Exhaust scenarios

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Acknowledgements:

Members of ITER Organization (especially R. Pitts) and many experts in the international fusion community

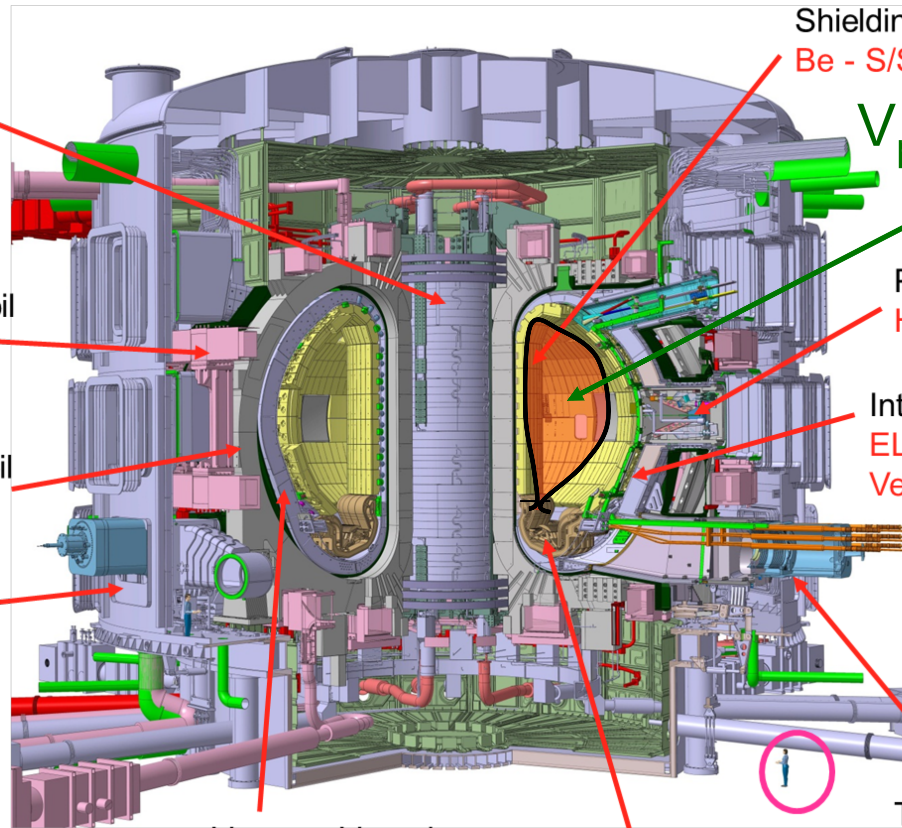
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

Outline

- Basic concepts of power and particle exhaust in ITER and DEMO reactors
- Power exhaust
- Helium exhaust
- Extrinsic and intrinsic impurity control

ITER - Main Features

I_p = 15 MA



B_t = 5.3 T

NBI (1 MeV)	ECH (170 GHz)	ICH (40-55 MHz)	LH (5 GHz)	Total
33 MW (+16.5 MW)	20 MW (20 MW)	20 MW (20 MW)	0 MW (20 MW)	73 MW (130 MW-110 MW simultaneous)

ITER – Power exhaust - Introduction

- ITER is a tokamak designed to confine a DT plasma in which α-particle heating dominates all other forms of plasma heating ⇒ an experimental nuclear fusion reactor

✓ Designed to achieve P_{fusion} = 500 MW with gain Q ≥ 10 for 300-500 s

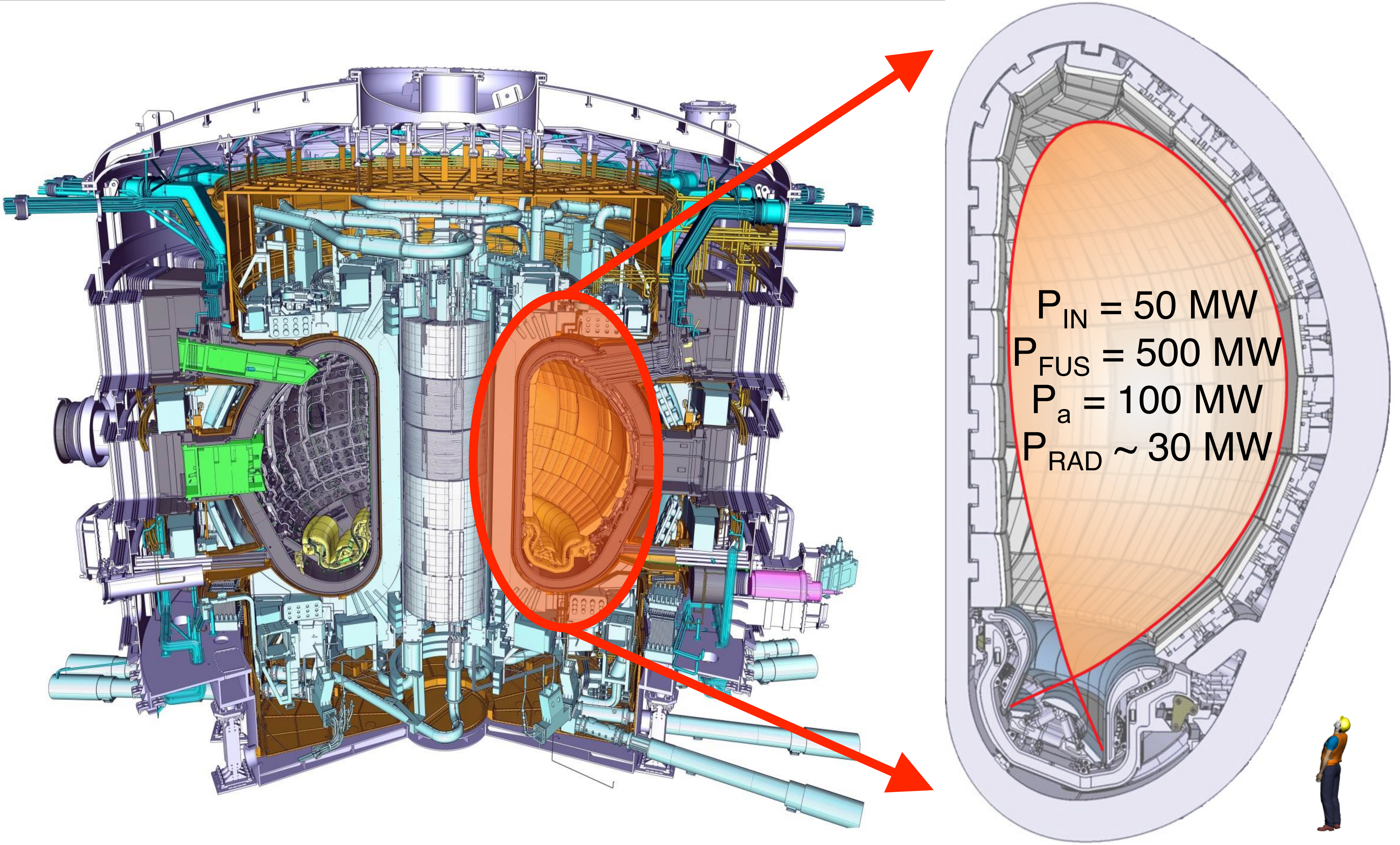
$D + T \rightarrow \alpha + n$ $\quad Q = P_{fusion}/P_{add} \rightarrow P_{\alpha}/P_{add} = Q/5$

P_{add} ~ 50 MW → direct heating of e+i → charged particles in B

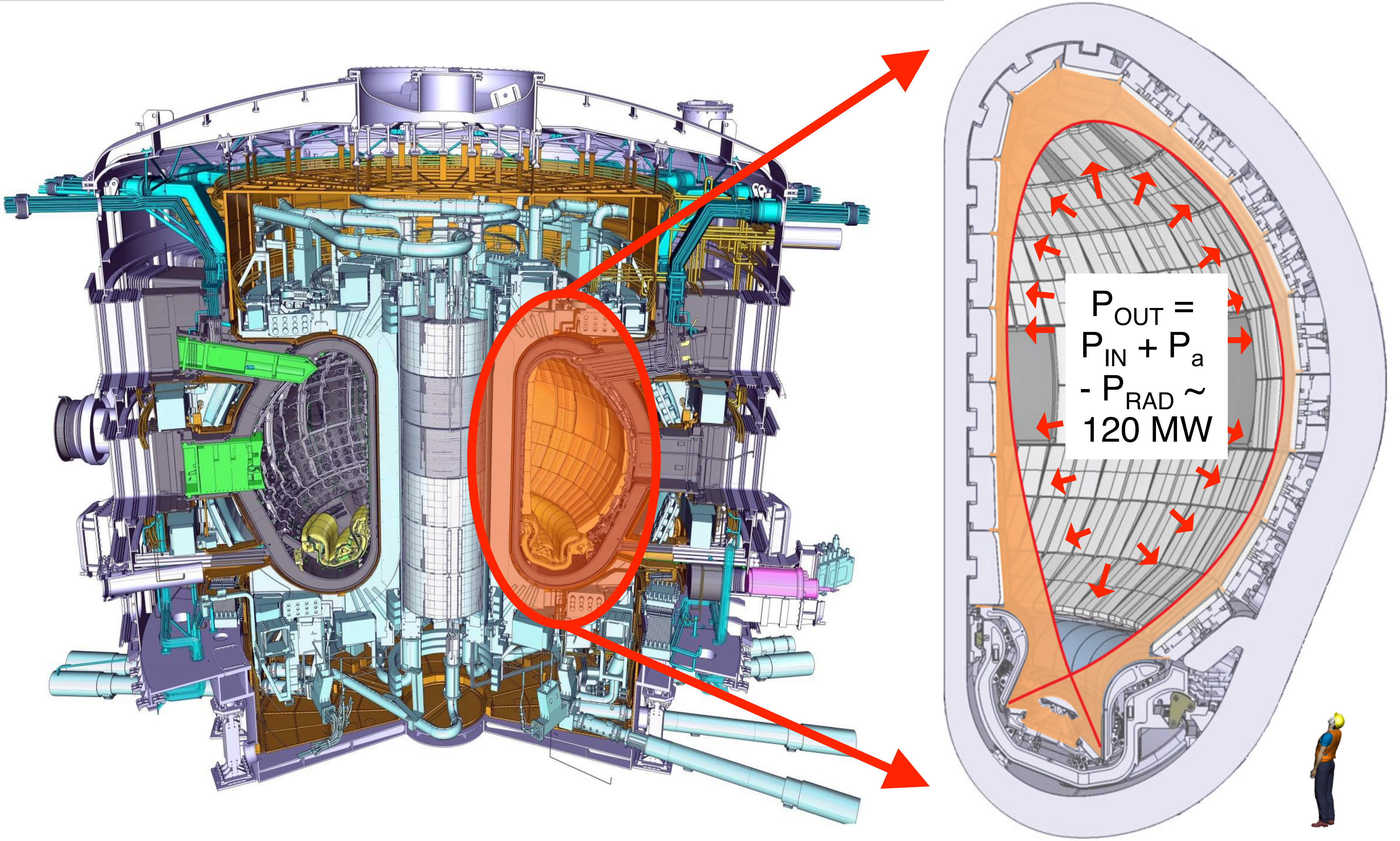
P_{α} ~ 100 MW → α slowing down → heating of e+i → charged particles in B

P_n ~ 400 MW → 14 MeV neutral particles (not affected by B) → well spread over tokamak inner components in space & depth

ITER – Power exhaust – Some details - I



ITER – Power exhaust – Some details - II



Power lost in charged particles concentrates in small areas (~0.1% of A_{wall})

