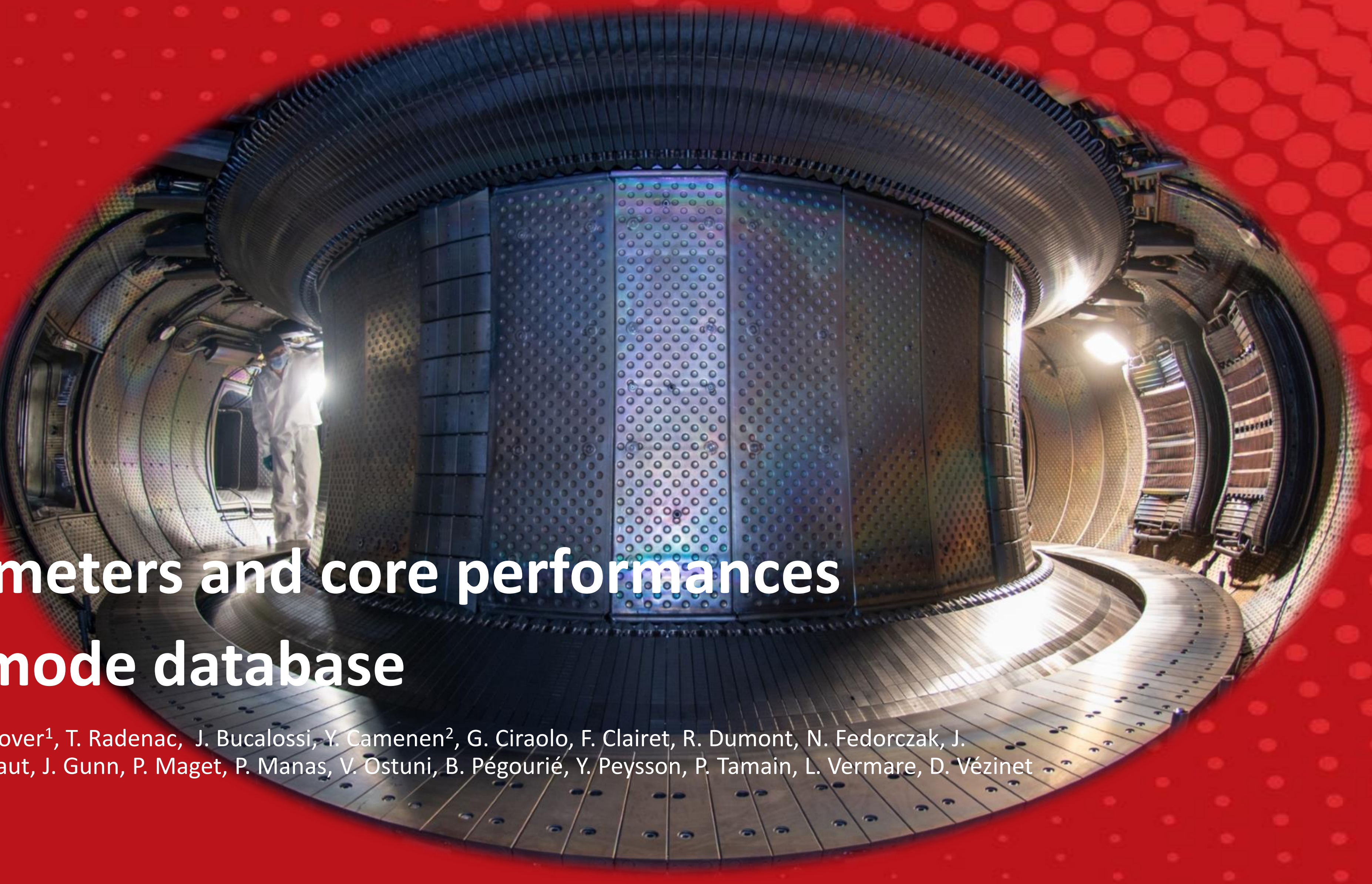
Separatrix parameters and core performances across WEST L-mode database

Clarisse Bourdelle, Jorge Morales, Jean François Artaud, T. Radenac, Jérôme Bucalossi, Frédéric Clairet, Guido Ciraolo, Rémi Dumont, Nicolas Fedorczak, Christophe Gil, et al.



Separatrix parameters and core performances across WEST L-mode database

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APS, Spokane, Oct. 2022

Explore the correlation between SOL and core across a whole database
Why?

- Since early tokamak operation, wall conditioning key impact on core performances

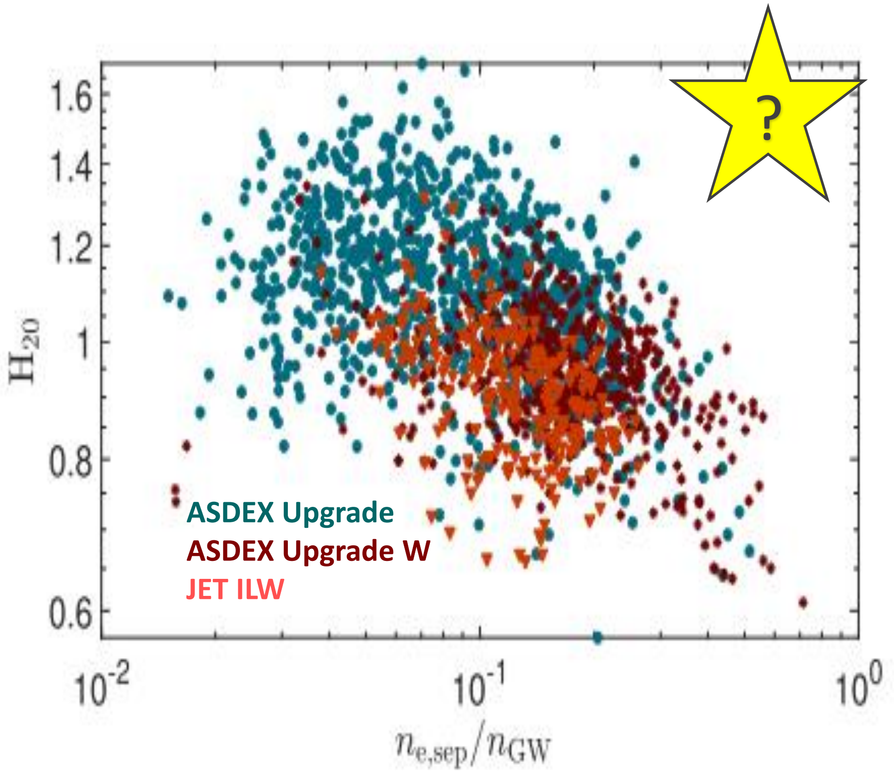
TFTR (limited) supershots [Strachan NF1994]. Lower recycling = better core performances.

$$\tau_E = 73 \boxed{H_\alpha^{-0.24}} \left(\frac{\beta_\parallel}{\beta_\perp}\right)^{0.85} n_e(0)^{0.60} B^{0.35} C_{NB}^{0.19}$$

Seen in Lithium conditioning in CDXU-LTX, (diverted) NSTX, EAST etc.

- Recently impact of n_{sep} (or T_{target}) on H factors reported [G. Verdoolaege, NF 2021, Lomanowski NF 2022]

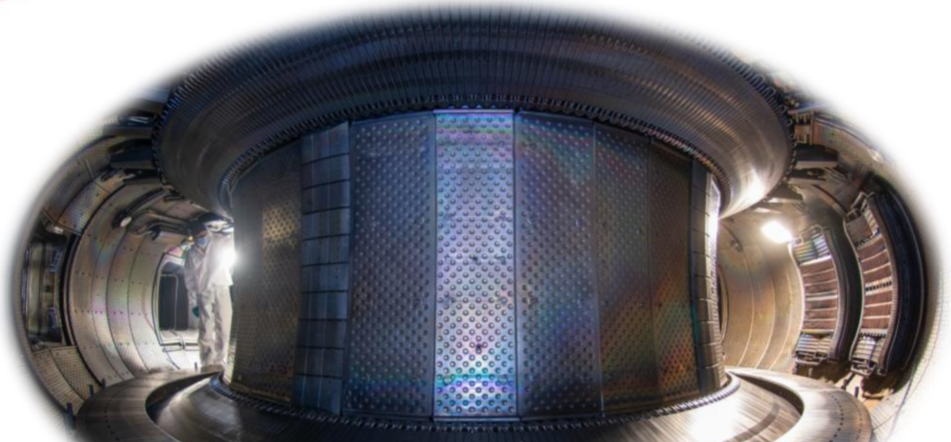
- In ITER or DEMO W environment need T_{target} <~eV to avoid W sputtering (and reduce heat load), hence large recycling, -depending on opacity- possibly large n_{sep}: this is not where the best performances of today/past tokamaks are reported



[G. Verdoolaege, NF 2021]

Explore the correlation between SOL and core across a whole database
How?

- systematic database analysis to avoid bias towards best performances
- WEST C4 and C5 campaigns exhaustive database of time averaged quantities over plateaus (>0.3s stable I_p and P_{tot}) 1249 Deuterium pulses [Morales @3:36PM 100C]
- Filtered P_{tot} >2MW (no ohmic pulses), I_p=0.5 MA, Lower Single Null, gas puff (no pellet): 800 plateaus



WEST

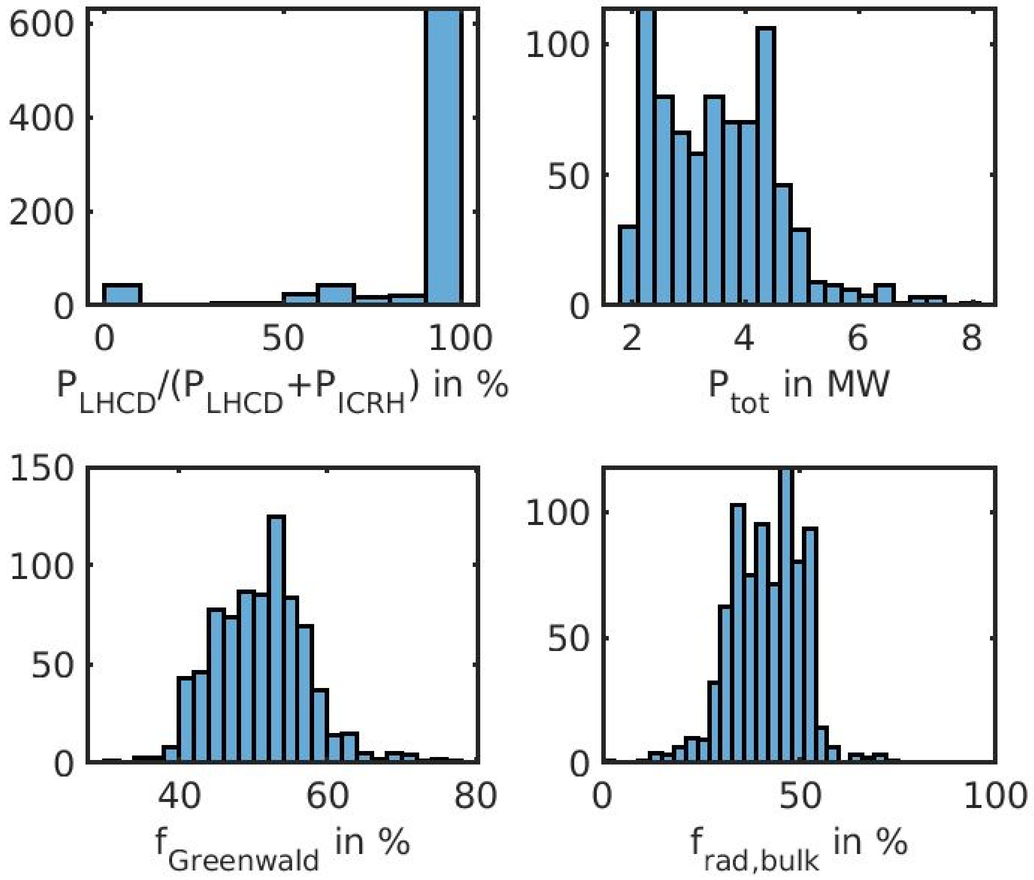
R=2.5m, a=0.4-0.5 m, A=5-6, plasma volume 15 m^3

