



L-H TRANSITION STUDIES AT JET: TRITIUM, HELIUM AND DEUTERIUM

Emilia R. Solano and JET L-H transition team*

JET



Laboratorio
Nacional
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Ciemat



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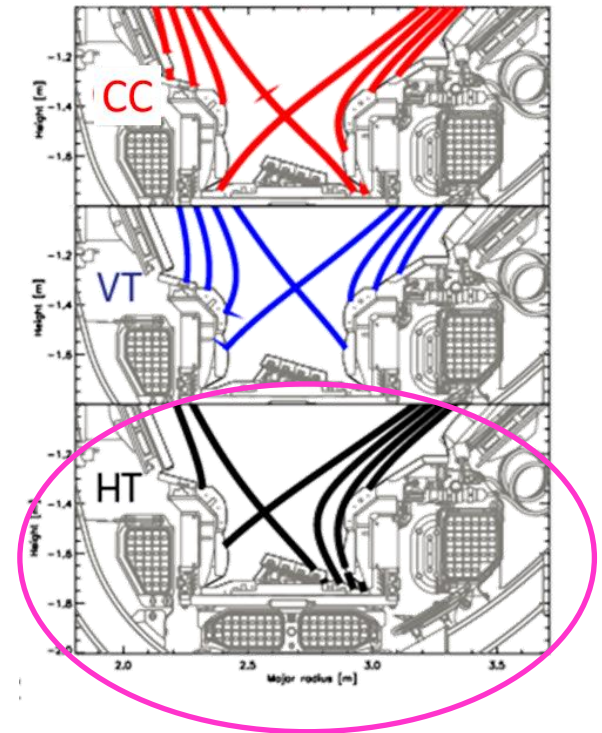
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** See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

L-H transition studies in JET



- RF-heated **Tritium** plasmas: L-H power threshold, preliminary!
- **Helium** plasmas, comparison with **Hydrogen**, **Deuterium**:
 - L-H power threshold, $n_{e,min}$
 - ELMs in Helium
 - Transition modelling
- **Deuterium** plasmas:
 - Doppler reflectometry
 - Ion heat flux: modelling and $n_{e,min}$
 - Scaling laws for L-H power threshold



Horizontal Target: HT

$$P_{loss} = P_{Ohm} + P_{Aux} - dW/dt$$
$$P_{sep} = P_{loss} - P_{rad,bulk}$$



- **RF-heated Tritium** plasmas: L-H power threshold, preliminary!
From JET-C P_{LH} studies: expect $P_{LH}(T) = 2/3 P_{LH}(D)$ [1]

