Plasma fuelling in JET ELMy H-mode: role of neutral dynamics and edge particle transport

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Motivation of the talk

Fuelling of the core plasma in ITER does not seem an easy job

- With increasing device size and power into the SOL plasmas are hotter and it is more difficult for neutrals to penetrate to the plasma core
- A minimum core outflux is required for maintaining He concentration within reasonable bounds

ITER can only achieve its reference performance by pellet fuelling

- Are these findings consistent with experimental evidence from Type I ELMy H-modes in present experiments ?
- Can we test in ITER-like conditions in present experiments the models and assumptions to model ITER to see if they describe correctly what is seen ?

Outline of the talk

- Review of particle balance and fuelling requirements in ITER
- Review of existing experimental and modelling studies concerning particle transport at high density and/or in ELMy H-modes
- Experimental evidence concerning fuelling of JET ELMy H-modes
- Open questions

Fuelling objectives and constraints

(1) To maintain the plasma density in the core

– partly accomplished via gas puff (n_s, Γ_{DT_s})

– will require core fuelling (Γ_{core})

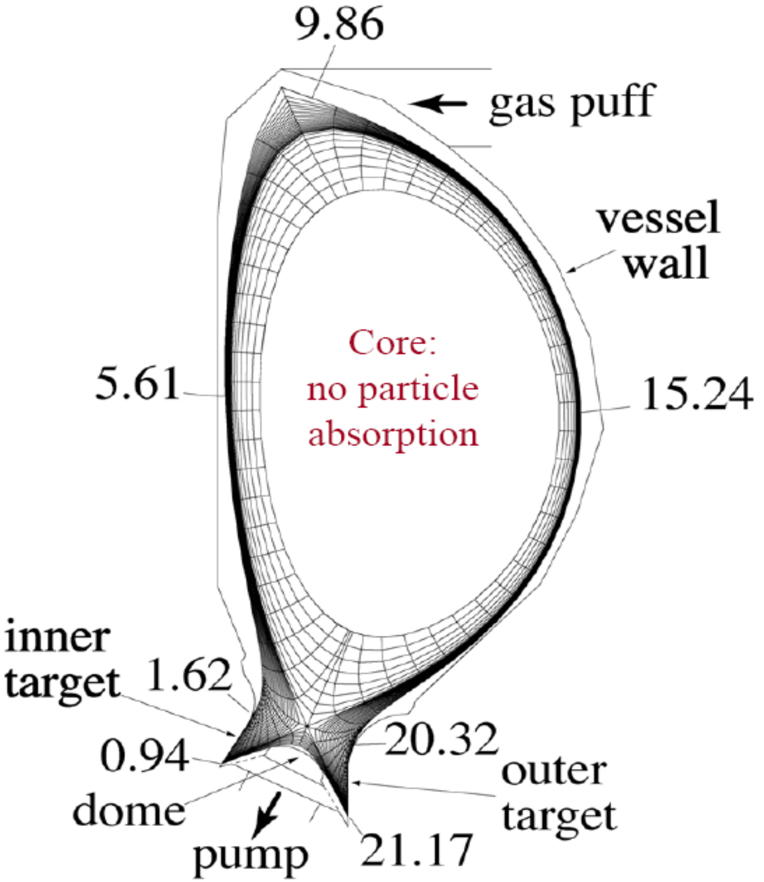
(2) To replenish the fuel pumped with helium

– could in principle be accomplished via gas puff (Γ_{DT})

(3) To control the D-T composition in the core

– will probably require core fuelling

– to be studied yet



⇒ Major constraint: all the particles delivered by fuelling must be pumped out

– pumping throughput is limited (Γ_{DT} +Γ_{core})

⇒ gas influx accompanying core fuelling might be a concern

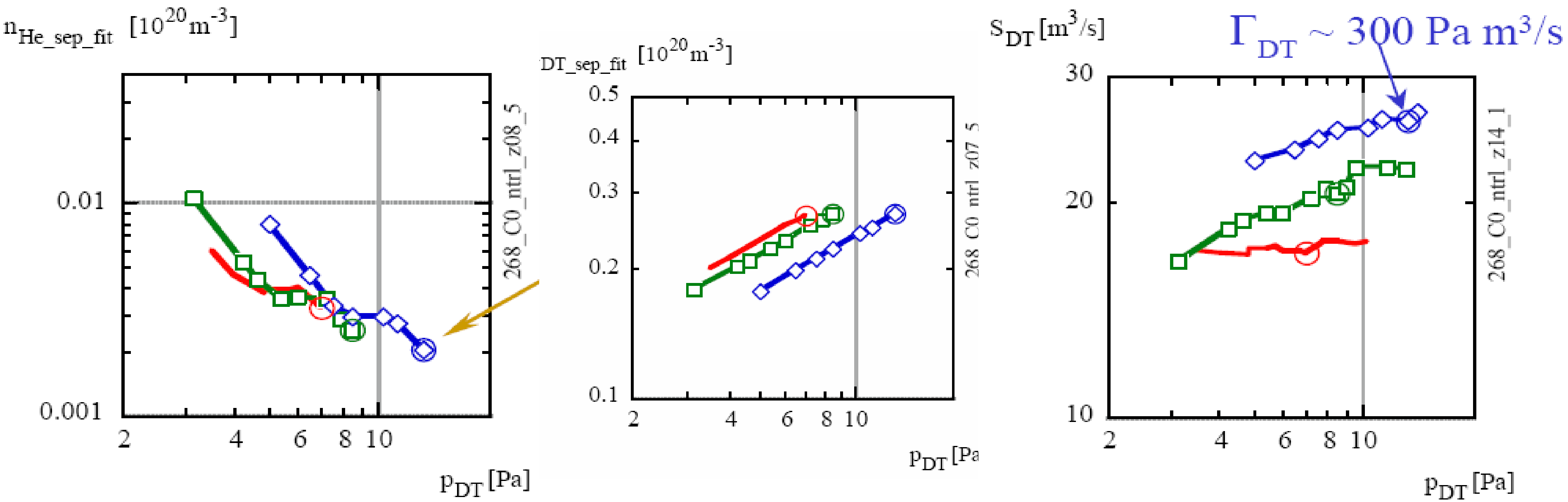
Particle Fluxes and Plasma Fuelling in ITER (II)

➢ He production for ITER Q_{DT} = 10 reference regime ~ 1.8 10^{20} s^{-1}

$n_{He}/n_D|_{core}$ ~ 5 % & $\eta_{He} = n_{He}/n_D|_{divertor} / n_{He}/n_D|_{core}$ ~ 0.1

