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

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Presented by

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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
Measuring and quantifying $P_{L-H}$

- Slow power ramps of ICRH and/or NBI used to identify $P_{L-H}$
- Transition usually clear in $D_\alpha$ 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

\[ P_L = P_{\text{OHM}} + P_{\text{abs}} - \frac{dW}{dt} - P_{\text{Floss}} \]

\[ P_{\text{sep}} = P_L - P_{\text{rad}} \]

$B_t=1.8$ T, $I_p=1.7$ MA
L-H Transition Database compiled including all JET-ILW $P_{L-H}$ measurements

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


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

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, $<n_e>\approx 1.5-5.0 \times 10^{19}$ 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

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

\[ P_{L-H,JET-ILW} = (0.046 \pm 0.009) B_t^{0.85 \pm 0.13} <n_e>^{1.31 \pm 0.09} d_{sp} \]

- 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 \textit{ad hoc} variable for strike point position necessary to capture divertor configuration effect
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 $P_{\text{tot}}/P_{L-H,2008} \sim 3-4$ to $\sim 1.5-2$, 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:

- Divertor target parameters (D plasma)
  - Te(eV)
  - Ne(m⁻³)
  - Jsat(Å⁻²)

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.
Neutral pathways in divertor change flux tube averaged ionization source

Chankin et al., PPCF 59, 045012 (2017)
Moulton et al., NF 58, 096029 (2018)
• Experimental results and modelling for:
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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)

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

- 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

Rasmussen et al., PPCF 58, 014031 (2016)
Madsen et al., PoP 23, 0323006 (2016)
Rasmussen TTF 2018
• Experimental results and modelling for:
  • Effect of divertor configuration
  • Isotope effect
  • **ion and electron heat fluxes**
  • Power threshold in mixed ion species plasmas
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 54, 083003 (2014).
    - Ryter et al, PPCF 58, 014007 (2016).
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
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 $\rho = 0.85$
JETTO and Qualikiz used for modeling of ion and electron heat fluxes

\[ P_{\text{sep}} = P_{\text{NBI},i} + P_{e,i} - \frac{dW_i}{dt} + P_{\text{NBI},e} - P_{e,i} + P_{\text{ohm}} - \frac{dW_e}{dt} - P_{\text{rad}} \]

- Direct ion heating is dominant
- \( P_{i,\text{thr}} \) 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 $q_{\text{ion,LH}}$:

$$q_{i,\text{fit}}^{\text{LH}} = 0.0021 n_e^{1.07\pm0.09} B_T^{0.76\pm0.2}$$

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
Experimental results and modelling for:

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- Power threshold in mixed ion species plasmas
Non-linear dependence on concentration 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.
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.
• 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 \( P_{L-H} \) low \( H/(H+D) \) in threshold
• Similar threshold at \( H/(H+D) \sim 0.2 \) 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)$\sim$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