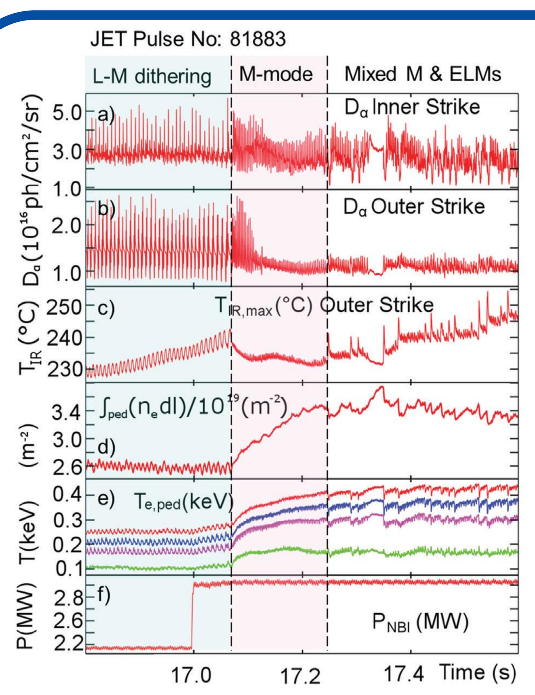
L-H transition and M-mode studies in JET-ILW

E. R. Solano[1] , E. Delabie[2], J.C. Hillesheim[3], C. Maggi[3]; N. Vianello[4], I.S. Carvalho[5], P. Carvalho[5], A. Huber[6], E. Lerche[7], D. van Eester[7], M. Mantsinen[8,9] and JET Contributors*
EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1] Laboratorio Nacional de Fusion, CIEMAT, Madrid, Spain; [2] Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA; [3]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK; [4] Consorzio RFX, Padova, Italy; [5] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal; [6] Forschungszentrum Jülich, Jülich, Germany; [7] LPP-ERM/KMS, Association EUROFUSION-Belgian State, TEC partner, Brussels, Belgium; [8] Barcelona Supercomputing Center, Barcelona, Spain; [9] ICREA, Barcelona, Spain;
*See the author list of ``Overview of the JET results in support to ITER" by X. Litaudon et al. accepted for publication in Nuclear Fusion

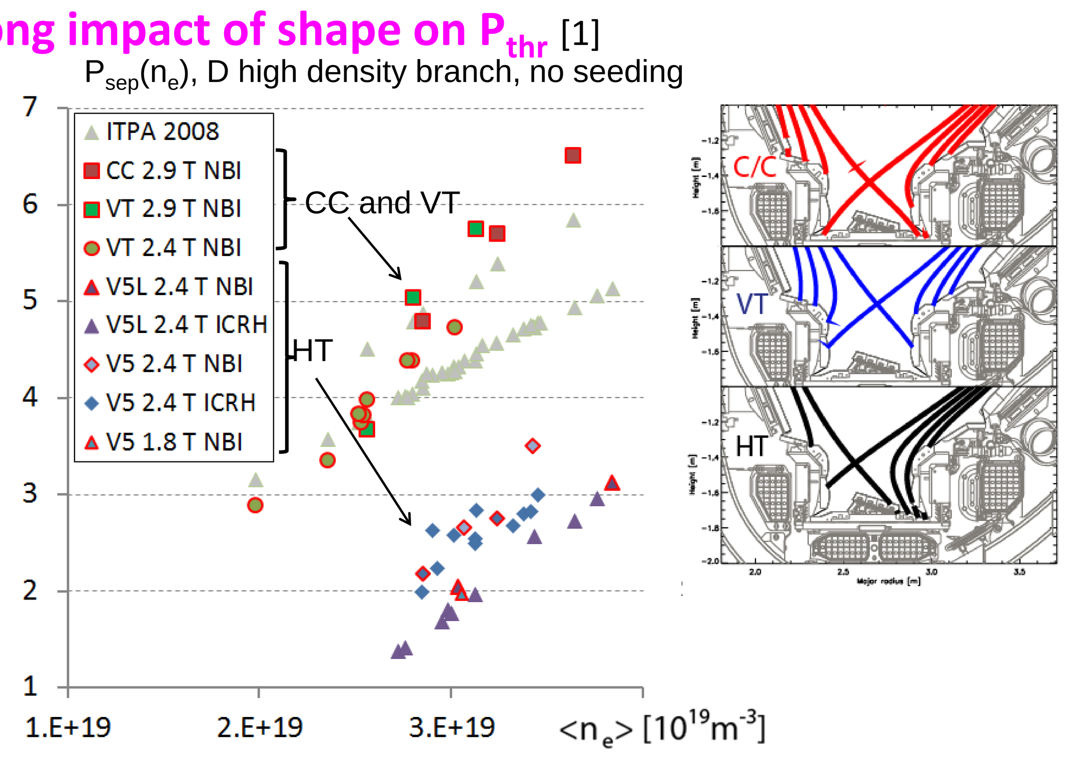
- Power threshold (P_{thr}) to access H-mode remains a significant uncertainty in the design of fusion experiments, such as ITER and DEMO.
- Although mixed isotope D-T plasmas will be required for burning plasmas, relatively little work has been done in mixed species plasmas.
- The unique capability for H, D, and T operation in JET-ILW can provide strong constraints for extrapolations to future experiments.
- P_{thr} has been found to depend in non-trivial ways on isotope and species mix.
- There is a ×2 variability in P_{thr} with plasma shape: identified, but not understood.



Slow power ramps to determine P_{thr}

- Slow power ramps of ICRH and/or NBI steps used to identify P_{L-H}
- At JET the L-H is defined as as the time from when the plasma stays in H mode: $n_{e,ped}$ and $T_{e,ped}$ rise. Sequence is L-H(M)-Elmy
- Sometimes the L-H change can be subtle, "quasi-continuous transition". Sometimes there are dithering transitions before the L-H transition proper. See discussion on M-mode below.

