L-H TRANSITION RESULTS FROM RECENT TRITIUM AND DEUTERIUM-TRITIUM CAMPAIGNS AT JET

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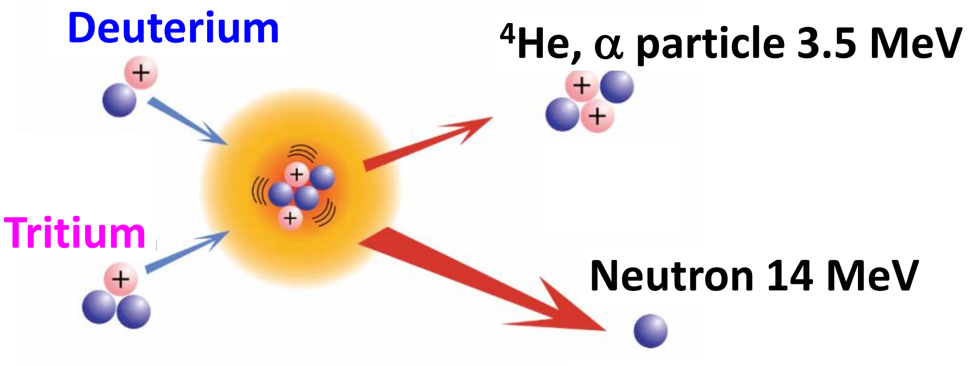
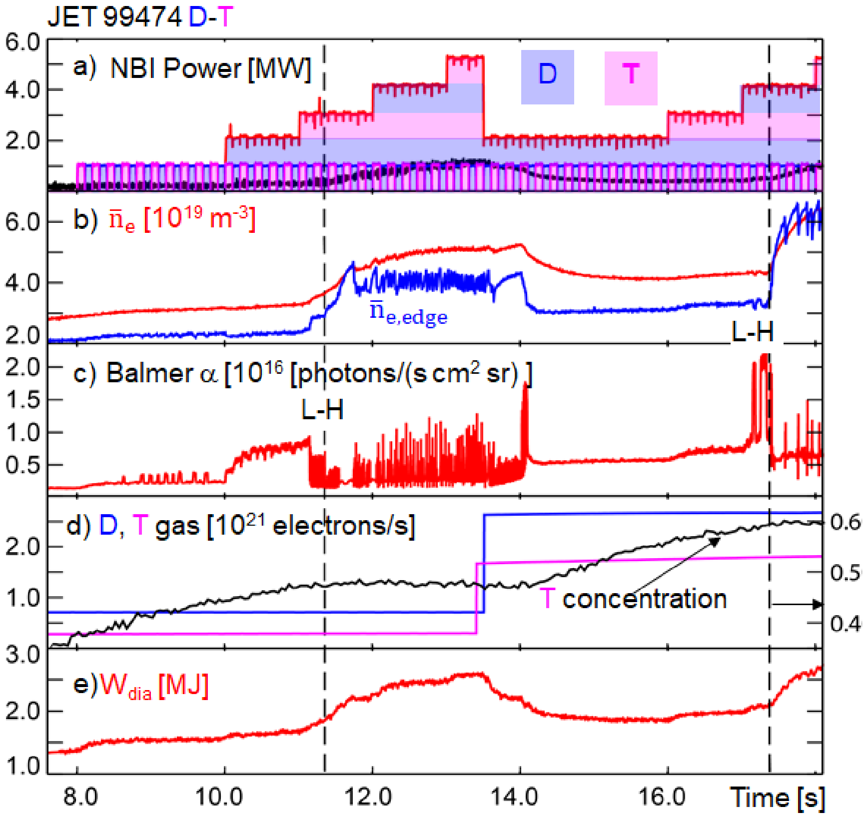
Motivation of T and DT L-H studies

- Most devices investigate isotope effects in **Hydrogen**, **Deuterium** and **H+D** plasmas
- **Tritium** can be used at JET: investigate **DT**, **T** and **H+T** plasmas to characterise and understand isotope effects
- Especially important to understand how plasma composition affects the power threshold to obtain good confinement: **L-H transition**!!!
- P_{LH} threshold in **DT** used to define size of next step devices (DEMO)



Isotopes, Mix	A_{eff}	
Hydrogen	1	●
Deuterium	2	■
DT 50/50	2.5	★
Tritium	3	◆

L-H transition experiments in DT



Minimize **Tritium** consumption

- NBI steps or ICRH ramps
- Horizontal Target only

$$P_{loss} = P_{Ohm} + P_{aux} + P_{\alpha} - dW_{plasma}/dt$$

$$P_{sep} = P_{loss} - \boldsymbol{P_{rad,bulk}}$$

Aim: update 2008 ITPA multi-machine power threshold (P_{loss}) scaling

$$P_{ITPA\text{-}iso} = 0.049\, n_{e20}^{\mathbf{0.72}}\, B_T^{0.83}\, S^{0.94} (2/A_{eff})$$

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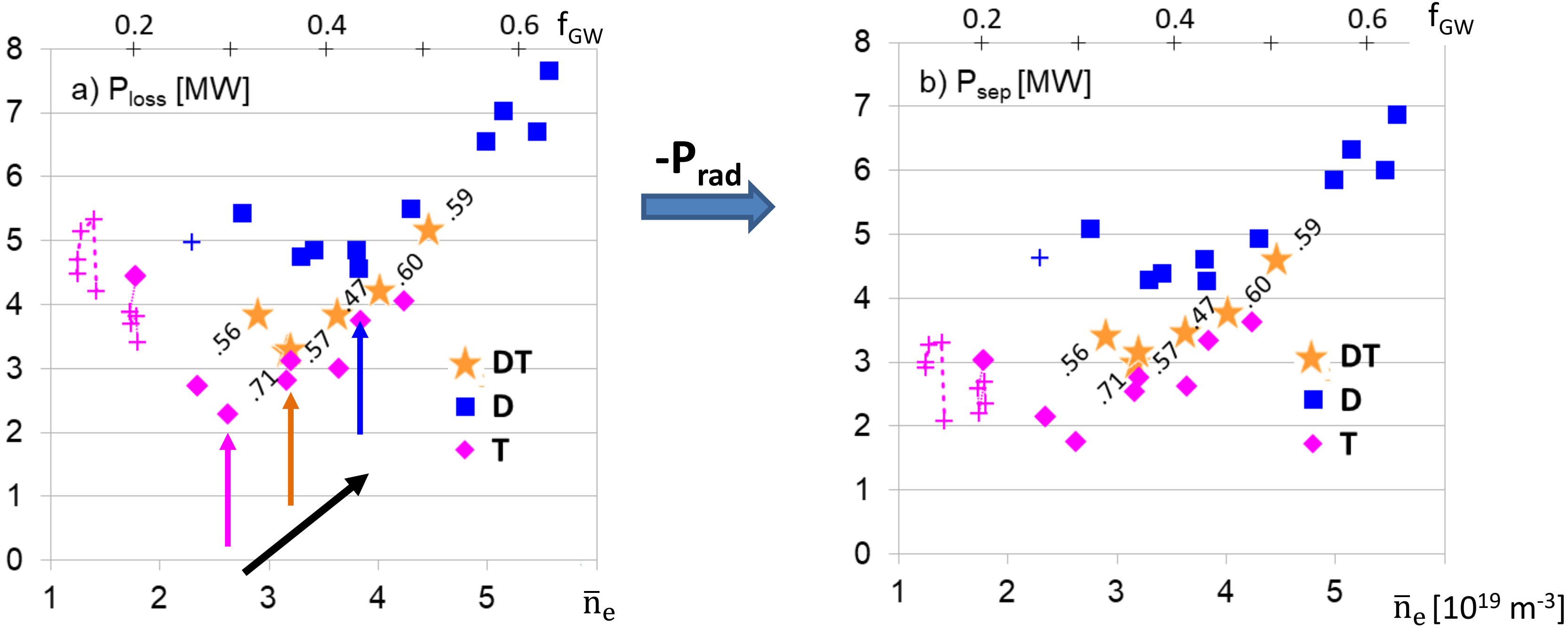
https://doi.org/10.1088/1741-4326/acee12

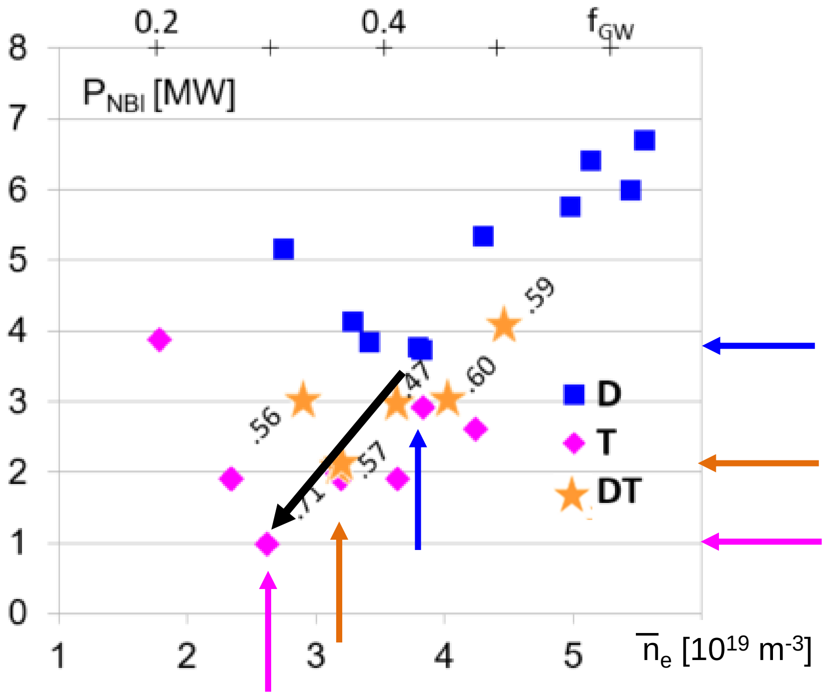
P_{LH} in 3T 2.5 MA dataset



Clear shift of $\bar{n}_{e,min}$: lowest for T, then DT, then D.