3.7 T, W environment $f_{rad,bulk}$ ~42%

Dominant electron heating (LHCD/ICRH)

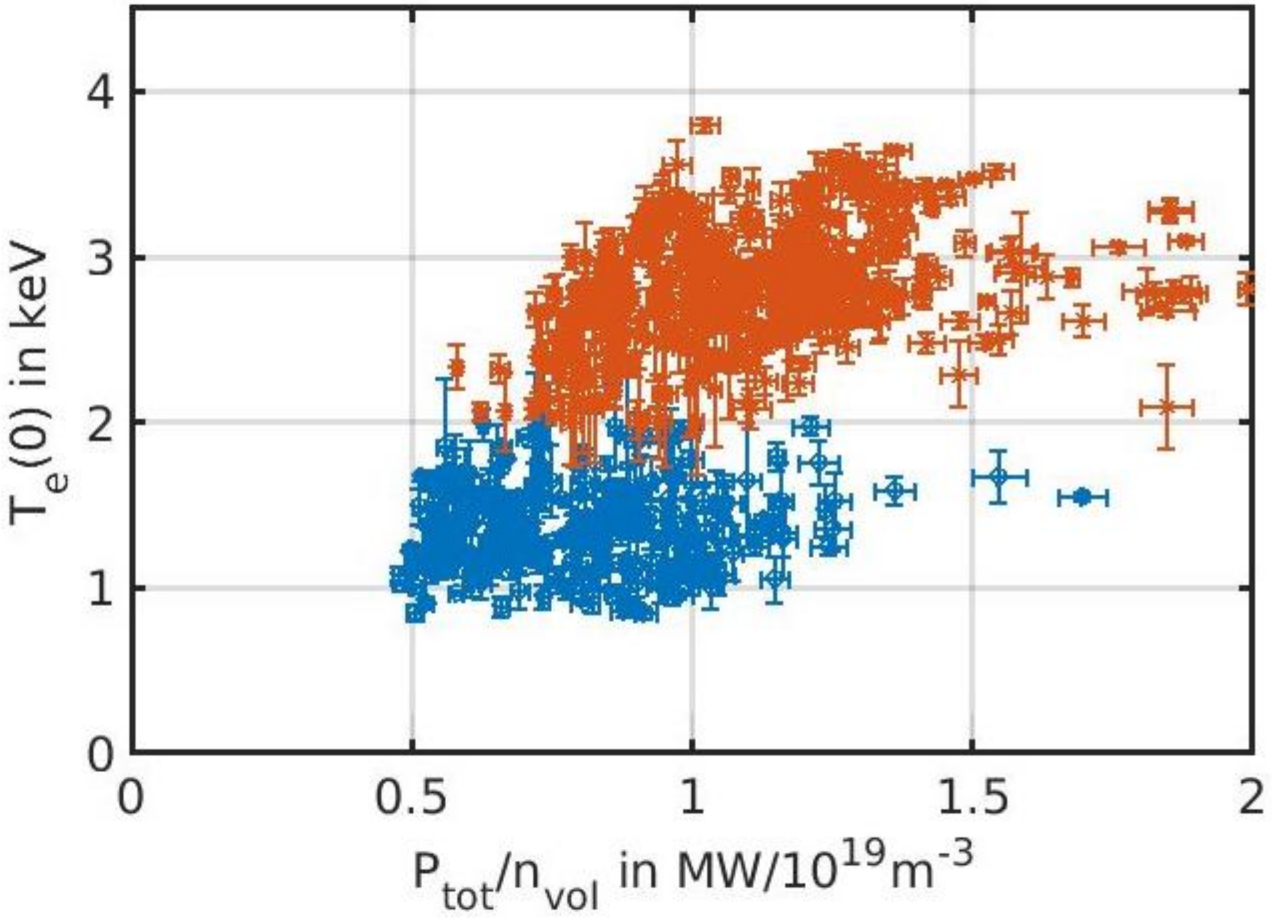
No NBI, hence intrinsic density peaking

L mode high recycling plasmas

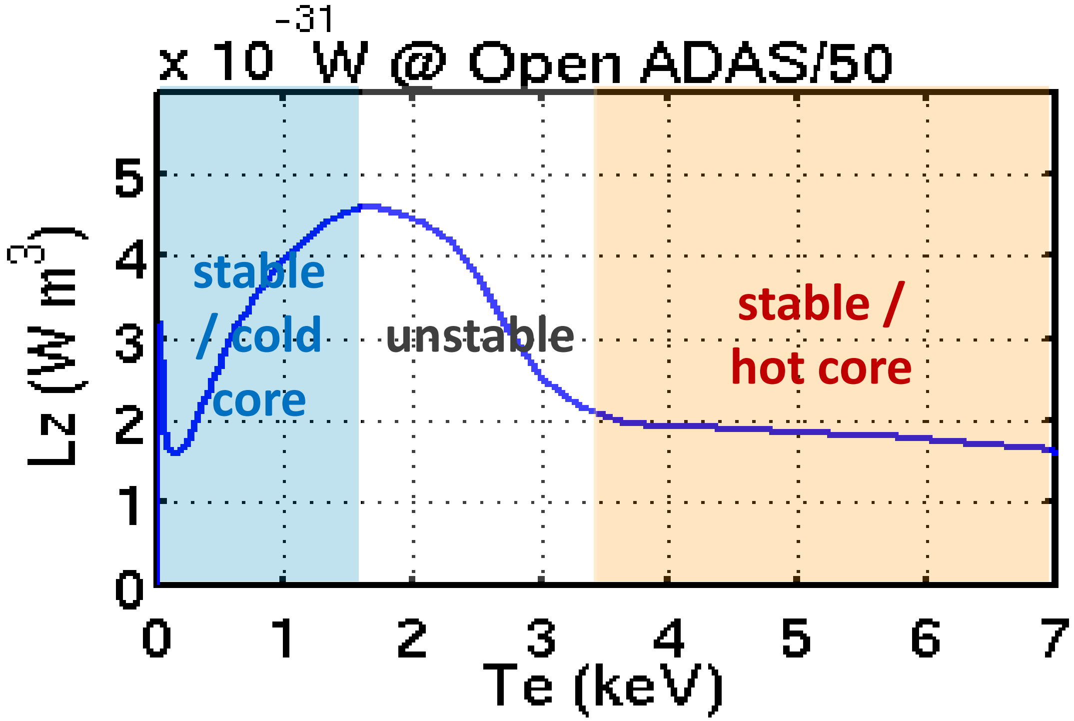


- Coexistence of a cold branch with a hot one in WEST W environment
- n_{sep}, $\bar{n}$, density peaking **and energy confinement time**
- Collisionality at separatrix **and energy confinement time**
- Recycled neutrals **and energy confinement time**
- Conclusions and perspectives

Coexistence of a cold branch with a hot one in WEST W environment



- Hot branch $T_e(0)$> 2 keV and increases with higher P_{tot}/n
- Cold branch: $T_e(0)$<2 keV no impact of larger P_{tot}/n



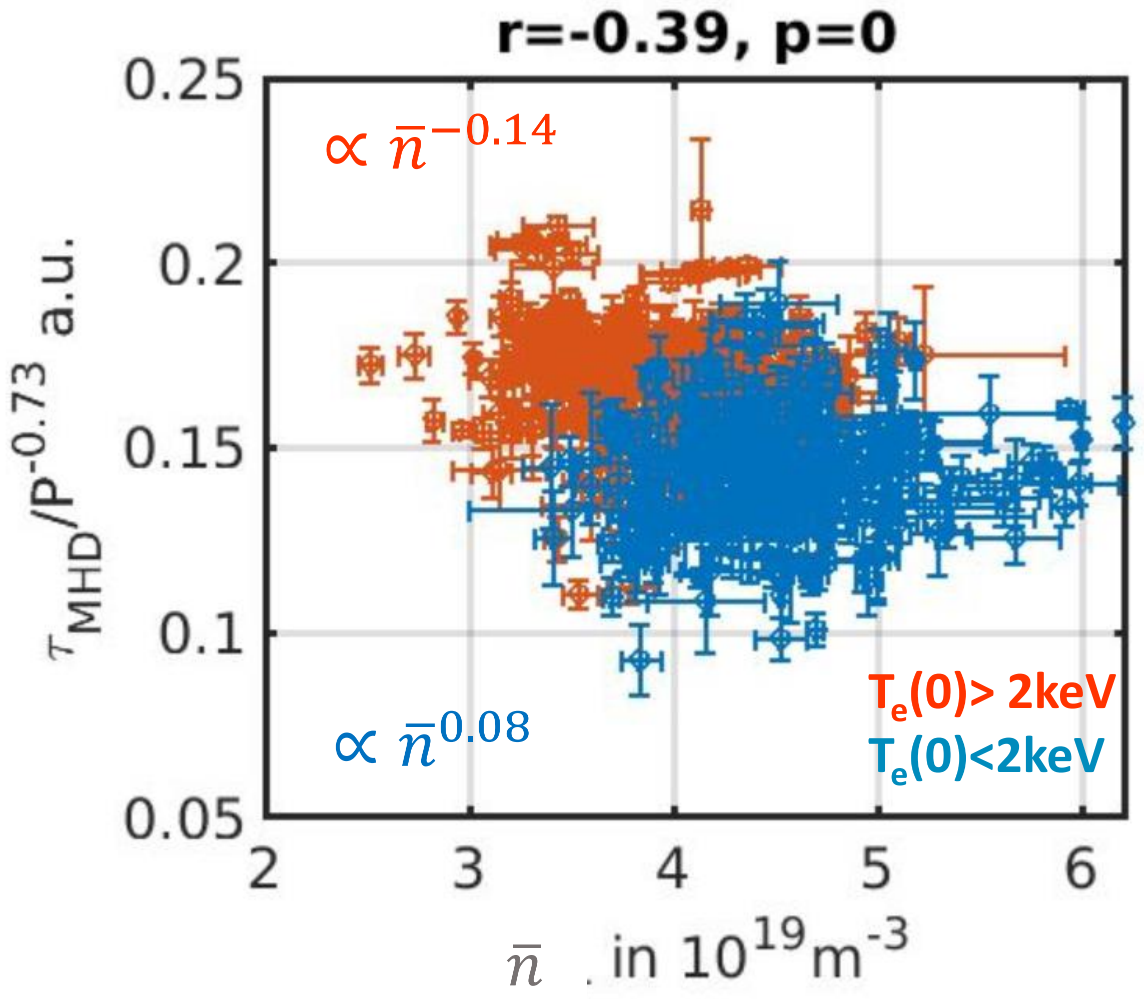
Same core n_W peaking and P_{rad}/P_{tot} on both branches

on hot branch: larger li, larger W_{MHD}

Core performance metric: $\tau_{MHD}/P^{-0.73}$ in a.u.