ITER – He exhaust - I

$$ {}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He\ (3.5\ MeV) + {}^{1}_{0}n\ (14.1\ MeV) $$

He is the product of fusion reactor & provides the energy to sustain the process

In steady-state

$$ P_{\alpha} \sim n_{DT}^{2} <\sigma v>_{DT} \sim (n_{DT}\ T_{plasma})^{2}\ + P_{add} = P_{radiation} + E_{plasma}/\tau_{E}\ \text{(convection/conduction)} $$

$$ n_{e} = 2n_{DT} + 2\ n_{He}\ ,\quad f_{\alpha} = n_{He}/n_{e} \rightarrow n_{DT} = n_{e}\ (1/2\text{-}f_{\alpha}) $$

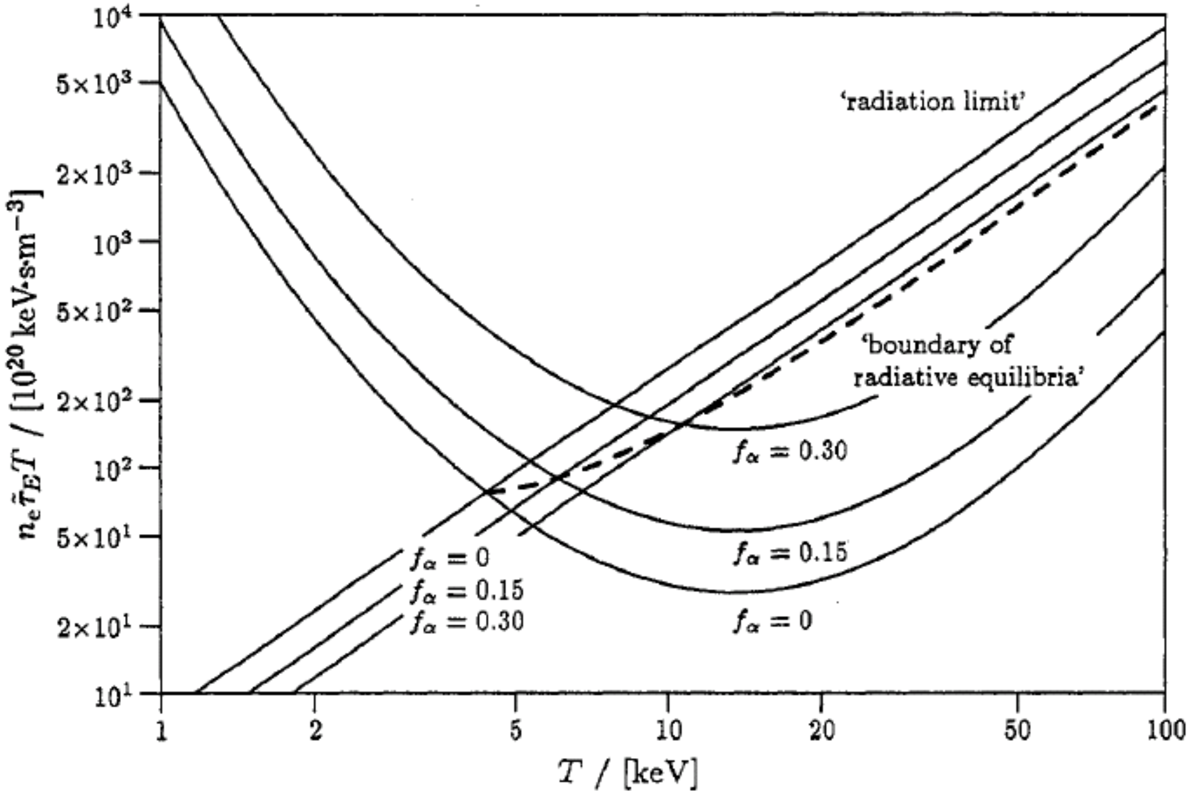
$$ E_{plasma} = 3/2\ nT\ V \sim (n_{e} + 2n_{DT} + n_{He})\ T \sim n_{e}\ (2 - f_{\alpha})T $$

$$ P_{radiation}\ (He) \sim P_{bremsstrahlung} \sim n_{e}^{2}\ (1+2f_{\alpha})\ T^{1/2} $$

$$ C_{1}\ n_{e}^{2}(1/2\text{-}f_{\alpha})^{2}\ T^{2} \sim C_{2}\ n_{e}^{2}\ (1+2f_{\alpha})\ T^{1/2} + C_{3}\ n_{e}\ (2 - f_{\alpha})T/\tau_{E}\ (P_{add} << P_{\alpha}) $$

ITER – He exhaust - II

Low f_α → ignition at lower $n_e T\tau_E$



Tokamak power plant → P_e = 1 GW → P_α = 750 MW → 1.3 10^{21} He s^{-1}

ITER P_α = 100 MW 1.7 10^{20} He s^{-1}

He must be exhausted from plasma in order to keep $f_\alpha < 0.1$

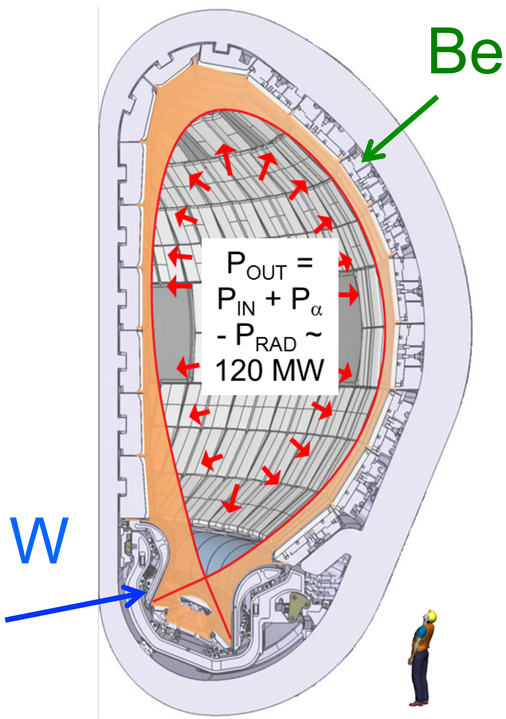
ITER – Impurity Control - I

Typical "natural" particle outflux of confined plasma in ITER

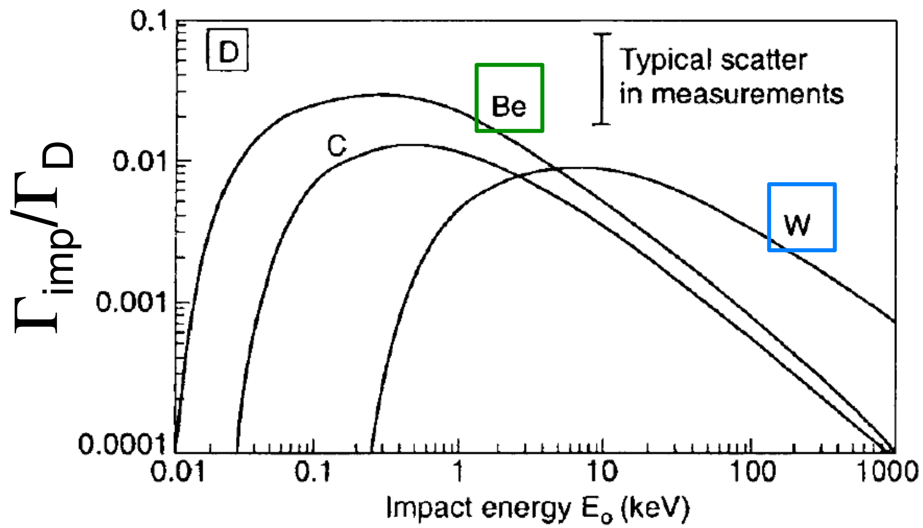
$\langle n \rangle \sim 1\ 10^{20}\ m^{-3}$, $V_{plasma} \sim 1000\ m^3$, $\tau_p \sim 5\ s \rightarrow \Gamma_{plasma} \sim 2\ 10^{22}\ s^{-1}$

$P_{plasma} = 120\ MW \rightarrow P_{plasma}/\Gamma_{plasma} \sim 37.5\ keV$

Typical $T_{edge} \sim$ 200-300 eV → Mostly conductive losses



Impact of energetic D/T ions on the divertor/wall of the reactor cause erosion and plasma contamination



ITER – Impurity Control - II

Control of divertor wall erosion and plasma contamination are essential in a fusion reactor

