Understanding the near edge physics
In L mode, H mode, ELM-free regimes
Recent progress in validation and core/edge integration
Role of particle source

C. Bourdelle

EU-US TTF Sept 12-15 2023, Nancy.

Disclaimer(s)

Thank you to the scientific committee for this invitation? A very broad and challenging topic!

From Today's experiments to ITER and beyond, 2 huge gaps:

- What our US colleagues call the Integrated Tokamak Exhaust and Performance gap (**most of sessions Today, Wed. and Thursday**)
- Burning plasma physics: $P_{\alpha}>P_{aux}$ impact on nonlinear turb/MHD interplay (session Friday)

TTF being a workshop, the goal here is to **trigger stimulating discussions for our future works.**

Not aiming at an (impossible) exhaustive review. This talk would have been much better if done after the workshop ;)

I will start addressing the "near edge physics" by **focusing on the density value/profile at the separatrix**

Density build up across separatrix impacts:

- Fusion power $P_{fus} \propto n_T n_D$
- Ratio of T burned to T fueled. Which impacts required TBR for tritium self-sufficiency, determines tritium start-up inventory, size of tritium reprocessing systems [Xie NF2020]
- L mode edge turbulence, hence H mode access and likely density limit
- MHD stability in H mode pedestal
- Bootstrap, hence pulse length
- Detachment access/control
- Impurity compressibility btw SOL vs confined plasma

➢ Essential interplays to be understood towards ITER and beyond

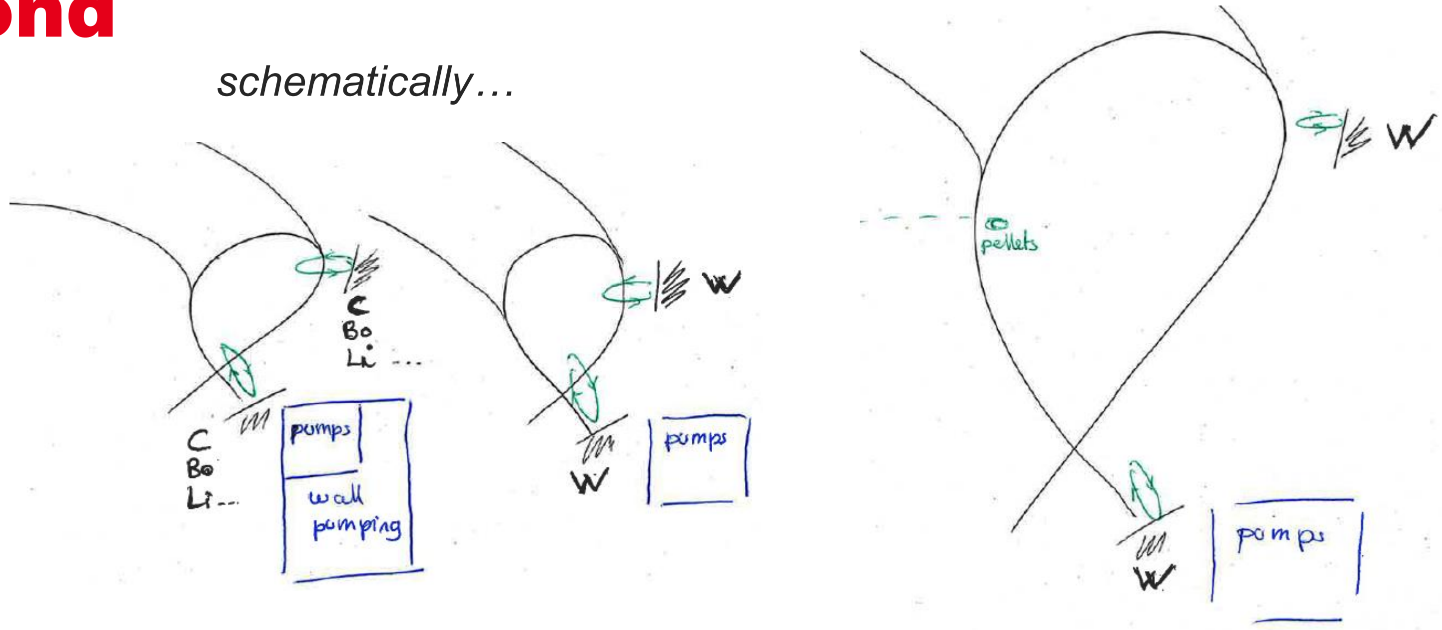
Not a linear extrapolation from Today's tokamaks towards ITER and beyond

What is different?

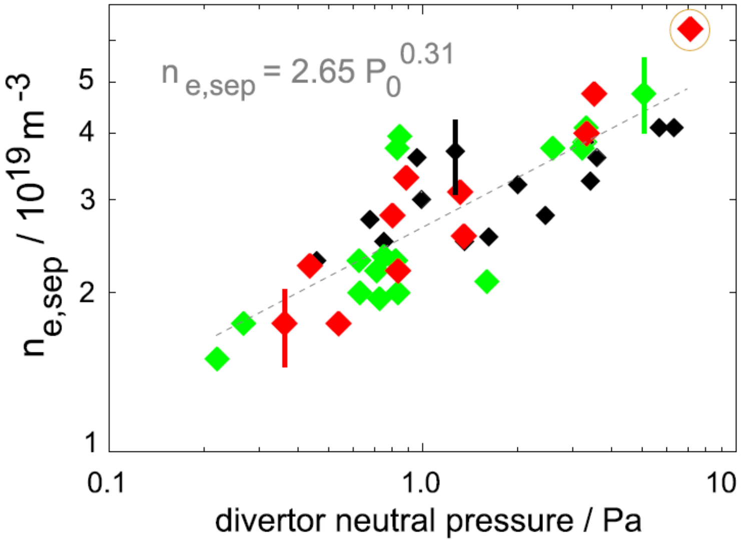
- Wall and divertor material: more neutrall recycling in W (to minimize T retention) than C/Be/Bo/Li
- Lower pumping efficiency (DEMO pumping eff. ~ 8 × AUG, while plasma vol. ~ 100 × AUG) again more neutrals recycling
- Larger divertor legs and wall clearance vs ionization length

➢ No external control on n_{sep} expected in ITER unlike AUG

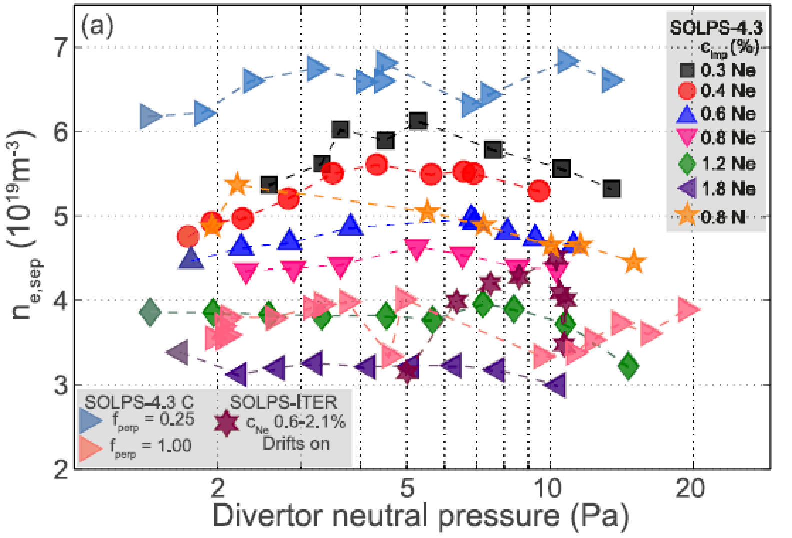
schematically…



AUG, expt [Kallenbach PPCF2018]



