Overview of Research Results from the Alcator C-Mod Tokamak*

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OV/2-4, 27th IAEA Fusion Energy Conference, Ahmedabad, India, October 22, 2018

*Supported by the U.S. Department of Energy, Fusion Energy Sciences
Compact, High B Tokamak Physics

• C-Mod Completed Operations in 2016
  – 23 highly productive years
  – Many groundbreaking physics results
  – Analysis ongoing

• Pointing to a high field path for future
  – High Temperature, High Field Superconductors enable compact burning plasma and reactor concepts
Achieved World Record Core and Pedestal Plasma Pressures

High Performance: $n \leq 1.5 \times 10^{21}$; $T \leq 10$ keV; $\langle p \rangle \leq 2.1$ atm, $P_{\text{ped}} \leq 0.8$ atm

- All RF Auxiliary Heating & Current Drive
  - ICRF: $P \leq 6.5$ MW, 50 MHz to 80 MHz
  - LHCD: $P \leq 1.5$ MW, 4.6 GHz

- High Power Density: $PB/R \sim 100$ MW-T/m, $q_{||} \sim 3$ GW/m$^2$
- High-Z Plasma Facing Components
  - Vertical plate divertor

Compact/High B: $R=0.67m$; $a=0.22m$; $\kappa \leq 1.8$; $B_0 \leq 8T$

Pedestal Pressure to 90% of ITER Target$^{[1]}$

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$^{[1]}$Snyder, et al., IAEA FEC 2018 EX/2-4
ELM Suppressed I-mode High Energy Confinement Regime: Operating Window Widens at High B

- I-mode, primarily studied on C-Mod, has many attractive features:
  - High energy confinement, low particle/impurity confinement
  - Weak confinement degradation with power
  - No ELMs to challenge the divertor
- May be particularly attractive for the high B approach to reactors
  - H-mode threshold increases with B, suppressing the I- to H- transition at high power
- Some of the remaining challenges
  - Power handling and robustness to detachment
  - Scaling to burning plasma conditions

Also see Wilks, et al., IAEA FEC 2018, EX/P6-19; Happel, et al., EX/2-3
Super H-Mode: C-Mod Extends Validation of Predictions to ITER Relevant Pedestal Pressure, in All-Metal Machine[1]

- Low $\nu^*$, high temperature peeling-limited pedestal region predicted by theory[2], observed on DIII-D[3]
- Explored on C-Mod by transitioning to H-mode from low density, low impurity content I-mode target
- Excellent agreement between EPED predictions and experiment
  - Extended pedestal pressures to 80 kPa on final day of C-Mod operation; $T_{e-ped} = 2$ keV


Non-Inductive Lower Hybrid Current Drive is Challenging at High Density

- C-Mod results\(^{[1]}\) show anomalously low current drive efficiency and sharply decreased production of fast electrons at high density, high Greenwald fraction \(f_G\).
- Increasing \(I_p\) at fixed density (and thus lowering \(f_G\)) reduces the anomaly
  - Current drive efficiency matches model

\(^{[1]}\)Wallace, et al., Phys. Plasmas 2010
Non-Inductive Lower Hybrid Current Drive is Challenging at High Density

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Direct Measurement of Lower Hybrid Wave Electric Field Confirms Scattering near the Outboard Midplane[1]

- Measurements of $E_{\text{LH}}$ using Polarization Spectroscopy of Stark-split $D_\beta$ spectrum confirm that LH waves are not being absorbed in the SOL

- The waves are scattered near outboard midplane
- Full-wave 3D modeling consistent with scattering due to density fluctuations

Low Greenwald Fraction is not attractive for Power Reactors
Possible Solution: High Field Side Launch

- High-field side SOL is quiescent:[1]

- Wave accessibility and damping also expected to improved with HFS launch[2]

- Plan to test on DIII-D[3]

C-Mod Results Show that “Eich” Scaling\cite{1} for SOL Power Width Continues to the ITER Poloidal Field

\[ \lambda_q \text{ database Extended with Operation at 8 Tesla} \cite{2} \]


Original $\lambda_q$ Scaling Developed for H-mode
C-Mod Results\textsuperscript{[1]} show $\lambda_q \propto \text{Pressure}^{-1/2}$ for L-mode, I-mode and H-mode

Each confinement regime gives $\lambda_q \propto 1/B_p$, but with different constants of proportionality

Plasma Pressure unifies all the C-Mod results

\textsuperscript{[1]}Brunner, et al., Nucl. Fusion 2018; Brunner, et al., IAEA FEC 2018, EX/P6-9
Divertor Solutions Needed For Reactor Regimes