$$P_\alpha \sim \tfrac{1}{4} (n_{D+T})^2\, T_{DT}^2$$

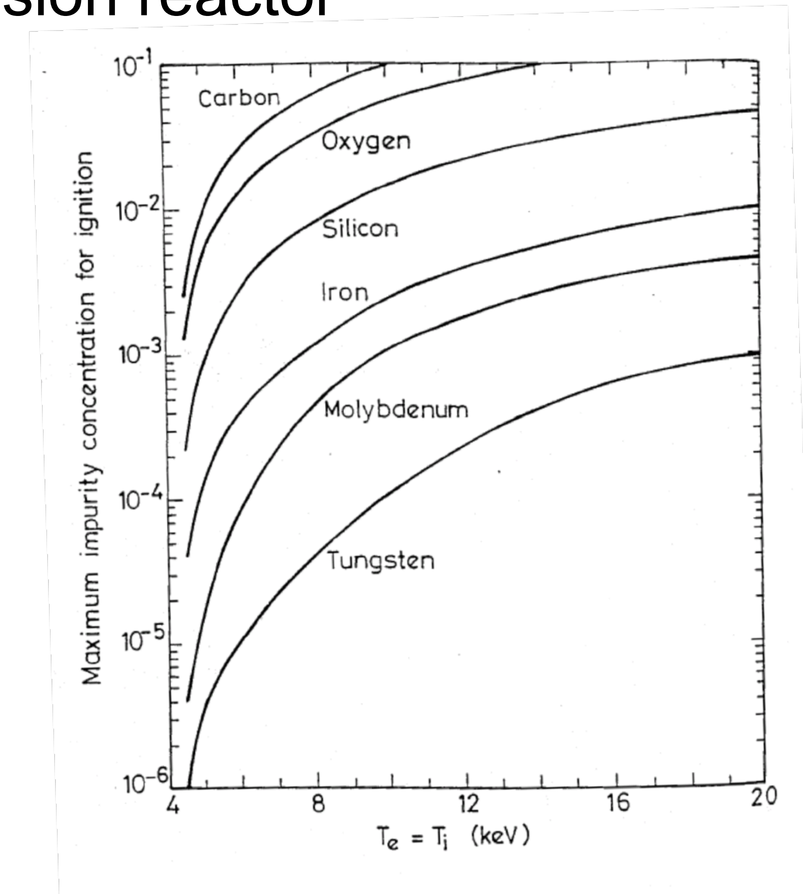
$$n_{D+T} \leq n_{e,max} - Z n_Z$$

$$P_\alpha + P_{add} = P_{radiation} + E_{plasma}/\tau_E$$

$$P_{radiation} = P_{line} + P_{bremsstrahlung}$$

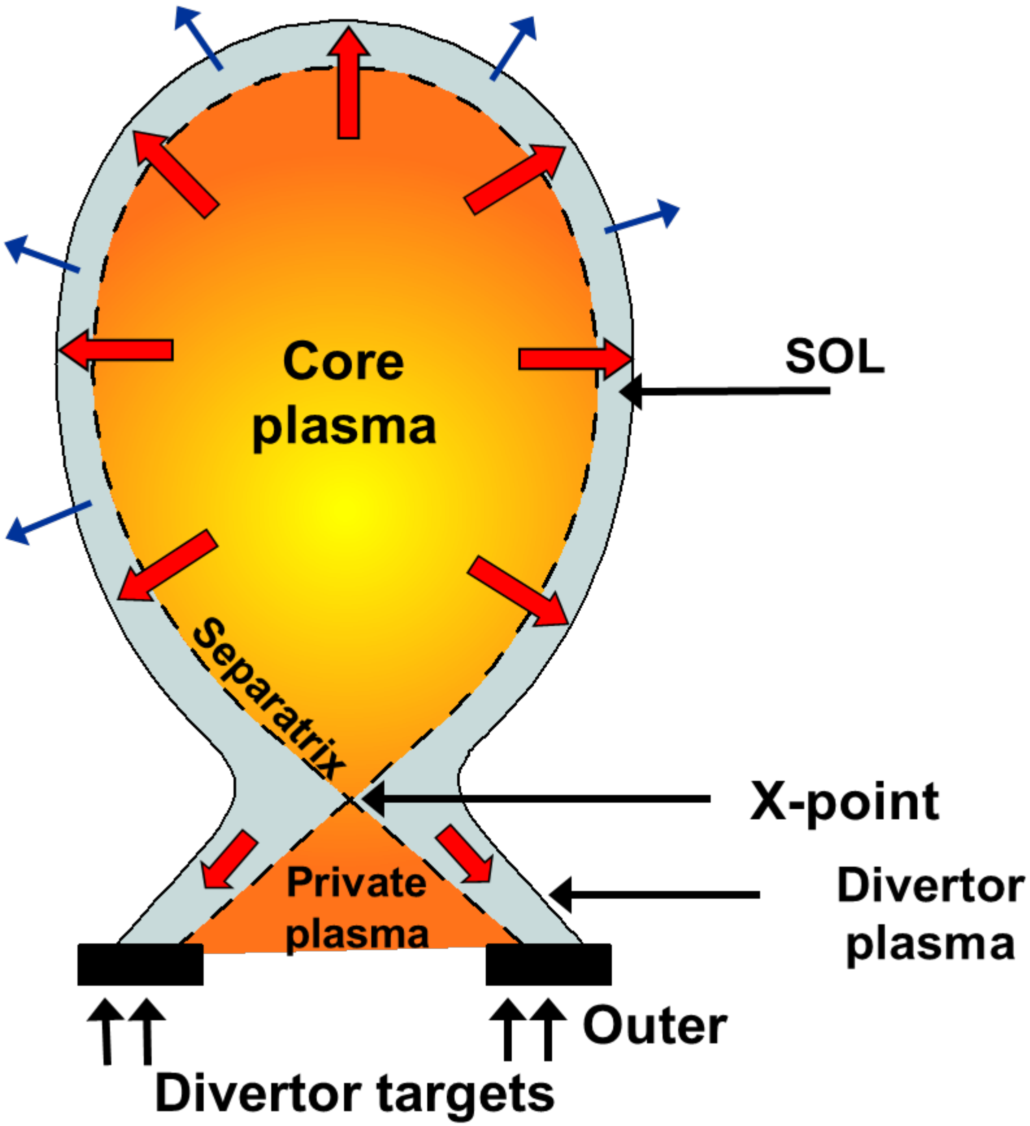
P_{line} & P_{brems} increase with n_Z & Z

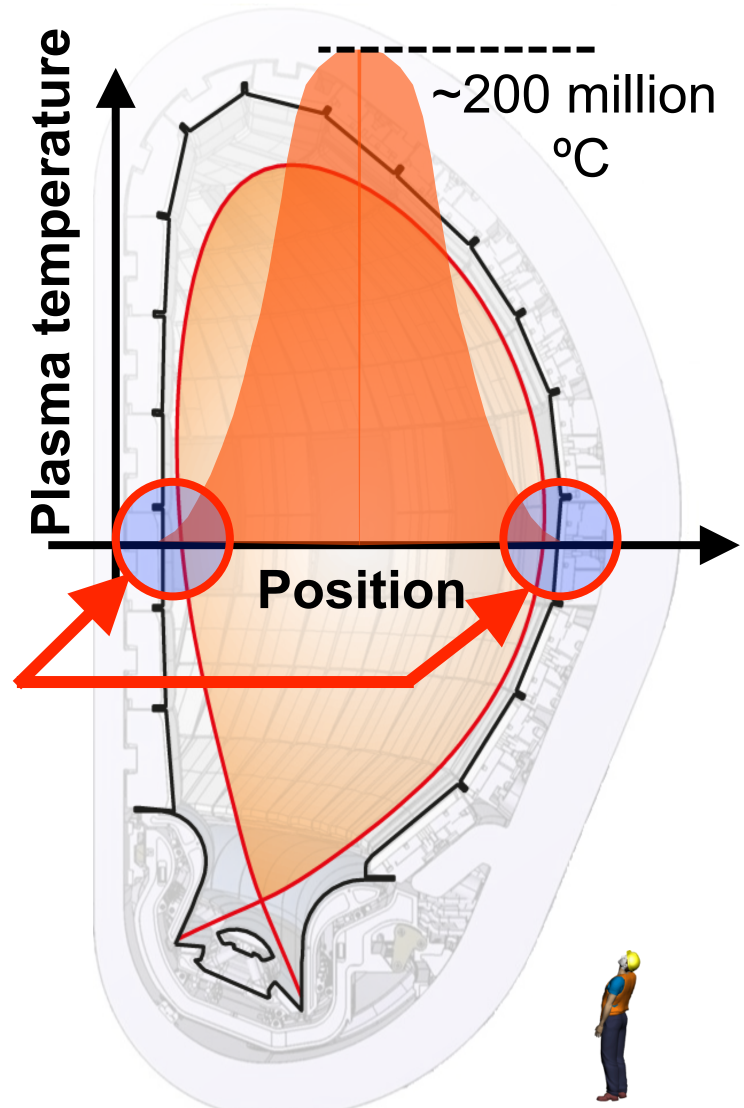
Plasma contamination and radiative losses by impurities in the confined plasma can decrease fusion power production a lot ☹ !!



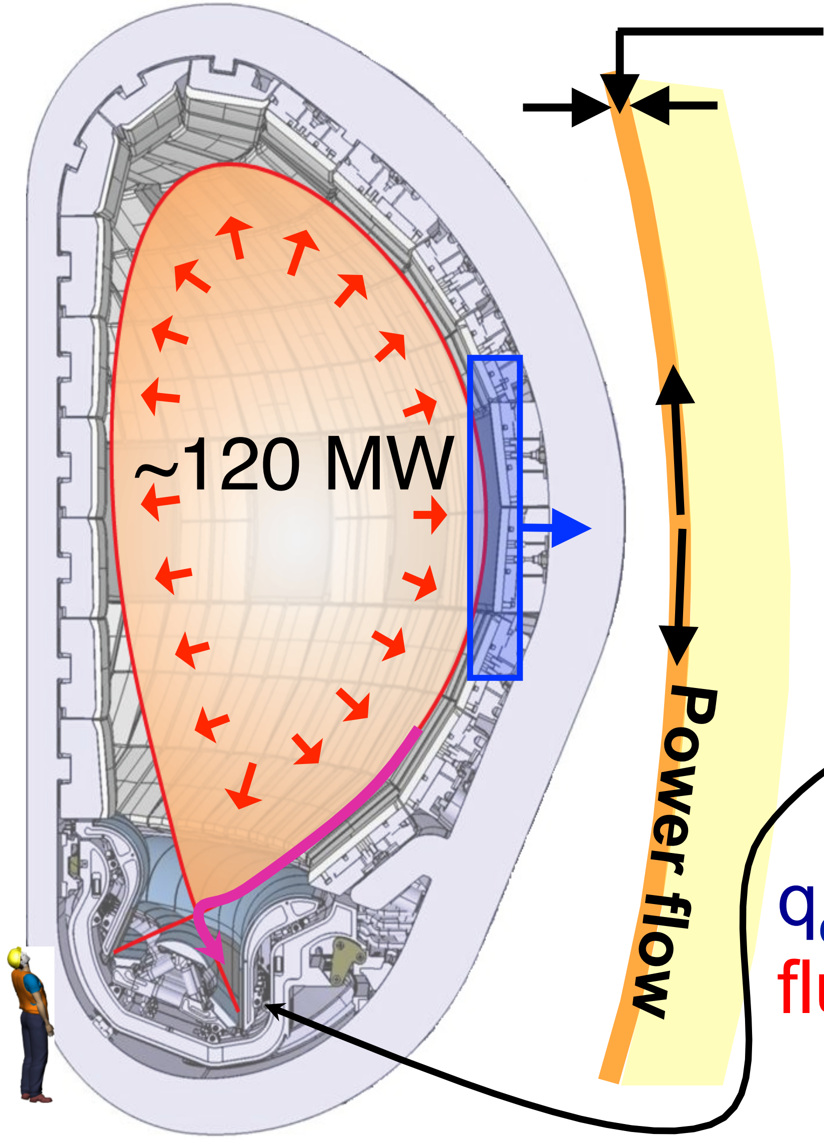
Low Z → higher n_Z allowed but larger Γ_{DT} by sputtering

ITER – Power Exhaust – The problem – I



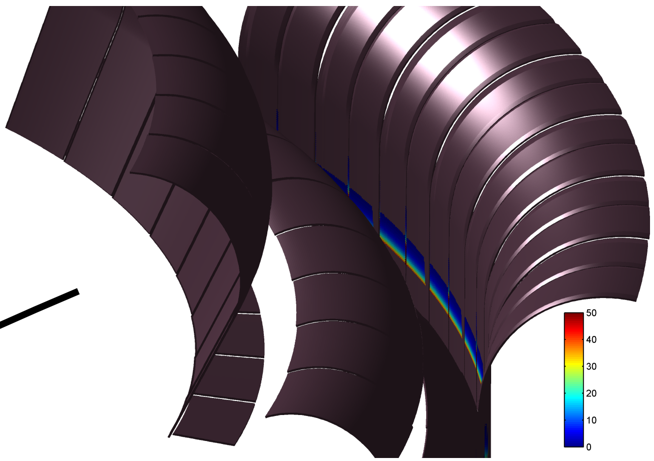


ITER – Power Exhaust – The problem – II



We expect the "thickness" (λ_q) for SOL power flow will be only a **few mm** on ITER

$A_{effective}$ ~ 1-2 m^2



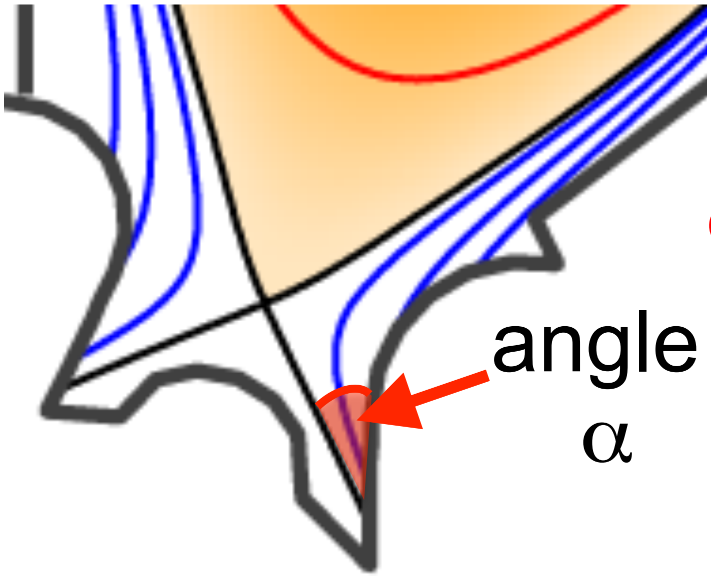
q_{div} ~ 50 MWm^{-2} → similar to heat flux on sun's surface (60 MWm^{-2})

What can we do about it ?