[1] E Righi et al 1999 Nucl. Fusion 39 309

RF-heated Tritium in JET-ILW: dithering transitions

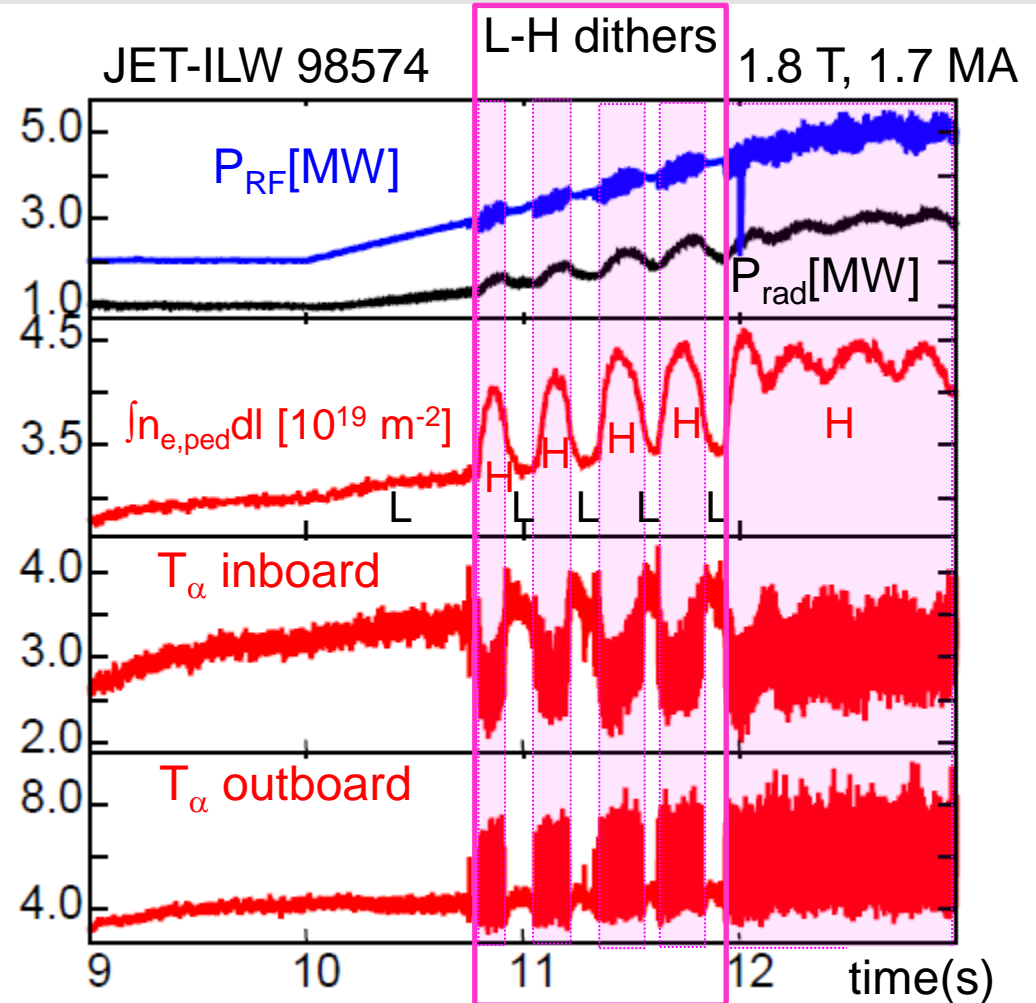


L-H transition experiments in **Tritium** with RF heating: difficult to enter good H-mode with ICRH

Clear **L-H dithers** observed:

- L-H transition, clear rise of \bar{n}_e
- Increase in P_{rad}
- H-L transitions

Eventually, at $0.77 n_{GW}$, weak H-mode: $T_{e,ped} \sim 100-150$ eV

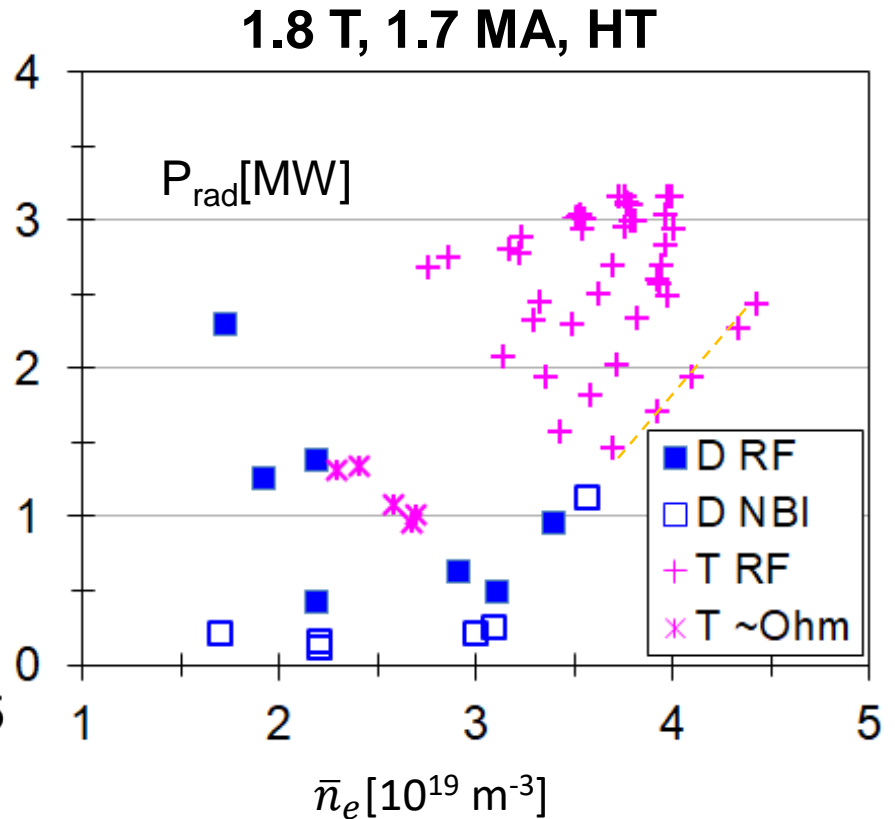
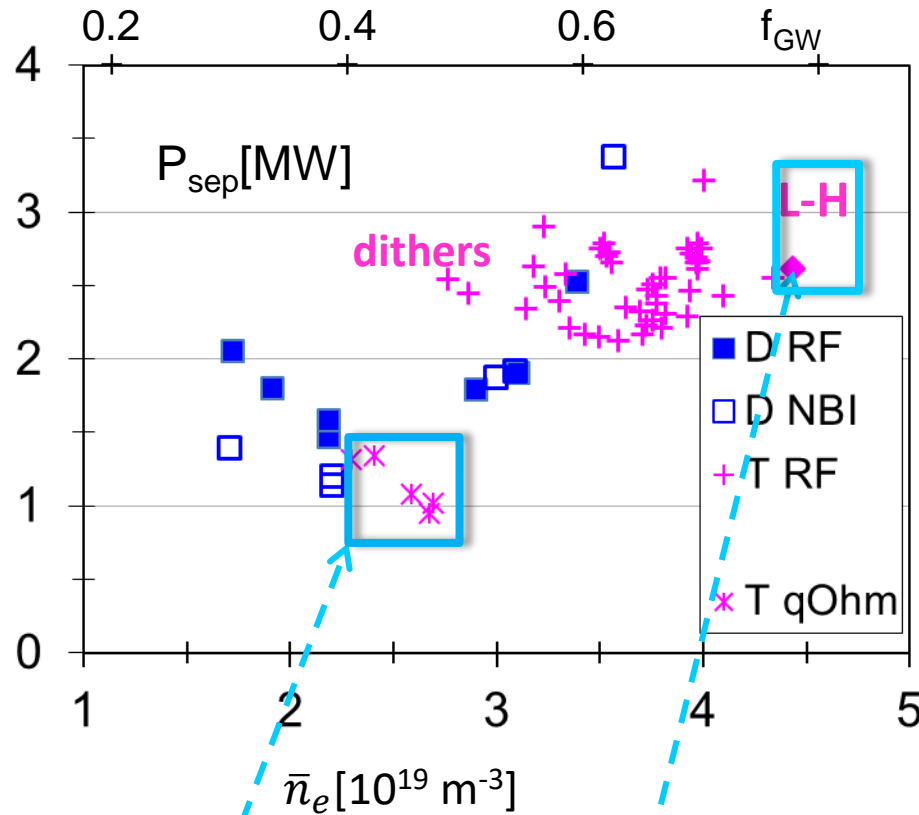


