Alcator C-Mod on the High-Field Tokamak Path to Fusion Energy*

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

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Compact, High B Tokamak Physics

Very Productive 2015-2016 Experimental Campaigns

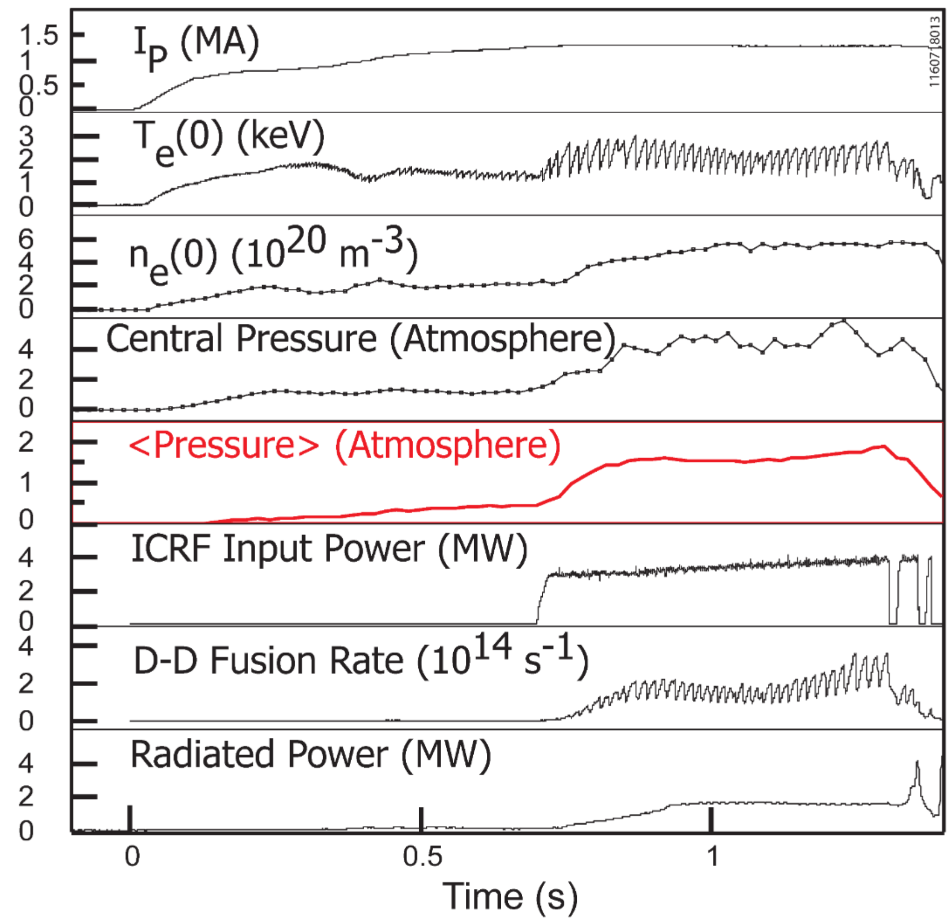
- Core and Pedestal Transport
  - ELM-less enhanced confinement regimes (EDA-H, I-mode)
  - Multi-scale gyrokinetic simulations
- ICRF: 3-ion mode conversion heating
- SOL and Divertor
  - feedback controlled detachment
  - Divertor Test Tokamak
- Compact, high magnetic field approach
  - Leverage high 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