Strong impact of shape on P_{thr} [1]



- 200 L-H transitions in JET-ILW database
- Hydrogen, deuterium, and mixed H/D plasmas
- B_t=1.8-3.4 T, I_p=1.7-3.2 MA, $<n_e>$~1.5-5.0x10^{19} m^{-3}
- HT, VT, and C/C divertor configurations
- Clear impact of plasma shape on power threshold
- Data with ICRH, NBI and mixed heating, compared to ITPA 2008 [2]

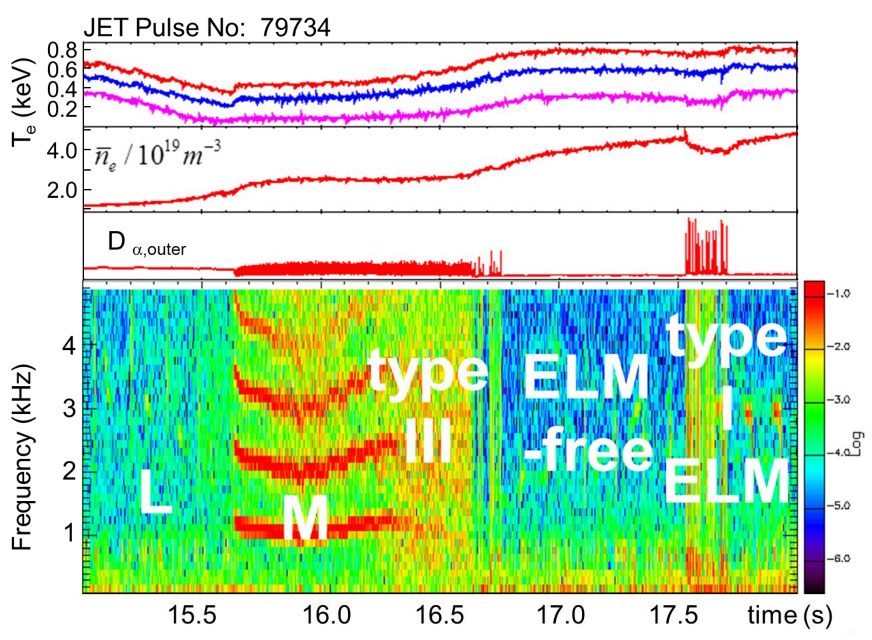
$$P_L = P_{OHM} + P_{abs} - dW/dt - P_{Floss} \qquad P_{sep} = P_L - P_{rad}$$

ITPA 2008
$$P_{Thresh} = 0.0488\, e^{\pm 0.057}\, n_{e20}^{0.717\pm 0.035}\, B_T^{0.803\pm 0.032}\, S^{0.941\pm 0.019}$$

M-mode (or I-phase, or Limit Cycle Oscillations)

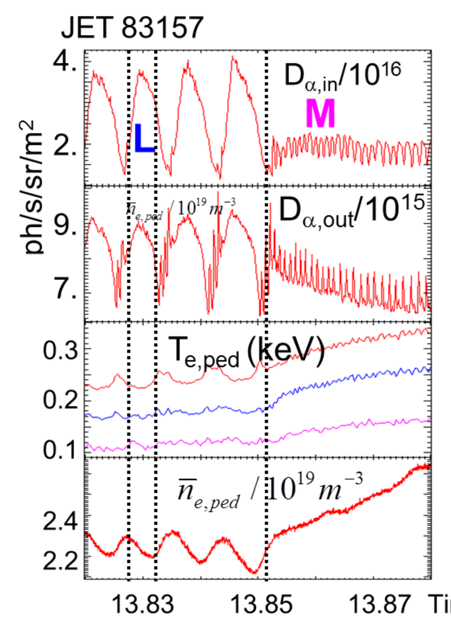
M-mode is a magnetic oscillation observed at the L-H transition. It is n=0, m=1, up-down. It is also seen in all pedestal fluctuation diagnostics at JET [3]. M-mode presence facilitates identification of L-H transition.

M-mode is a combination of an up-down oscillation of flux surfaces in the pedestal gradient region, punctuated by periodic expulsions of particles and energy from the pedestal top, which occur as the plasma current centroid moves upwards (or the toroidal current near the X-point erodes?).



High density branch:

- dithering transitions [4], then clean M-mode.
- M-mode seen during H phases of dithers
- As power increases, type type III and type I ELMs can be mixed with M-mode, eventually transition to ELM free, followed by type I ELMy.



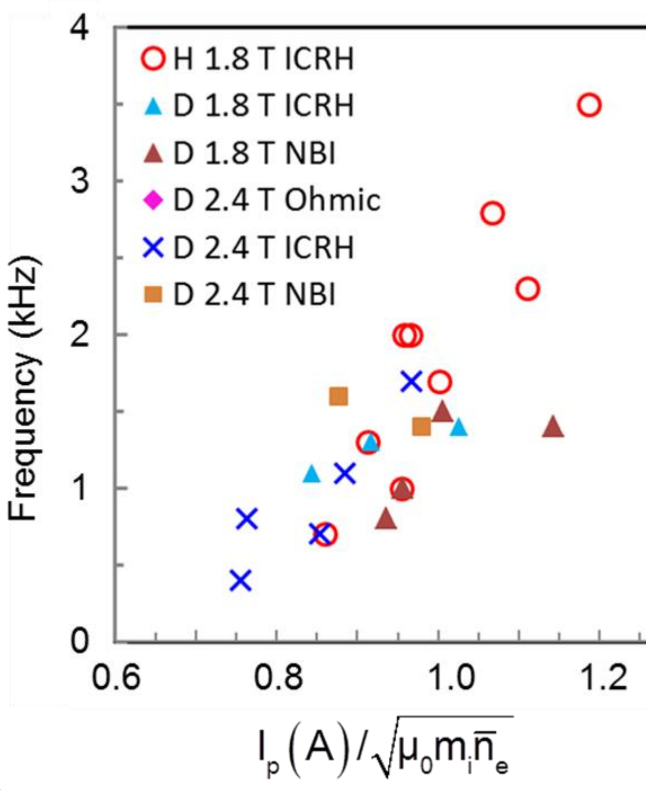
Inner detachment precedes transition to M-mode.

