EUROfusion

EX/6-1

Isotope identity experiments in JET with ITER-like wall

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JET

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**See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)*

Isotope identity experiment

- Dimensionless expts test the invariance of plasma physics to changes in the dimensional parameters when the canonical dimensionless plasma physics parameters are conserved:

[Connor and Taylor, NF 1977]

$$\rho_i^* \sim \frac{\sqrt{m_i T_i}}{a B} \qquad \beta \sim \frac{n T}{B^2} \qquad \nu^* \sim \frac{n_e R Z_{eff}}{T_e^2} \qquad q \sim \frac{B}{R j} \qquad \text{Mach} \sim \frac{\sqrt{m_i} v_{tor}}{\sqrt{k T_e}}$$

- $\Omega_i \tau_{E,th} \sim \rho^{-*\alpha_\rho} \beta^{-\alpha_\beta} \nu^{*-\alpha_\nu} q^{-\alpha_q} M^{-\alpha_M} A^{-\alpha_A} Z^{-\alpha_Z} \ldots$

[Luce, PPCF 2008]

$A = m_i/m_p$

$\Omega_i = eB/A$

- **Plasma boundary effects (neutrals recycling, impurities…) not included → could potentially invalidate approach**

- Isotope identity: **exploiting the change in isotope mass A, achieve discharges with matched dimensionless profiles in the same tokamak:**

[Cordey et al., PPCF 2000]

→ B & $I_P \sim A^{3/4}$; $n \sim A$; $T \sim A^{1/2}$; $\omega_{tor} \sim A^{-1/4}$

Isotope identity not trivially expected a priori

- Although isotope mass appears explicitly only in ρ_i^* and Mach-number, changing A in experiment affects all plasma kinetic profiles:
  - Numerous plasma parameters and transport processes have isotope mass dependence [*Weisen et al., J Plasma Phys 2020*]
  - Operational effects are impacted by changes in isotope mass (NBI, RF heating)
  - → isotope identity not trivially expected a priori

- Isotope identity obtained in JET with C-wall in H and D with type I ELM H-mode
  - Profile similarity achieved over entire plasma radius [*Cordey et al., PPCF 2000*]

Outline of the talk

- L-mode isotope identity in H and D
- Type I ELMy H-mode isotope identity in H and D
- Conclusions and outlook

JET-ILW

*Isotope identity technique revisited in **JET-ILW**, with the addition of:*

- *Improved edge kinetic profiles → H-mode pedestal*
- *Sought similarity in Mach number*
- *Investigated role of v_{tor} and ExB shear on core transport*

Hydrogen and Deuterium L-mode

In JET-ILW:

- $\tau_{E,th} \sim \mathbf{A^{0.15\pm0.02}\ P_{abs}^{-0.63\pm0.02}}$
- Edge particle and heat transport larger in H than D

[Maggi et al., PPCF 2018]

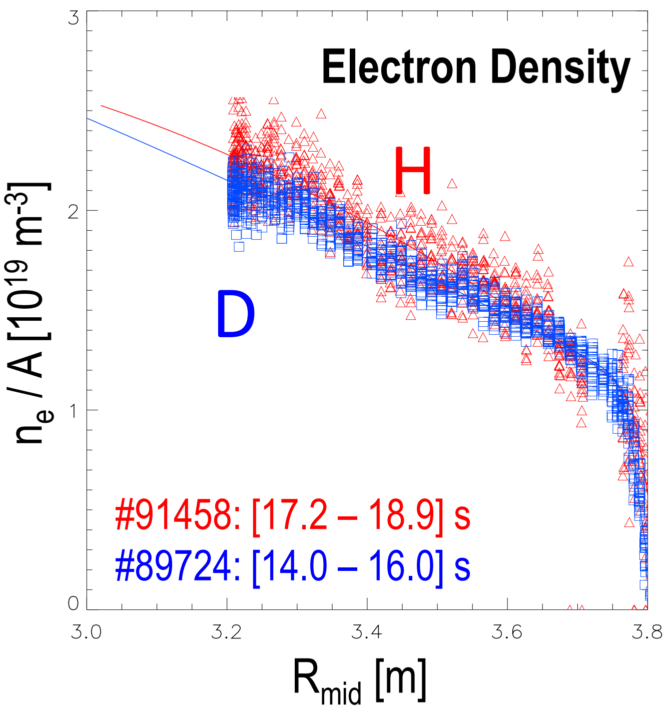
[Bonanomi et al., NF 2019]

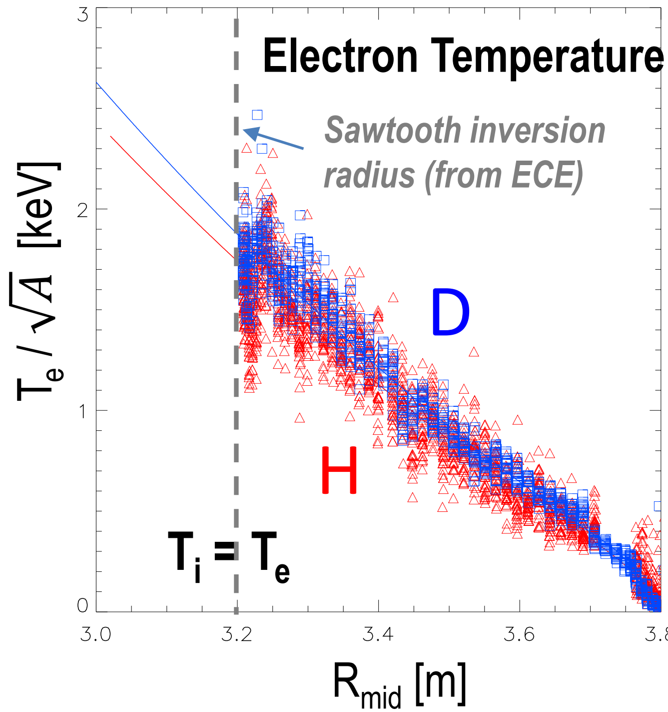
H & D L-mode pair with good match of scaled profiles

D: #89724 (3.0T/2.5MA) and H: #91458 (1.74T/1.44MA)