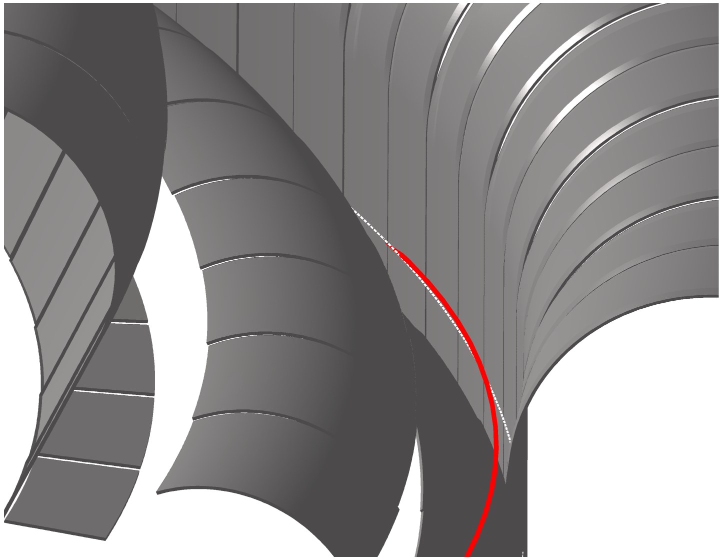
ITER – Power Exhaust – The solution - I

Three ingredients (engineering + plasma physics)

- Develop plasma facing components to cope with very large power fluxes → 10-20 MWm^{-2} achieved
- Use geometry and plasma physics to our advantage (heat flux flows II B) within engineering limits (α ~ 3°)



$q_{PFC} = q_{II} \sin \alpha$

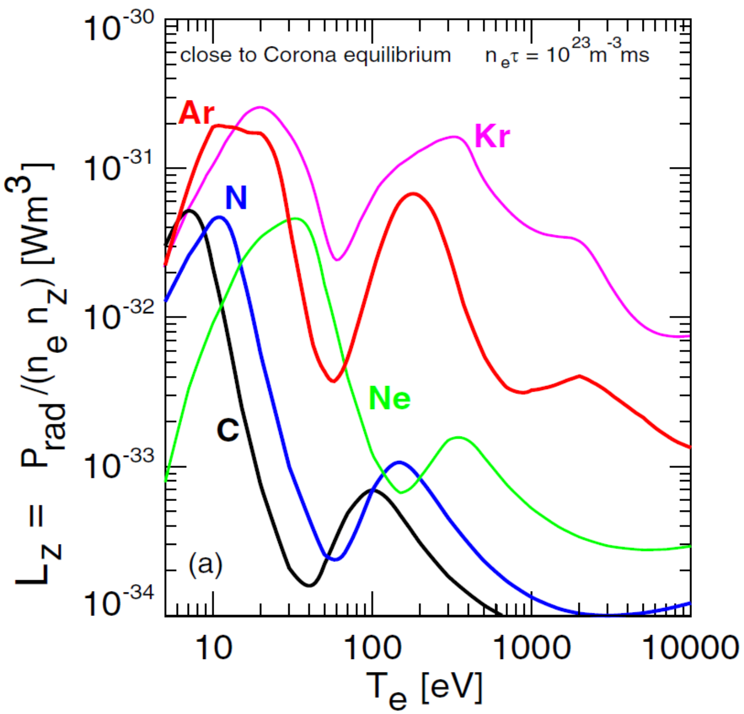


- Remove plasma power before it reaches PFCs

ITER – Power Exhaust – The solution - II

Power can be lost from the plasma by impurity radiation

- ☹ for confined plasma (dilution + power losses → lower P_α)
- ☺ for SOL + divertor plasma (power radiated by impurities spreads over large surface) → low q_{div}



$$P_{rad} = L_z(T_e)\, n_e\, n_Z$$

High P_{rad}

↓

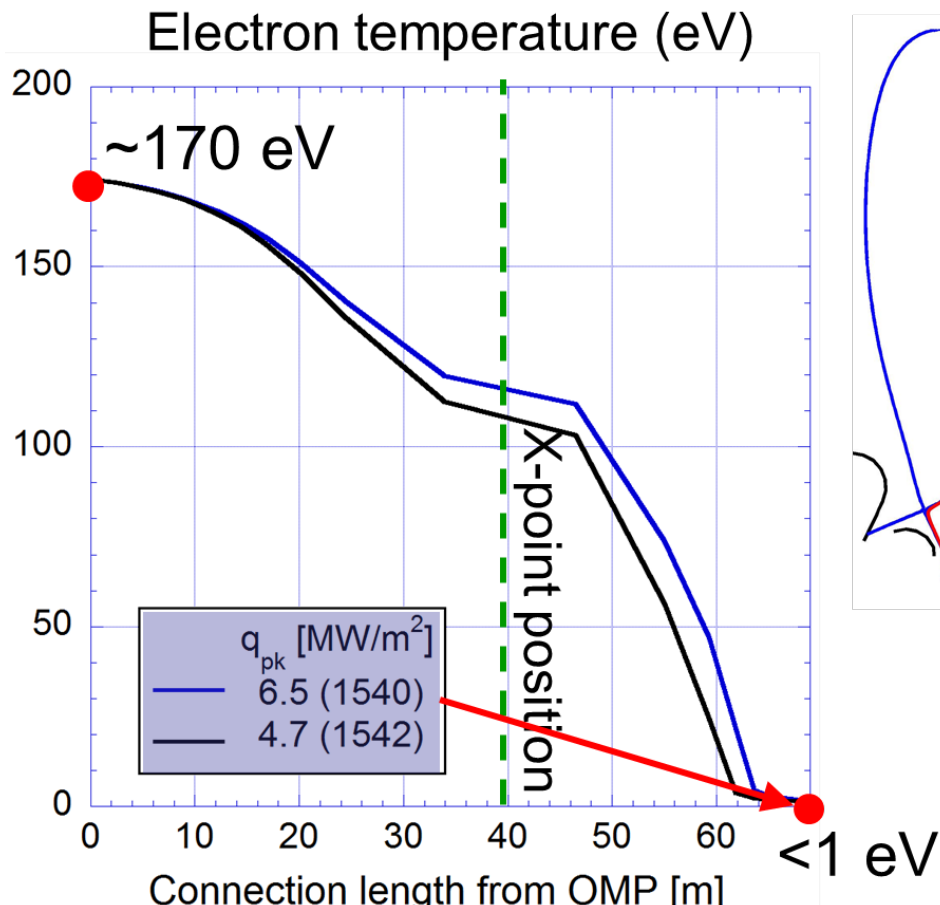
high n_e & n_Z
and
low T_e

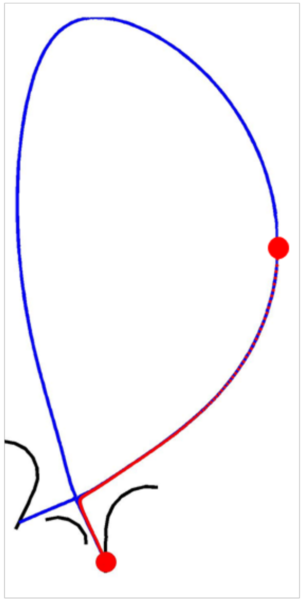
Optimum impurity : high SOL+divertor radiation ($T_e \leq 200$ eV) and low core radiation ($T_e \geq 1000$ eV) → Ar, Ne, N, …

ITER – Power Exhaust – The solution - III

How do we get this solution in practice ?

➢ Increasing edge plasma density and injecting impurities at the plasma edge → low T_e and high n_e divertor plasma → low q_{div}





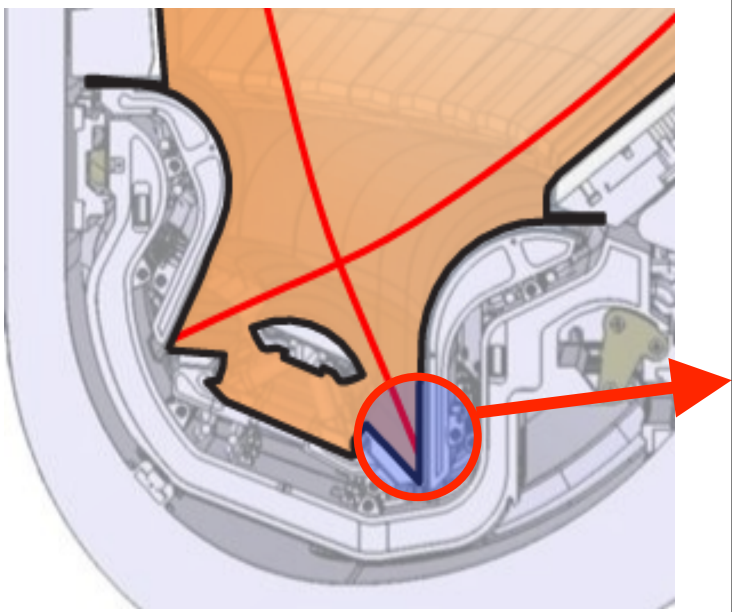
$\kappa \sim T_e^{5/2}$

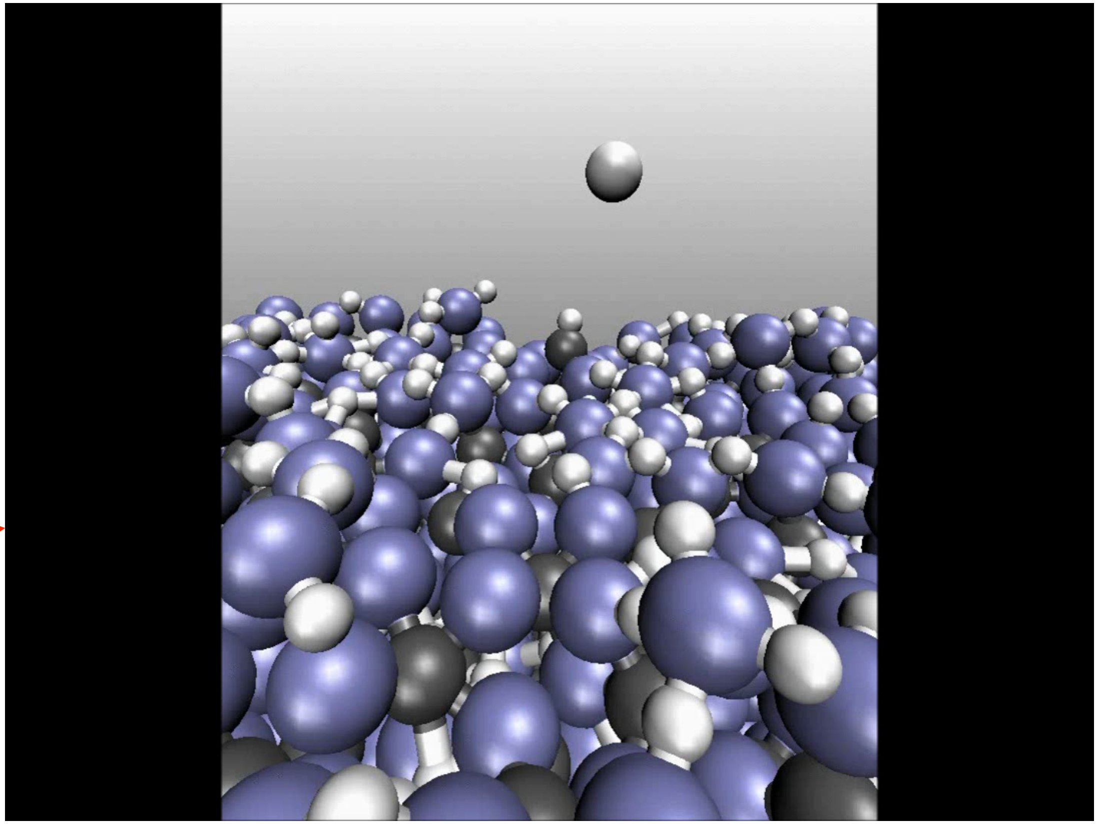
Calculations using the ITER plasma boundary simulation code, SOLPS