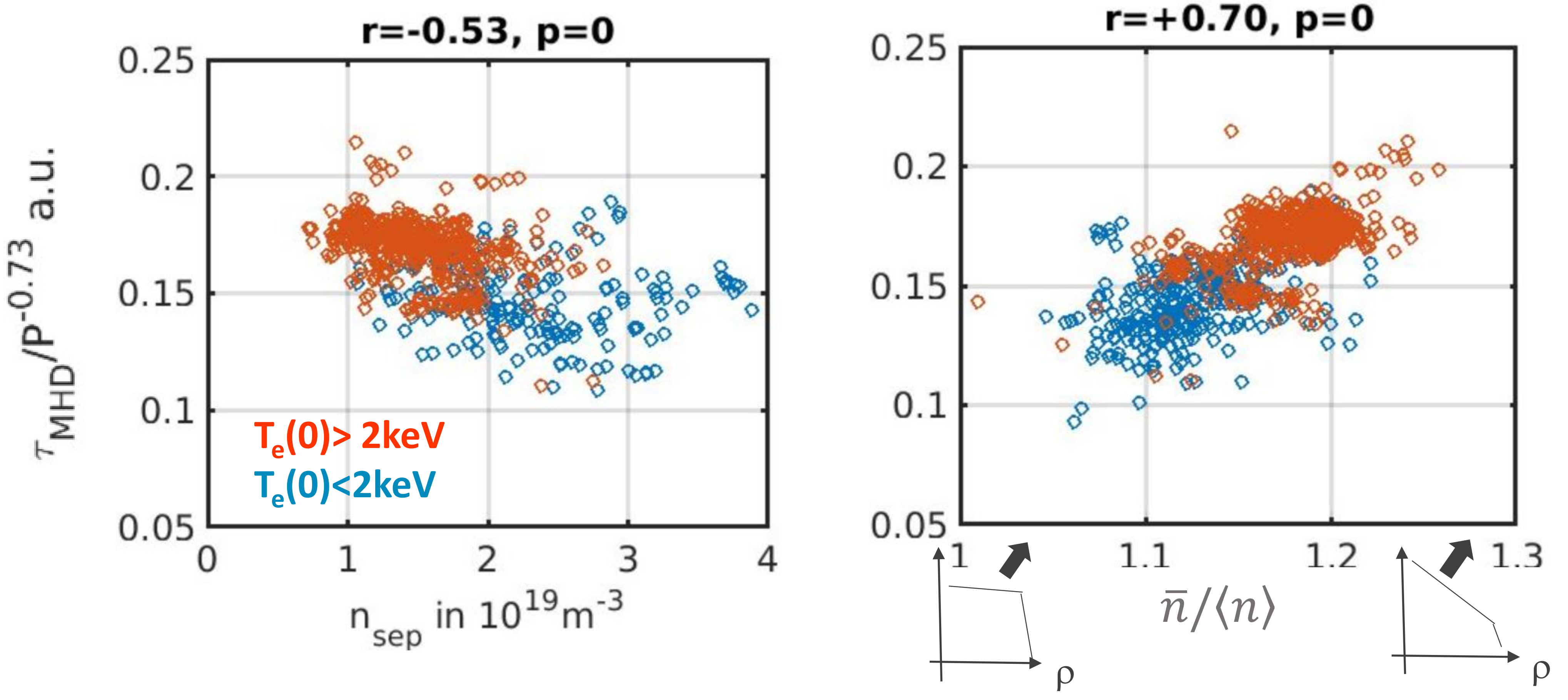
All data at 3.7T and 0.5 MA

- Power degradation on WEST database [Goniche NF 2022]: $P^{-0.73}$ as ITER L96 scaling
- Weak correlation $\tau_{MHD}/P^{-0.73}$ with line average density $\bar{n}$ (interf.) unlike $L_{96} \propto \bar{n}^{0.40}$ closer to ITPA2020 $\propto \bar{n}^{0.147\pm0.097}$
- next plots confined plasma perf. characterized by $\tau_{MHD}/P^{-0.73}$ in a.u.



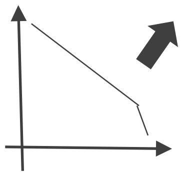
n_{sep}, density peaking and energy confinement time

- Energy confinement degradation with higher n_{sep} (reflectometry) as H mode in AUG/JET [Verdoolage NF2021]
- higher correlation btw larger $\tau_{MHD}/P^{-0.73}$ and larger density peaking (interferometry)



Short focus on density peaking: scaling with ν_{eff} or with n_{sep}?

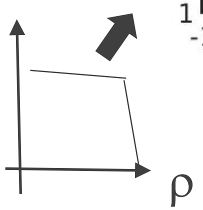
- $\bar{n}/\langle n\rangle$ is larger for lower n_{sep}

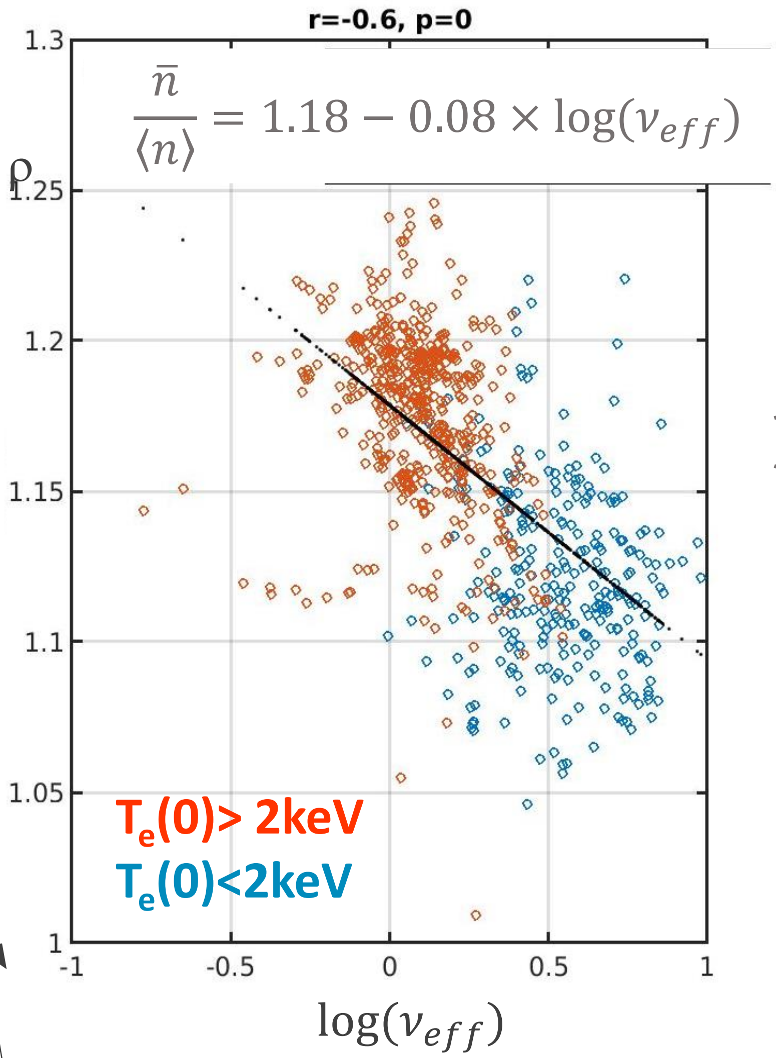


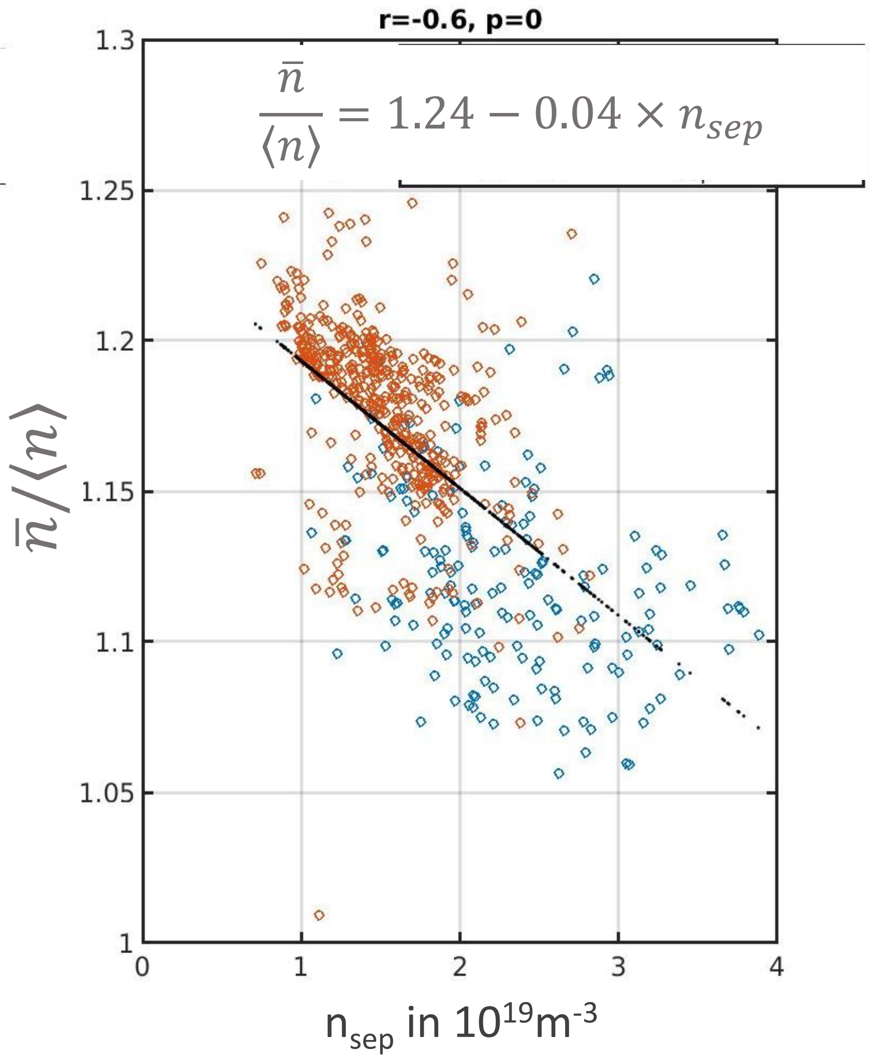
- AND recover $\bar{n}/\langle n\rangle$ scaling with vol. averaged ν_{eff} as found on AUG and JET H mode database [Angioni NF2007]

$$pk_{\mathrm{scl}\,\nu} = 1.347 \pm 0.014 - (0.117 \pm 0.005)\log(\nu_{\mathrm{eff}}) + (1.331 \pm 0.117)\Gamma^{*}_{\mathrm{NBI}} - (4.030 \pm 0.810)\beta, \qquad (3)$$

- Extrapolation towards ITER density peaking likely differ if using correlation with ν_{eff} or with n_{sep}



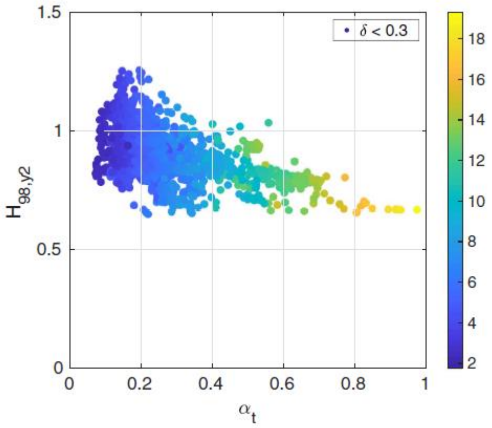




Correlation core energy confinement with n_{sep}: source or transport?