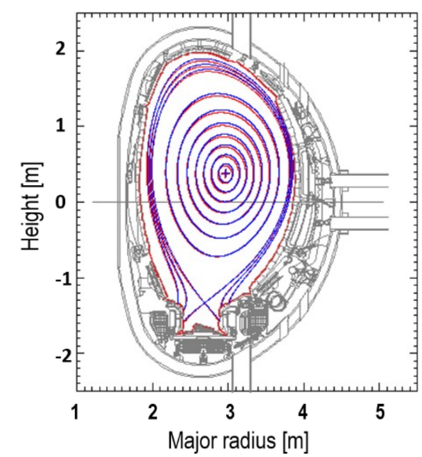
Isotope purity ≥ 98%

Composite HRTS profiles over steady time window of discharge





Strike points on divertor vertical targets → maximizes L-mode domain



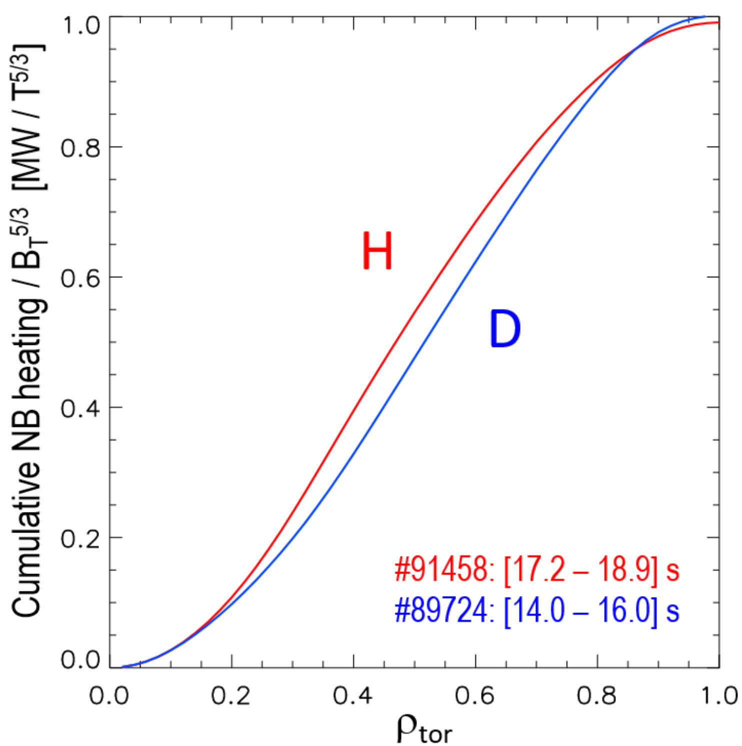
- **→ Similar density peaking in H and in D at same ρ*, ν*, β, q**
- Both pinch and NB particle source contribute to core n_e peaking (flux driven predictive modelling)

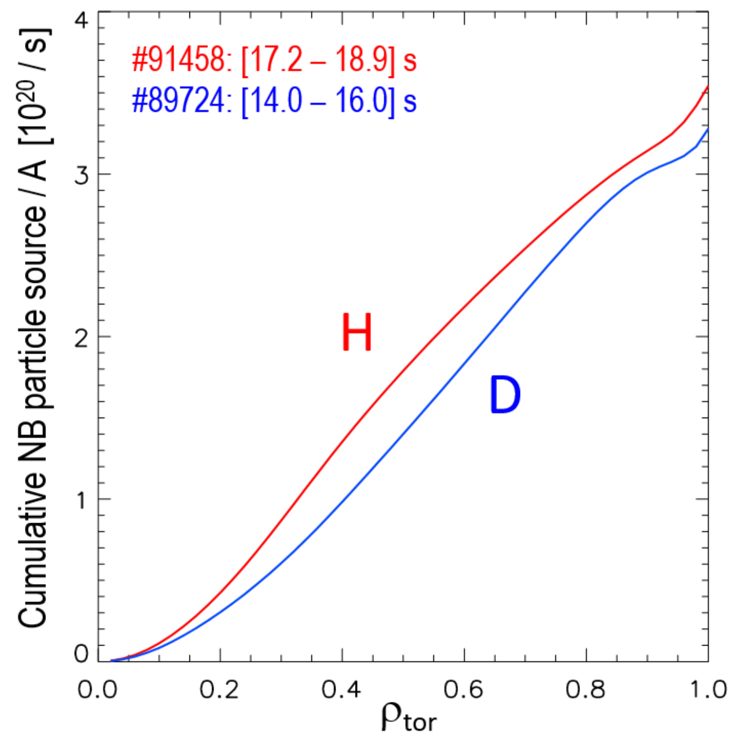
[Maggi et al., NF 2019]

Similar NB heating profiles in H and D

D: #89724 (3.0T/2.5MA) and **H: #91458 (1.74T/1.44MA)**

Beam energy: 82 – 91 keV; P_{NBI} = 6.24 MW   Beam energy: 64 – 71 keV; P_{NBI} = 2.56 MW