H-minority RF heating

$n_T/n_{HDT} > 94\%$, $n_H/n_{HDT} < 6\%$

G. Birkenmeier, to be submitted to NF.

L-H power threshold: Deuterium/Tritium comparison



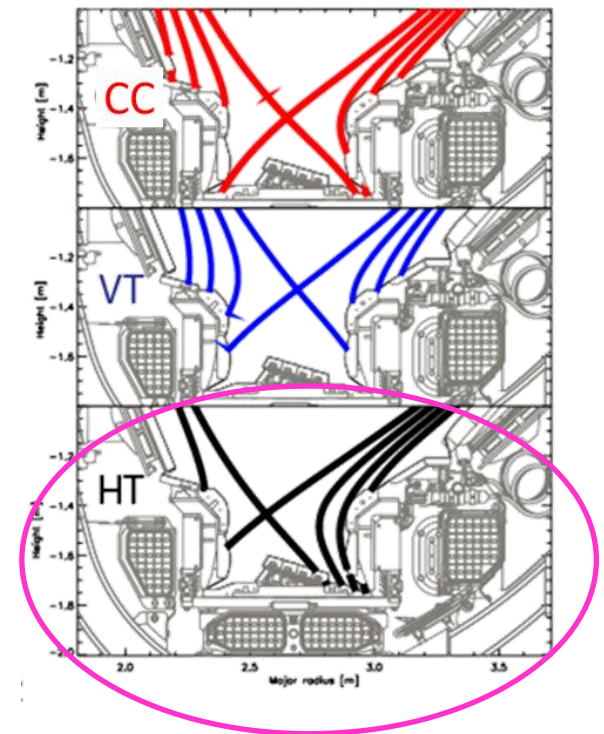
- $P_{sep}(T) < P_{sep}(D)$ at high density, $f_{GW} = 0.77$
- Dithers: power sufficient for L-H transition in **Deuterium** fails to produce steady H-mode in **Tritium**
- Ohmic and quasi-ohmic **transient** H-modes

- Radiation higher in RF heated **Tritium**: increased W influx
- $P_{rad,bulk}$ already subtracted from P_{sep} : *not the whole story?*

