OV/2-5: Overview of Alcator C-Mod Results

Research in Support of ITER and Steps Beyond*

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High Field Research on the Path to Fusion Energy

- I-mode scalings, joint experiments and extrapolation
- Inter-ELM H-mode pedestal modes: direct detection of KBM
- Lower Hybrid RF improvement of pedestal pressure, global confinement
- Understanding interactions of LHRF with SOL Plasma
- Increased runaway loss, below the Connor-Hastie density limit
- Narrow SOL power channel and the ITER inner-wall design
- Looking to the future:
  - Solving the sustainment, exhaust and PMI challenges
  - The high field development to fusion energy utilizing high temperature superconductors
I-mode would be very favorable regime for burning plasma

- ELMy H-mode is ITER baseline
  - Challenged by ELMs
  - Some ELM suppression approaches reduce confinement
- I-mode exhibits H-mode energy confinement with no edge particle barrier
- ELMs not needed for density/impurity control
- Operational window:
  \[ P_{L-1} < P < P_{L-H} \]
  - window expands with \( B \times \nabla B \) drift away from X-point

A.E. Hubbard, et al., EX/P6-18
I-mode: Confinement does not degrade with input power

- C-Mod experiments show $P_{L-I} \propto n$, $\tau_E$ nearly indep. of $P_{in}$
- Very different from H-mode scaling
  - $\tau_E \propto P_{in}^{-0.7}$
  - or Stored Energy $\propto P_{in}^{+0.3}$
  - I-mode edge pedestal away from stability boundary, even at highest performance

A.E. Hubbard, et al., EX/P6-18
I-mode: Threshold independent of B; power window widens at high fields

- Overall approximate threshold scaling
  \[ P_{L-I} \sim n \times S \]
- C-Mod data indicate \( P_{L-I} \sim \) independent of B
- H-mode threshold increases with B
  - Strongly favors high B for I-mode
- May help explain narrow I-mode power windows on DIII-D and AUG
  - also seen at 2.8 tesla on C-Mod
- Favorable for prospects on ITER (B=5.3 T)

A.E. Hubbard, et al., EX/P6-18
H-mode Inter-ELM Pedestal: Evidence for KBM limiting pressure

- EPED model* predicts pedestal saturation at intersection of Peeling-Balloning and Kinetic Ballooning stability boundaries
- See direct evidence of KBM-like turbulence in pedestal when pedestal pressure saturates prior to ELM
  - plasma frame propagation in ion-diamagnetic direction, $k_\theta \rho_s \sim 0.04$
  - compatible with KBM, not microtearing

LH current drive efficiency improved at high line average density by reducing SOL density

- For $n_{\text{ave}} \sim 0.5 \times 10^{20} \text{ m}^{-3}$, LH current drive efficiency, $\eta = n_{20}IR/P = 0.25 \text{ A}\cdot\text{m}/\text{W}$, in line with simulations.
- Fast electron production and $\eta$ fall sharply at higher line average density; similar effects seen in other tokamaks.
- In C-Mod, this falloff, as well as the onset of PDI\(^1\), well correlated with $n_e$ in the SOL can be controlled by adjusting plasma current.
- High field side launch in double null would provide best possibility to control SOL parameters, minimize coupler PMI, and optimize wave physics to achieve high efficiency.\(^2\)

\(^1\)R. Parker, et al., EX/P6-17
\(^2\)B. LaBombard, et al., FIP/P7-18
Confinement improves with injection of LHRF into high-density H-modes

For these conditions: LHRF waves are not driving current and are not accessible to the core

up to 35% change in $H_{98}$ for 17% increase in $P_{\text{tot}}$

Pedestal Profiles

LHRF - ON
LHRF - OFF
Electron Scale Turbulence Coexists with Ion Scale Eddies

- Core electron heat transport still not well understood
  - very important for ITER and reactors
- Gyrokinetic simulations can underpredict \( \chi_e \)
- First GYRO simulations using realistic experimental profiles & mass ratio, with both ion and electron spatio-temporal scales, show:
  - electron scale turbulence can play dominant role
  - radially elongated ETG streamers \((k_\theta \rho_s \sim 6)\) coexist with ion-scale eddies

Runaway electron suppression requires much less density than expected from collisions

Very important issue for ITER
- Runaways must be quenched during disruptions
- Reaching densities required for collisional suppression challenges mitigation technologies and pumping system

ITPA joint experiments indicate challenge may be reduced
- Anomalous loss process(es) dominate (~5x reduction in required density)
- Mechanism(s) not yet identified