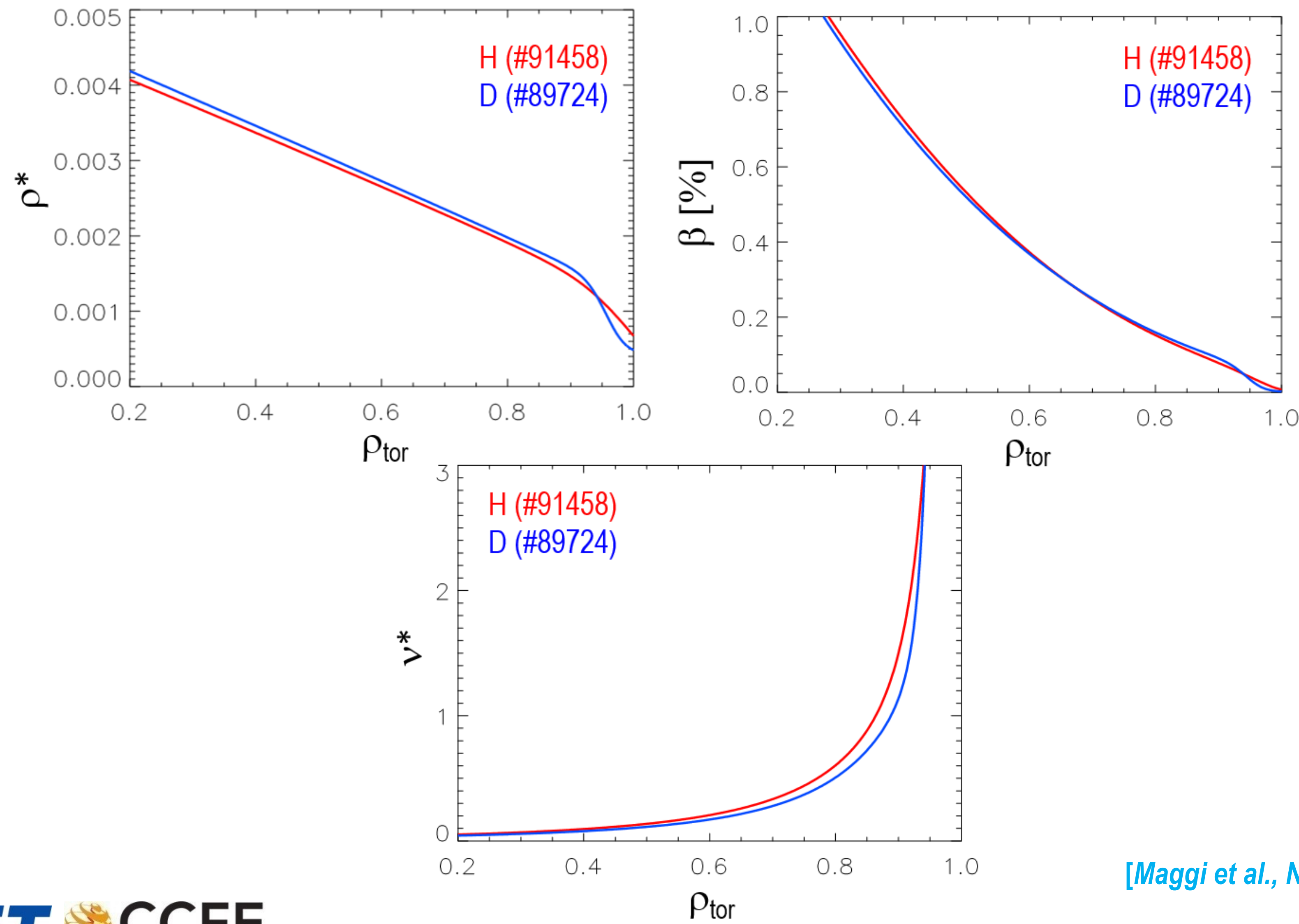
TRANSP/NUBEAM, with $T_i = T_e$

Similar NB heating profiles in H and D

Larger NB particle source in H plasma core

Dimensionless profiles matched in H and D pair

D: #89724 (3.0T/2.5MA) and **H: #91458 (1.74T/1.44MA)**



[*Maggi et al., NF 2019*]

H & D isotope identity achieved in confinement region

[*Maggi et al., NF 2019*]

Pulse # / Isotope	**H: #91458**	**D: #89724**
Time interval [s]	17.2 – 18.9	14.0 – 16.0
B_T [T] / Ip [MA] / q_{95}	1.74 / 1.44 / 3.4	2.95 / 2.46 / 3.4
P_{abs} [MW] (±10%)	2.56	6.24
$\tau_{E,th}$ [s] (±10%)	0.155	0.19
T_i / T_e	1.0	1.0
$P_{abs} / B_T^{5/3}$ [MW/T$^{5/3}$]	**1.02**	**1.03**
Z_{eff} (±10%)	**1.4**	**1.35**
$\Omega_i \tau_{E,th}$ [T s]	**0.27**	**0.28**

Input power required for L-mode isotope identity: $P_{abs} \sim B_T^{5/3}$

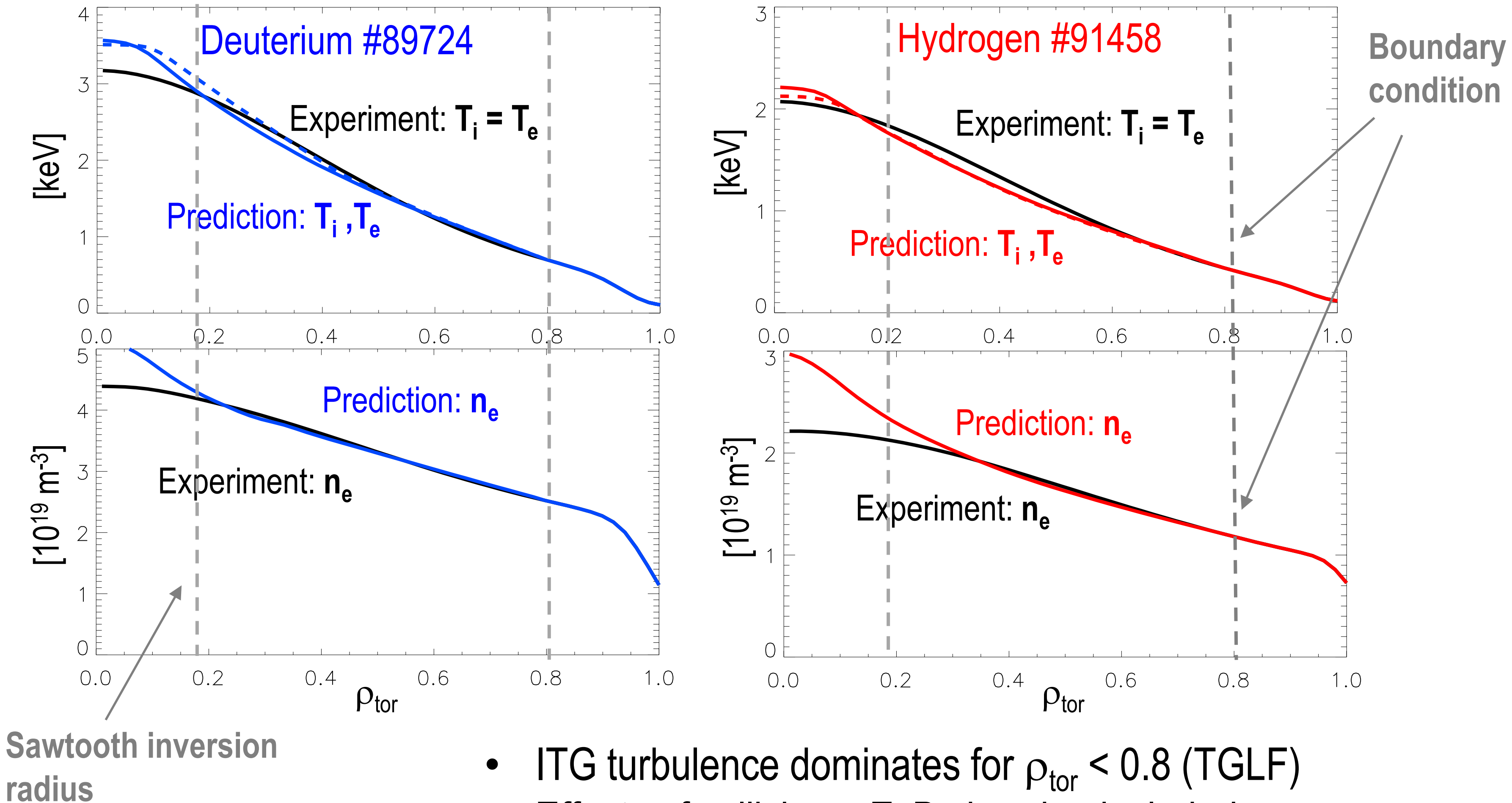
$\Omega_i \tau_{E,th}$ identical in H and D