↓

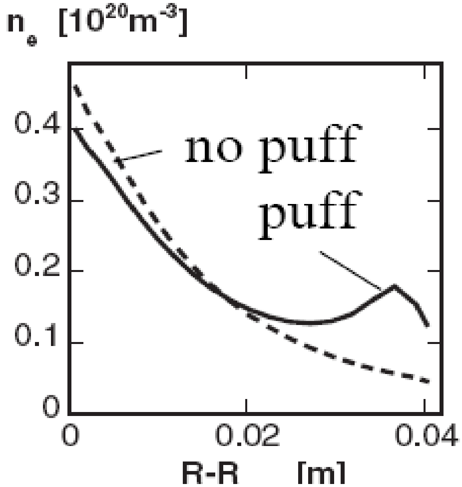
$n_{He}/n_D|_{divertor}$ ~ 0.5 % → $\Gamma_{D,core}^{pumped}$ = 3.6 10^{22} s^{-1} = 67 Pa m^3 s^{-1}

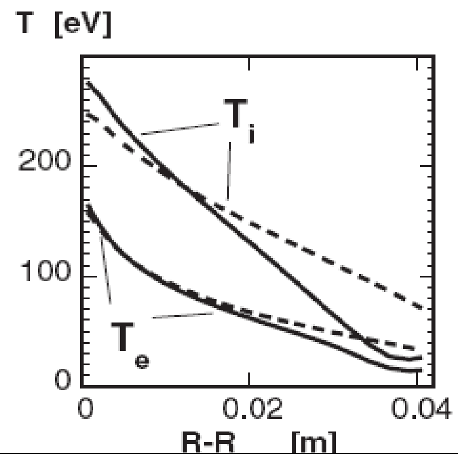


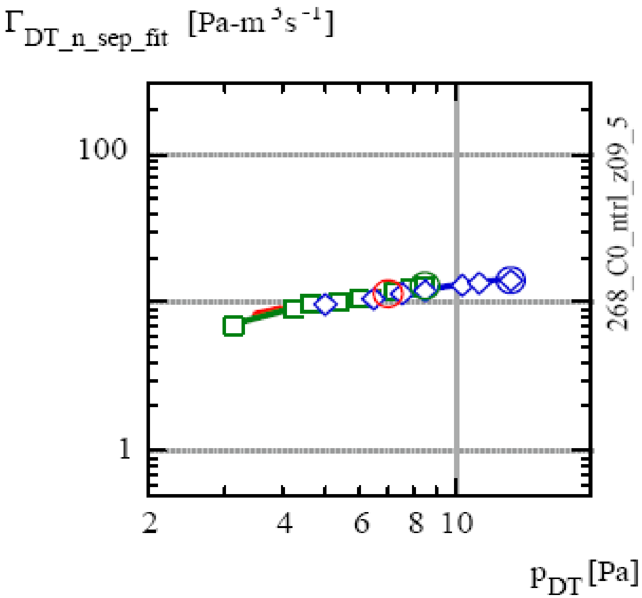
Particle Fluxes and Plasma Fuelling in ITER (III)

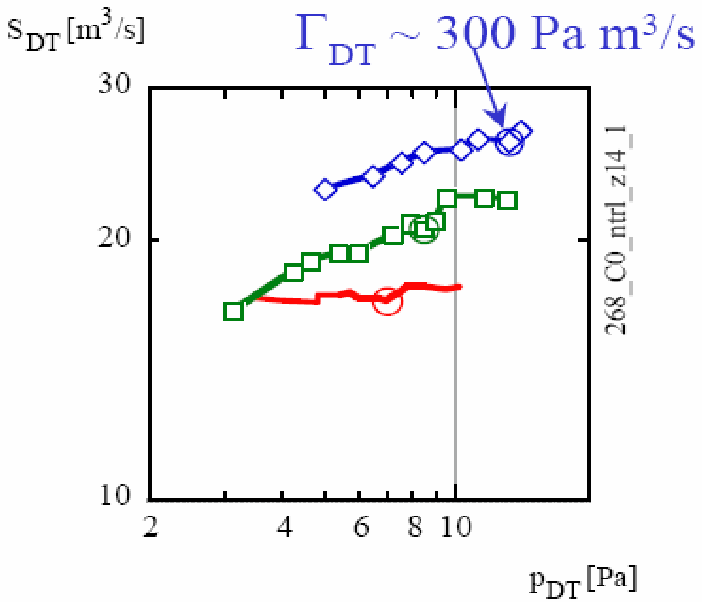
- Gas fuelling in ITER
  - ✓ SOL plasma in ITER is dense and hot → thick to gas puff
  - ✓ Most of fuel gas ionised in far SOL and does not reach separatrix

Typically < 10% of fuelled gas reaches separatrix ($\Gamma_{gas} \sim \Gamma_{recycling}$)









Particle Fluxes and Plasma Fuelling in ITER (IV)

➢ Core fuelling of ITER

Rough estimate:

$S_{sep} \sim 700\ m^2$, $\Delta_{ped} \sim 0.1\ m$, $D_{ped} \sim (0.03\ \text{to}\ 0.1)\ m^2/s$

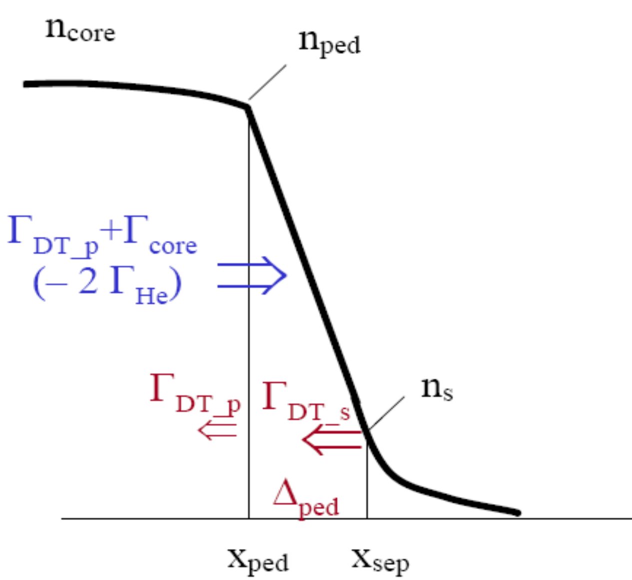
$n_{core} \sim 10^{20} m^{-3}$, $n_s \sim 3\ 10^{19} m^{-3}$, $T_{ped} \sim 4\ keV$

$\Gamma_{DT\_p} = \Gamma_{DT\_s} \exp(-\Delta_{ped}/\lambda_{ped}) \sim 3\ 10^{21}\ s^{-1}$