ITER SOLPS model [Pitts NME20019]



outline

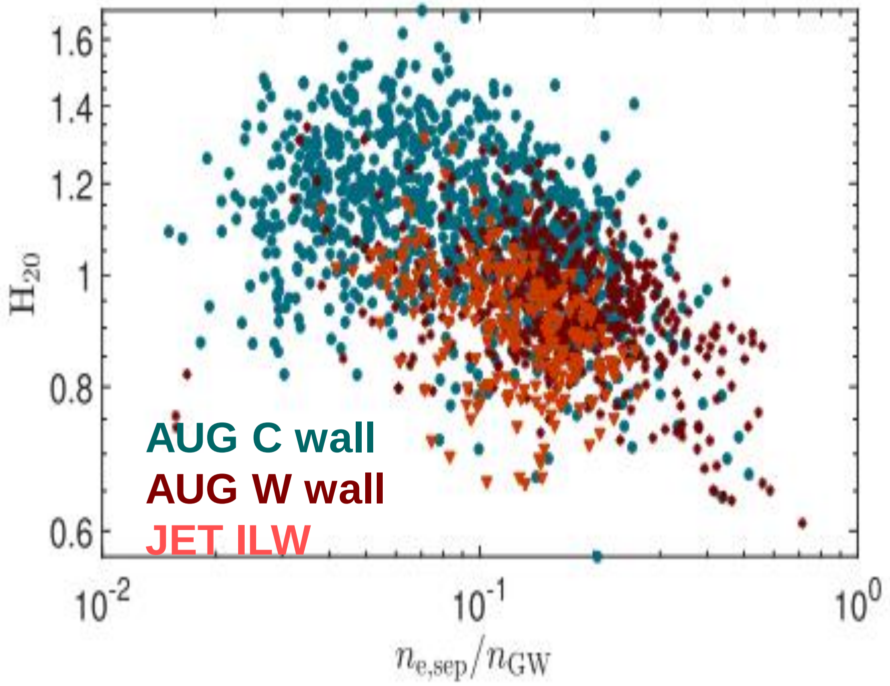
- Database analysis: correlations btw separatrix, SOL and core performances in L and H modes

- Advances in addressing the integrated problem of particle source and transport around the separatrix

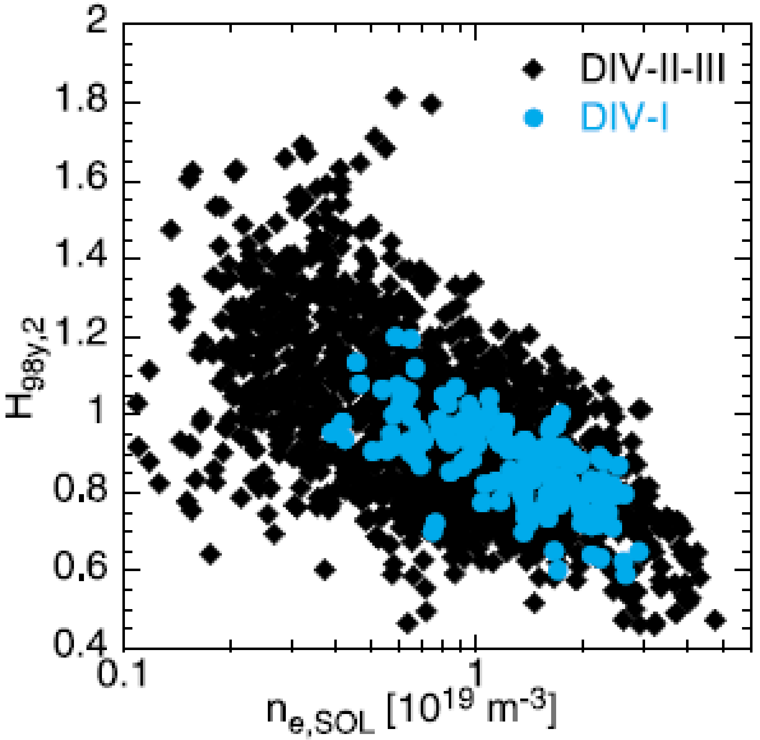
- Remaining experimental and modelling challenges towards ITER and beyond

Higher energy confinement correlates with lower n_{sep} but… n_{sep} not a scaling law parameter

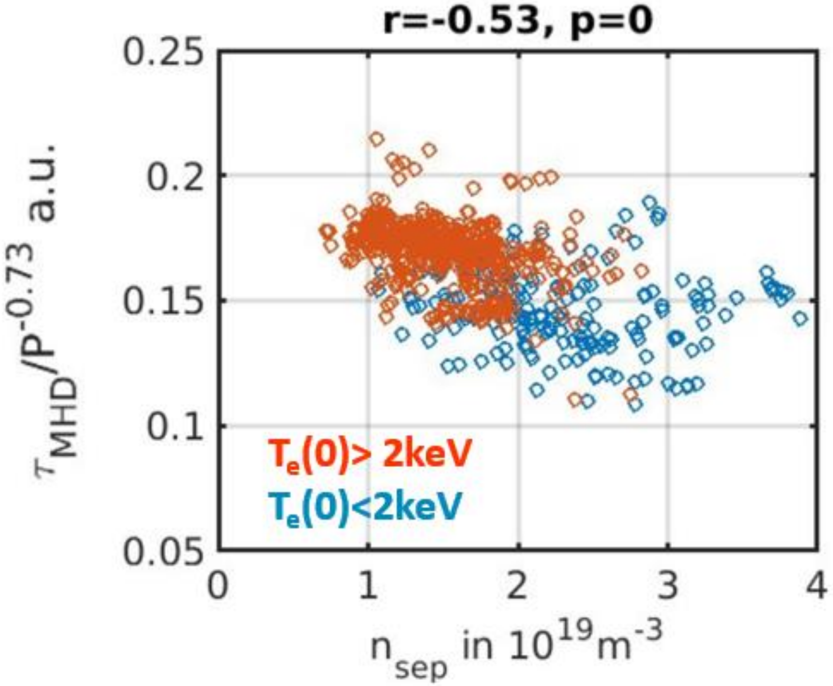
JET and AUG H modes
[Verdoolaege, NF 2021]



AUG H modes
[Ryter, NF 2021]



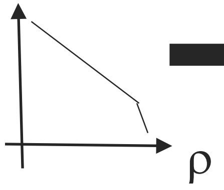
WEST L Modes at 3.7T / 0.5 MA
[Bourdelle NF2023]

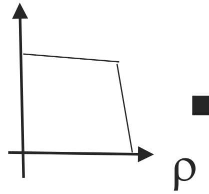


Lowest n_{sep} values obtained with lower recycling:
C vs W wall, closed divertor geometry rather than open

Higher density peaking correlates with lower n_{sep}

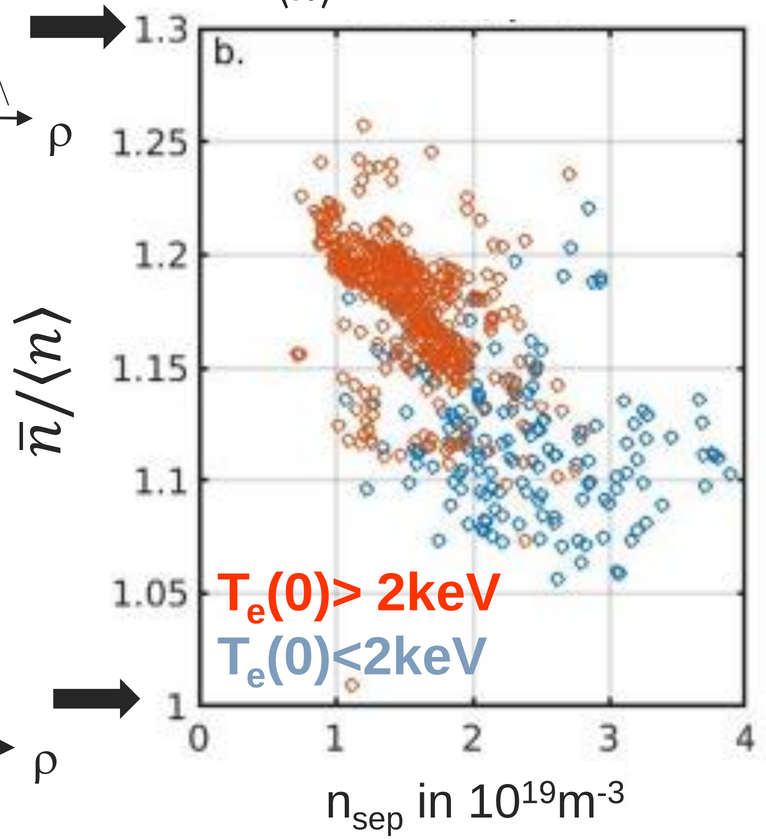
- Higher $\bar{n}/\langle n\rangle$ allow for larger P_{fus} in DT
- AUG-JET reported higher $\bar{n}/\langle n\rangle$ to correlate with lower core ν_{eff} [Angioni NF2007]
- correlates also with lower n_{sep}
- ➢ Projections towards ITER differ, need SOL/core understanding





