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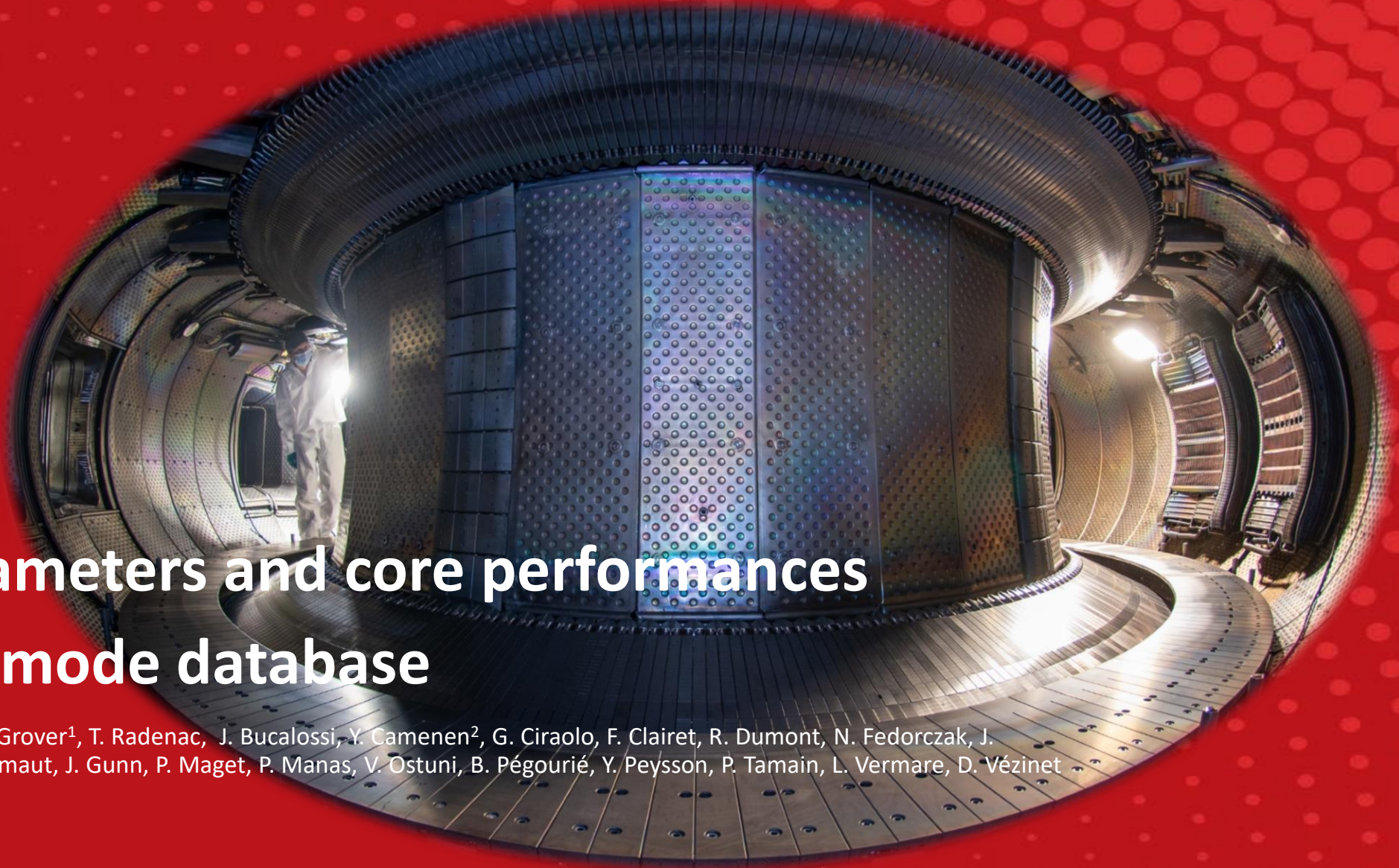
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The logo for IRFM (Institut de Recherches pour les Fusions Magnétiques) features the letters 'IRFM' in a stylized font with a green and yellow circular graphic element.The logo for WEST (WEST-Upgrade Tokamak Experiment) features the word 'WEST' in a stylized font with a green and yellow circular graphic element.The logo for CEA (Commissariat à l'énergie atomique et aux énergies alternatives) features the word 'cea' in a stylized font with a green horizontal line underneath.

Separatrix parameters and core performances across WEST L-mode database

C. Bourdelle, J. Morales, J.F. Artaud, O. Grover¹, T. Radenac, J. Bucalossi, Y. Camenen², G. Ciraolo, F. Clairet, R. Dumont, N. Fedorczak, J. Gaspar³, Ch. Gil, M. Goniche, Ch. Guillemaut, J. Gunn, P. Maget, P. Manas, V. Ostuni, B. Pégourié, Y. Peysson, P. Tamain, L. Vermare, D. Vézinet and the WEST team*

APS, Spokane, Oct. 2022

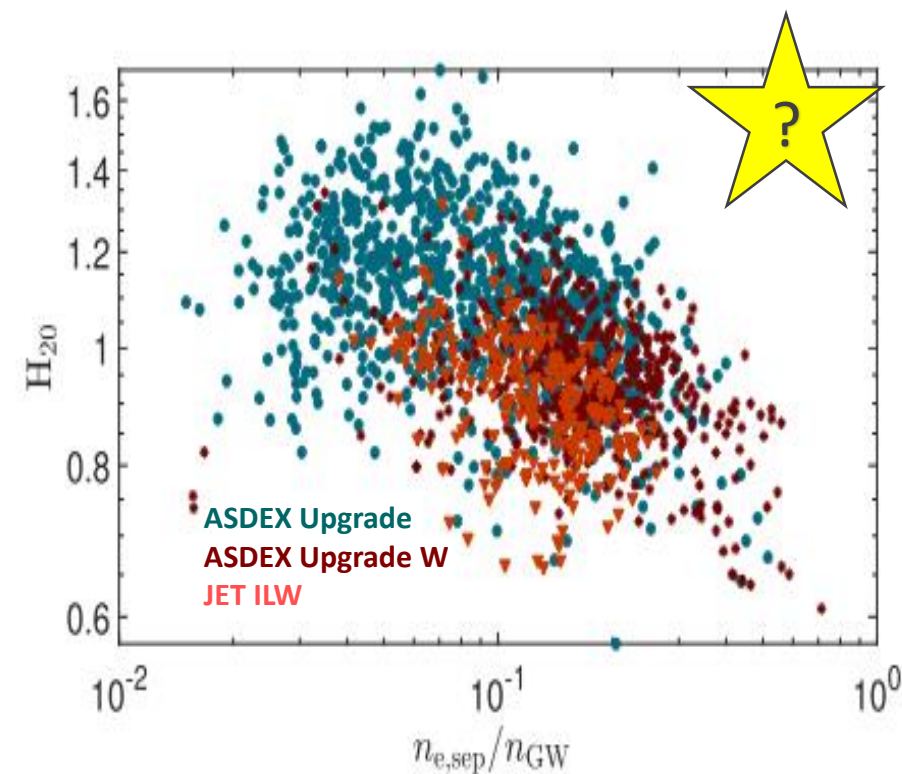
- ▶ Since early tokamak operation, wall conditioning key impact on core performances

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

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

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

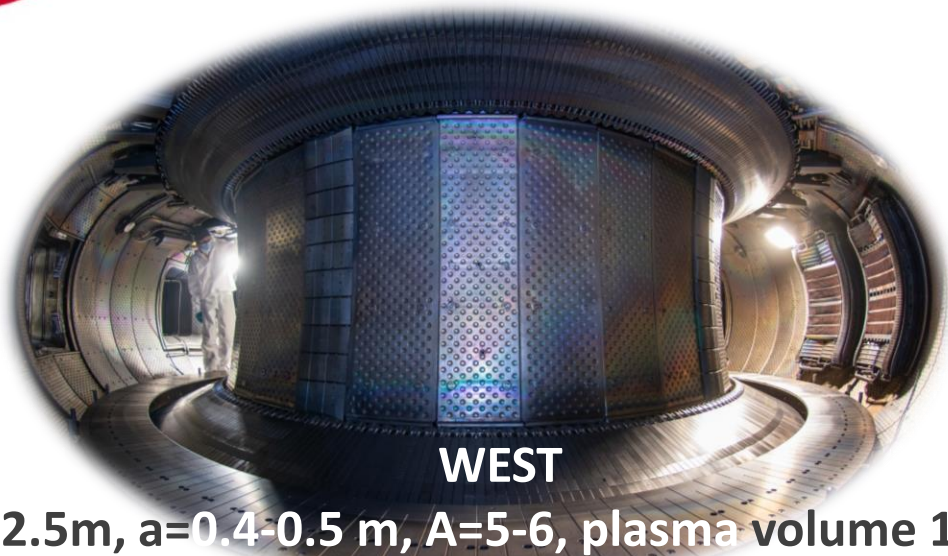
- Recently impact of n_{sep} (or T_{target}) on H factors reported [G. Verdoolaege, NF 2021, Lomanowski NF 2022]
- In ITER or DEMO W environment need $T_{target} < \sim eV$ to avoid W sputtering (and reduce heat load), hence large recycling, - depending on opacity- possibly large n_{sep} : this is not where the best performances of today/past tokamaks are reported