Strong in/out asymmetry in divertor recycling pattern is beneficial for H-mode access at reduced power [2]

Low density branch:

- L-mode, transition to M-mode (without dithering), then M-mode mixed with type III ELMs (incoherent n=0), followed by ELM-free and type I ELMy (NBI).

SCALING OF M-MODE FREQUENCY: isotope dependence

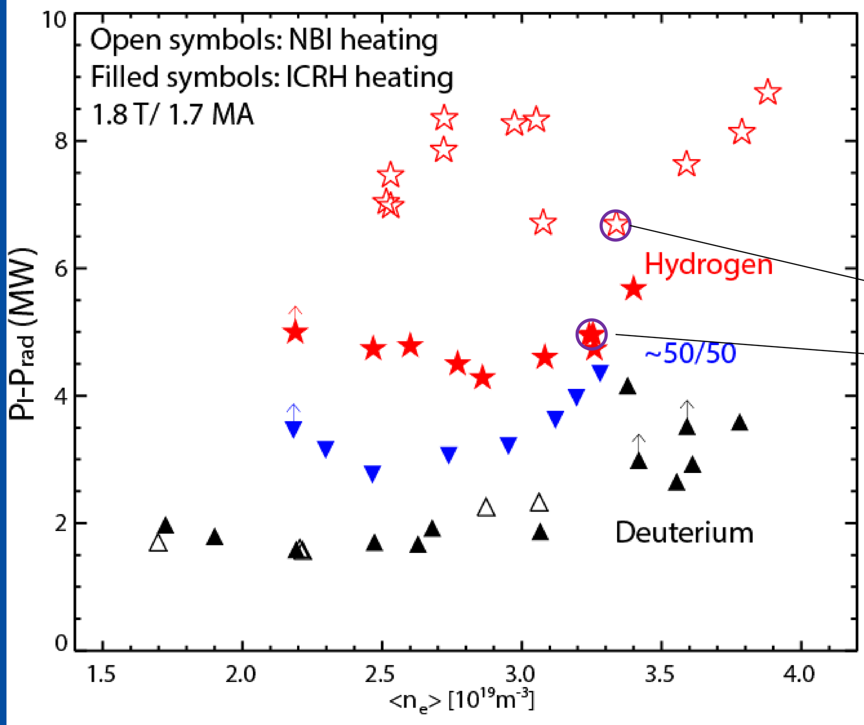


- Best ordering of data in M-mode phases with steady frequencies is achieved with poloidal Alfvén velocity,

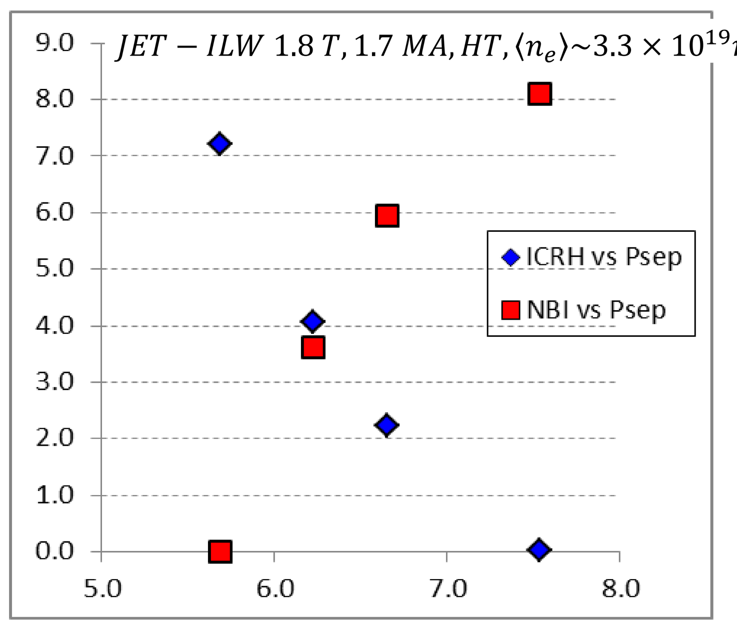
$$V_{Alfvén,\theta} = B_\theta / \sqrt{\mu_0 m_i n_i}$$

- B_θ dependency expected in axisymmetric modes (k_ζ=0)
- No available theory for this steady fluctuation: poloidal Alfvén wave?
- M-Mode frequency does not scale with sound speed or $T_{e,ped}$. It is not a GAM!
- In NBI plasmas density rises and mode frequency drops, although pedestal rotation rises.
- At high densities mode slows down to the point of disappearing in magnetic signals. Only in those cases it is difficult to disentangle natural mode frequency and vertical position control.