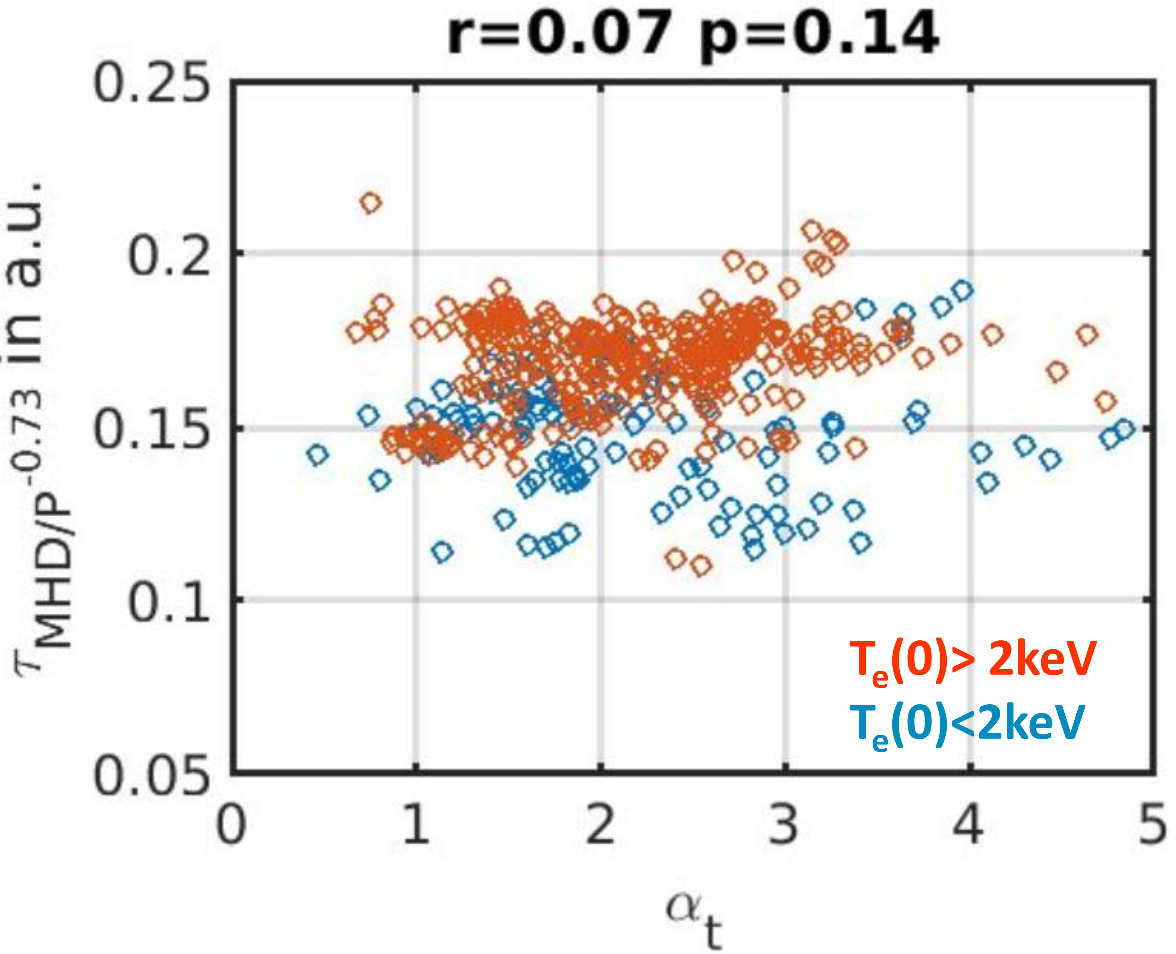
- Resistive interchange turbulence drive in separatrix figure of merit : $\alpha_t = 3.1310^{-18} R_{geo} q_{cyl}^2 \frac{n_{sep}}{T_{sep}^2} Z_{eff}$ [Scott PoP2005] similar to α_d of [Rogers PRL98]

- In AUG H mode database, lower H factor for higher α_t [Eich NF2020]



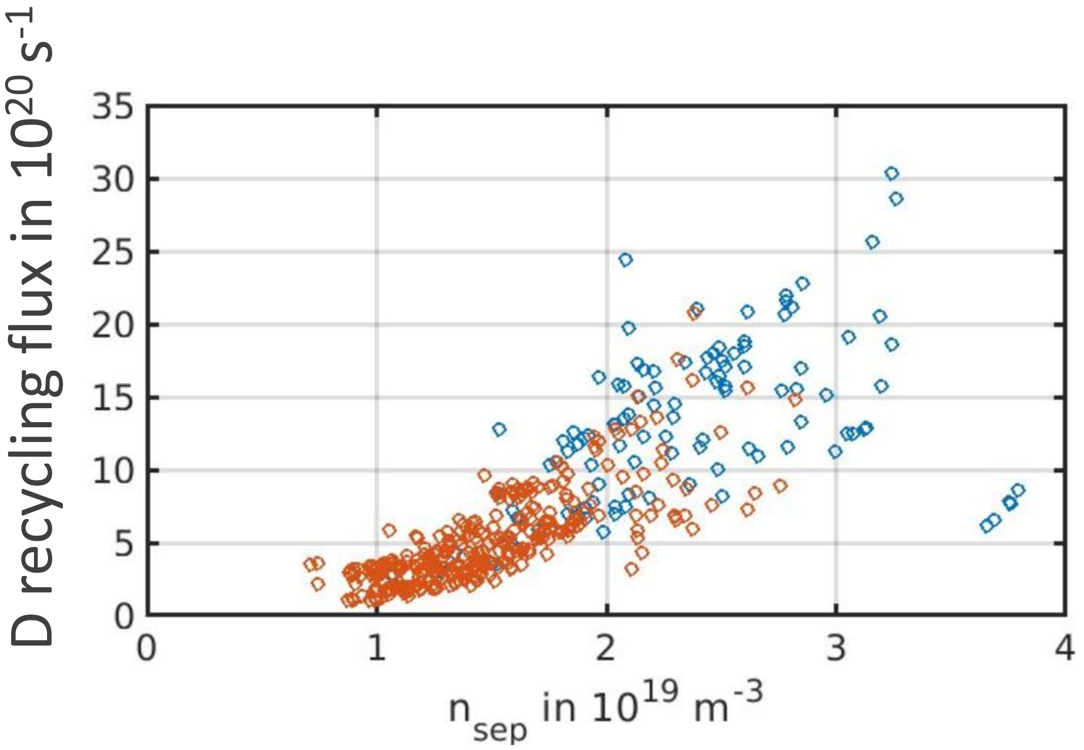
- Here: n_{sep} from reflectometry, T_{sep} from reversed 2 point model using Langmuir Probes in divertor target

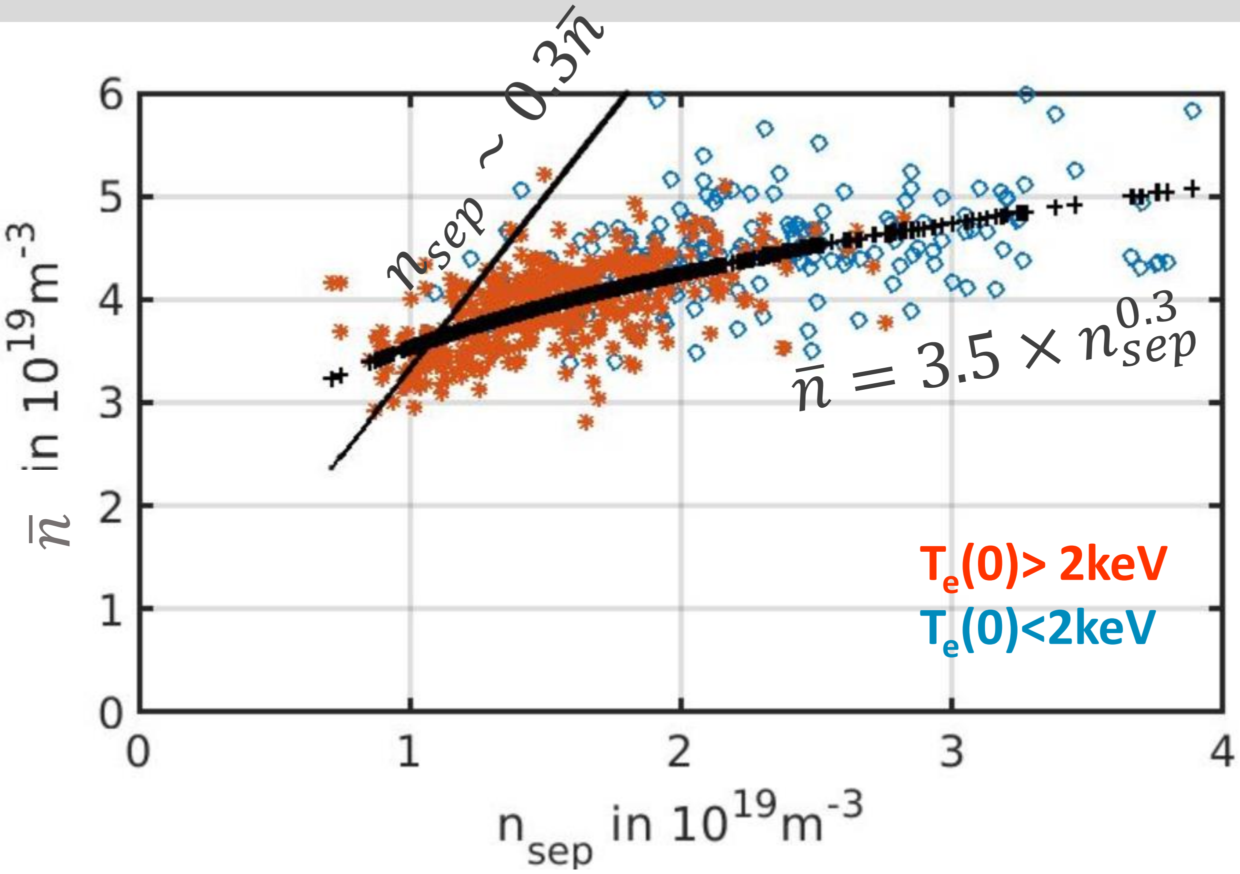
- No correlation between confinement quality and α_t reported in our L mode database



Correlation core energy confinement with n_{sep}: source ~~or transport~~?