$\Gamma_{He} << \Gamma_{DT\_p}$

$\Gamma_{ped} = S_{sep} D_{ped}(n_{ped} - n_s) / \Delta_{ped} \sim (1.5\ \text{to}\ 5)\ 10^{22}\ s^{-1}$

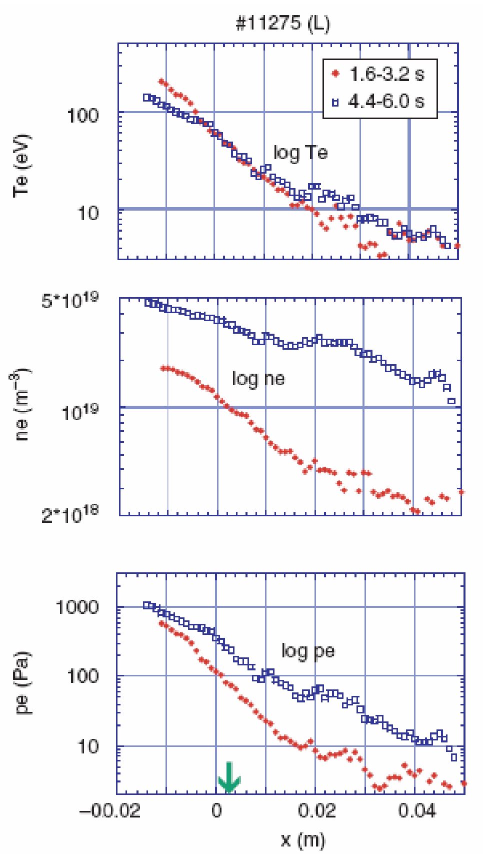
$\Rightarrow \Gamma_{core} \sim (1.2\ \text{to}\ 4.7)\ 10^{22}\ s^{-1} \sim (25\ \text{to}\ 90)\ Pa\ m^3/s$



Typically $\Gamma_{DT\_p} \sim 40\%\ \Gamma_{DT\_s} \sim 5\ Pa\ m^3\ s^{-1}$ → missing ~ 50 Pa $m^3\ s^{-1}$ by pellets

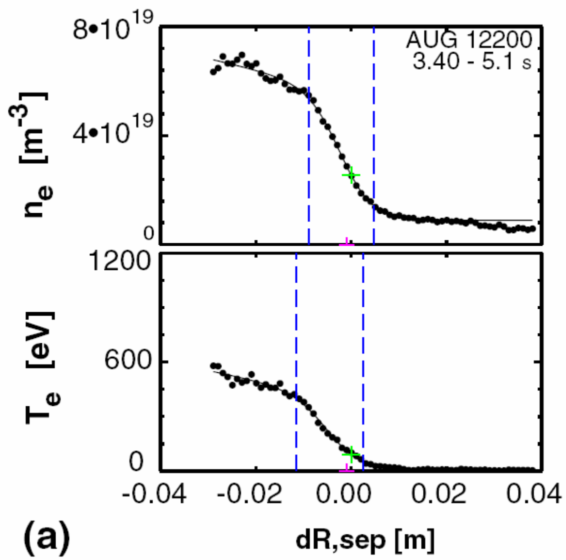
Experimental and modelling studies of particle transport (I)

Tails in SOL n_e profiles are seen in various divertor tokamaks (AUG, C-mod)

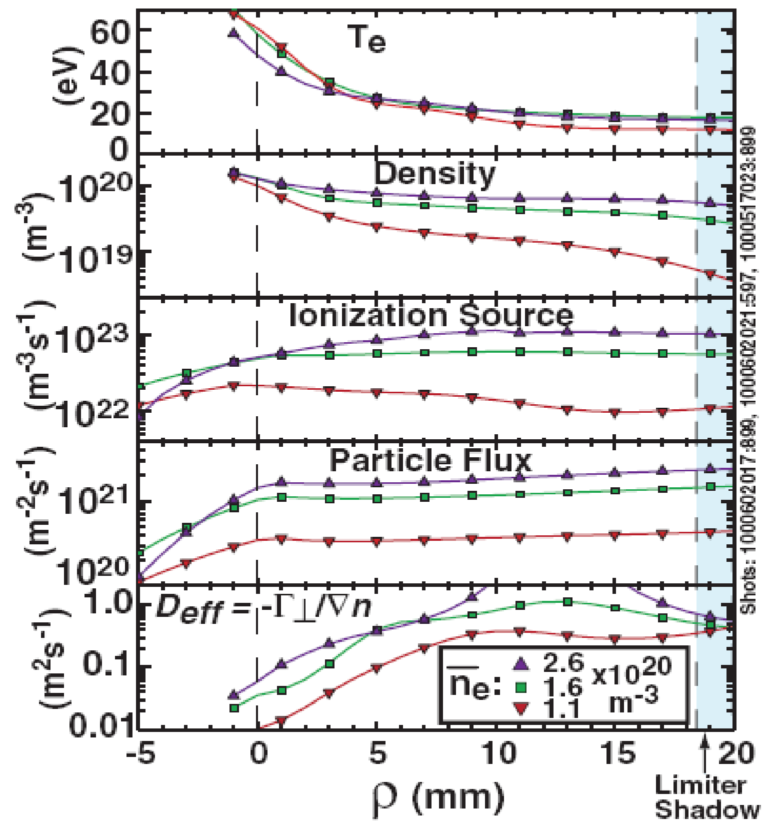


Neuhauser PPCF 2002

H-mode



Kallenbach JNM 2005

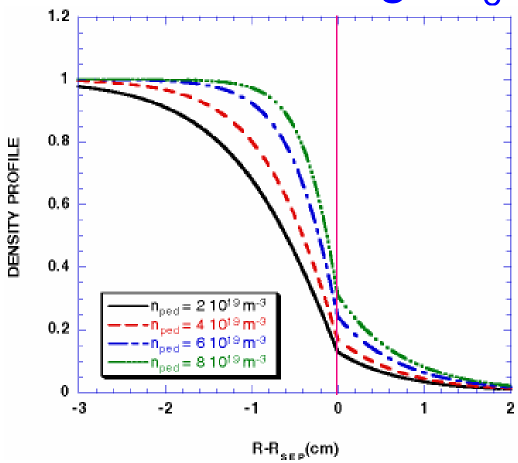


L-mode Lipschultz IAEA 2000

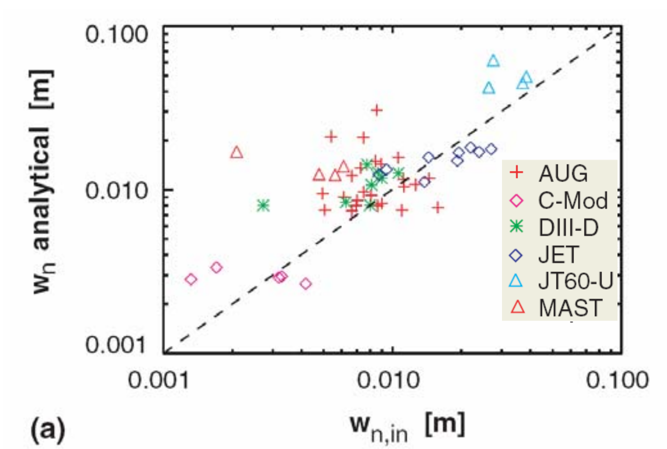
is this due to transport enhancement at low Te (large ν_e*) or neutral ionisation ?