Alcator C-Mod

- 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

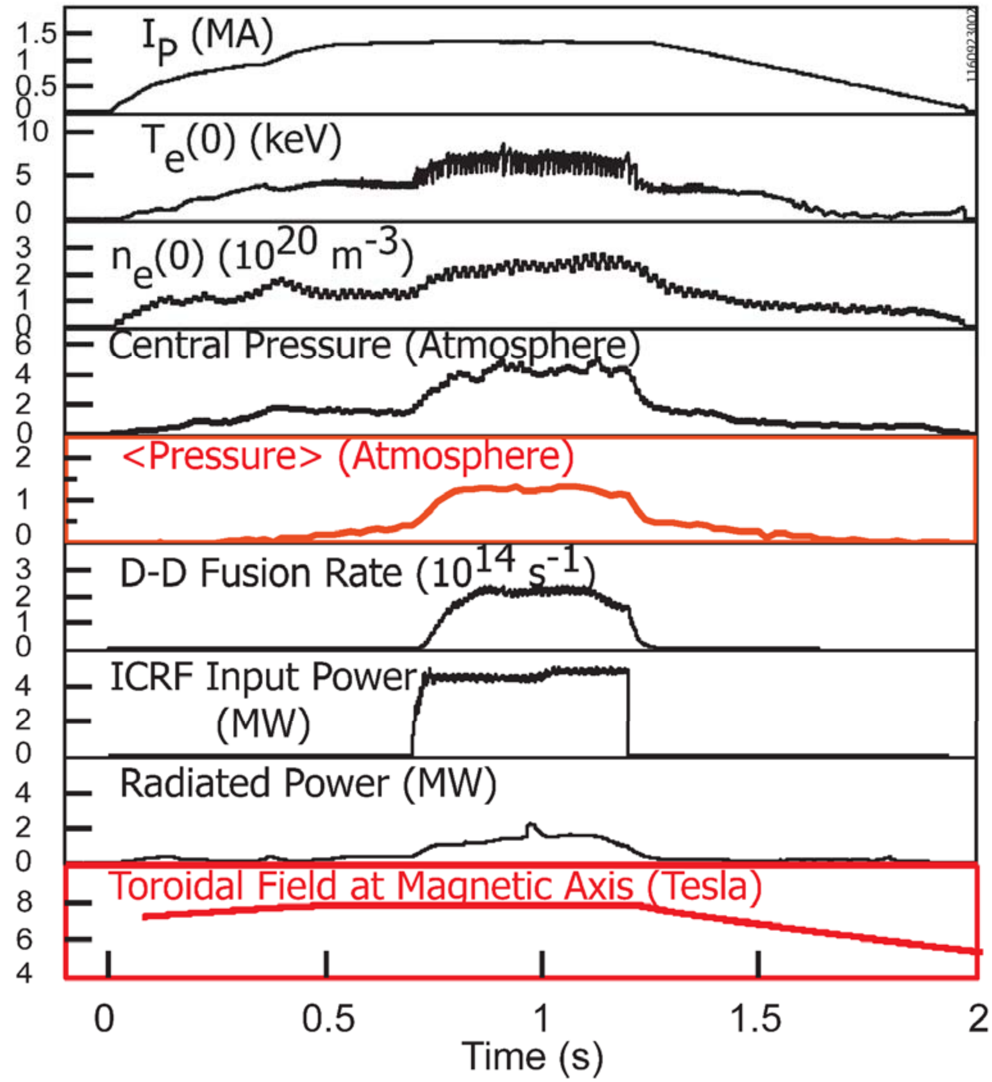


At High Field, C-Mod Naturally Accesses Enhanced Confinement with no ELMS

Alcator C-Mod

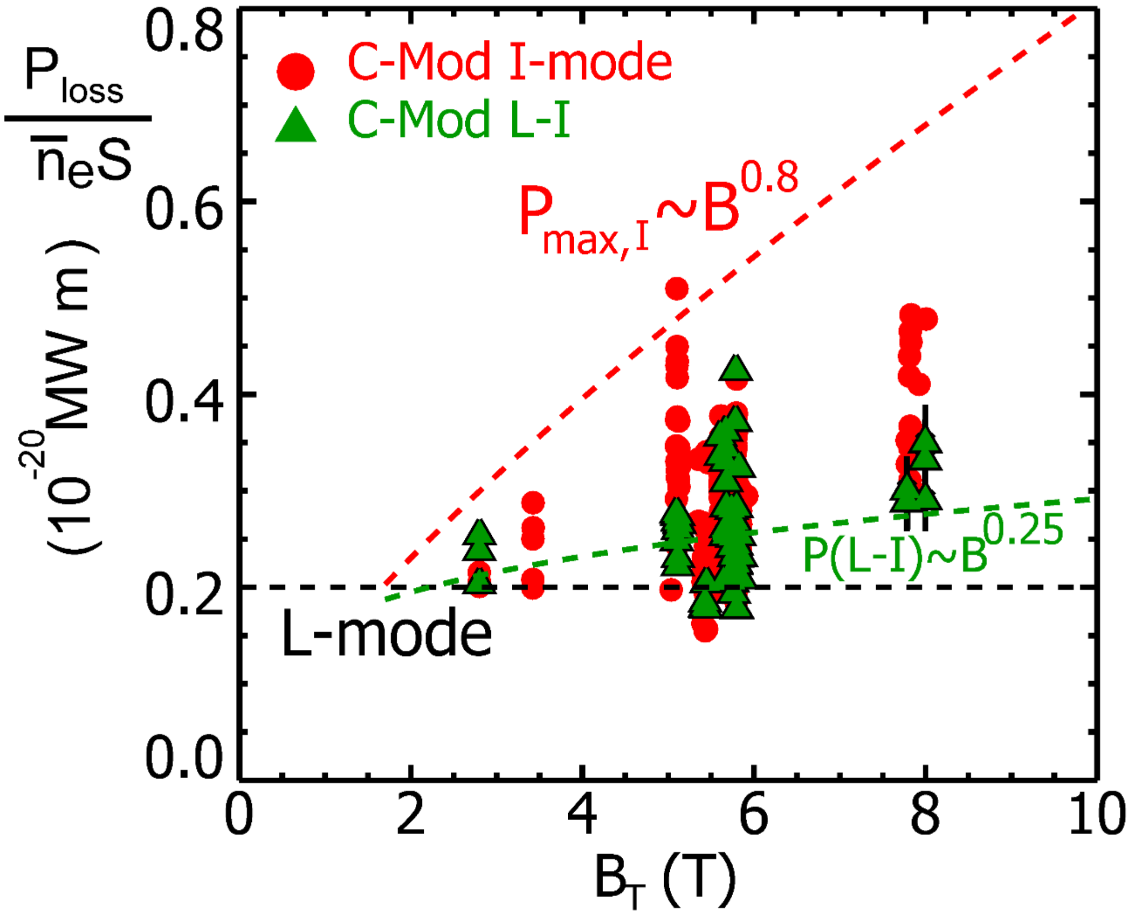
- I-mode*
  - H-mode energy confinement, L-mode density pedestal, low particle/impurity confinement
  - Edge regulation through continuous (weakly-coherent) modes/broadened by GAMs
  - Best access with ion ∇B drift away from active X-point
  - Highly attractive for fusion energy