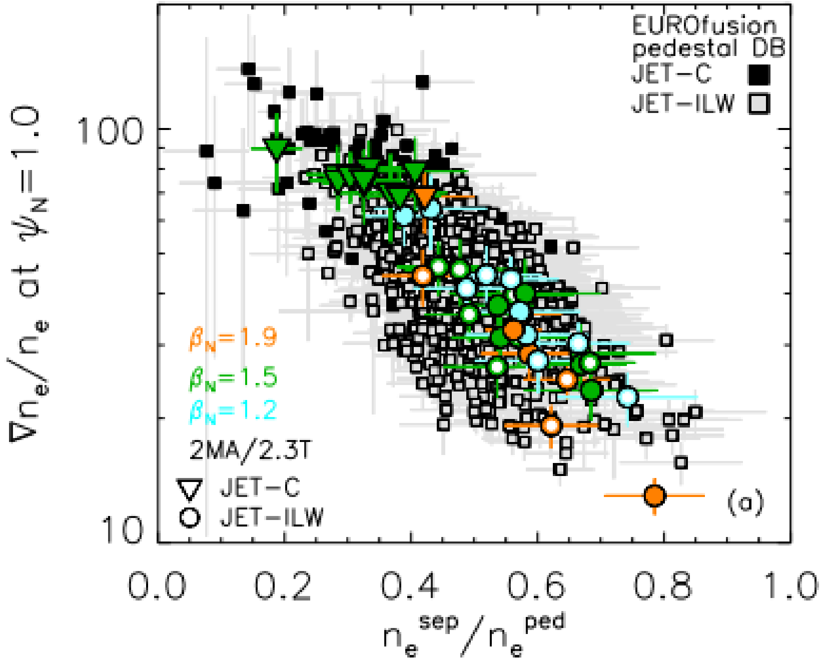
WEST L modes

$$\frac{\bar{n}}{\langle n\rangle} = 1.24 - 0.04 \times n_{sep}$$



[Bourdelle NF2023]

JET ILW and C-wall H mode pedestal



[Frassinetti NF2021]

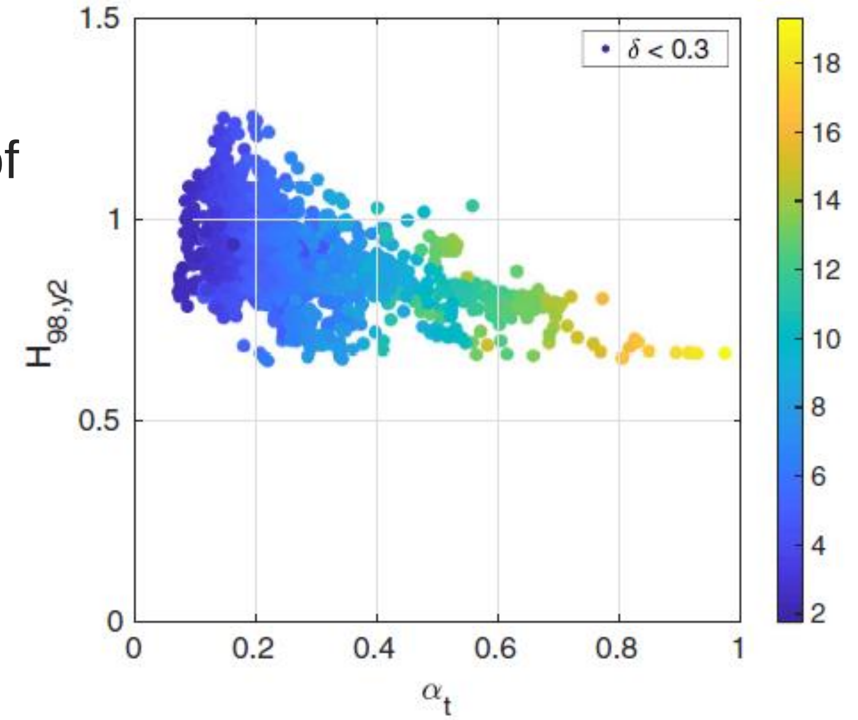
Correlation core performances with n_{sep}: source or transport?

- 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
- No correlation between confinement quality and α_t reported in WEST L mode high recycling database

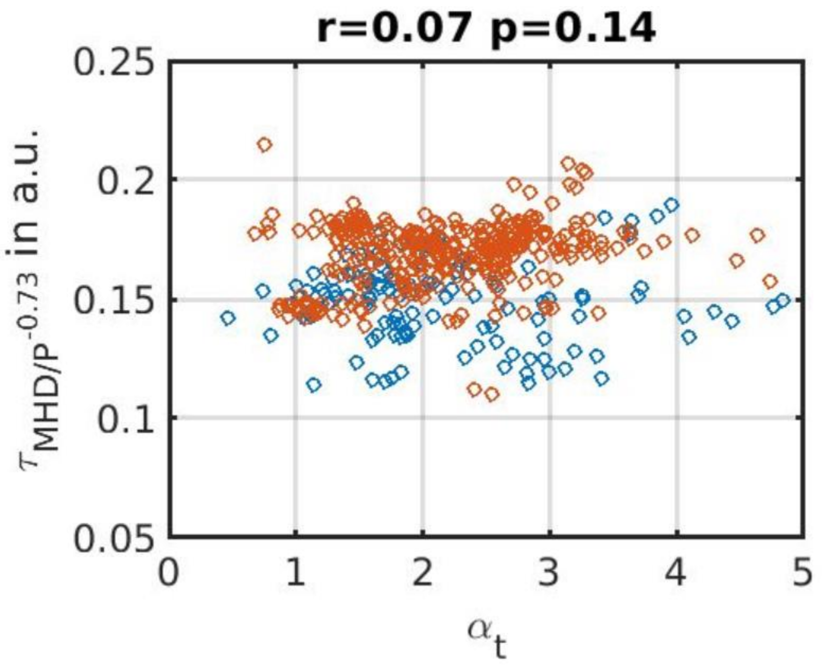
➢ Due to L vs H mode? Or low vs high recycling?

