EUROfusion

Implications of JET-ILW L-H Transition Studies for ITER

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Presented by

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Contributors

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Summary

- Extrapolating L-H transition threshold power remains a significant uncertainty for ITER

- Database of JET-ILW L-H power threshold measurements is consistent with the leading trends from multi-machine studies, but shows specific effects that may be important for ITER

- Experimental results and modelling for:
  - Effect of divertor configuration
  - Isotope effect
  - Ion and electron heat fluxes
  - Power threshold in mixed ion species plasmas

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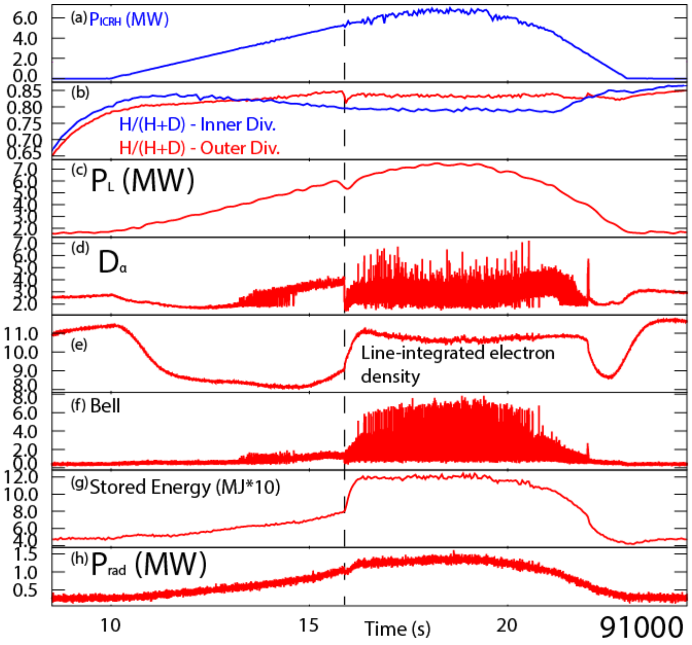
Measuring and quantifying P_{L-H}



B_t=1.8 T, I_p=1.7 MA

- Slow power ramps of ICRH and/or NBI used to identify $P_{L\text{-}H}$
- Transition usually clear in D_α and interferometer density time traces
- Thermal loss power variation over an energy confinement time before transition used to determine uncertainty
- Tomographic reconstruction completed for subset of data set, scales with direction estimate for P_{rad}, with a small offset

$$P_{\mathrm{L}} = P_{\mathrm{OHM}} + P_{\mathrm{abs}} - \mathrm{d}W/\mathrm{d}t - P_{\mathrm{Floss}}$$

$$P_{sep} = P_L - P_{rad}$$

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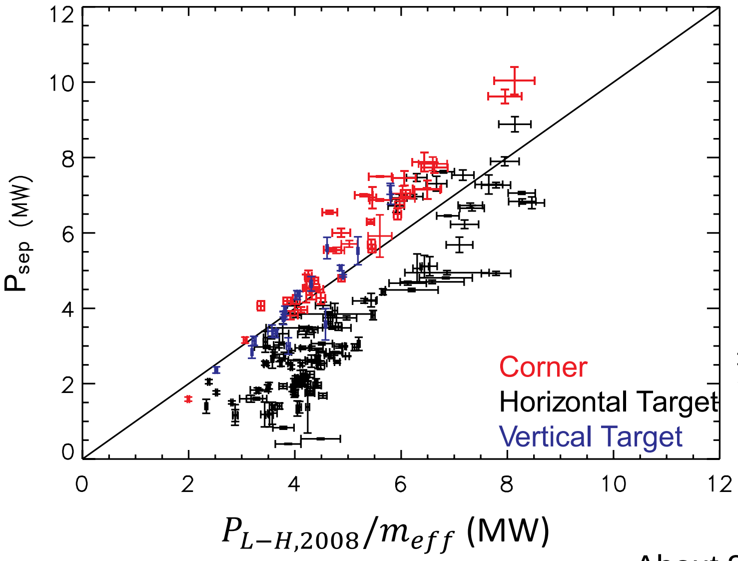
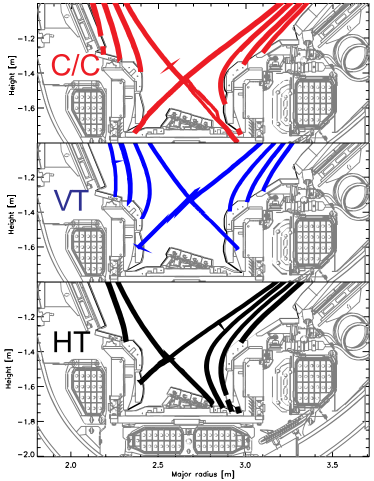
L-H Transition Database compiled including all JET-ILW P_{L-H} measurements





$$P_{L-H,2008} = 0.049\, B_t^{0.80} < n_e >^{0.72} S^{0.94}$$

Martin et al., Journal of Physics: Conference Series 123, 012033 (2008).

$$m_{eff} = 1, D$$
$$m_{eff} = 0.5, H$$

About 200 L-H threshold measurements in JET-ILW

- Hydrogen, deuterium, and mixed H/D plasmas
- Nitrogen, neon, and helium seeding
- B_t=1.8-3.4 T, I_p=1.7-3.2 MA, <ne>~1.5-5.0x10^{19} m^{-3}
- HT, VT, and C/C divertor configurations
- Mixes of ICRH and NBI heating

Deuterium, high density branch data used for regression analysis to determine scaling law for JET-ILW