G. Birkenmeier, to be submitted to NF.

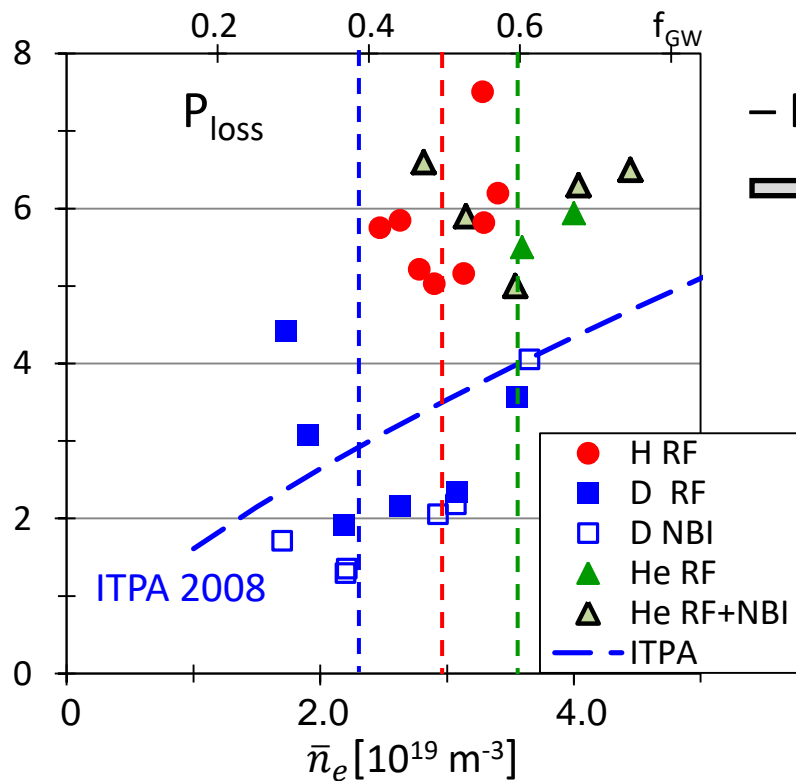


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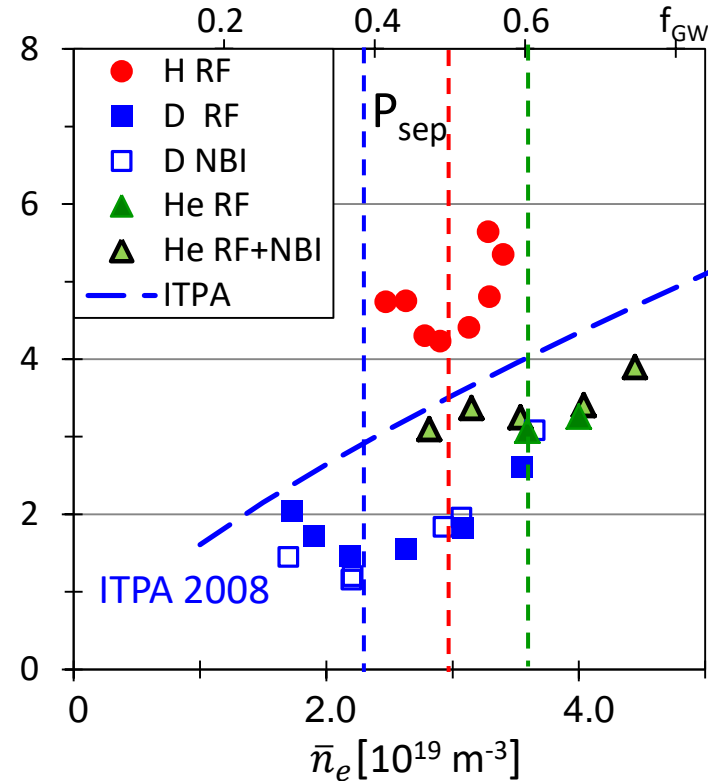


Horizontal Target: HT

P_{L-H} in Hydrogen, Deuterium, Helium: 1.8 T, 1.7 MA HT



$-P_{rad}$



- Clear shift in $\bar{n}_{e,min}$ towards higher densities for **H** and **⁴He**
- Above $\bar{n}_{e,min}(\text{He})$: $P_{LH}(\text{He}) \sim P_{LH}(\text{D})$ (not 40% higher) [2]
- Although $P_{rad}(\text{He}) > P_{rad}(\text{H or D})$, $\bar{n}_{e,min}$ shift not due to P_{rad}
- Increase in $\bar{n}_{e,min}(\text{He})$ compensated by decrease in P_{LH} : unchanged ITER estimate, provided $P_{rad}(\text{He})$ is not very high in ITER

$$\bar{n}_{e,min}(\text{D}) = 0.4 f_{GW}$$

$$\bar{n}_{e,min}(\text{H}) = 0.5 f_{GW}$$

$$\bar{n}_{e,min}(\text{He}) = 0.6 f_{GW}$$

[2] D McDonald et al, PPCF 46 519 (2004)