ITER – Power Exhaust – The solution - IV

Neutral recycling

Plasma fuel ions striking the target can be backscattered as neutrals or recombine with an atom in the surface → molecule emitted from the surface





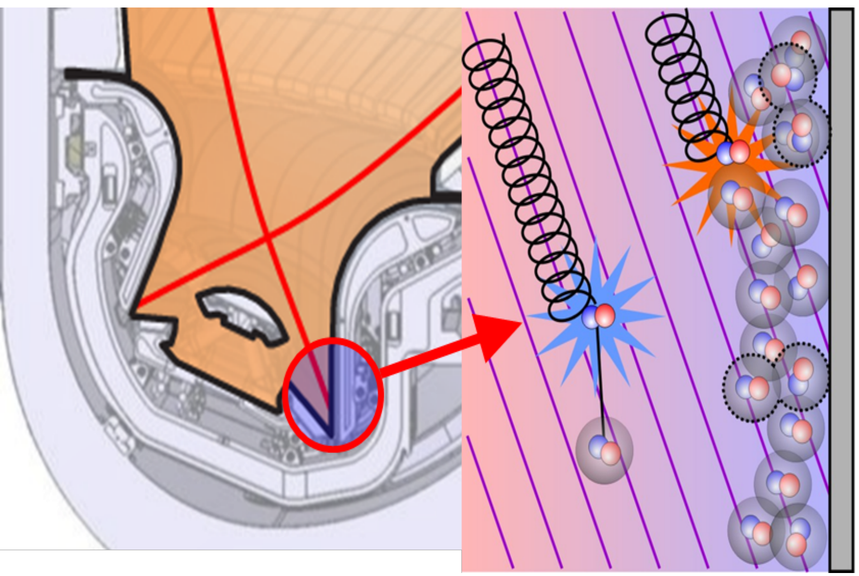
Courtesy Kai Nordlund, TEKES

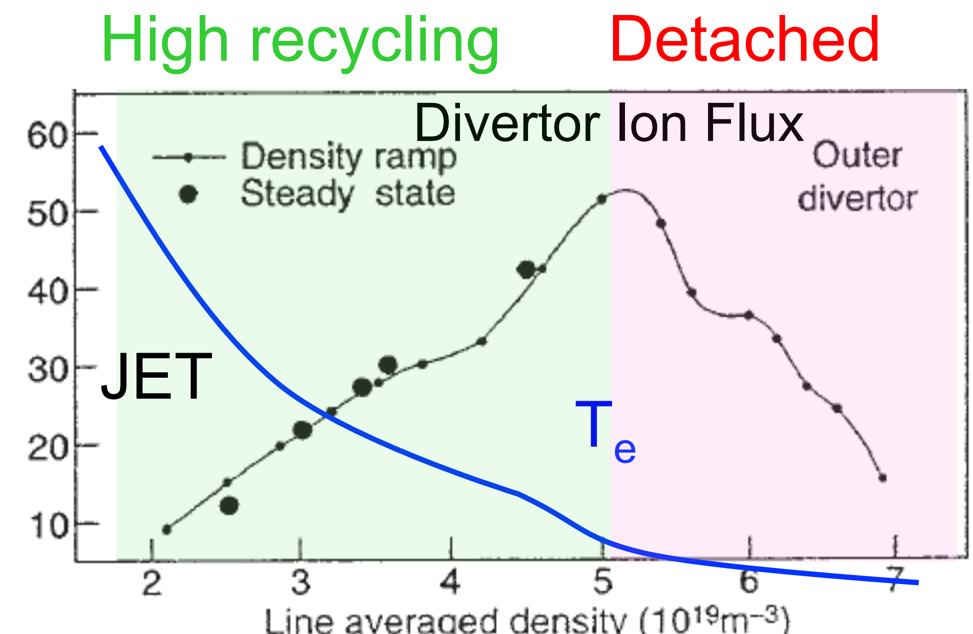
ITER – Power Exhaust – The solution - IV

High recycling divertor and detachment

Increasing divertor n_e → neutrals locally ionized

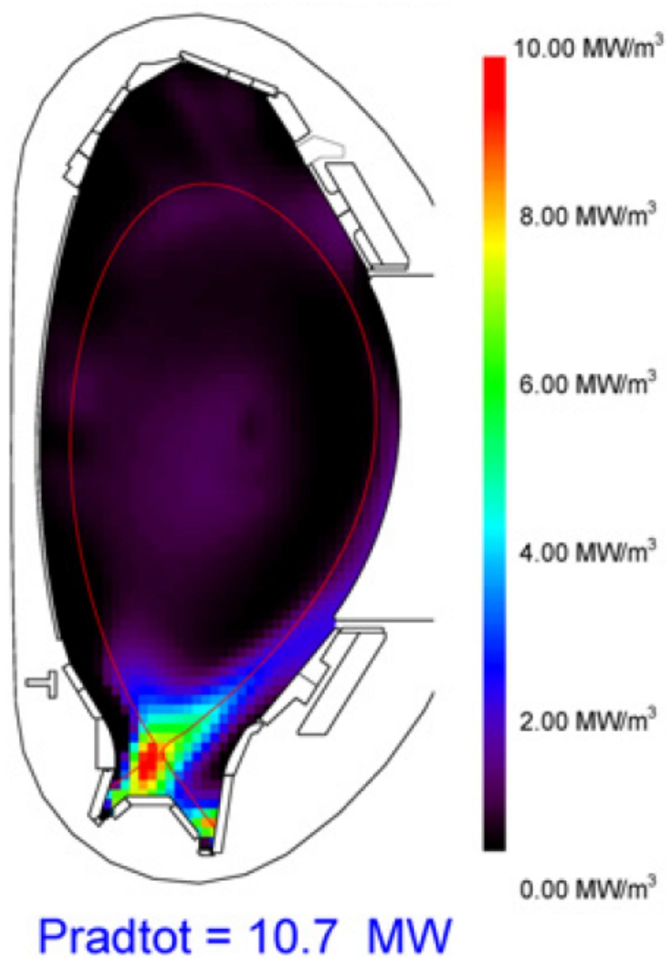
- ➢ Energy lost by plasma shared by more particles → lower T_e
- ➢ At very low T_e plasma can be extinguished → detachment → no direct plasma flux nor power to the divertor target → only neutral flux and radiation

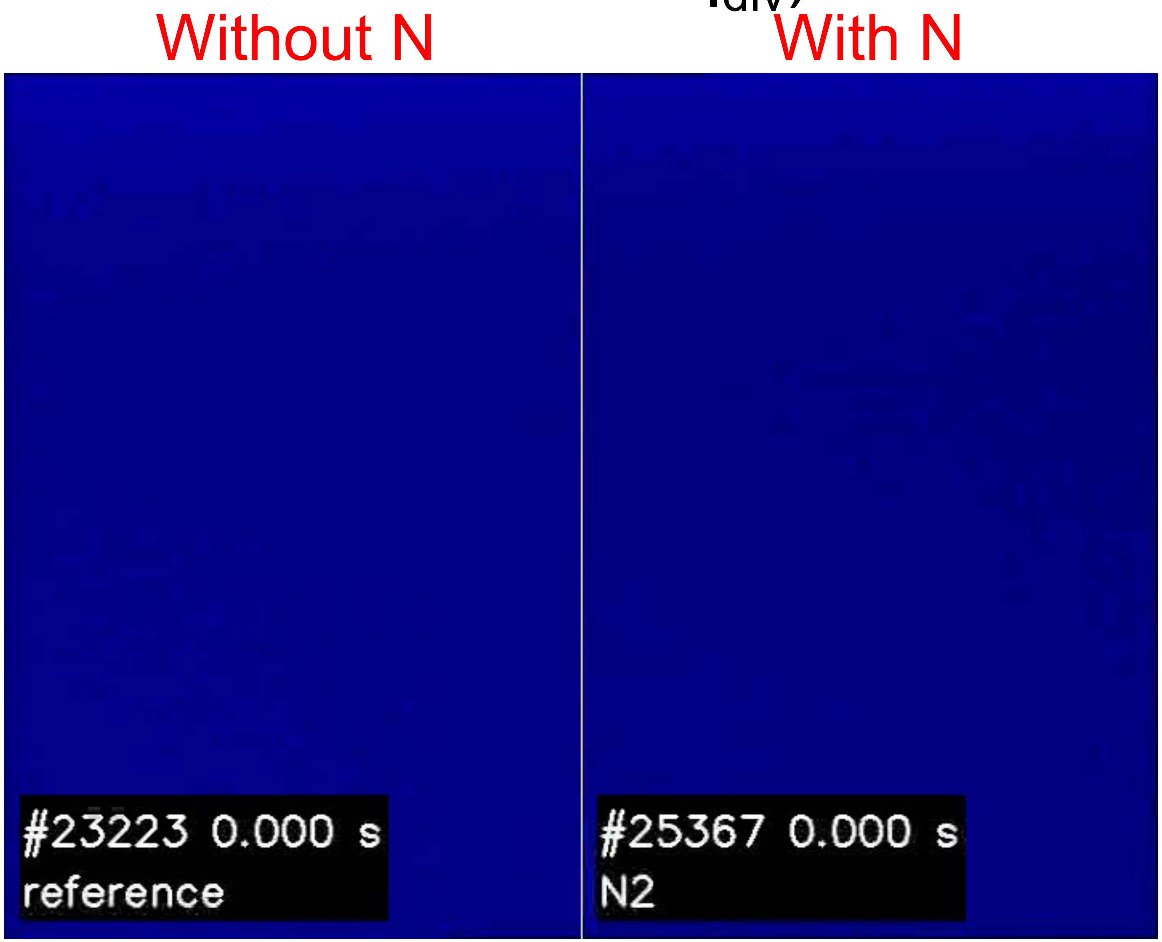




ITER – Power Exhaust – The solution - V

Example → nitrogen gas puffed into the ASDEX Upgrade divertor for detachment (P_{rad} and IR measurements of q_{div})





ITER – Power Exhaust – The solution - V

The radiative detached divertor solution does not only solve the power exhaust problem but also comes with some bonus materials for free ☺!