Large P_{rad} at low $\bar{n}_e$ for Tritium

"+" for unsteady transitions, typical at low density

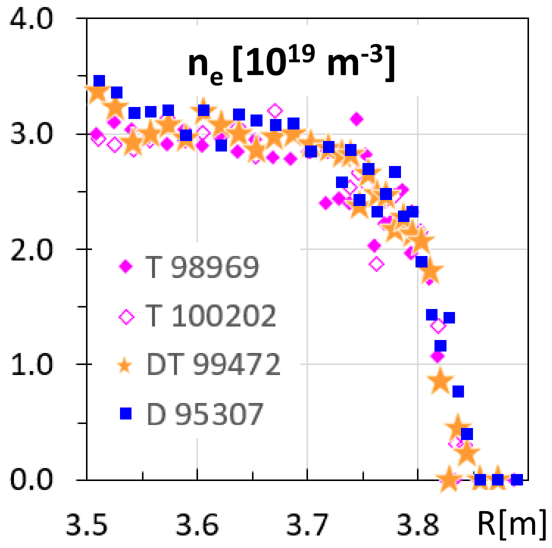


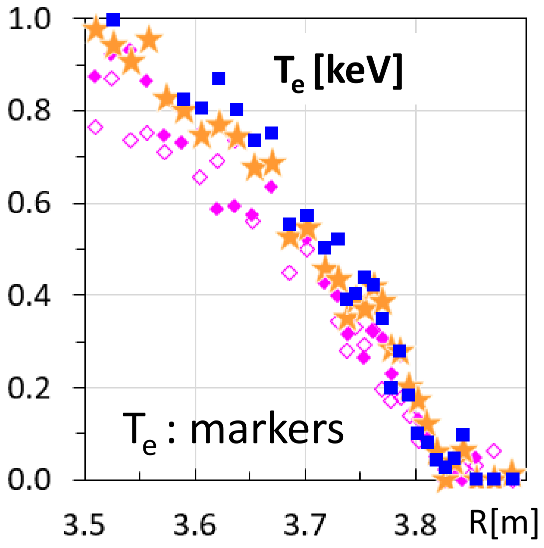
min	f_{GW}	$\bar{n}_{e,min}$	NBI	P_{loss}	P_{sep}
D	0.44	3.8	3.8	4.6	4.3
DT	0.37	3.2	2.1	3.3	3.0
T	0.30	2.6	1.0	2.3	1.75

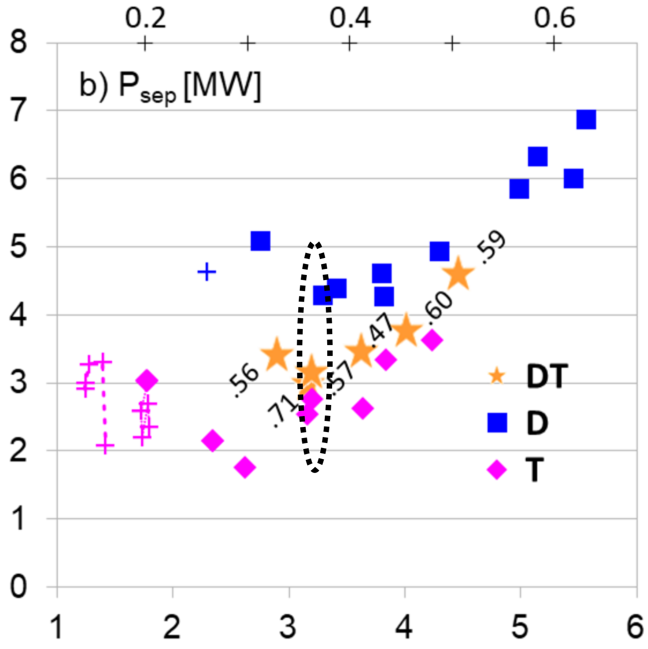
- Easier access to H-mode in T-rich plasmas at lower density
- Let the H-mode raise the density
- To be evaluated *vs.* T consumption for ITER, ~~DEMO~~, SPARC?

3T 2.5 MA critical profiles?

Thomson Scattering < 50 ms before L-H







From r/a=0.5, very similar n_e, T_e, T_i profiles just before the transition in D, DT ,T

3T 2.5 MA critical profiles?

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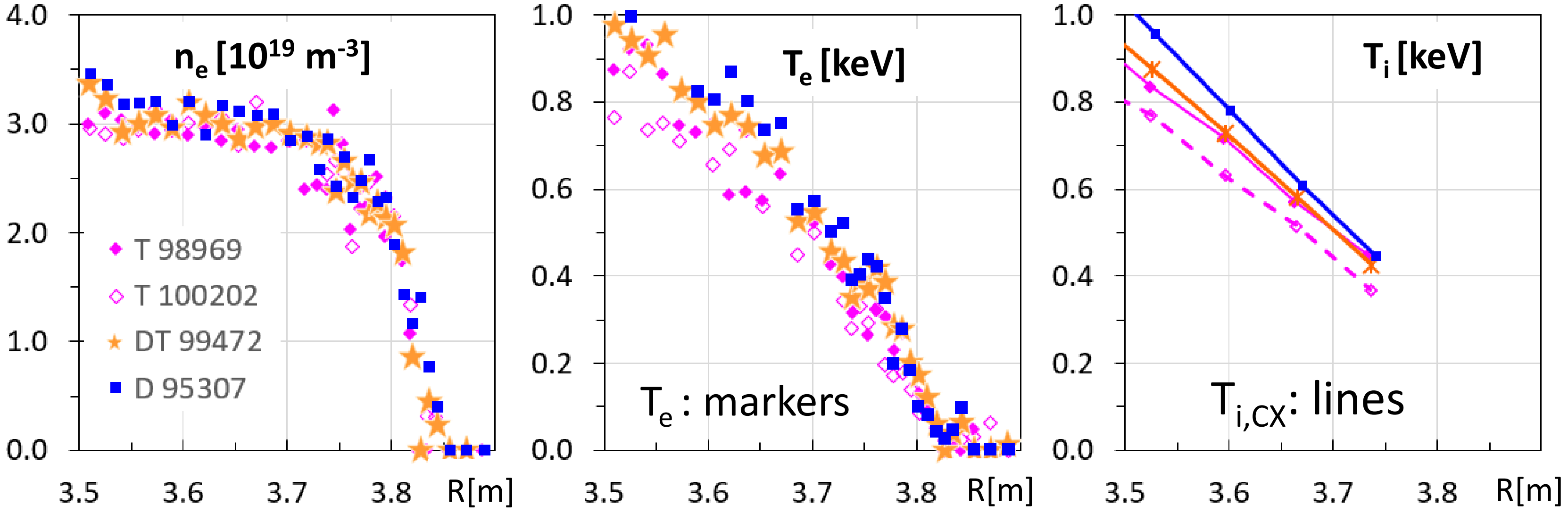

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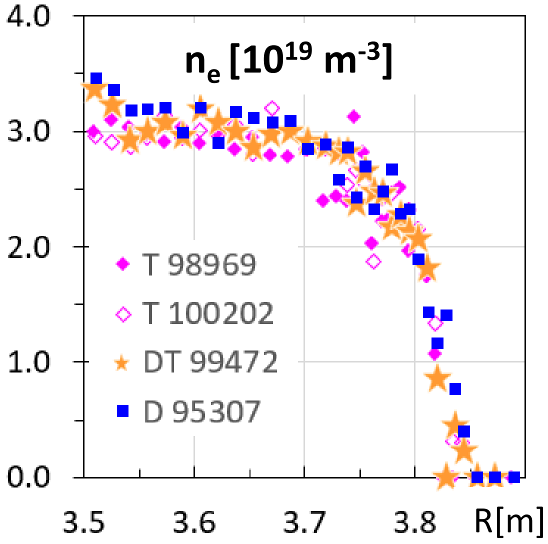
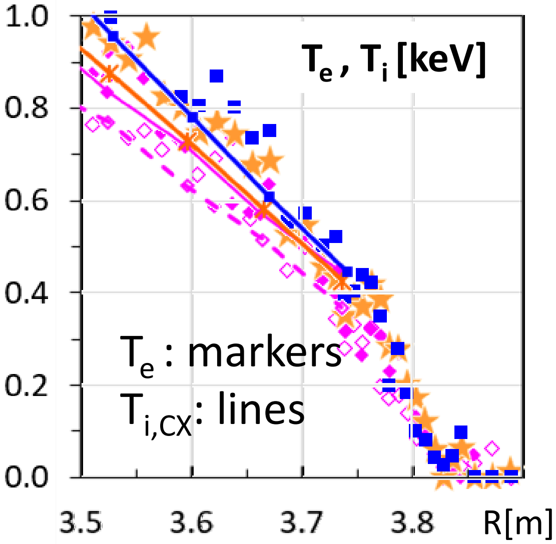


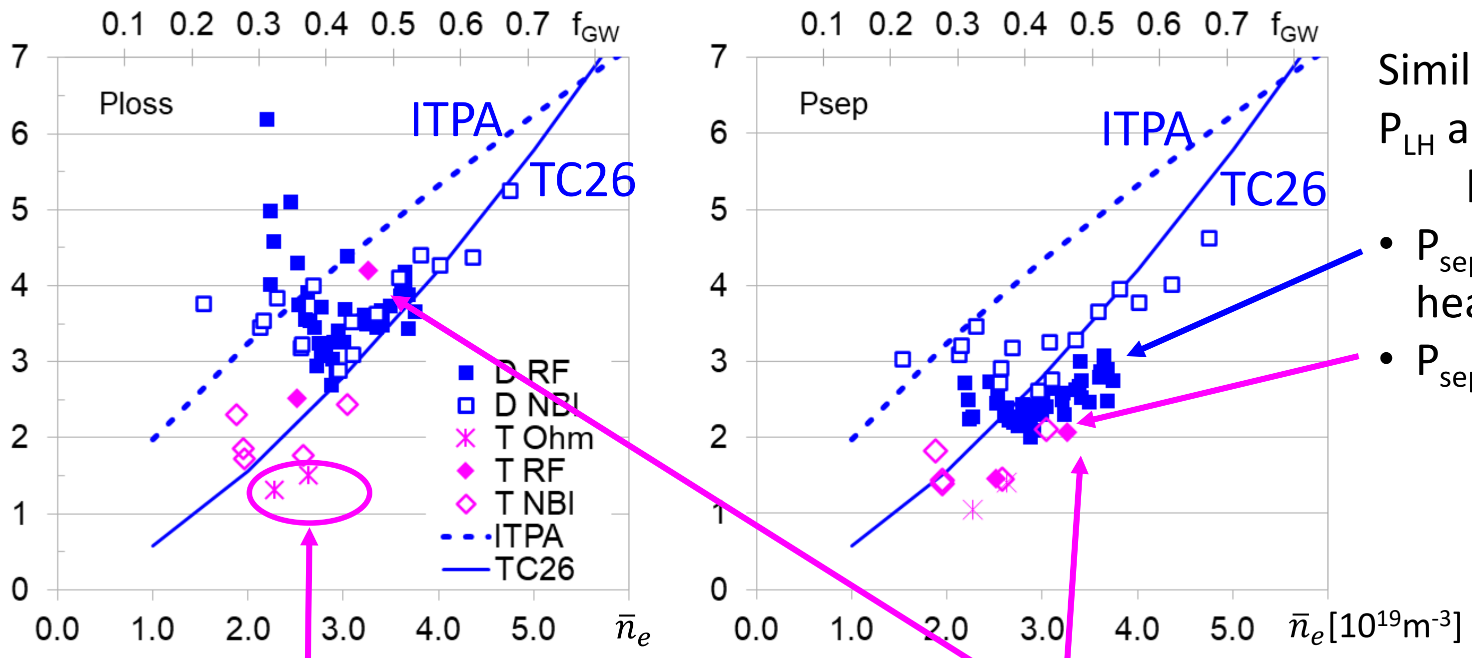


- Core CX Ti measurements
- No T_i measurements near very edge, but T_i=T_e up to the edge seems like a reasonable assumption
- $v_\perp$ measurements available, being analysed