→ Confinement scale invariance principle satisfied in L-mode confinement region

- Scaled thermal energy confinement independent of isotope mass: $\Omega_i \tau_{E,th} \sim A^{0.05\pm0.1}$

Flux driven JETTO-TGLF (SAT1) predictive modelling

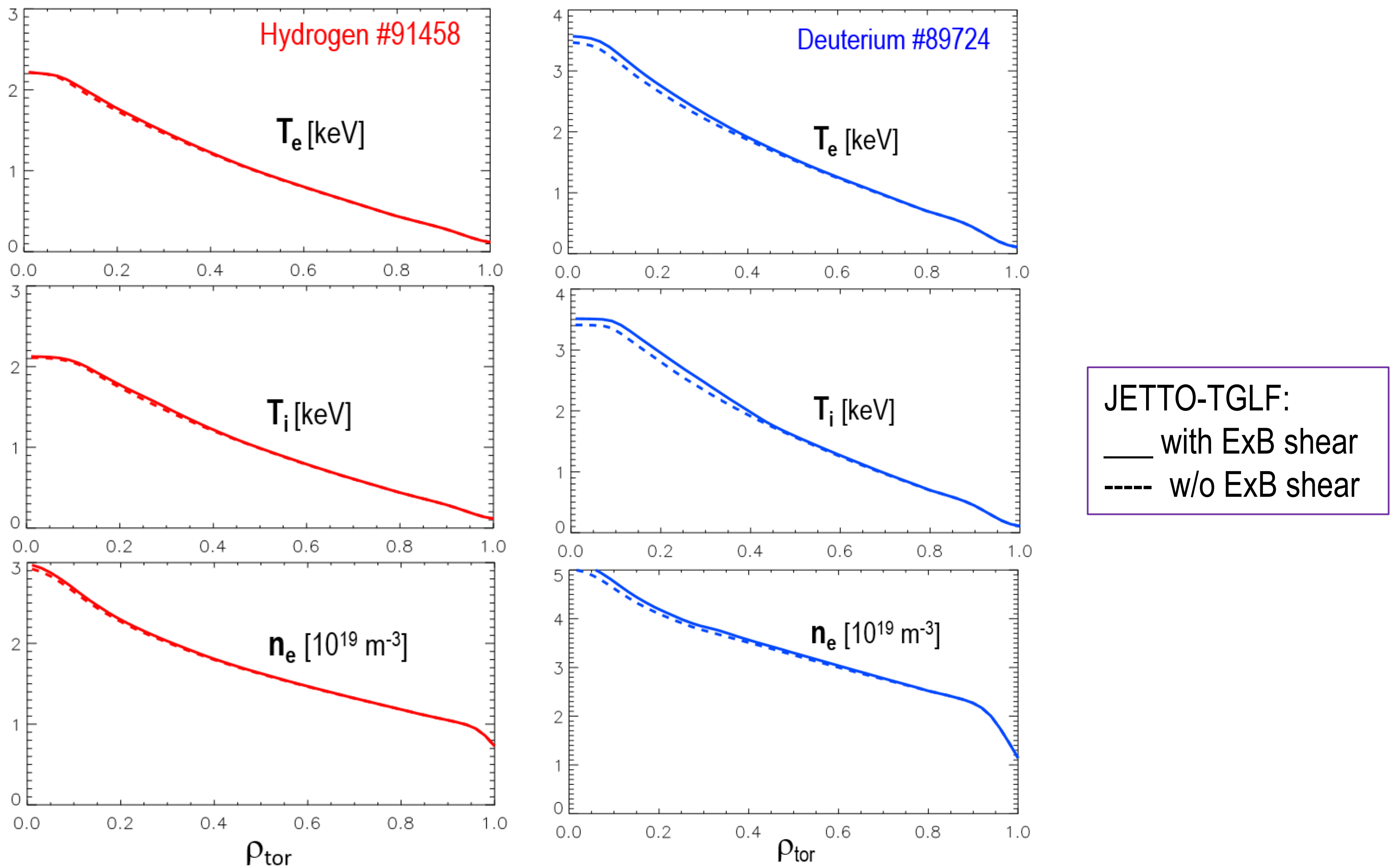
Very good agreement with experiment for both isotopes:
- Stiff core heat transport offsets
- Local gyro-Bohm scaling



- ITG turbulence dominates for ρ_{tor} < 0.8 (TGLF)
- Effects of collisions, ExB shearing included
- No sawtooth model used

[*Maggi et al., NF 2019*]

Negligible effect of ExB shear on core transport



v_{tor} and ExB shearing very low → do not affect heat and particle transport of H and D L-mode

Hydrogen and Deuterium
Type I ELMy H-mode at moderate beta

In JET-ILW:

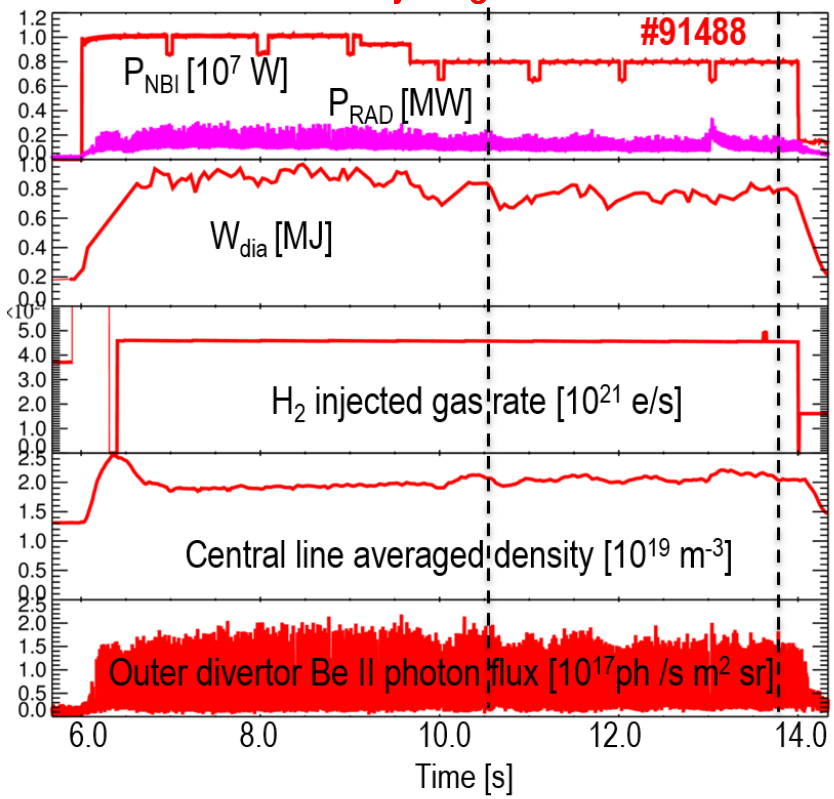
[*Maggi et al., PPCF 2018*]
[*Weisen et al., J Plasma Phys 2020*]
[*Horvath et al., NF 2021*]
[*Schneider et al., this conference*]