- Low T_e and low Γ_{div} → low divertor erosion & impurity control (from PFCs) (see later)
- High neutral density → good for particle (and He exhaust) (see later)

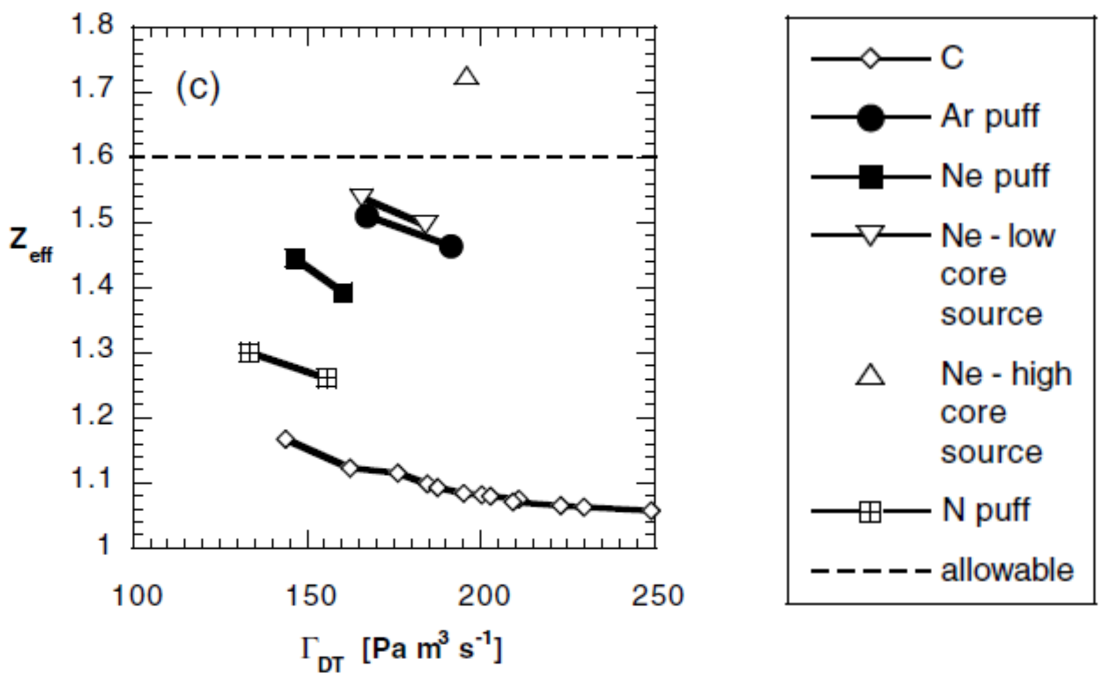
But there is no such a thing as a free lunch !

ITER – Power Exhaust – problems of the solution - I

The problems are related to integration with the core plasma that in which fusion reaction take place

- ➢ Impurity contamination of the core plasma → some of the impurities puffed at the divertor enter the core plasma → P_α can decrease

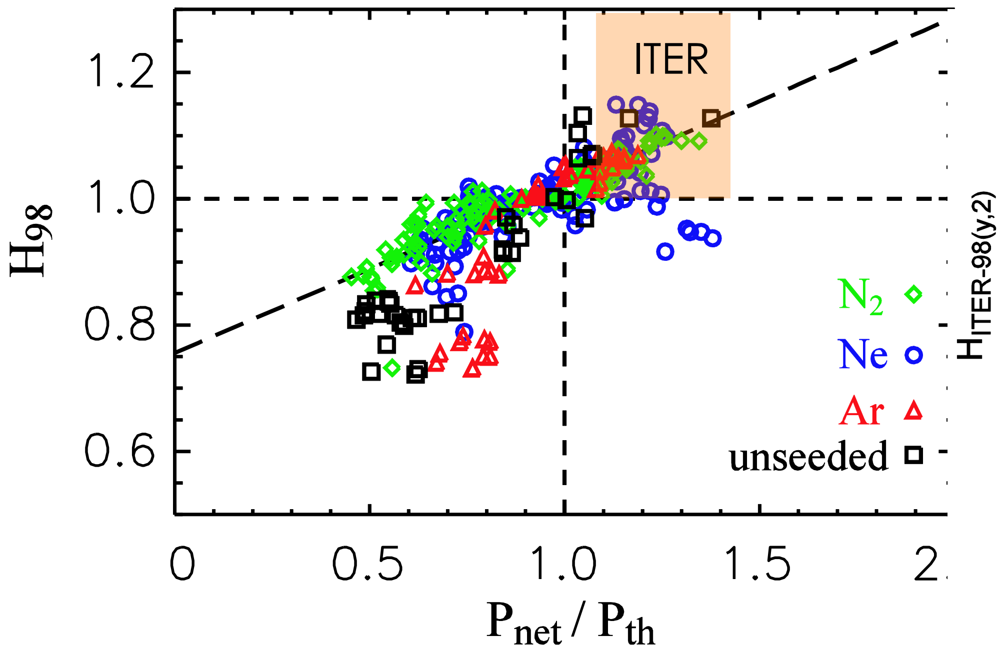
SOLPS ITER Modelling

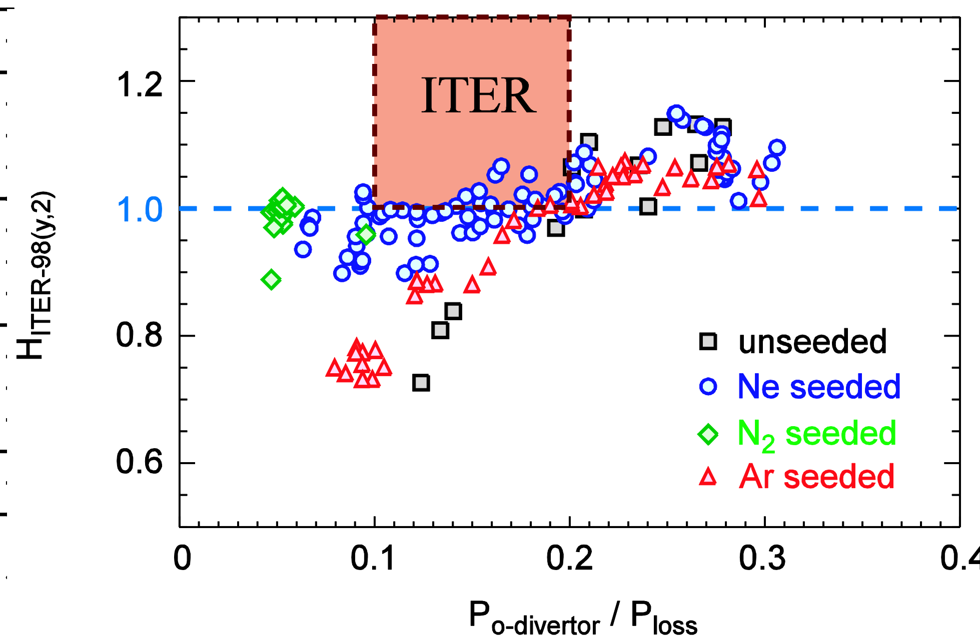


ITER – Power Exhaust – problems of the solution - II

- If core plasma radiation is too high → power flowing out of main plasma maybe to low to keep H-mode and τ_E) (more serious issue in ITER than in DEMO)

Alcator C-Mod



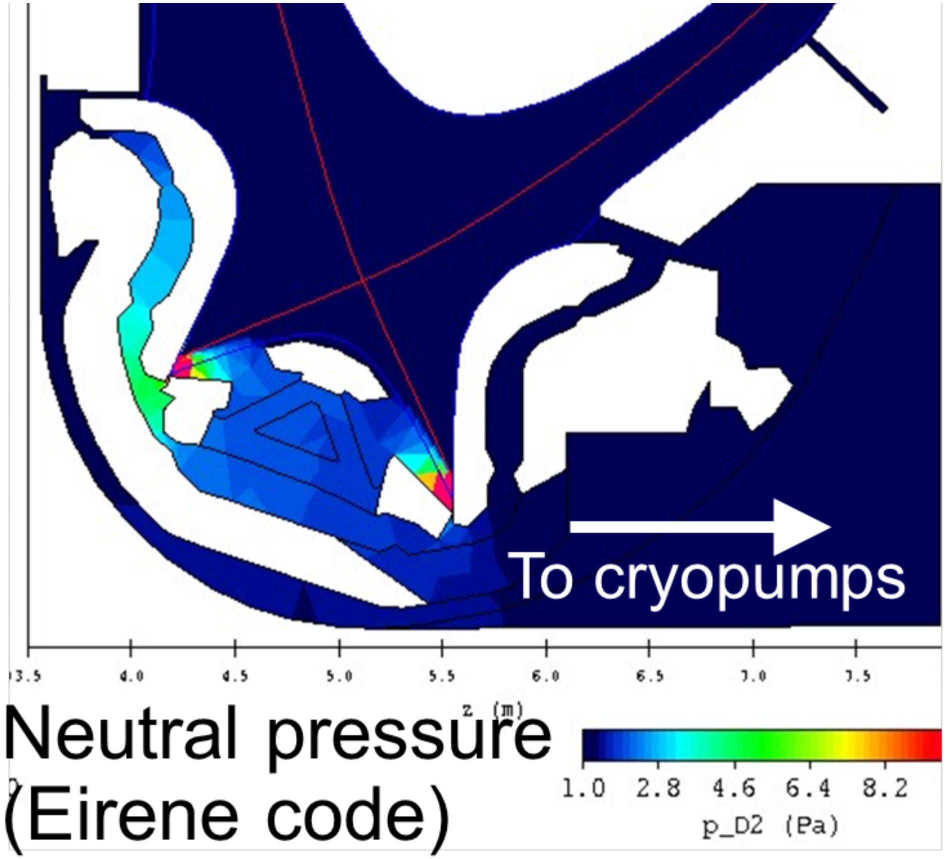


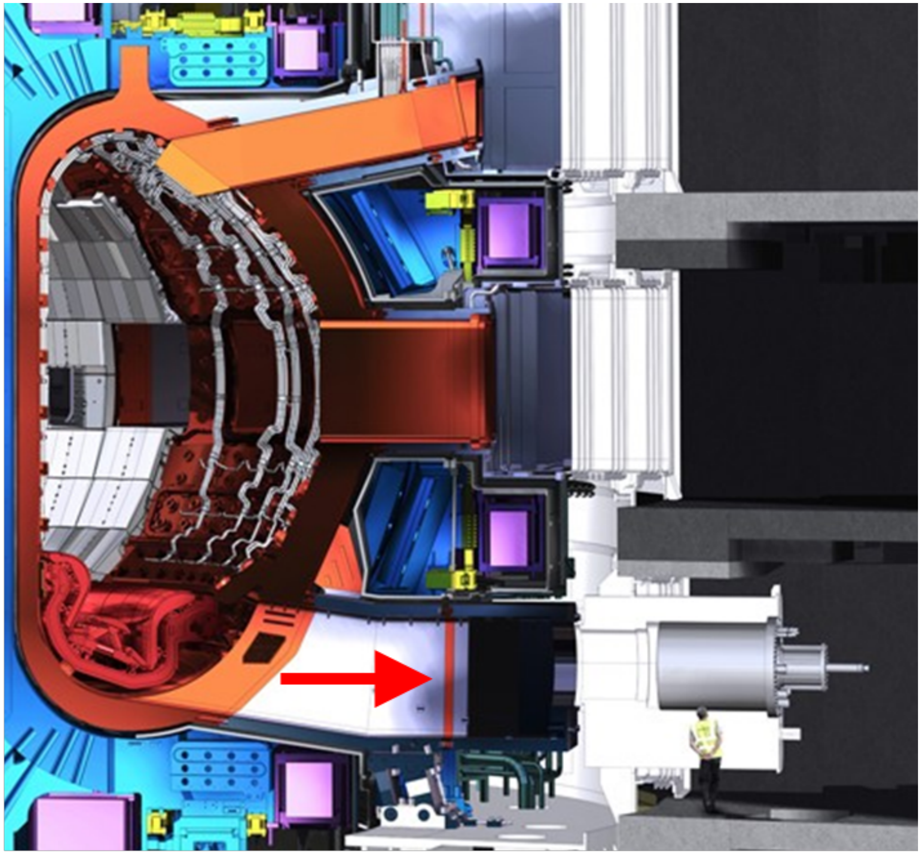
Experiments (ASDEX-Upgrade, Alcator C-Mod, etc.) have shown viable solution (high τ_E and low q_{div}) but extrapolation is non-trivial

Final answer to be found in ITER

ITER – Helium exhaust - I

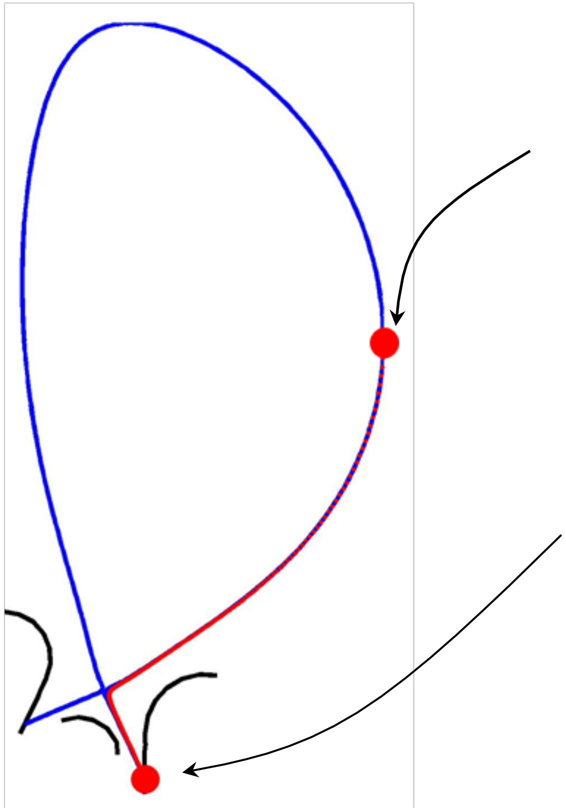
- The α-particles produced by fusion reaction have to be removed to prevent the fusion reaction to be stopped by the accumulation of ashes
- Neutral He can be removed from the divertor by cryo-pumps.