[G. Verdoolaege, NF 2021]



- ▶ 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 $P_{tot} > 2\text{MW}$ (no ohmic pulses), $I_p = 0.5\text{ MA}$, Lower Single Null, gas puff (no pellet): 800 plateaus



WEST

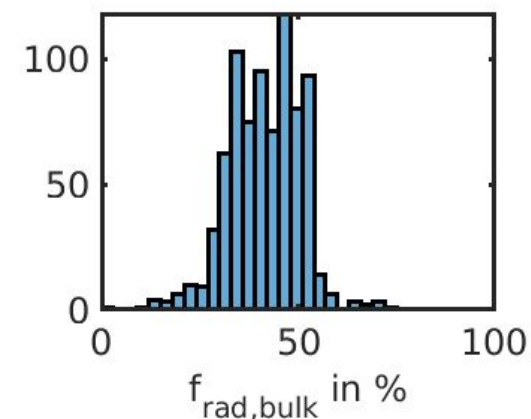
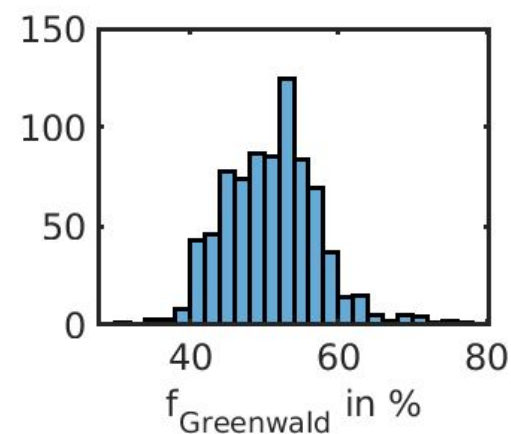
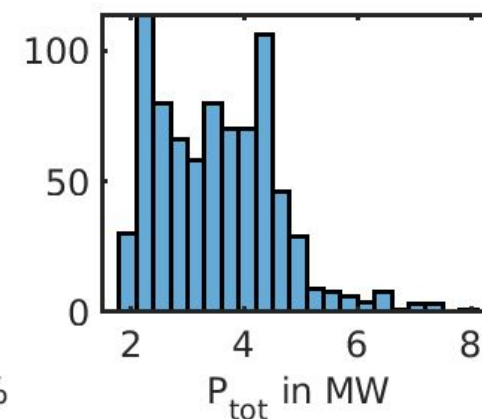
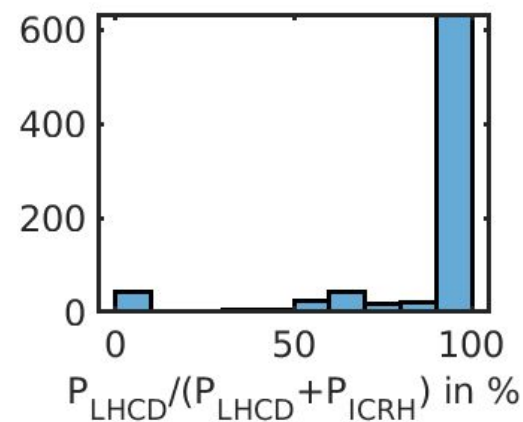
$R=2.5\text{m}$, $a=0.4\text{-}0.5\text{ m}$, $A=5\text{-}6$, plasma volume 15 m^3

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

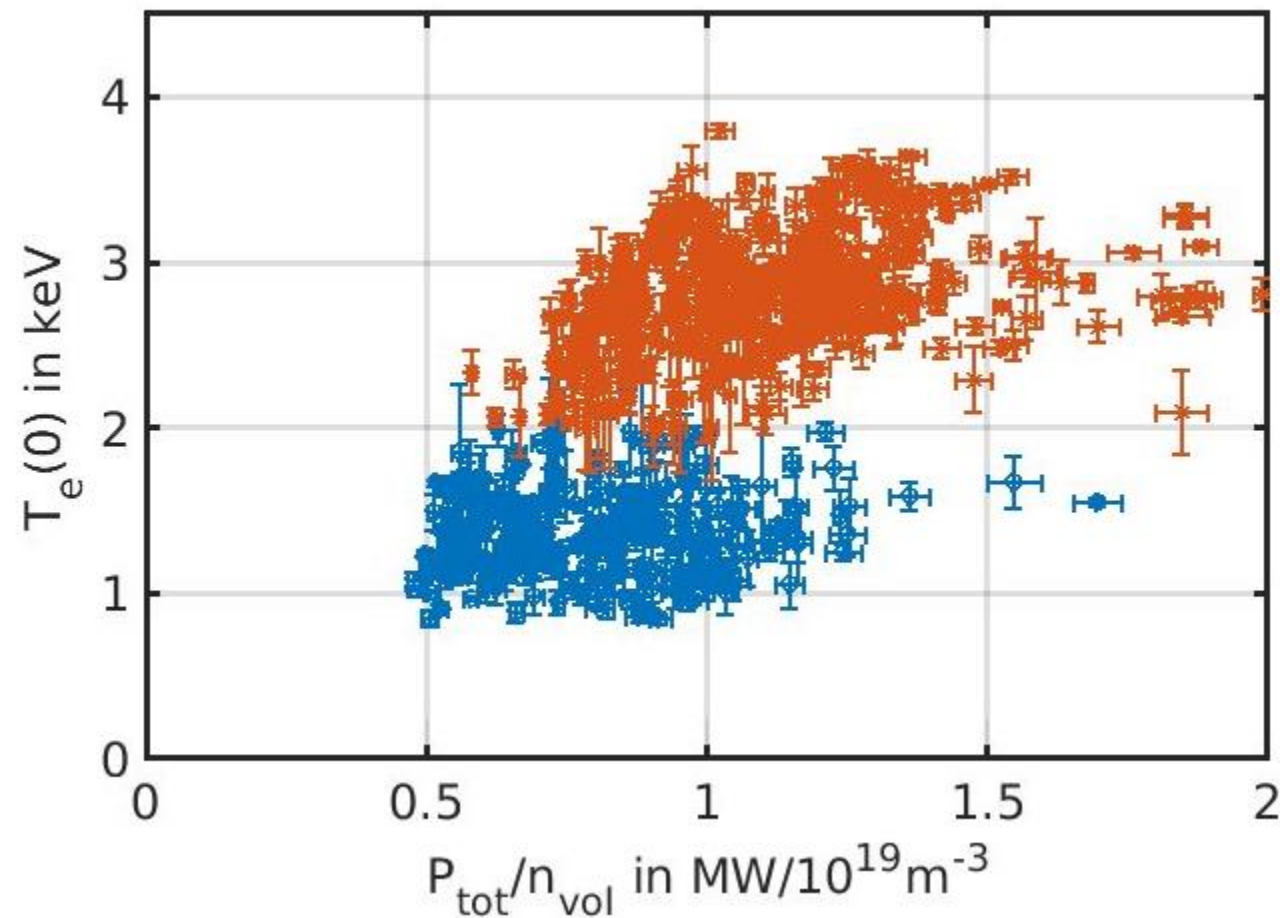
Dominant electron heating (LHCD/ICRH)

No NBI, hence intrinsic density peaking

L mode high recycling plasmas



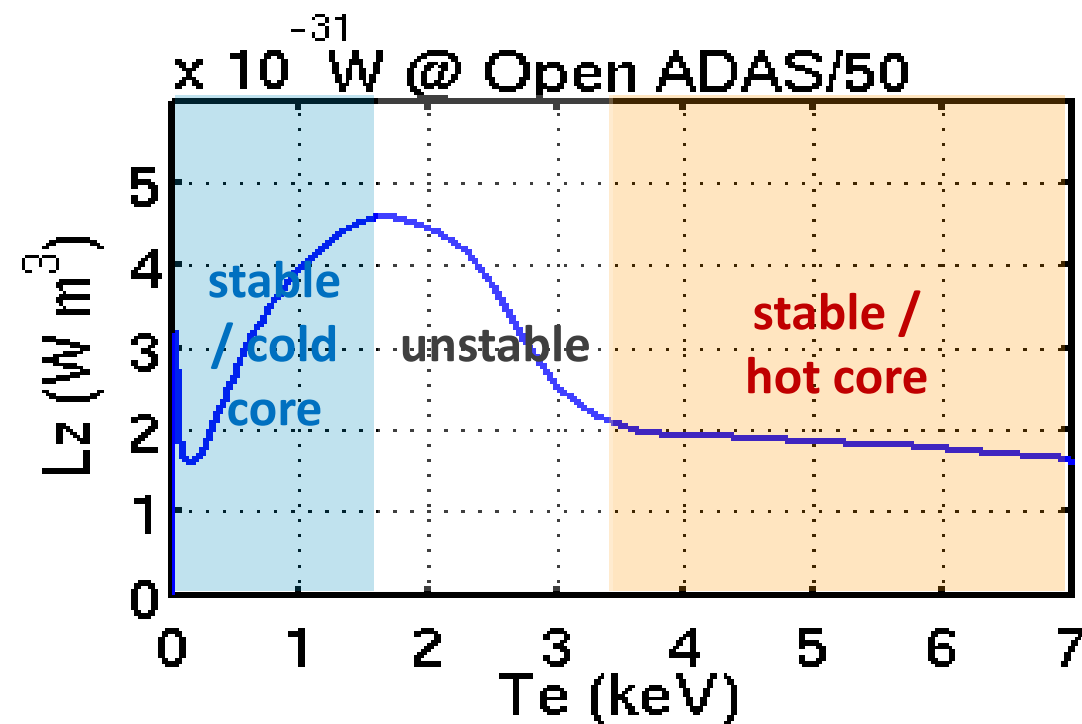
- ▶ **Coexistence of a cold branch with a hot one in WEST W environment**
- ▶ **n_{sep} , \bar{n} , density peaking and energy confinement time**
- ▶ **Collisionality at separatrix and energy confinement time**
- ▶ **Recycled neutrals and energy confinement time**
- ▶ **Conclusions and perspectives**