Strong dependence on heating method in hydrogen



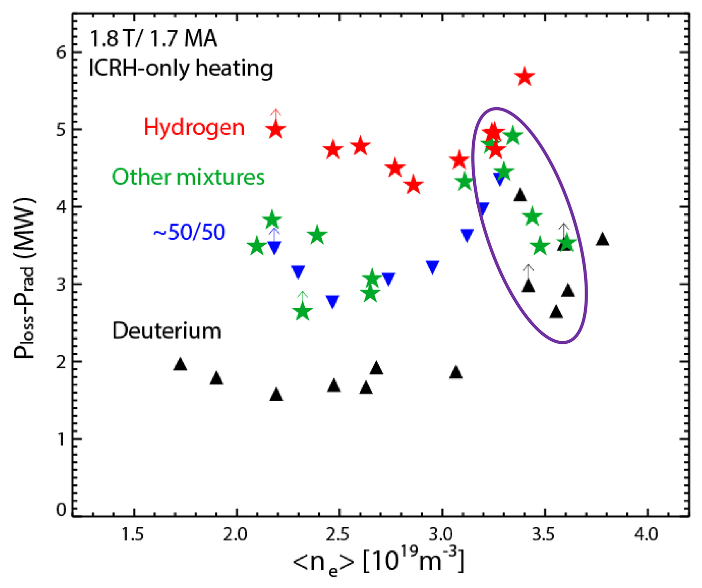
- For ICRH heated plasmas, $P_{thr}(H)$ ~2x$P_{thr}(D)$, consistent with most past results
- Location of $n_{e,min}$ shifts with isotope and heating. N=2 H majority ICRH in H; H minority ICRH in D.
- P_{thr} higher with more input torque (NBI) [5]
  - NBI case: $P_{ions} \approx P_{electrons} \approx$ 3.3 MW
  - ICRH case: P_{ions}= 4.2 MW, $P_{electrons}$ = 0.9MW



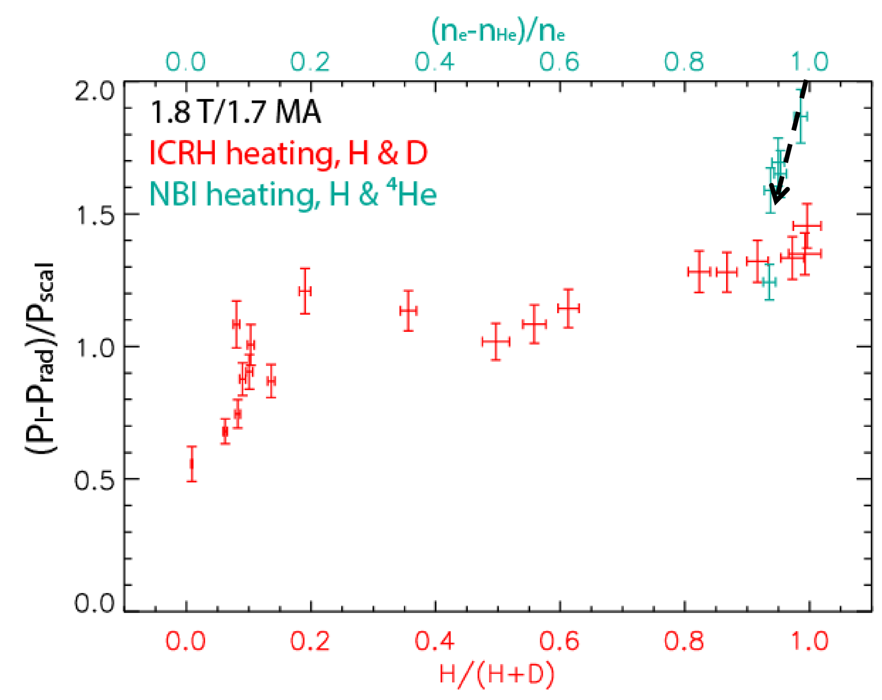
Dedicated scan with NBI power ramp on top of different levels of ICRH power performed in Hydrogen, at fixed density, field (HT V5)

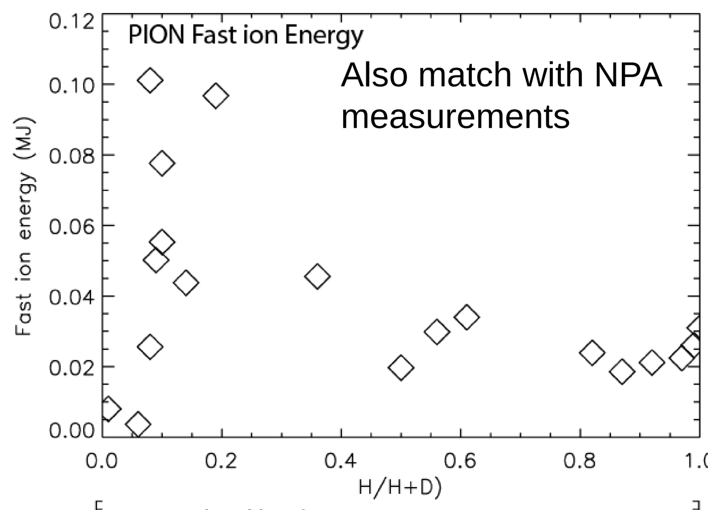
In D, NBI vs ICRH difference near $n_{e,min}$ observed in some shapes/fields/densities (HT3R 2.4 T $n_{e,min}$), not in others (CC, VT high n_e branch?).