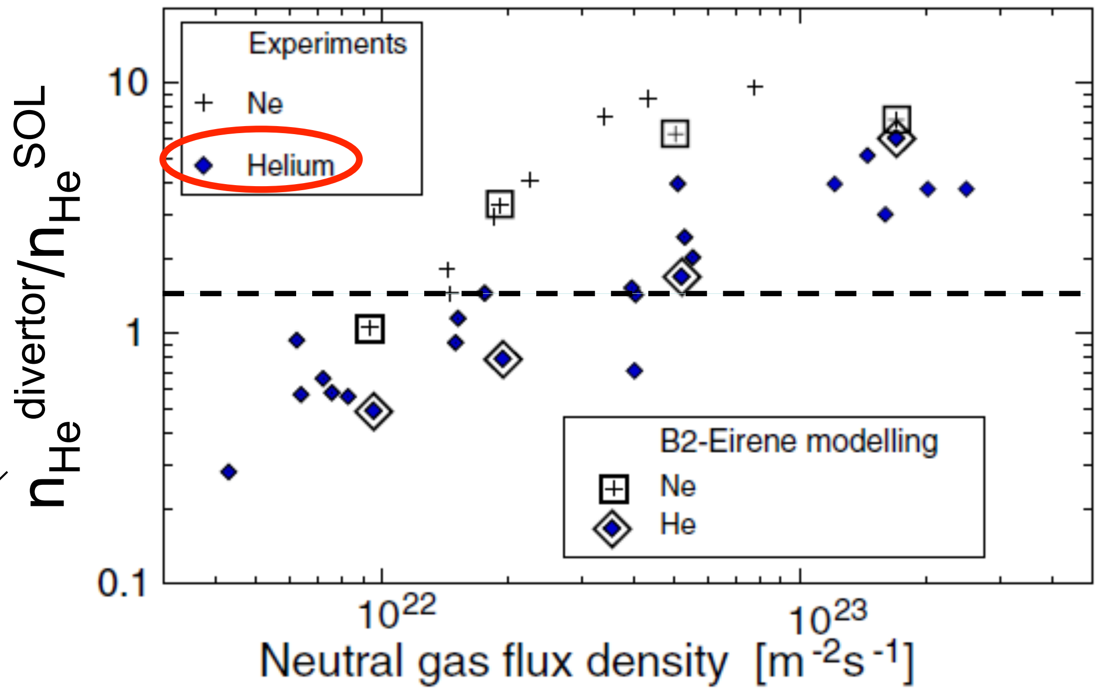


ITER – Helium exhaust - II

- The divertor indeed helps if one goes to conditions of high divertor densities/neutral pressures → more He in divertor plasma than elsewhere in edge plasma

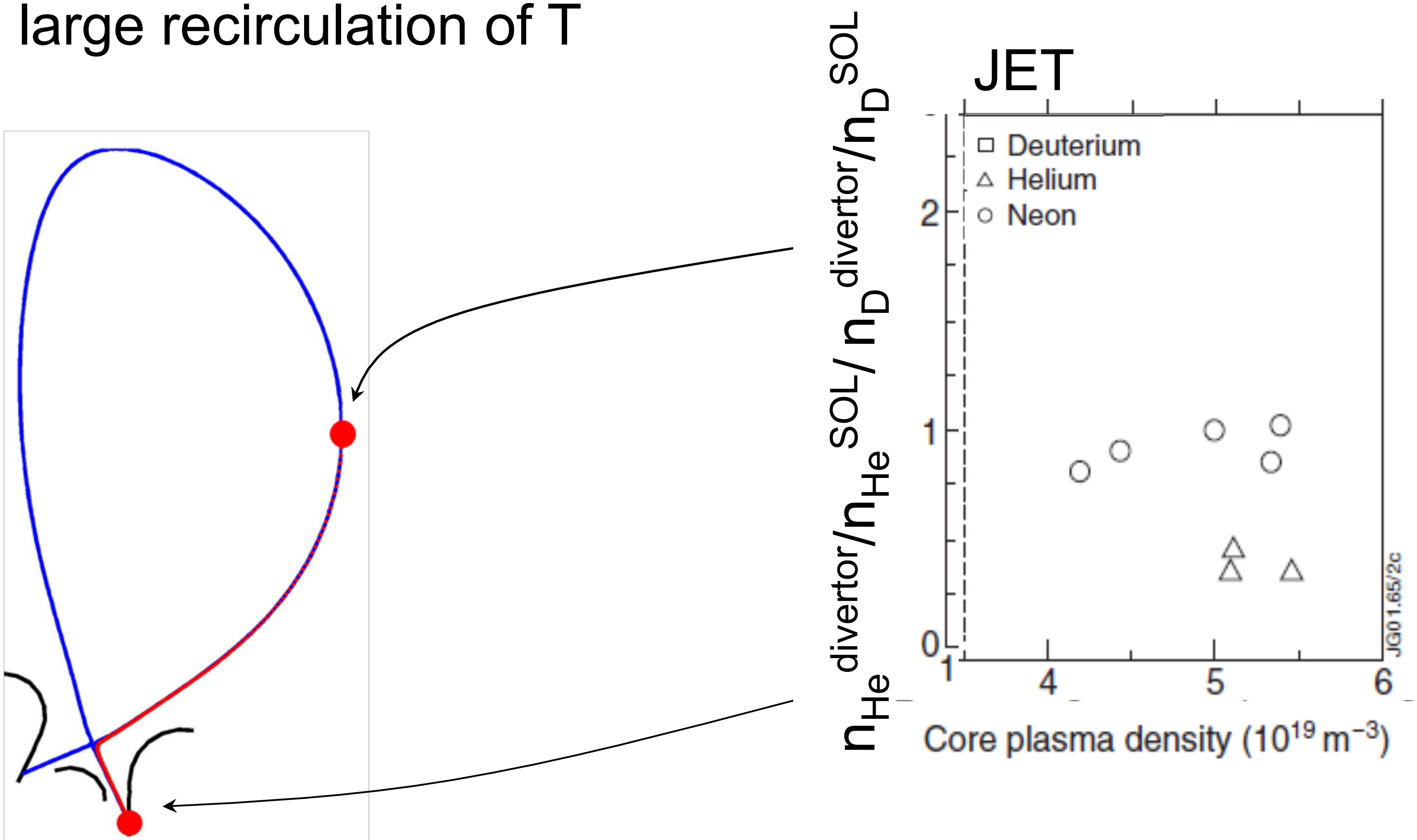


ASDEX-Upgrade



ITER – Helium exhaust - III

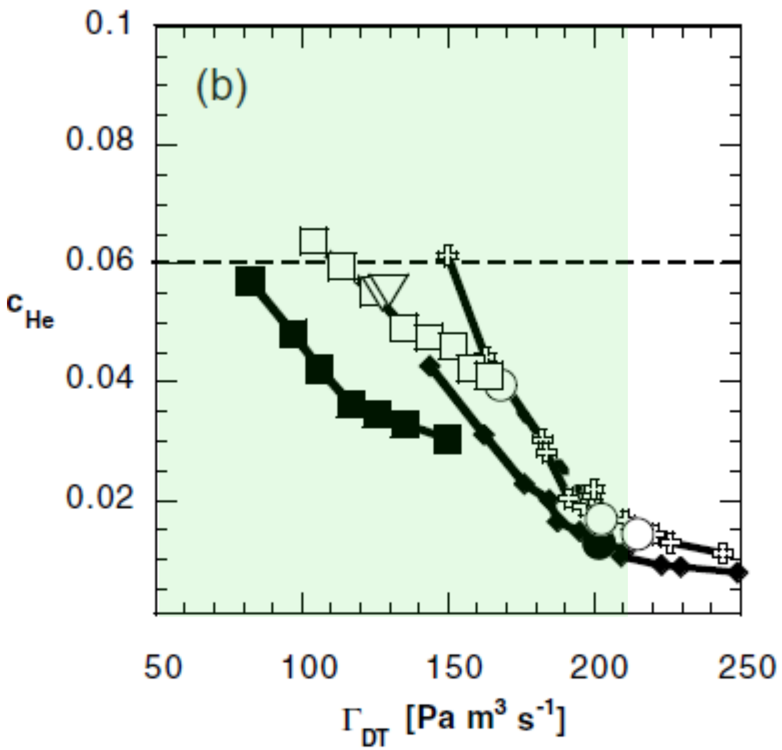
- The divertor also increases DT density → ratio of He density increase to DT increase unfavourable
- Typically one has to remove 3-10 DT atoms per He atom → large recirculation of T

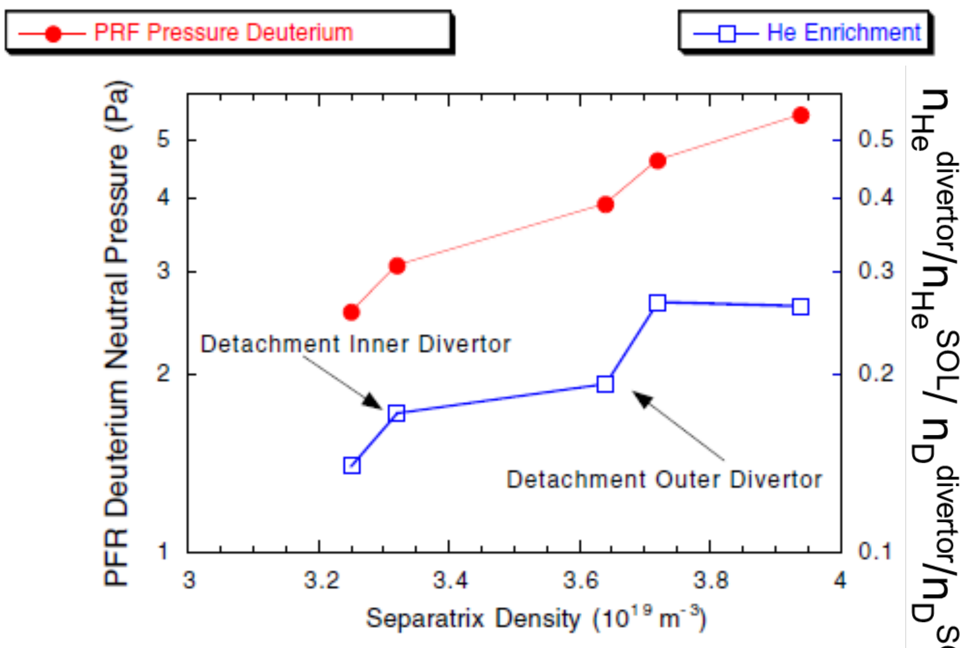


ITER – Helium exhaust - IV

- Present estimates for TER show that it is possible to keep He concentration in core plasma under 6% with T recirculation capability available (200 Pa m^3s^{-1} ~ 10^{23} DT atoms/s)
- Access to detached divertor conditions helps in increasing He proportion in exhaust gas