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

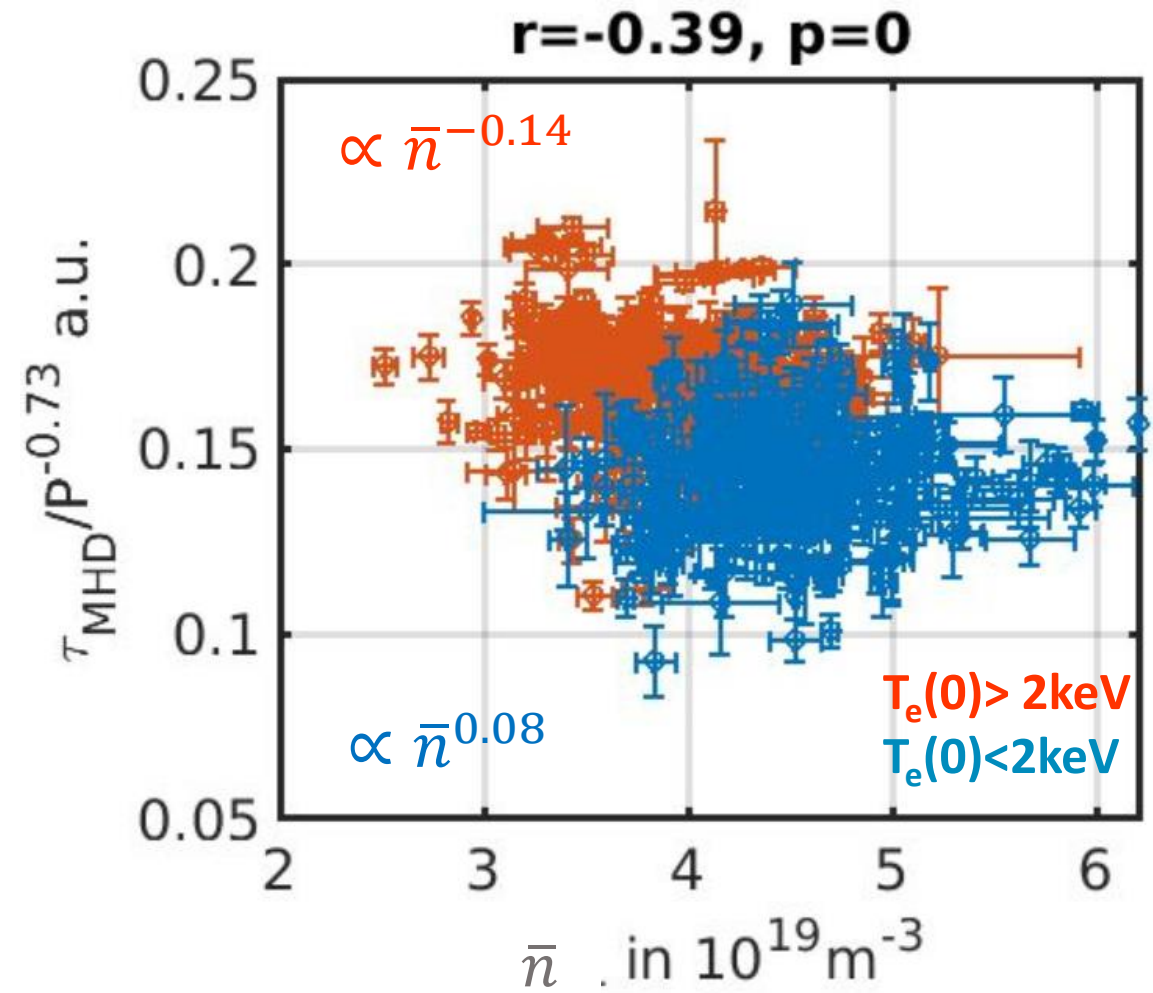
on hot branch: larger li, larger W_{MHD}

- 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

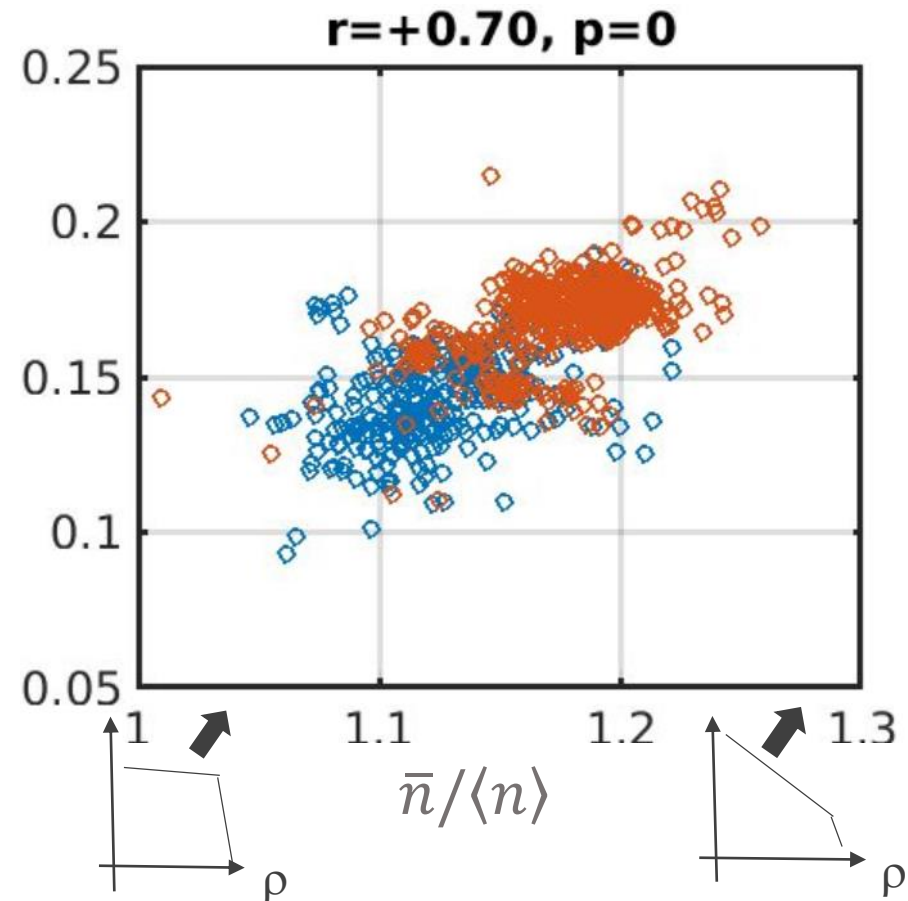
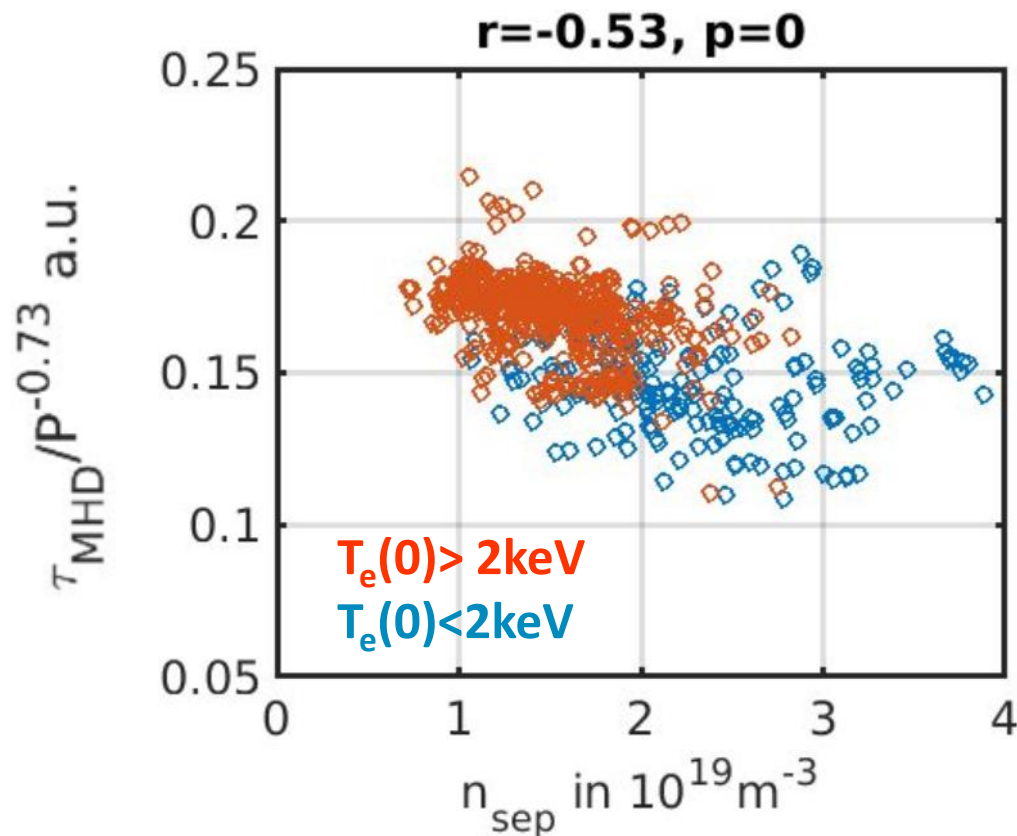


All data at 3.7T and 0.5 MA

- 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 $\propto \bar{n}^{0.147 \pm 0.097}$
- next plots confined plasma perf. characterized by $\tau_{MHD}/P^{-0.73}$ in a.u.