AUG H modes



[Eich NF2020]

WEST L modes at 3.7T / 0.5 MA



[Bourdelle NF2023]

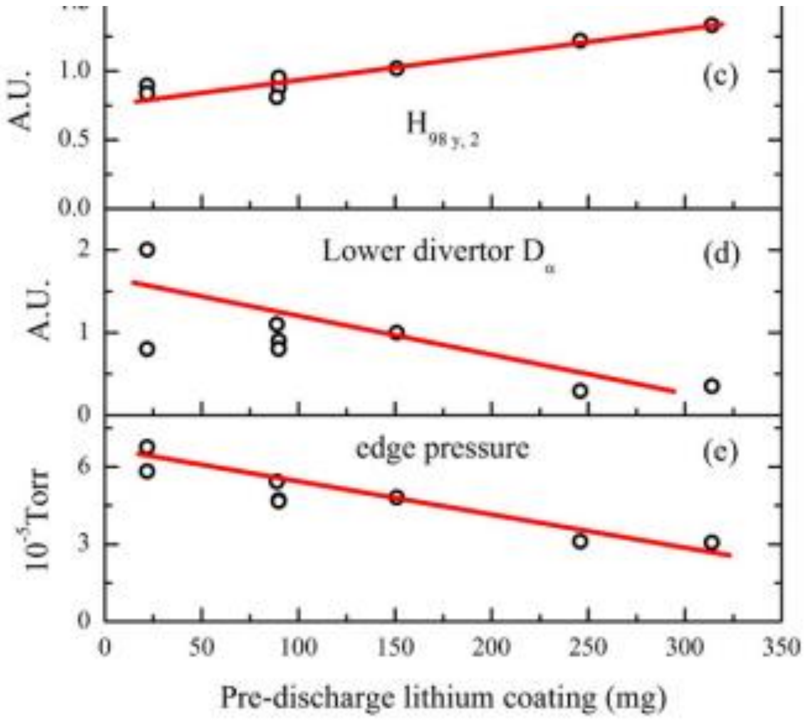
Correlation core performances with n_{sep}: source or transport?

- Since early tokamak operation, low recycling / pumping surfaces (Bo/Li) correlate with good core perf. e.g. TFTR supershots [Strachan NF1994]

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

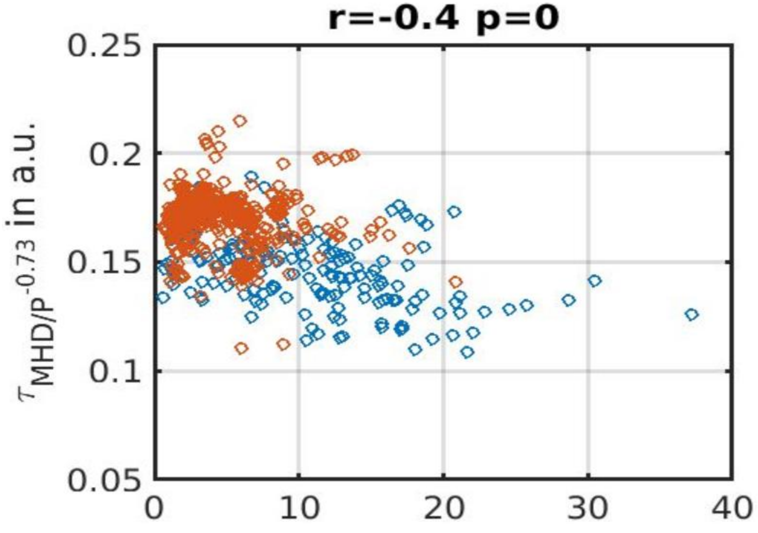
- Lithium conditioning in CDXU-LTX, NSTX, etc
- TEXTOR Radiative Improved modes [Unterberg FST2005] H_{98}=1 and f_{Gr}=1 in low recycling operation
- JET higher H factor correlate with higher T_{target} , lower recycling [Lomanowski NF 2022]

NSTX Li coating



[Cao PPCF2012]

WEST L mode at 3.7T / 0.5 MA



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

[Bourdelle NF2023]

Good core performances correlate with less recycling

Database analysis, summary

- Need to extend τ_E and $\bar{n}/\langle n\rangle$ scaling laws to n_{sep} and recycling flux. n_{sep} and recycling flux expected to drastically change in ITER and beyond
- Best energy content and density peaking at low n_{sep}: due to less turbulent transport ? Or to less recycling flux? Some contrasted results
- In L and H mode, more database investigation to test gas vs pellet, pumps on/off, wall conditioning (distance to boro) impact, C vs W wall, wall clearance, shaping impact (A, δ), etc Data is there in all tokamaks!
- Need to avoid cheery picking and coordinate multi machines activity
  ITPA T&C activity started on L mode database: AUG, Cmod, DIII-D, JET, WEST
  https://gitlab.mpcdf.mpg.de/itpa-tc-sep/wiki

Multi-machine Joint Activity: L-mode database analysis, cross-machines, to explore the competition of neutral particle source and turbulent transport for the density build-up

Coordinated by C. Bourdelle clarisse.bourdelle@cea.fr

1. Impact of separatrix parameters (Tsep, nsep, collisionality at sep, gradient lengths at sep) on density peaking and core energy confinement
2. Correlation between the volume or line average density and the density at the separatrix. Role of pumping level, boronization, strike point position vs pumps etc
3. Impact of SOL (target temperatures, neutral pressures, recycling –Dalpha- etc) on separatrix density and its gradient

outline

- Database analysis: correlations btw separatrix, SOL and core performances in L and H modes

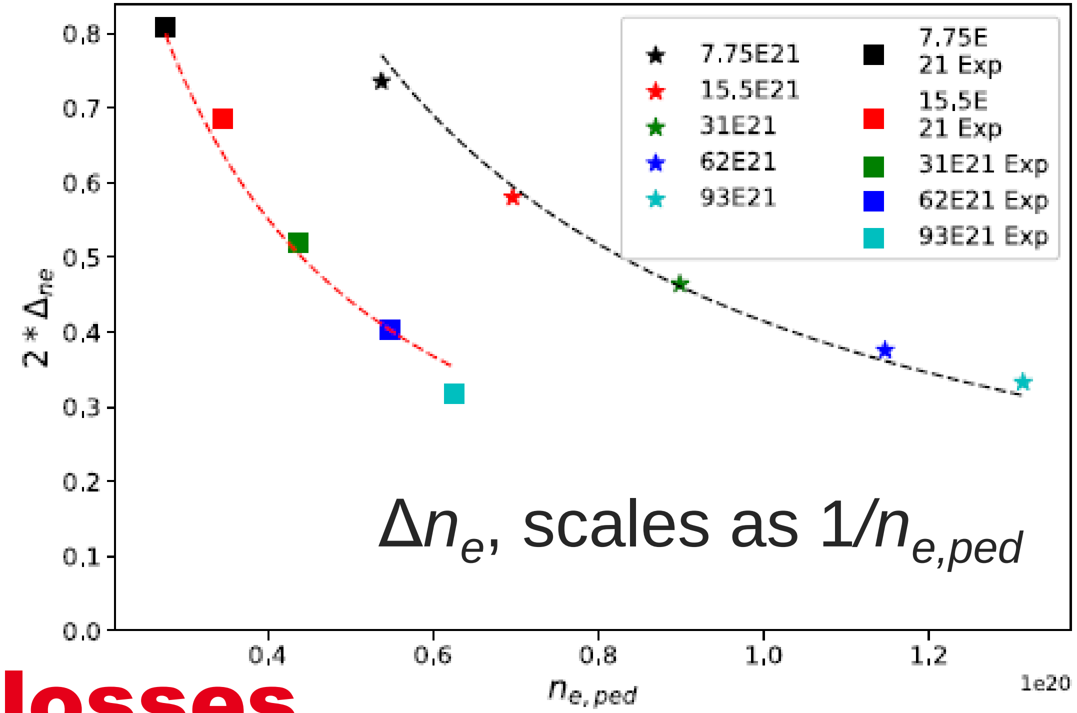
- Advances in addressing the integrated problem of particle source and transport around the separatrix
  - Source
  - ExB
  - Transport
  - Integrated modelling