- Energy, particle, momentum confinement ~ $\mathbf{A^{0.5}}$
- Strong, favourable isotope mass dependence of energy confinement at pedestal
  - Primarily in particle channel (likely from inter-ELM particle transport)

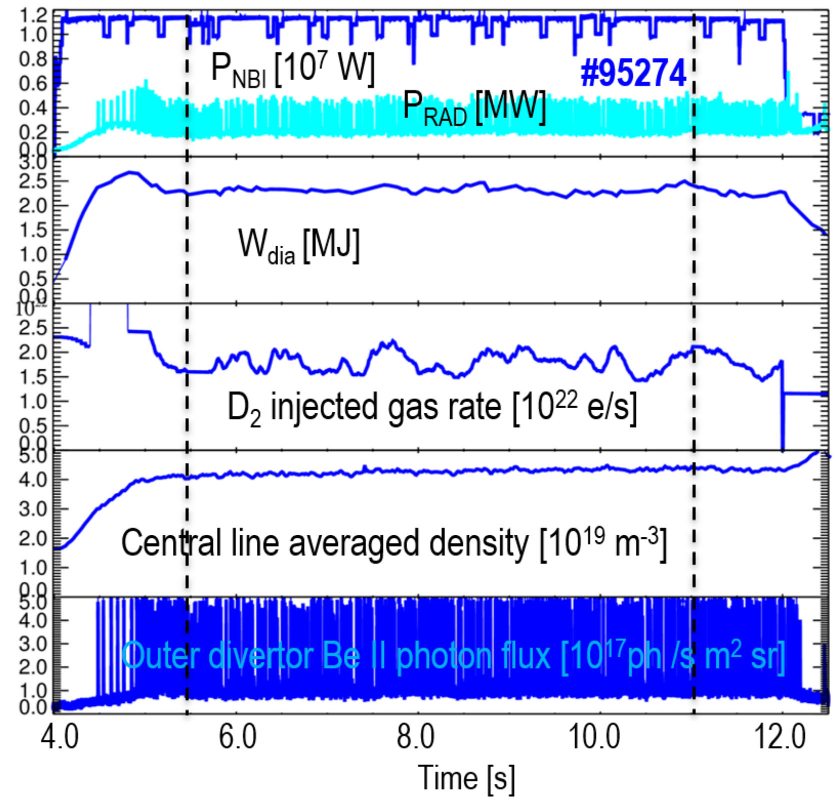
Type I ELMy H-mode pair in H and D

- Varied parameters:
  - Input NBI power and beam energies
  - Injected gas rate
  - f_{ELM} in D, via feedback control of D_2 gas rate → same f_{ELM}/Ω_i in H and D → match of $n_{e,PED}/A$