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



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

Alcator C-Mod

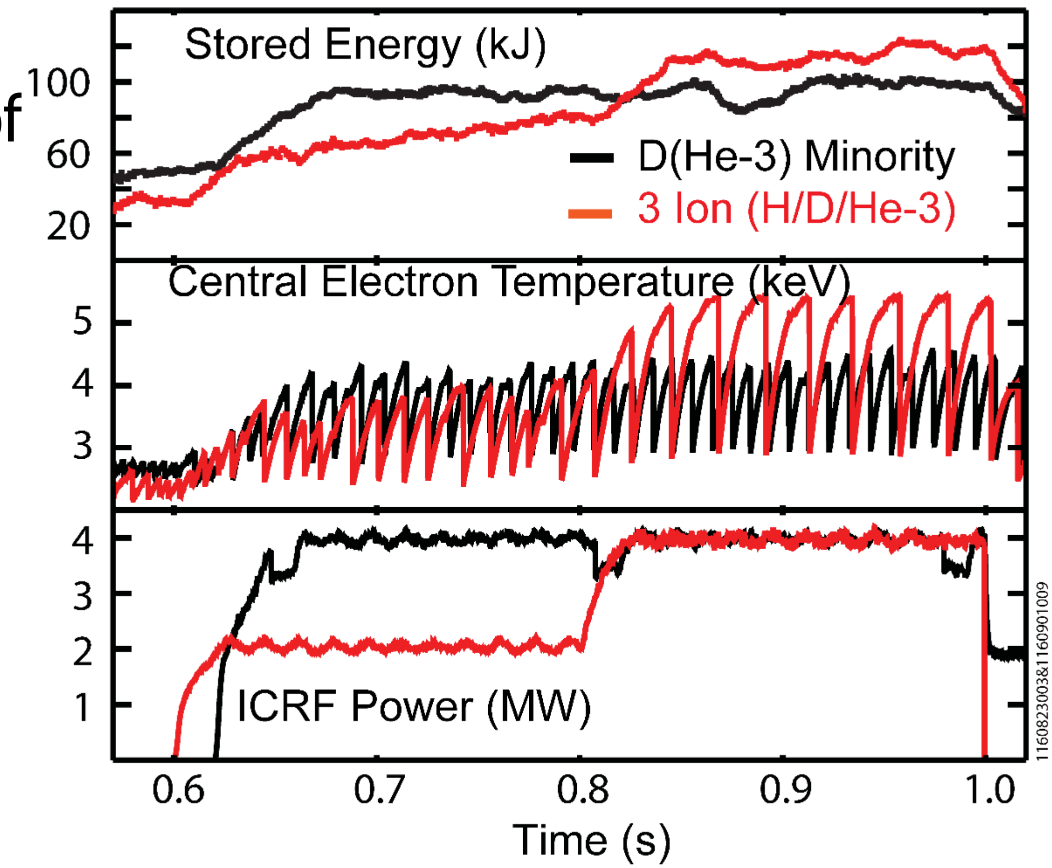


- **$P(L\text{-}I)/n_e \sim B_T^{0.25}$**
  - Weak B_T threshold dependence (agrees with ASDEX-U results)
- Power range at 8 T even larger than at ~5.5 T
  - No 8 T discharges had I-H transitions, up to maximum ICRF power (P_{tot}/S = 0.63 MW/m^2)

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

- 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



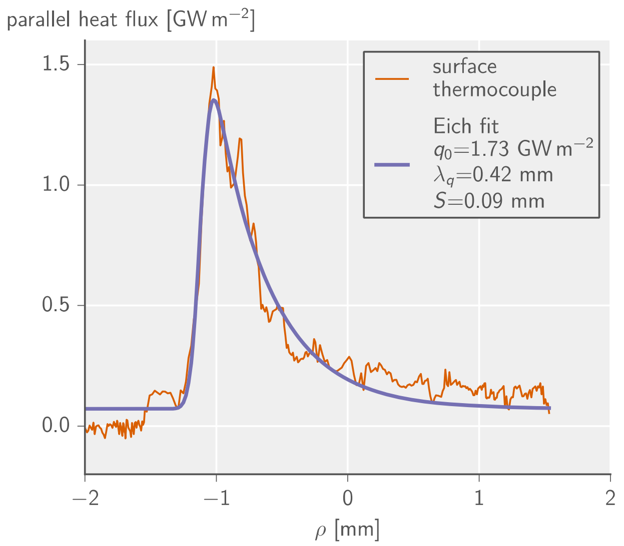
*Kazakov NF 032001 (2015)

Power Exhaust Challenges

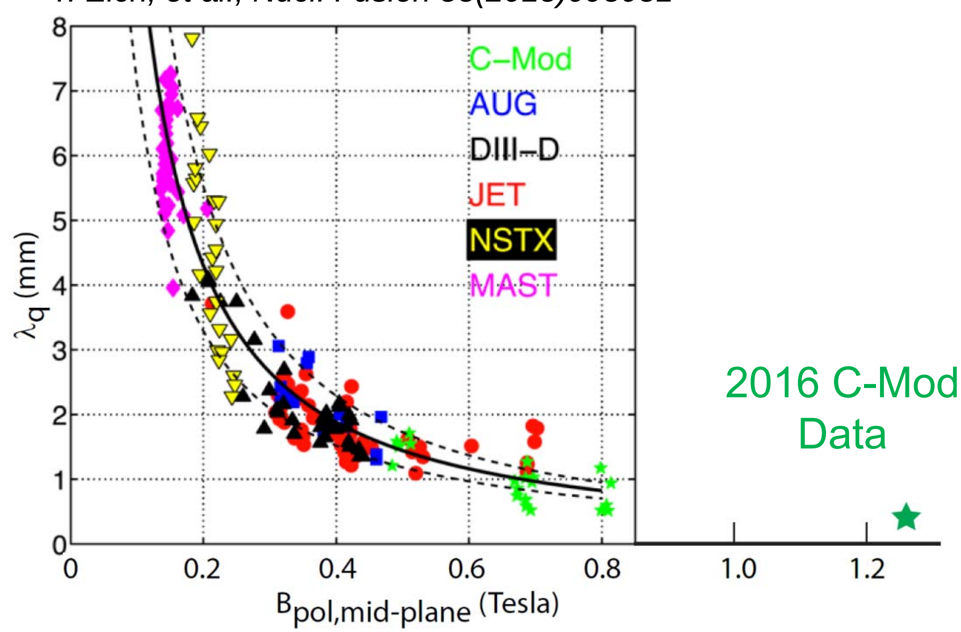
Power exhaust e-folding width (λ_q) continues to decrease with increasing B_{pol}