- Current experiments (and ITER) push to the limits of conventional vertical plate divertor
- New solutions will be needed for the ~5x bigger challenge anticipated in reactors
Advanced Divertor Concepts are being Developed:
Must be Tested at Ultra-High Power Density

Modeling shows great promise for the long-leg X-point target concept[1]

$P_{\text{rad}}$ and $T_e$ contours with $P_{\text{sol}}= 6$ MW ($PB/R = 70$ MW-T/m)

ADX is a DTT concept that can test many advanced divertor configurations[2]

[1]Umansky, et al., IAEA-FEC 2018 (TH/7-2)
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\[ P_{\text{rad}} \text{ and } T_e \text{ contours with } P_{\text{sol}} = 6 \text{ MW (PB/R = 70 MW-T/m)} \]

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Long-Leg Divertor Compatible with Reactor Concepts (e.g. ARC\(^2\))

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\[ \text{Prad and Te contours with Psol= 6 MW (PB/R = 70 MW-T/m)} \]
REBCO High Temperature/High Field Superconductor: Game-Changer for High B/Compact Fusion Energy Path

- Conventional superconductor (Nb$_3$Sn) limits maximum on-axis B to about 5 tesla (R/a \~ 3)
- Development of High-Temp Superconductors (HTS) opens the window for increased B
  - Field limit is no longer B at the coil, but engineering stresses instead
  - Higher T (~20 K) operation also has engineering advantages, and may allow for jointed coils
SPARC technical objectives:

- Burn D-T fuel
- $Q > 2$ (with headroom)
- $P_{\text{fusion}} > 50\text{MW}$
- Pulsed with 10s flattop burn (about $2 \times \tau_{\text{CR}}$)
- ~1,000 D-T pulses, >10,000 D-D full-power pulses
- ~1 hr D-T pulse repetition rate
- ~15 minutes between D-D shots

Desired Schedule:
3 yrs R&D (already started) + 4 yrs construction

Size of DIII-D/ASDEX-U, $B_0=12$ Tesla
The $H_{98}=1$ Confinement Projection Puts SPARC within the Footprint of the Existing Tokamak Database
Recent design concept for a compact, high field, reactor using HTS magnets
- incorporates long-leg X-point target divertor for power handling
- Joints in TF coil could dramatically ease maintainability
- About the size of JET, but at \( B_0 = 9.2 \) T
  - \( P_{\text{fusion}} \approx 525 \) MW
  - \( P_{\text{electric}} \approx 200 \) MW

Exciting Path for Fusion Energy

High-Field, High Power Density Plasma Science Experiments

- Alcator C-Mod
- ADX/DTT
- SPARC
- ARC Pilot Plant

Magnet and Fusion Technology, Burning Plasma
Related Presentations at 2018 IAEA FEC

**Tuesday Morning**
- E. Tolman: Conceptual design study for heat exhaust management in the ARC fusion pilot plant, FIP/P1-22

**Wednesday Morning**
- P.B. Snyder: High Fusion Performance in Super H-Mode Experiments on Alcator C-Mod and DIII-D, EX/2-4

**Wednesday Afternoon**
- T. Tala: Core Density Peaking Experiments in JET, DIII-D and C-Mod in Various Operational Scenarios Driven by Fuelling or Transport, EX/4-4

**Thursday Afternoon**
- D. Brunner/M.V. Umansky: Extending the Boundary Heat Flux Width Database to 1.3 Tesla Poloidal Magnetic Field in the Alcator C-Mod Tokamak, EX/P6-9
- T.M. Wilks: Access Requirements for Stationary ELM-Suppressed Pedestals in DIII-D and C-Mod Plasmas, EX/P6-19
- R.S. Granetz: Machine Learning for Disruption Warning on Alcator C-Mod, DIII-D, and EAST Tokamaks, EX/P6-20
- S.G. Baek: Observation of Efficient Lower Hybrid Current Drive at High Density on Alcator C-Mod, EX/P6-28

**Friday Morning**
- M.R.K. Wigram: Performance assessment of tightly-baffled long-leg divertor geometries in the ARC reactor concept, TH/P7-20

**Friday Afternoon**
- E.H. Martin/G.M. Wallace: Experimental Evidence of Lower Hybrid Wave Scattering in Alcator C-Mod Due to Scrape Off Layer Density Fluctuations, EX/8-2
- M.V. Umansky: Study of Passively Stable, Fully-Detached Divertor Plasma Regimes Attained in Innovative Long-Legged Divertor Configurations, TH/7-2
- M.G. Dunne: Impact of Impurity Seeding on Pedestal Structure in ASDEX Upgrade and Alcator C-Mod, EX/P8-2