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

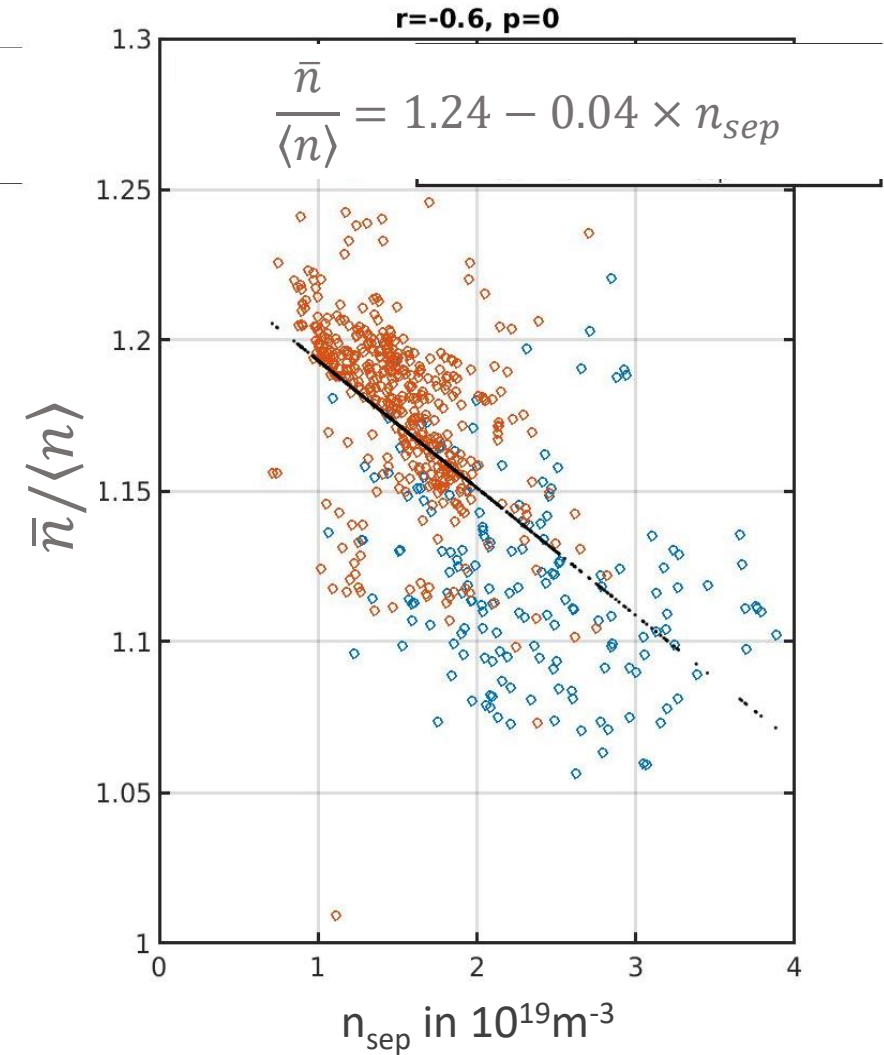
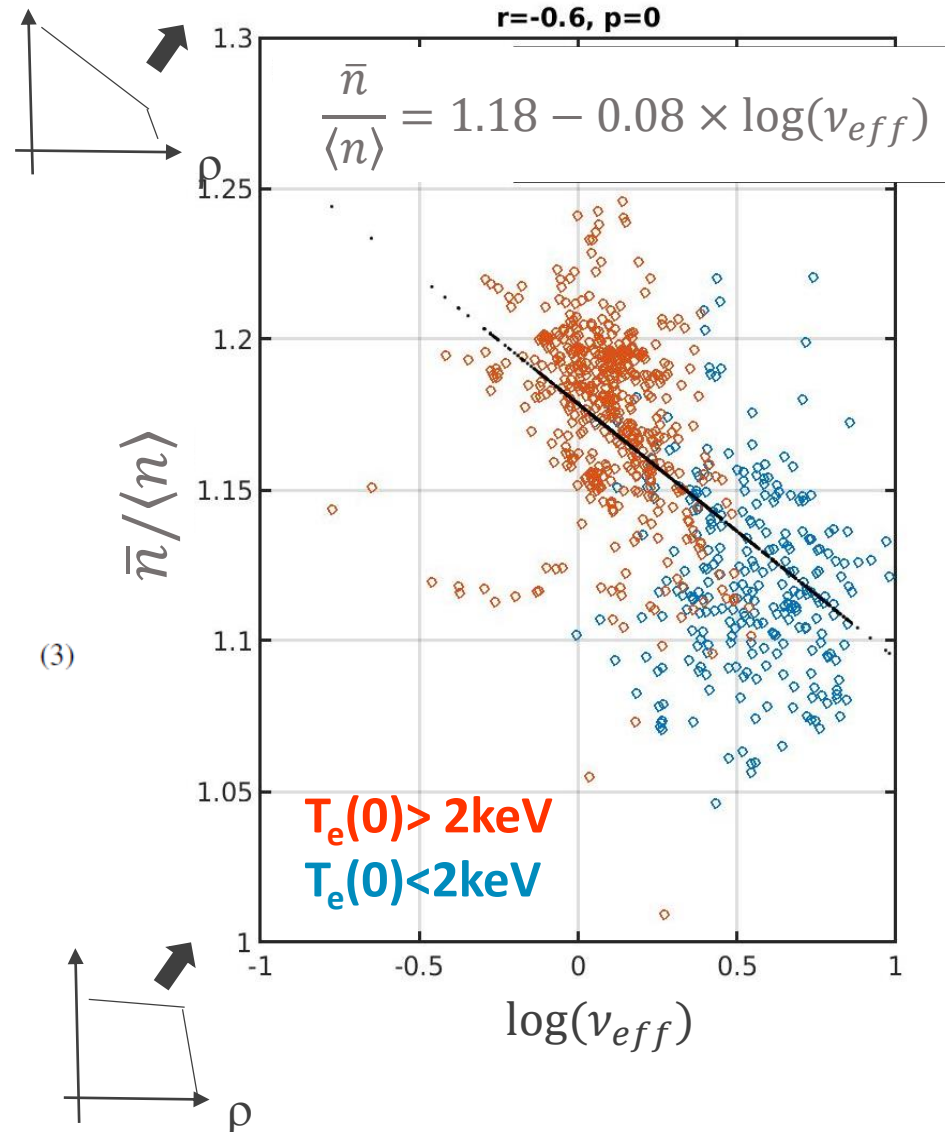


► $\bar{n}/\langle n \rangle$ is larger for lower n_{sep}

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

$$pk_{sclv} = 1.347 \pm 0.014 - (0.117 \pm 0.005) \log(\nu_{eff}) + (1.331 \pm 0.117) \Gamma_{NBI}^* - (4.030 \pm 0.810) \beta, \quad (3)$$

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

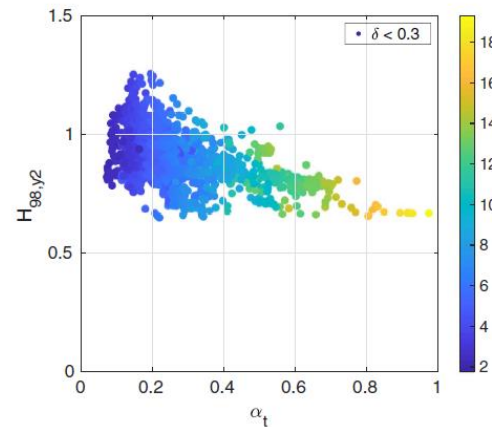


- ▶ Resistive interchange turbulence drive in separatrix

$$\text{figure of merit : } \alpha_t = 3.1310^{-18} R_{geo} q_{cyl}^2 \frac{n_{sep}}{T_{sep}^2} Z_{eff}$$