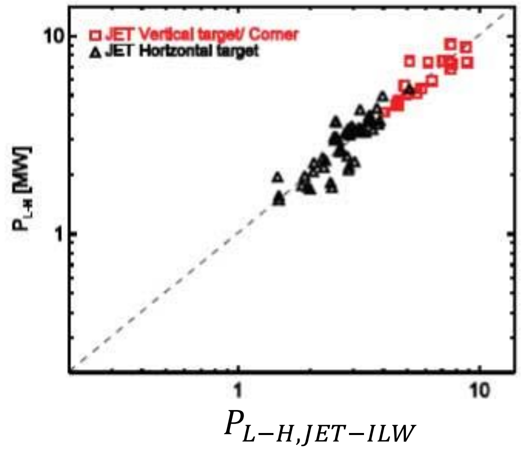
$$P_{L-H,2008} = 0.049\, B_t^{0.80} < n_e >^{0.72} S^{0.94}$$

$$P_{L-H,JET-ILW} = (0.046 \pm 0.009) B_t^{0.85\pm0.13} \langle n_e \rangle^{1.31\pm0.09} d_{sp}$$

S^1 assumed

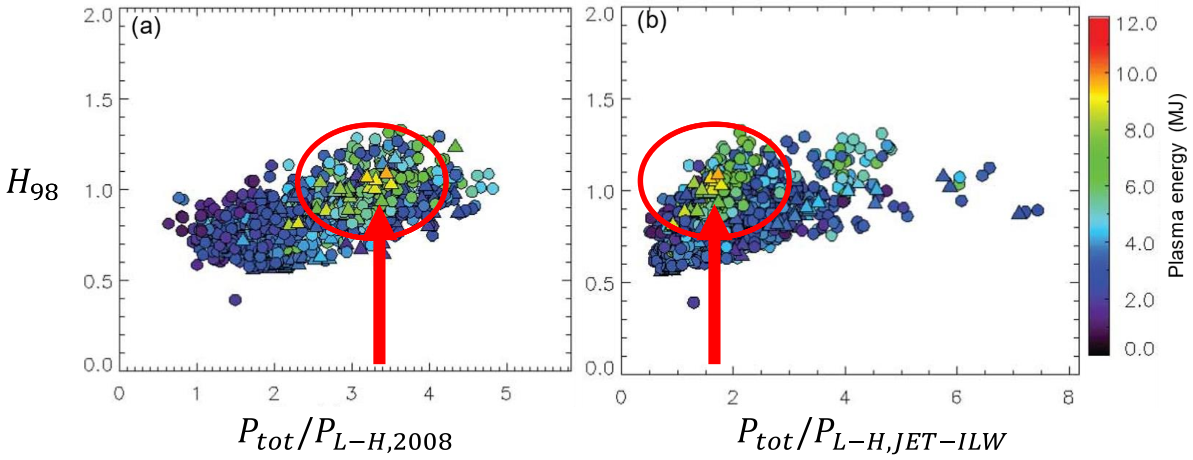
$d_{sp} = 1, HT$

$d_{sp} = 2.06, VT/Corner$



- Threshold reduced going from JET-C to JET-ILW for similar plasmas [Maggi et al., NF 54 023007 (2014)], but exponents for density and magnetic field are larger
- Introduction of *ad hoc* variable for strike point position necessary to capture divertor configuration effect

Using JET-ILW scaling law modifies interpretation of high performance plasmas



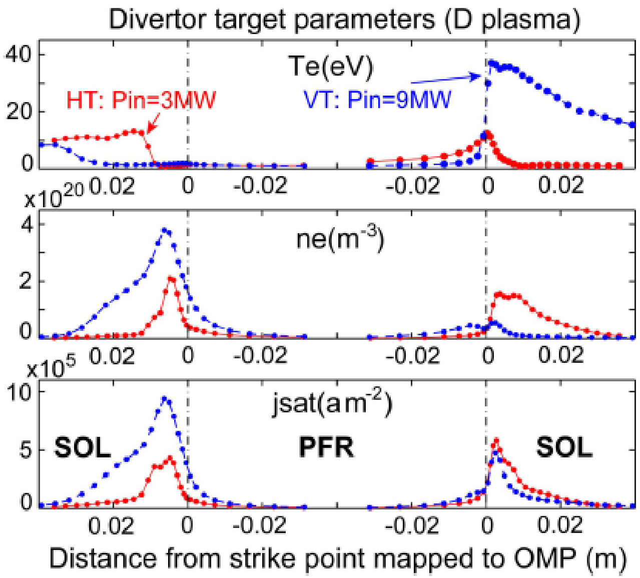
- Comparison of total input power to threshold power made over all deuterium pulses in JET-ILW pedestal database [Frassinetti EPS 2018]
- Note that in neither case is radiation subtracted, which would further reduce the power fraction
- Using JET scaling law changes high performance, high stored energy pulses from P_{tot}/P_{L-H} ~**3-4** to ~**1.5-2**, mostly due to divertor configuration effect and stronger scaling to high density

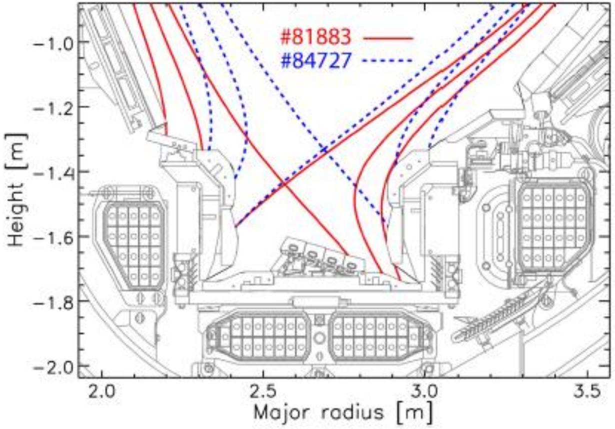
Outline

- Experimental results and modelling for:
  - **Effect of divertor configuration**
  - Isotope effect
  - Ion and electron heat fluxes
  - Power threshold in mixed ion species plasmas

Langmuir probe measurements show difference in target temperature prior to L-H transition

