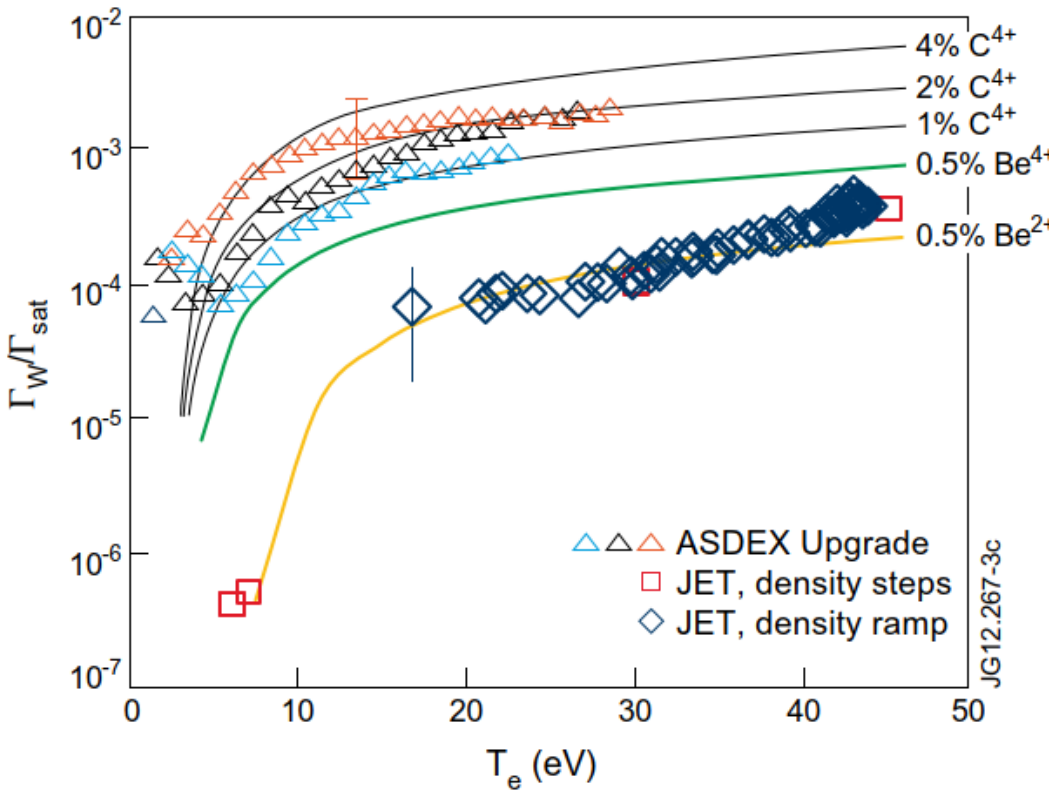
Core radiative losses are calculated quite accurately (max. error factor 1.5)

more on impurity transport: see talk bei Ralph Dux

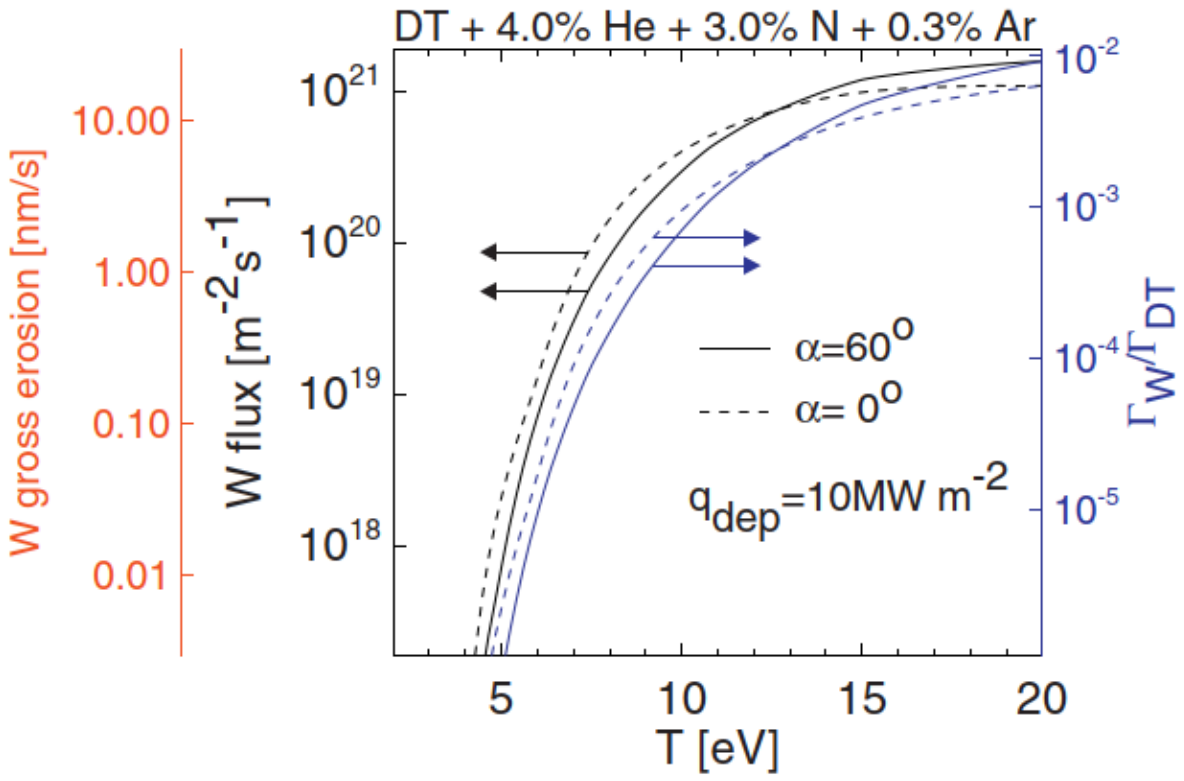
# Integration with tungsten plasma facing components

**Low plasma temperature at PFCs required** to suppress tungsten sputtering

- this is equivalent to the demand of low heat flux (at surfaces with high impinging fluxes), i.e. detachment