New record low for λ_q attained at record high $B_{pol,MP}$ = 1.26T
Eich scaling*: 0.48+/-0.07 mm; C-Mod: 0.42 mm

Outer divertor heat flux profile in I-mode:
I_p=1.67 MA, B_T =7.8 T, P_{rf} = 3.7 MW
$B_{pol,MP}$ = 1.26 T, λ_q = 0.42 mm



*T. Eich, et al., Nucl. Fusion 53(2013)093031

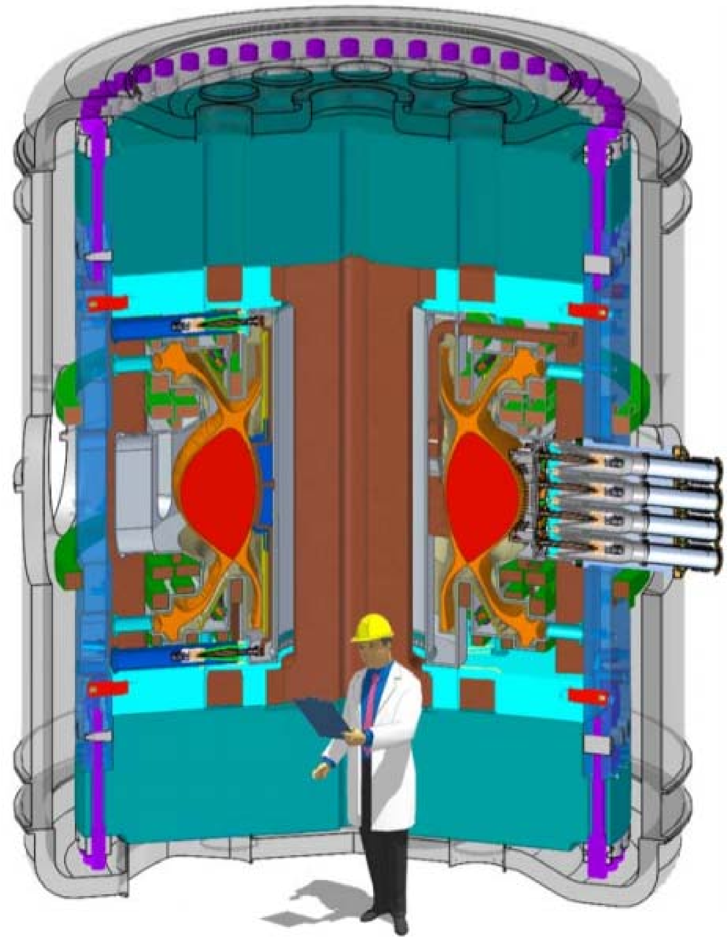


Divertor Power Handling and Sustainment Challenges

Alcator C-Mod

- (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

ADX Concept for a Divertor Test Tokamak*



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

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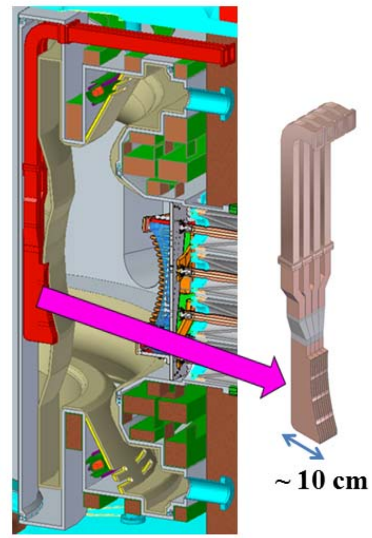
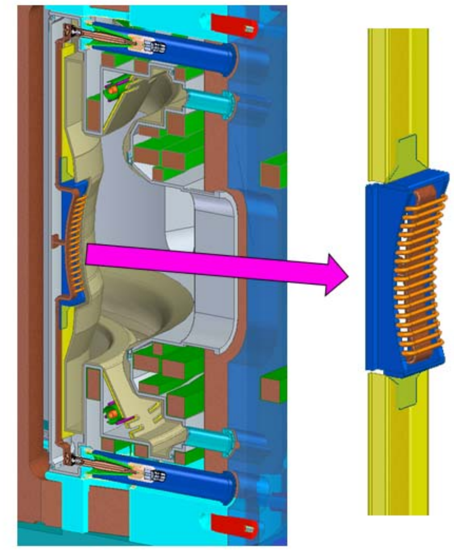
High-Field Side very favorable for RF Launchers