Measurements just prior to L-H transition with Langmuir probes:

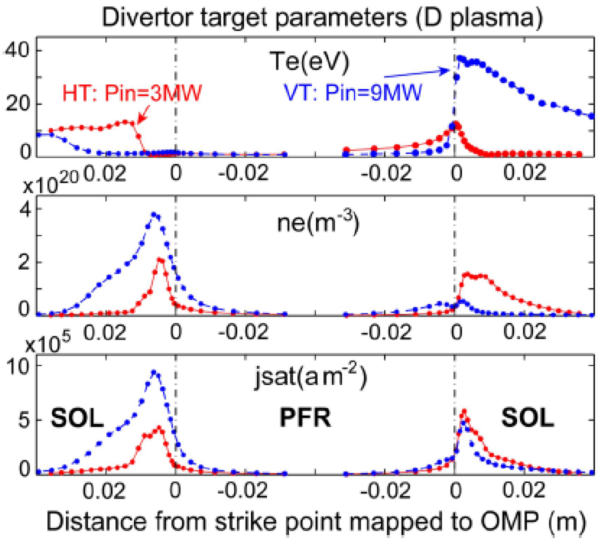




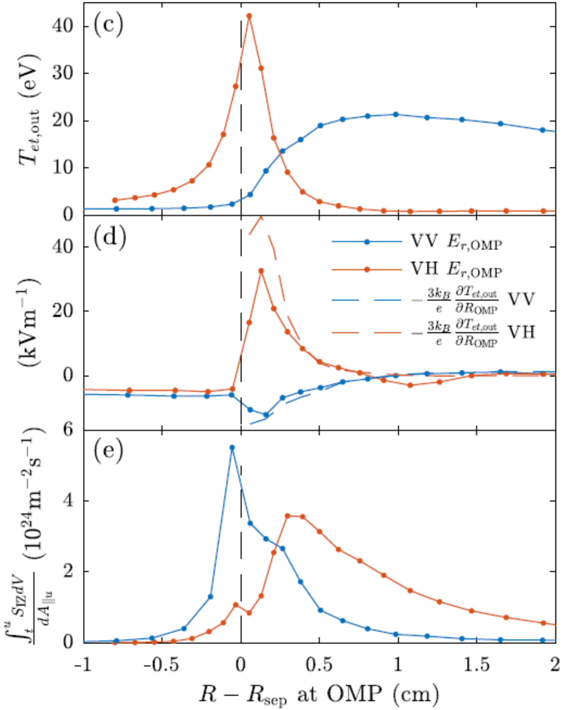
Chankin et al., PPCF 59, 045012 (2017)
Moulton et al., NF 58, 096029 (2018)

Edge fluid simulation with EDGE2D-EIRENE reproduce characteristics of Langmuir probe measurements

Measurements just prior to L-H transition with Langmuir probes:



EDGE2D-EIRENE simulations:



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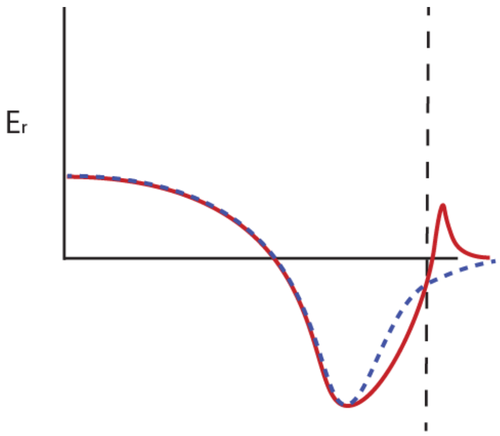
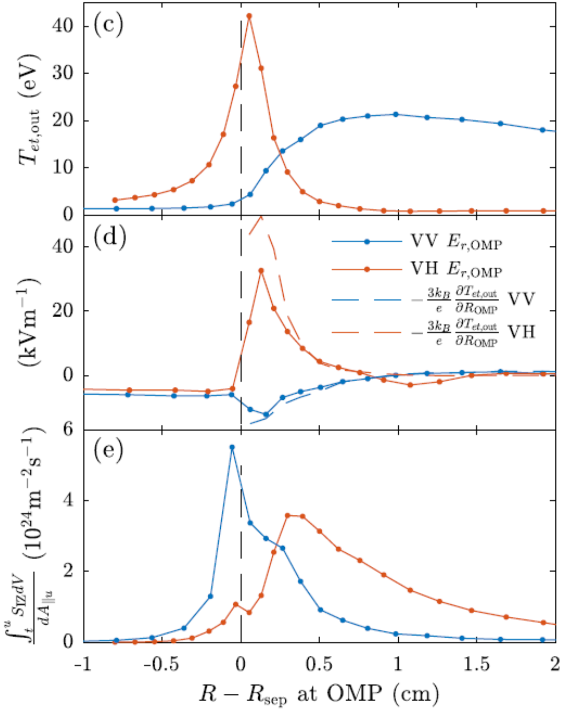
Edge fluid simulation with EDGE2D-EIRENE reproduce characteristics of Langmuir probe measurements