Experimental and modelling studies of particle transport (II)

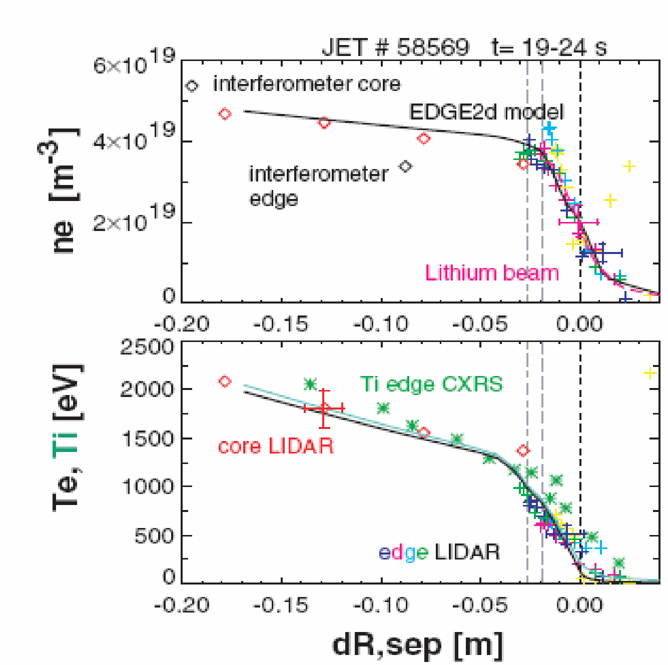
Neutral ionisation can explain some features of edge n_e profiles



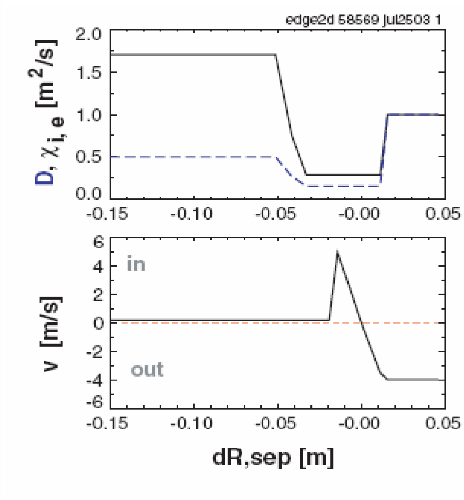
Kallenbach JNM 2005



but detailed modelling of n_e profiles still requires some important assumptions on anomalous transport



Kallenbach PPCF 2004



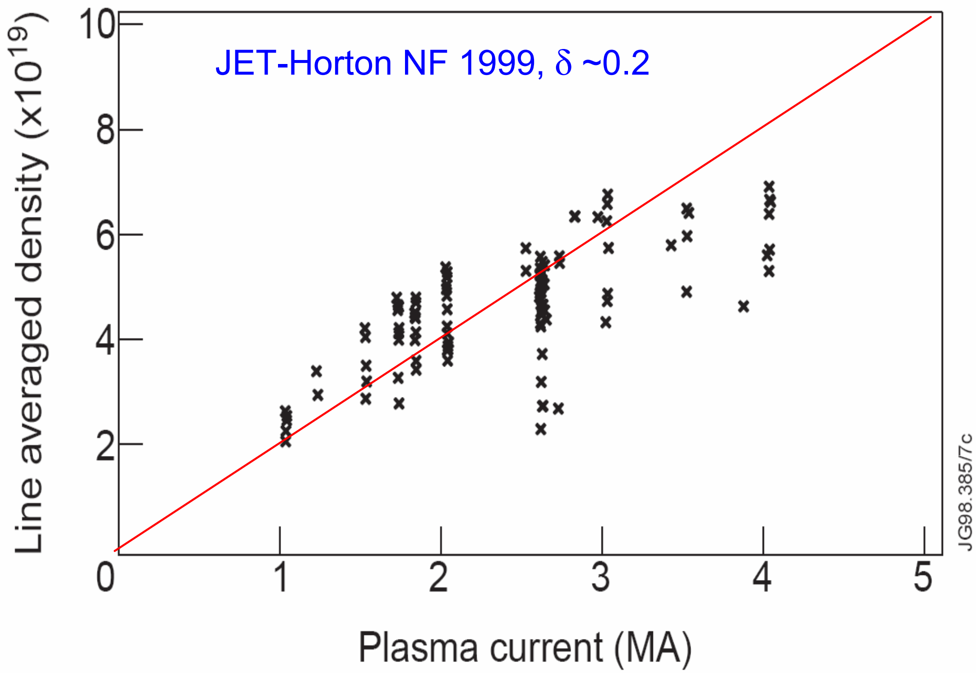
if there exists an inwards pinch close to the separatrix in H-mode → core fuelling of ITER would be possible