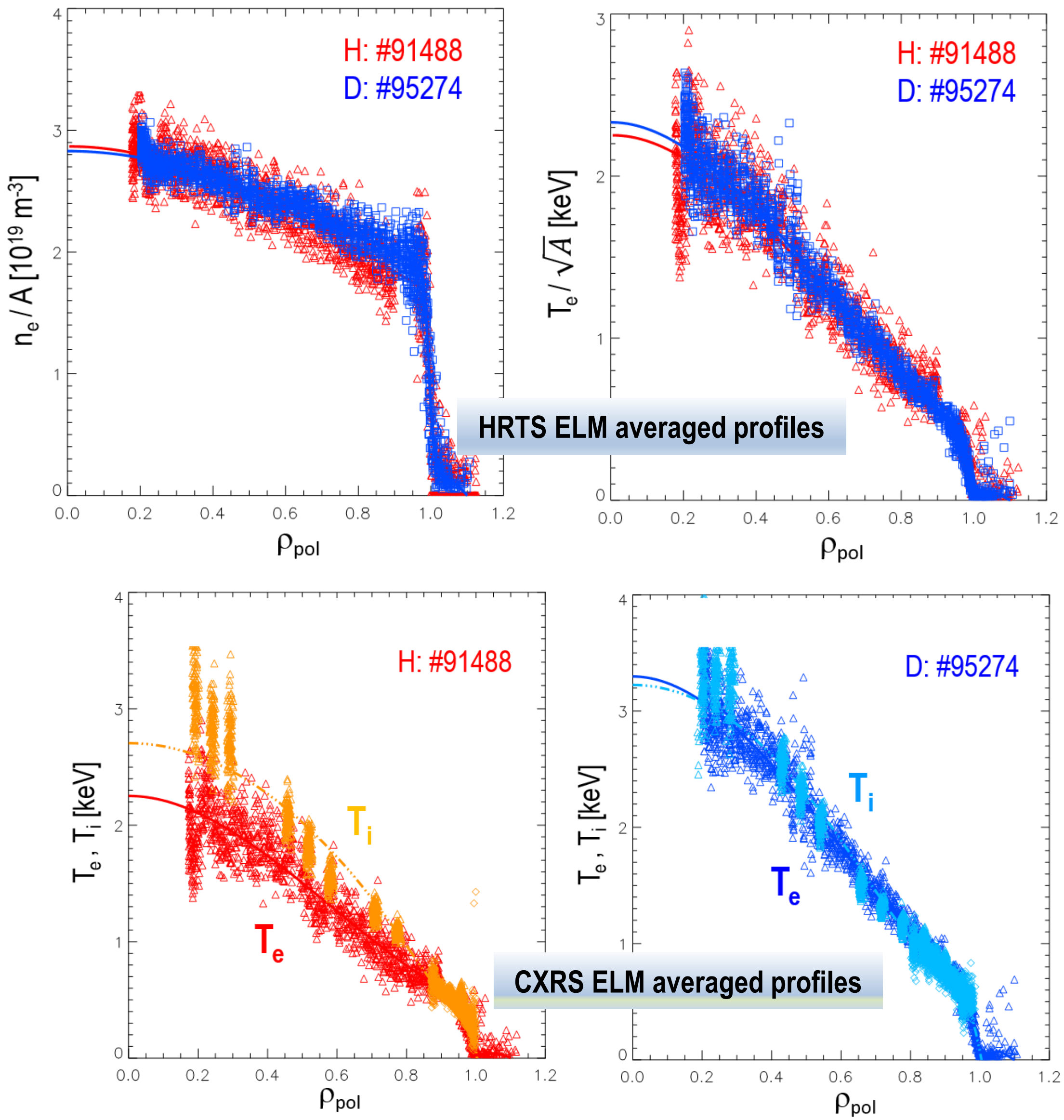
Hydrogen



Deuterium



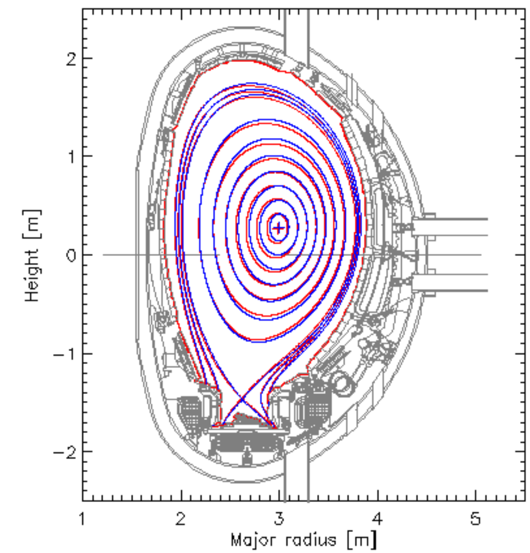
Similar ELM-averaged profiles in plasma core and pedestal



H: [10.5 – 13.8] s = 31 x $\tau_{E,th}$

D: [5.5 – 11.0] s = 31 x $\tau_{E,th}$

Same plasma shape - Strike points in divertor corner configuration for improved pumping and density control



- $T_i = T_e$ in D
- $T_i \sim 1.2\ T_e$ in core plasma of H

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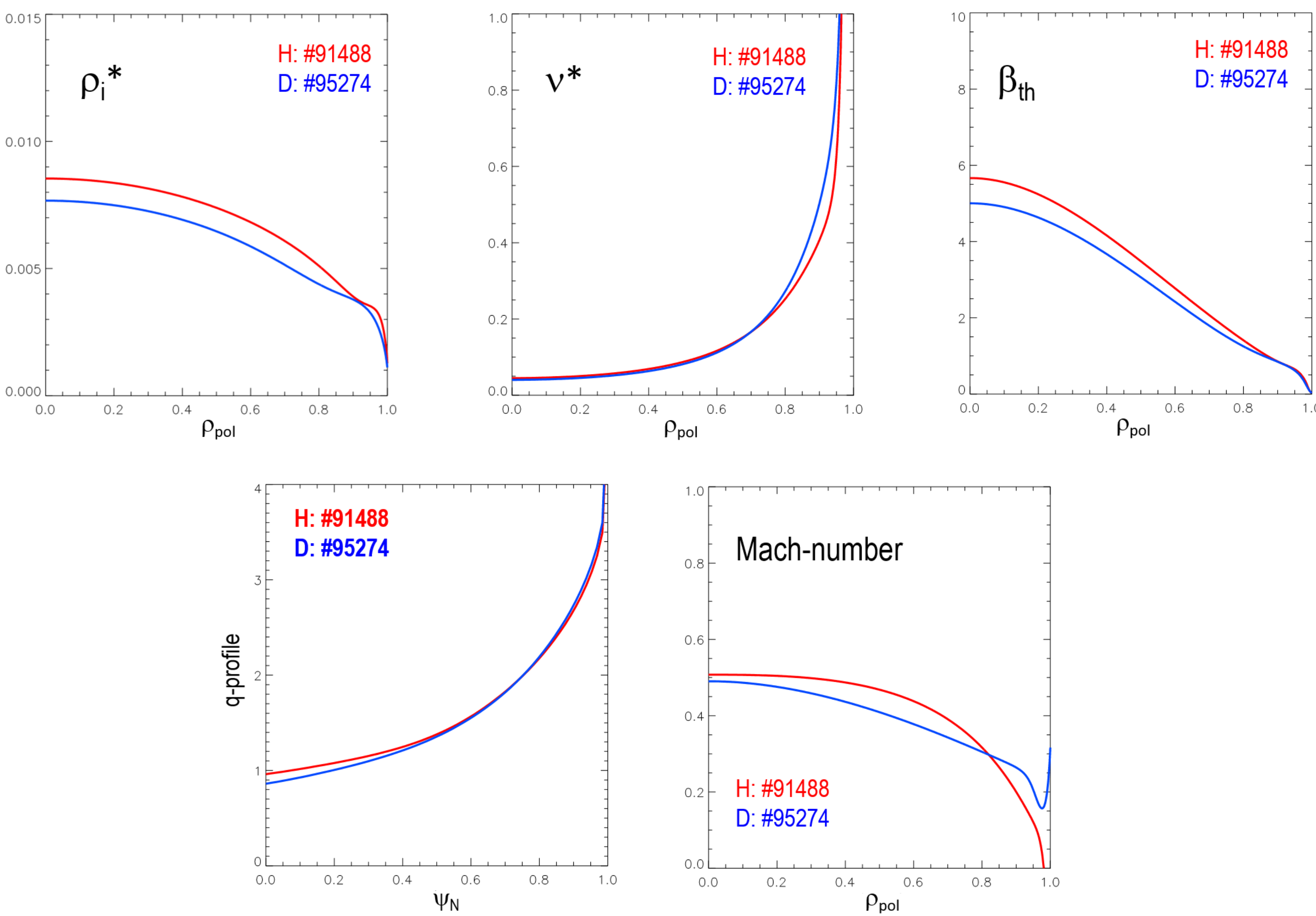
Similar dimensionless profiles in H and D pair



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$\Omega_i \tau_{E,th}$ not identical in H and D dimensionless pair

Pulse # / Isotope	H: #91458	D: #95274
Time interval [s]	10.5 – 13.8	5.5 – 11.0
B_T [T] / I_P [MA] / q_{95}	1.0 / 1.0 / 3.0	1.7 / 1.7 / 3.0
P_{abs} [MW] (±10%)	7.0	11.5
$\tau_{E,th}$ [s] (±10%)	0.105	0.175
T_i / T_e	**1.0 – 1.2**	**1.0**
P_{abs} / B_T [MW/T]	**7.0**	**6.8**
Z_{eff} (±10%)	**1.4**	**1.4**
$\Omega_i \tau_{E,th}$ [T s]	**0.105**	**0.15**
f_{ELM} / Ω_i [Hz / T]	**54**	**54**