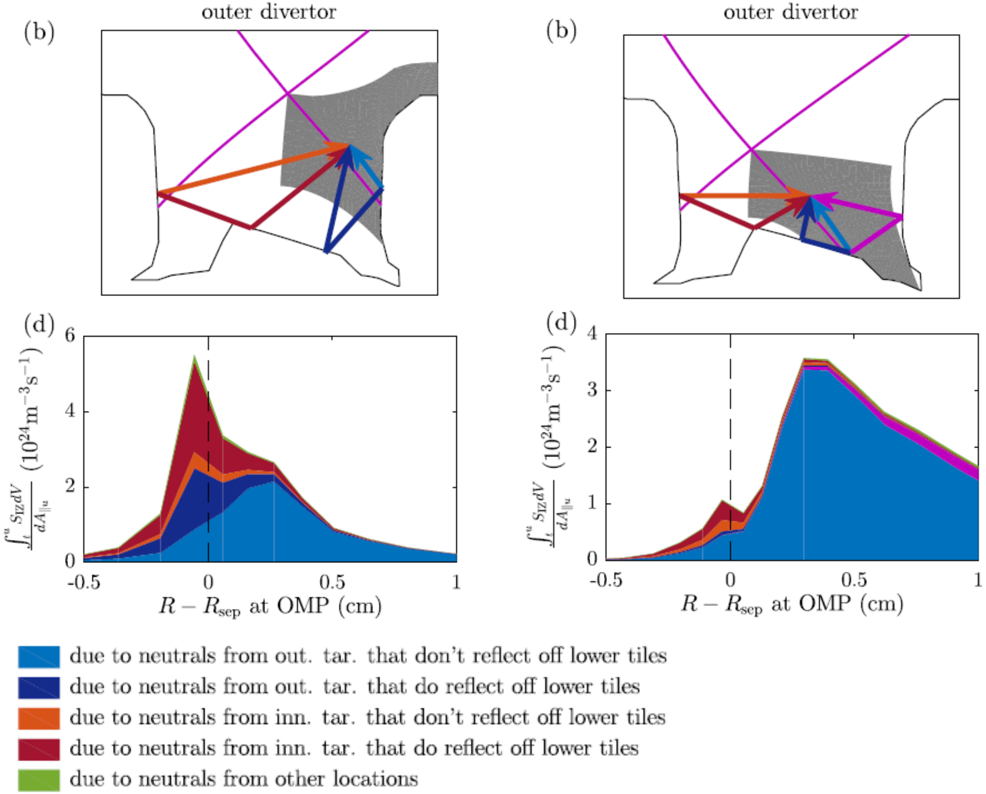
Change in near-SOL Er could affect boundary condition for Er well, edge Er shear, and requirements for achieving shear suppression at L-H transition

EDGE2D-EIRENE simulations:



Chankin et al., PPCF 59, 045012 (2017)
Moulton et al., NF 58, 096029 (2018)

Neutral pathways in divertor change flux tube averaged ionization source



Neutral reflections

Flux tube averaged ionization source

Chankin et al., PPCF 59, 045012 (2017)
Moulton et al., NF 58, 096029 (2018)

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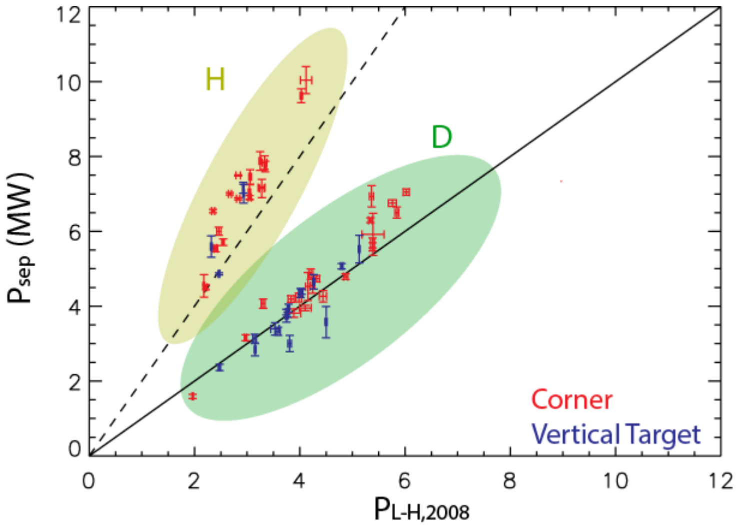
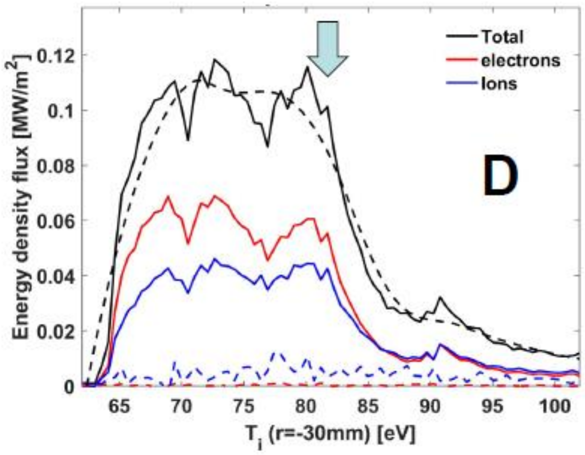
Isotope effect in Corner and VT configuration consistent with $1/m_i$ scaling

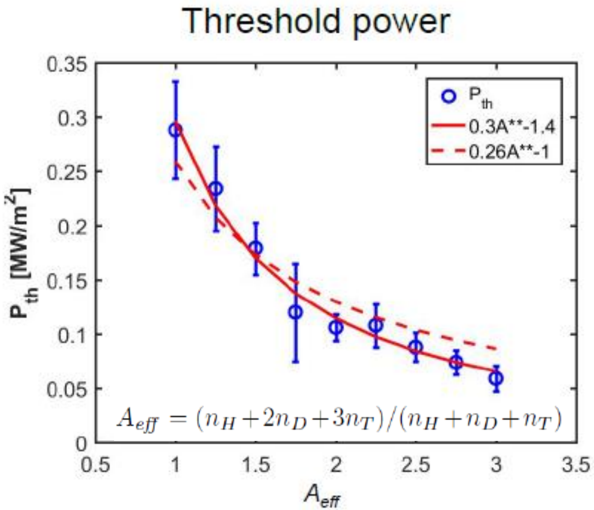


- Isotope effect on L-H threshold consistent with inverse mass scaling seen on multiple experiments
  - Right et al., NF 39, 309 (1999)
  - Gohil et al., ITR/P1-16, IAEA 2012
  - Ryter et al, PPCF 58, (2016)