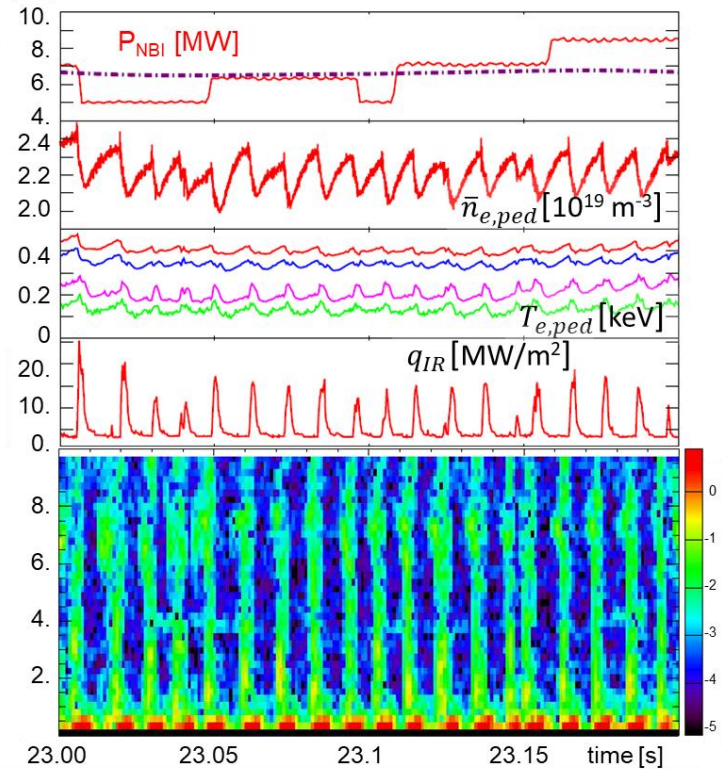
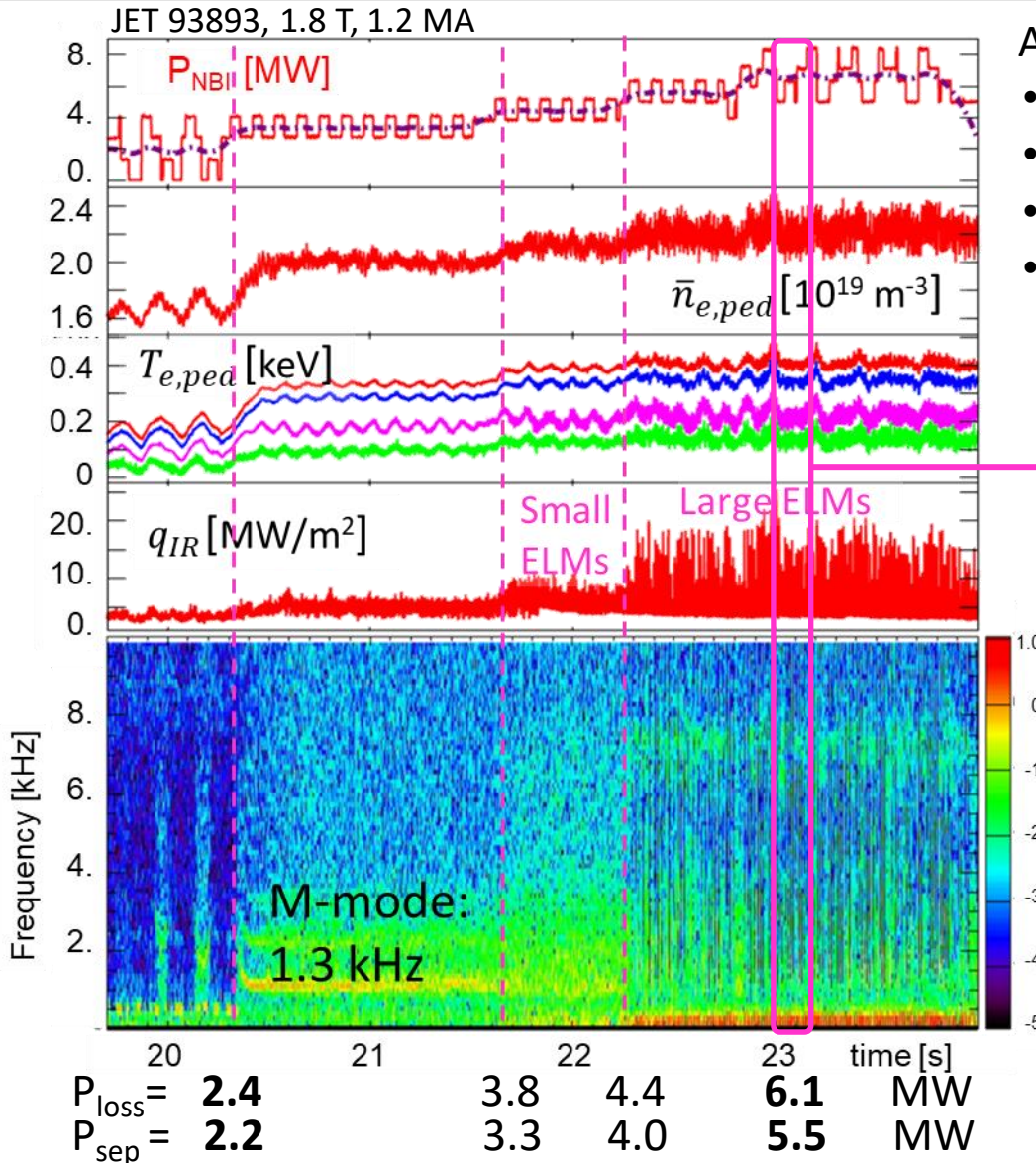
Helium Type I ELMs, 1.8 T, 1.2 MA HT



As average NBI power increases:

- 3.3 MW: M-mode, 1.3 kHz
- 4.4 MW: small ELMs (type III?), M-mode
- 5.6 MW: 100 Hz isolated + small ELMs
- 6.5 MW: 100 Hz isolated ELMs, **Type I**