From r/a=0.5, very similar n_e, T_e, T_i profiles just before the transition in D, DT ,T

R[m]

P_{LH} in 2.4T 2 MA dataset



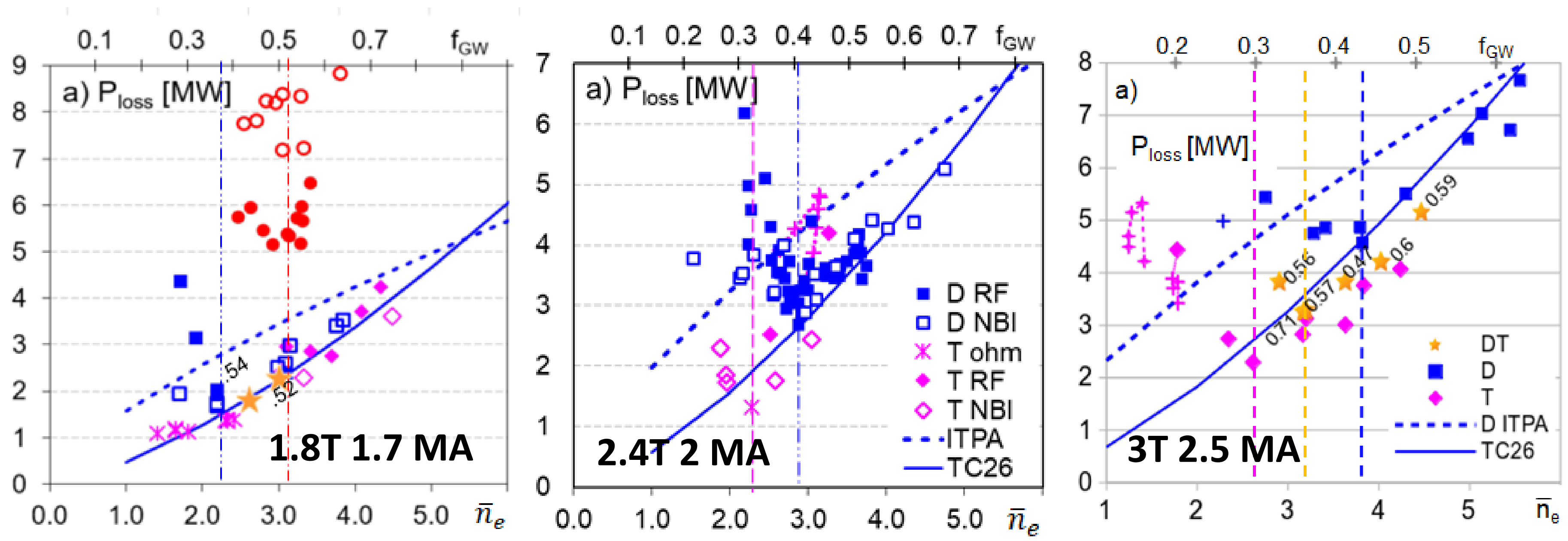
Similar observations on P_{LH} and $\bar{n}_{e,min}$:
lower for **T**.

- P_{sep} lower for RF vs. NBI heating in **D**,
- P_{sep} RF vs NBI same in **T**

Ohmic transitions in **T** near $\bar{n}_{e,min}$

Large radiation for RF heated **T**, even at medium density

JET $P_{L\text{-}H}$ threshold scaling for high density branch

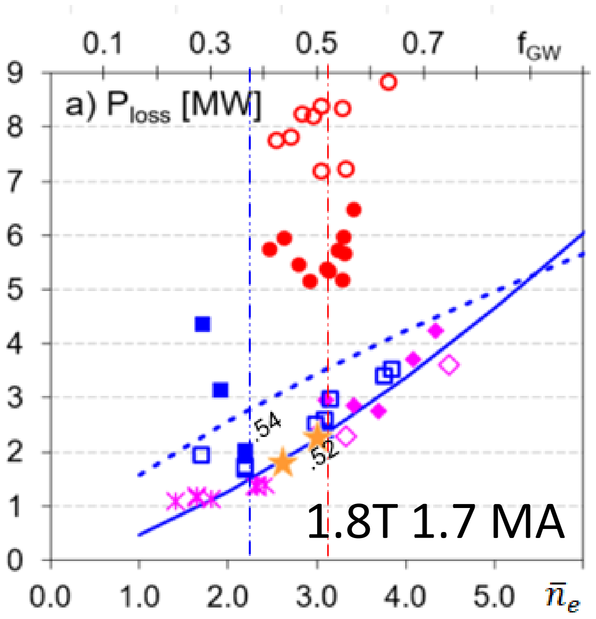


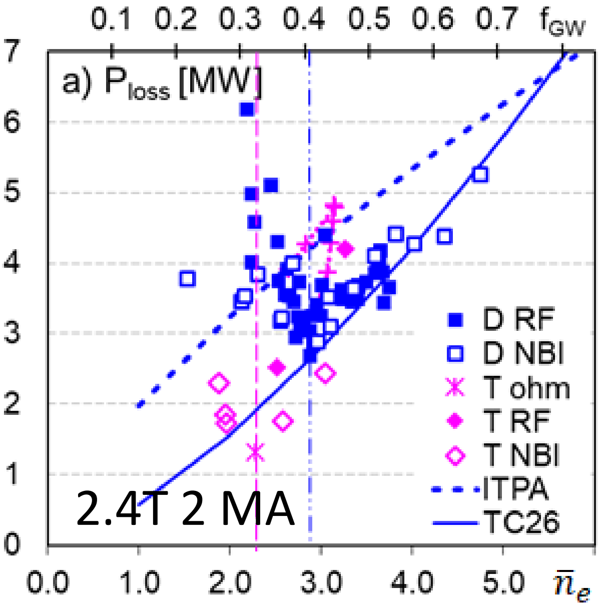
ITPA scaling: $P_{ITPA\text{-}iso}=0.049\,\bar{n}_{e20}^{0.72}\,B_T^{0.83}\,S^{0.94}(2/A_{eff})$ overestimate

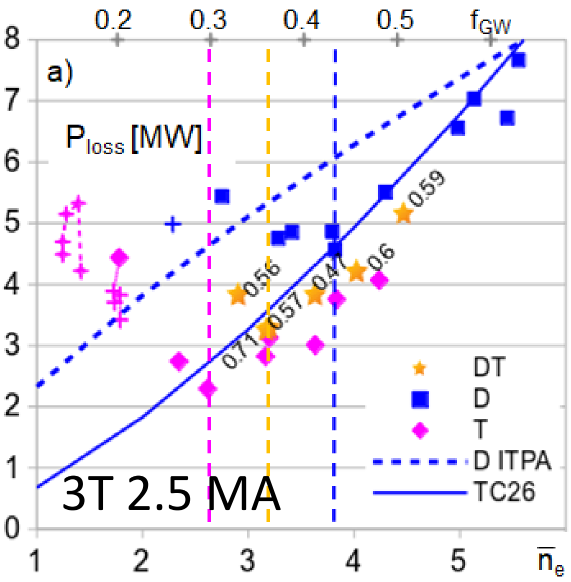
JET TC26 scaling: $P_{TC26\text{-}iso}=0.057\,\bar{n}_{e20}^{1.43}\,B_{tor}^{0.77}\,S\,(2/A_{eff})$ quite good (unsurprising)