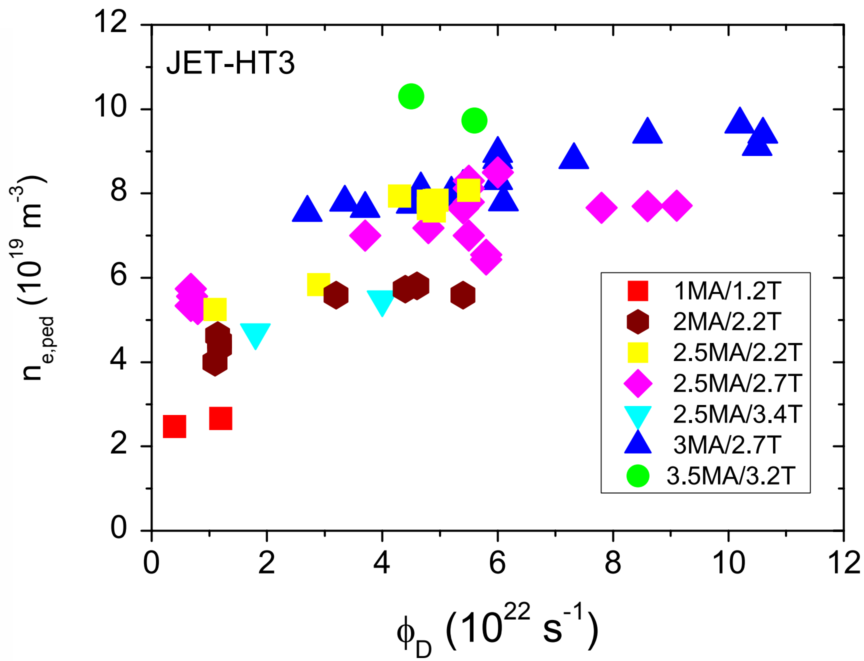
$n_{sep} = 3\ 10^{19}\ m^{-3}$, $v_{pinch} = 5\ ms^{-1}$ → $\Gamma_{D+,sep}^{in} = 1.0^{23}\ s^{-1}$

Particle balance in JET ELMy H-modes (I)

in H-modes $<n_e>$ is not a free parameter :

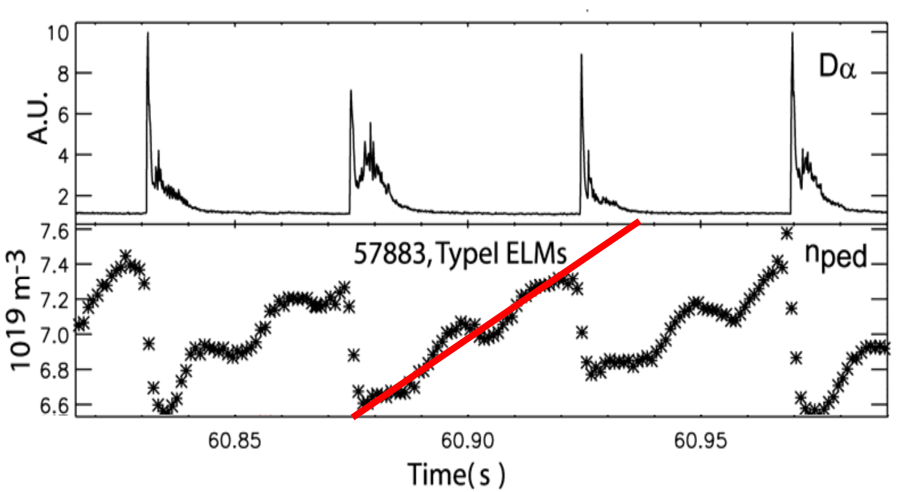
- $<n_e> \sim I_p$ even when $\phi_{gas} \sim 0$
- n_{ped} can be changed with gas puffing only by ~ 30%

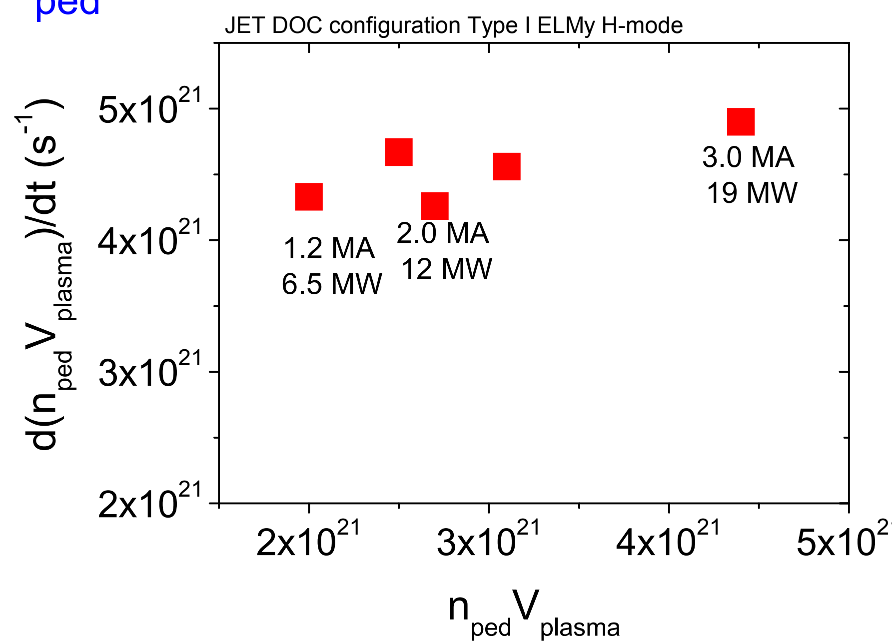




Particle balance in JET ELMy H-modes (II)

dN/dt between ELMs in unfuelled Type I H-modes weakly dependent on I_p & N_{ped}





$$dN/dt = S_{core} - N/\tau_p$$

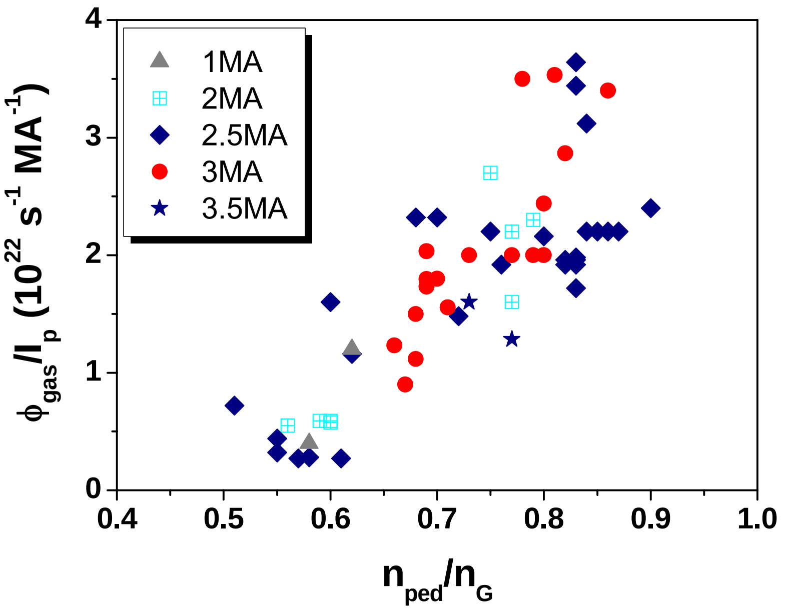
If ionisation dominates core influx → $S_{core} \sim n^{\alpha} \exp(-d/\lambda_{ion}) \sim n_{SOL}^{\alpha} \exp(-d n_{SOL}^{\beta} \langle\sigma v\rangle_i / v_o)$