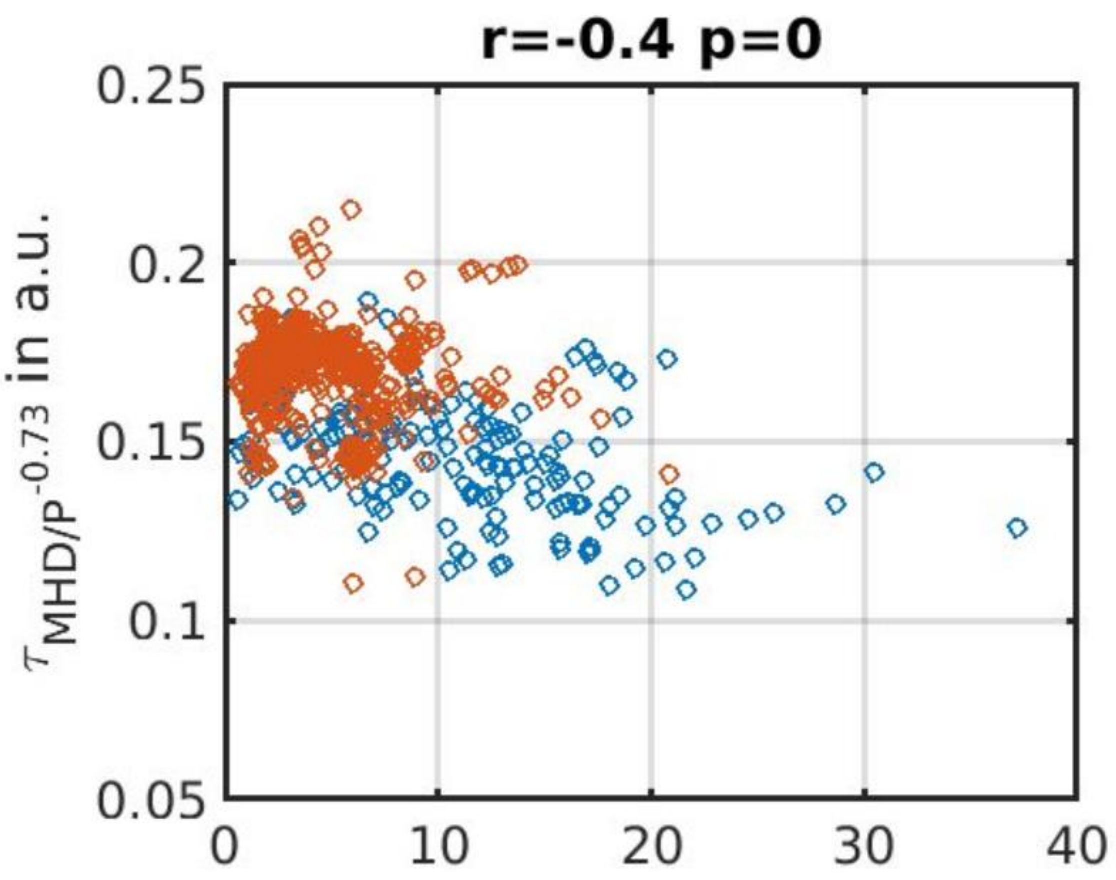
- High recycling regime. no control of n_{sep} through feedback controlled interferometry central line integrated density, $\bar{n}$



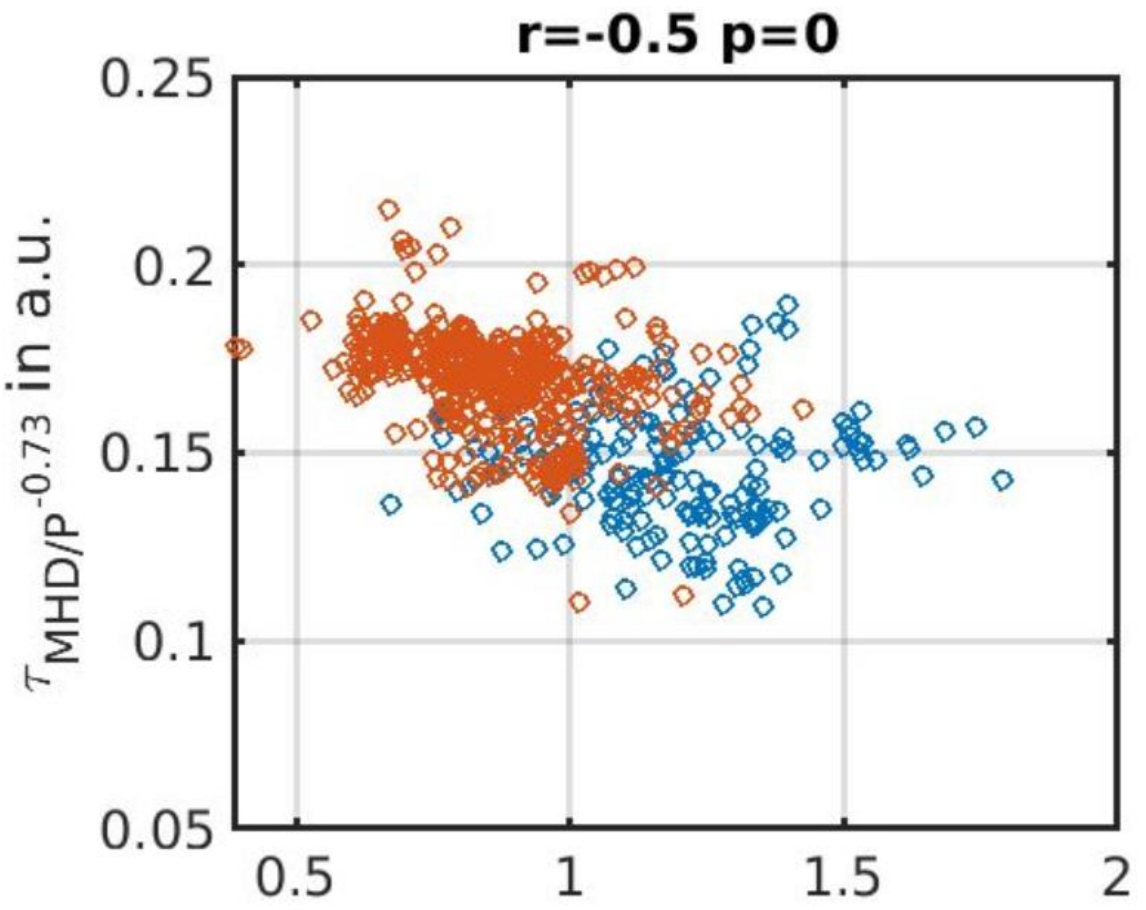


- On contrary n_{sep} correlates strongly with D recycling flux (visible spectro, 4341 Å corrected for S/XB) at divertor target (inner and outer)

Lower D recycling at divertor targets, less opacity correlate with better core performances



D recycling flux, outer div., in 10^{20} s^{-1}



$$opacity = a.\frac{n_e(0.95) \ + n_{e,sep}}{2}$$

Summary, perspectives

In WEST L mode high recycling database, higher core performances correlate with:

- Lower: n_{sep}, opacity, D recycling flux at divertor, volume average collisionality
- Higher: $\bar{n}/\langle n \rangle$, $\frac{-\nabla n}{n}$ at separatrix (reflec.), $T_e(0)$, internal inductance

[Bourdelle sub. to NF]

I. Extend such analysis to **multi machines databases** (using IMAS data format standard)**, to H mode database, to different divertor closures (with metric for closure)** to challenge universality of trends

II. Causality chain? **integration of neutral models with L-mode edge validated turbulent transport** TGLF-sat2 [Angioni NF22] in the High Fidelity Pulse Simulator [more @ my poster Tomorrow]

III. Extrapolation towards future machines ITER, DEMO,… where smaller ratio of the ionization/CX length to machine size & weaker pumping w.r. vessel. Also guide the divertor/wall material choice also with respect to core performances. Liquid metals, an optimized choice? Reinforce R&D on liquid metal loops?

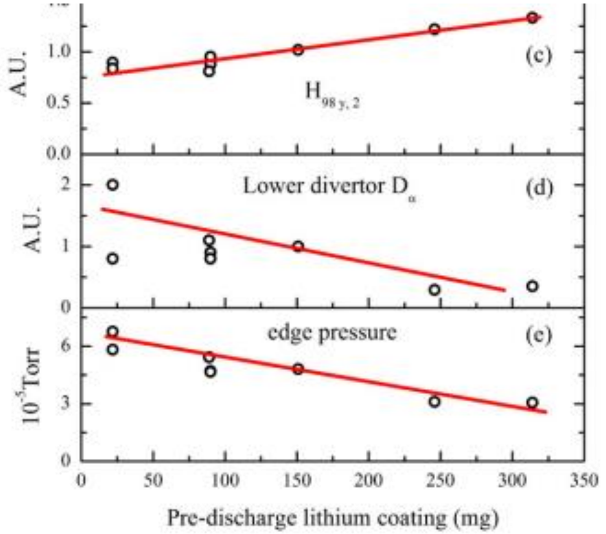
Thank you for your attention

Some experimental observations:

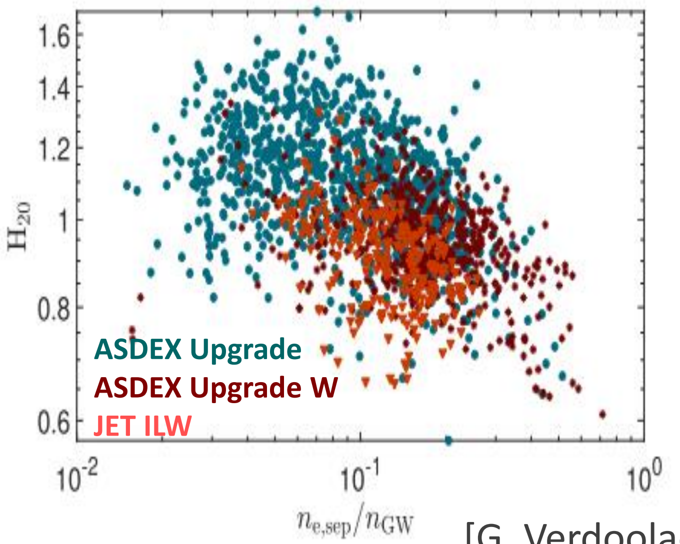
$$\tau_E = 73 H_\alpha^{-0.24} \left(\frac{\beta_\parallel}{\beta_\perp}\right)^{0.85} n_e(0)^{0.60} B^{0.35} C_{NB}^{0.19}$$

[Strachan PoP1994] TFTR C limiter

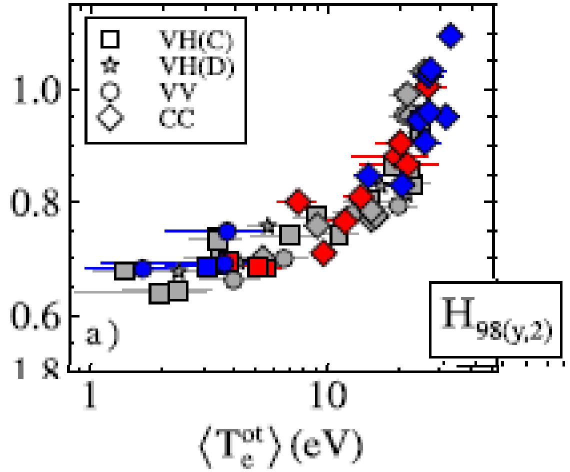
- Neutral recycled from wall, divertor and/or limiters impacting the performances.
- Better performances if lithiumisation/boronization/siliconisation (NSTX, EAST, TEXTOR etc)
- Higher H factor correlates with lower n_{sep} and also higher T_{target}