*J.W. Connor, R.J. Hastie, Nucl. Fusion 15 (1975) 415

R.S. Granetz, et al., EX/5-1
ITER inner-wall redesigned to deal with very narrow near SOL $\lambda_q$

- ITER inner wall originally designed assuming $\lambda_q = 50$ mm
- Measurements (JET, COMPASS, TCV, DIII-D) indicate narrow $\lambda_q$ in near-SOL
- Detailed measurements on C-Mod, at the ITER B fields, power density
  - mirror langmuir probe profiles with unprecedented detail
- near SOL $\lambda_q < 2$ mm
- ITER has redesigned inner wall PFC tile shape to accommodate

$T. Golfinopoulos, et al., EX/P6-19$
Key Challenges for the Future: Linked to High Magnetic Field (High Density, Power, Current Drive)

- **Exhaust/PMI**
  - Recent results project to very narrow power exhaust channel (~1 mm in ITER and DEMO)**
  - $q_{\parallel} \approx P_{\text{SOL}} B/R$
  - DEMO $\sim 4q_{\parallel}$ compared to ITER, plus steady-state*

- **Equally important:** efficient, low PMI, RF current drive and heating technologies that scale to DEMO must be developed
  - High field side launch promises enormous advantages (efficiency and quiescent SOL plasma)**

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** B. LaBombard, et al., FIP/P7-18

** R. Parker, et al., EX/P6-17
**ADX -- A high-power, advanced divertor national test facility, using Alcator magnet technology**

**Advanced Divertor Experiment**

- Development platform for Advanced Divertors
- Reactor-level $q_{||}$, $B$, plasma pressures

\[ P_{\text{sol}} \frac{B}{R} \sim 125 \]

=> above ITER, $Q_{DT} = 10$

operating point (90)

- Development platform for low PMI, efficient RF
- Inside launch LHCD
- Inside launch ICRF

B = 6.5 T

$I_p = 1.6$ MA

$R/a = 0.7/0.2$ m

**Vertical Target**

**X-point Target**

B. LaBombard, et al., FIP/P7-18
High Temperature/High Field Superconductors: Game-Changer for Fusion Energy Development

• Conventional (Nb$_3$Sn) superconductors limit field at the coil to ~14T
  – implies large burning plasma (and DEMO) designs, with B~5T at plasma
• Recent developments in high-temp SC technology (e.g. YBCO) dramatically opens the design space
• Doubling the field allows for smaller reactor design
  – more economical, and tractable steps
ARC*: 10 tesla superconducting FNSF/Pilot

- Emerging Technology
  - Combines high-field, high temp. YBCO SC technology with liquid blanket
- Superconducting JET at 10 tesla
  - Net electric production ~200 MW ($Q_{\text{eng.}} \sim 4$)
- 20 $^0$K magnet operation
  - Can incorporate joints with acceptable thermal losses
- Demountable coils
  - Eases maintenance, allows for core replacement
- Magnet R&D should start now

High-Magnetic Field Development Path

C-Mod → ADX → ITER

Jointed SC Magnet Development
C-Mod Presentations at FEC2014

- OV/2-5 E. Marmar: Alcator C-Mod: Research in Support of ITER and Steps Beyond, Mon. PM
- EX/2-3 D. Ernst: Controlling H-Mode Particle Transport with Modulated Electron Heating in DIII-D and Alcator C-Mod via TEM Turbulence, Wed. AM
- FIP/2-3 S. Wukitch: ICRF Actuator Development at Alcator C-Mod, Wed. AM
- EX/3-2 A. Diallo: Edge Instability Limiting the Pedestal Growth on Alcator C-Mod Experiment and Modeling, Wed. PM
- EX/5-1 R. Granetz: An ITPA Joint Experiment to Study Runaway Electron Generation and Suppression, Thurs. AM
- EX/P6-17: R. Parker: High Density LHRF Experiments in Alcator C-Mod and Implications for Reactor Scale Devices, Thurs. PM
- EX/P6-19 T. Golfinopoulos: New Insights into Short-Wavelength, Coherent Edge Fluctuations on Alcator C-Mod, Thurs. PM
- EX/P6-20 L. Delgado: Destabilization of Internal Kink by Suprathermal Electron Pressure Driven by Lower Hybrid Current Drive, Thurs. PM
- EX/P6-21 D. Whyte: New In-Situ Measurements for Plasma Material Interaction Studies in Alcator C-Mod, Thur. PM
- EX/P6-22 A. Hubbard: Multi-device Studies of Pedestal Physics and Confinement in the I-mode Regime, Thur. PM
- FIP/P7-18 B. Labombard: ADX: a High Field, High Power Density, Advanced Divertor Test Facility, Fri. AM