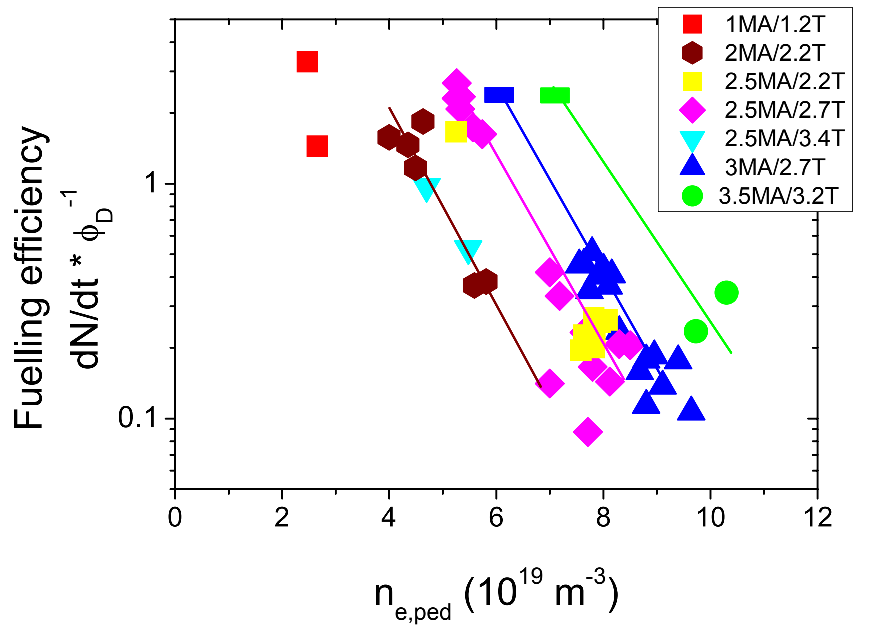
($\alpha=\beta=1$ main chamber source, $\alpha= 2$, $\beta=3$ high recycling divertor source)

Going from 1 to 3 MA if λ_{SOL} ~ constant → S_{core} ↓ 10 but N ↑ 3 → $\tau_p \sim I_p^{\gamma}$ with $\gamma > 1$

Particle balance in JET ELMy H-modes (III)

Fuelling JET Type I ELMy H-modes by (divertor) gas puffing is as effective at low and high currents



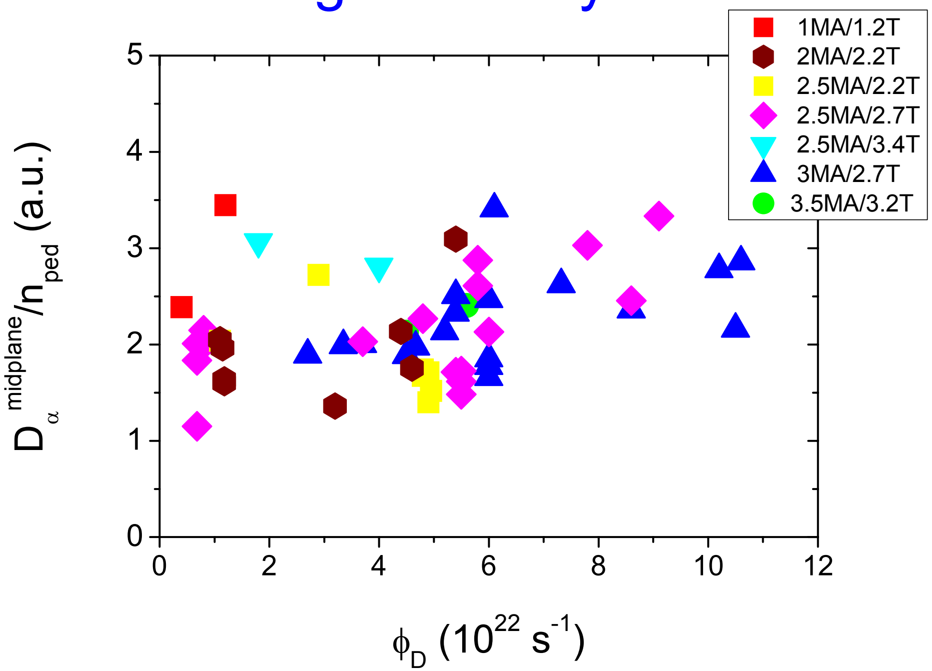


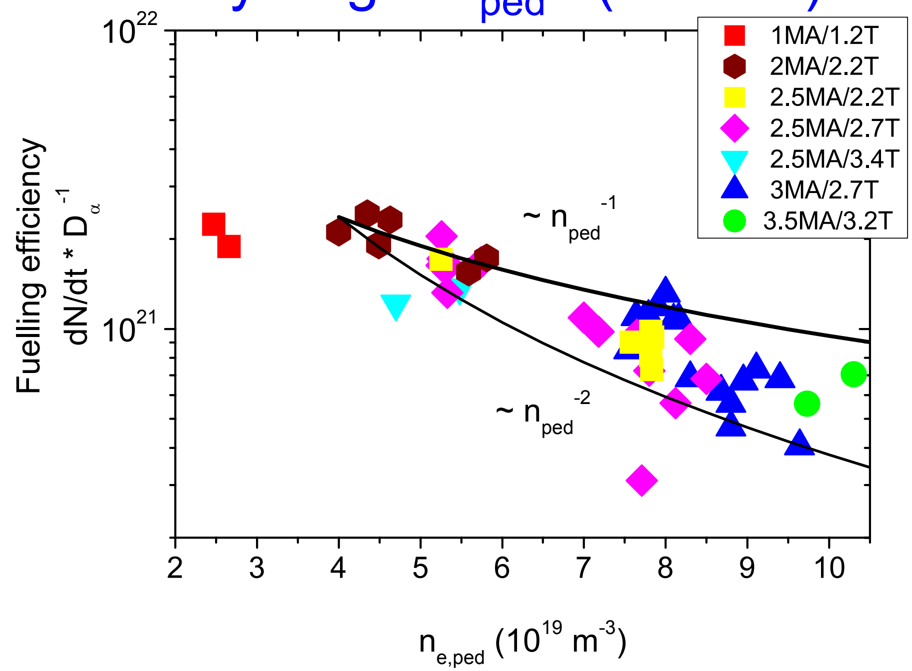
- ϕ_{gas} ~ N_{plasma} independent of I_p
- Gas "fuelling efficiency"
  - ✓ decreases with n_e at fixed I_p (as expected from λ_{ion})
  - ✓ increases with I_p for same n_{ped} → influence of recycling and transport