[Cao PPCF2012] NSTX Li coating

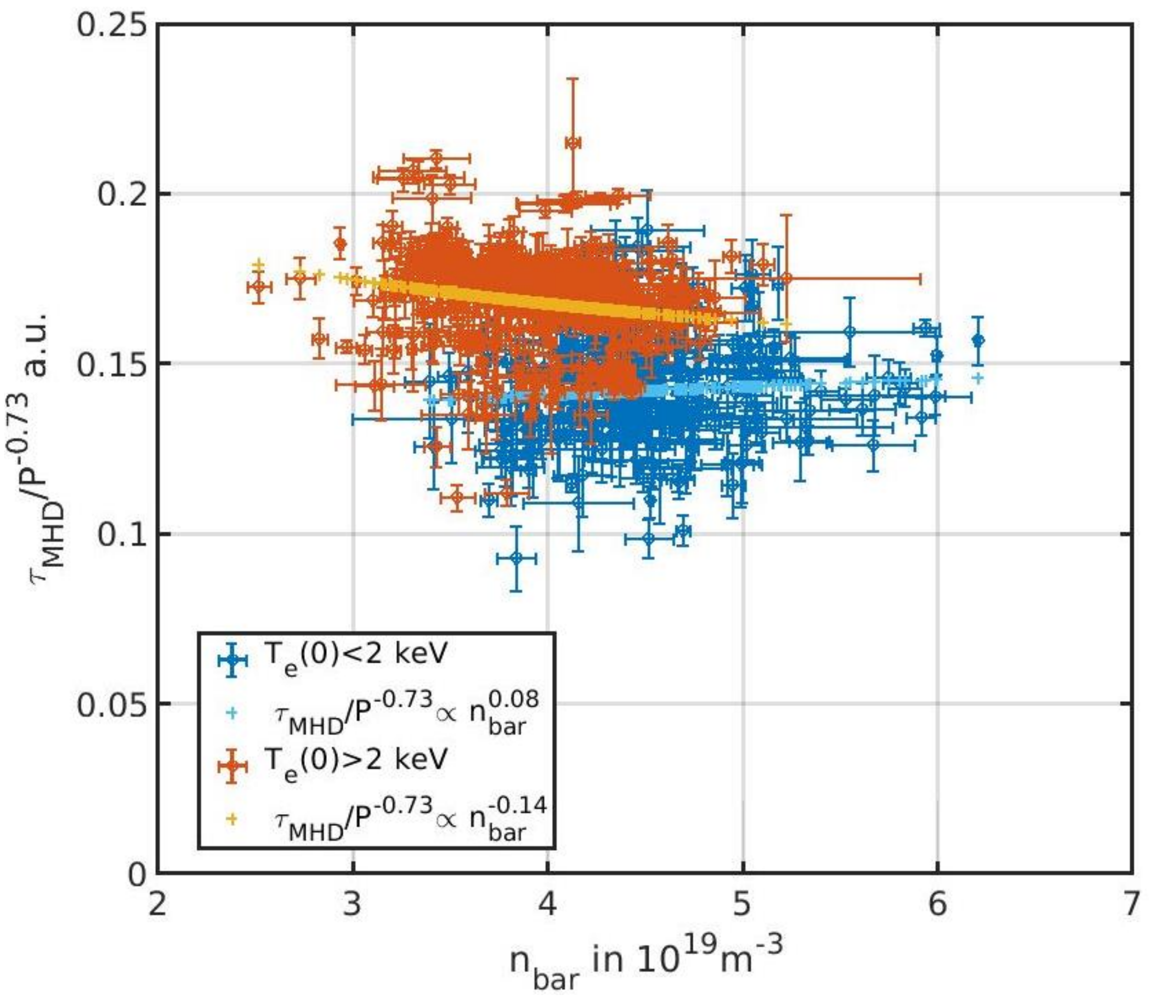


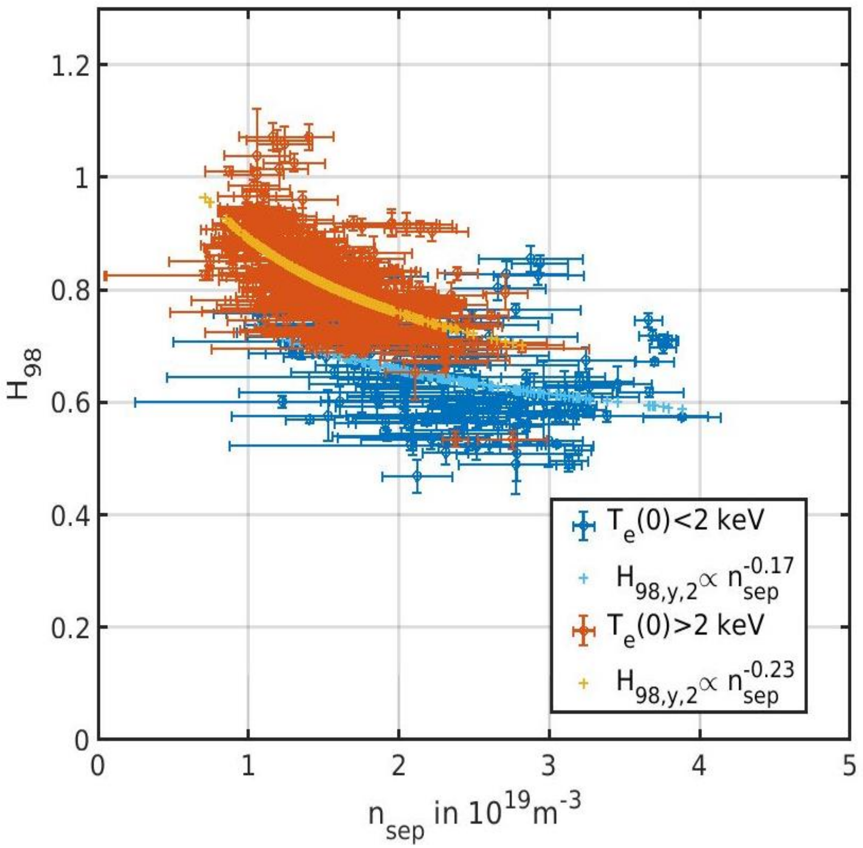
[G. Verdoolaege, NF 2021]



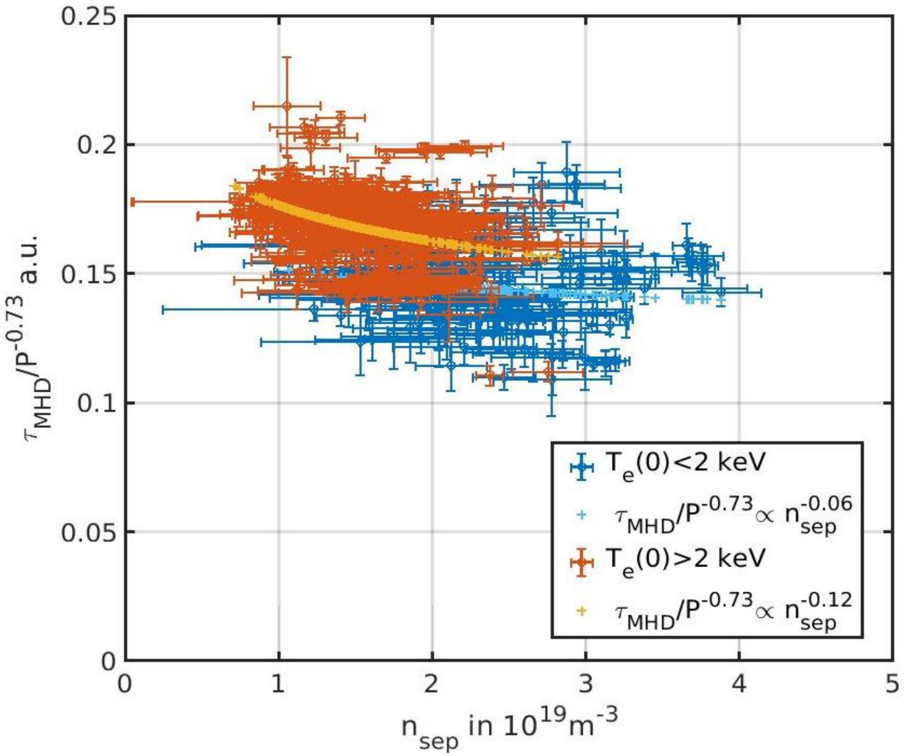
[B. Lomanowski, NF 2022], JET ILW

Pointing towards an impact of neutral recycling source on core performances


0.25
0.2
0.15
0.1
0.05
0
2
3
4
5
6
7
$\tau_{MHD}/P^{-0.73}$ a.u.
n_{bar} in $10^{19}m^{-3}$
$T_e(0)$<2 keV
$\tau_{MHD}/P^{-0.73} \propto n_{bar}^{0.08}$
$T_e(0)$>2 keV
$\tau_{MHD}/P^{-0.73} \propto n_{bar}^{-0.14}$



H98
n sep in 10^19 m^-3
Te(0)<2 keV
H98,y,2 ∝ n sep^-0.17
Te(0)>2 keV
H98,y,2 ∝ n sep^-0.23



τMHD/P^-0.73 a.u.
n sep in 10^19 m^-3
Te(0)<2 keV
τMHD/P^-0.73 ∝ n sep^-0.06
Te(0)>2 keV
τMHD/P^-0.73 ∝ n sep^-0.12

T_{sep} from the '2 Point Model'

parallel heat flux conservation to infer from the measured target T_t and parallel heat flux, $q_{\parallel,t}$ by Langmuir Probes, the upstream temperature, T_u

2 equations (inner and outer targets), 2 unknowns T_u and $L_{\parallel,out}$:

$$T_{e,u}^{7/2} = T_{e,t,in}^{7/2} + \frac{7}{2}\frac{1}{\kappa_{\parallel 0}}(L_\parallel - L_{\parallel,out})\left(q_{\parallel,e,u} f_{cond} f_{in}\right)$$

$$T_{e,u}^{7/2} = T_{e,t,out}^{7/2} + \frac{7}{2}\frac{1}{\kappa_{\parallel 0}} L_{\parallel,out}\left(q_{\parallel,e,u} f_{cond} f_{out}\right)$$

With:

$q_{\parallel,e,u} f_{cond} f_{in} = q_{\parallel,e,t,in}/(1 - f_{cooling,in})$ and $q_{\parallel,e,u} f_{cond} f_{out} = q_{\parallel,e,t,out}/(1 - f_{cooling,out})$

$q_{\parallel,e,t} = \gamma T_t j_{sat}^{+}/e$ the electron heat flux on target measured by the probes, $\gamma \approx 5.3$.