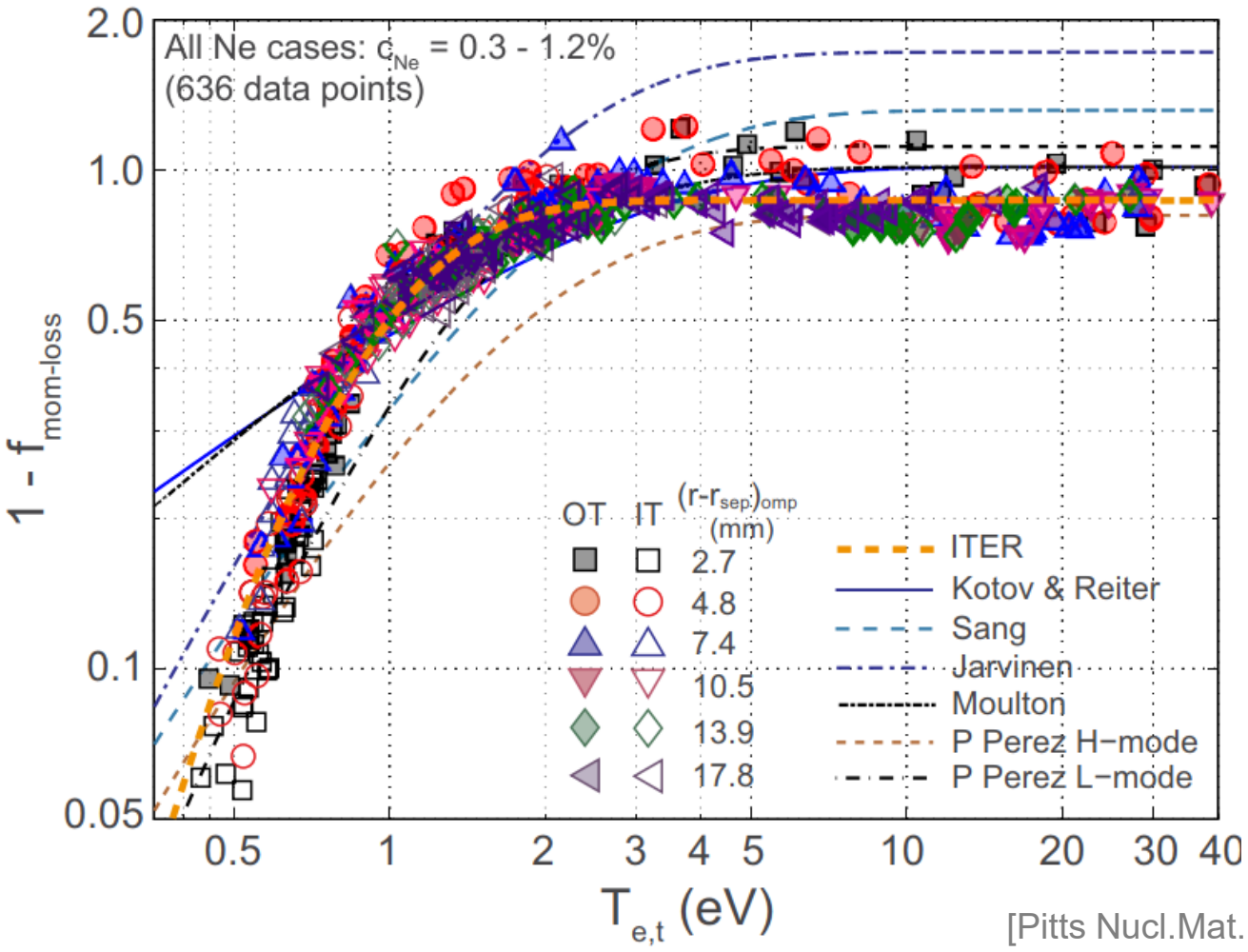

[Van Rooij, J. Nucl.Mat (2013)]




[Dux, Nucl.Mat.Energy (2017)]

# Momentum loss / pressure drop facilitated at low $T_e$ (SOLPS+exp.)

- low $T_e$ at the target facilitates **detachment** - solves both power exhaust and erosion problems



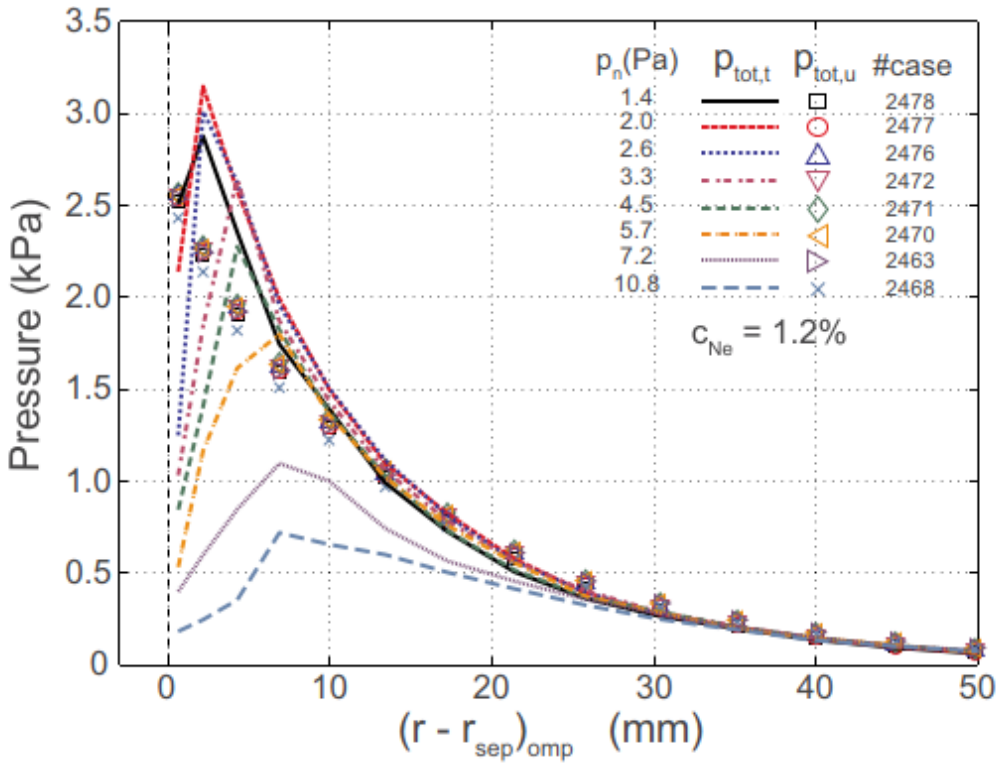

found both in experiment and modelling

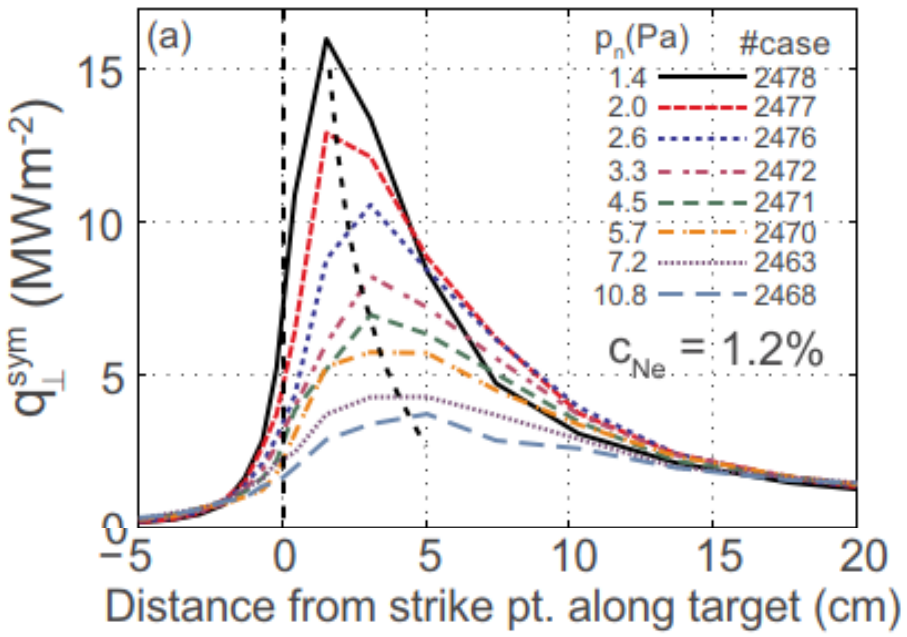
(a bit higher threshold Te in exp.)