Input power required for dimensionless pair: $P_{abs} \sim B_T$

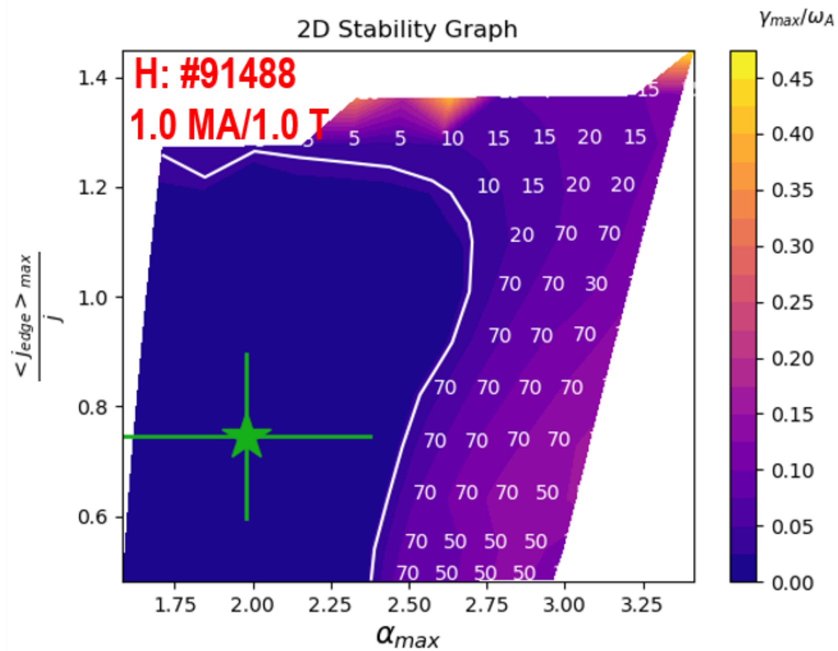
$\Omega_i \tau_{E,th}$ not identical in H and D

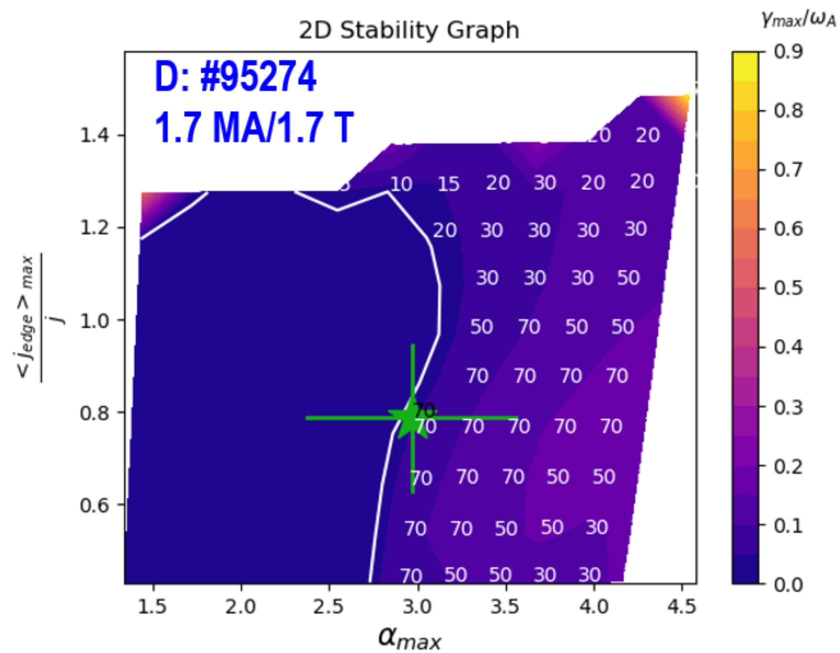
Confinement scale invariance principle not satisfied in type I ELMy H-mode at moderate beta

- Scaled thermal energy confinement time: $\Omega_i \tau_{E,th} \sim A^{0.51}$

Linear MHD pedestal stability

Stability analysis with HELENA / ELITE





Although type I ELMy, H pedestal is found to be stable to P-B modes

D pedestal is at P-B boundary

See, e.g [*Horvath et al., NF 2021*]

- Scaled pre-ELM pressure gradient not matched in H and D (larger in D) → **pedestal similarity not achieved for pre-ELM profiles**

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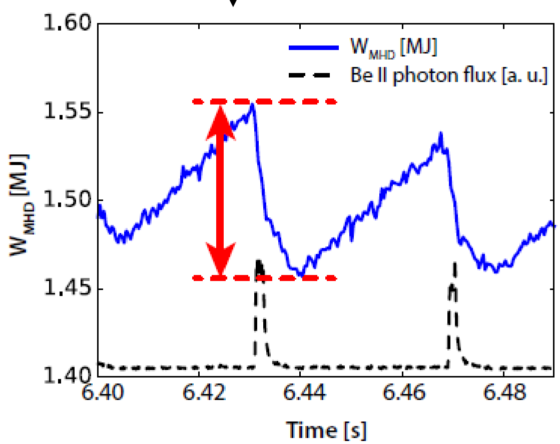
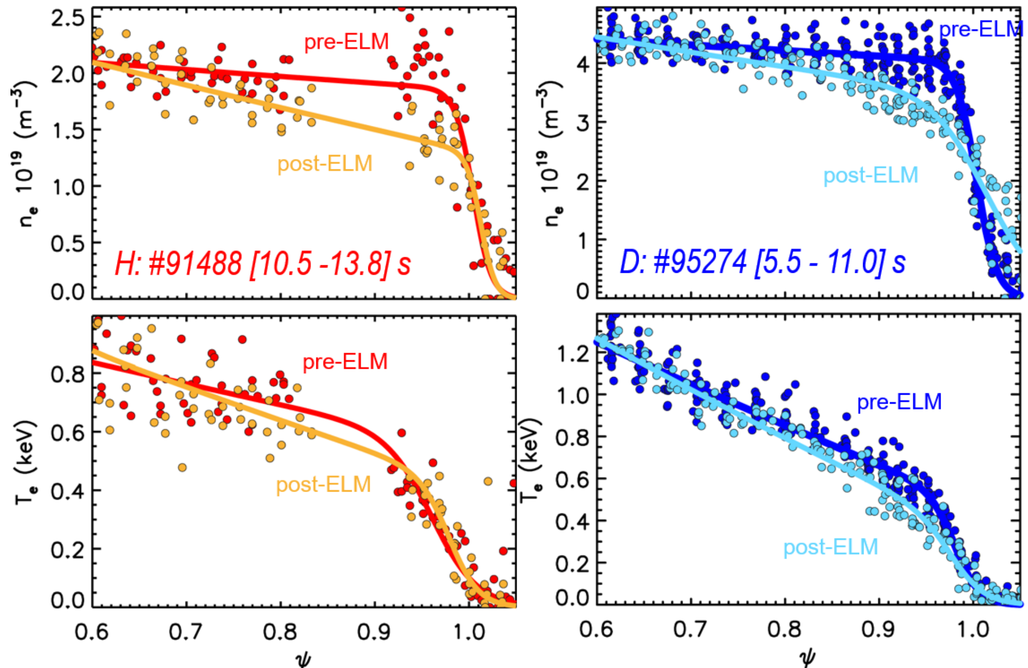
Fractional pedestal energy and ELM losses similar in H and D