$A = \frac{7}{2}\frac{1}{\kappa_{\parallel 0}}$, $\kappa_{\parallel 0} \approx 2000/Z_{eff}$

$L_\parallel = 2\pi R_{geo} q_{cyl}$

Assuming:

$T_i = T_e$

$(1 - f_{cooling}) \approx 1$

2 Point Model consistency check validate T_{sep} estimate

$T_{sep}=T_u$ in momentum conservation equation :

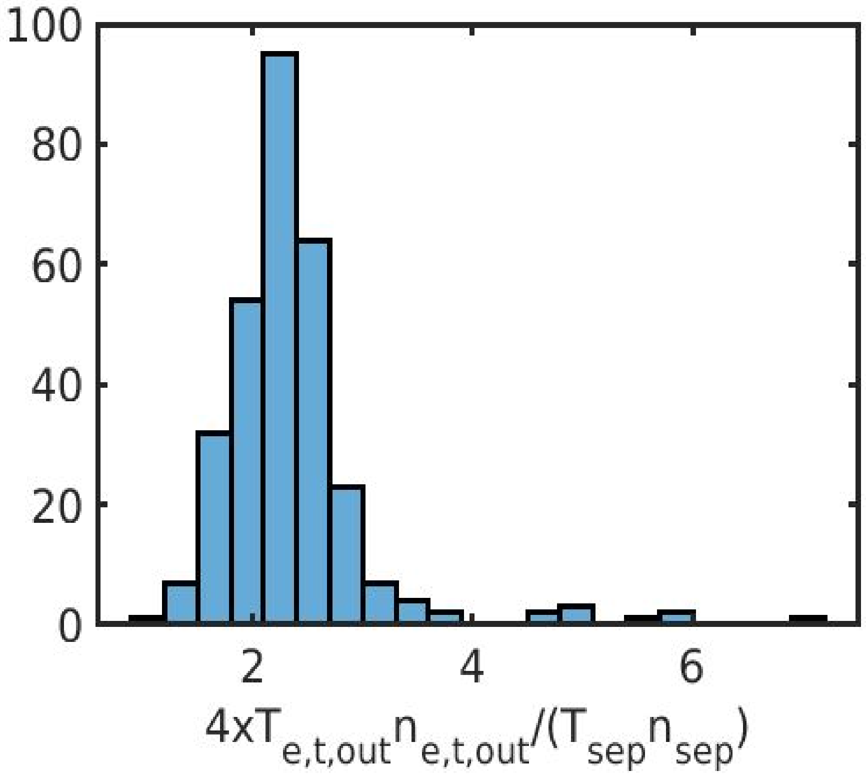
$$n_{e,u}T_{e,u}\left(1+\frac{T_{i,u}}{T_{e,u}}\right)f_{mom} = 4n_{e,t}T_{e,t}$$

assuming no dilution of the main ions and

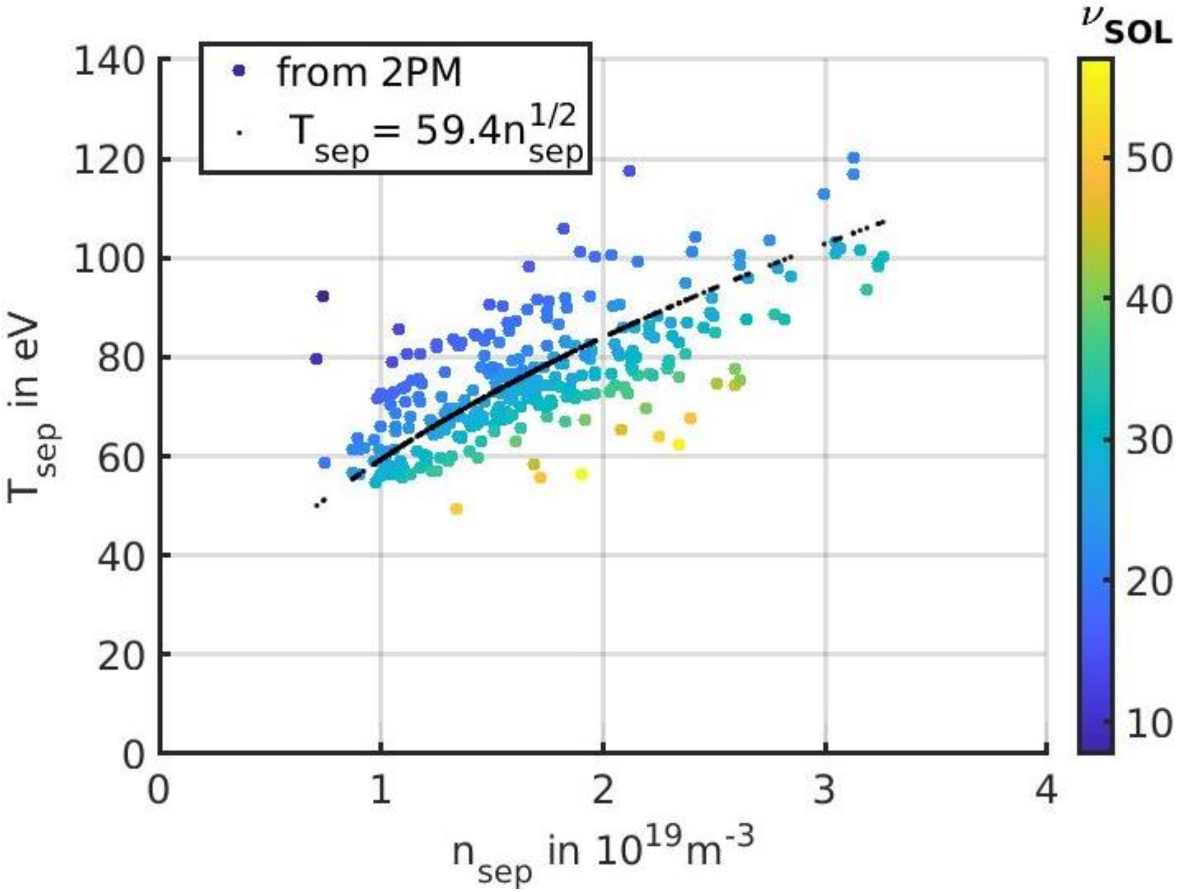
$T_i = T_e$ on the target plates.

$n_{e,t}$ from Langmuir probes measurements

If $T_{e,u}$ is meaningful, $\frac{4n_{e,t}T_{e,t}}{n_{e,u}T_{e,u}} = \left(1+\right.$



No correlation between collisionality at separatrix and n_{sep}



As reported in JET and Cmod
High recycling L and H modes

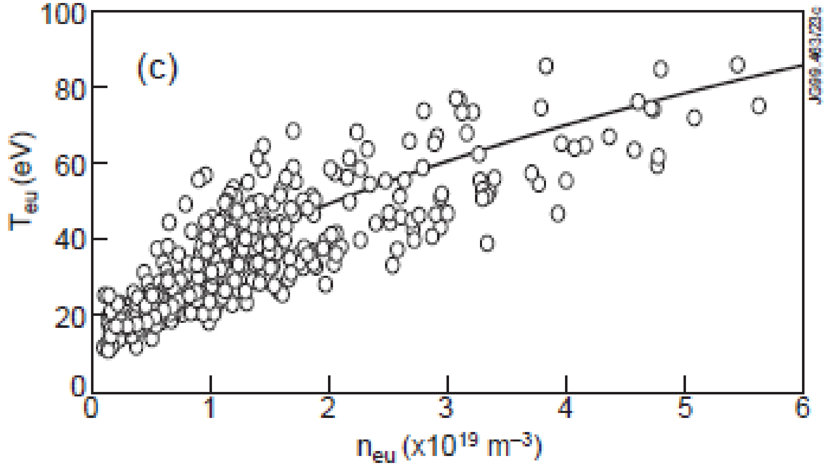
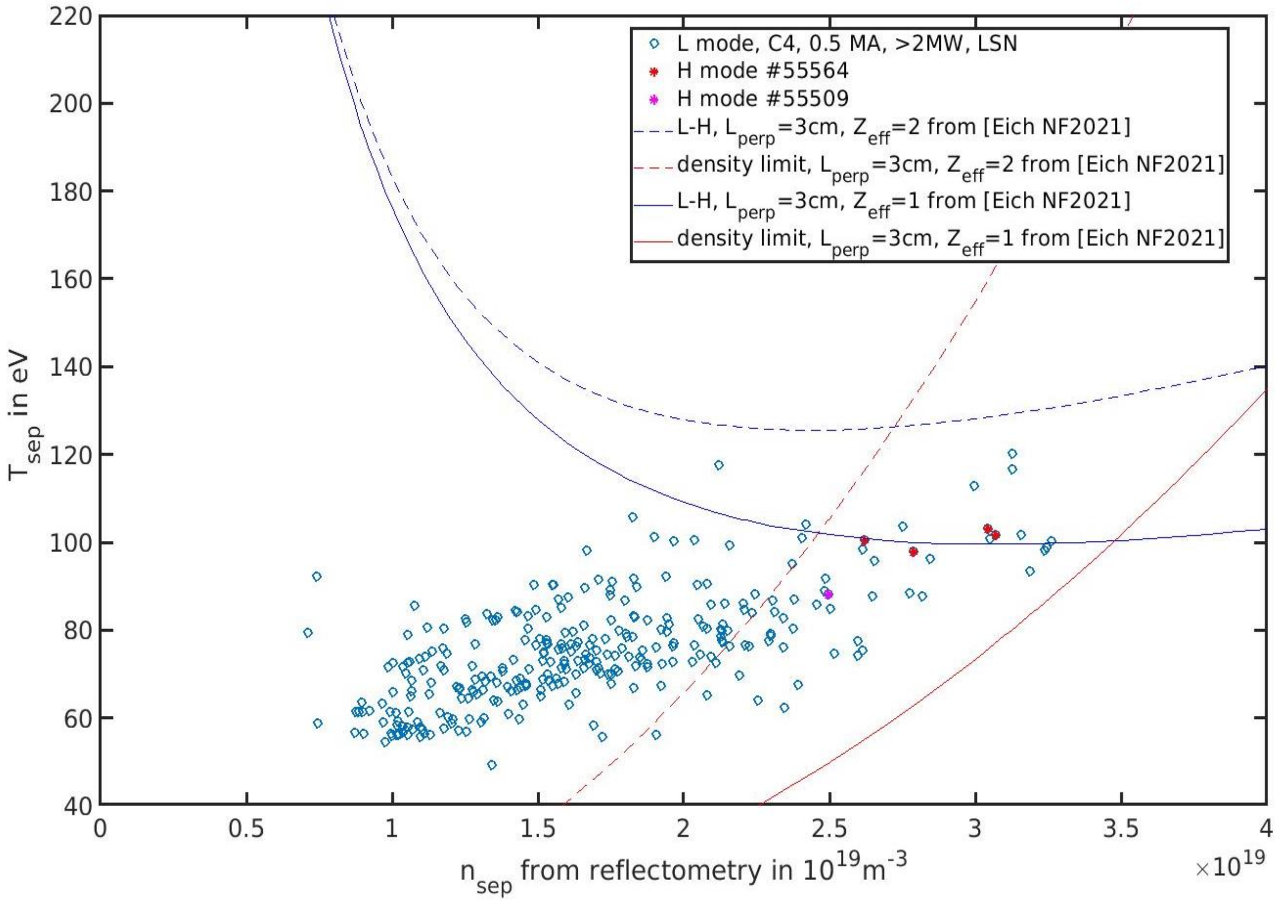
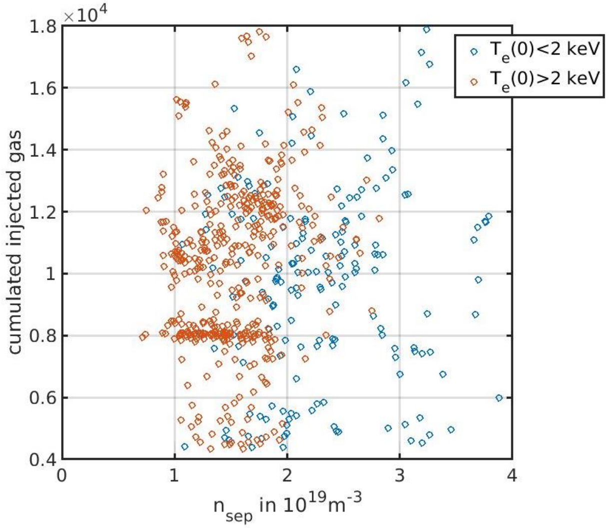