[Pitts Nucl.Mat. Energy (2019)]

# Low divertor Te, momentum loss, peak power reduction and high $p_0$ are closely interlinked (SOLPS)

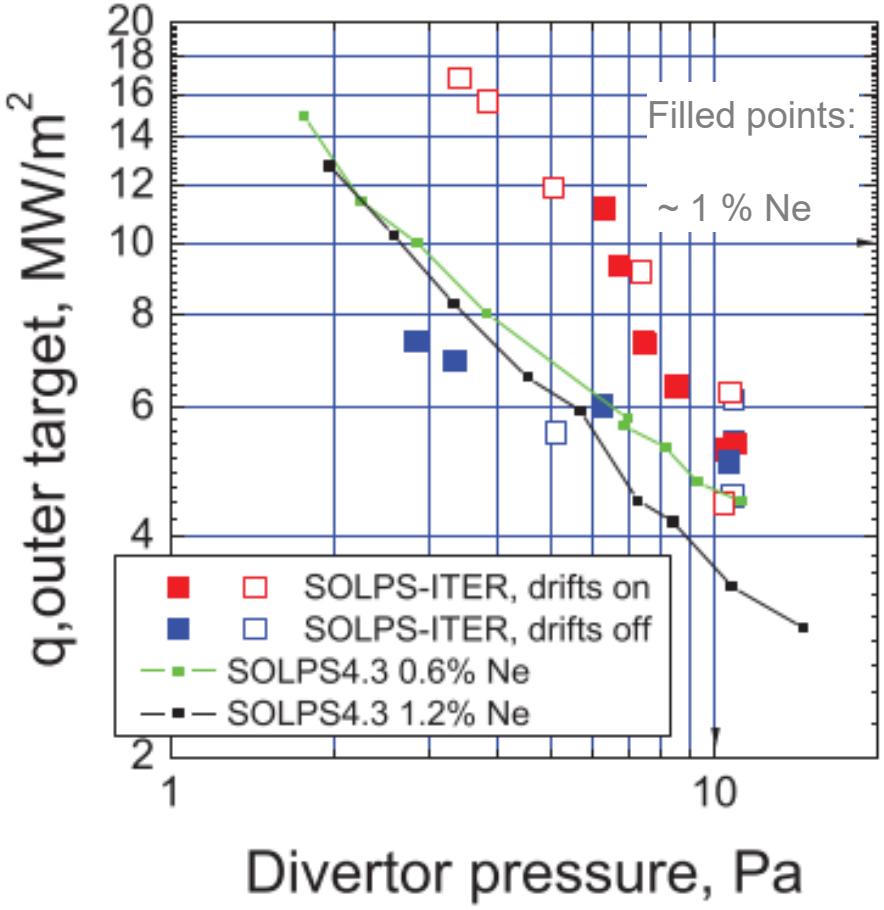
ITER, Psol = 100 MW, 1.2 % neon




[Pitts Nucl.Mat. Energy (2019)]

# ITER divertor modelling with SOLPS-ITER




[Kaveeva, Nucl. Fusion (2020)]

**General trends in line with experiments**

experiments see higher divertor compression of N, Ar vs. Ne

SOLPS-ITER similar compression for N, Ne in ITER,

higher N compression in mid-size tokamak

[Rozhansky, Nuclear Fusion (2021)]

divertor pressure $p_0$: engineering parameter

# Simple scaling for the onset of detachment

- ASDEX Upgrade experiments and simple 1d flux tube modelling

$$P_{sep}/R|_{det.point} = \frac{1}{1.3} p_0 (1 + f_z c_z) \cdot (\lambda_{int}/0.005\ \mathrm{m}) \cdot (R/1.65\ \mathrm{m})^{r_z}$$
$$\times\ [\mathrm{MW\ m^{-1}},\ \mathrm{Pa},\ \mathrm{m}]$$

| Element | Nitrogen | Neon | Argon |
|---|---|---|---|
| $f_z$ | 18 | 45 | 90 |
| $r_z$ ($L_{div} = 5$ m ) | 0.038 | 0.033 | 0.043 |
| $r_z$ ($L_{div} = 5\ \mathrm{m} \cdot R/1.65$ m ) | 0.1 | 0.19 | 0.11 |

[Kallenbach PPCF (2016)]

Prediction for detachment onset for ITER Ne seeding: $P_{sep}$= 100 MW, R=6.2 m, $\lambda_{int}$= 5 mm, $p_0$= 10 Pa: $c_{Ne}$= 1.4 %

Divertor impurity concentration $c_z$: divertor compression essential to maintain low $c_{z,core}$

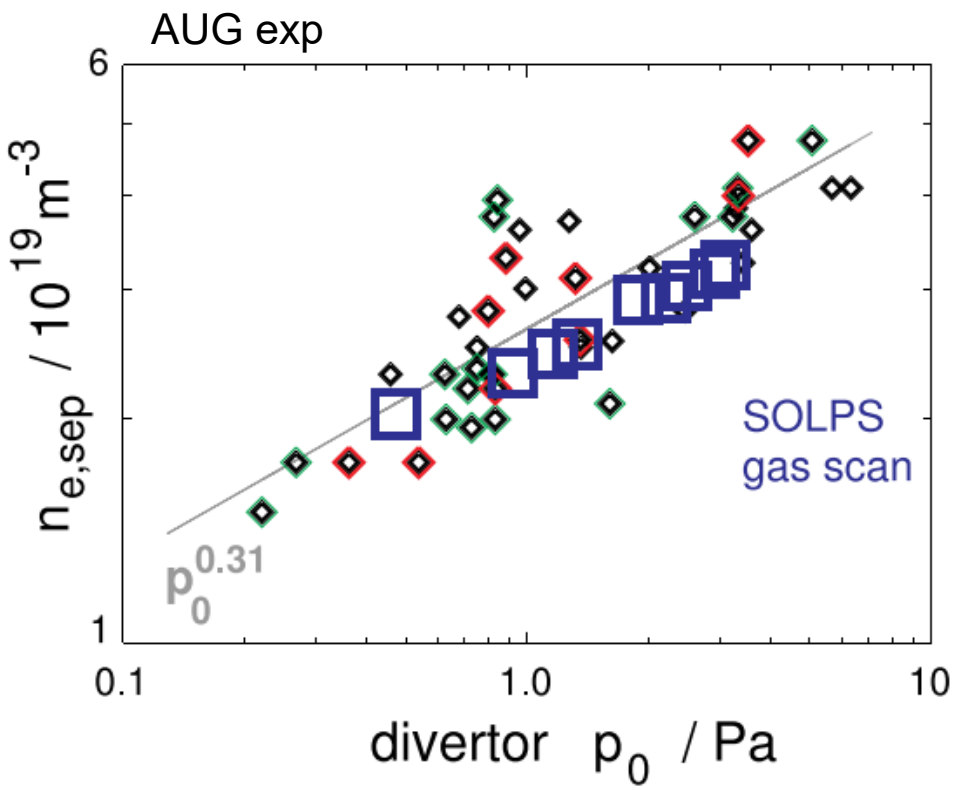
# Relation of separatrix density - neutral pressure – energy confinement

# Separatrix is important interface between core and divertor

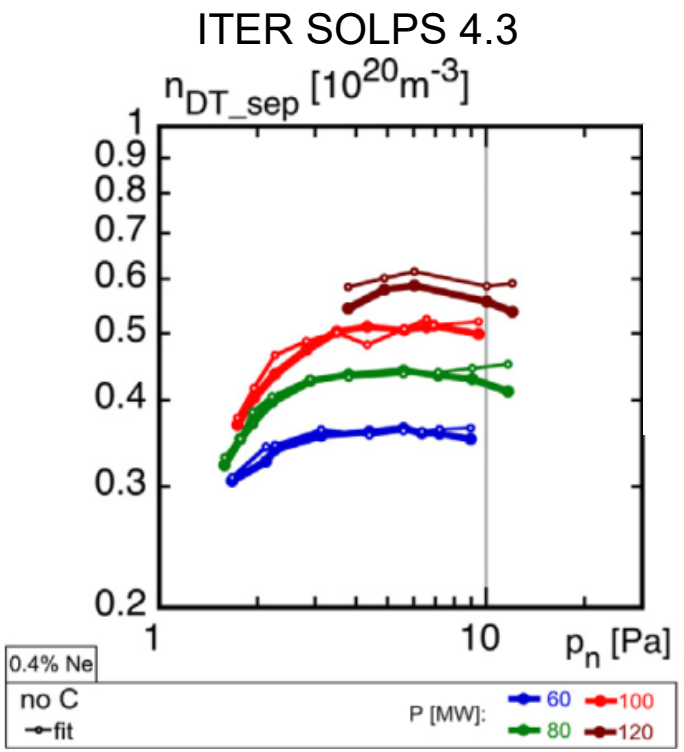
- $n_{e,sep}$ rises weakly with $p_0$
- high $n_{e,sep}$ favours power exhaust and He pumping
- low $n_{e,sep}$ favours confinement and current drive