- High performance JET scenarios planned for DT campaign use Corner configuration

Fluid turbulence simulations based on JET input parameters reproduce strong isotope scaling





- HESEL model*: energy conserving 4-field drift fluid model, slab geometry at outer midplane, connects confined plasma and SOL, with parallel losses in SOL, flux driven interchange turbulence
- Single ion species simulation with effective mass

*Nielsen et al., Phys. Lett A 79, 2097 (2015)
Rasmussen et al., PPCF 58, 014031 (2016)
Madsen et al., PoP 23, 0323006 (2016)
Rasmussen TTF 2018

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  - **Ion and electron heat fluxes**
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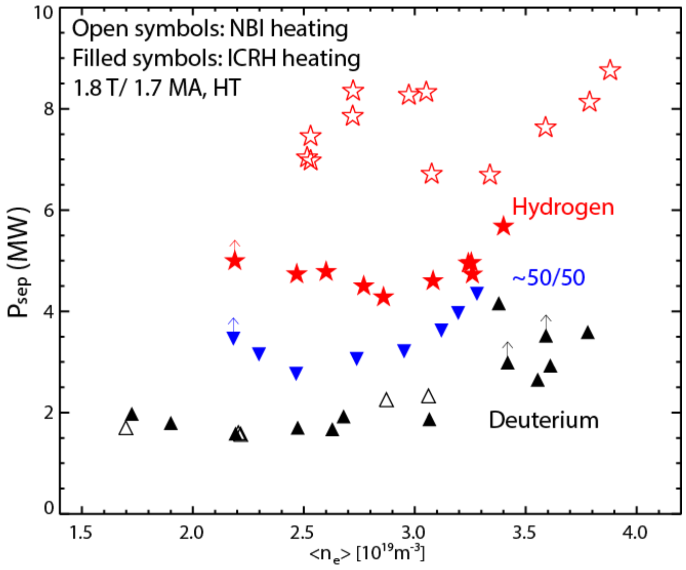
Strong dependence on heating source in hydrogen, but not deuterium for HT data



- Density minimum depends on isotope
- For ICRH heated plasmas, threshold in H about twice D, generally consistent with most past results
  - With NBI at low density, hydrogen can be as much as **4x** deuterium!
- Similar to DIII-D results [Gohil et al., NF 50, 064011 (2010)], threshold much higher in hydrogen with more input torque
- Differences at low density raise question of role of ion and electron heat fluxes:
  - Ryter et al, NF 53, 113003 (2013).
  - Ryter et al, NF 54 083003 (2014).
  - Ryter et al, PPCF 58, 014007 (2016).

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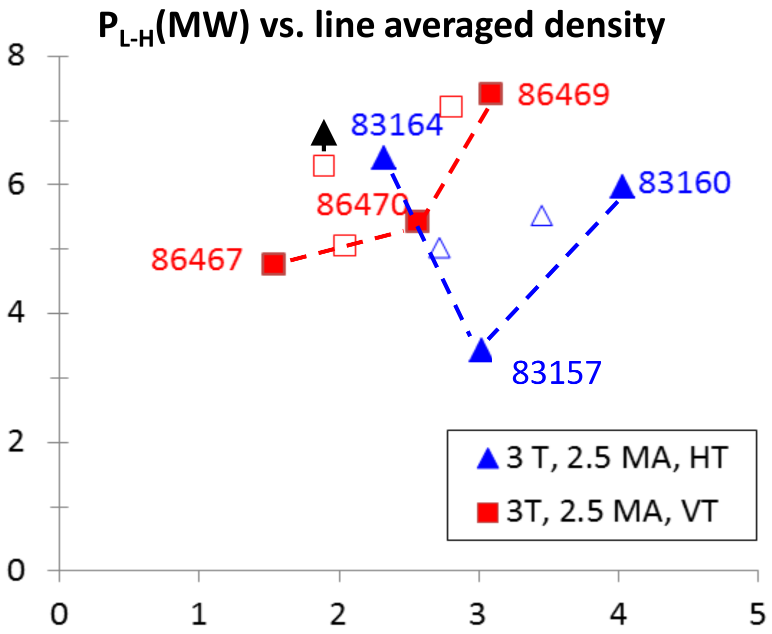
Two datasets chosen for detailed investigation of heat fluxes



- P_{L-H} departs from high density Branch scaling and exhibits a minimum, or flattening, as density decreases below $n_{e,min}$
- In JET, both P_{L-H} and the value of $n_{e,min}$ depend on plasma shape.
- We choose datasets at high field (3T) with NBI heating as the best case to study, because of the high threshold power and high fraction of ion heating

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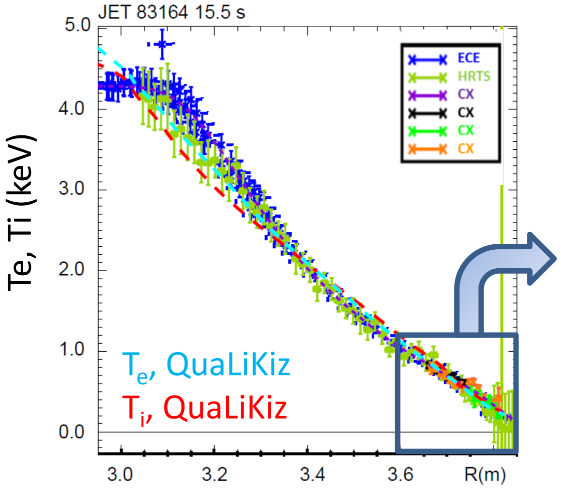
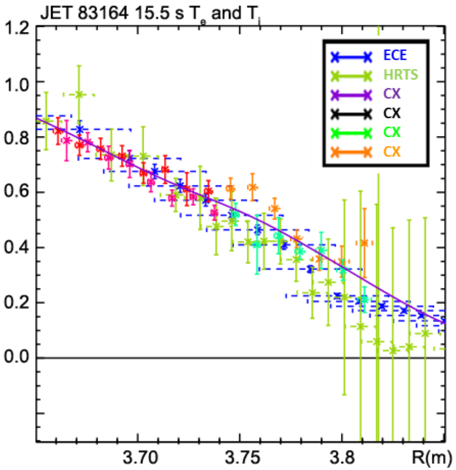
JETTO and Qualikiz used for modeling of ion and electron heat fluxes