- Remaining experimental and modelling challenges towards ITER and beyond

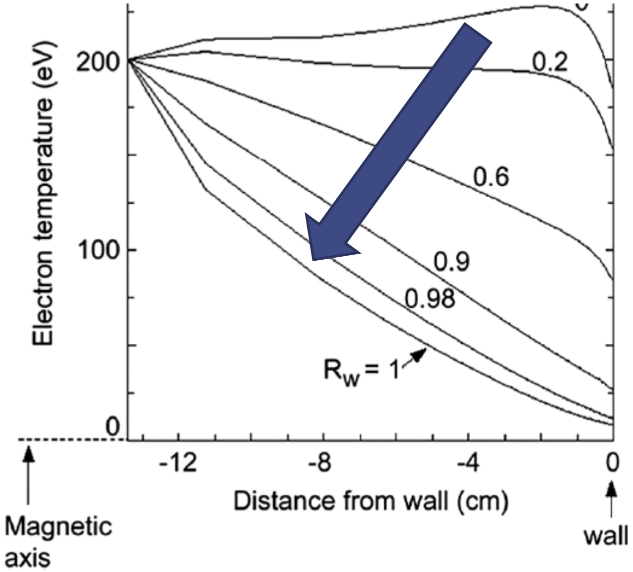
Neutrals: impact on particle source

[Simpson NME2020] EDGE2D-EIRENE vs NPM in JET

- To discriminate transport vs source need… reliable particle source models, fast for extensive validation Ex: Neutral Penetration Model [Groebner PoP2002] Δn_e, scales as $1/n_{e,ped}$, compared to EDGE2D-EIRENE,
- Simple model trends could be systematically compared to SOLcode-neutralcode database and experimental database n_e profiles: reflec., HRTS



UEDGE for LTX [Doyle PRL13]



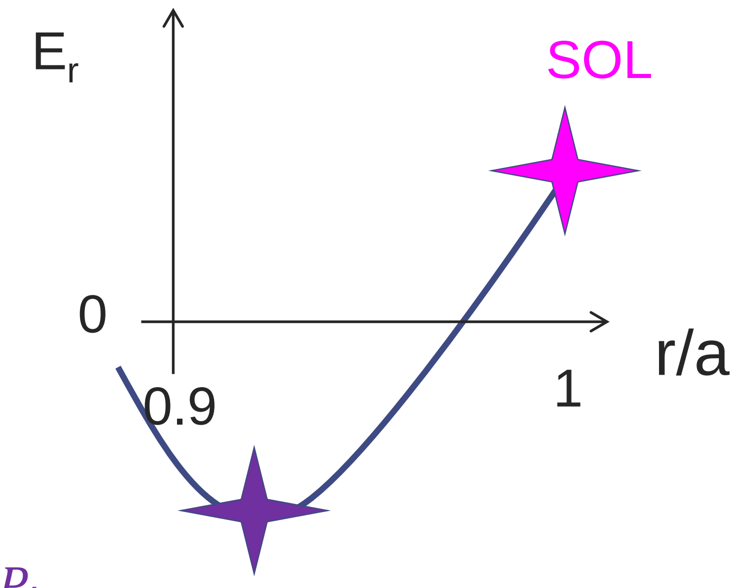
and... on heat losses

More neutrals in the SOL means more CX losses hence steep T, more turbulence drive [XGC1 Stotler NF2017]

NB: flat, high T in SOL measured in low recycling plasma in Lithium Tokamak Experiment [Doyle PRL13]

More tomorrow

Impact of the boundary condition on E_r and its shearing rate



$$E_r = \frac{\nabla P_i}{Z_i n_i} + V_\varphi B_\theta - V_\theta B_\varphi$$

Measurements: Doppler across separatrix compared to target profiles measured by LP [Brida NME2022]

At the outboard mid-plane:

E_r=-d(plasma potential)/dr + other terms $\nabla_{//}(P_e, T_e)$

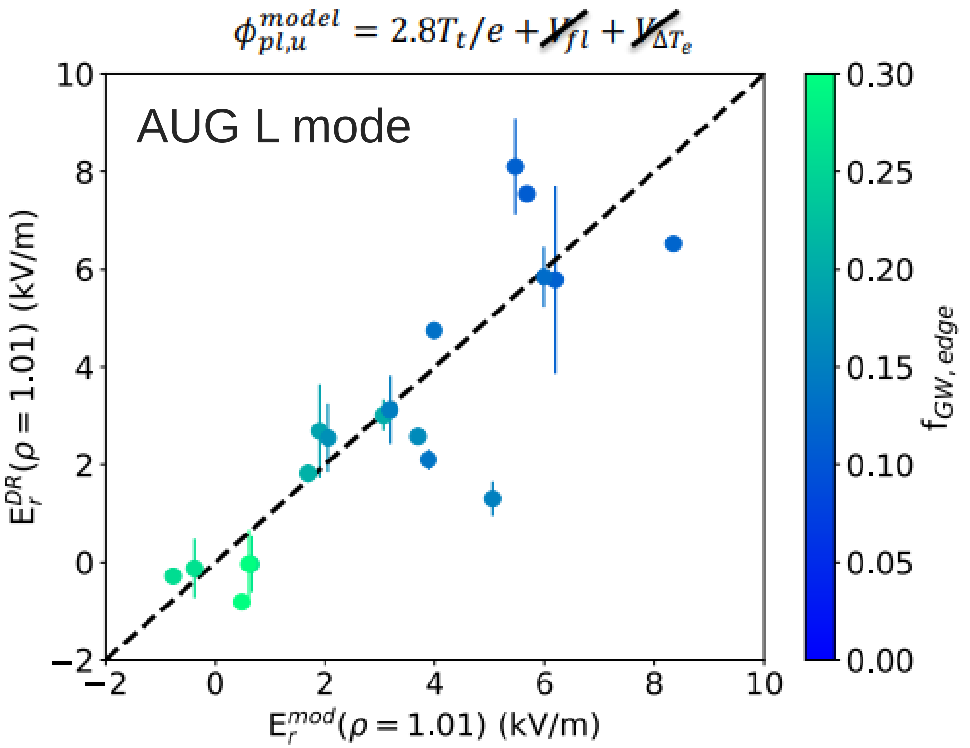
In sheath limited regime: [McCracken NF1979]

Plasma potential ~ $3 \times T_{e,divertor\ target}$

Hence:

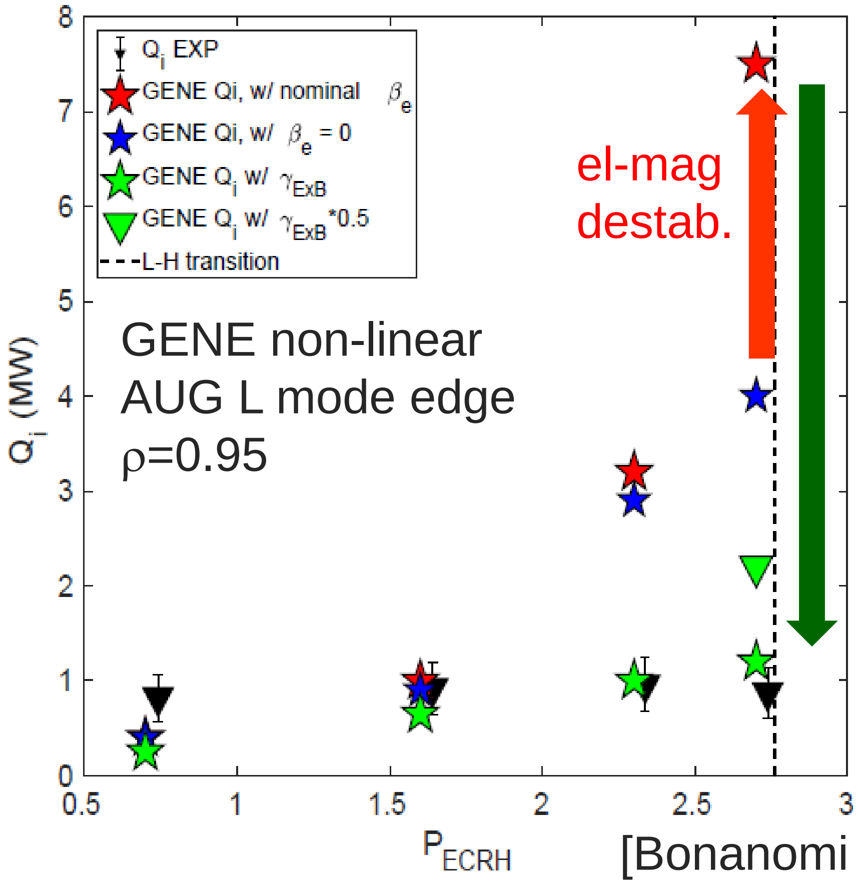
$\boldsymbol{E_r \sim -3\nabla T_{e,divertor\ target}}$

+ fast ion losses
+ 3D mag breaking
+ turb. [Sarazin next & Vermare Reinacker Thur.]



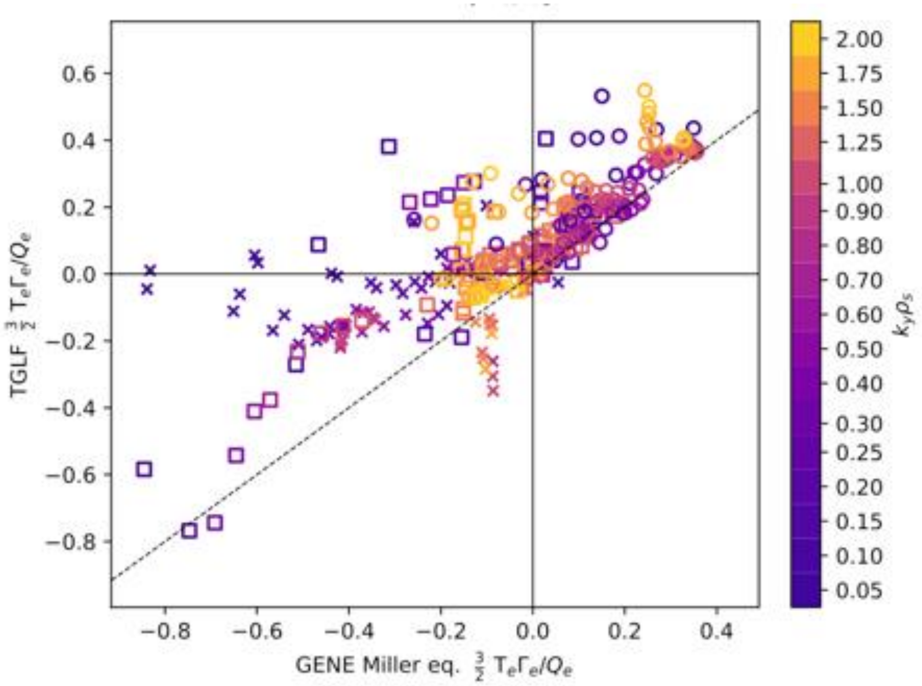
L mode edge turbulence: role of resistivity, electro-magnetic destabilization, ExB

- As collisionality rises: resistive modes destab ITG-TEM stab [Bourdelle NF2014, Bonanomi NF2019]
- Electromagnetic effects destabilizing [Scott PoP2005, DeDominici NF2019] low toroidal mode numbers, more sensitive to ExB shear [Bonanomi EPS2023]



[Bonanomi EPS2023]

Higher fidelity QL GENE vs lower fidelity TGLF in terms of heat and particle flux [Snoep Wed]

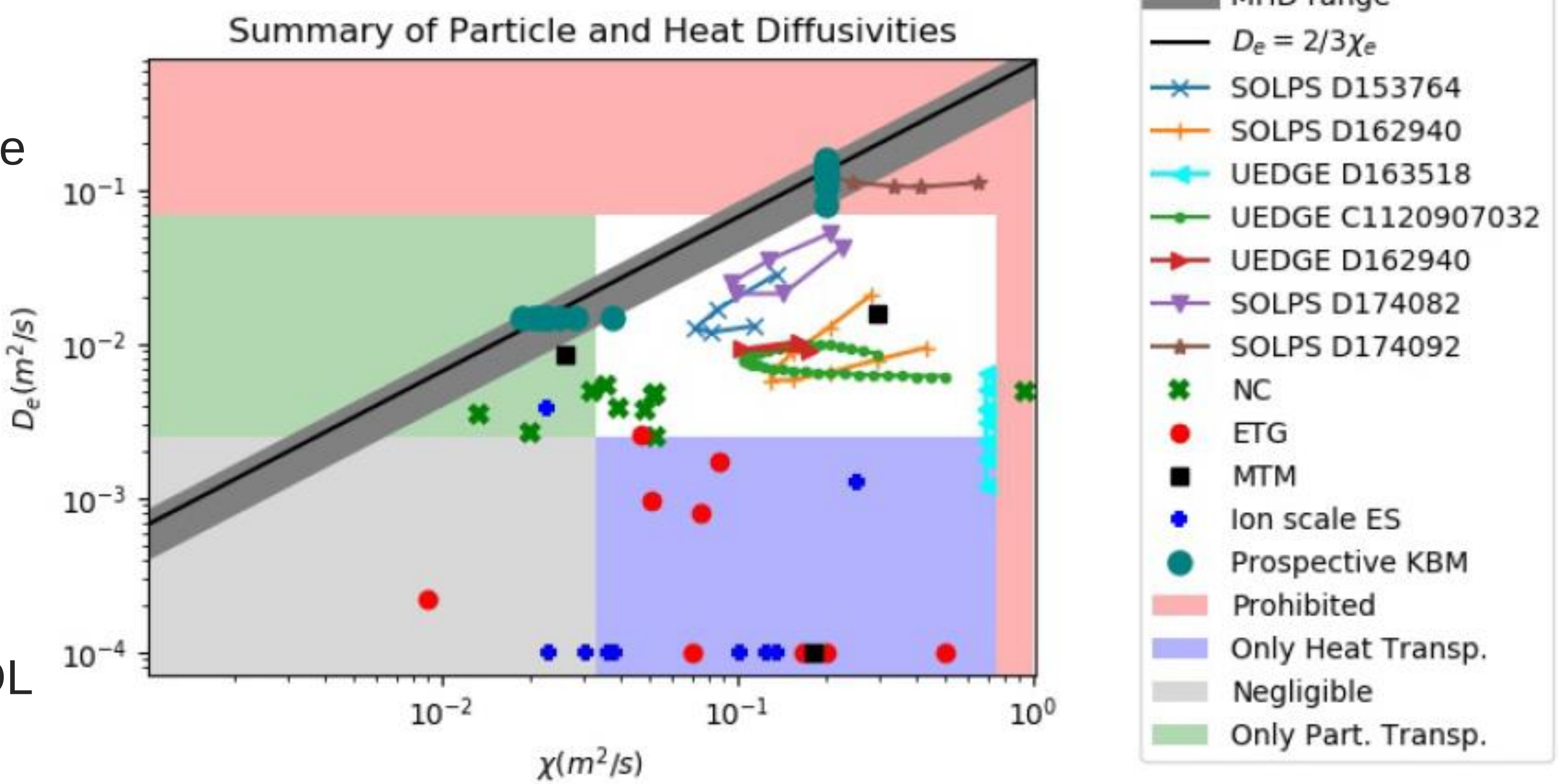


➢ Validity of reduced models essential to disentangle source vs transport [TalaToday] and explore role in density lim [Giacomin PRL23] & H mode access [Eich, Manz NF2021]

Turbulent transport of heat <u>and particles</u> in the H mode pedestal

- SOLPS, UEDGE on DIII-D, Cmod cases. Particle < heat diffusion, but higher than neoclassical See also particle balance btw ELMS at JET [Horwarth PPCF2023] and Salmi Poster Today
- Gyrokinetic ETG simulation: mostly heat flux [QL vs NL Hatch PoP22]
- MicroTearing modes can have larger particle fluxes [QL vs NL Hamed Pop23]
- Neoclassical transport not negligible

Particle and heat balance: DIII-D and CMod



[Hatch FY19 Theory Performance Target]