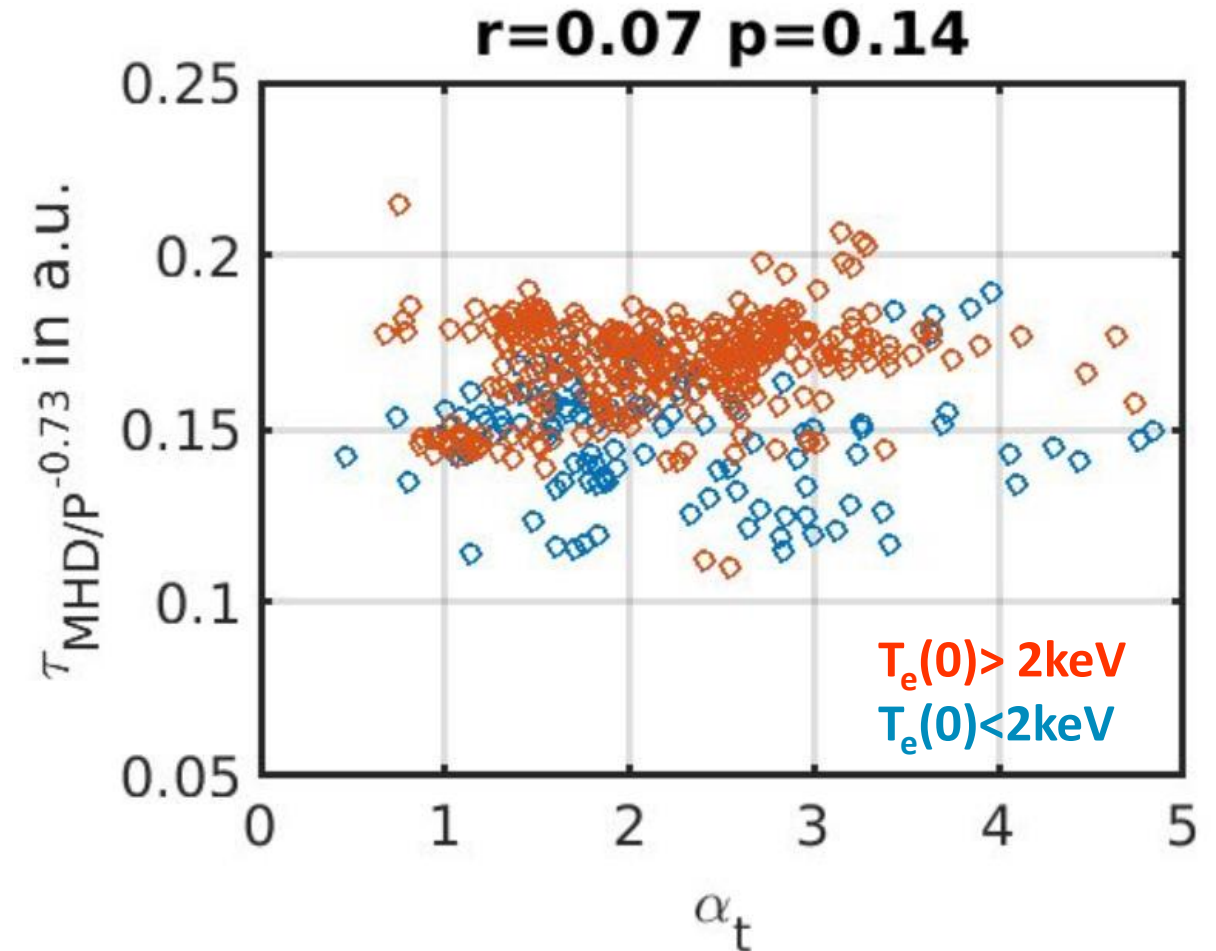
[Scott PoP2005] similar to α_d of [Rogers PRL98]

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

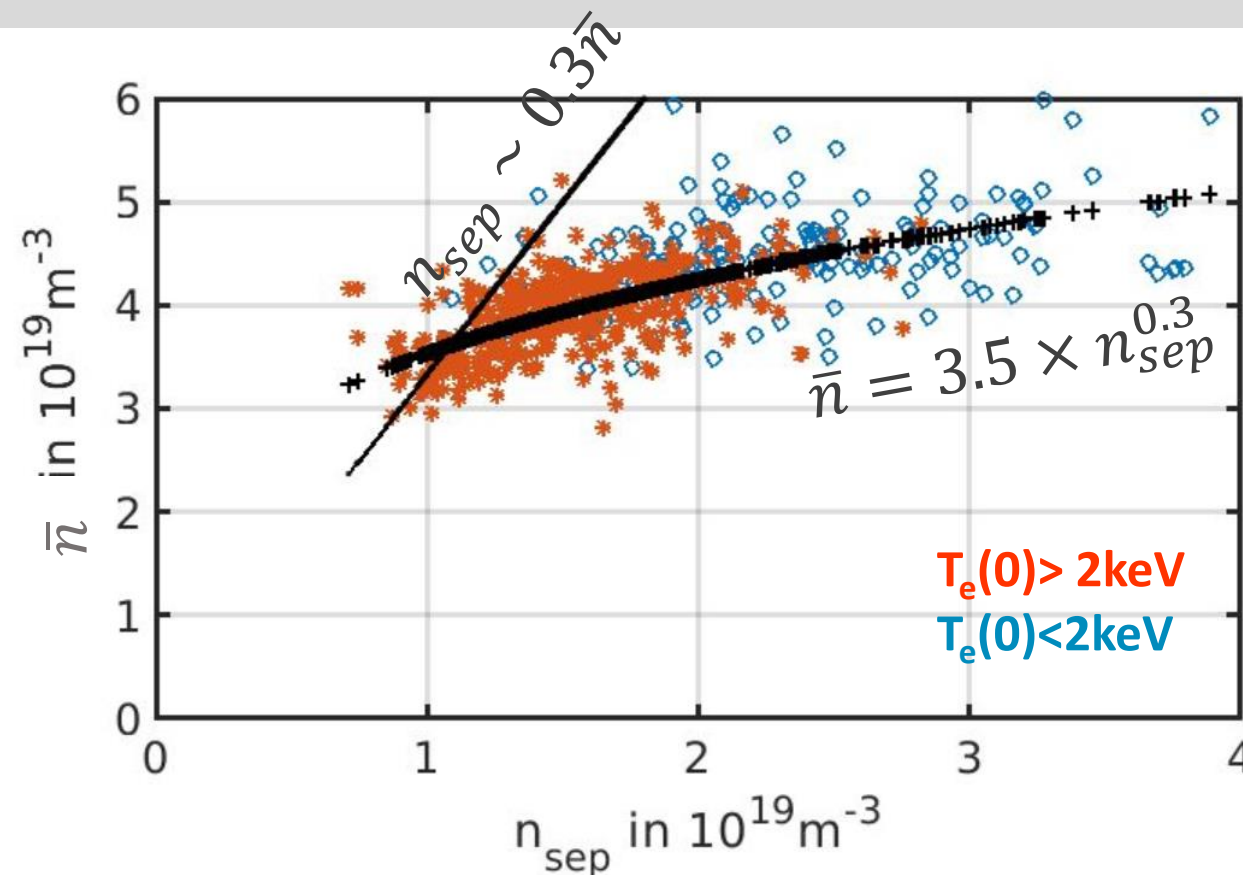
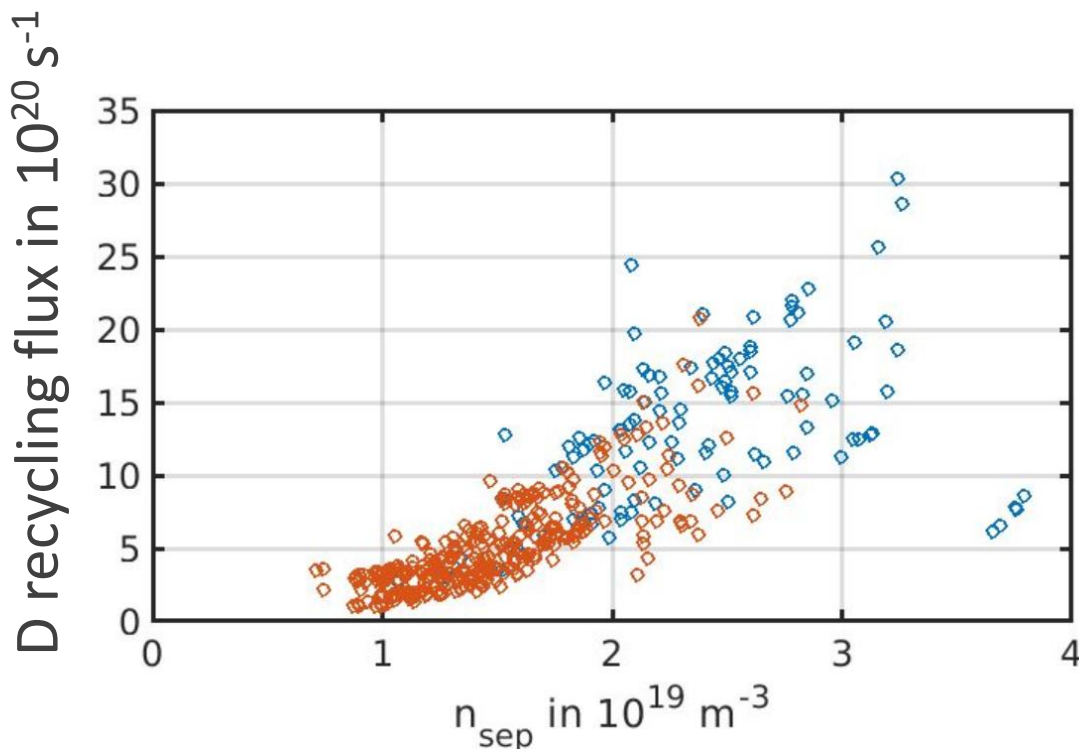


- ▶ Here: n_{sep} from reflectometry, T_{sep} from reversed 2 point model using Langmuir Probes in divertor target

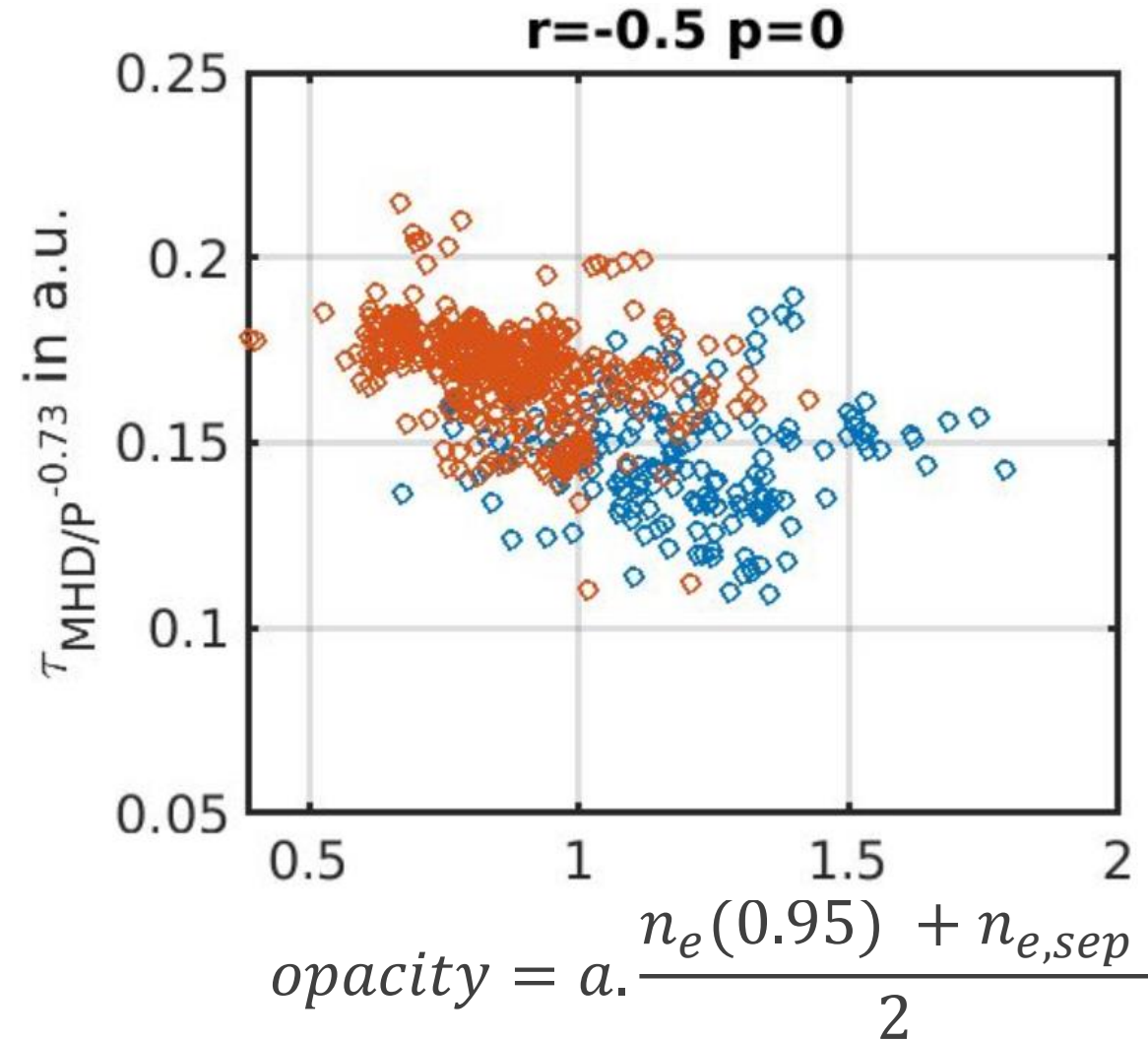
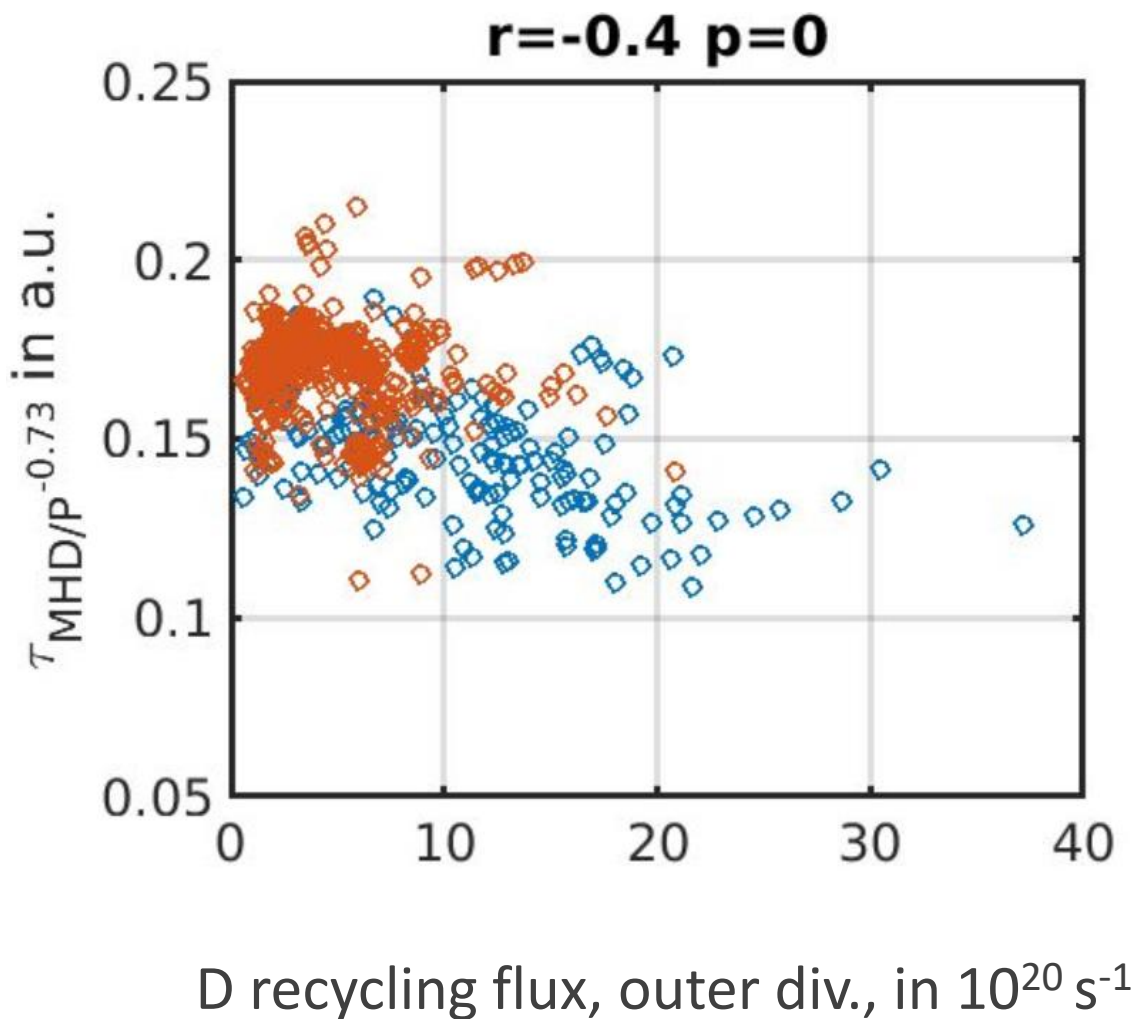
- ▶ No correlation between confinement quality and α_t reported in our L mode database



- 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)



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

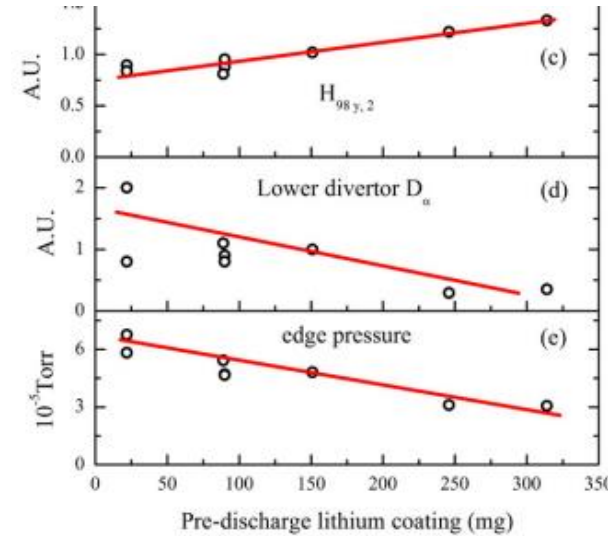


Some experimental observations:

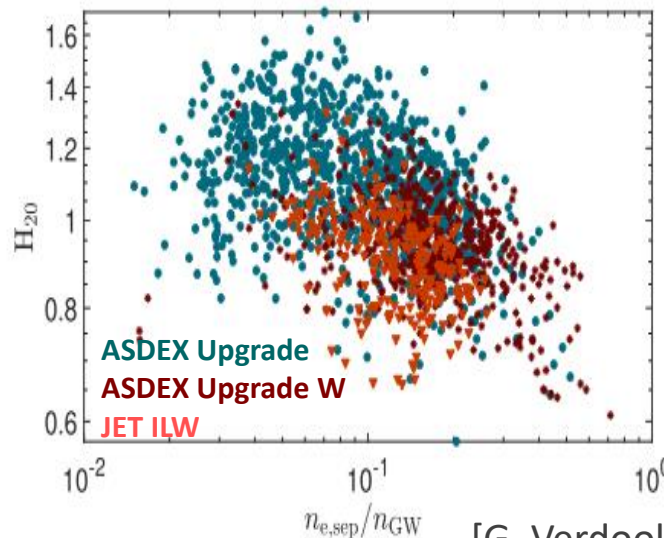
- ▶ Neutral recycled from wall, divertor and/or limiters impacting the performances.
- ▶ Better performances if lithiumisation/boronization/siliconisation (NSTX, EAST, TEXTOR etc)
- ▶ Higher H factor correlates with lower n_{sep} and also higher T_{target}

Pointing towards an impact of neutral recycling source on core performances

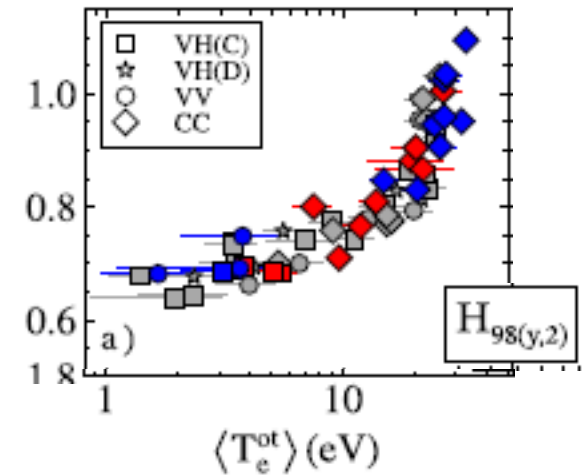
$$\tau_E = 73 H_\alpha^{-0.24} \left(\frac{\beta_{||}}{\beta_{\perp}} \right)^{0.85} n_e(0)^{0.60} B^{0.35} C_{NB}^{0.19} \quad [\text{Strachan PoP1994}] \text{ TFTR C limiter}$$



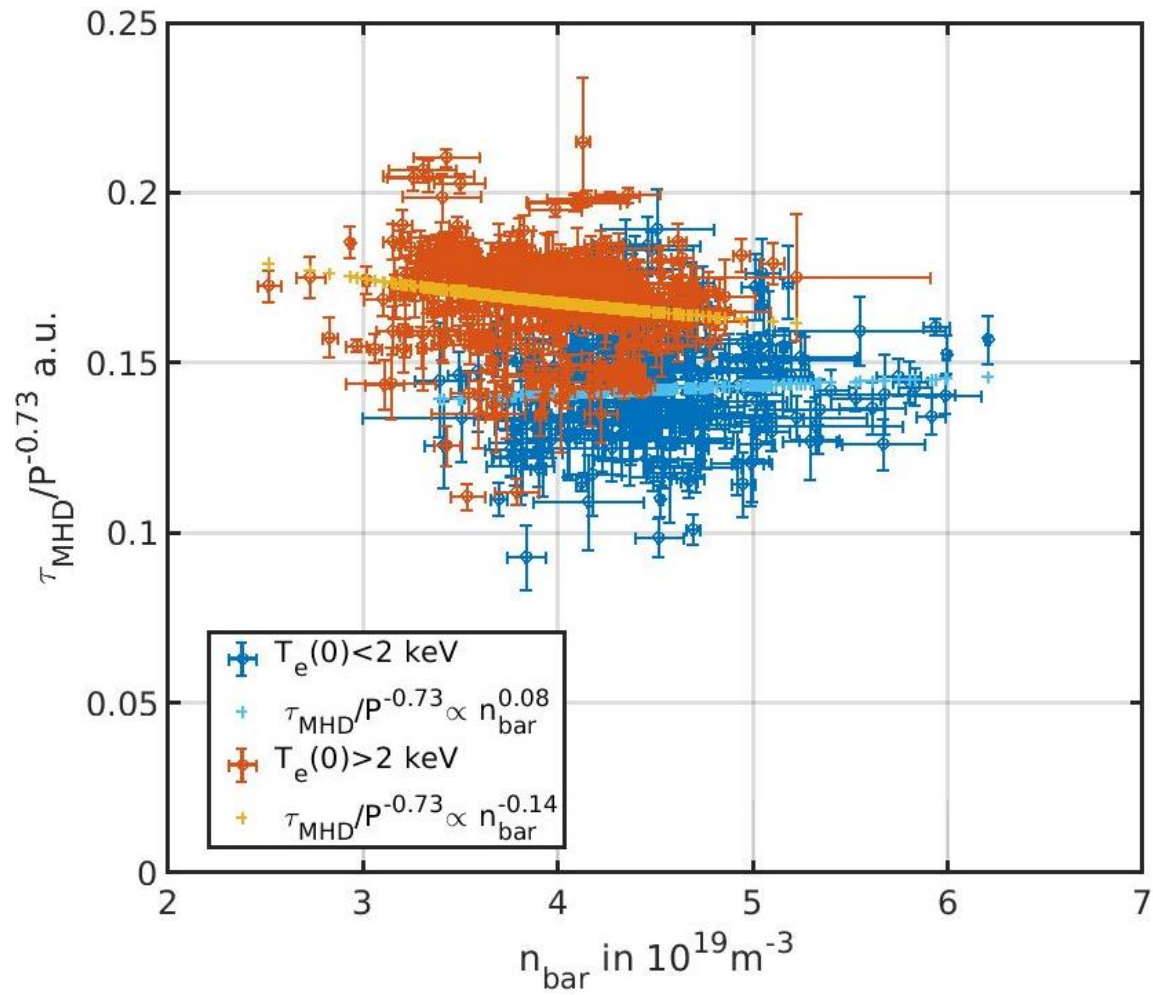
[Cao PPCF2012] NSTX Li coating

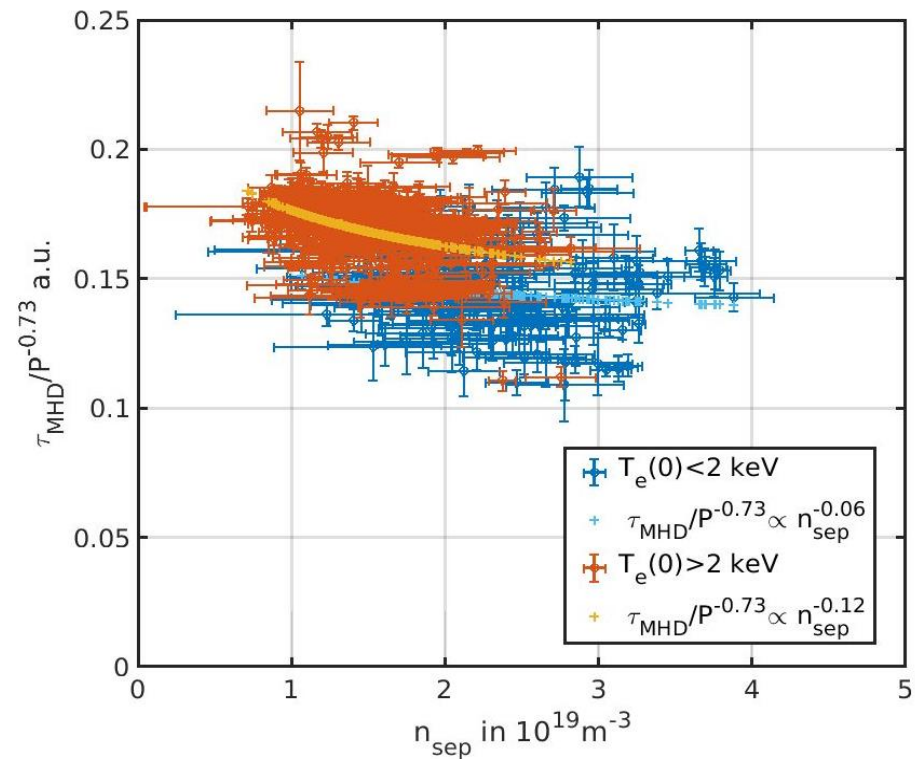
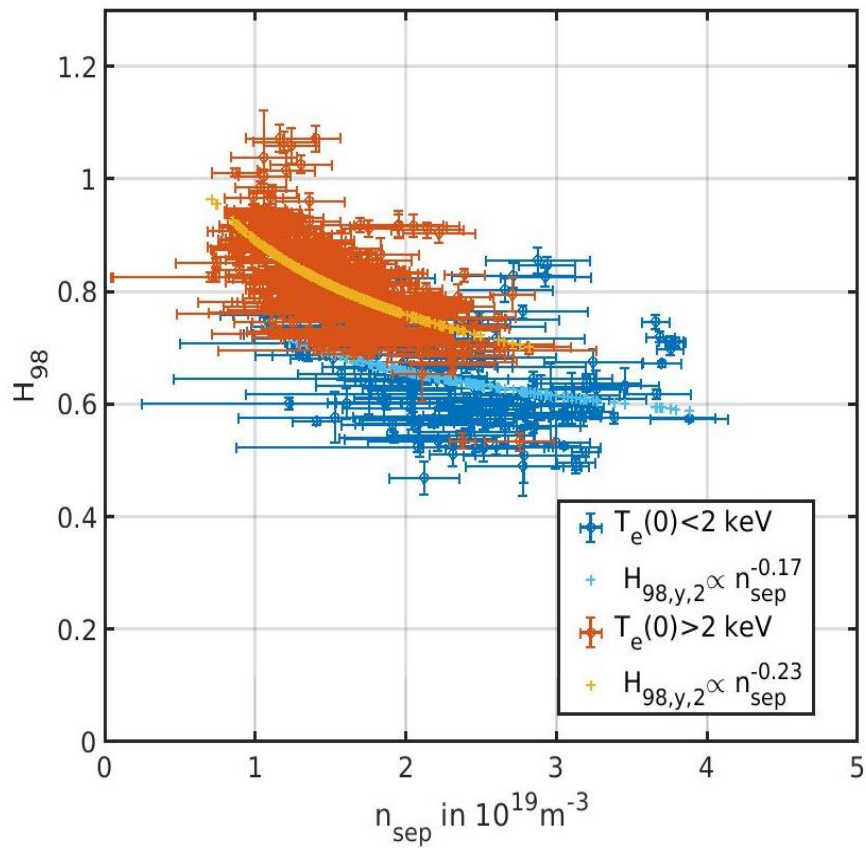