$n_{e,sep}$ limited by H-L to ~ 0.5 $n_{GW}$, 6 $10^{19}$ $m^{-3}$ in ITER

[Eich Nucl. Fusion (2021)]



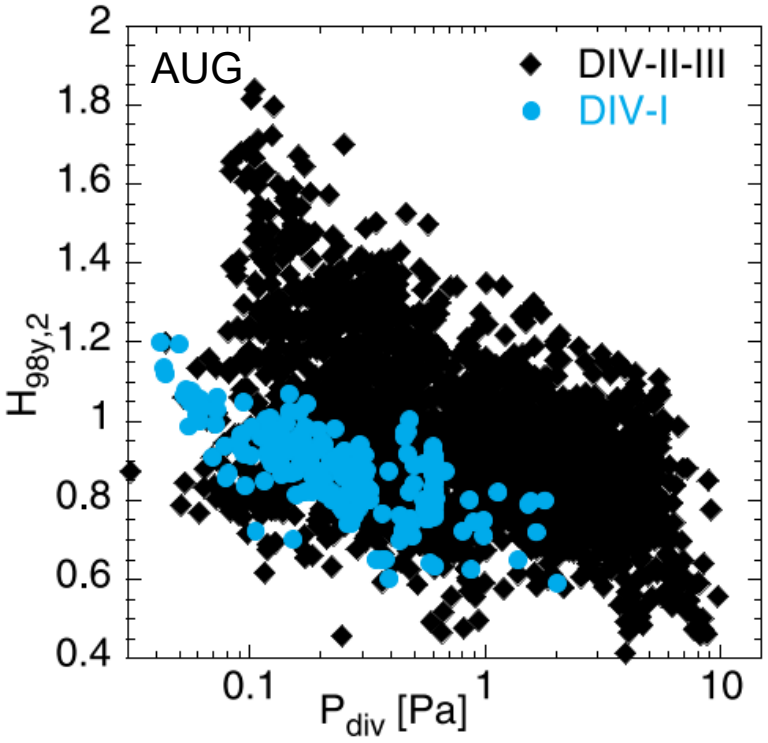

[Kallenbach, Nucl. Mat. Energy (2019)]



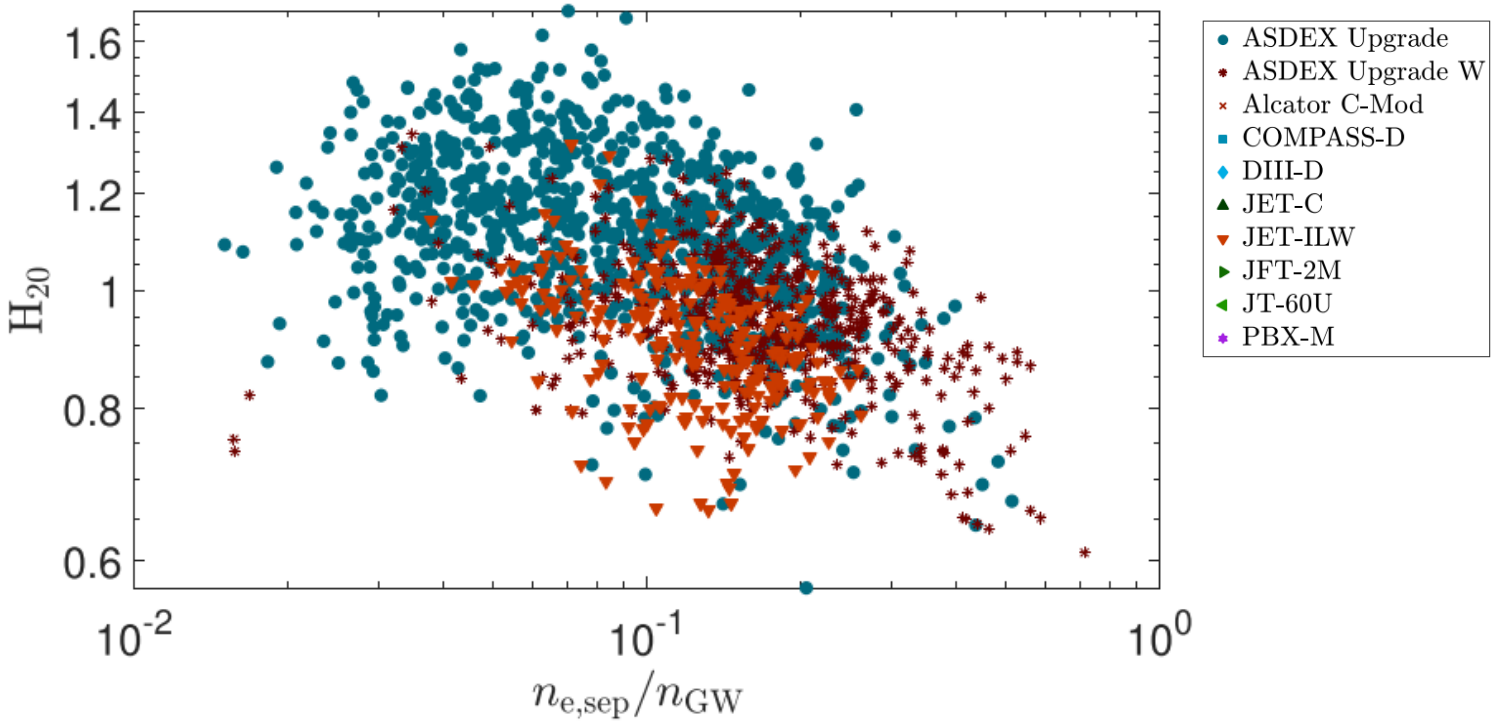

[Pacher, J. Nucl. Mat. (2015)]

# High divertor pressure related to reduced energy confinement

- density profile outward shift at high $p_{0,div}$ reduces stability and thus pedestal top pressure
- more interchange-like transport with increased collisionality parameter $\alpha_t$




Ryter Nucl. Fusion (2021)