[Leppin, Herschel, Cano-Meggias next]

outline

- Database analysis: correlations btw separatrix, SOL and core performances in L and H modes

- Advances in addressing the integrated problem of particle source and transport around the separatrix
  - Source
  - ExB
  - Transport
  - **Integrated modelling**

- Remaining experimental and modelling challenges towards ITER and beyond

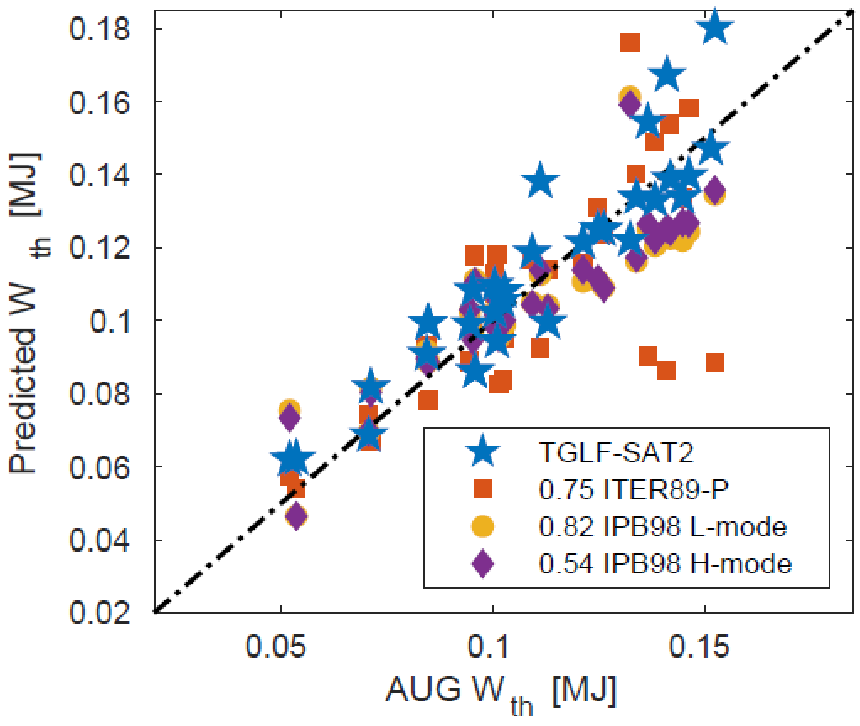
Integrated modelling up to the separatrix: L mode

AUG L mode database

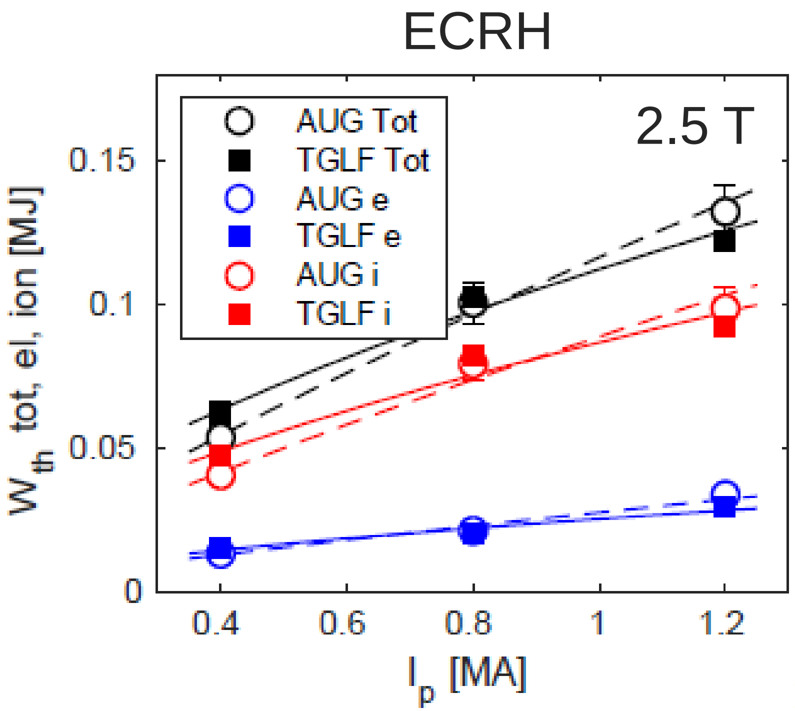
ASTRA-TGLFsat2-NCLASS-TORBEAM(ECRH)-RABBIT(NBI)

- Flux driven prediction of T_e, T_i, n_D from **core up to separatrix**
- j, n_W and n_{Bo} fixed
- Turbulence: quasilinear fluid code TGLF sat2
- Separatrix:
  - T_{sep} from 2 point model using λ_q scaling [Goldston],
  - T_i=1.5xT_e,
  - n_{sep} =0.3<n> with neutral source feedback on <n>

better than empirical scaling laws, quantitatively ….



and qualitatively!



Explains the I_p impact on confinement by stabilization of turbulence at lower q

[Angioni NF2022]

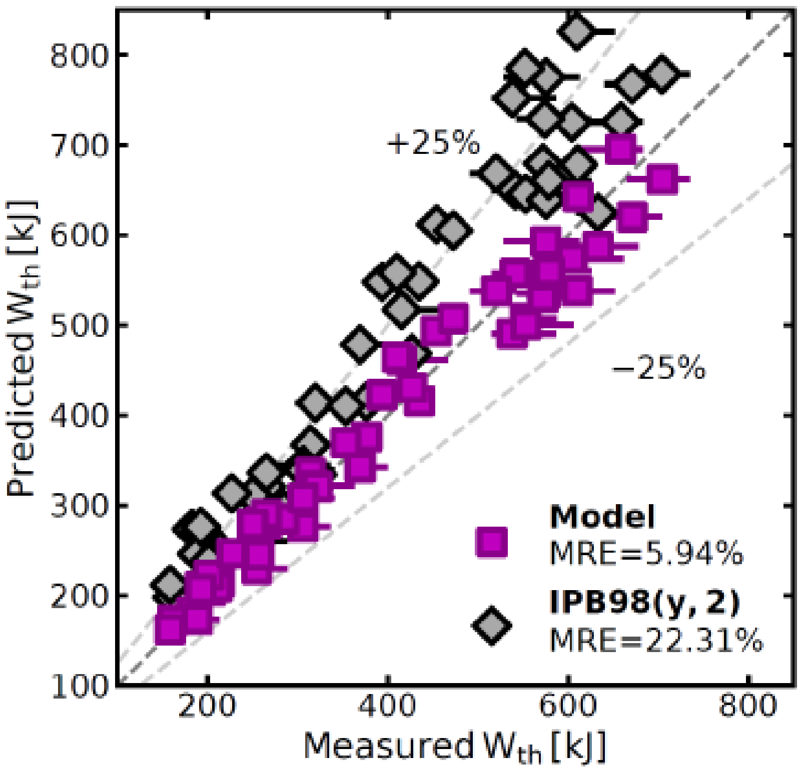
Integrated modelling up to the separatrix: H mode

AUG H mode database

ASTRA-TGLFsat2-NCLASS-IMEP-TORBEAM(ECRH)-RABBIT(NBI)

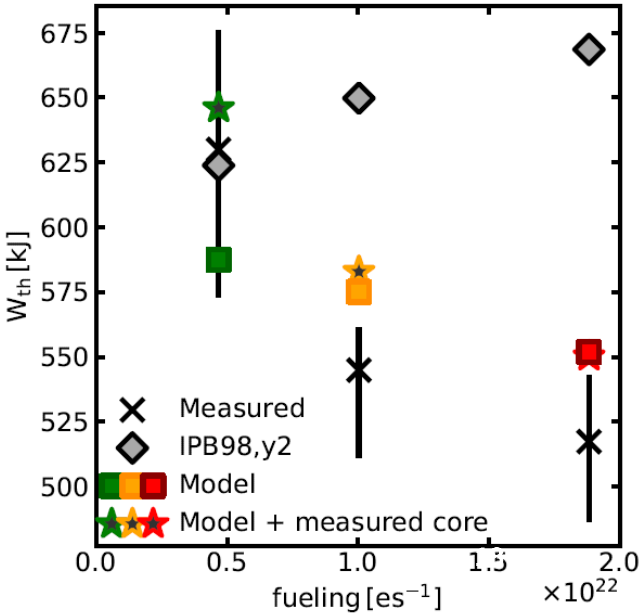
- Flux driven prediction of T_e, T_i, n_D from **core up to separatrix mixing physics based and scalings.**
- Core Turbulence: quasilinear fluid code TGLF sat2, incl. fast ion dilution for T_e, T_i, n_D. V_{tor} up to ped top Pr=1.
- IMEP:
  - Pedestal: ideal MHD stability + ad-hoc $R < \nabla T_e > / T_{e,top} = -82.5$
  - Separatrix: T_{sep} from 2 point model using λ_q scaling [Eich] n_{sep} machine specific scaling, on AUG $\propto \Gamma_D^{0.2}$ neutral source feedback on <n>

better than empirical scaling laws, quantitatively ….