ELM energy losses ΔW_{ELM} derived by:

- Pre- and post-ELM HRTS profiles →
- Drop in EFIT W_P at ELM crash

[Horvath et al., NF 2021]





ΔW_{ELM} primarily convective both in H and in D

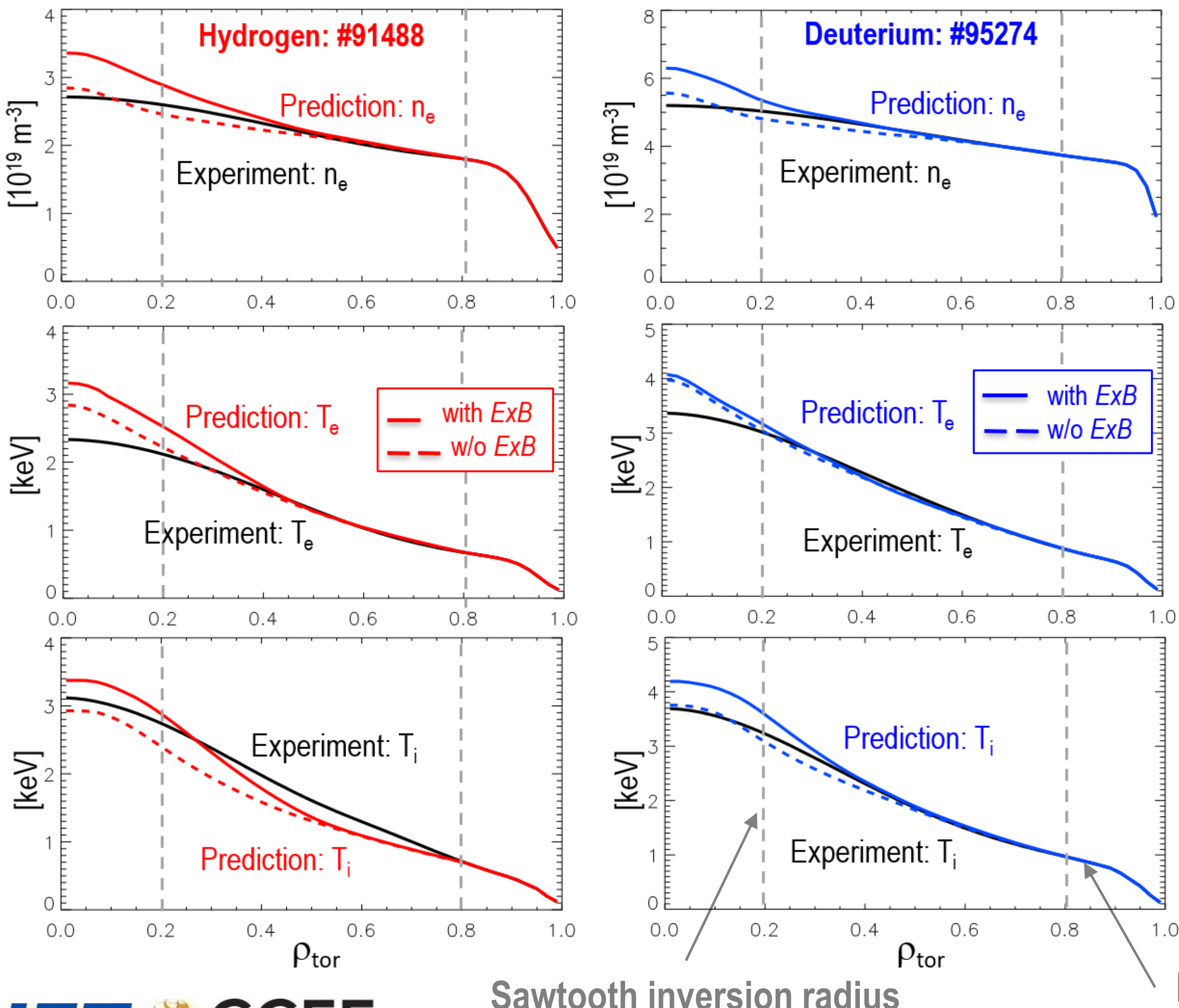
Isotope / Pulse#	H / #91488	D / #95274
W_{PED} [kJ]	259.1	657
W_{PED} / W_{th}	0.35	0.33
ΔW_{WP}; ΔW_{HRTS} [kJ]	36 ± 10 ; 50 ± 9	82 ± 15 ; 103 ± 12
ΔW_{WP}/ W_{PED}; ΔW_{HRTS}/ W_{PED}	0.14 ± 0.04 ; 0.19 ± 0.03	0.12 ± 0.02 ; 0.16 ± 0.02
$P_{ELM\ (WP)}$ [MW]	1.94 ± 0.54	3.77 ± 0.69
P_{ELM} / P_{abs}	0.28	0.33

Similar fraction of pedestal to total stored energy in H & D

Similar fraction of P_{loss} carried away by ELMs in H & D

Flux driven TRANSP-TGLF (SAT1) predictive modelling

- **Stiff core heat transport offsets local gyro-Bohm scaling of TGLF → consistent with increase of confinement with A, originating in pedestal region**



- Weak effect of v_{tor} and ExB shearing on heat and particle transport
- Core ITG stabilization by fast ions pressure gradient not included
  - Expected to be weak, as f.i. content is low in these plasmas

Conclusions

- Isotope identity achieved with H and D plasmas in JET-ILW in L-mode → invariance principle satisfied in core confinement region

- Similarity achieved for dimensionless ELM-averaged profiles with H and D in type I ELMy H-mode at moderate beta both in core and pedestal
  - but $\Omega i\ \tau_{E,th}$ not identical → invariance principle not satisfied
  - scaled pre-ELM pressure gradient not similar in H and D → needs further investigation

- Sought similarity for ion ρ_i^* is (a posteriori) consistent with core transport dominated by ITG turbulence (ρ_e^* not matched) → approach likely not valid for plasmas dominated by electron and/or mixed ion-electron scales turbulence

- Predictive flux driven simulations of core transport in agreement with experiment: stiff core heat transport overcomes local gyro-Bohm scaling of TGLF, explaining
  - Lack of isotope mass dependence of core confinement in L-mode pair
  - Increase of confinement with A in H-mode pair, originating in pedestal region