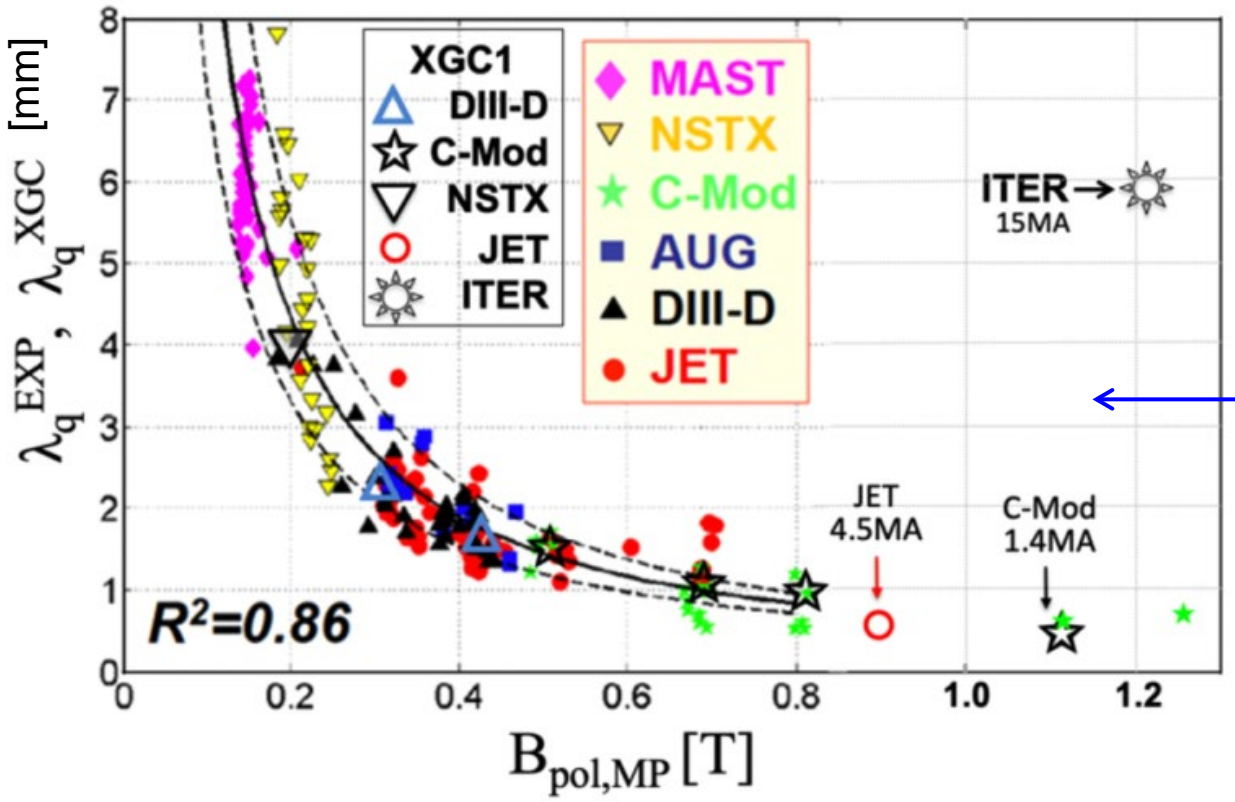



Verdoolaege Nucl. Fusion (2021)

# Open physics questions on exhaust to be solved for extrapolation

# Open question for extrapolation: power width $\lambda_q$

- experimental (Eich scaling) results follow $\lambda_q \sim 1/B_p$ - for attached conditions
- reproduced by XGC1 calculations, but much larger $\lambda_q$ predicted for ITER (6 mm instead of 1 mm due to TEM turbulence across the separatrix)



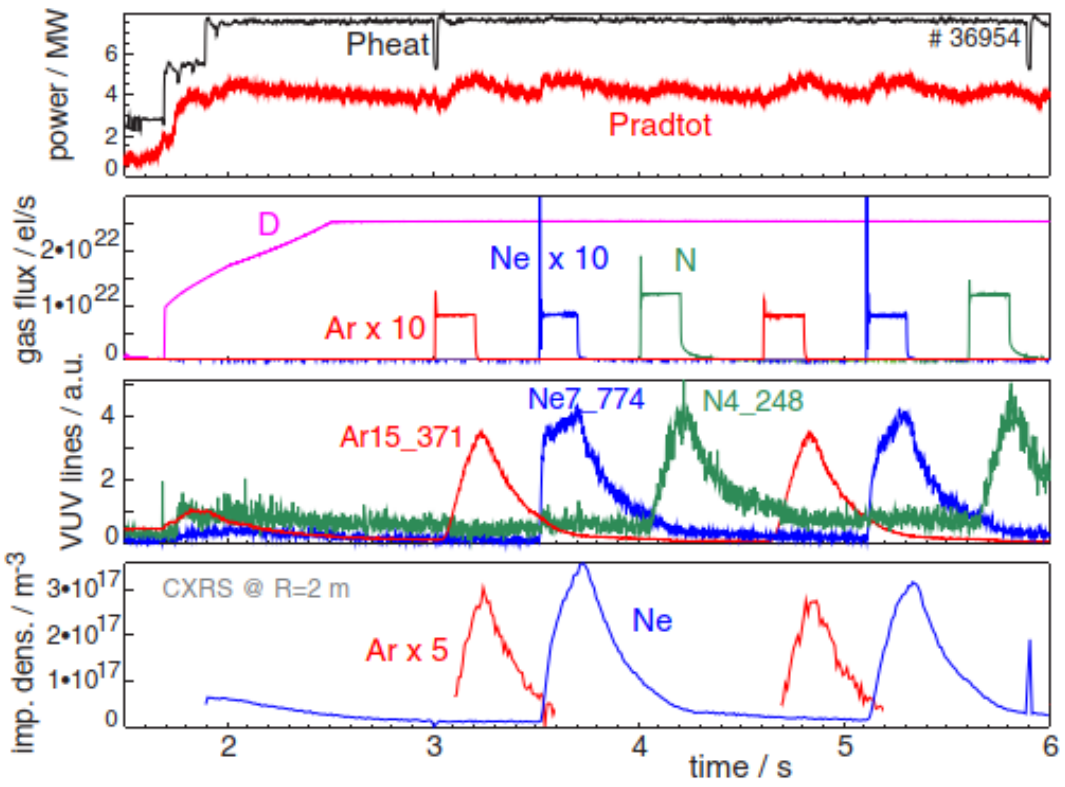

A large $\lambda_q$ allows detachment at lower $n_{e,sep}$ or $Z_{eff}$

SOLPS modelling for ITER detachment uses $\lambda_q \cong 3.4$ mm

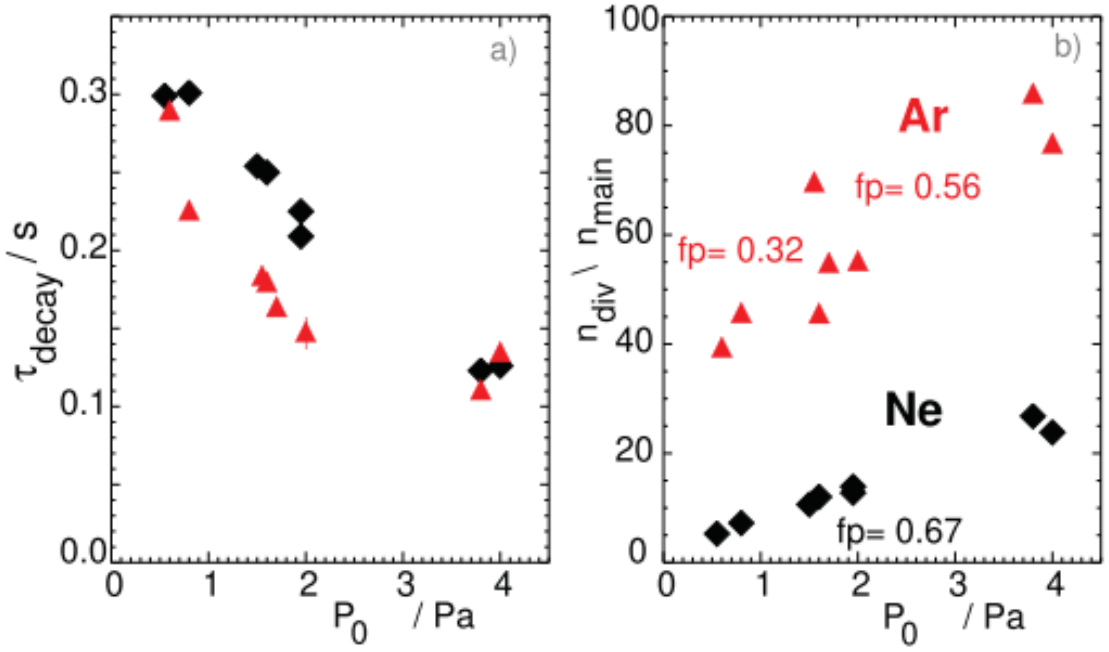
C.S Chang, Phys. Plasmas (2021)

