Overview of High-Field Divertor Tokamak Results from Alcator C-Mod*

Earl Marmar
on behalf of the Alcator C-Mod Team
MIT Plasma Science and Fusion Center and Collaborating Institutions

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OV/2-5, 26th IAEA Fusion Energy Conference,
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Compact, High B Tokamak Physics

Alcator C-Mod

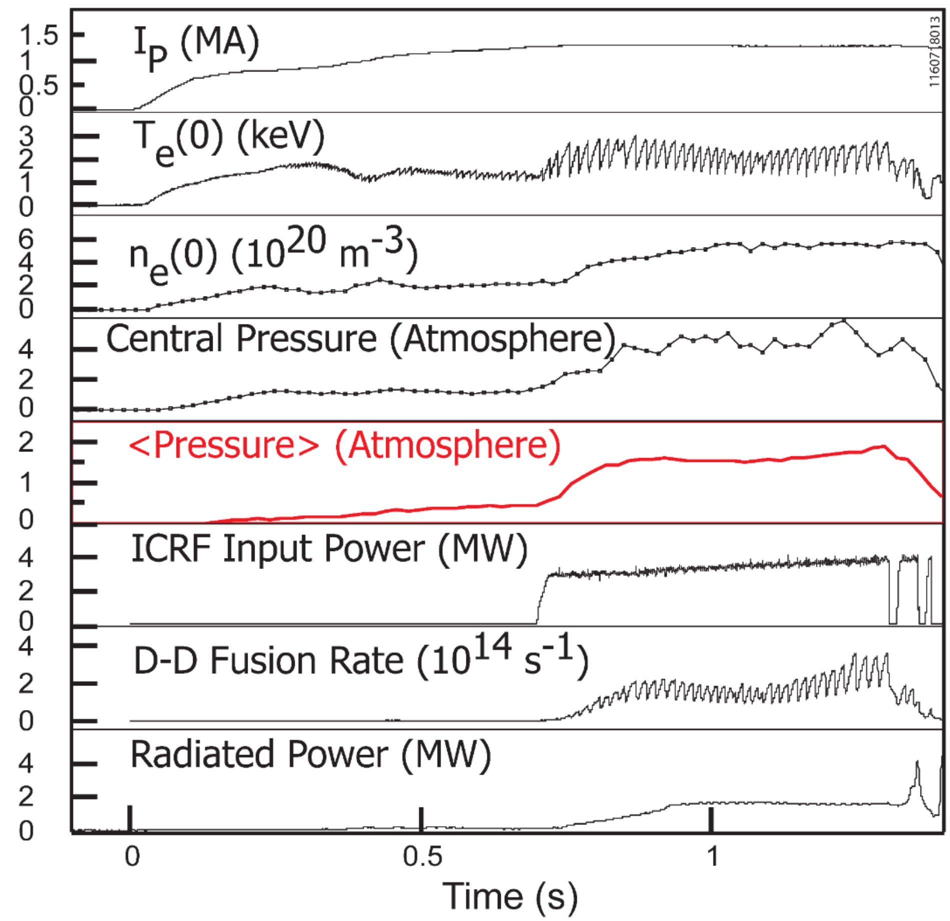
Very Productive 2015-2016 Experimental Campaigns

- Core and Pedestal Transport
  - ELM-less enhanced confinement regimes (EDA-H, I-mode)
  - Multi-scale gyrokinetic simulations
- ICRF: 3-ion mode conversion heating
- SOL and Divertor
  - feedback controlled detachment
  - Divertor Test Tokamak
- Compact, high magnetic field approach
  - Leverage high field, HTS superconductor technology
  - ARC Pilot Plant
- Completion of C-Mod operations in FY2016
  - Plasma pressure record
  - Plans

At High Field, C-Mod Naturally Accesses Enhanced Confinement with no ELMS

- EDA H-mode
  - Peeling-Ballooning stable pedestal, avoids damaging ELM heat pulses
    - Edge regulation through continuous (quasi-coherent) modes
    - τ_E and τ_{imp} comparable to ELMy H-mode

High Performance 5.4T EDA H-mode



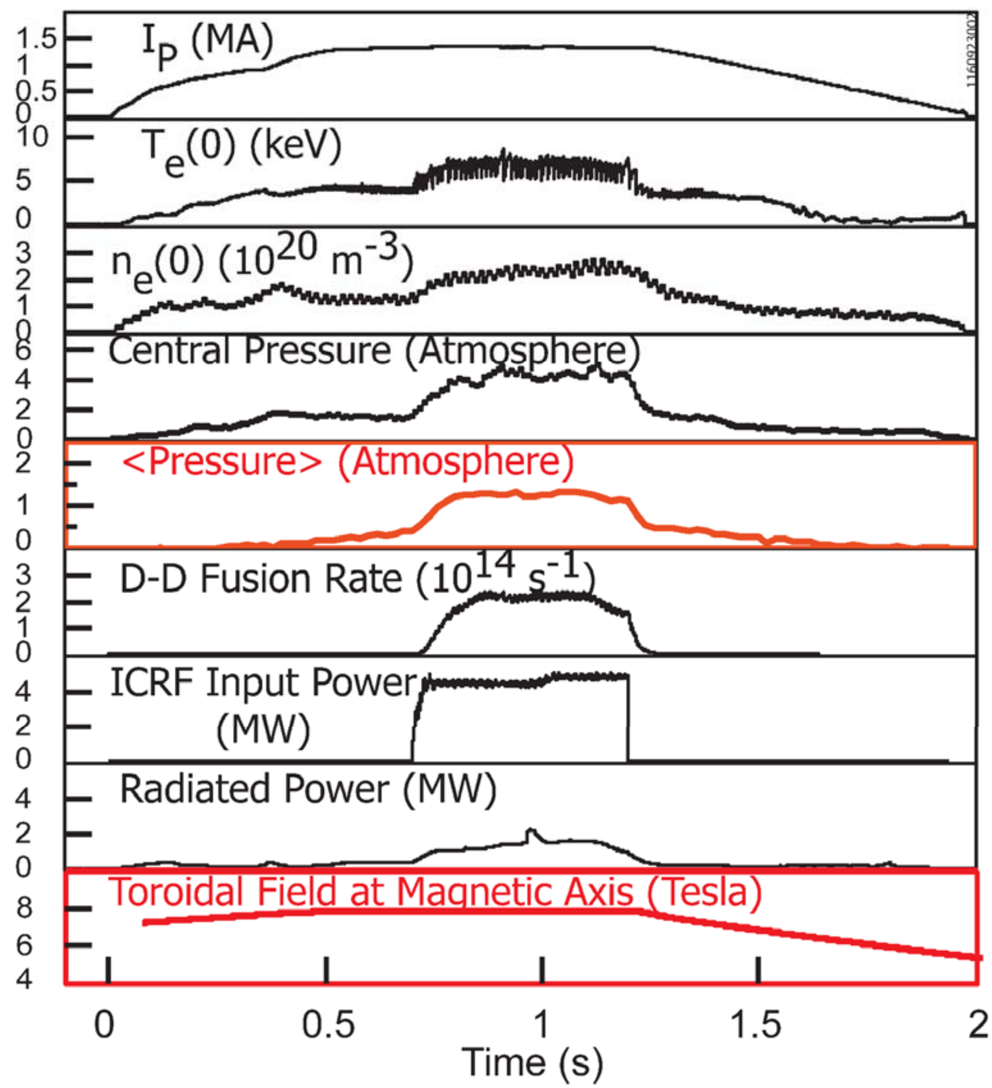
At High Field, C-Mod Naturally Accesses Enhanced Confinement with no ELMS

