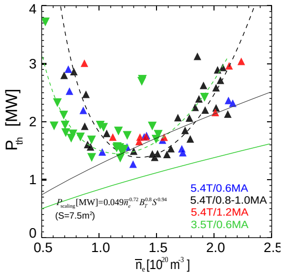
Study of H-mode Access in the Alcator C-Mod Tokamak: Density, Toroidal Field and Divertor Geometry Dependence

Y.Ma, J.W.Hughes, B.Labombard, A.E.Hubbard, R.M.Churchill, J.Terry, S.Zweben, E.S.Marmar, and the Alcator C-Mod team

Motivation: H-mode is envisioned as a potential baseline scenario for ITER plasma operation. Therefore, knowing the global H-mode threshold power and local plasma edge conditions for H-mode access is important. This poster presents a comprehensive study of H-mode access conditions on the Alcator C-Mod tokamak. All cases included in this study are deuterium plasmas, with the ion grad-B drift in the favorable direction for H-mode access, i.e. towards the active X-point. All H-mode transitions were induced with ICRF as the sole auxiliary heating power, configured in the fundamental hydrogen minority heating scenario.

1. Global H-mode threshold power (P_{th})

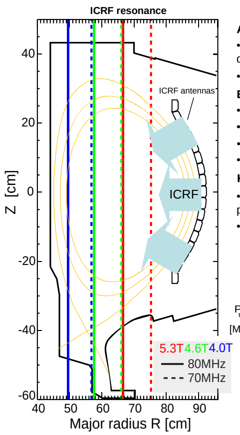
$P_{th}=P_{OH}+P_{aux}-dW_{plasma}/dt$, at the L-H transition time



Dependence of P_{th} on density, B_T, and I_p

- Studied using C-Mod L-H transition database [1], covering ITER relevant parameter ranges, in standard C-Mod LSN magnetic geometry
- Density dependence of P_{th} is U-shaped, with a local minimum
- No clear I_p dependence in P_{th}
- B_T dependence of P_{th} seen at low density, becomes weaker at higher density
- Densities for minimum P_{th}, n_{min}, reduced for lower B_T, confirming the speculation from an earlier multi-machine database analysis that n_{min}~B/R
- Large departures from scaling law predictions, especially at low and high density, and lower magnetic field
- Behavior of P_{th} is complex, can be described by $P_{th}\sim n_e^x B_T^y I_p^z$

[1] Y.Ma *et al.* Nucl.Fusion 52 023010 (2012).



Dependence of P_{th} on ICRF resonance location

An ITER-relevant Issue:

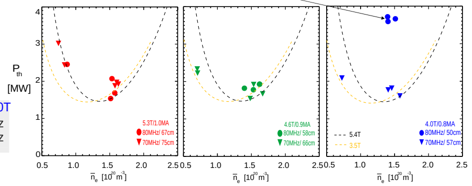
- ITER will use combination of multiple heating methods, each may have different power deposition profiles
- Dedicated C-Mod experiment studying the dependence of P_{th} on ICRF resonance location

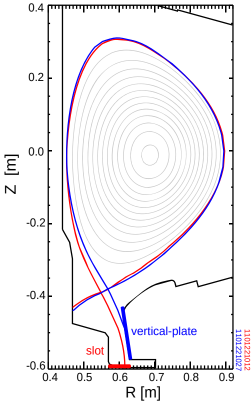
Experimental Setup:

- Use two-frequency (80 and 70MHz) ICRF antennas, B_T also scanned
- Single-frequency (80 *or* 70MHz) ICRF waves injected in each discharge to induce H-mode
- ICRF resonance locations shifted in *R*, scanned at four locations (left figure)
- Standard C-Mod LSN magnetic geometry, n_e=0.7-1.7e20

Key Results:

- P_{th} is *not* affected by ICRF power deposition location, unless ICRF resonance is placed in plasma edge near the inner wall (R_{res}=50cm, as in the left figure)
- Significant increase (~2MW) in P_{th}, possibly due to a degradation in ICRF power absorption





Dependence of P_{th} on divertor geometry

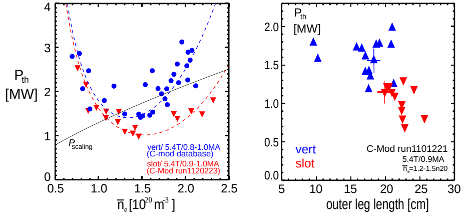
Divertor/X-point configuration can strongly influence P_{th}, dedicated C-Mod experiments [2] conducted to study the effect of divertor geometry on P_{th}

Experimental Setup:

- Performed in vertical-plate vs. slot divertor (normally, C-Mod is operated with the vertical-plate divertor), by varying the outer separatrix strike point location
- 5.4T/0.9-1.0MA, ICRF on-axis heating

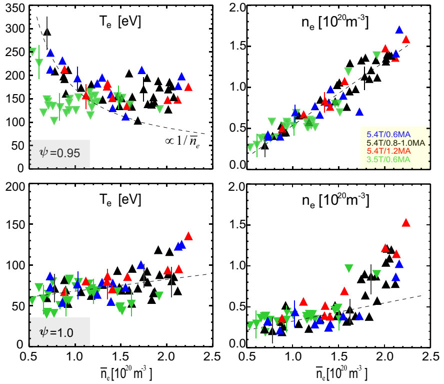
Key Results:

- Significant (>50%) reduction in P_{th} when plasma is operated with the slot divertor, at moderate and high density; this effect disappears at low density
- Density scaling of P_{th} remains U-shaped with slot divertor
- Reduction in P_{th} best correlate with outer leg length, or LFS SOL connection length



[2] Y.Ma *et al.* Plasma Phys. Control. Fusion 54 082002 (2012).