# Divertor impurity compression measured in ASDEX Upgrade

- Important for getting high divertor radiation and low core fuel dilution
- dynamic response to impurity puffs allows the determination of divertor compression




**Divertor compression**




[Kallenbach, Nucl. Fusion (2021)]

Ar, N show much higher divertor compression compared to Ne – translates into higher divertor radiation at given dilution

this effect is not observed in SOLPS modelling for ITER parameters. Impurity pedestal transport: see talk by Ralph Dux

# Integration with no-ELM scenario mandatory for sufficient divertor lifetime

# Different no-ELM scenarios under investigation

| | | | |
|---|---|---|---|
| EDA H-mode | low $n_{e,sep}$ | compatible with detachment | H98 > 1 |
| QCE H-mode | high $n_{e,sep}$ | compatible with detachment | H98 $\leq$ 1 |
| X-point radiator | high $n_{e,sep}$ | full detachment | H98 < 1 |
| RMP ELM-suppression | very low $n_{e,sep}$ | no detachment (in AUG) | H98 $\sim$ 1 |
| | | | |
| QH-mode | very low $n_{e,sep}$ | no detachment (in AUG) not stable (in AUG) | |
| I-mode | low $n_{e,sep}$ | inner div. detached, outer not (in AUG) | H98 < 1 |
| Neg. triangularity | | parameter space restricted in AUG | |

Need to be integrated with burn condition and exhaust

Not possible in small devices (no low ped and high sep. collisionality simultaneously)

→ first principle theory required (developing well, but slowly)

# Scenario integration: no-ELM regime is the largest challenge

## Toolbox for an integrated no/small-ELM scenario

Outer core radiative cooling to reduce Psep


Mechanism for reduction of pedestal pressure (gradient, current, ..)

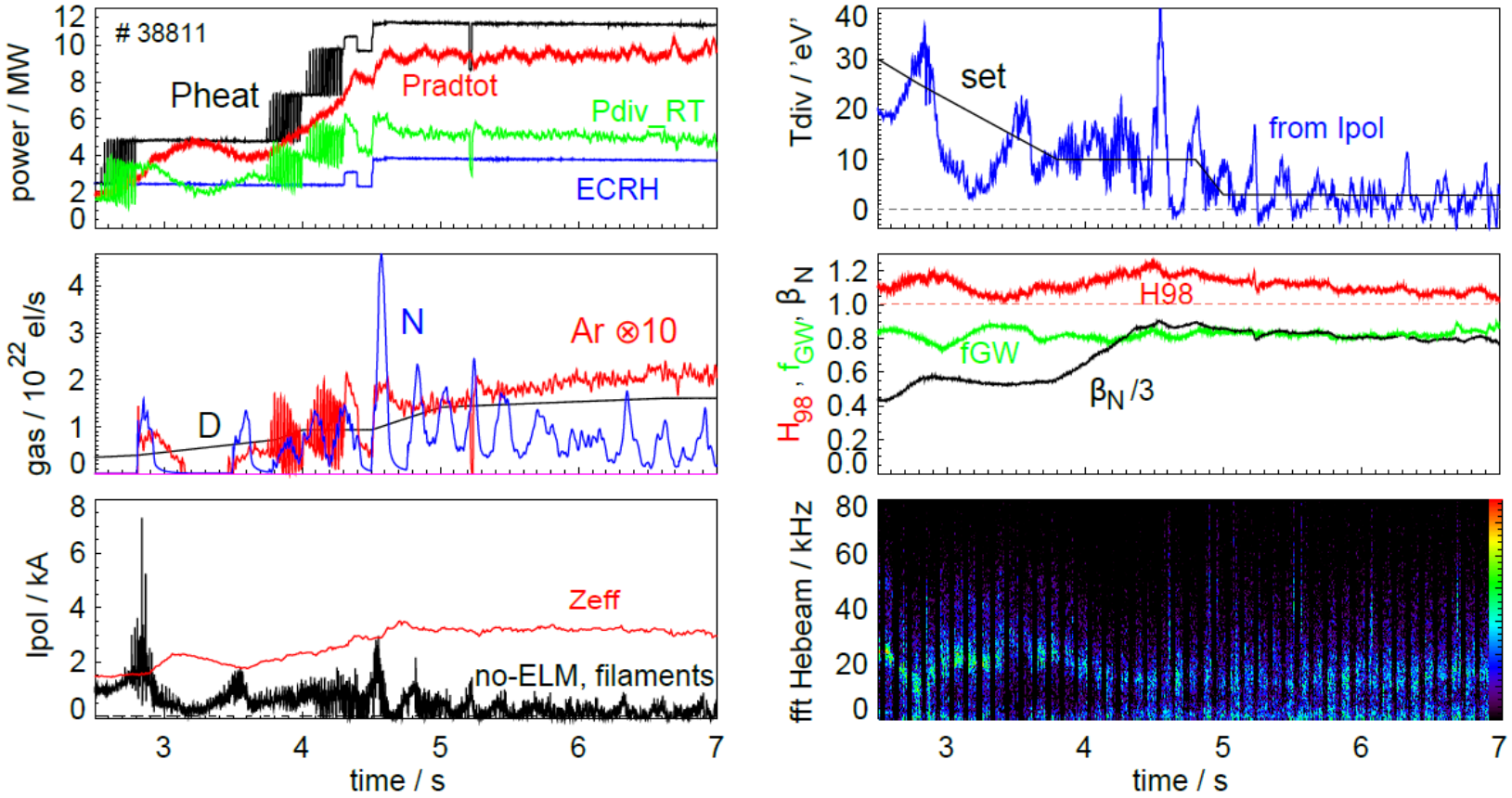


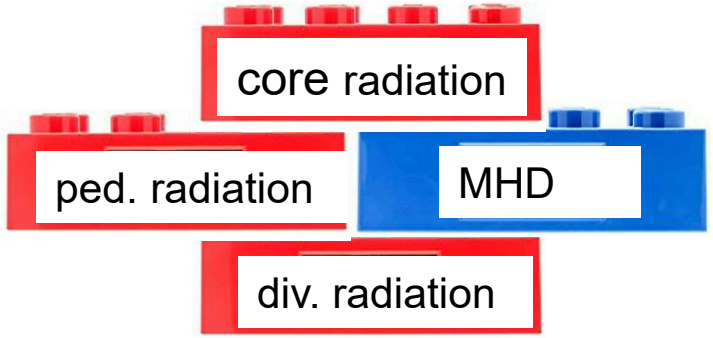


Divertor radiation to achieve detachment

# ASDEX Upgrade integrated EDA scenario (exhaust)

- Argon to maintain quasi-coherent mode and no-ELM state
- Nitrogen for divertor partial detachment