$$P_{\text{sep}}(\text{type I})/P_{\text{sep}}(\text{L-H}) \sim 2.5$$



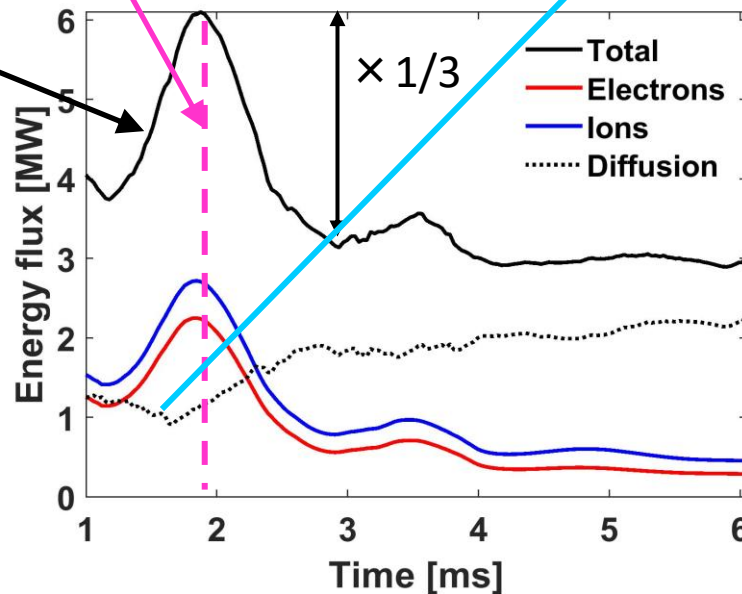
ER Solano et al, NF 57, 022021 (2017)



Helium: HESEL modelling of L-H transition



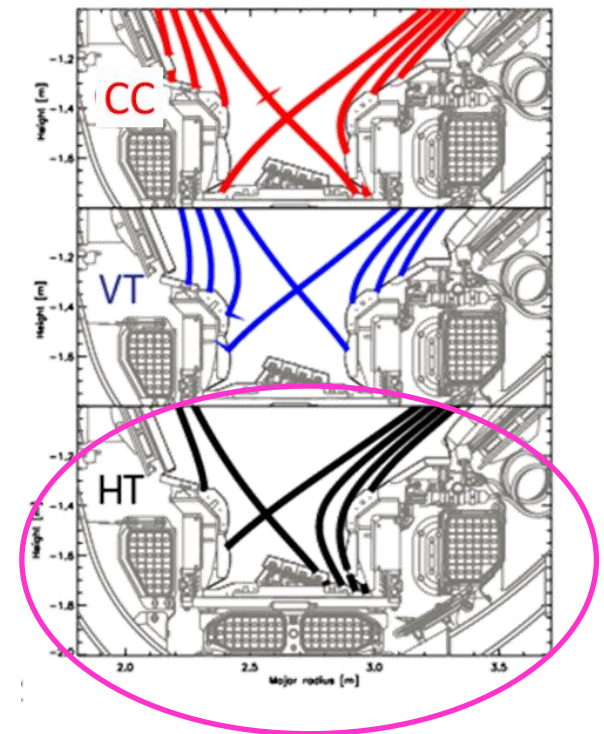
Electrostatic 4-field drift fluid model, slab
Connects confined edge region and SOL
Flux driven - interchange turbulence
Increase in ∇T_i induces L-H transition



Helium: transition at similar total power to **Deuterium**, but at $\sim 2 \times \nabla T_i$, $n_i = n_e/2$
Collisional diffusion $\sim 0.5 \times$ turbulent transport before L-H, unlike **H**, **D**, **T**
Significant drop in interchange transport at L-H, below collisional diffusion

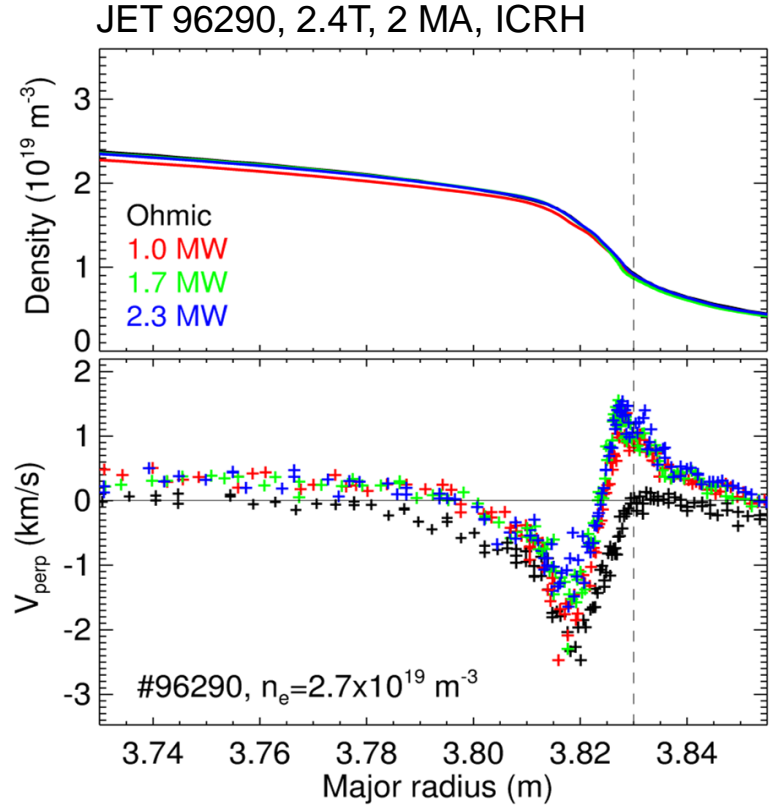


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Horizontal Target: HT

Deuterium: Doppler reflectometry $v_{\perp} \sim E_r$ measurements



Evolution of $v_{\perp} \sim E_r/B$ measured with Doppler reflectometry along especially slow RF power steps (200 kW every 0.5 s)