LHCD Launcher



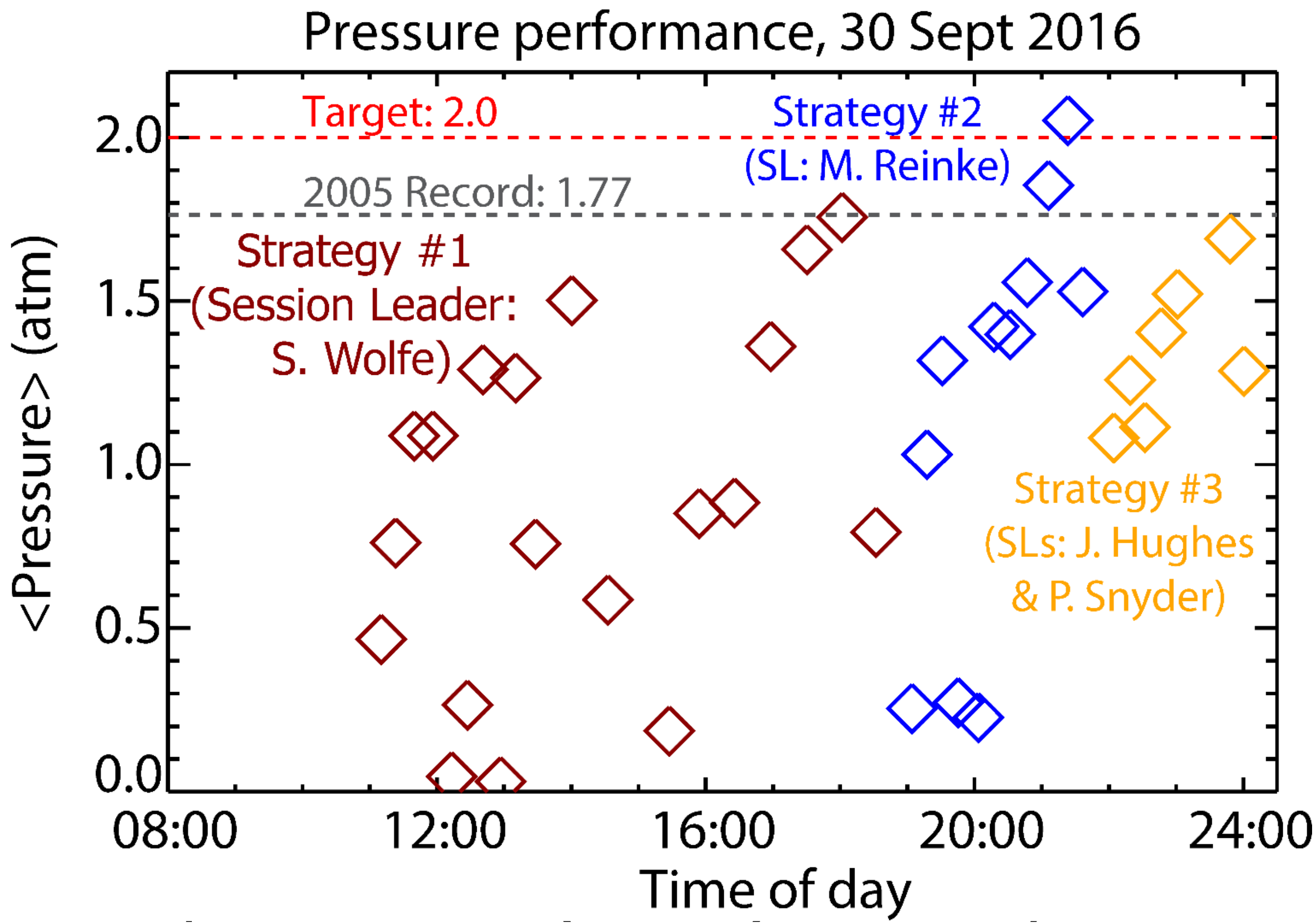
ICRF Antenna

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

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