*Delabie ITPA TC-26 (2017), Solano Nucl. Fusion **62** 076026 (2022)*

JET $P_{L\text{-}H\ threshold}$ scaling: select high density branch





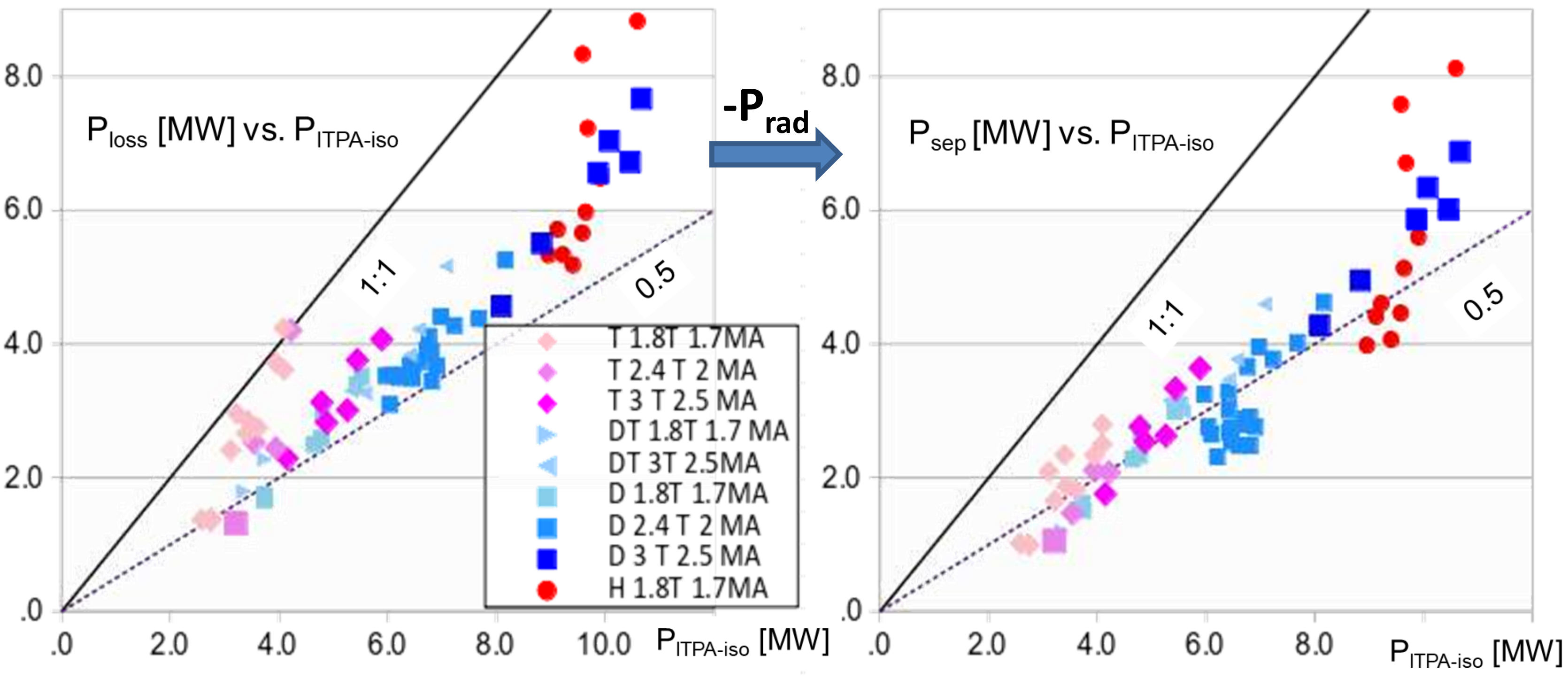


	$f_{GW,min}$	$\bar{n}_{e,min}$
H	0.54	3.1
D	0.38	2.2
T	**<0.40**	**2.3**

	$f_{GW,min}$	$\bar{n}_{e,min}$
D	0.41	2.9
T	**0.33**	**2.3**

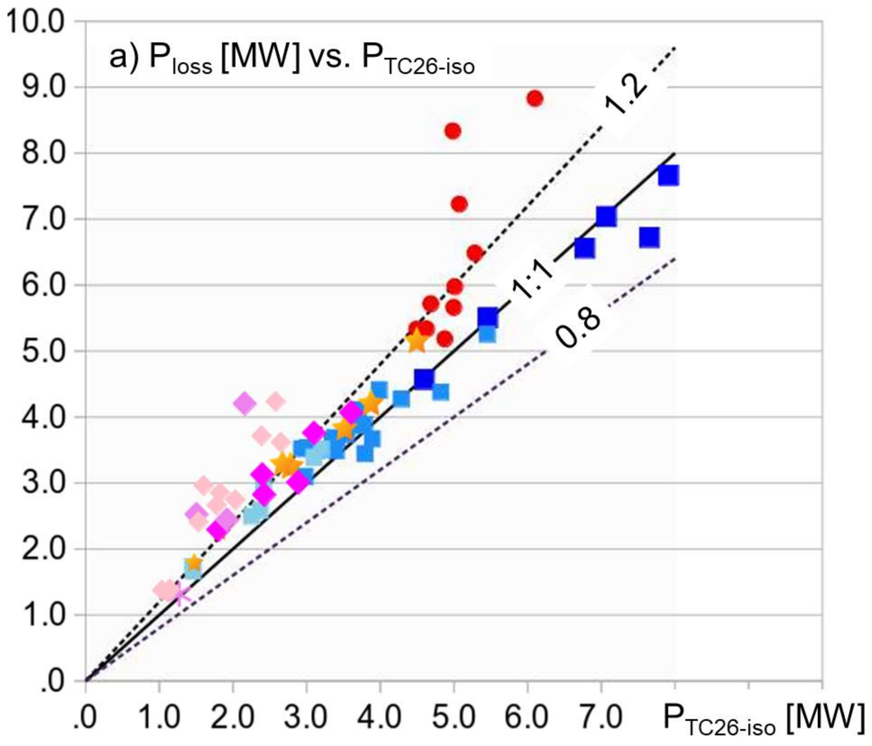
	$f_{GW,min}$	$\bar{n}_{e,min}$
D	0.44	3.8
DT	**0.37**	**3.2**
T	**0.30**	**2.6**

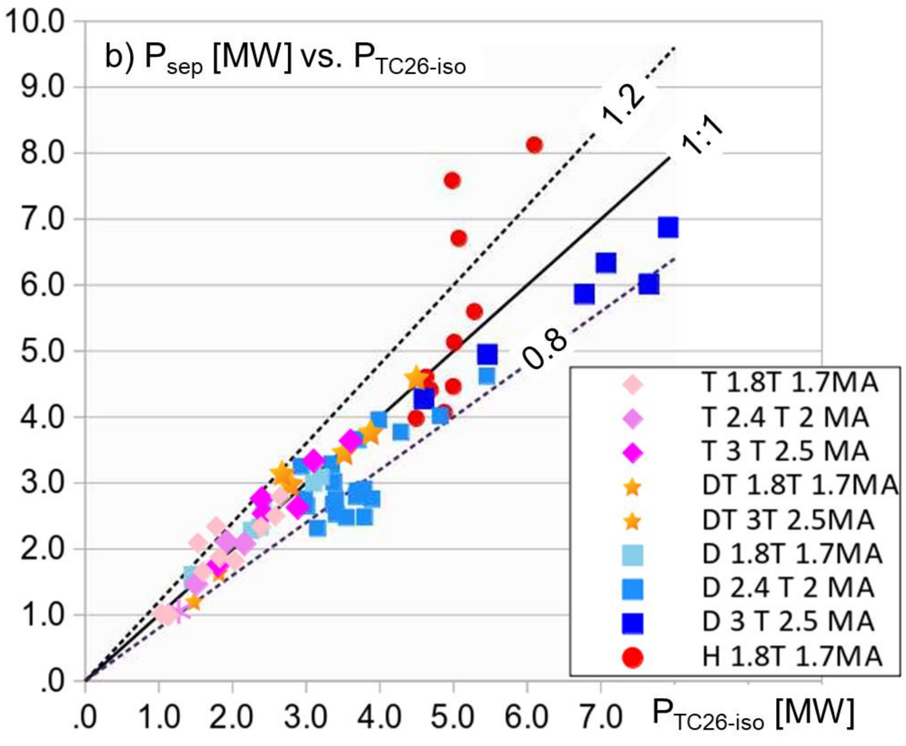
High density branch vs ITPA-iso scaling



- ITPA-iso scaling overpredicts P_{loss} and P_{sep} in Horizontal Target plasmas

High density branch vs JET TC26-iso scaling

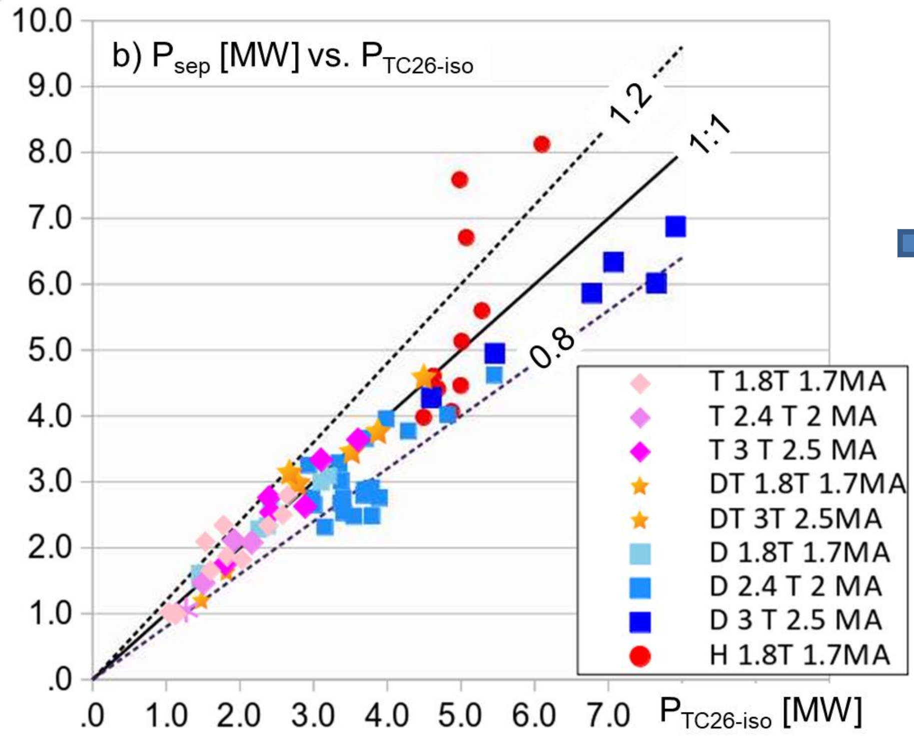


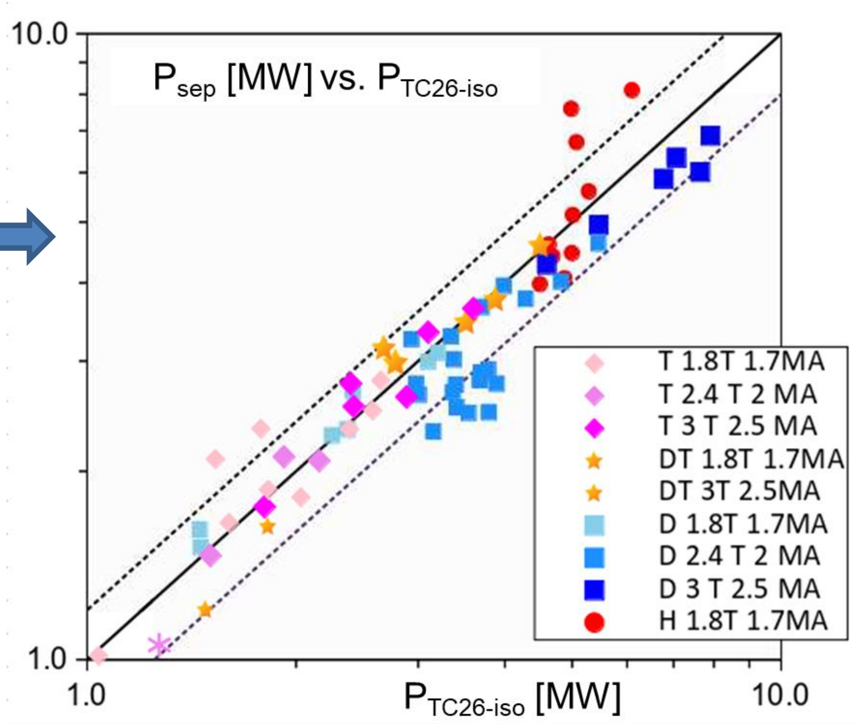


$$P_{TC26\text{-}iso} = 0.057\, \bar{n}_{e20}^{1.43}\, B_{tor}^{0.77}\, S\, (2/A_{eff})$$