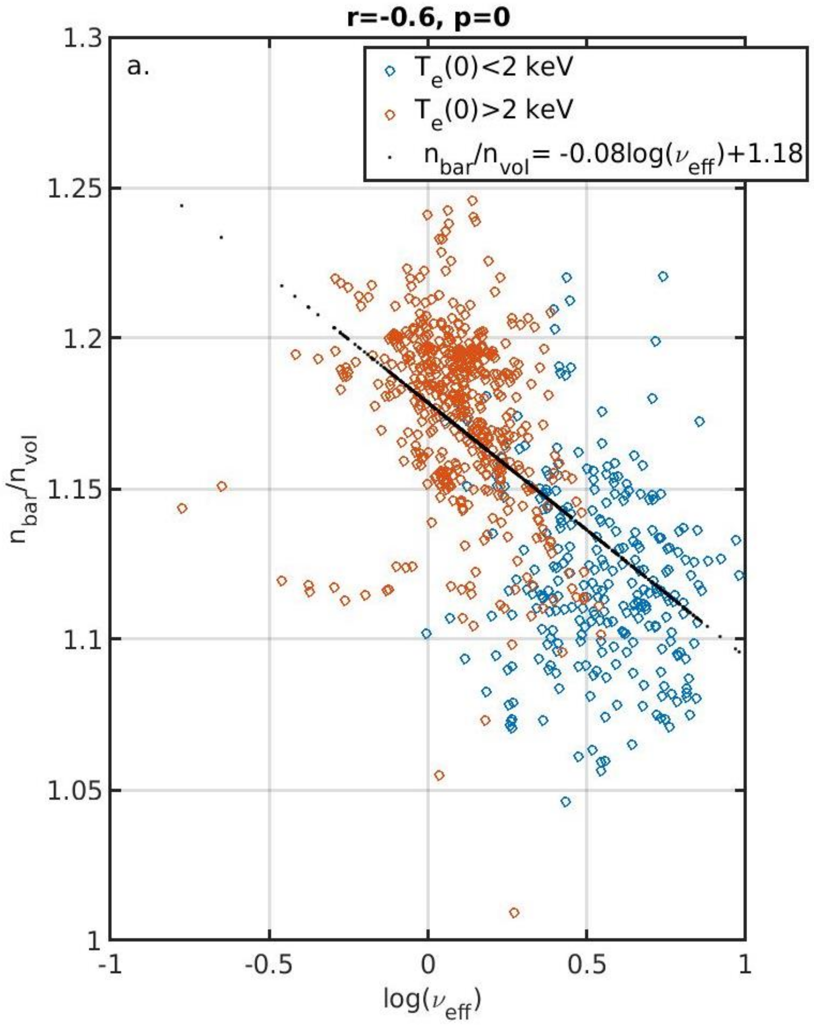
Figure 2. (a) T_{eu} versus n_{eu} for separatrix values: OSM results for the JET Mark II divertor, H mode. A sin-

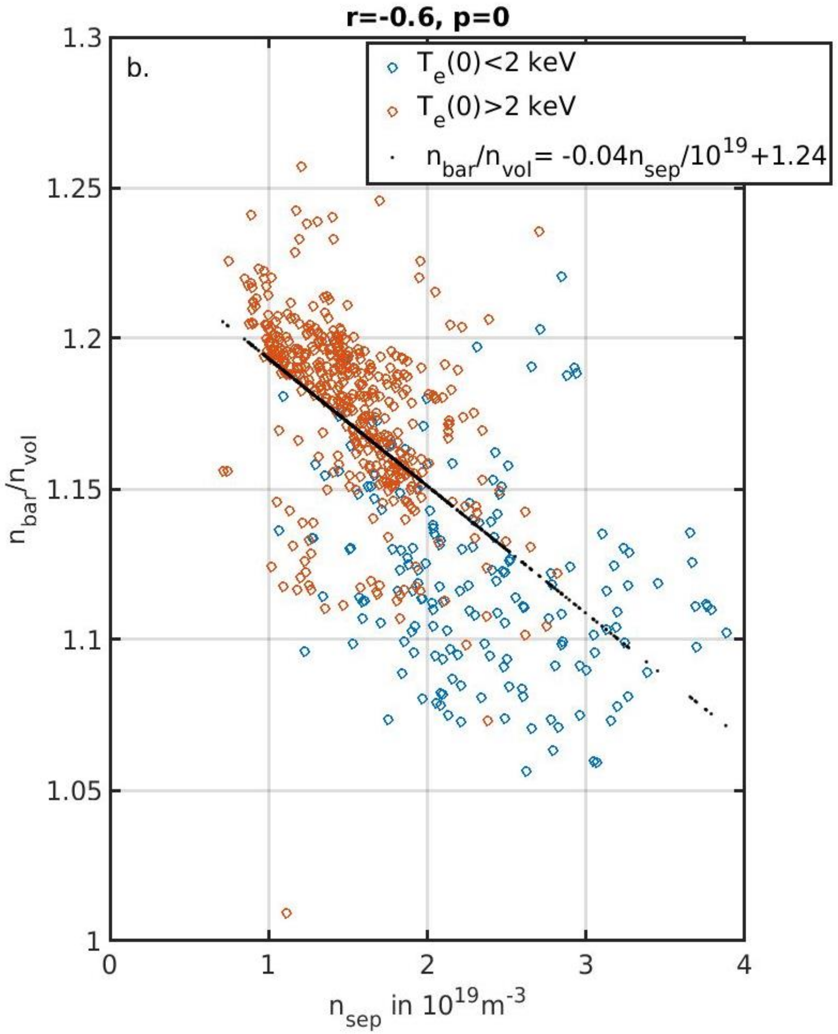
Erents NF2000


L mode, C4, 0.5 MA, >2MW, LSN
H mode #55564
H mode #55509
L-H, Lperp=3cm, Zeff=2 from [Eich NF2021]
density limit, Lperp=3cm, Zeff=2 from [Eich NF2021]
L-H, Lperp=3cm, Zeff=1 from [Eich NF2021]
density limit, Lperp=3cm, Zeff=1 from [Eich NF2021]
Tsep in eV
nsep from reflectometry in 10^19 m^-3
×10^19
220
200
180
160
140
120
100
80
60
40
0
0.5
1
1.5
2
2.5
3
3.5
4

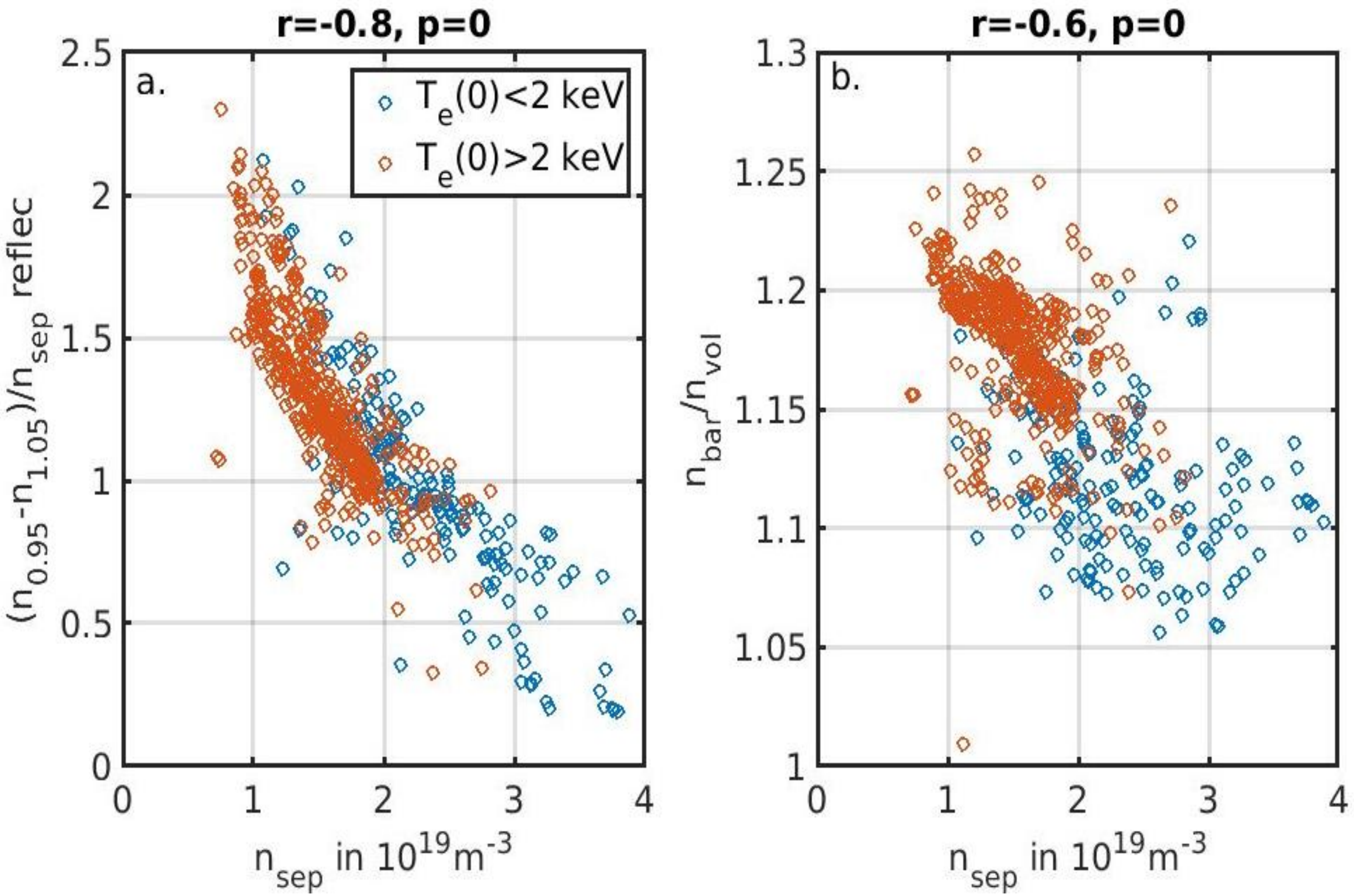

×10^4
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0
1
2
3
4
cumulated injected gas
n_sep in 10^19 m^-3
T_e(0)<2 keV
T_e(0)>2 keV

Density peaking highest at lowest vol. av. collisionalities [Angioni 2007] and also at lowest nsep, how to extrapolate towards ITER for example?





Density pealing at separatrix is higher when global peaking is higher



Boronization not allowing to reduce recycling