Ohmic: low v_{\perp} at separatrix/SOL, deep well

During power ramp:

- high v_{\perp} at separatrix/SOL when ICRH on
- reduction in depth of v_{\perp} well with ICRH
- similar $v_{\perp \text{ maximum}}$ shear during power ramp
- L-H: 200 ms after last v_{\perp} profile, 2.5 MW

It doesn't appear likely that E_r shear controls the transition.

C. Silva, to be submitted to NF.

Deuterium: Edge ion heat flux Q_i



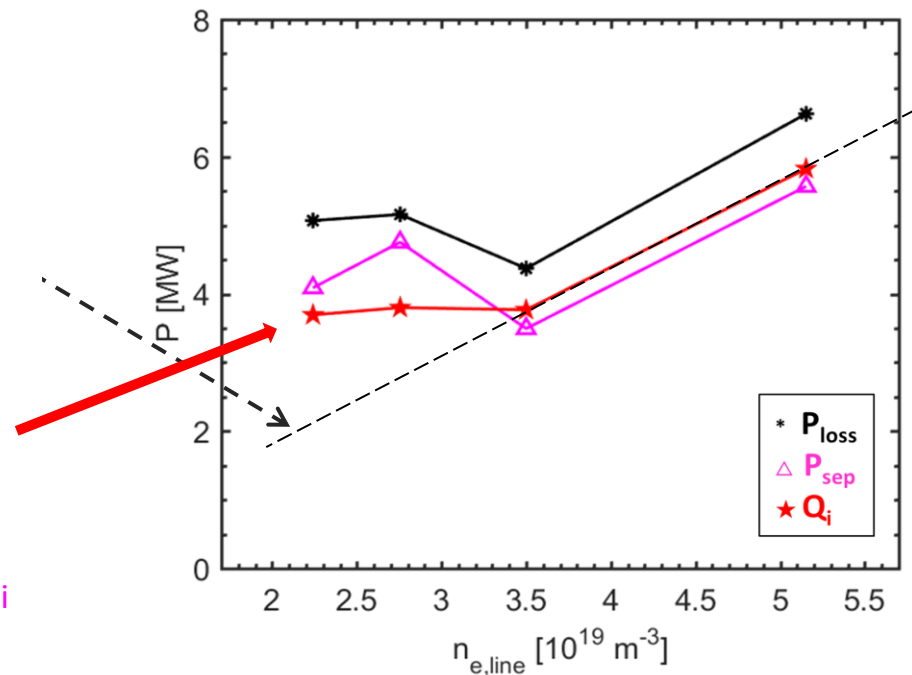
$B_{tor} = 3 \text{ T}$, $I_p = 2.5 \text{ MA}$, NBI, n_e scan, measured T_i , T_e , n_e , P_{rad} profiles, JINTRAC+ASCOT¹

Linear Q_i trend below $\bar{n}_{e,min}$ reported for e-heated plasmas in C-mod and AUG¹

$$P_{sep} = P_{loss} - P_{rad} = \underbrace{(P_{aux,i} + P_{ei} - dW_i/dt)}_{\text{Edge ion heat flux, } Q_i} + \underbrace{(P_{aux,e} - P_{ei} + P_{ohm} - dW_e/dt)}_{Q_e} - P_{rad}$$

Results from JET power balance analysis²

- strong ion heating from NBI and P_{ei}
- dominant ion heat transport, confirmed by QuaLiKiz gyrokinetic simulations
- Core $T_e > T_i$, edge $T_e \approx T_i$
- Non-linear Q_i vs n_e , like P_{loss} and P_{sep}
- Non-linear Q_i similar to AUG NBI³
- In this case $\bar{n}_{e,min}$ is not determined by P_{ei}