[G. Verdoolaege, NF 2021] Clarisse Bourdelle, APS October 2022



[B. Lomanowski, NF 2022], JET ILW





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 $L_{\parallel,out}$:

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

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

With:

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

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

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

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

Assuming:

$$T_i = T_e$$

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

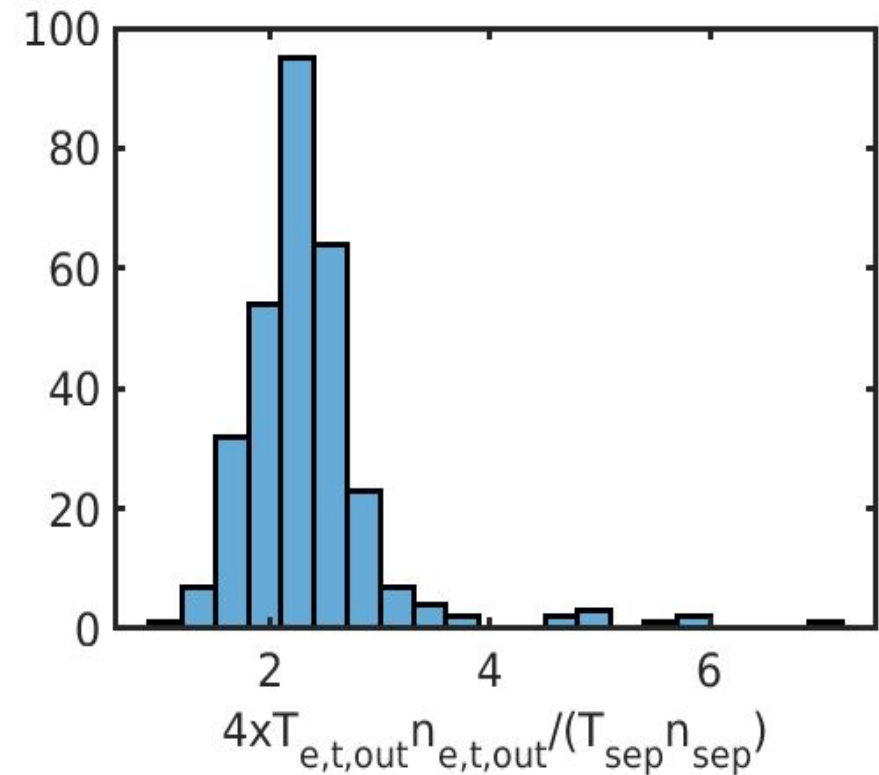
$T_{\text{sep}} = T_u$ in **momentum conservation equation** :

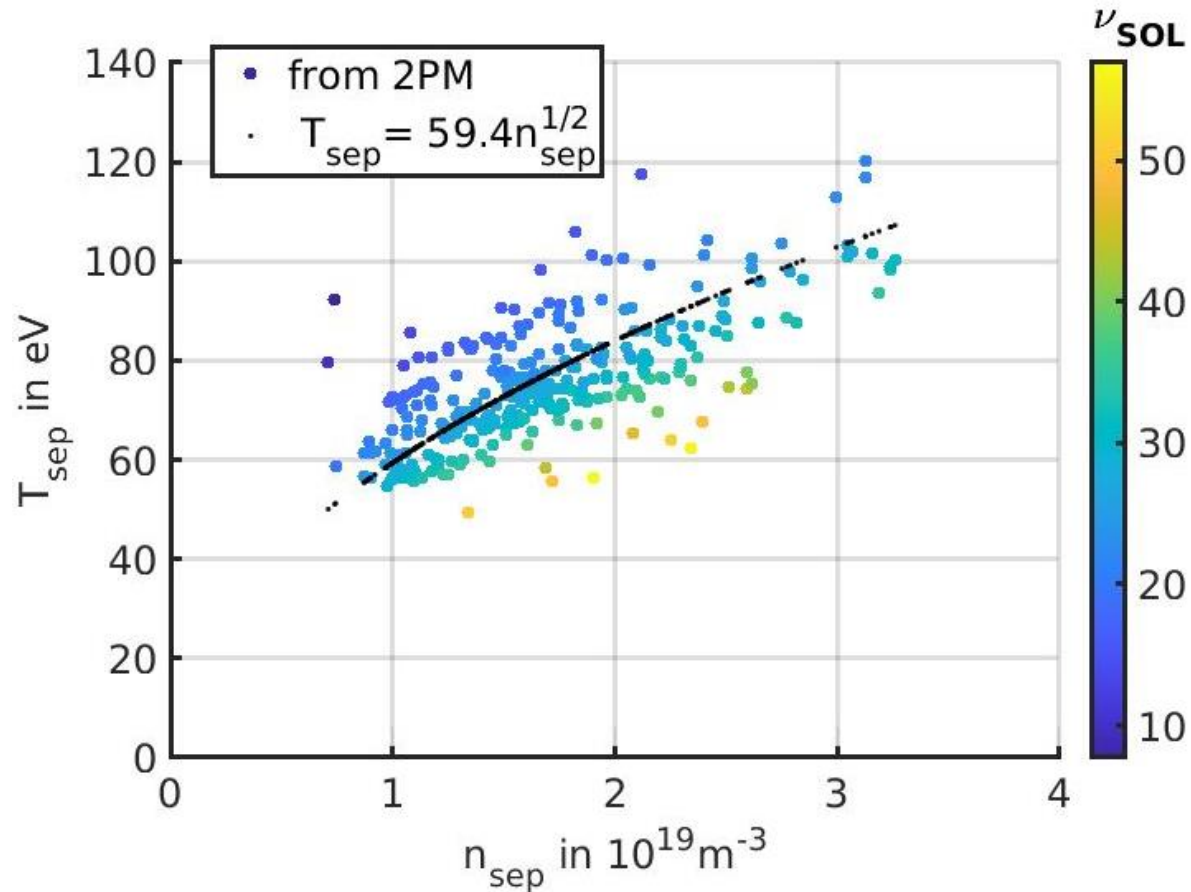
$$n_{e,u} T_{e,u} \left(1 + \frac{T_{i,u}}{T_{e,u}} \right) f_{\text{mom}} = 4 n_{e,t} T_{e,t}$$

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





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

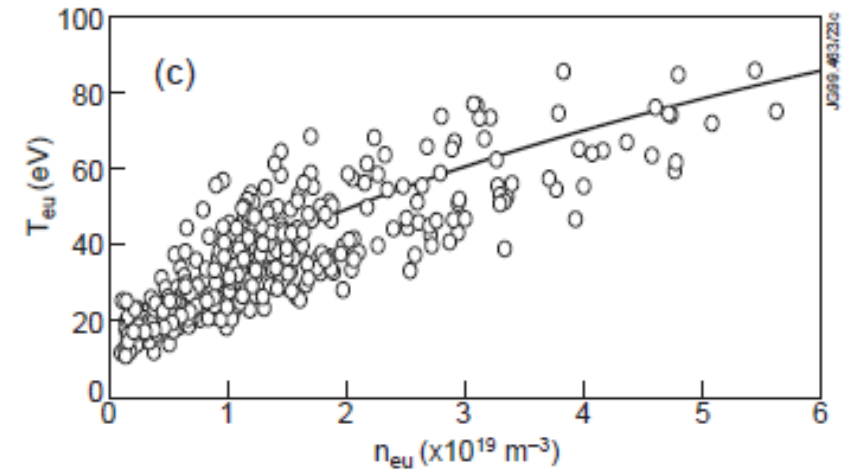


Figure 2. (a) T_{eu} versus n_{eu} for separatrix values: OSM results for the JET Mark II divertor, H mode. A sin-

Erents NF2000