[Luda NF2021 and poster Today]

and qualitatively!



Explains W_{th} degradation increased fuelling: n_{sep} higher, $\alpha=\alpha_c$ for narrower pedestal, lower P_{ped}

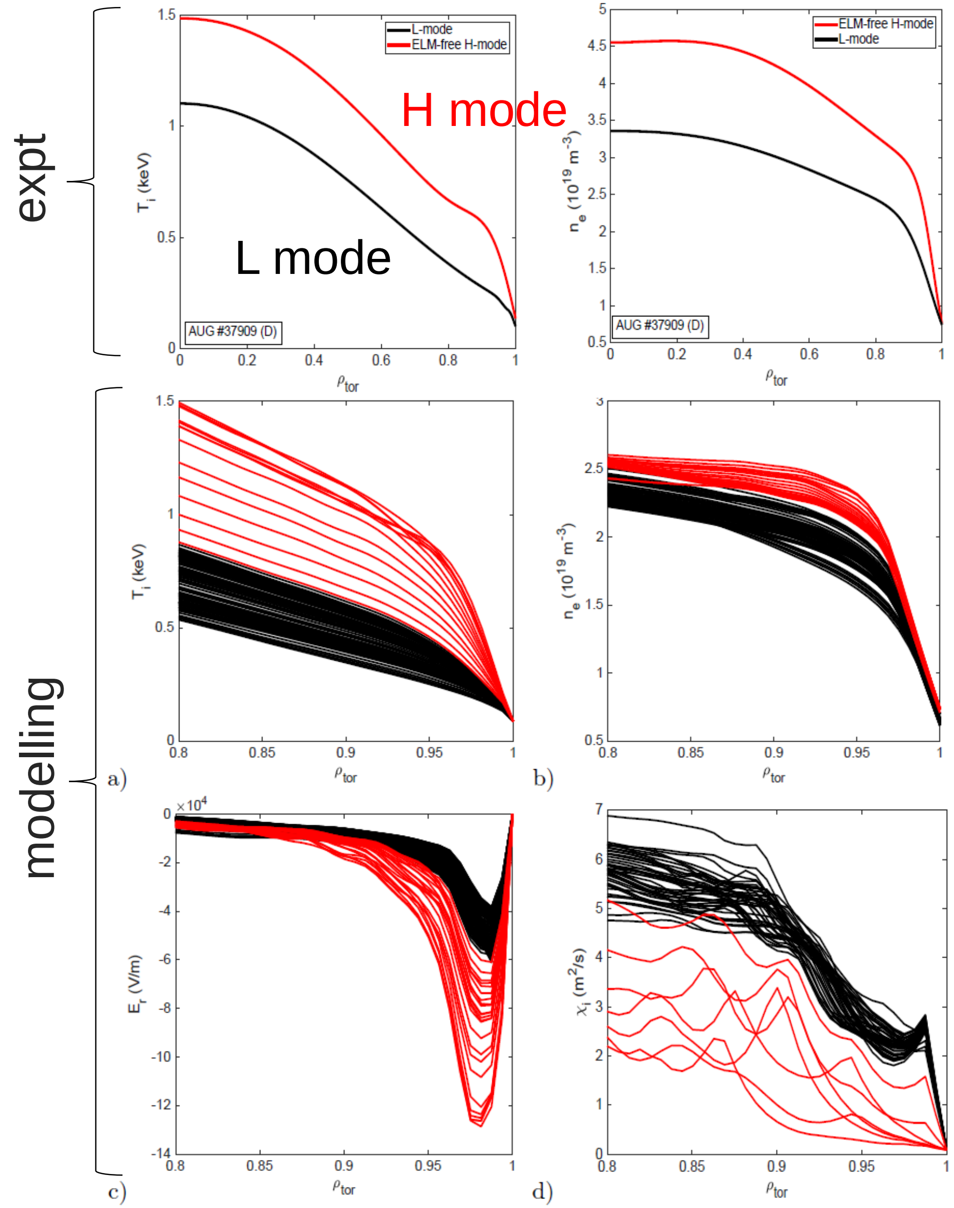
Integrated modelling up to the separatrix: L to H mode transition

AUG D discharge spanning from L to H-mode phases

ASTRA-TGLFsat2-NCLASS-TORBEAM(ECRH)

- Flux driven prediction of T_e, T_i, n_D from **core up to sep.**
- Turbulent heat/particle fluxes: TGLF-sat2 (elmag effect, ITG-TEM & resistive modes, ExB stab)
- Feedback control on neutral influx at the separatrix to maintain <n>
- n_{sep} = 0.25 <n> and T_{sep} from 2 point model
- Force balance E_r up to ρ=0.995. ρ=1 E_r=0 to mimic SOL constrain, enhancing ExB shear near separatrix

As the power is ramped, the simulation shows H-mode pedestal-like structure [Bonanomi Sub to NF letter, EPS2023]
E_r=0 at sep. key ingredient to obtain a ETB formation similar to flux driven non-linear fluid simulations [Chôné PoP2015, Bourdelle NF2020]



outline

- Database analysis: correlations btw separatrix, SOL and core performances in L and H modes

- Advances in addressing the integrated problem of particle source and transport around the separatrix

- Remaining experimental and modelling challenges towards ITER and beyond

Remaining challenges

- Need to understand how neutrals crossing separatrix impact Today's observations before extrapolating to very different fueling conditions in ITER and beyond:

➢ More open/shared multi-machine databases including core, pedestal and SOL, to explore extensively correlation btw core energy and particle perf. against sep, SOL parameters. Any reported universal trends = ideal challenge for int. modelling. Playground for ML training [Kit Today, Järvinen Thur].

➢ More physics model integration:
  - ➢ Validation of L mode edge turbulence: resistive, electromagnetic, shaping impact. TGLF enough? need higher fidelity models, GENE/GKW based neural network? [GKDB Fuhr Wed]
  - ➢ Validation of H mode pedestal turbulence: QL vs NL on-going, might need global gyrokinetic modeling? how to speed-up such complex models for integrated modeling?
  - ➢ SOL physics imposing boundary conditions: n_{sep}, T_{sep} and E_r, need to be based on higher fidelity modeling, SOLPS database + ML enough? Ideally incl. turbulence [SOL Wed]
  - ➢ Neutrals flux/energy crossing separatrix need to be coherent with SOL plasma, likely only possible with kinetic/fluid neutral model integration up to wall? [SOL Wed]
  - ➢ Model also impurity seeding/transport, for exhaust control while avoiding fuel dilution [Imp Thur]

- More integrated modelling now! Mixing physics models with scalings, allowed understand complex physics at play in L, H modes on AUG already. Large scale validation tools dev. in TSVV11, to become widely used on various tokamak databases to extend further AUG pioneer work [Ho poster Wed]