- Ion temperature measurements in these plasmas not sufficient for interpretative transport calculations, so we use predictive JETTO+Qualikiz simulations:
  - First perform interpretative analysis assuming $T_i = T_e$
  - Using sources and sinks form interpretative run to perform predictive simulation of ion and electron profiles
  - On basis that predictive T_e profile matches experiment well, use predictive profiles for heat flux and energy exchange analysis
  - Since edge $T_e \approx T_i$, evaluate only up to $\rho = 0.85$





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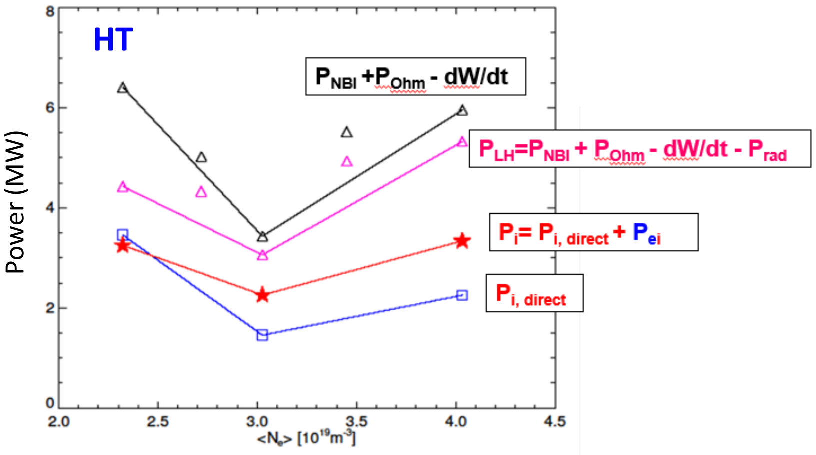
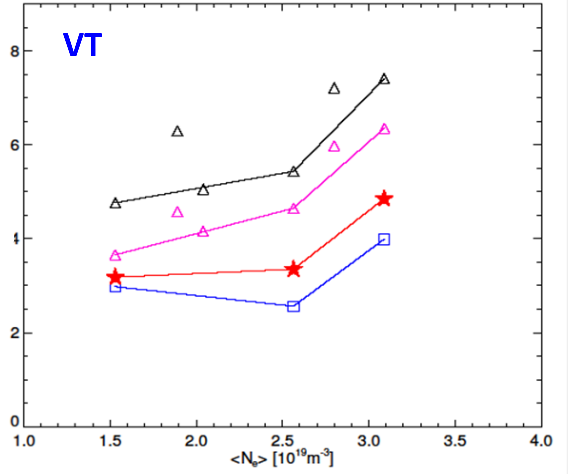
JETTO and Qualikiz used for modeling of ion and electron heat fluxes

$$P_{sep} = \underbrace{\overbrace{P_{NBI,i} + \mathbf{P_{ei}} - dW_i/dt}^{}}_{P_i} + \underbrace{P_{NBI,e} - \mathbf{P_{ei}} + P_{ohm} - dW_e/dt}_{P_e} - P_{rad}$$

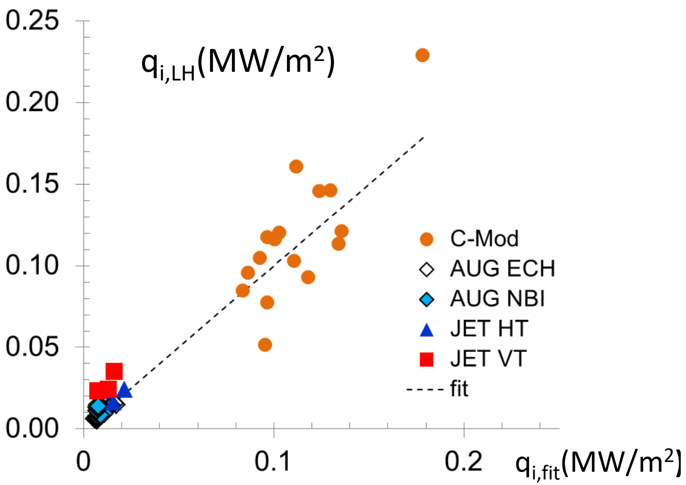
$P_{LH} = P_{NBI,i} + P_{ei} - dW_i/dt + P_{NBI,e} - P_{ei} + P_{ohm} - dW_e/dt$

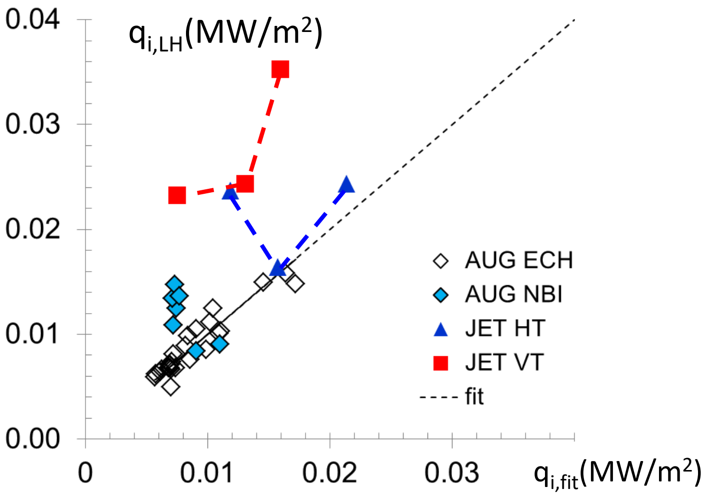
- Direct ion heating is dominant
- $P_{i,thr}$ is not proportional to n_e





