L-H transition and M-mode studies in JET-ILW
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• Power threshold (Pthr) to access H-mode remains a significant uncertainty in the design of fusion experiments, such as DEMO and ITER.
• 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.
• Pthr has been found to depend on non-trivial ways on isotope and species mix.
• There is a 2± variability in Pthr with plasma shape, identified, but not understood.

Slow power ramps to determine Pthr:
- Slow power ramps of ICRH and/or NBI steps used to identify Pthr.
- At JET the L-H is defined as the time from when the plasma stays in L-mode, nabs, and Tthr rise.
- Sometimes the L-H change can be subtle, "quasi-continuous transition". Sometimes there are differing transitions before the L-H transition proper. See discussion on M-mode below.

M-mode (or l-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, fluctuated by periodic expulsion of particles and energy from the pedestal, which occur as the plasma current centroid moves upwards (or the toroidal current near the X-point erodes)?

High density branch:
- differing transitions [4], then clean M-mode.
- M-mode seen during H phases of others.
- As power increases, type II, III and type ELMs can be mixed with M-mode, eventually ELM-free, as indicated by IELM.

- Data with ICRH, NBI, and mixed heating, compared, to ITPA 2008 [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 ELMs (NBI).

SCALING OF M-MODE FREQUENCY: isotope dependence

- Best ordering of data in M-mode phases with steady frequencies is achieved with poloidal Alfven velocity, $V_A^\parallel$, and $B_0$.
- $B_0$ dependency is observed in asymmetric modes (k=0).
- No available theory for this steady fluctuation: poloidal Alfvén wave.
- M-Mode frequency does not scale with sound speed or $V_{Te}$, it is not a GAM.
- In NBI plasma 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 distinguish normal mode frequency and vertical position control.

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Conclusions

- L-H power threshold in hydrogen in JET depends on heating method, but not 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, providing conclusions in a ion-ion selective M-mode during scan, 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 collision range.
- Strong reduction in threshold also observed for helium seeding in hydrogen plasmas. This may provide an avenue for lower H-mode access in the active phase of ITER operation.
- M-mode is identified and characterised. Its frequency scales with poloidal Alfven frequency. Further work required to analysed mixed isotope results.

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Latest Pedestal ITPA, TC-26:

JET-ILW compared to 2008 scaling

Non-linear dependence of $P_{IH}$ 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 at $0.2 < H/(H+D) < 0.8$
- Experiments at end of campaign for hydrogen-helium mixtures show drop of power threshold with helium seeding in hydrogen plasmas
- Heliium concentration measurements from both divertor spectroscopy and core charge exchange
- Core helium profiles are peaked
- Edge CX results scale consistently with divertor measurements
- Heating deposition to ions and electrons studied with PION
- $N=1$ minority $H$ at low $H/(H+D)$
- $N=2$ majority $H$ above $H/(H+D)\sim 0.1$
- 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

Latest Pedestal ITPA, TC-26: