Isotope Dependence of Confinement in JET-ILW Deuterium and Hydrogen Plasmas

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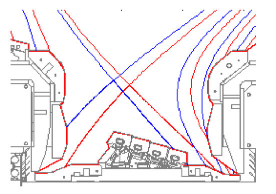
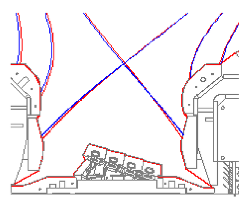
Datasets

- **Deuterium & Hydrogen type I ELMy H-modes**, 171 samples (*Maggi, PPCF 2018*)
  B_T=1T, I_p=1MA ($q_{95} \cong 3$) and B_T=1.7T, I_p=1.4MA ($q_{95} \cong 3.7$)
  (also 1.7T, 1.7MA in D only for dimensionless identity)
  Mostly 'corner-corner (C/C)', configuration for best pumping and lowest P_{L-H} power (some V/H too)
  Gas scans and power scans:
  Deuterium: 3.5MW≤ P_{NBI}≤17MW, only NBI
  Hydrogen: 5 MW≤ P_{NBI}≤10MW, 0 ≤ P_{ICRH}≤6.5MW
  NBI+ICRH required to achieve type I ELMy H-modes at 1.7T/1.4MA



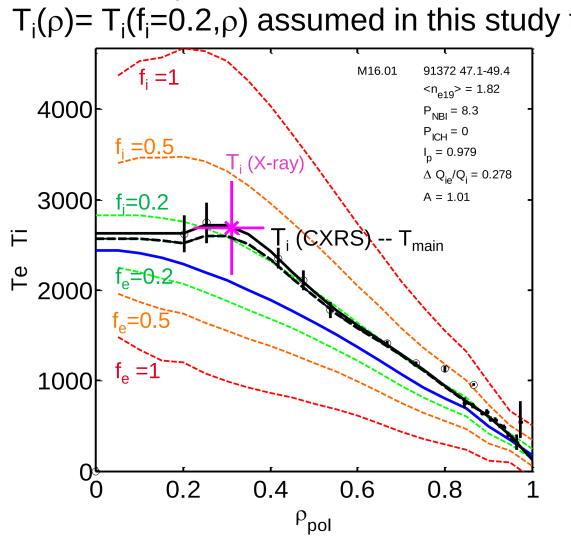
- **Deuterium & Hydrogen L-modes**, 20 samples
  B_T=2.9 T, I_p=2.5 MA, $<n_e>$≅3.1×$10^{19}m^{-3}$ NBI power scan only, 20 samples,only NBI power scans 1.5MW≤ P_{NBI}≤9.5MW
  Divertor strike points on vertical tiles for highest P_{L-H}

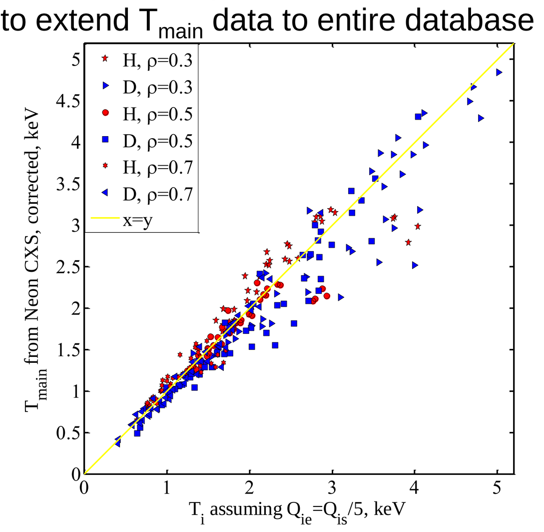


- **Diagnostics**
  Isotope ratio from high resolution Balmer-α spectroscopy and RGA
  T_e and n_e from Thomson scattering (HRTS as used here and LIDAR)
  T_i , ω_t and from CXRS (mostly Ne X line, only for 86 samples in H-mode)
  n_i from n_e and Z_{eff}, assuming Z_{eff}-1 is due to Be only

Main ion temperature constrained by power balance

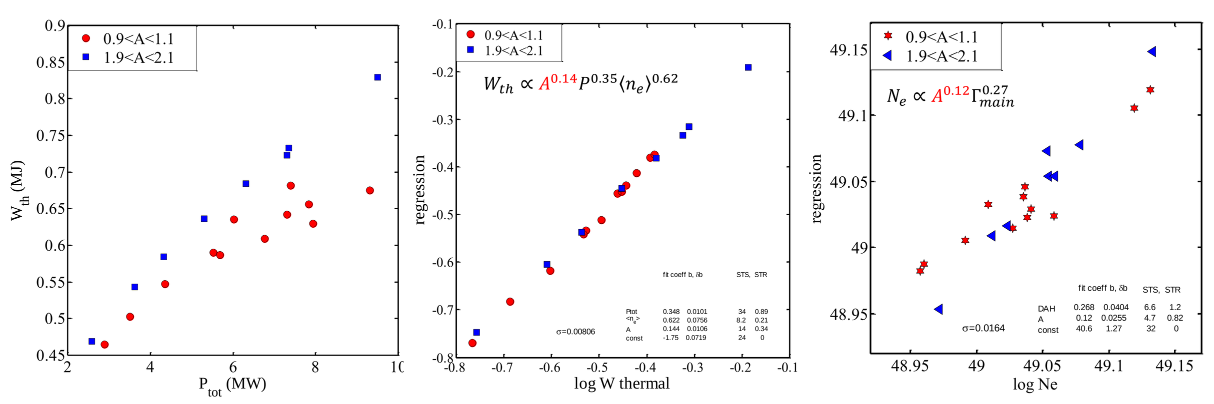
- Previous anlyses (Maggi PPCF 2018) assumed Ti=Te. Since then, CXRS data (C, Ne) became available, but only for half the dataset (and still noisy).
- Detailed analysis (H Weisen 201?) extends T_{imp} data to whole dataset for the main ions T_{main}
- A family of assumed $T_i(f,\rho)$ can be defined, assuming a certain fraction f_i of Q_{is} is transferred to electrons by equipartition.
  Shown: f_i=0.2,0.5 & 1 (& if Q_{ie}<0, $f_e=Q_{ie}/Q_{es}$)
- Multi-ion power balance shows T_{main} in range (0.95-1)× T_{imp} in core Most $T_{main}(\rho)$ close to $Ti(f_i=0.2,\rho)$, i.e. net ion heat flux is ~80% of deposited
- $T_i(\rho)= T_i(f_i=0.2,\rho)$ assumed in this study to extend T_{main} data to entire database





L-modes: isotope dependence is weak

- NBI power scans in D and H at n_e ≈ const

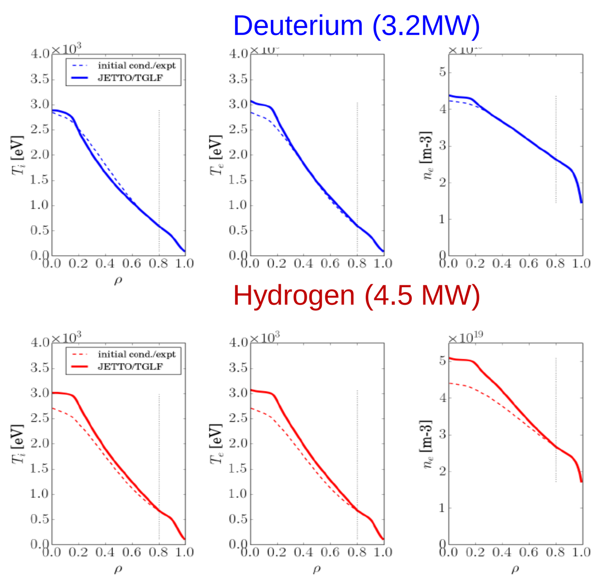


- Stiff temperature profiles: R/L_{Te}≈8 m^{-1}, T_i/T_e ≈1
- GK analysis shows dominant mode is ITG in core (*Maggi EPS 2018*)
- Robust regressions for thermal stored energy W_{th} without and with n_e
  $W_{th} \propto A^{0.15} P^{0.37}$ *or* $W_{th} \propto A^{0.14} P^{0.35} \langle n_e \rangle^{0.62}$ (figure)
- Small (±10%, unintended) variations in density show global particle confinement also weakly dependent on isotope:
  $N_e \propto A^{0.12} \Gamma_{main}^{0.27}$

with $N_e=\int n_e dV$ total electron content and Γ_{main} the main chamber Balmer-alpha emission (a.u.) from a horizontal midplane viewing line, taken as a proxy for the particle source

TGLF modelling of H & D L-modes with same W_{th}

- Predictive JETTO-TGLF (Staebler 2007, Romanelli 2014) modelling finds ~**identical confinement** in D and H due to temperature profile shapes (stiffness)
- Largest D / H differences in particle channel (not stiff)
- Weak "anti-GB" scaling in experiment, **missing in model**
- Including ExB effects does not improve confinement D relative to H **in this case**



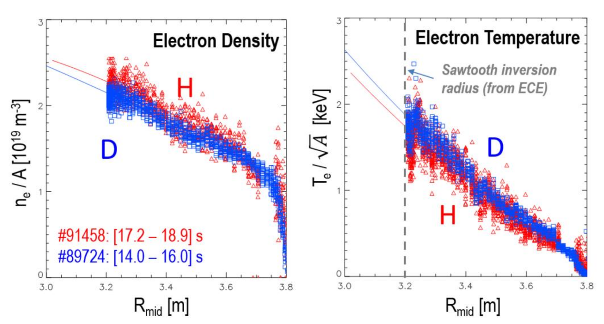
Discussion:

- Expectation of GB mass scaling of global confinement is naive!
- Assumes ion driven transport (ITG), neglects subdominant TEM, collisions
- Assumes that fluxes are proportional to gradients
- No complex non-linear / zonal flow / multi-scale effects
- Assumes all else equal when isotope is changed (e.g. ExB shear in GB units, fast ion density, edge conditions…)
- Assumes local property maps to a global confinement.
- **Boundary conditions can overrule local scaling with stiff profiles as recognised by Bateman et al, 1999**

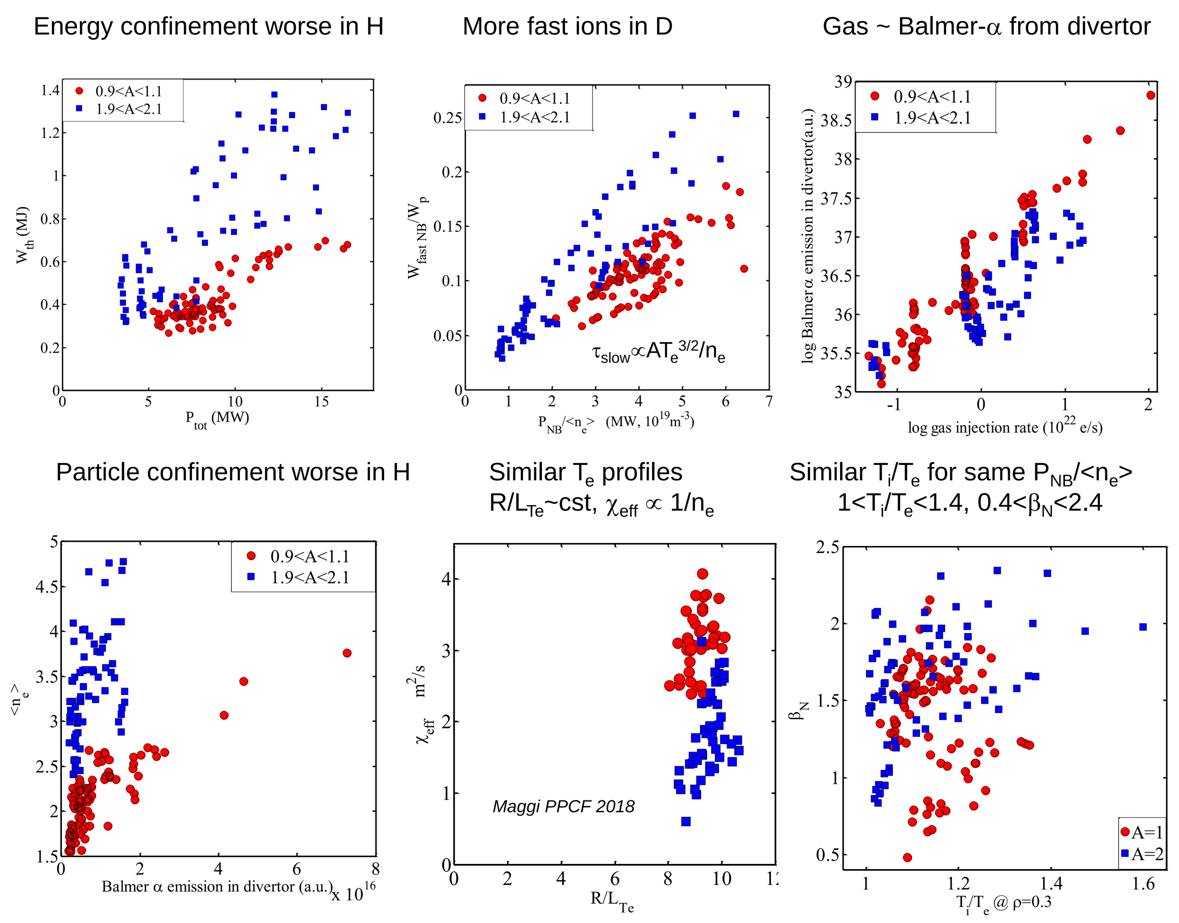
L-mode isotope identity experiment satifies scale invariance

- An H/D dimensionless L-mode identity pair in ρ*, β, ν* and *q* was successfully created by scaling the dimensional parameters as follows:
  $I_P, B_T \propto A^{3/4}$; $n \propto A, T \propto A^{1/2}$
- Scale invariance was achieved, i.e. the pair had identical normalised confinement time
  $\omega_{ci}\tau_{Eth} \propto B_T \tau_{Eth}/A$
- This is consistent with ion scale transport depending on ρ*, β, ν* and, within errors, no additional isotope dependence
- This difference in scaling compared to the dimensional set still calls for understanding (Maggi, NF, to be submitted)

Pulse #	#91458	#89724
Isotope	H	D
Time interval [s]	17.2 – 18.9	14.0 – 16.0
B_T [T]	1.74	2.95
I_P [MA]	1.44	2.46
P_{abs} [MW] (±10%)	2.56	6.24
$P_{abs}/B_T^{5/3}$ [MW/$T^{5/3}$]	**1.02**	**1.03**
Z_{eff} (±10%)	**1.4**	**1.35**
$\tau_{E,th}$ [s] (±10%)	0.155	0.19
$B_T \tau_{E,th}$ / A [T/s]	**0.27**	**0.28**



Type I ELMy H-mode: overview



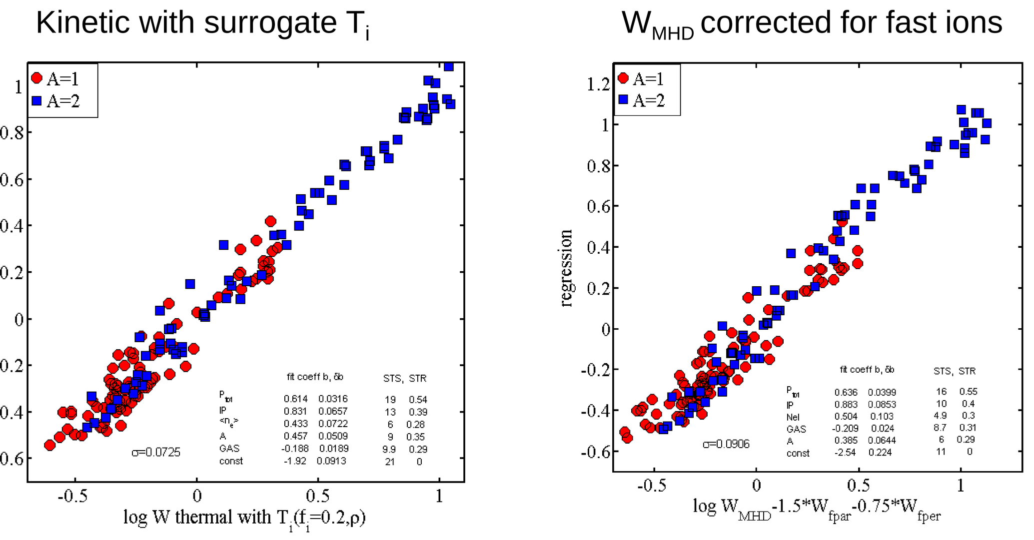
Type I ELMy H-mode:

Global thermal energy confinement depends strongly on ion mass

Kinetic: $W_{th} \propto A^{0.46\pm0.06} P^{0.61\pm0.03} I_p^{0.83\pm0.07} \langle n_e \rangle^{0.43\pm0.08} G^{-0.19\pm0.02}$

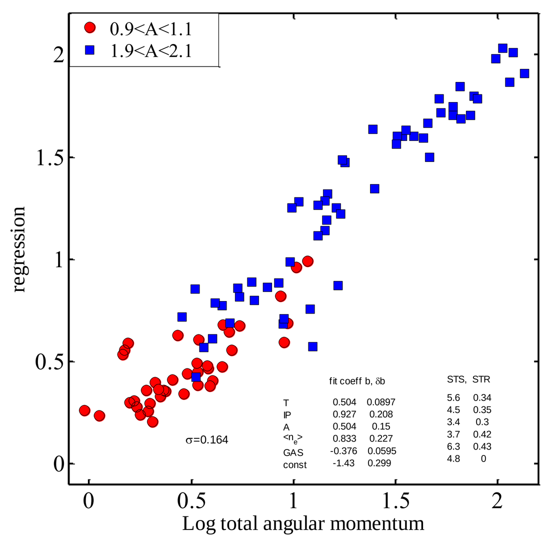
EFIT-based: $W_{th\text{-}EFIT} \propto A^{0.39\pm0.06} P^{0.64\pm0.04} I_p^{0.88\pm0.09} \langle n_e \rangle^{0.5\pm0.11} G^{-0.21\pm0.025}$

G is gas injection rate; is as statistically relevant and more significant than $\langle n_e \rangle$



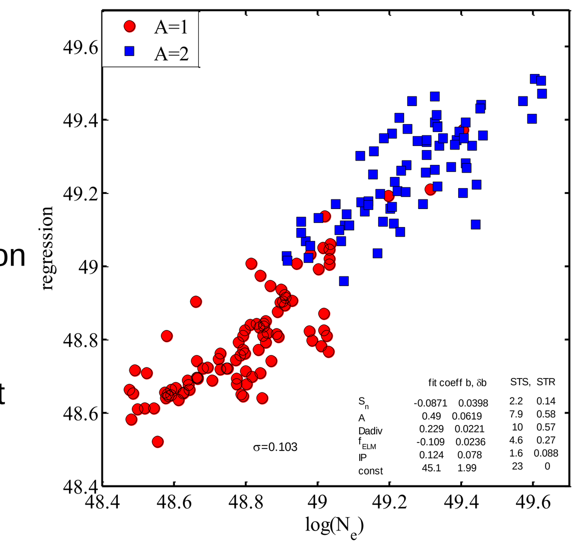
H-mode: Momentum dependence strong

- τ_ϕ/τ_E in range 0.8-1.6
- Dependencies for angular momentum L are similar to total thermal energy
  $L \propto A^{0.5} T^{0.5} I_p^{0.93} \langle n_e \rangle^{0.83} G^{-0.38}$
  T is total NBI torque
- Significant, because momentum carried by ions only, no issue with equipartition with electrons
- Consistent with overall transport being dominated by ion channel if Prandtl number ≈1, consistent with core GK modelling finding that ITG turbulence dominates in core



H-mode: particle confinement dependence strong

- $N_e=\int n_e dV$ total electron content Divertor Balmer-alpha $\Gamma_{div}$and NBI source S_{NBI} as proxies for source
- Regression:
  $N_e \propto A^{0.49} \Gamma_{div}^{0.23} S_{NBI}^{-0.08} I_p^{0.12} f_{ELM}^{-0.11}$ or
- Strongest dependences of N_e are on ion mass and divertor source
- Beam fuelling contribution S_n to N_e insignificant (STS<2) and irrelevant (STR~0.1, negative).
  Weak I_p dependence intriguing…
- Weak but significant negative dependence on ELM frequency f_{ELM}



Energy, momentum and particle confinement have isotope dependency ~$A^{0.4}$ to $A^{0.5}$ in type I ELMy H-mode! Coincidence or clue?