2. Local edge conditions just before the L-H transition



Evaluated using Thomson scattering measured upstream (outboard midplane) T_e and n_e profiles, at two radial locations: ψ=0.95 and ψ=1.0 (ψ is the normalized poloidal flux)

Used to test models for L-H transition and P_{th}, bridge experiment and theories

ψ=0.95:

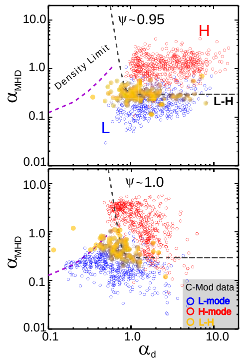
- T_e rises substantially at low density, becomes nearly independent of density at higher density
- Local n_e linearly correlates with line averaged density, independent of B_T
- T_e is lower at reduced B_T, at low density
- No clear I_p dependence in T_e and n_e

ψ=1.0:

- T_e~50-100eV, weakly depend on density, B_T, I_p
- Local n_e increases sharply (stronger than linear) at high density

Local L-H threshold conditions are not affected by ICRF power deposition or divertor geometry

More results about local L-H threshold conditions can be found in [1][2]



3. Comparison to the RDZ model for the L-H transition

- Two key parameters of the RDZ model [3]:

$$\alpha_{MHD}=\frac{2\mu_0 q^2 R}{B^2}\frac{d(P_e+P_i)}{dr}\qquad \alpha_d=\frac{1}{8\pi q}\left(\frac{2m_i}{m_e}\right)^{1/4}\left(\frac{\lambda_e}{\sqrt{RL_n}}\right)^{1/2}$$

- Based on numerical simulations of edge turbulence in a simplified shift-circular geometry (X-point, SOL, divertor not included), predicts local L-H threshold conditions as:

α_{MHD}=0.3-0.4, α_d=0.5-0.6 (an 'L'-shaped boundary)

- C-Mod experimental results show reasonable agreement with the RDZ model predictions [1]
- Suggest: enhancement in finite-beta effect (due to increasing pressure gradient)→ stronger nonlinear interaction between drift-waves and shear Alfvén-waves → trigger L-H

[3] B.N. Rogers *et al*. Phys. Rev. Lett. 81 20 (1998).

4. Comparison to the FM³ model for H-mode threshold power

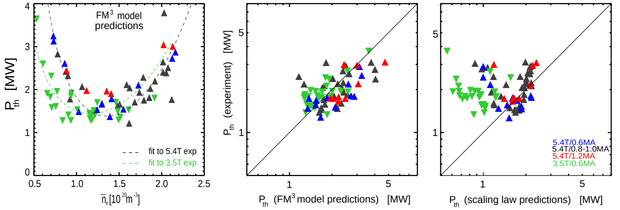
- The Fundamenski (FM³) model [4] predicts P_{th} based on edge-SOL physics
- The FM³ model gives asymptotic expressions for P_{th}

ν_{SOL}<<15: $P_{th}^{sh}=c_1 n_{e,sep}^{-2}B^3S^{-0.5}(a/R)^{9/2}\kappa^{0.75}A^2Z^{-9/4}q_{sep}^{-1.5}\nu_{SOL}^{-5}$

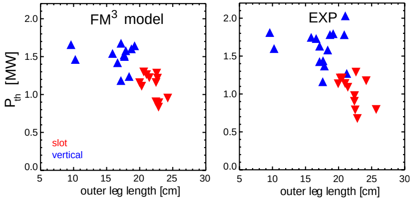
ν_{SOL}>>15: $P_{th}^{cd}=c_2(n_{e,sep}B/\sqrt{A}q_{sep})^{7/9}a^{16/9}\kappa^{0.5}q_{cyl n}^{5/9}Z^{2/3}\nu_{SOL}^{-5/9}/A^{1/9}$

ν_{SOL}: SOL collisionality

c_1 and c_2 are undetermined numerical factors resulting from the assumptions made by the model



- For mathematical simplicity: $P_{th}=P_{th}^{cd}+P_{th}^{sh}$
- c_1, c_2 difficult to determine from experiment, 'calibrate' the model to C-Mod 5.4T data→ best fit: c_1=120, c_2=20 → these values are fixed in the comparison
- Good agreement: reproduce the complex density and B_T dependence, no clear I_p dependence, consistent with experiment; quantitatively agreement also good
- A significant implication of the FM³ model: n_{min} at sheath-to-conduction limited regime transition (ν_{SOL}~10-15); this is also consistent with experiment



- The FM³ model also reproduces the divertor geometry effects
- Reason for the P_{th} reduction in slot divertor: longer connection length →higher ν_{SOL}→ lower P_{th}, since for the density range of this experiment, $P_{th,FM^3}\sim P_{th}^{cd}\propto\nu_{SOL}^{-5/9}$
- The agreement with the FM³ model is encouraging

[4] W.Fundamenski *et al*. Nucl. Fusion 52 062003 (2012).

Presented on the 24th IAEA FEC, San Diego, USA, 9/10/2012