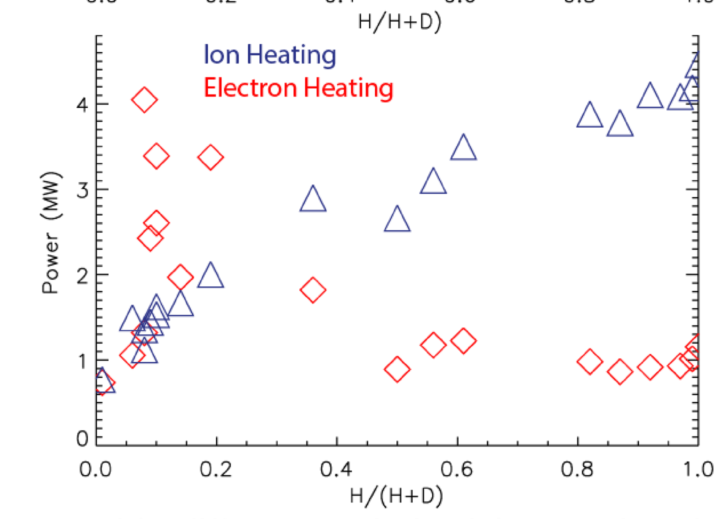
Non-linear dependence of P_{LH} in H+D mixture scan (HT)



- Multiple H/(H+D) ratio measurements consistent
- Neutron rate consistent with square of thermal deuterium density over broad range
- **Largest variations of threshold power observed at high and low concentration**
- Little variation $0.2 < \frac{H}{(H+D)} < 0.8$







Experiments for H+He3 mixtures show drop of P_{thr} with helium seeding in hydrogen plasmas (NBI heating!)

- Heating deposition to ions and electrons studied with PION. Plots show calculation results at L-H transition time.
  - N=1 minority H at low H/(H+D)
  - N=2 majority H above H/(H+D)~0.1
- Density is sufficiently high for energy exchange to dominate over energy deposition.

- Notable differences in ion/electron heating split as a function of H concentration, in 0.2<H/(H+D)<0.8 range
- Ion/electron heating difference by itself can't explain the dependence of P_{thr} on isotope mix.
- P_{thr} changes little in range 0.2<H/(H+D)<0.8.

Conclusions

- L-H power threshold in hydrogen in JET depends on heating method, but less clearly in deuterium pulses. Effect also demonstrated in systematic scan of ICRH and NBI power.
- Non-linear dependence of power threshold observed in hydrogen/deuterium mixture scan.
  Large variations in ion and electron heating during scan, but lack of change in threshold during variations in heating power consistent with sufficiently high density for energy exchange to dominate over power deposition. Implies non-linear dependence requires other physics for explanation, such as a role for H-D ion-ion collisions
- Strong reduction in threshold also observed for helium seeding in hydrogen NBI heated plasmas. This may provide an avenue for lower H-mode P_{thr} in the non-active phase of ITER operation.
- M-mode identified and characterised. Its frequency scales with poloidal Alfvén frequency. Further work required to analysed mixed isotope results.

[1] Maggi C. F. et al, "L–H power threshold studies in JET with Be/W and C wall", Nucl. Fusion 54 (2014) 023007; [2] Y. Martin, "Power requirement for accessing the H-mode in ITER", ITPA 2008, 8 J. Phys.: Conf. Ser. **123**, 012033, (2008); [3] E. Delabie et al., "Dithering transitions" in Proc. of the 24th IAEA FEC (2014), EX/P5–24. *in JET;* [4] E. R. Solano et al., "Axisymmetric oscillations at L-H transitions in JET: M-mode", Nucl. Fus., 57, 022021 (2017); [5] P Gohil et al, "L-H transition studies on DIII-D to determine H-mode access for operational scenarios in ITER" Nucl. Fus. 51 (2011) 103020

59th Annual Meeting of the APS Division of Plasma Physics October 23 - 27, 2017 • Milwaukee, Wisconsin

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

L-H transition and M-mode studies in JET-ILW

E. R. Solano[1] , E. Delabie[2], J.C. Hillesheim[3], C. Maggi[3]; N. Vianello[4], I.S. Carvalho[5], P. Carvalho[5], A. Huber[6], E. Lerche[7], D. van Eester[7], M. Mantsinen[8,9] and JET Contributors*

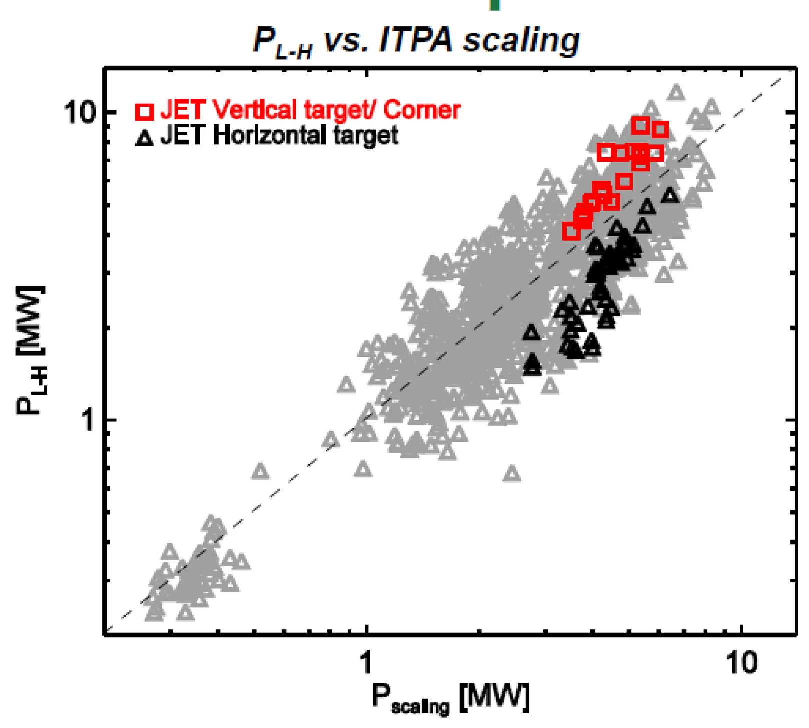
EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