based on JET-ILW D P_{loss} data, better fit than ITPA

High density branch vs $(2/A_{eff})$*TC-26 scaling





Not bad in Log-Log plot

Extreme P_{LH} datapoints can have strong influence on fits

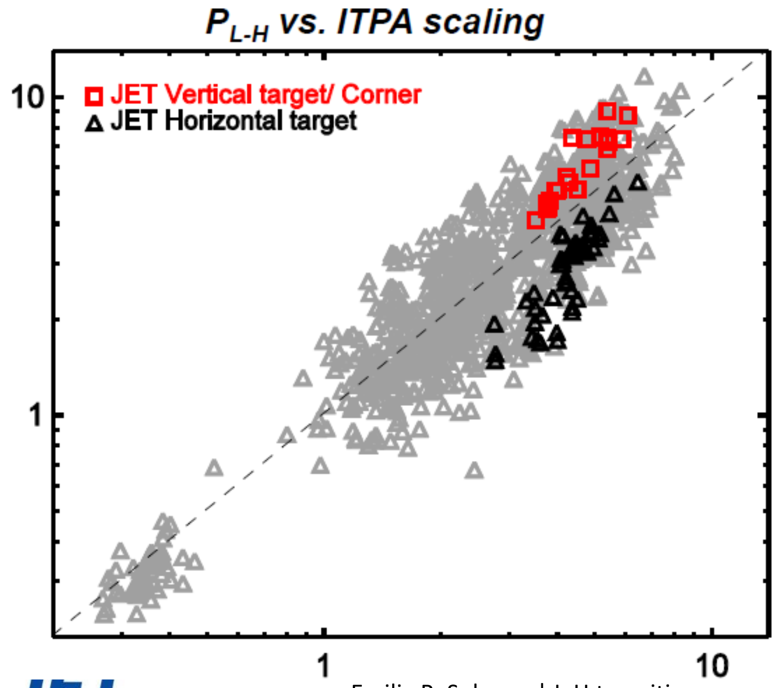
but shape effects…

P_{LH} scaling: Impact of shape, JET ITPA TC-26 scalings

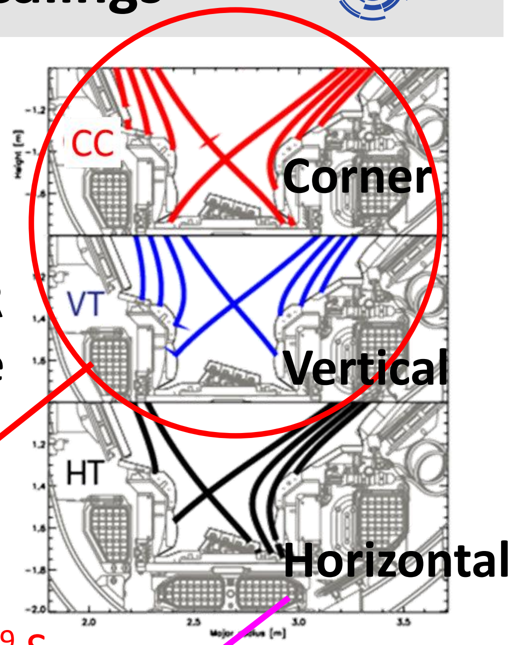
- In JET-ILW, P_{LH} is a strong function of strike point location/ divertor configuration, $P_{LH}(CC,VT) \sim 2 * P_{LH}(HT)$ plasmas

Delabie ITPA TC-26 2017 Report, based on early JET-ILW D data

*Solano Nucl. Fusion **62** 076026 (2022)*



Extrapolation of P_{LH} to ITER requires understanding the difference, as well as size scaling



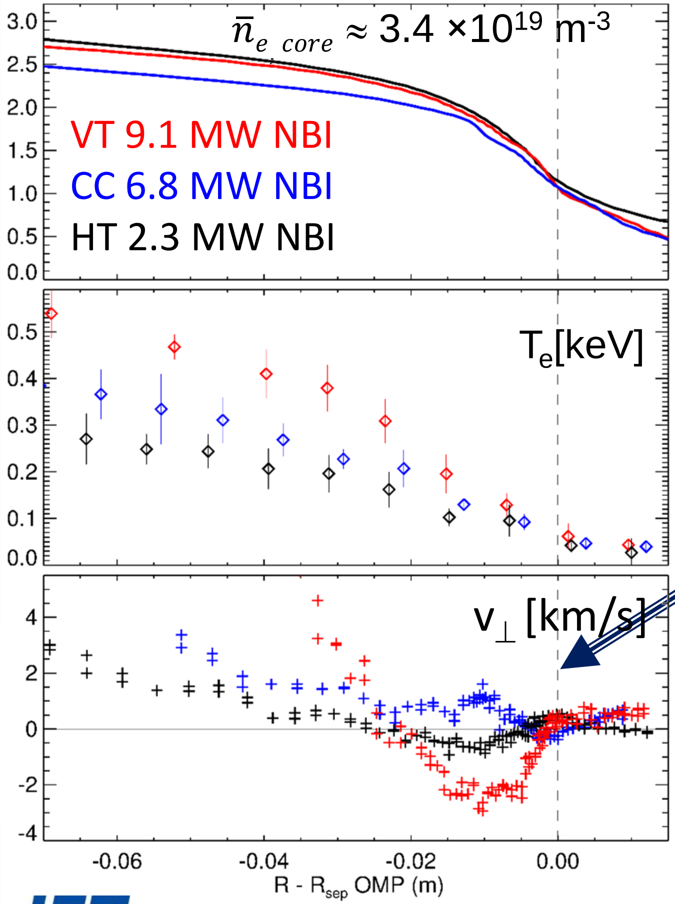
$$P_{TC26\text{-}VT/CC} = 0.031\, \bar{n}_{e20}^{0.77}\, B_{tor}^{1.29}\, S$$

$$\mathbf{P_{TC26\text{-}HT} = 0.057\, \bar{n}_{e20}^{1.43}\, B_{tor}^{0.77}\, S}$$

or

$$P_{TC26} = \begin{Bmatrix} 2.06 & \text{VT or CC} \\ 1 & \text{HT} \end{Bmatrix} \times 0.046\, \bar{n}_{e20}^{1.31}\, B_{tor}^{0.85}\, S$$

SHAPE EFFECT on P_{LH}: $v_\perp$ measurements (in Deuterium)



- In **D** **no evolution of $v_\perp$ profile along power ramps**

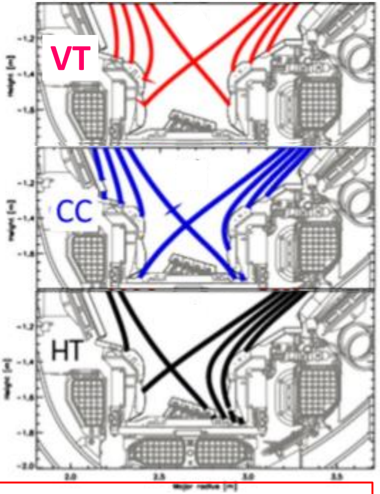
C Silva, NF 2021, Solano NF 2022

*Data available in **DT** and **T***

Shape dependence of P_{LH}:

Delabie IAEA 2014

- In **D**: highest P_{LH} for Vertical, then Corner, then HT
- $v_\perp$ hill in Corner, deep well in Vertical Target, shallower well in Horizontal Target



- **No "Critical" $v_\perp$ shear flow before L-H**
- **$v_\perp$ profile alone doesn't explain difference in P_{LH} for different shapes** *C Silva NF 2022*

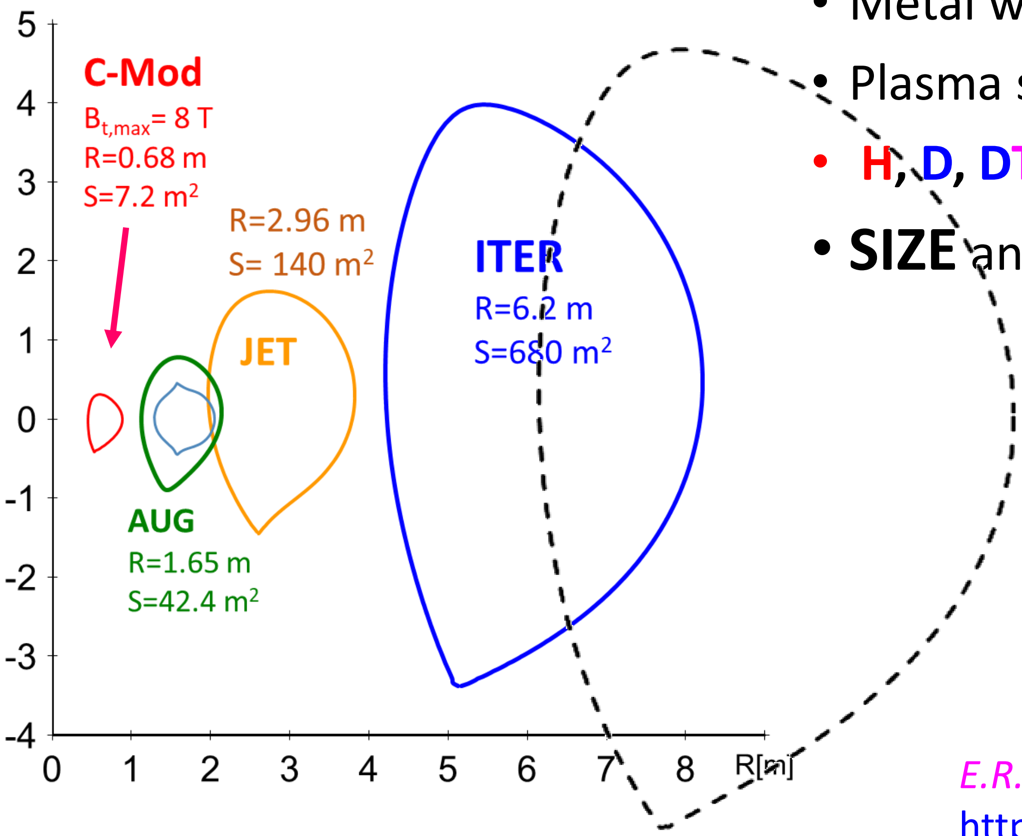
Scaling to next step devices?