Alcator C-Mod

- I-mode*
  - H-mode energy confinement, L-mode density pedestal, low particle/impurity confinement
  - Edge regulation through continuous (weakly-coherent) modes/broadened by GAMs
  - Best access with ion ∇B drift away from active X-point
  - Highly attractive for fusion energy

***A. Hubbard EX/3-1**

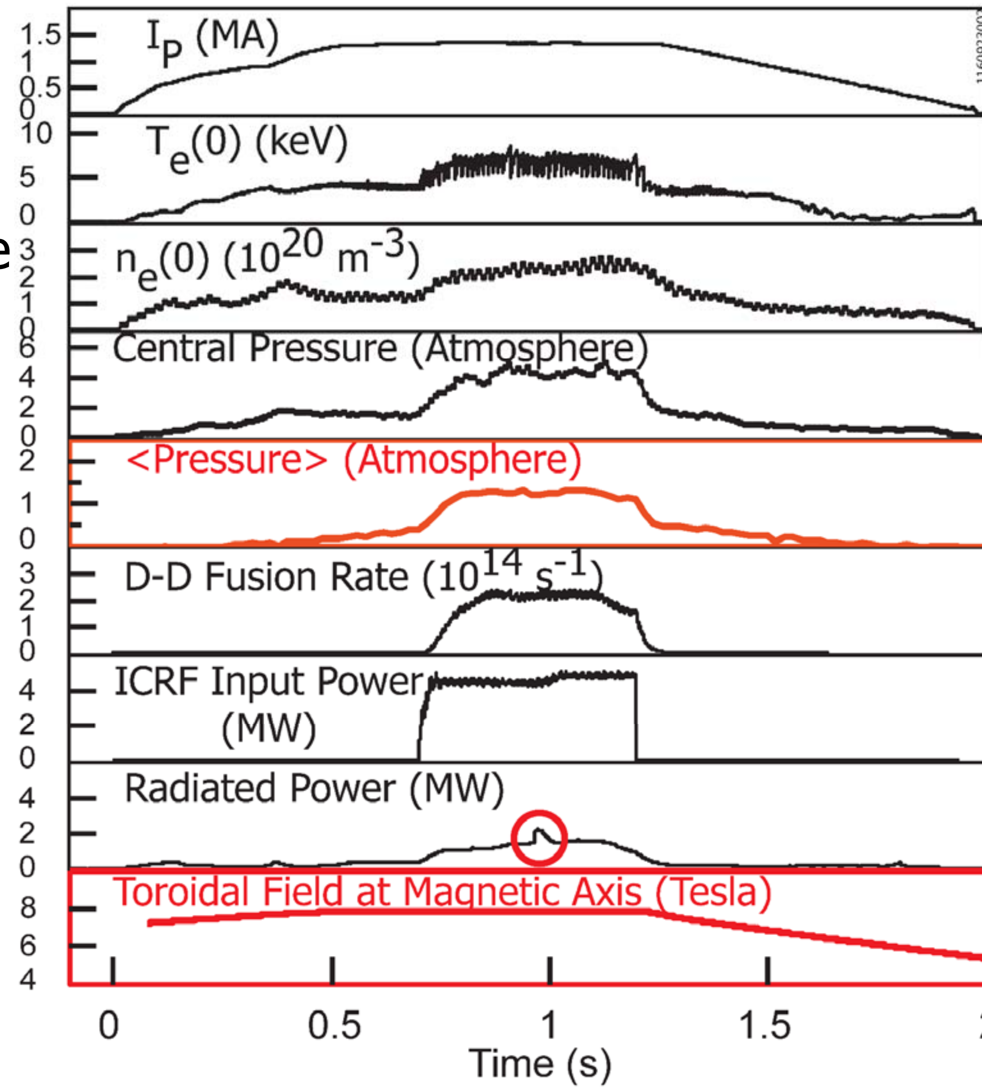
High Performance 8T I-mode: H_{98}~1



At High Field, C-Mod Naturally Accesses Enhanced Confinement with no ELMS

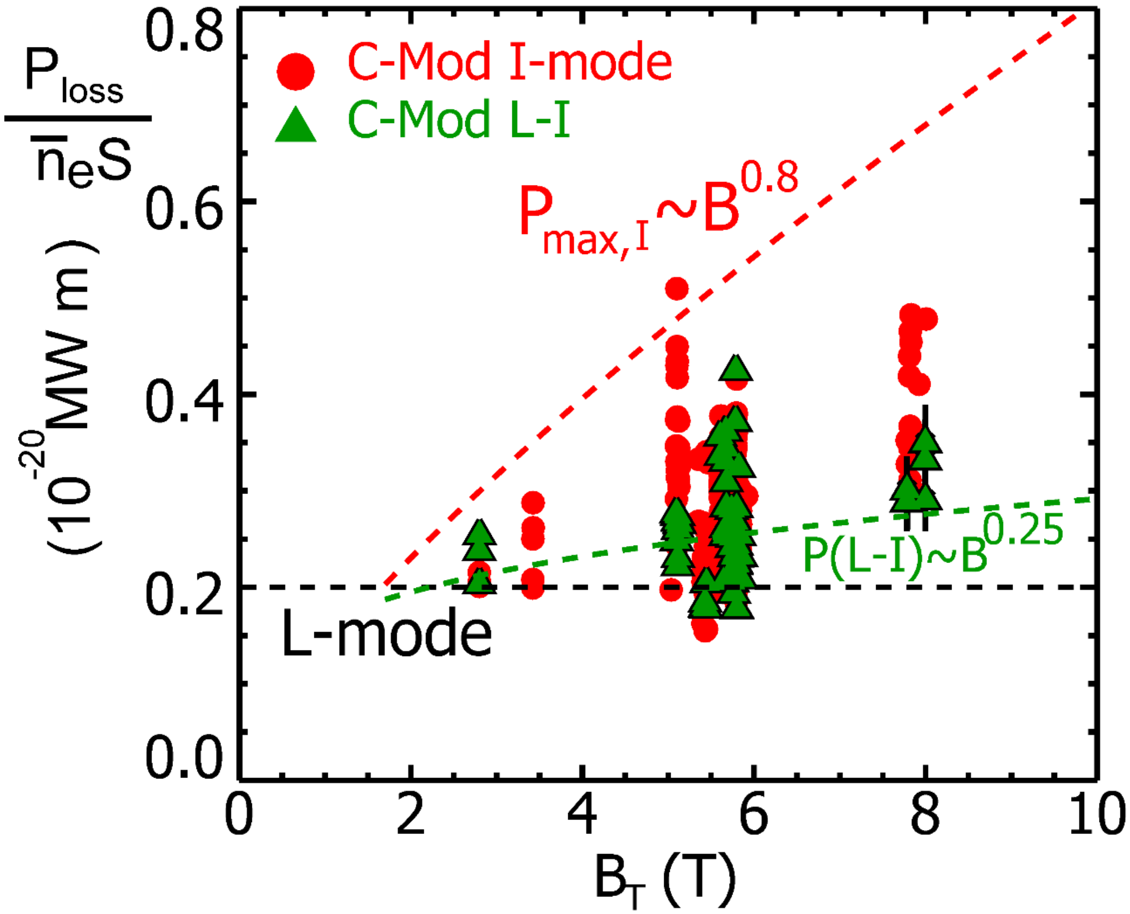
- I-mode*
  - H-mode energy confinement, L-mode density pedestal, low particle/impurity confinement
  - Stationary densities, which are readily controlled
  - Edge regulation through continuous (weakly-coherent) modes/broadened by GAMs
  - Highly attractive for fusion energy

High Performance 8T I-mode: H_{98}~1



***A. Hubbard EX/3-1**

8 T I-modes confirm & extend the promising trends with B_T



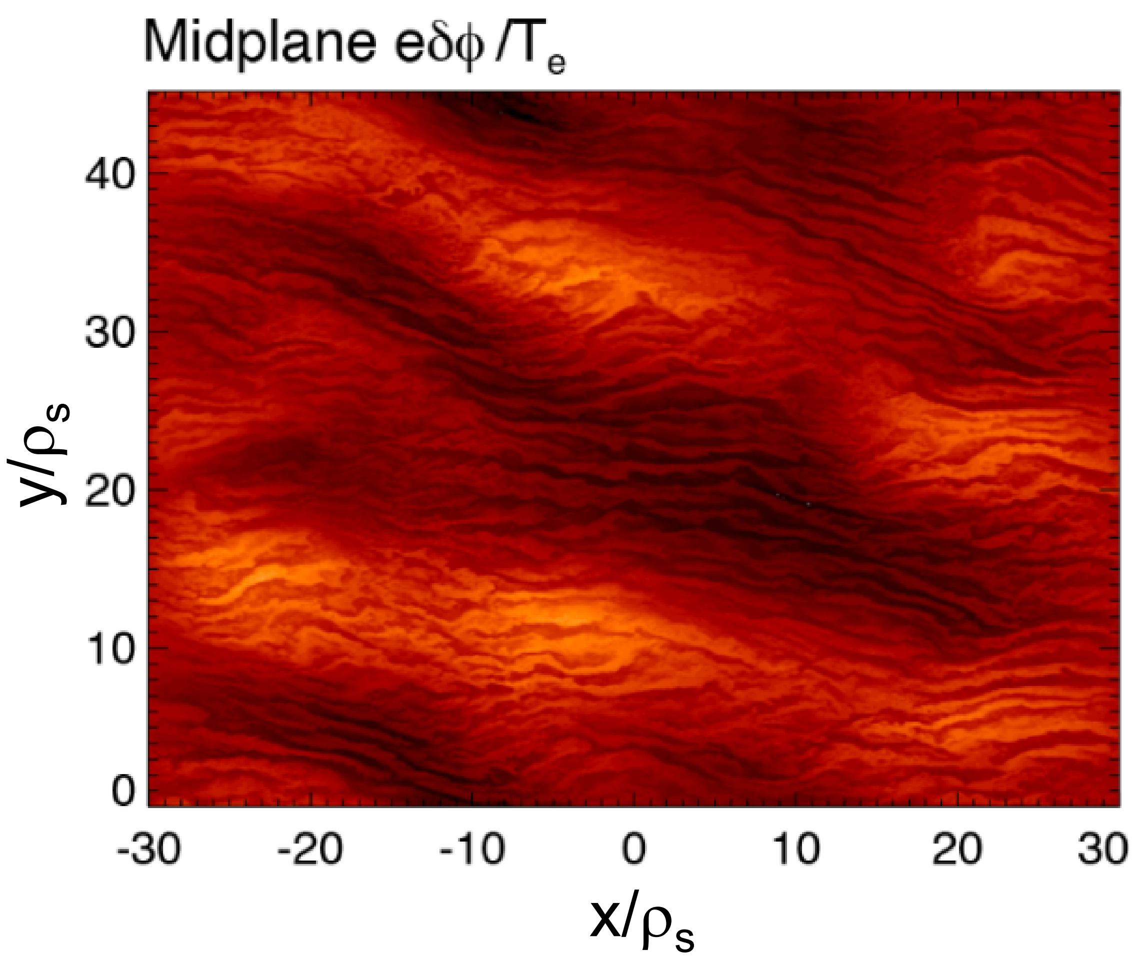
- $P(L\text{-}I) / n_e \sim B_T^{0.25}$
  - Weak B_T threshold dependence (agrees with ASDEX-U results)
- Power range at 8 T even larger than at ~5.5 T
  - No 8 T discharges had I-H transitions, up to maximum ICRF power (P_{tot}/S = 0.63 MW/m^2)

***A. Hubbard EX/3-1**

Multi-Scale Gyrokinetic Simulations Help Resolve Long-Standing Transport Puzzle*

Alcator C-Mod

- Gyrokinetic simulations incorporating only ion-scale turbulence shows shortfall in electron channel heat flux (esp. in reactor-relevant equilibrated e-i regimes)
- State-of the art multiscale simulations, including ion- and electron-scales simultaneously, show important interactions



**N.T. Howard et al., Phys. Plasma 23(2016)056109*

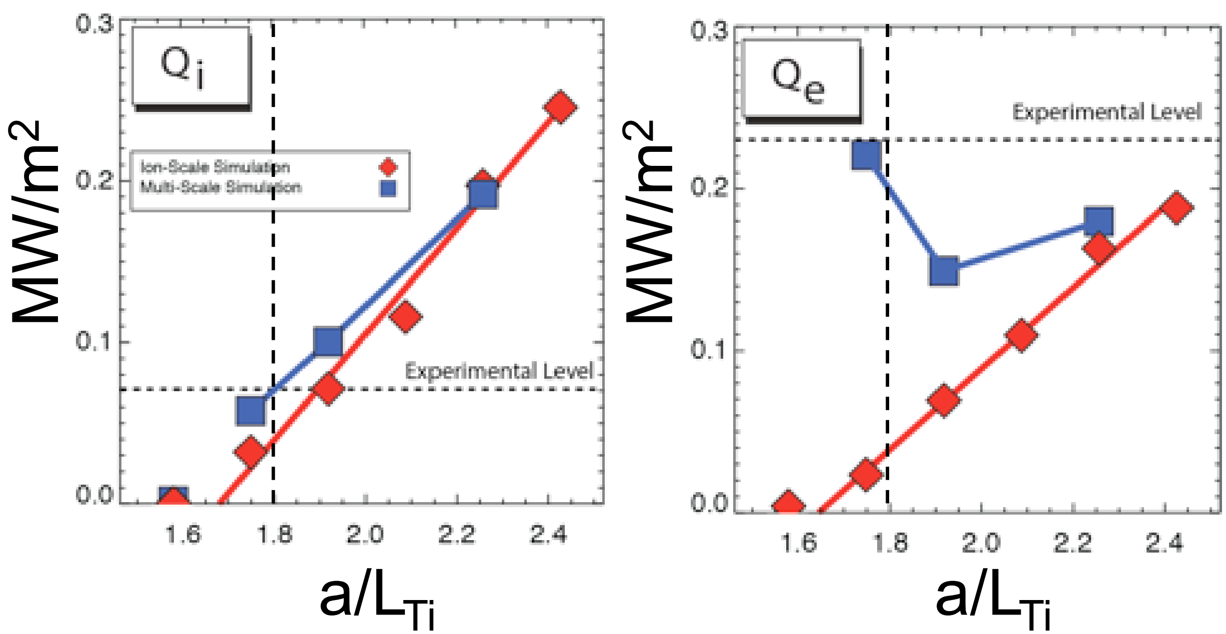
C. Holland TH/6-1

Multi-Scale Gyrokinetic Simulations Help Resolve Long-Standing Transport Puzzle*

Alcator C-Mod

- State-of the art multiscale simulations, including ion- and electron-scales simultaneously, show important interactions
  - Resolves Q_e discrepancy

Ion and Electron Heat Fluxes:
Ion-scale simulation in red
Multiscale simulation in blue



Particularly relevant for coupled ion-electron regimes (as on C-Mod and in reactors)

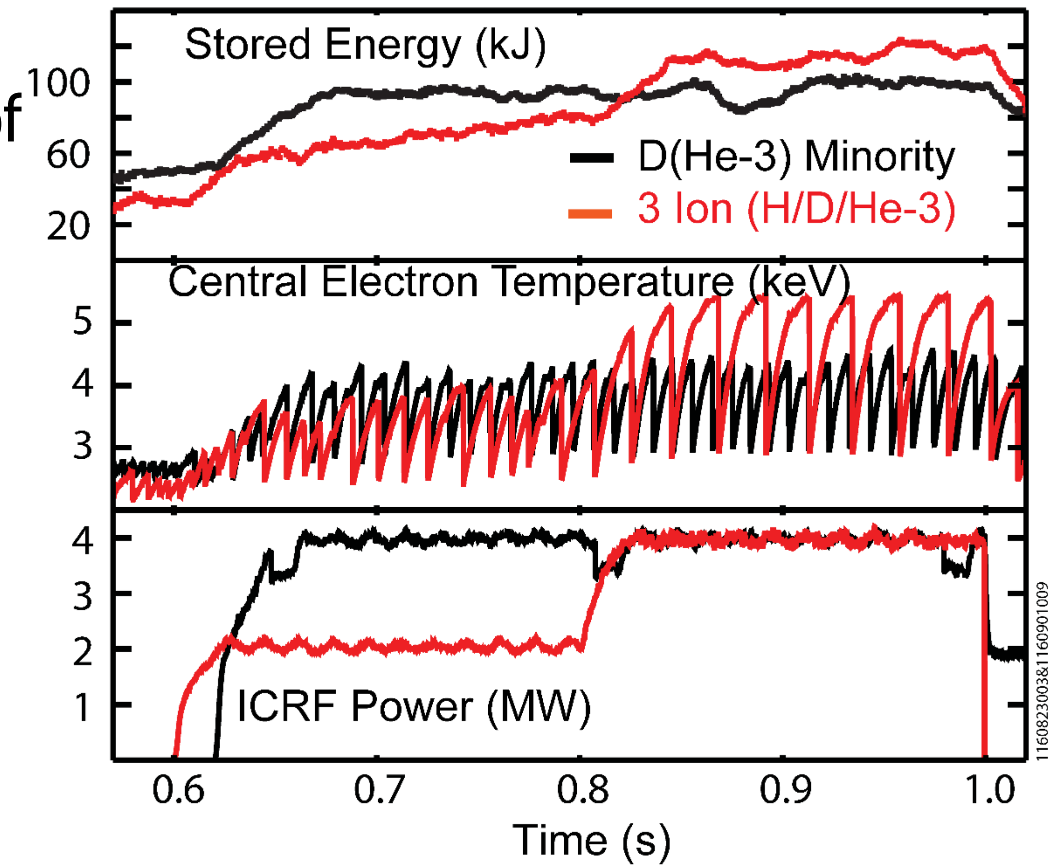
*N.T. Howard et al., Phys. Plasma 23(2016)056109

Experimental Demonstration of Novel 3-ion (H-D-^{3}He) ICRF Scenario

Alcator C-Mod

- On C-Mod (in collaboration with JET colleagues): first experimental verification of 3-ion species heating scenario*
  - Heating efficiency ($\Delta W/P_{ICRF}$) significantly greater than for ^{3}He minority
    - 24 kJ/MW versus 14 kJ/MW

B=7.8T



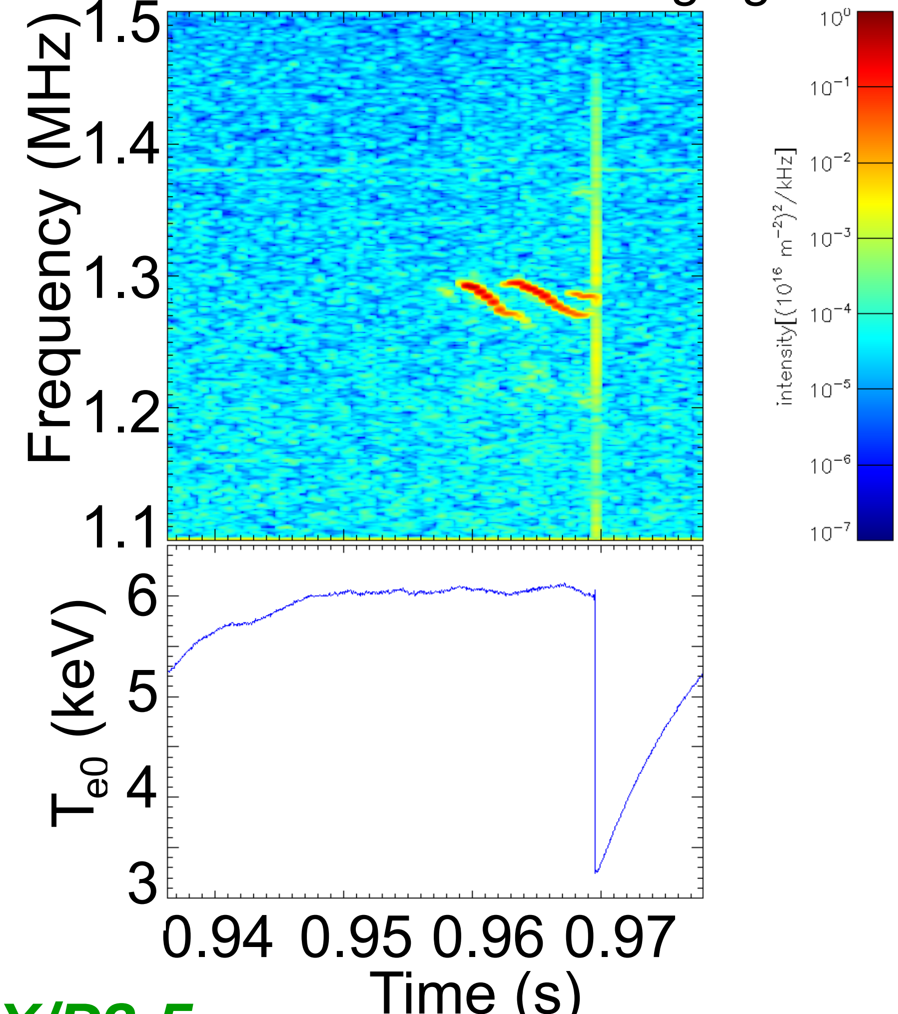
*Kazakov NF 032001 (2015)

 J. Wright EX/P3-5

Experimental Demonstration of Novel 3-ion (H-D-^{3}He) ICRF Scenario

- Destabilization of core TAE modes (Tornado modes) indicates production of ~ MeV ^{3}He ion populations –proxy for fusion alphas
  - Could be applied during non-nuclear phase on ITER
- Could also be used for D-T majority plasmas*
  - 3rd ion candidates: ^{7}Li, ^{9}Be or ^{11}B

Tornado modes measured with Phase Contrast Imaging



*Kazakov NF 032001 (2015)

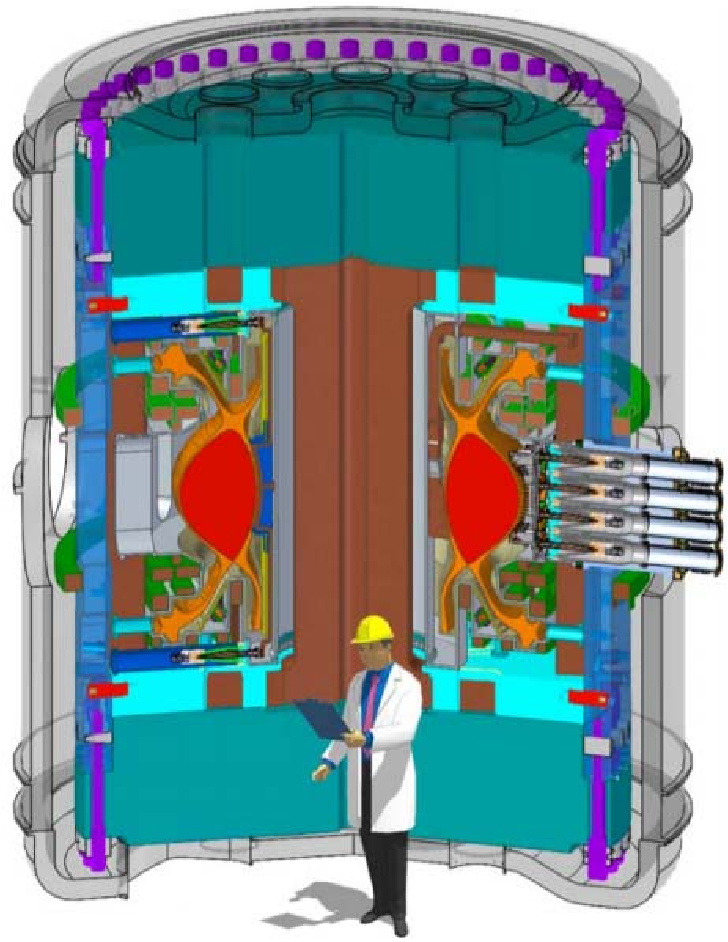
 J. Wright EX/P3-5

Divertor Power Handling and Sustainment Challenges

- (Multiple) Facilities needed to solve dual (related) challenges of power handling and sustainment
- Current devices (especially C-Mod) and ITER design at limits of power handling for divertor
  - Challenge in reactors increases by nearly an order of magnitude*
- Sustainment in reactor regimes (high density, equilibrated ions/electrons, low or no rotation drive) not yet developed**
- Divertor Test Tokamak with Advanced RF sustainment should be designed and built

*****G. Wallace, EX/7-1; P. Bonoli TH/5-1***

ADX Concept for a Divertor Test Tokamak*



***B. LaBombard, et al., Nuclear Fusion 55(2015)053020**

Divertor Power Handling and Sustainment Challenges

Alcator C-Mod

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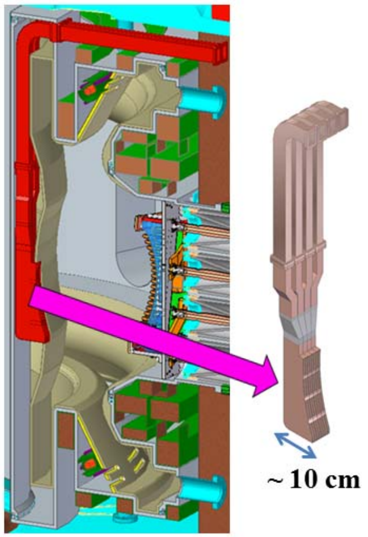
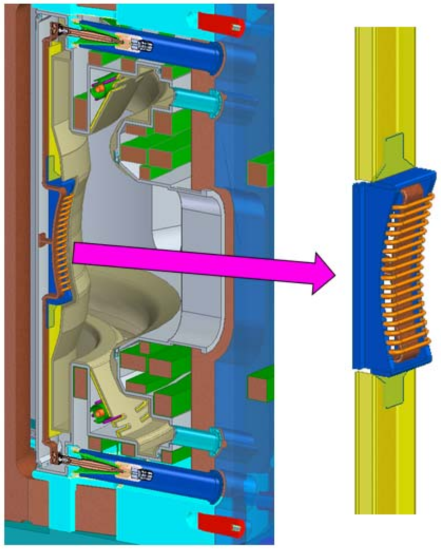
High-Field Side very favorable for RF Launchers**



LHCD Launcher



ICRF Antenna

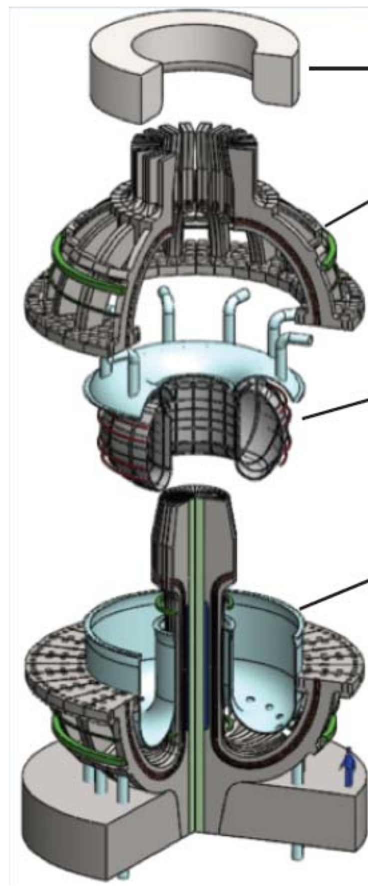
Improves: RF coupling, CD, impurity screening
Reduces: erosion, neutron loading

High B HTS Superconductors: New Technology Opens Pathway to High Field Reactors

Alcator C-Mod

- Leverage High Temperature (High Field) Superconductors
- Device about the size of JET, but at 10 Tesla
  - Projects to 500 MW fusion power, ~200 MW net power
  - Takes advantage of the many designs for high B copper burning plasma concepts (BPX, FIRE, Ignitor, etc.)
  - C-Mod data base gives increased confidence in performance
- HTS could also accommodate jointed coils, allowing for modular construction, removable internal components
- R&D needed to develop coils at scale, joints

ARC Pilot Reactor Concept*

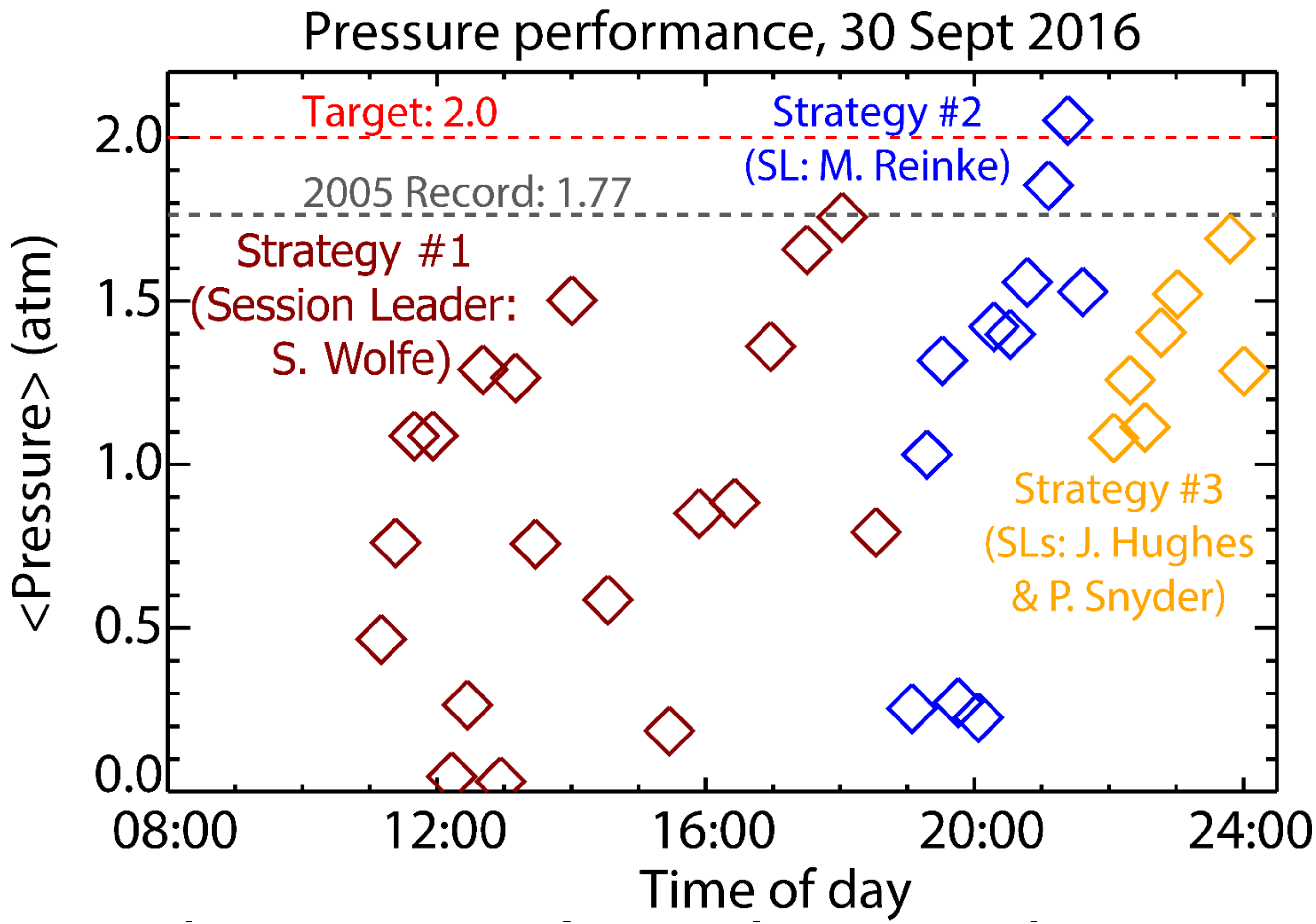


*Sorbom, et al., Fus. Eng. Des. 100(2015)378; ***D. Whyte TIP/P7-6***

September 30, 2016: Attained New Tokamak World Record for Volume Average Pressure (2.05 atm)

Alcator C-Mod

- Lawson: Require high absolute ($P*\tau_E$) for fusion power

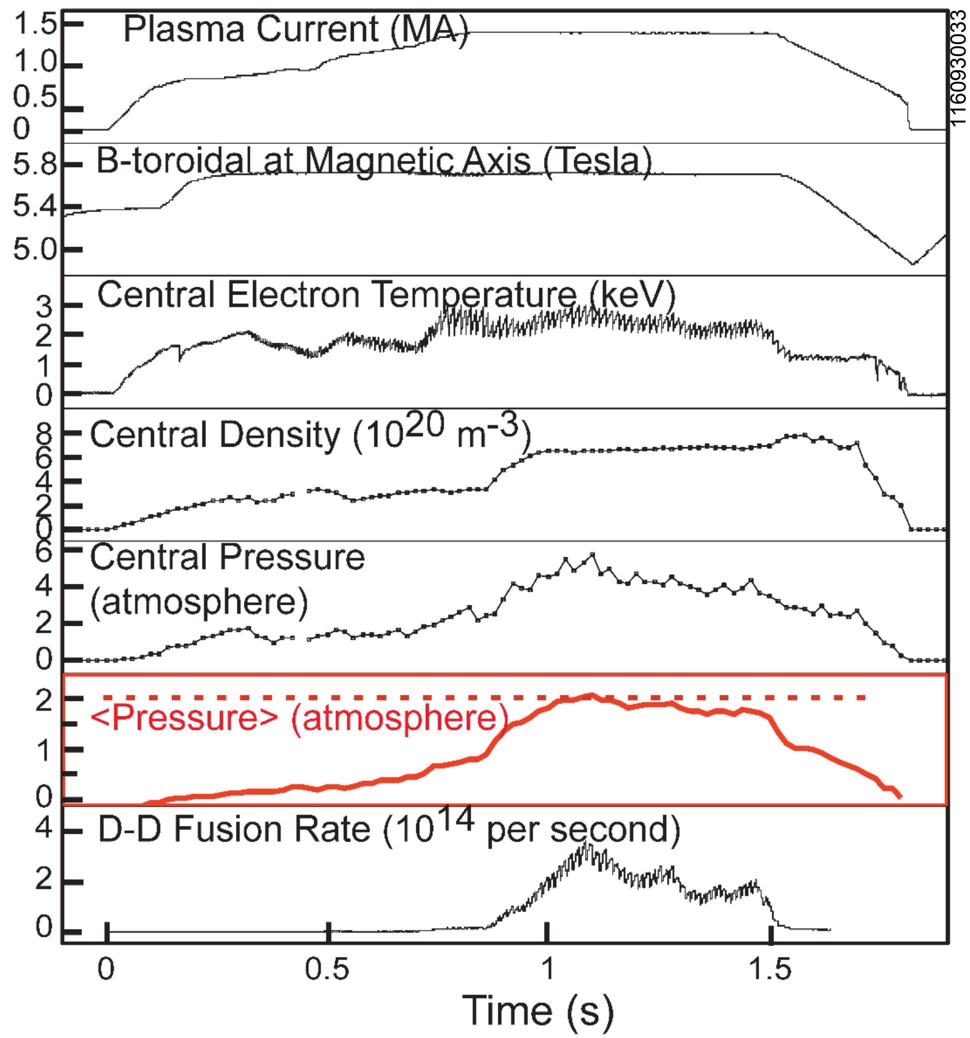


- 3 different approaches were pursued
  - Each produced high performance

September 30, 2016: Attained New Tokamak World Record for Volume Average Pressure (2.05 atm)

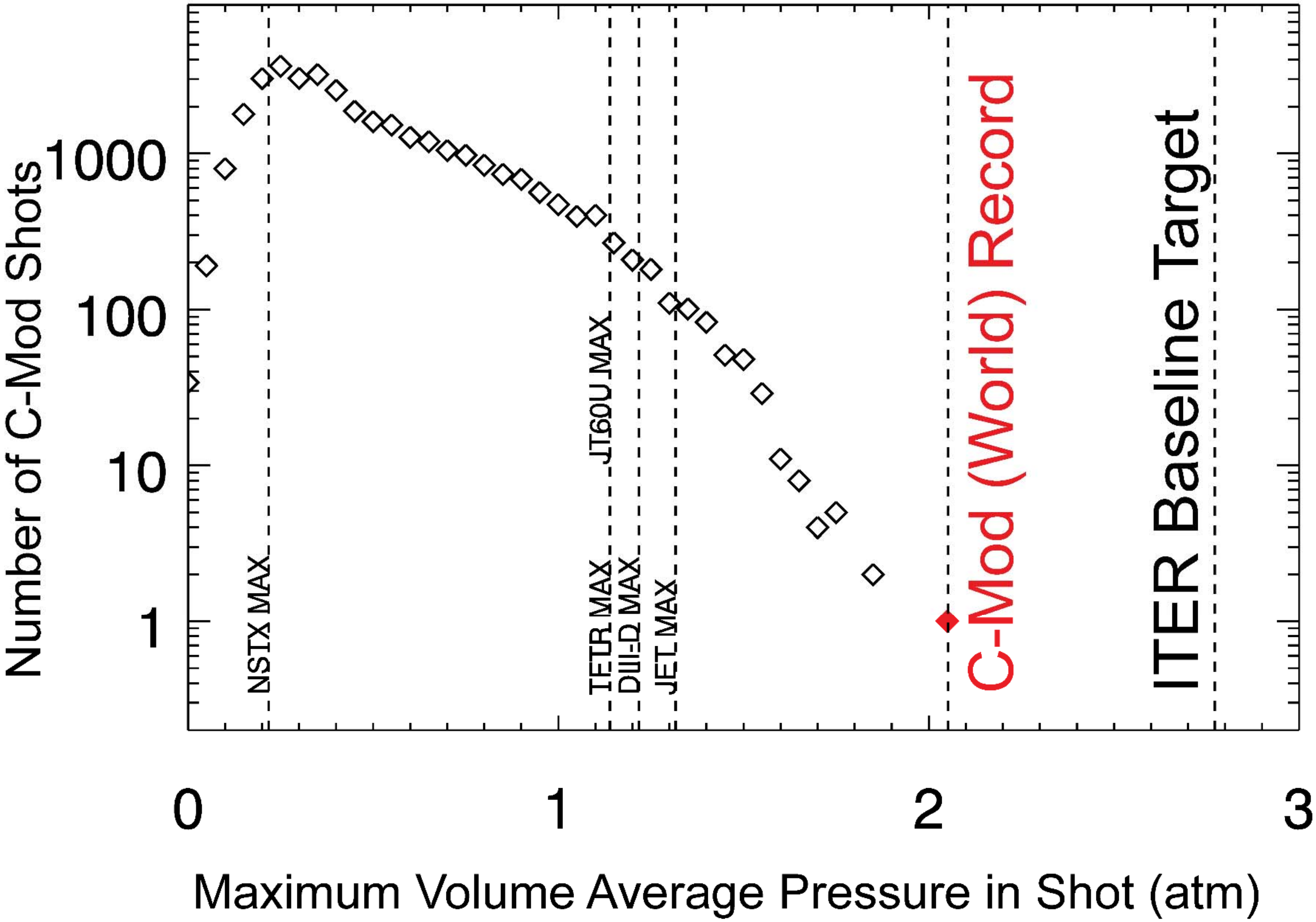
- Maintained above <P>=1.7 atm for 10 energy confinement times
- Utilized nitrogen seeding to keep molybdenum source/core radiated power low
- B=5.7 T, q_{95}=3.2, β_N=1.5, $n/n_{greenwald}$=0.56
  - Safely away from all operational and stability limits

EDA H-Mode

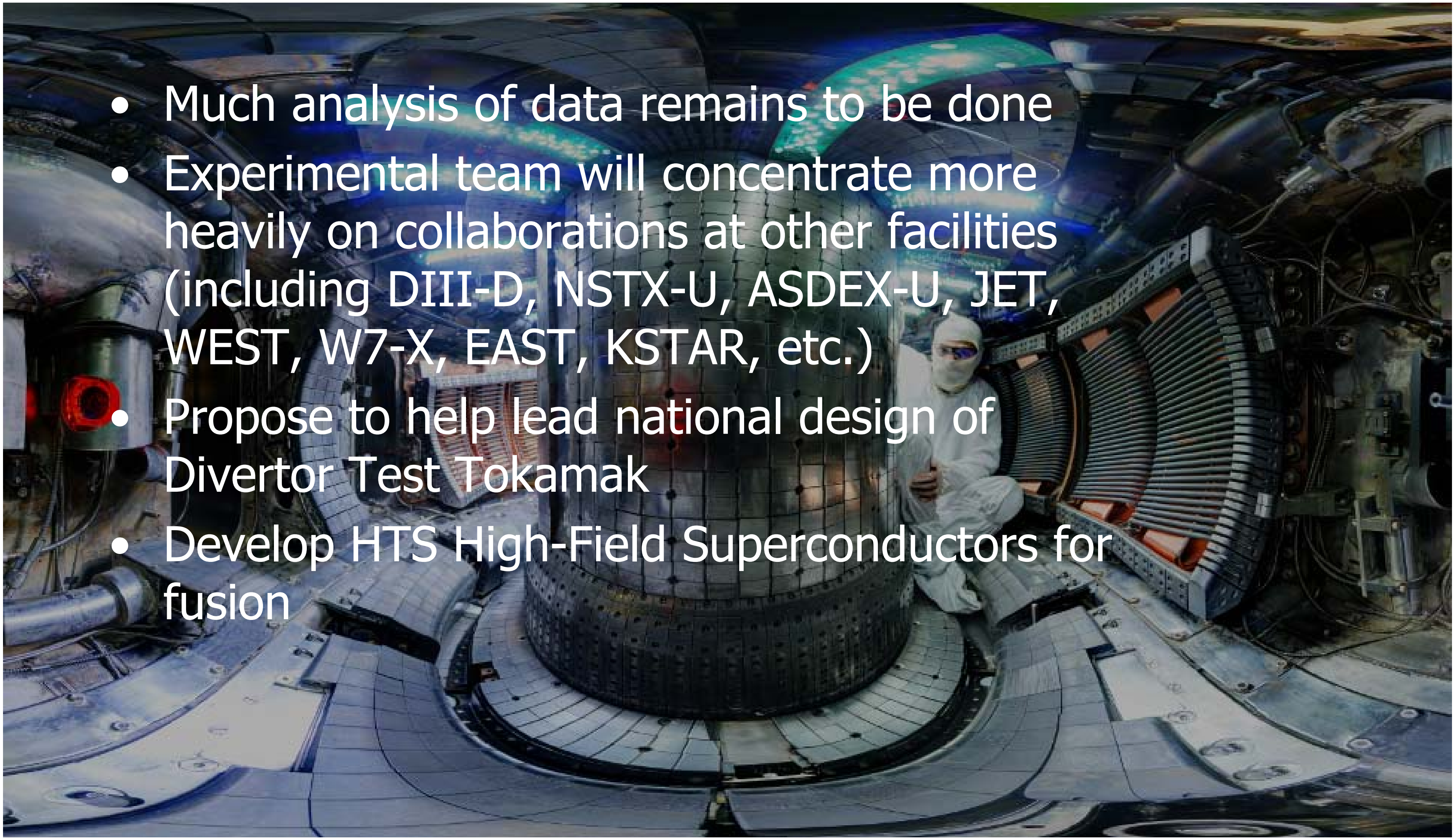


E. Marmar, IAEA FEC 2016 OV/2-5

Histogram of Maximum <Pressure> from the Entire C-Mod Database



Plans



- Much analysis of data remains to be done
- Experimental team will concentrate more heavily on collaborations at other facilities (including DIII-D, NSTX-U, ASDEX-U, JET, WEST, W7-X, EAST, KSTAR, etc.)
- Propose to help lead national design of Divertor Test Tokamak
- Develop HTS High-Field Superconductors for fusion

Summary

Alcator C-Mod

- ELM-suppressed confinement modes look increasingly promising for reactor operation
  - Particularly I-mode at high magnetic field
- Important progress on low z-seeding, with feedback to ameliorate divertor power handling challenge
- High field side in near double-null
  - impurity shielding confirmed
  - significant advantages for RF launchers and heating/current-drive effectiveness
- State-of-the art multi-scale gyrokinetic simulations reveal important role of coupling between ion and electron scale turbulence in Q_e
- New absolute tokamak pressure record: <P>=2.05 atmosphere
- High-field, High Temperature Superconductors open new path to compact, high B pilot plant/reactors

C-Mod Related Presentations at 2016 IAEA FEC

Wednesday Morning:

- M. Porkolab: Studies of Turbulence and Transport in the Alcator C-Mod and DIII-D Tokamaks with Phase Contrast Imaging and Gyrokinetic Modelling, EX/P3-1
- J.E. Rice: Effects of the q Profile on Toroidal Rotation in Alcator C-Mod LHCD Plasmas, EX/P3-2
- M. Reinke: Investigations of Radial High-Z Transport Mechanisms in ICRF-Heated Alcator C-Mod H-Mode Plasmas, EX/P3-3
- J.C. Wright: Experimental Results from Three-Ion Species Heating Scenario on Alcator C-Mod, EX/P3-5
- B. LaBombard: Plasma Profiles and Impurity Screening Behaviour of the High-Field Side Scrape-Off Layer in Near-Double-Null Configurations: Prospect for Mitigating Plasma-Material Interactions on RF Actuators and First-Wall Components, EX/P3-6
- D. Brunner: Divertor and Core Plasma Performance Optimization Enabled by Direct Feedback Control of Surface Heat Flux on Alcator C-Mod's High-Z Vertical Target Plate Divertor, EX/P3-7
- R. Granetz: Developing Disruption Warning Algorithms Using Large Databases on Alcator C-Mod and EAST Tokamaks, EX/P3-8
- D. Shirakid: Disruption Mitigation in the Presence of Pre-Existing MHD Instabilities, EX/P3-20

Wednesday Afternoon:

- A. Hubbard: Advances in Physics and Performance of the I-Mode Regime over an Expanded Operating Space on Alcator C-Mod, EX/3-1
- T. Jenkins: High-Performance Computational Modelling of Plasma-Surface Interactions and RF Antennas, TH/P4-34
- L. Delgado-Aparicio: Locked-Mode Avoidance and Recovery without External Momentum Input Using ICRH, EX/P4-39

Thursday Afternoon

- C. Myers: A Multimachine Analysis of Nonaxisymmetric and Rotating Halo Currents, EX/P6-46

Friday Morning:

- G. Wallace: Influence of the Scrape-Off Layer on RF Actuator Performance, EX/7-1
- C. Holland: Demonstrating the Multiscale Nature of Electron Transport through Experimentally Validated Simulations, TH/6-1
- D. Whyte: Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path, FIP/P7-6
- B.J. Ding: Recent Experimental and Modelling Advances in the Understanding of Lower Hybrid Current Drive in ITER-Relevant Regimes, EX/P7-5

The C-Mod Team (2014-2016)

Alcator C-Mod

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