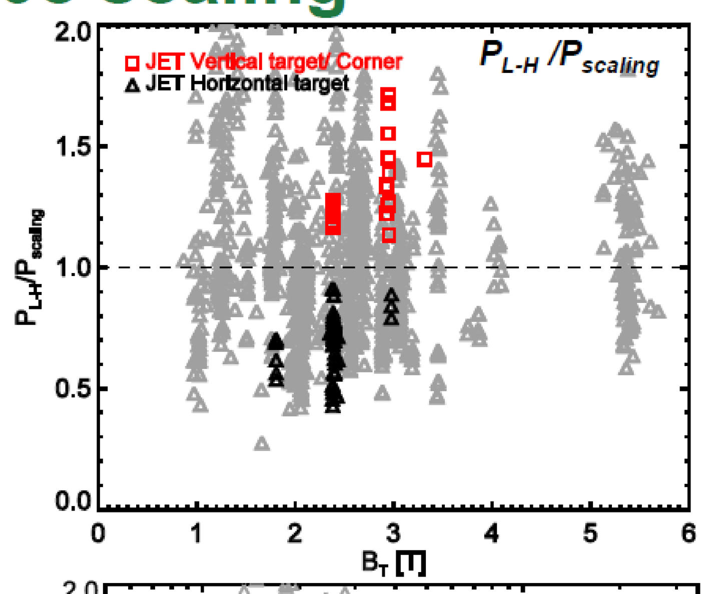
[1] Laboratorio Nacional de Fusion, CIEMAT, Madrid, Spain; [2] Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA; [3]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK;[4] Consorzio RFX, Padova, Italy; [5] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal; [5] Forschungszentrum Jülich, Jülich, Germany; [7] LPP-ERM/KMS, Association EUROFUSION-Belgian State, TEC partner, Brussels, Belgium; [8] Barcelona Supercomputing Center, Barcelona, Spain; [9] ICREA, Barcelona, Spain;

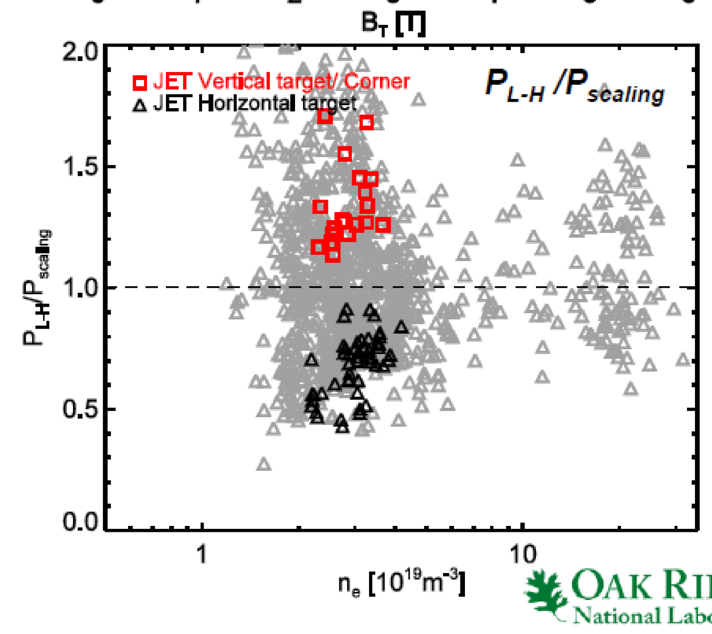
**See the author list of ``Overview of the JET results in support to ITER" by X. Litaudon et al. accepted for publication in Nuclear Fusion*

Latest Pedestal ITPA, TC-26:

JET-ILW compared to 2008 scaling







- Vertical target/ corner above scaling
- Horizontal target pulses below scaling
  - Like-for-like pulses show reduction in threshold between JET-C and JET-ILW [C.F. Maggi NF2014]
- **Tendency for steeper density and B_t scaling**

8 TC-26 status September 2017

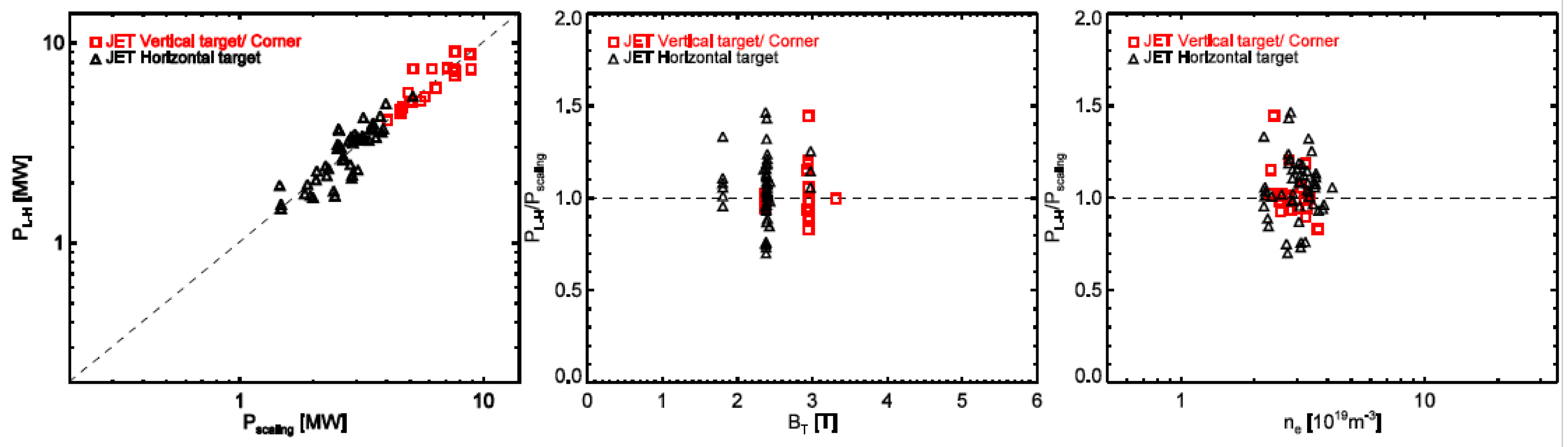
Redo scaling on JET data only

When fitting each dataset individually: relatively large uncertainty on exponents — RMSE