JET results compared to AUG and C-mod





Combination of AUG(ECH) and C-Mod data used to produce a scaling law for $q_{ion,LH}$:

$$q_{\mathrm{i,fit}}^{\mathrm{LH}} = 0.0021\bar{n}_{\mathrm{e}}^{1.07\pm0.09} B_{\mathrm{T}}^{0.76\pm0.2}$$

C-Mod and AUG(ECH) data from *M. Schmidtmayr et al 2018 Nucl. Fusion* ***58*** *056003, courtesy of F. Ryter and J. Hughes*

- Divertor effect also present in ion heat flux analysis
- Departure from scaling in NBI heated plasmas may be related to rotation

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- Experimental results and modelling for:
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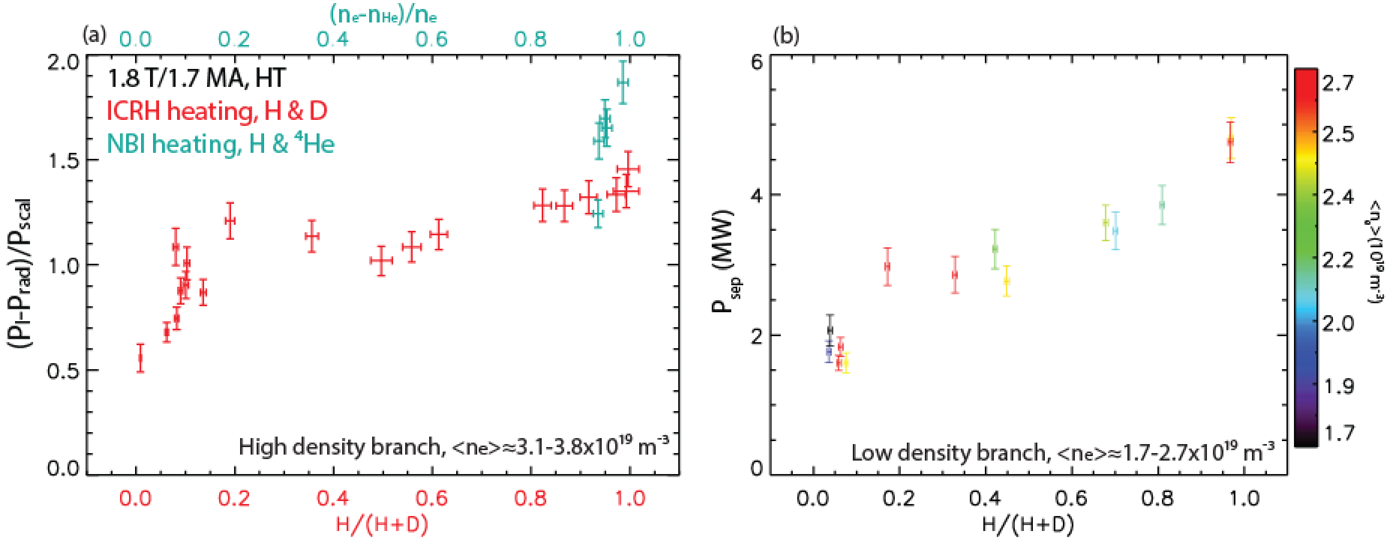
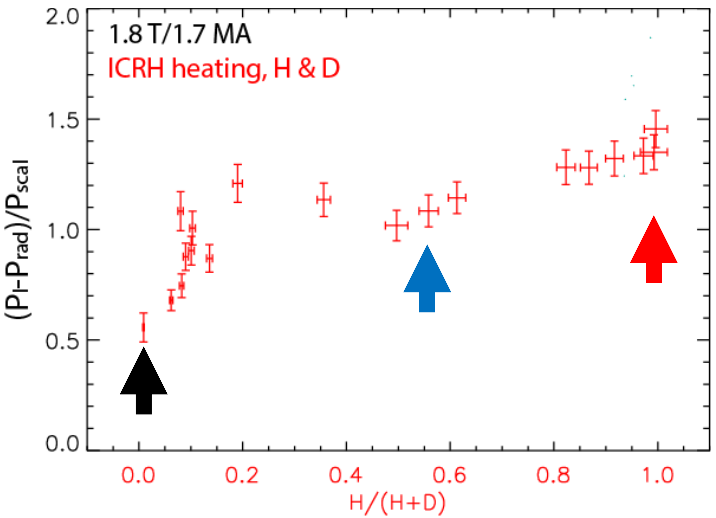
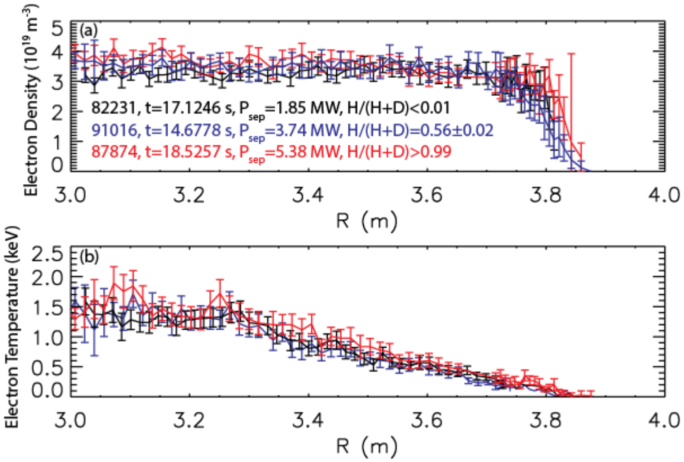
Non-linear dependence on concentration observed in mixed ion species plasmas