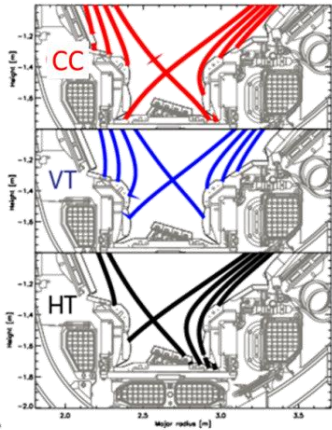


¹P. Vincenzi et al., submitted to NF

²M. Schmidtmayr et al, 2018 Nucl. Fusion 58 056003

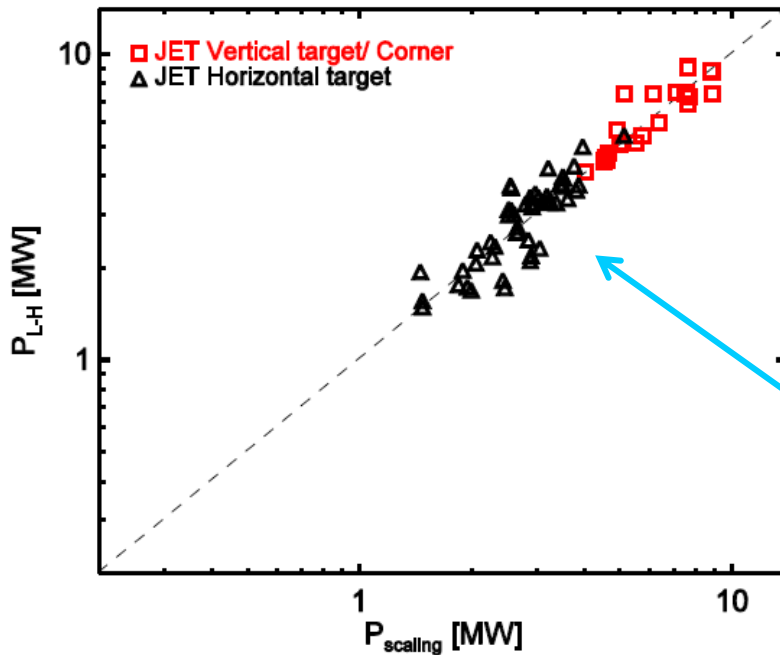
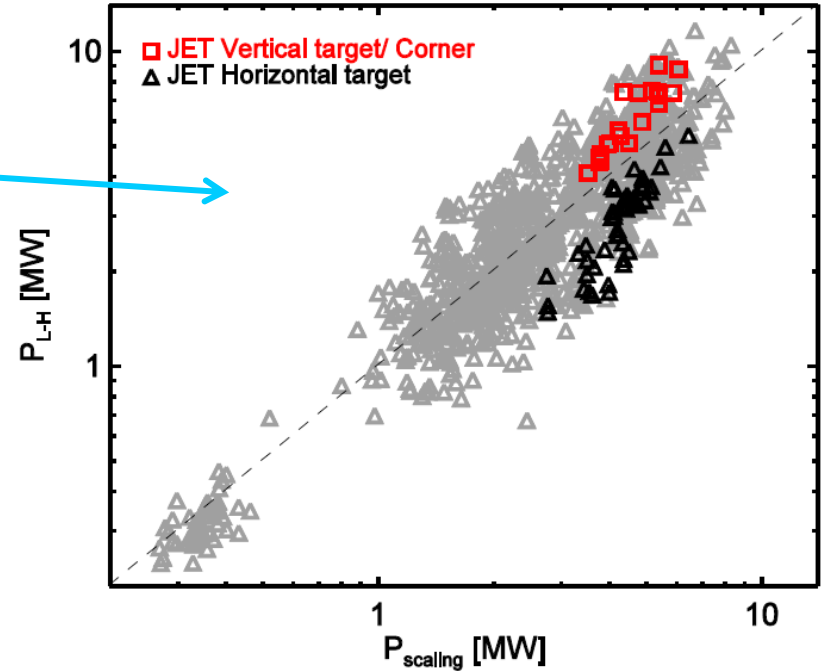
³F Ryter et al, 2014 Nucl. Fusion 54 083003

Deuterium: P_{LH} Scaling Laws. ITPA TC-26



JET-ILW vs 2008 ITPA scaling: $P_{LH} = (0.049 \pm 0.006) n_{e20}^{0.72 \pm 0.03} B_T^{0.83 \pm 0.03} S^{0.94 \pm 0.02}$

- JET-ILW added 106 data points
- New data points don't fit old scaling law
- Introduce shape parameter D , new fit to JET-ILW data only



$P_{LH} = D (0.046 \pm 0.009) n_{e20}^{1.31 \pm 0.09} B_T^{0.85 \pm 0.13} S^1$
 RMSE= 16%
 with $D=1.0$ for HT and $D=2.06 \pm 0.07$ for VT/CC

Stronger n_e trend, especially for HT

E. Delabie et al, ITPA meeting Sept. 2017



- **RF heated Tritium** plasmas: dithers indicated that $P_{LH}(T) > P_{LH}(D)$ (preliminary results)
- **Helium** plasmas, comparison with **Hydrogen, Deuterium**:
 - Shifts in $n_{e,min}$: $\bar{n}_{e,min}(D) = 0.4 f_{GW}$, $\bar{n}_{e,min}(H) = 0.5 f_{GW}$, $\bar{n}_{e,min}(He) = 0.6 f_{GW}$
 - Above $n_{e,min}$: $P_{LH}(He) = P_{LH}(D)$
 - Transition modelling: Z^2 collisional diffusion
 - Observed high frequency Type I ELMs in Helium
- **Deuterium** plasmas:
 - Doppler reflectometry: E_r shear doesn't evolve along power ramp
 - Ion heat flux is not a linear function of density below $n_{e,min}$
 - Scaling laws for L-H power threshold in JET-ILW
- **Outlook**: further L-H transition studies in **Tritium** and **DT** planned in 2021