Particle balance in JET ELMy H-modes (IV)

Main chamber recycling is proportional to n_{ped} & "independent" of ϕ_D & I_p

Fuelling efficiency of main chamber recycling ~ $n_{ped}^{-\alpha}$ (α = 1-2)



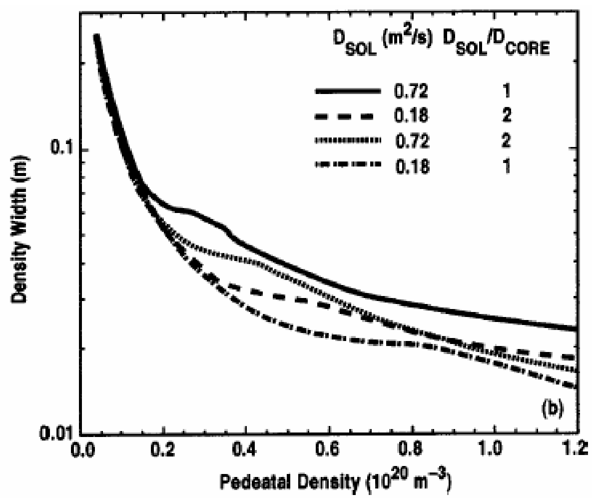


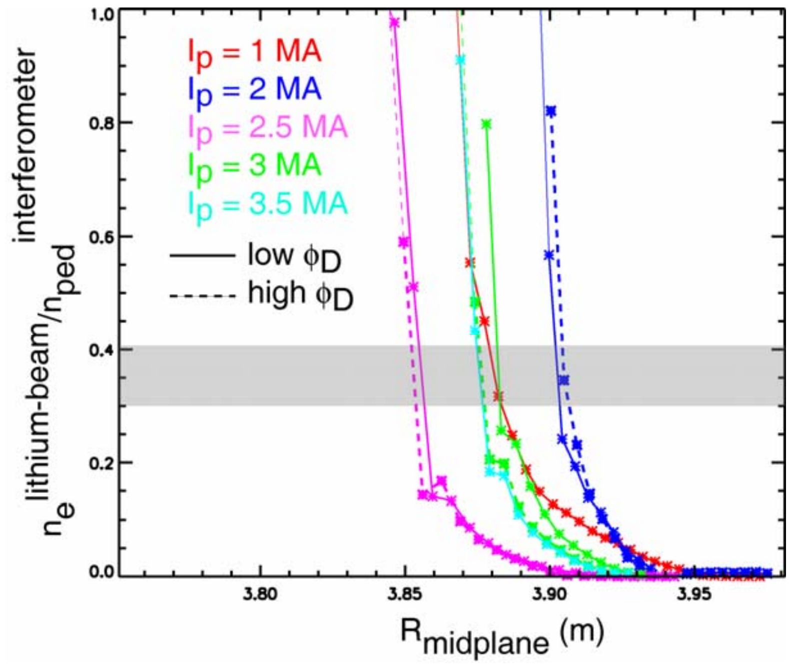
- No sign of non-linear enhancement of ϕ_{wall} with n_{ped} at high n_{ped} & n_{ped}/n_{GW} unlike C-mod, ASDEX Upgrade (?)
- Only weak decrease of fuelling efficiency with n_{ped} & positive trend with I_p
- For I_p ~ 3 - 3.5 MA → $n_{ped}^{JET} > n_{ped}^{ITER}$ and T_{ped}^{JET} = 1.0 - 1.5 keV

Particle balance in JET ELMy H-modes (V)

SOL n_e profiles change little with I_p and n_e (for fixed I_p)

Effect of transport is small of n_e shape if ionisation determines edge profiles





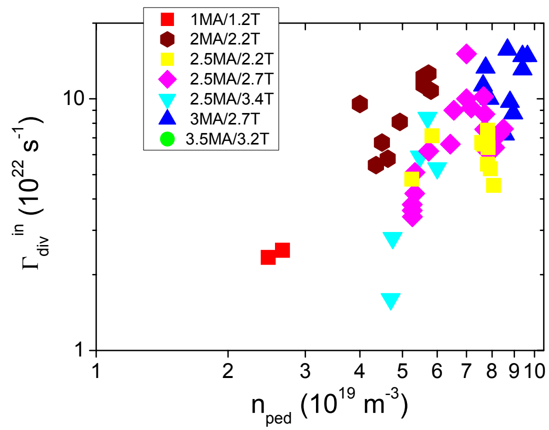
If edge ionisation determine edge profiles

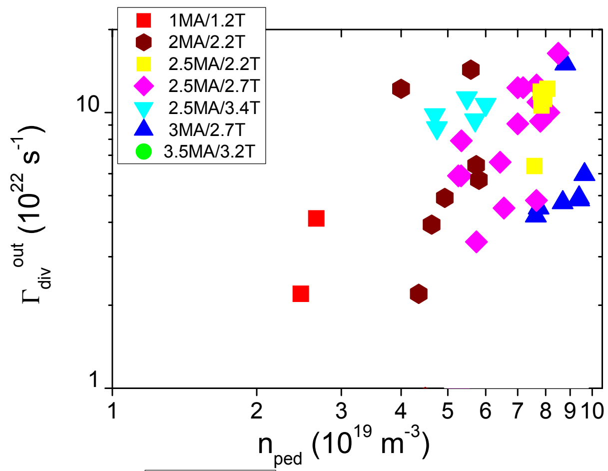
$n^{-1}\, dn/dR \sim I_p$

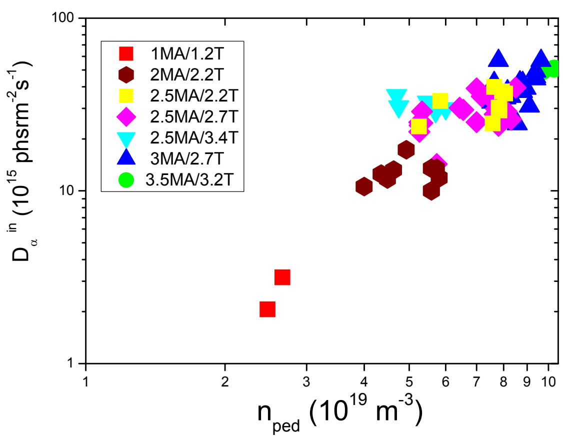
no clear evidence for enhanced ionisation and/or transport even for $n_{ped} \sim 10^{20}\ m^{-3}$ $T_{ped} \sim 1$ keV (I_p > 3MA)