- Non-linear dependence observed in both high and low density branch, with relatively weak dependence over broad intermediate range of concentration values
- Reduction of threshold with helium in hydrogen plasmas provides route to lower threshold in pre-fusion power operational phase of ITER

Measured kinetic profiles just prior to L-H transition similar across H/(H+D) scan





- Electron temperature and density profiles similar prior to transition, implying difference in transport responsible for isotope effect
- Low electron temperature results is strong energy exchange
    - No ion temperature measurements available, but TRANSP simulations varying the T_i profile show $T_i \approx T_e$ within ~10% or energy exchange exceeds input power

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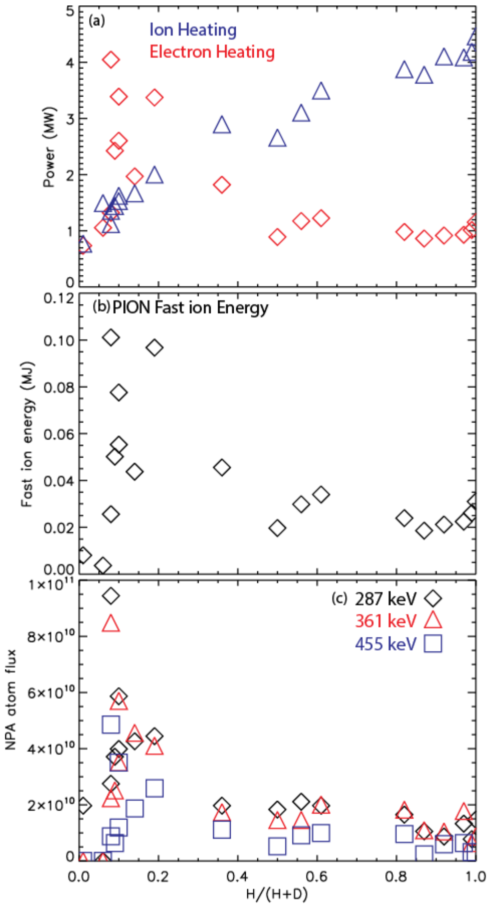
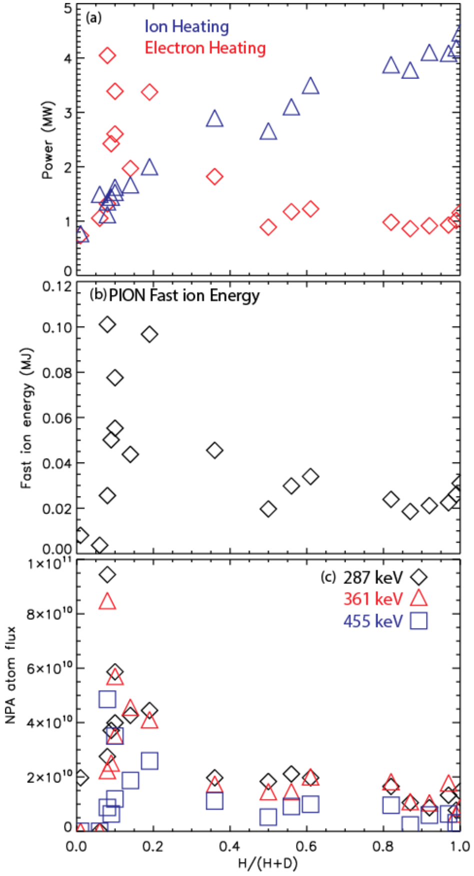
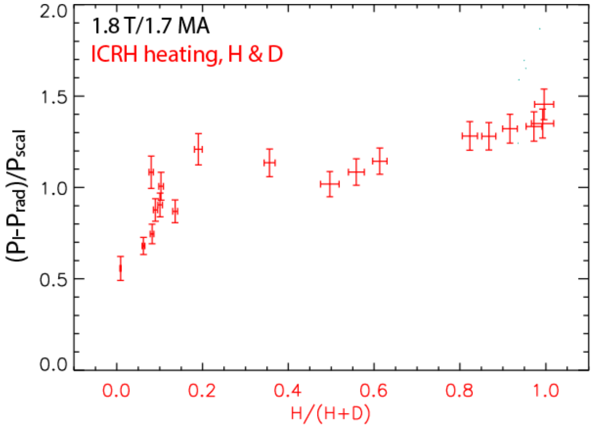
ICRH power deposition analyzed with PION for high density branch H/(H+D) scan



- Electron heating non-monotonic at low hydrogen concentration due to fast ion population produced by ICRH
  - Variation of predicted fast ion energy consistent with measurements from a neutral particle analyzer
- No peak at in P_{L-H} low H/(H+D) in threshold
- Similar threshold at H/(H+D)~0.2 and 0.6 despite large difference in heating fractions

ICRH power deposition analyzed with PION for high density branch H/(H+D) scan





- No peak at in P_{L-H} low H/(H+D) in threshold
- Similar threshold at H/(H+D)~0.2 and 0.6 despite large difference in heating fractions
- Transport and heating calculations show energy exchange dominates over heat deposition, so dependence cannot be explained on basis of difference in ion and electron heat fluxes with current data

Conclusions

- Largest uncertainty for extrapolation of power threshold to ITER is effect of divertor configuration
  - Differences in target temperature, which could change radial electric field near separatrix, qualitatively reproduced with EDGE2D-EIRENE simulations
  - Different observations from different experiments on X-point position, effect of pumping
- Strong isotope effect reproduced with HESEL simulations for single ion species plasmas, but does not reproduce observation of non-linear dependence in mixtures
- Predictive transport modelling with JETTO and Qualikiz show ion heat flux does not depend linearly on density, consistent with AUG NBI-heated pulses, and also exhibits divertor effect
- Experimental non-linear dependence of P_{L-H} in mixed species plasmas clear and provides route to lowering threshold in non-active phase of ITER, but we cannot explain observations with available data on basis of transport and heating calculations

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