Extending the boundary heat flux width database to 1.3 Tesla poloidal magnetic field in the Alcator C-Mod tokamak


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Motivations and Key Results

• “Eich” heat flux width scaling [1]:
  \[ \lambda_b \propto B_p^{0.5} \]
  \[ q_\| \propto P_{\text{loss}} B_0 / R \]

• Unmitigated parallel heat fluxes in reactor 
  \(-10 \text{GW/m}^2\) in reactor-class devices [2].
  “The result is that practically only the poloidal magnetic field is identified to be statistically important” [1].

• ITER 15 MA scenario at 50% higher \( B_p \) than maximum in database.
  C-Mod has been the only diverted tokamak operated at and above ITER-level \( B_p \).
  Major focus of C-Mod’s last campaign to characterize \( \lambda_b \) at reactor-level \( B_p \).

• Initial look at multi-machine H-mode scaling shows that it matches new C-Mod scaling

Database Extent and Confinement Regimes

Criteria: Good divertor heat flux profile from strike point sweep with low dissipation and relatively steady upstream conditions:

• \( \sim B_p^3 \) EDA H-mode (energy and particle transport barrier), all forward field (IF-PP drift to x-point), no ELMs
• \( \sim B_p^3 \) mode (only energy transport barrier), all reverse field (IF-PA drift away from x-point), no ELMs
• \( \sim B_p^2 \) mode (no transport barriers), half-and-half forward and reverse fields, no ELMs

• Wide range of engineering parameters, arrow range of shape due to need to keep strike point on sensors.

Poloidal Field Scaling Continues to ITER-Level \( B_p \)

• New C-Mod H-mode data extends beyond ITER (1.2 T)
  Inverse poloidal field scaling continues
  Lower scatter from probe measurements due to better resolution and improved analytic fitting equation

Comparison to Heuristic Drift Model and Simulations

• Heuristic Drift (HD) model assumes cross-field particle transport dominated by classical drifts in H-mode and sets \( \lambda_b \) [14]
• HD model fit multi-machine database well [15]
• New C-Mod data follows HD model as well
• However, L-mode has L-mode like particle confinement yet still follows HD model, which challenges transport assumption of HD model

Cross-Machine Scaling Indicates the Trend is Maintained

• Combine ITFA H-mode databases as first look at cross-machine scaling pressure-\( \lambda_b \) scaling
• Examine individual machines at high and low \( B_p \) values
• Take the maximum extent of heat flux widths from ITFA \( \lambda_b \)-database \( B_p \) plot (Fig. 3 in [12])
• Sort ITFA H-mode confinement database by \( B_p \), take mean volume-averaged plasma pressure \( \pm 5\% \) [13]
• Remarkable overlap of multi-machine data with C-Mod; should be extended to cross-confinement regime

Diagnostics, Measurements, and Profile Fitting

• IR thermography only heat flux diagnostic used in multi-machine ITFA database.
• IR on C-Mod has oblique view of outer divertor [3]
• Resolution estimated at \( \pm 0.5 \text{mm} \), same as projected \( \lambda_b \) at \( B_p = 1.2 \) [12] (mapped to outer mid-plane) [4]

• Extensive suite of probe-base sensors in divertor plate [5,6]
  • Shot-integrated energy flux benchmarked across sensors
  • Conservative resolution estimate \( \pm 0.05 \text{mm} \) (mapped to outer mid-plane)

Cross-Region Pressure Scaling: \( \lambda_b \) [mm] \( \approx 1 / \sqrt{p} \) [atm]

• Across regimes, \( \lambda_b \) scales with inverse square-root of core plasma pressure (“stored energy”)
• Non-hybrid shots, no ITBs, only ETBs
• L-mode: intermediate core pressure and \( \lambda_b \)
  Simple rule-of-thumb:
  \[ \lambda_b \approx 1 / \sqrt{p} \text{[atm]} \]
• Or, in SI units:
  \[ \lambda_b \approx 10 \div \sqrt{p} \text{[mm]} \]
• Same core pressure and \( \lambda_b \) over a wide range of poloidal magnetic fields.
• Direct link between physics setting core and boundary cross-field physics.
• Marginal stability from core, through pedestal, and to divertor?

• Similar trend seen previously at C-Mod
• Heat flux widths decrease with increased stored energy over much smaller range, trend was less clear [8]
• Overlap of L- and H-mode in 2010, but forgotten [9]
• Links to results elsewhere
  • Increased confinement and decreased heat flux width in NSTX with \( L < 0.5 \) [10,11]
  • ADEXX-II (Hippel AUG talk at PSI)
• Connection between core and boundary confinement identified in C-Mod 20 years ago [12]