$H_{98}$= 1.05

$\beta_N$= 2.4

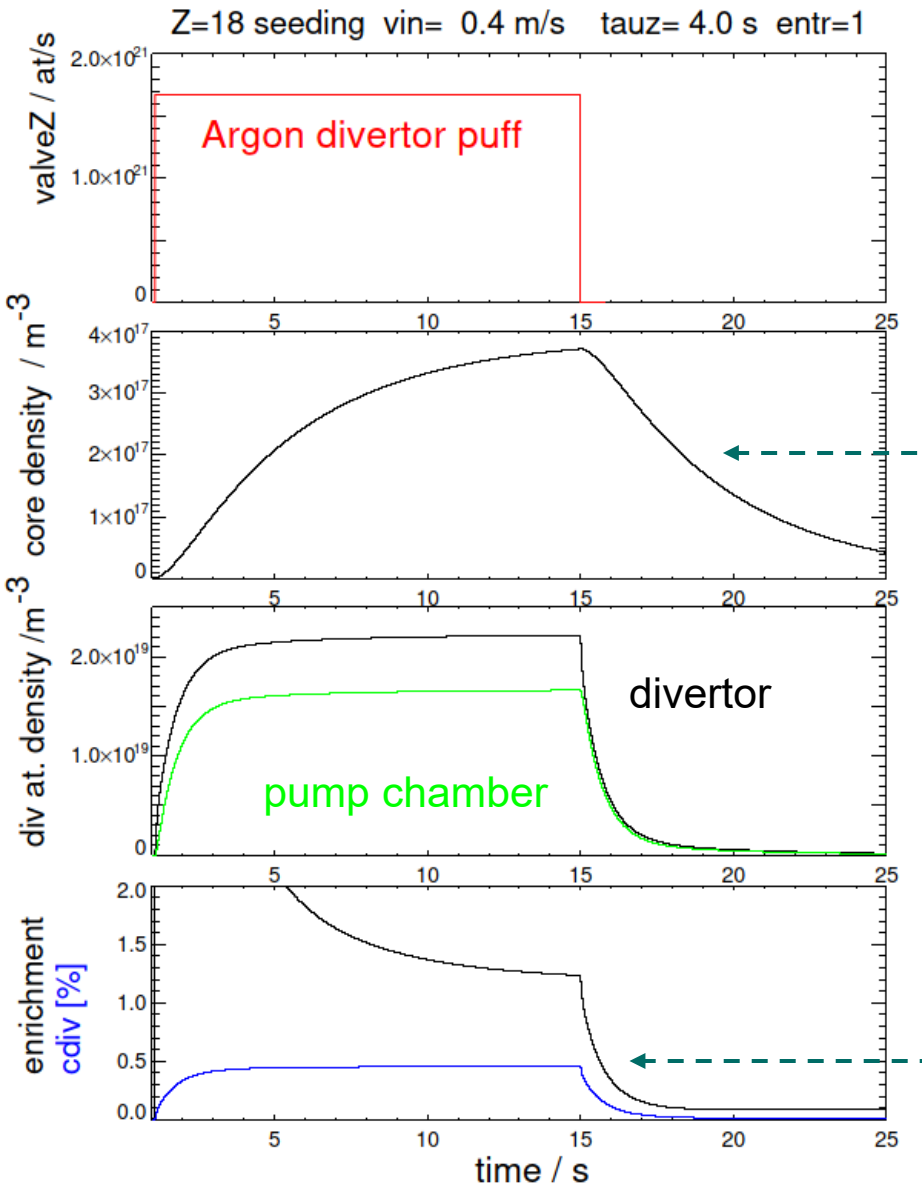
$q_{95}$= 5.8

[Kallenbach, Proc. IAEA FEC (2021)]

# Pumping and divertor radiation time scales

DEMO has similar pumping speed, but much larger volume and residence times compared to present day devices

# Long time scales for radiation variation with gas seeding in DEMO




- Simple impurity particle balance model predicts time scale O(sec.)
- Issue regarding treatment of transient re-attachment

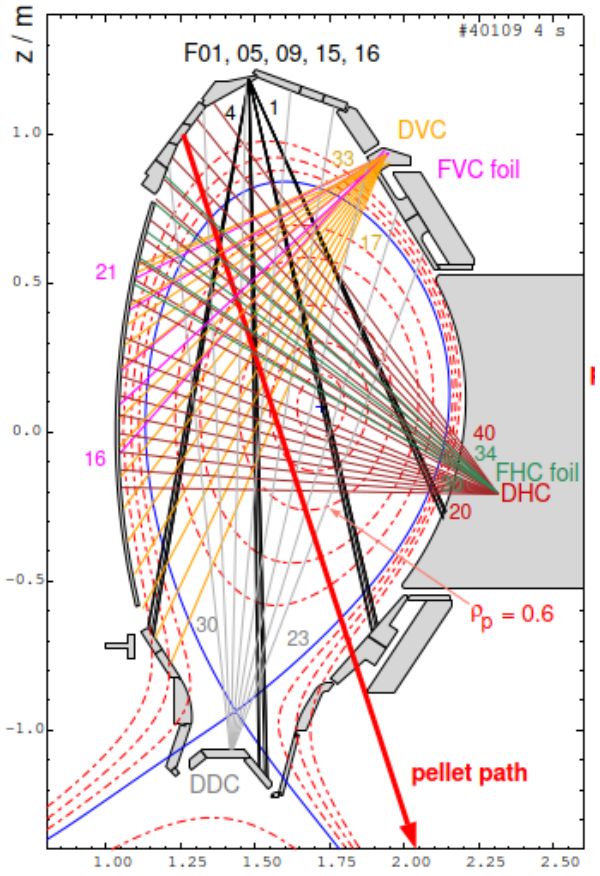
long timescale for main plasma (transport)

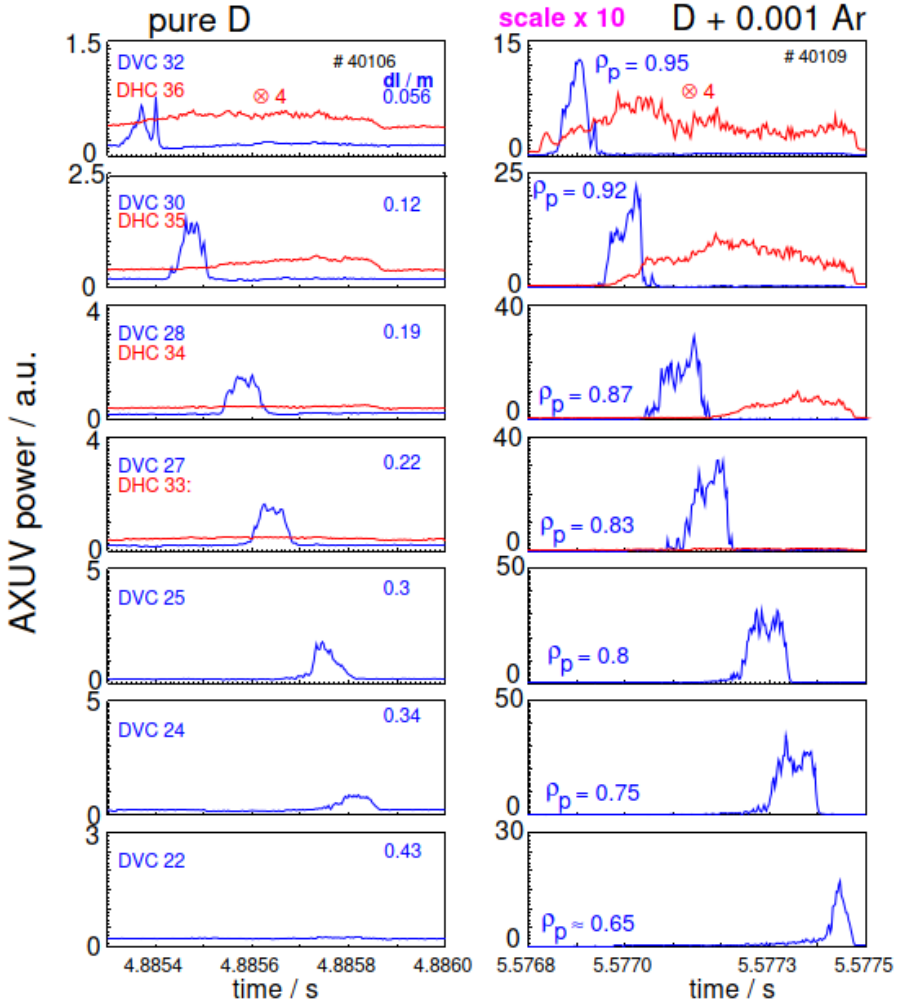
D+T pressure = 10 Pa, $n_{DT}$= 5 $10^{21}$ $m^{-3}$ , 300 K

$S_{pump}$= 100 $m^3$/s, $S_{div\text{-}pumpchamber}$= 300 $m^3$/s

Faster divertor removal timescale determined by pumping speed

# Alternative to gas puff seeding: fuelling with impurity doped pellets



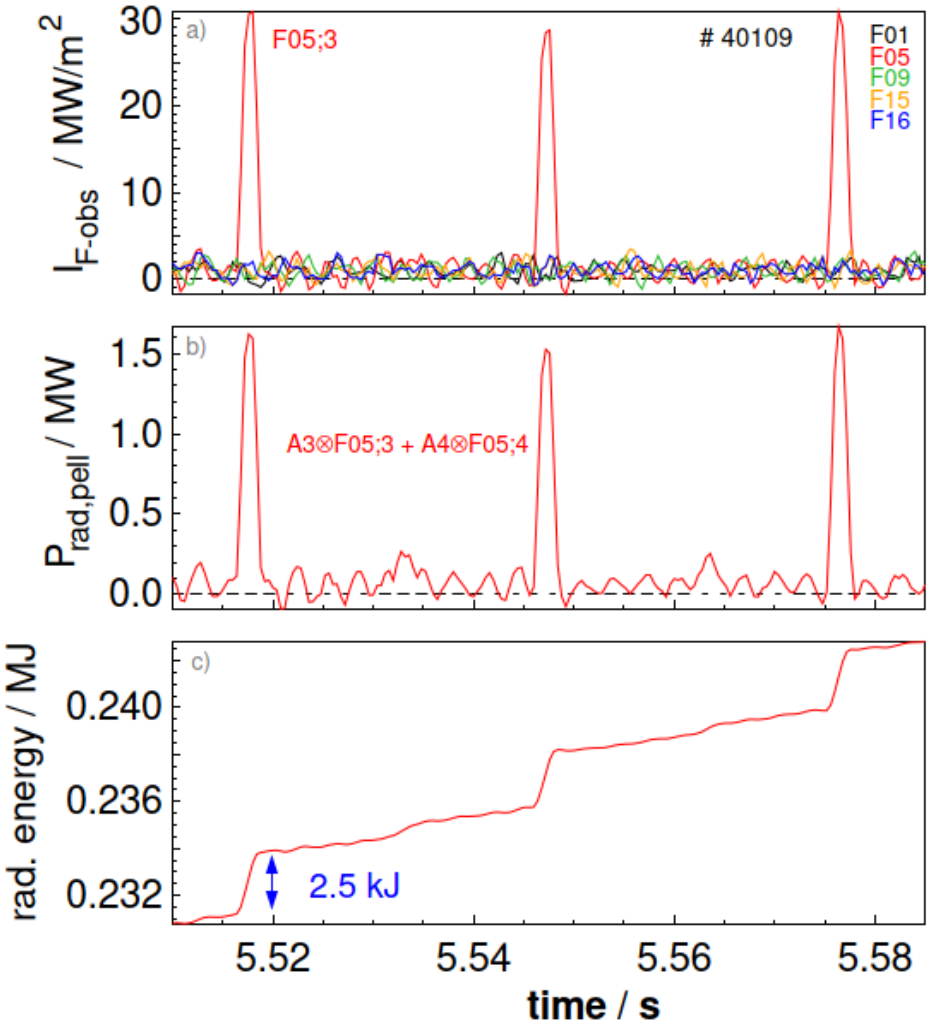



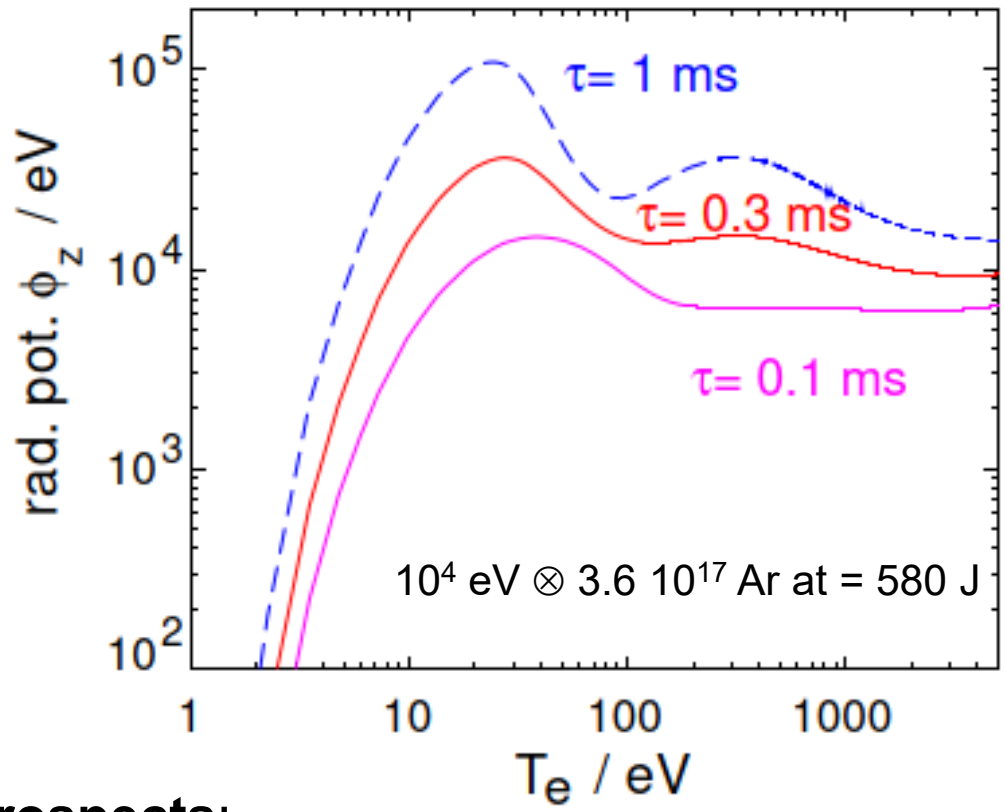

High, toroidally localized radiation

.. more on pellets see in talk by Peter Lang tomorrow

[Kallenbach Nucl. Fusion (2022)]

# Ar radiation enhanced compared to gas puff by factor 4




**Prospects**:

faster radiation rise / reaction to attachment

more radiation per dilution ? - depends on $\tau_{z,depos}$

many injectors required.

# Take-home messages

- Impurity seeding required for core/pedestal and divertor radiative cooling
- (Partial) detachment and low T required in the divertor (power handling, tungsten erosion)
- Integration with no-ELM conditions requires special pedestal control
- A high neutral divertor pressure supports detachment and He exhaust
  (but may reduce, via a high $n_{e,sep}$, energy confinement and current drive)
- Current experiments cannot combine low pedestal and high sep. collisionality

→ **validated first-principle codes required for extrapolation**

In case $n_{e,sep}$ required for exhaust is too high, alternative divertor concepts have to be implemented