SOLPS ITER Modelling

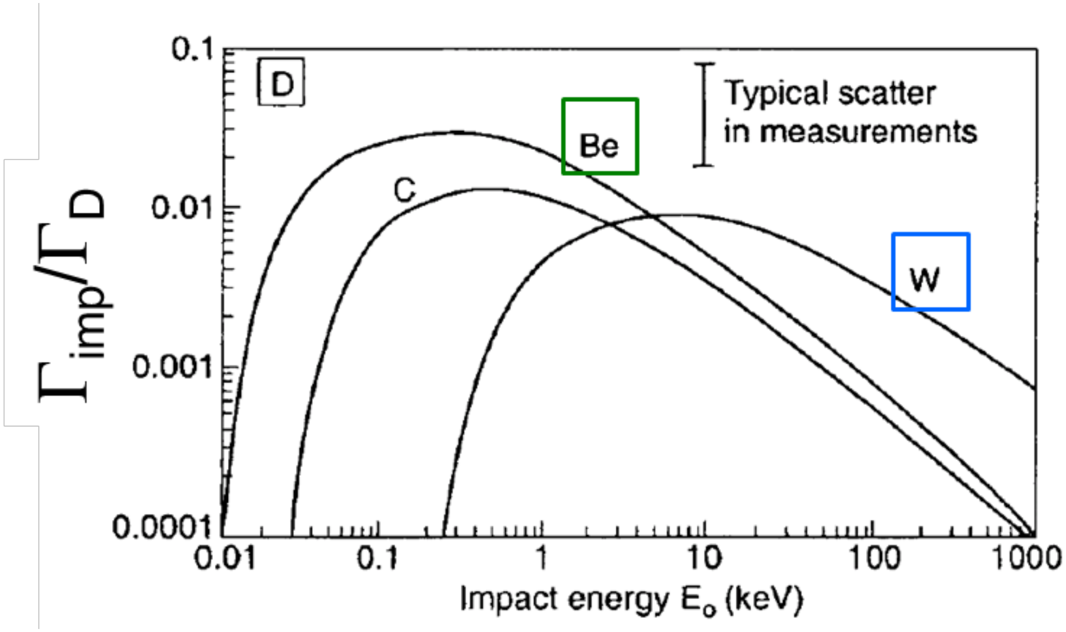




(b)

ITER – Impurity control - I

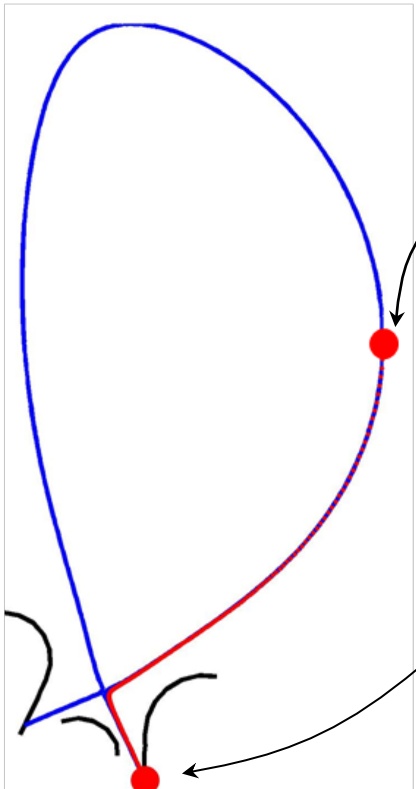
- Impurity control has two aspects → control of intrinsic impurities (eroded atoms from PFCs) and control of extrinsic impurities that we inject in the plasma for power exhaust
- To a large degree the solution to the power exhaust problem solves the intrinsic impurity control → low T_e (~1 eV) → low ion impact energy (few eV) → no erosion

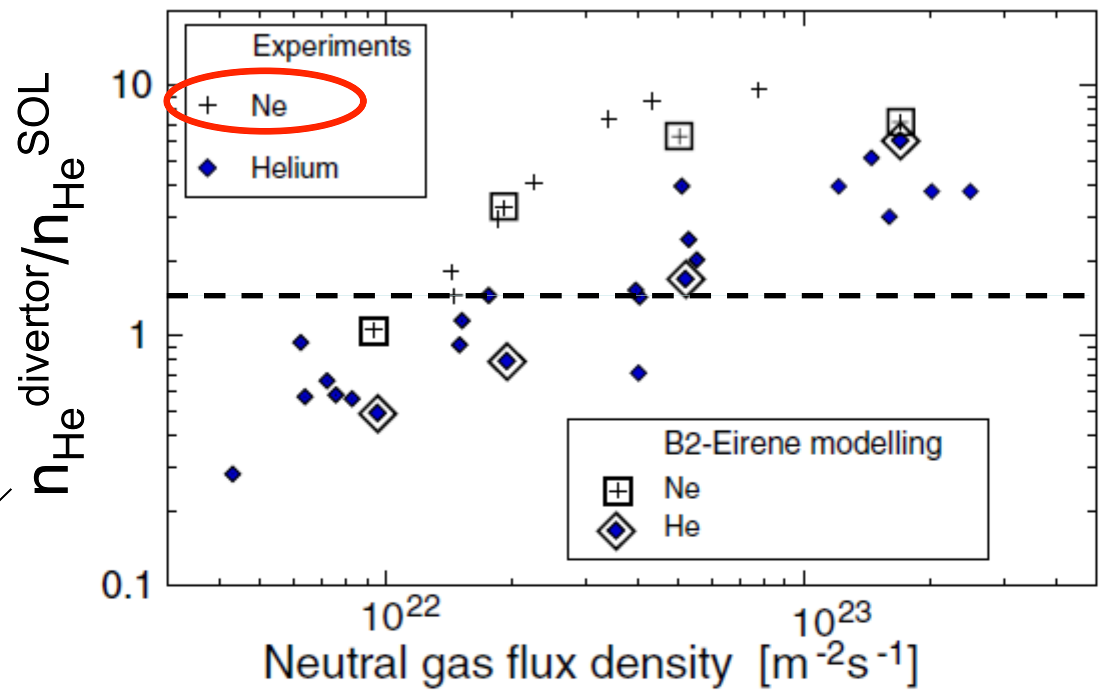


ITER – Impurity control - II

- Control of extrinsic impurities has some similarities with He exhaust → high divertor densities/neutral pressures → more Ne in divertor plasma than elsewhere

ASDEX-Upgrade



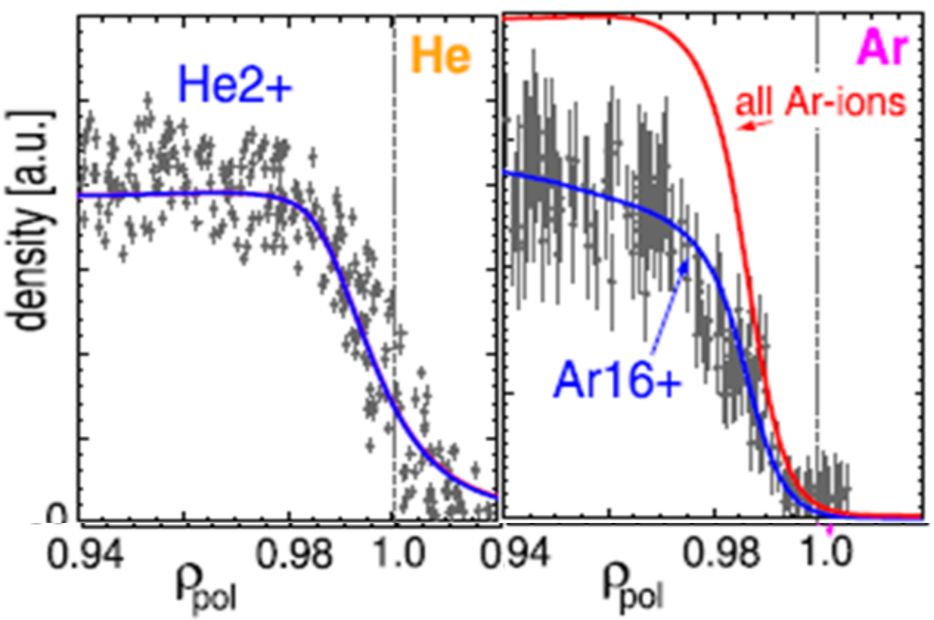


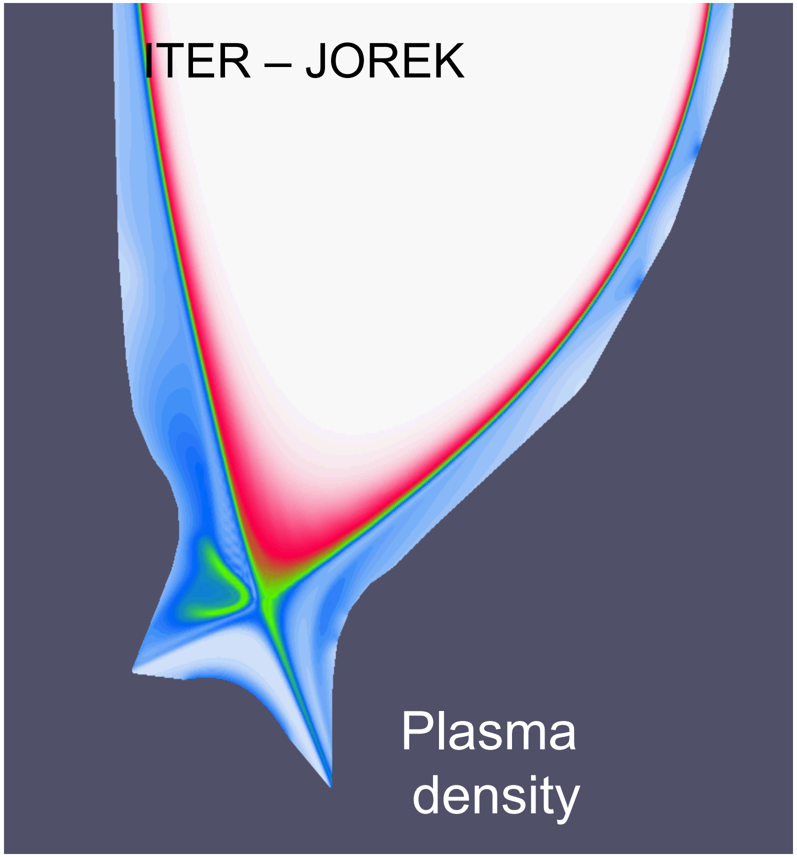
But one big difference → impurity transport in edge of confined plasma limits the impurity outflux to the divertor

ITER – Impurity control - III

- Transport at edge of plasma slows down impurity outflux → $n_Z^{core} >> n_Z^{SOL}$
- Expulsion of impurities from the plasma needs to be increased (i.e. by control of ELMs)

ASDEX-Upgrade





Conclusions

Solving the exhaust problem in ITER and DEMO requires understanding of a wide range of physics processes
(plasma physics, atomic and molecular physics, physics of materials, etc.)

The solution developed over the last ~ 30 years of R&D should allow coping with heat fluxes as large as those at the sun's surface (without getting burnt ☺)

ITER will have to demonstrate that this solution works together with a burning plasma