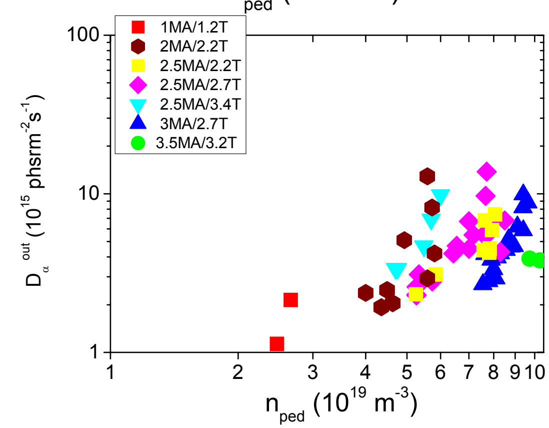
Particle balance in JET ELMy H-modes (VI)

Divertor fluxes in JET ELMy H-modes are usually > ϕ_D and in/out asymmetric



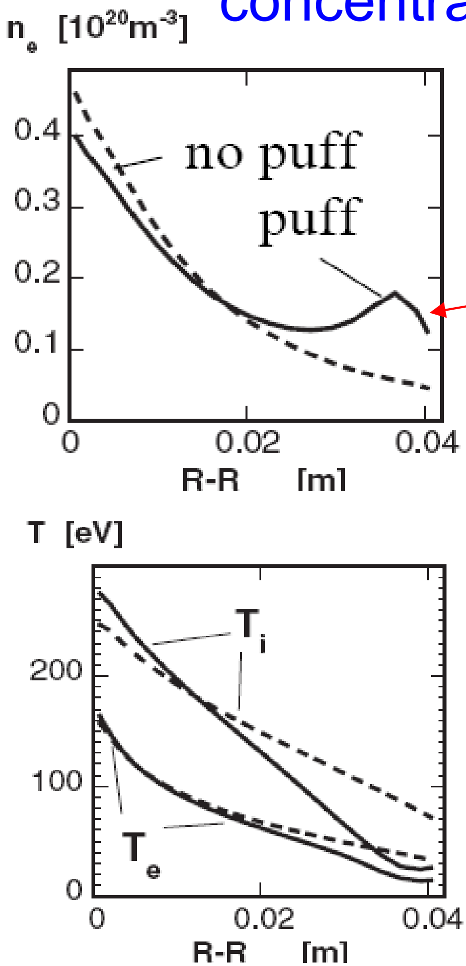


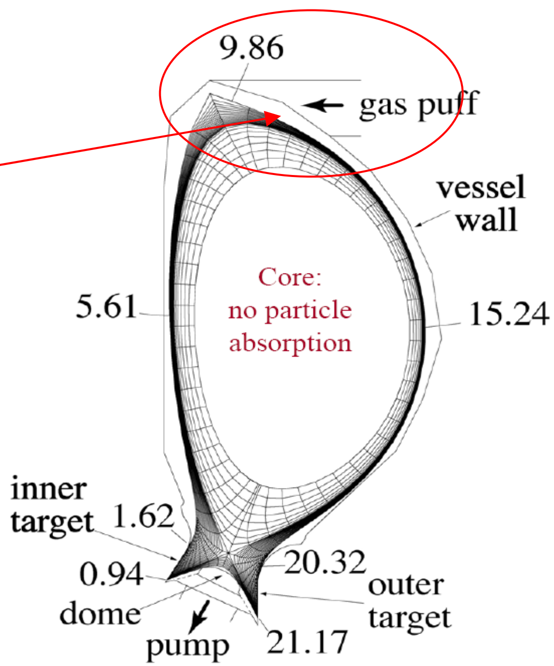


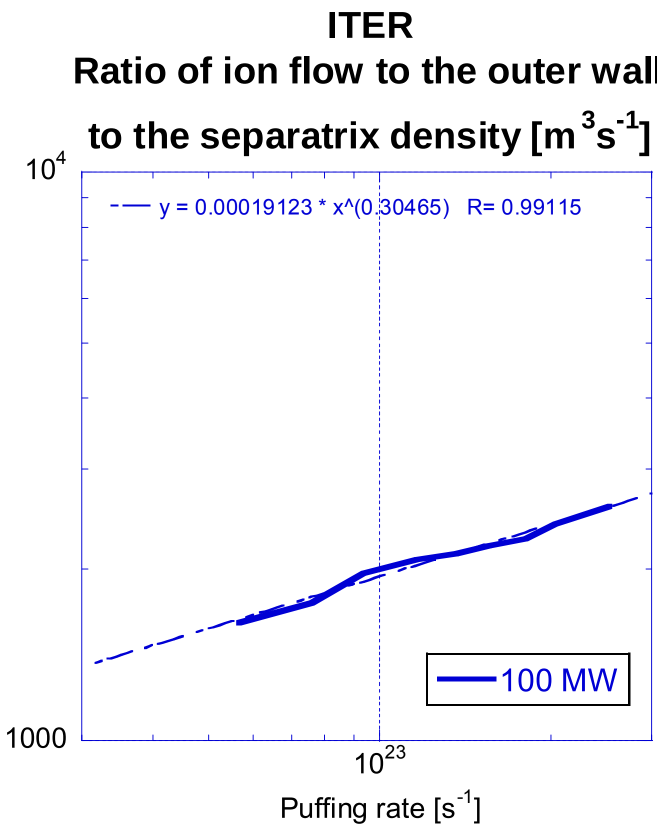


Role of divertor source versus main chamber source on fuelling of JET ELMy H-modes requires quantification can this explain JET/ITER difference ??

Modification of SOL profiles in ITER by gas puffing is locally concentrated near the gas puff location ($\phi_{wall} \sim \phi_D$)







Γ_{wall}/n_{sep} depends weakly on ϕ_D

Conclusions

- Gas fuelling of high density H-modes is expected to become ineffective with device size (particularly in ITER) due to SOL ionisation effects
- Fuelling of JET ELMy H-modes do not apparently back such expectations when comparing HT3 discharges 1 to 3.5 MA
- Reasons are not clear :
  - JET SOL opacity to neutrals could be insufficient to see effect
  - Edge particle transport description by D_{perp} is too simplistic
  - II SOL flows affect particle transport and neutral penetration

Given potential simplification of ITER operations detailed measurements at JET & modelling are required to determine if standard 2-D modelling explains particle balance in H-modes