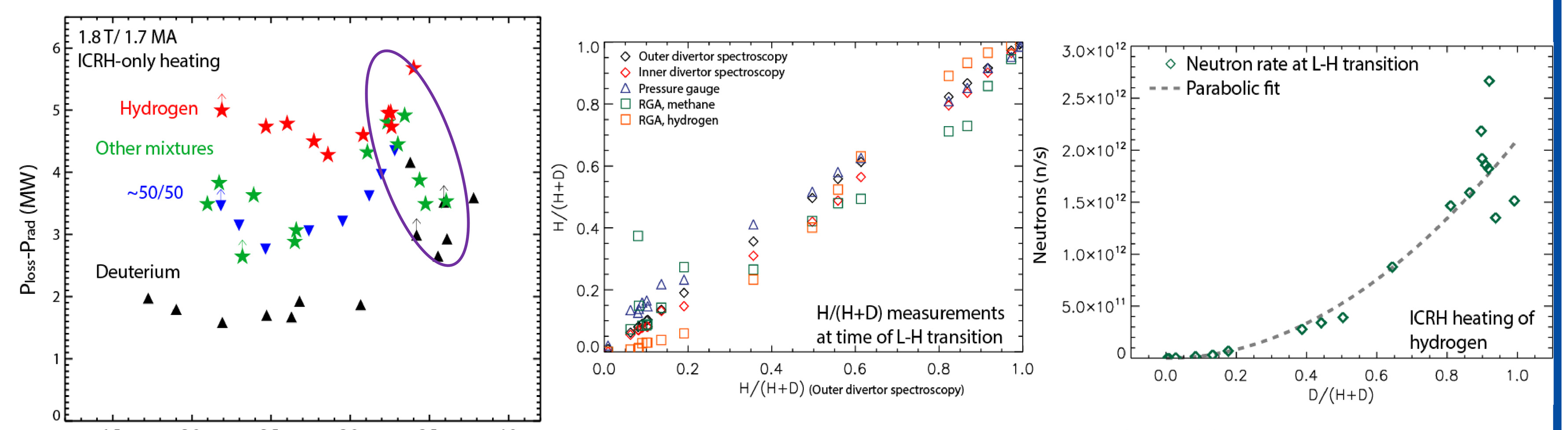
- **JET-ILW (HT)** P_{L-H}= (0.057 +/- 0.012) B $^{0.77 +/- 0.15}$ <ne>$^{1.43 +/- 0.10}$ S^{1} — 17%
- **JET-ILW (VT)** P_{L-H}= (0.031 +/- 0.013) B $^{1.29 +/- 0.24}$ <ne>$^{0.77 +/- 0.20}$ S^{1} — 10%

Combine both configurations with a simple factor for the difference in configuration, with hardly any change to relative RMSE.

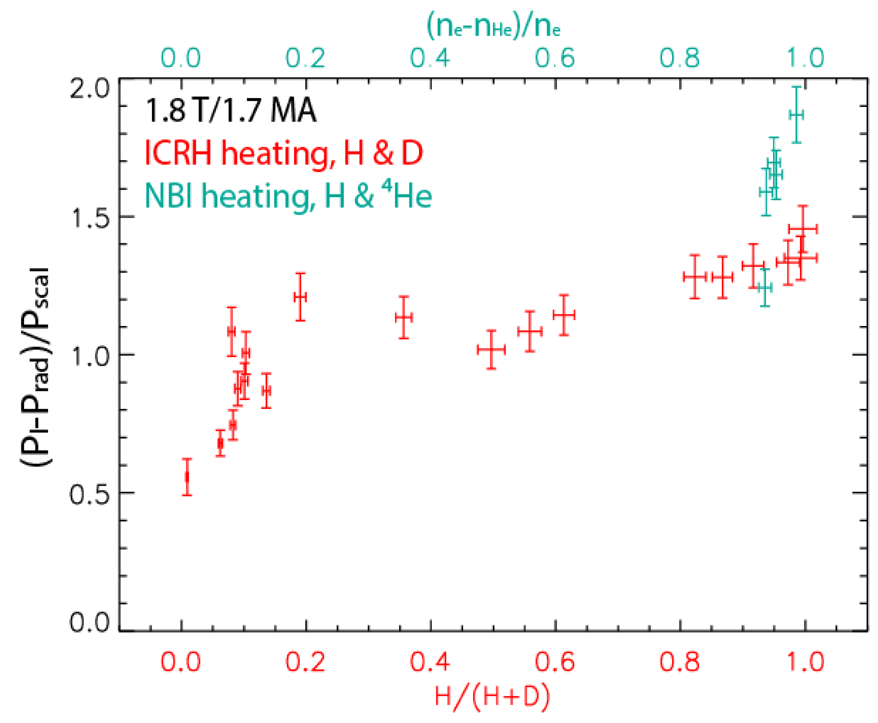
- **JET-ILW** P_{L-H}= (0.046 +/- 0.009) B $^{0.85 +/- 0.13}$ <ne>$^{1.31 +/- 0.09}$ S^{1} D — 16%
  D=2.06 +/- 0.07 for VT/CORNER