- Need to investigate in detail impact of A_{eff} and shape on P_{LH}
- Investigate conditions for L-H transition: kinetic profiles, v_{perp} shear? *Modelling!*

Revisit multi-machine ITPA P_{LH} scaling:

- multi-machine metal wall P_{LH} scaling, add recent JET data in **H**, **D**, **DT**, **T**
- include various mixtures (**H**+**D**, **H**+**T**)
- consider scaling of low density branch
- SIZE and its many physical implications: neutral penetration, gradient scale lengths, edge radiation, turbulence characteristics …

Scaling of the L-H transition power threshold in metal walls



- Metal wall reduces P_{LH}
- Plasma shape affects P_{LH}
- **H, D, DT, T** affects P_{LH}
- **SIZE** and **current** matters

Scaling P_{LH} to future fusion devices?
ITER, DEMO, …

*E.R. Solano et al., Nucl. Fusion **63** (2023) 112011*
https://doi.org/10.1088/1741-4326/acee12

Summary

- P_{LH} studies carried out in **H**, **D**, **T**, **DT** and mixtures in JET-ILW
- Large shifts observed in $n_{e,min}$, correlated with f_{GW} for each isotope H, D, T
- In **H+T** mixtures, A_{eff} can be a suspect variable. *Multi-fluid modelling*
- Strong scaling of $P_{Aux,min}$ with A_{eff} suggests T-rich plasmas for H-mode entry in next step devices.
- Critical kinetic profiles, not v_{perp}
- More work on P_{LH} scaling, shape effects

Next:

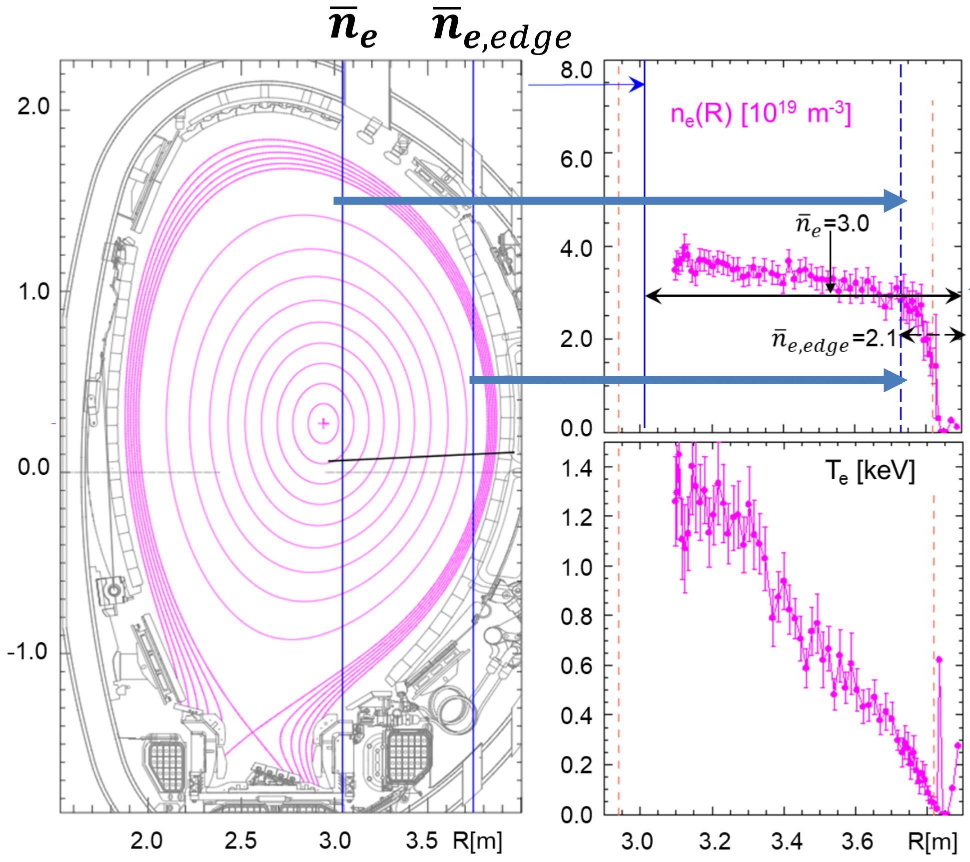
- L-H transition model test/validation
- multi-machine comparisons

Nuclear Fusion Special Issue on JET T & DT Campaign

*E.R. Solano et al., Nucl. Fusion **63** (2023) 112011*

https://doi.org/10.1088/1741-4326/acee12

$\bar{n}_e$ scaling of P_{LH}? Typical L-mode profiles have $n_{e,ped} \cong \bar{n}_e$



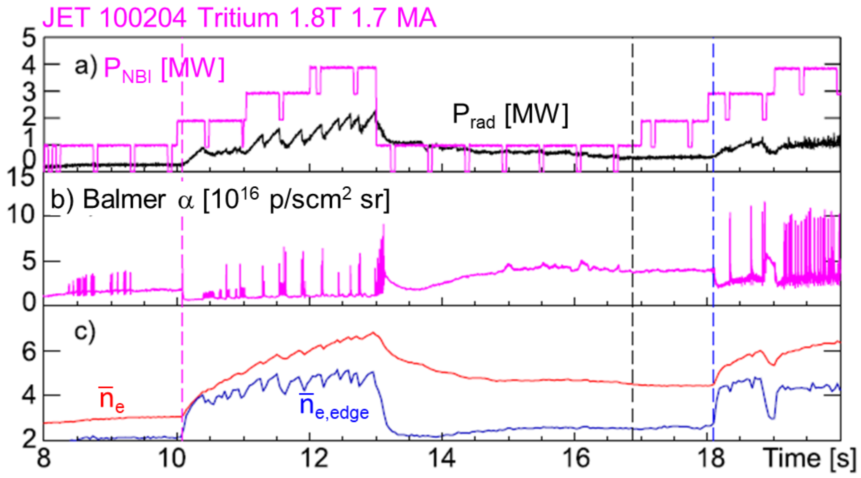
In typical L-modes the density profile is quite flat and $\bar{n}_e \cong n_{e,ped}$

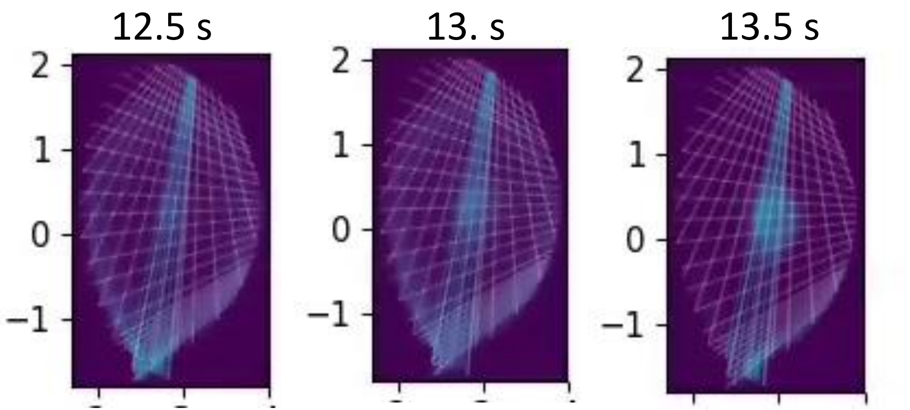
Line averaged edge density $\bar{n}_{e,edge}$ is an average across the pedestal, about 2/3 of $\bar{n}_e$

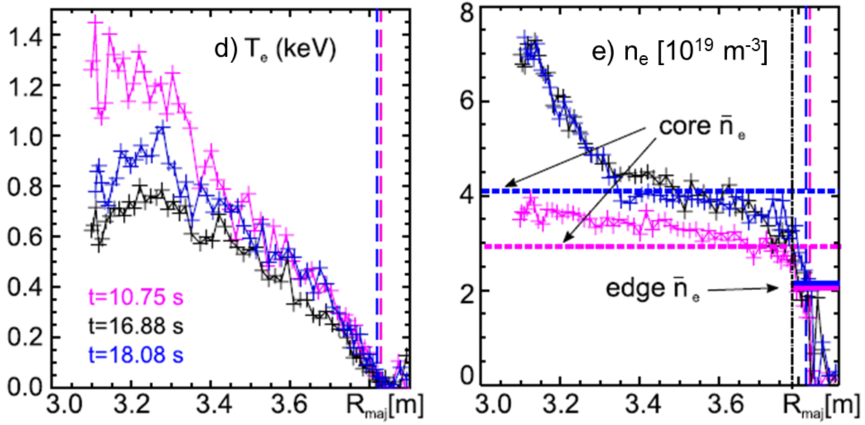
Therefore $\bar{n}_e$ is a good variable to characterise $n_{e,ped}$

This isn't always the case

W poisoning and $\bar{n}_e$

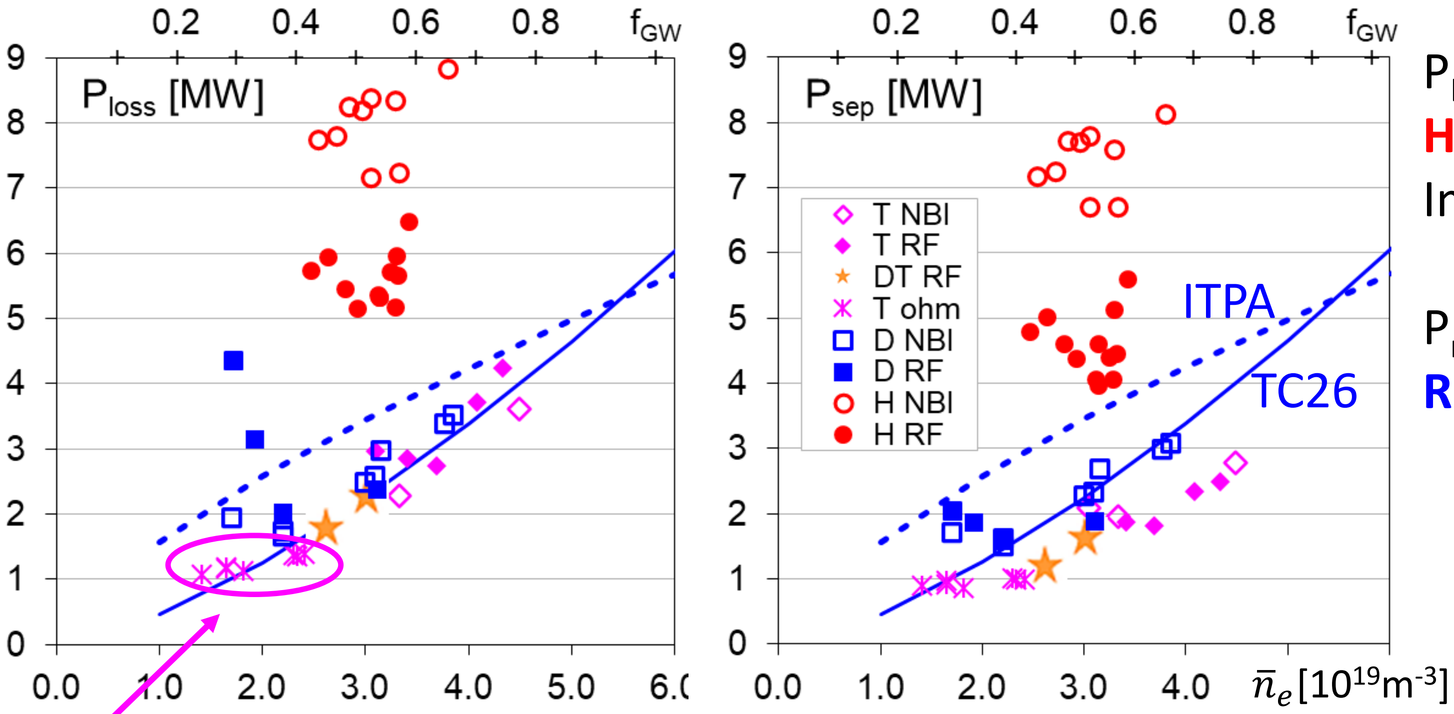






Double power ramps help obtain more transitions per shot, but sometimes the 2nd one must be discarded