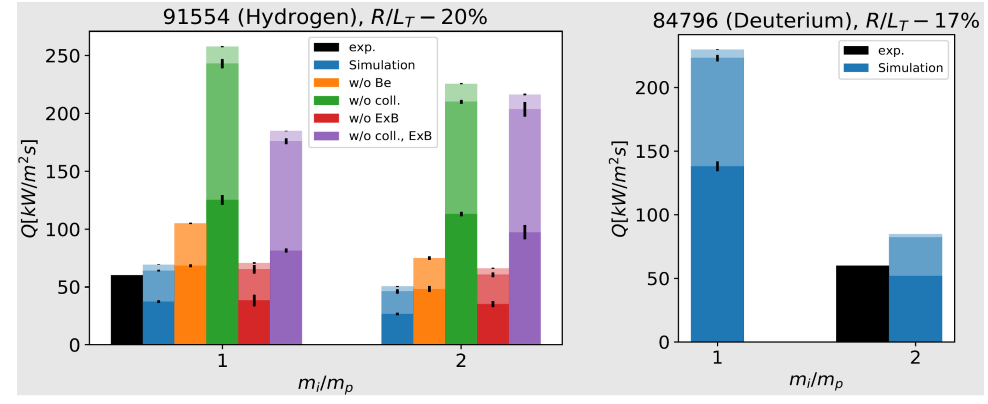
- Particle density n_e lower in hydrogen entails lower energy ($\propto n_{e,i}T_{e,i}$) confinement because absolute temperatures are similar in shape (stiff) and in absolute value

⇒**global confinement scaling with mass is BAKED INTO PEDESTAL**

- This conclusion was already drawn by Bateman et al, 1999

H-mode: Nonlinear GENE simulations reverse GyroBohm scaling

- Pair (H&D) with P_{aux}=10MW simulated, non-linear, flux-tube, ρ=0.5, assuming A=1 & 2
- Absolute heat fluxes reproduced if ∇T_e reduced by ~20%, provided
  - collisions are included
  - dilution by Be impurities included
- Strong overprediction if collisions are neglected
- Note this is local – results may be different in future global simulations with imposed boundary conditions (M. Oberparleiter, 2019)

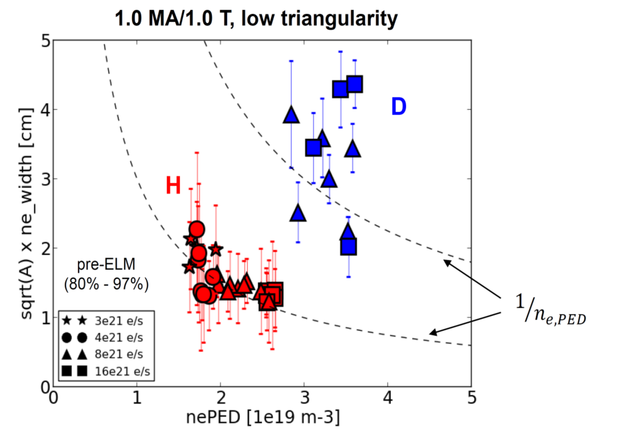


Transparency code: main ions, electrons, Be impurities

Type I ELMy H-mode: role of pedestal

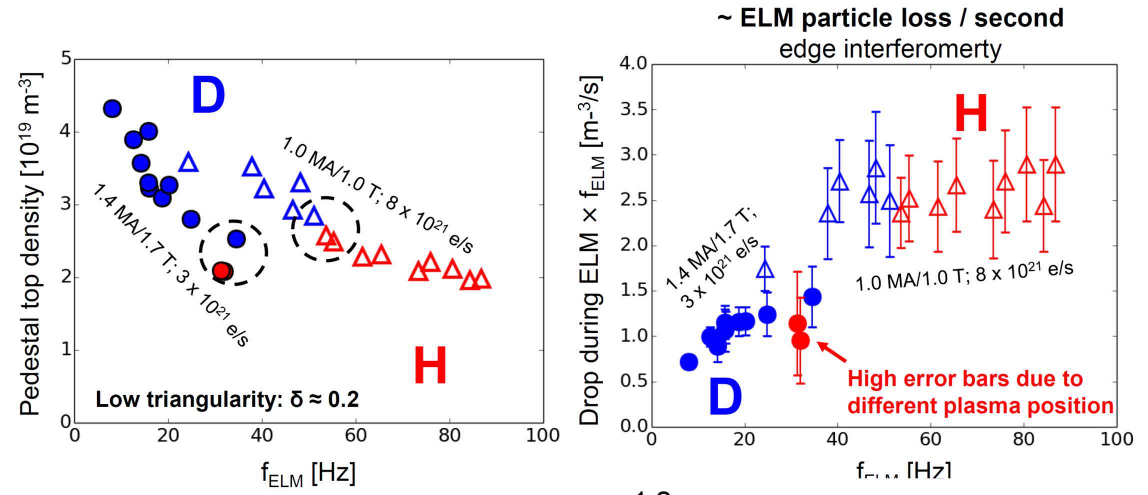
- The lower particle confinement in hydrogen is add odds with idea that the higher thermal velocity should make fuelling easier
- ⇒ Transport more than overrides fuelling by neutrals
- Pedestal width model based on neutral penetration (Groebner 2002):
  $\Delta_{ne} \propto A^{-1/2}(T_{iped}/T_{eped})^{-1/2} n_{eped}^{-1}$
- Scaling is not followed in the dataset, even reversed at 1MA, 1T !

⇒ **Transport processes that override neutral penetration differences are at work in pedestal** (Horvath, NF to be submitted)



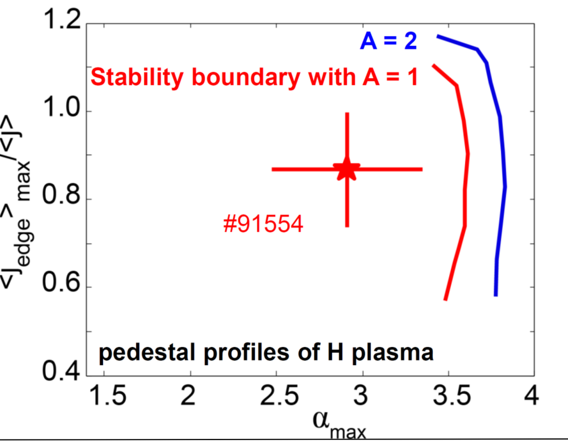
- Type I ELMs more frequent in H than D from same gas rate & power
- Pedestal density decrease with f_{ELM}
- However for f_{ELM}>40Hz, ELM particle loss/ELM decreases and time average losses $\delta n \times f_{ELM}$ saturate

⇒ **ELMs alone cannot explain differences in density between H and D**
(Horvath, NF to be submitted)



Differences in pedestal stability may play a role:

- Operating point for H well inside s-α stability boundary (D is ~at boundary)
- Small (5%) reduction of stability boundary expected from peeling-ballooning stability criterion $\gamma>\omega_{dia}/2$ because $\gamma \propto A^{-1/2}$
- A possibly larger effect (up to 15%) would be expected if $T_{e,sep}$ is higher in H than in D ($T_{e,sep}$≈100eV), as suggested by EDGE2D-EIRENE simulations ($T_{e,sep}$≤160eV in H),
- Strong ∇p region would be shifted outwards
  ⇒ P-B stability reduced, boundary shrinks
- Experimental data validation undergoing, but challenging



Summary & discussion

Type I ELMy H-mode:

- Strong isotope dependence in all transport channels: ~$A^{0.4}$ to ~$A^{0.5}$
- Gyrokinetic GENE analysis shows ITG is dominant
- GENE reverses GB scaling thanks to collsions and impurities
- Low particle confinement in hydrogen likely due to pedestal and edge transport processes
- Low particle confinement in hydrogen Low particle confinement in hydrogen, leads to lower n_e, entailing lower energy and lower momentum confinement than in D

L-mode:

- Weak dependence of global energy / particle confinement on isotope (~$A^{0.14}$)
- Stiffness in TGLF QL modelling overcomes intrinsic GB dependence in local QL models, leading to ~no isotope scaling, but NOT to observed anti-GB scaling

Take home:

- Key to understanding and prediction remains edge/pedestal physics

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JET PEAK

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