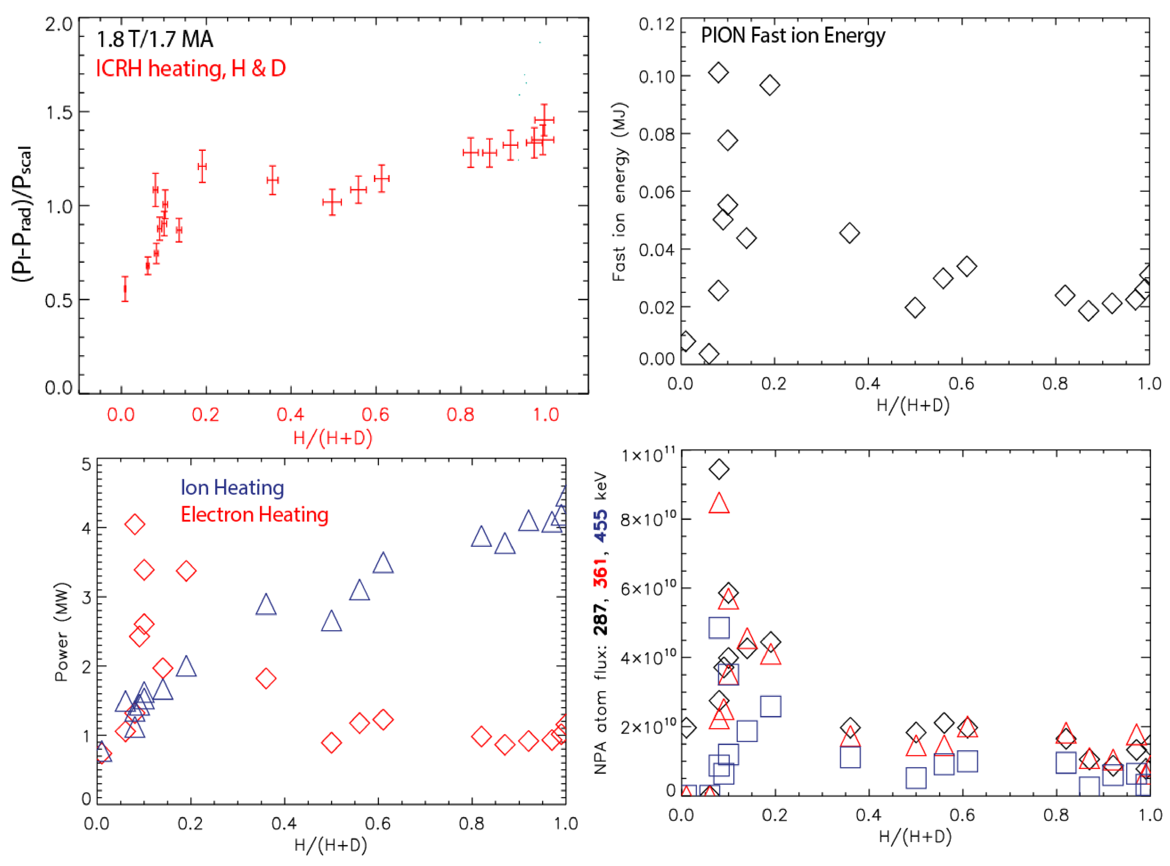


Non-linear dependence of P_{LH} in isotope mixture scan: more diagnostic and analysis details



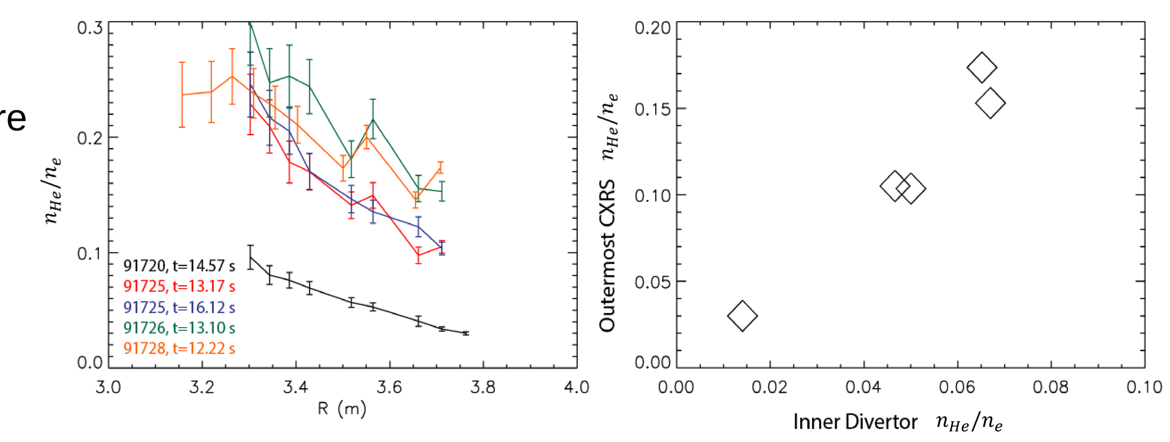
- Multiple H/(H+D) ratio measurements consistent
- Neutron rate consistent with square of thermal deuterium density over broad range
- Largest variations of threshold power observed at high and low concentration
- Little variation $0.2 < \frac{H}{(H+D)} < 0.8$
- Experiments at end of campaign for hydrogen-helium mixtures show drop of power threshold with helium seeding in hydrogen plasmas





- Heating deposition to ions and electrons studied with PION
  - N=1 minority H at low H/(H+D)
  - N=2 majority H above H/(H+D)~0.1
- PION results at right from time of L-H transition in each pulse
- Non-monotonic heating to electrons, while ion heating increases with H/(H+D)
- PION calculation of fast ion energy correlates with neutral particle analyzer measurements
- Large differences in heating split while threshold changes little 0.2<H/(H+D)<0.8 consistent with density sufficiently high for energy exchange to dominate over energy deposition

- Helium concentration measurements from both divertor spectroscopy and core charge exchange
- Core helium profiles are peaked
- Edge CX results scale consistently with divertor measurements



This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.