P_{LH} in 1.8T 1.7 MA dataset H, D, T, DT



P_{LH} much higher with **H-NBI** than **H-RF**

Impurities? Cu w. NBI

P_{rad} high at low n_e for **RF-D**

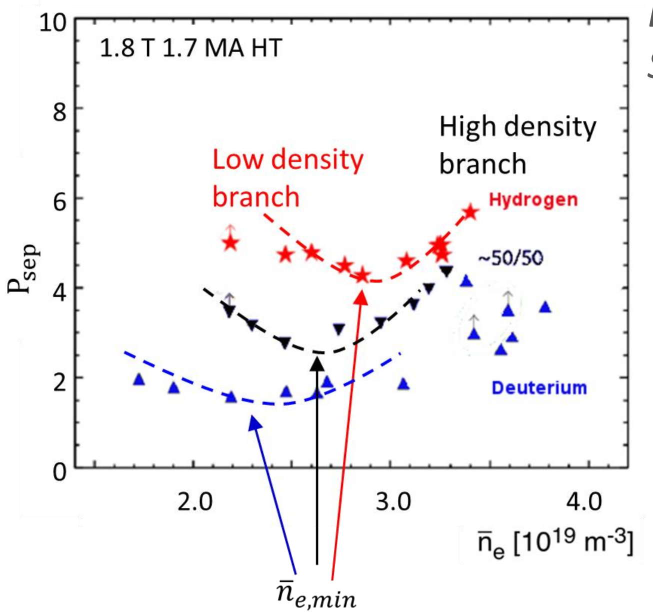
This is the dataset with **H**, **D**, **T** and various mixtures

Ohmic transitions in **T**, presumed $\bar{n}_{e,min}$, no low n_e branch identified

Background: what we already knew

- In JET-ILW, P_{LH} is a strong function of strike point location/ divertor configuration, P_{LH}(CC,VT)~2*P_{LH}(HT) plasmas

Delabie et al, ITPA TC-26 2017 Report
*Solano et al 2022 Nucl. Fusion **62** 076026*

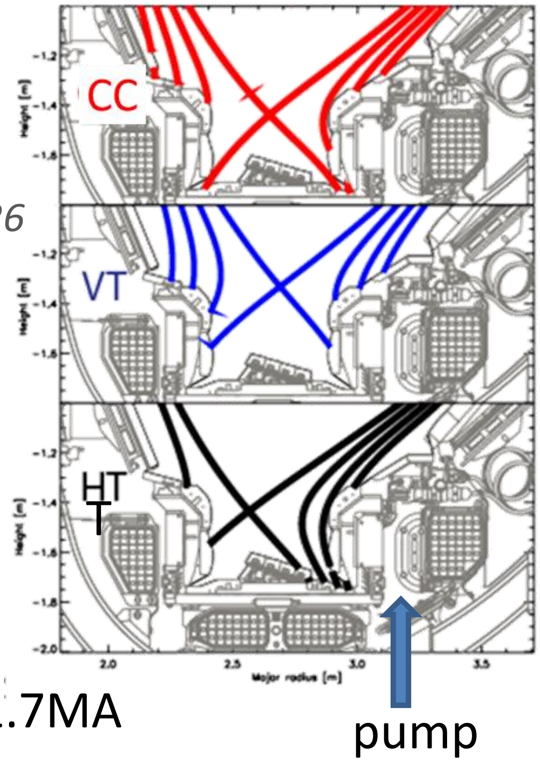


*Maggi et al 2014 Nucl. Fusion **54** 023007*

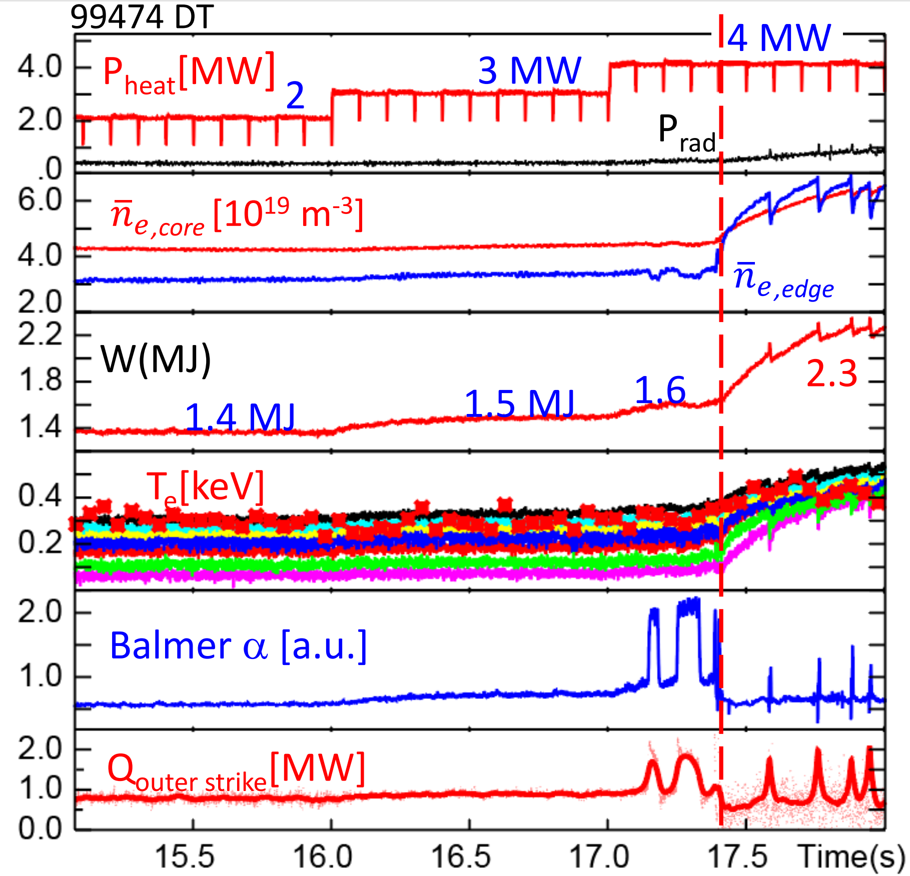
- P_{LH} in H, H+D, D shows clear shift of $n_{e,min}$

T & **DT** choices to reduce consumption:

- P_{LH}(HT) 3T 2.5MA, 2.4T 2MA, 1.8T 1.7MA
- Wide n_e scan
- RF ramps when possible, NBI steps



L-H transition: from Low to High confinement (H-mode)



In L-mode

2 MW NBI: 1.4 MJ

3 MW NBI: 1.5 MJ

4 MW NBI: 1.6 MJ

L-H transition: 1.66 MJ

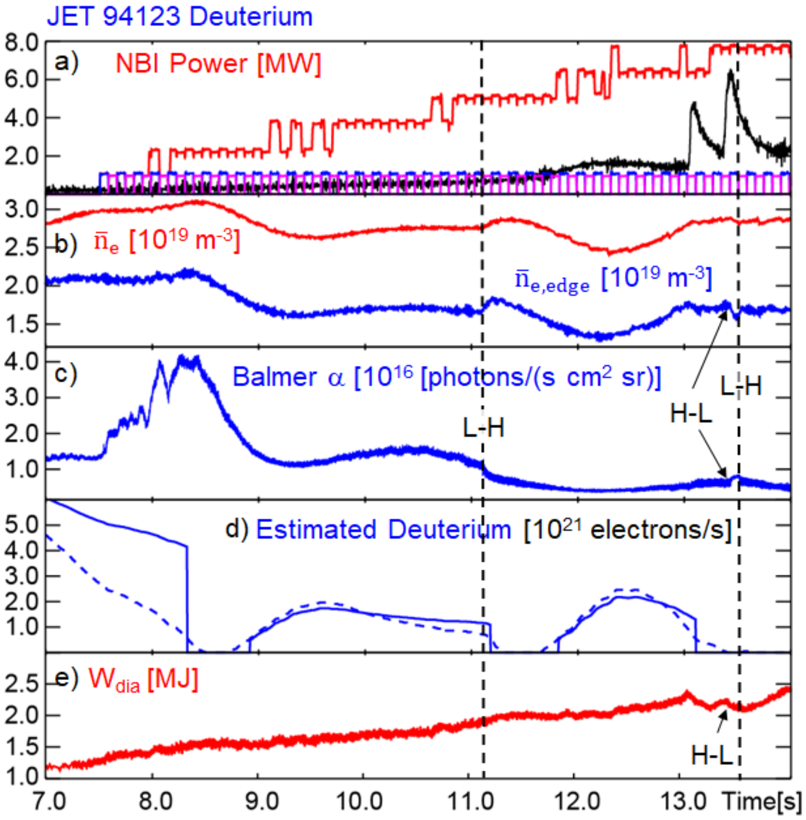
H-mode:

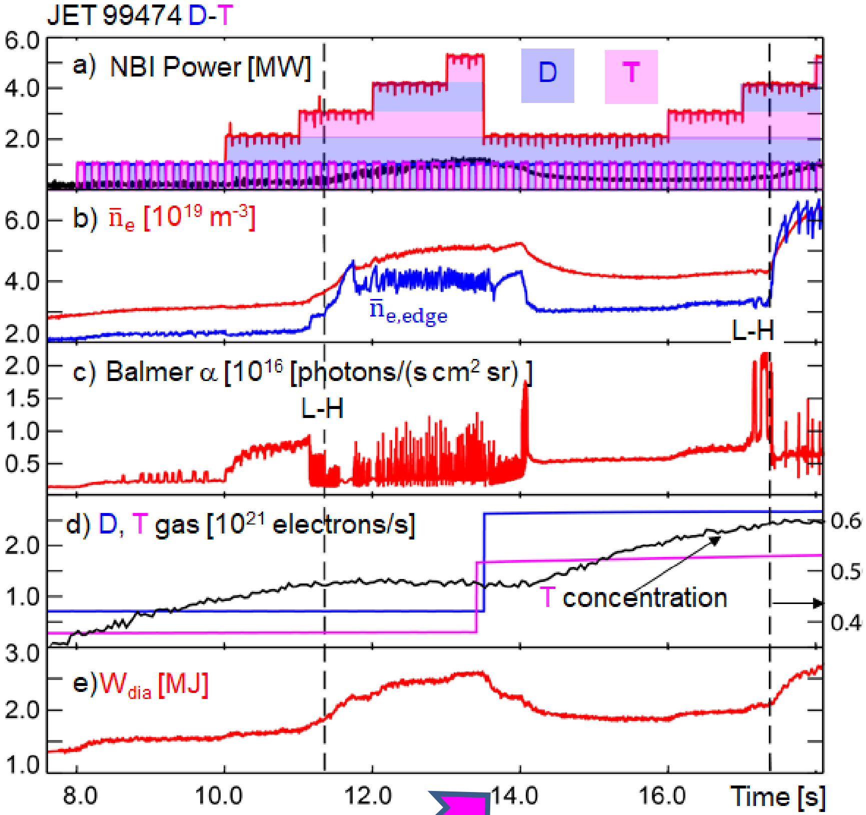
4 MW NBI: 2.3 MJ

…

L-H transition allows the plasma to keep heat and particles in

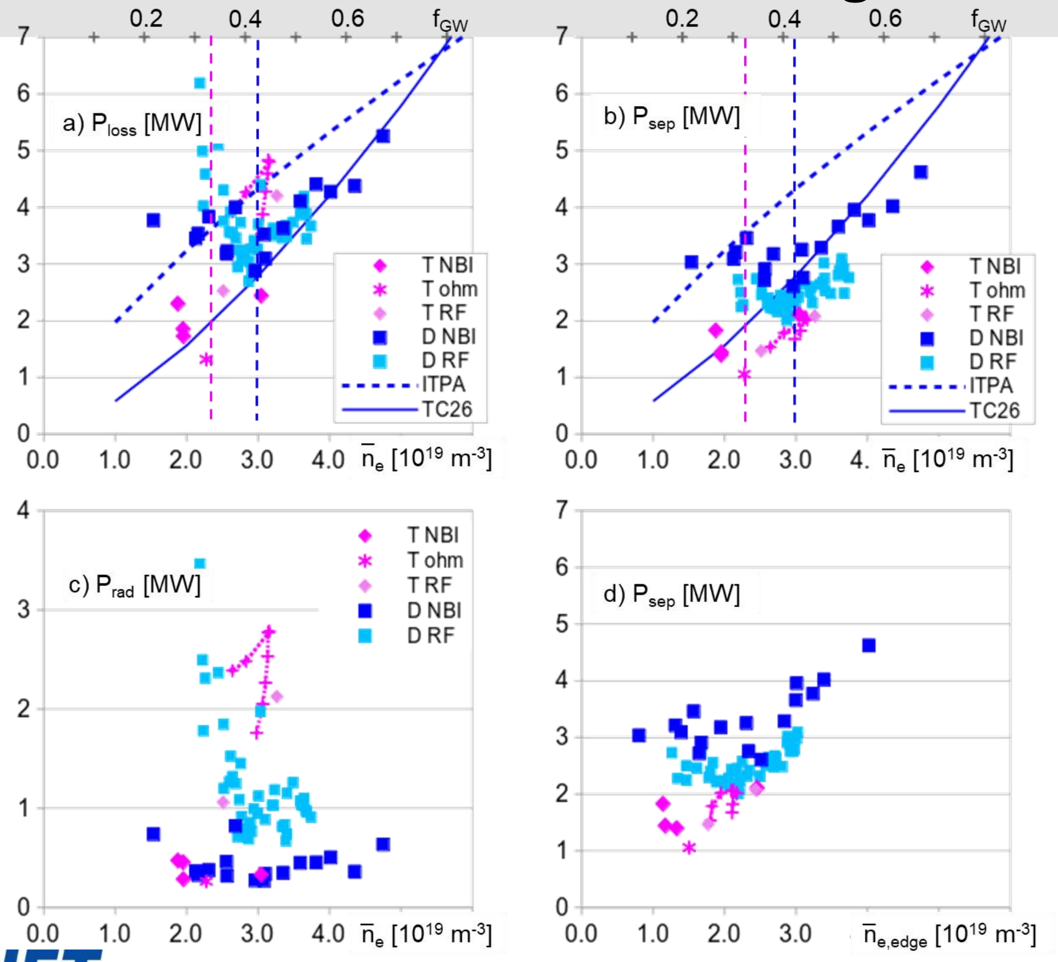
NBI heated L-H transition experiments in D-T





To minimize Tritium consumption and optimise NBI reliability

Horizontal Target 2.4 T 2 MA: T, D



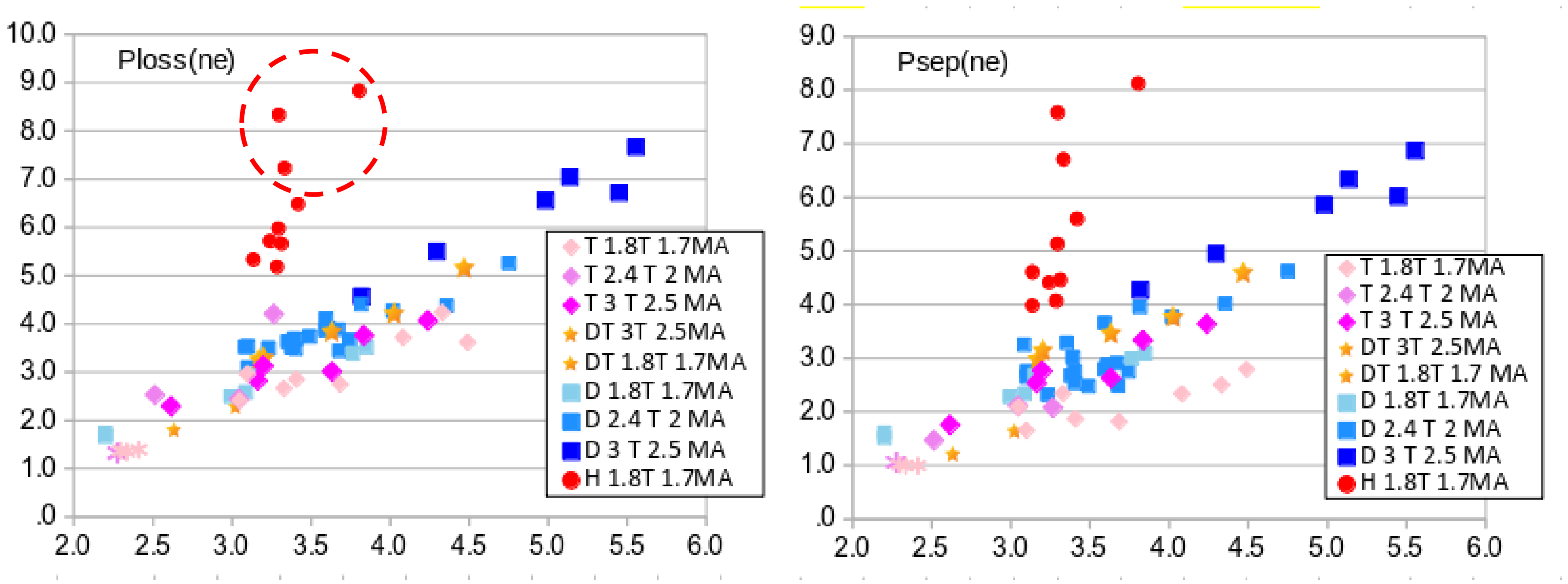
Similar observations on $\bar{n}_{e,min}$, lower for T.

P_{sep} lower for RF heating.

Very lucky to have an ohmic transition, at $\bar{n}_{e,min}$

Large radiation for RF heated T, even at medium density

High density branch vs n_e: all data together, mixing NBI and RF

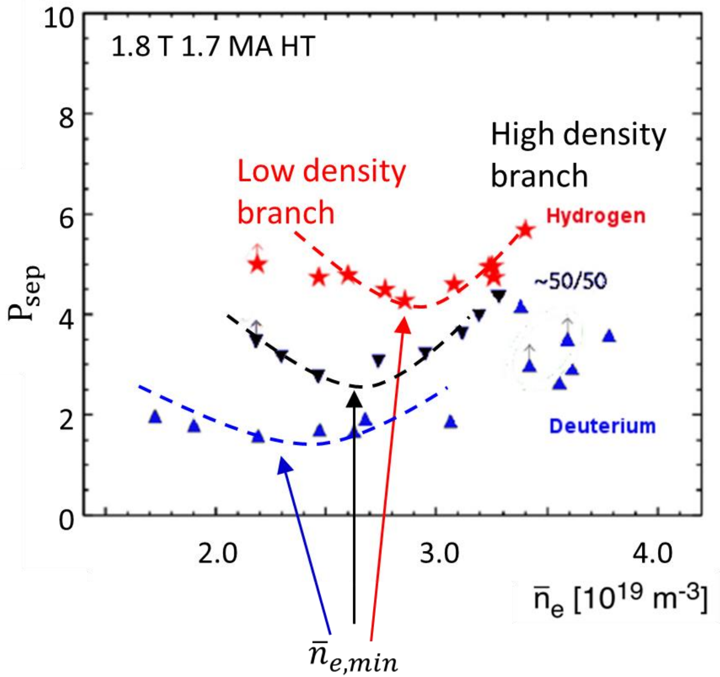


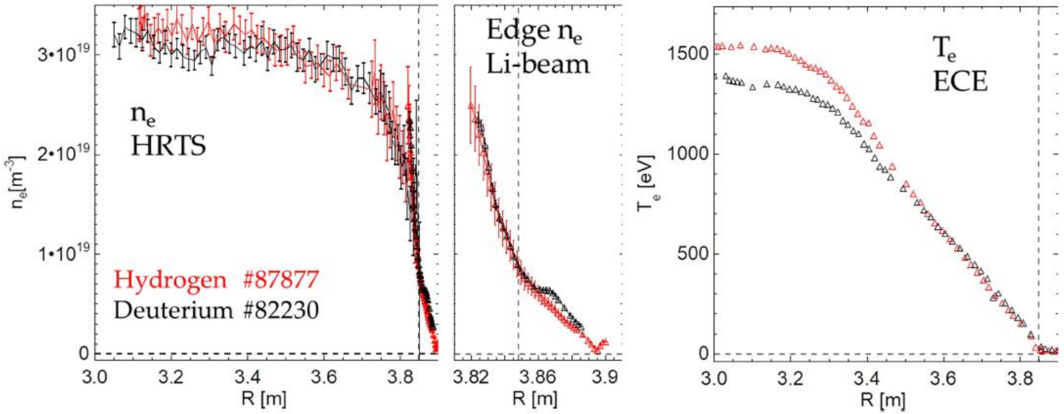
Isotope effect on P_{LH}: **H**, **D** **and** **H+D** **mixtures**

HT (Horizontal Target) in JET-ILW

- $\bar{n}_{e,min}$ and P_{LH} are different in **H**, **D and H+D mixtures**

*C.F. Maggi et al 2016 PPCF **54** 023007*





Profiles just before transition: very similar in H and D. Isotope effect due to the need for more fuelling and/or heating to reach same conditions in H than in D

N. Bonanomi et al, NF 59 126025 (2019)

CF Maggi PPCF 60, 014045 (2018)