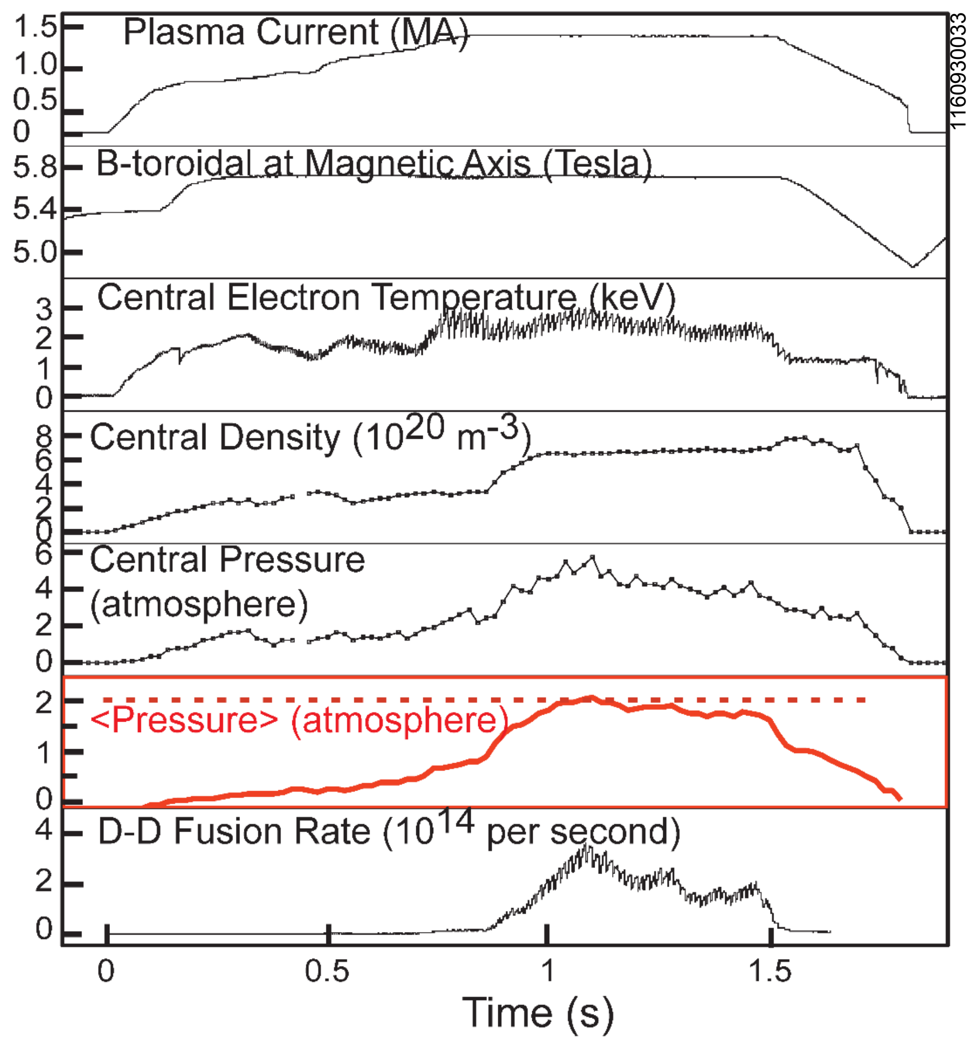
- 3 different approaches were pursued
  - Each produced high performance

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

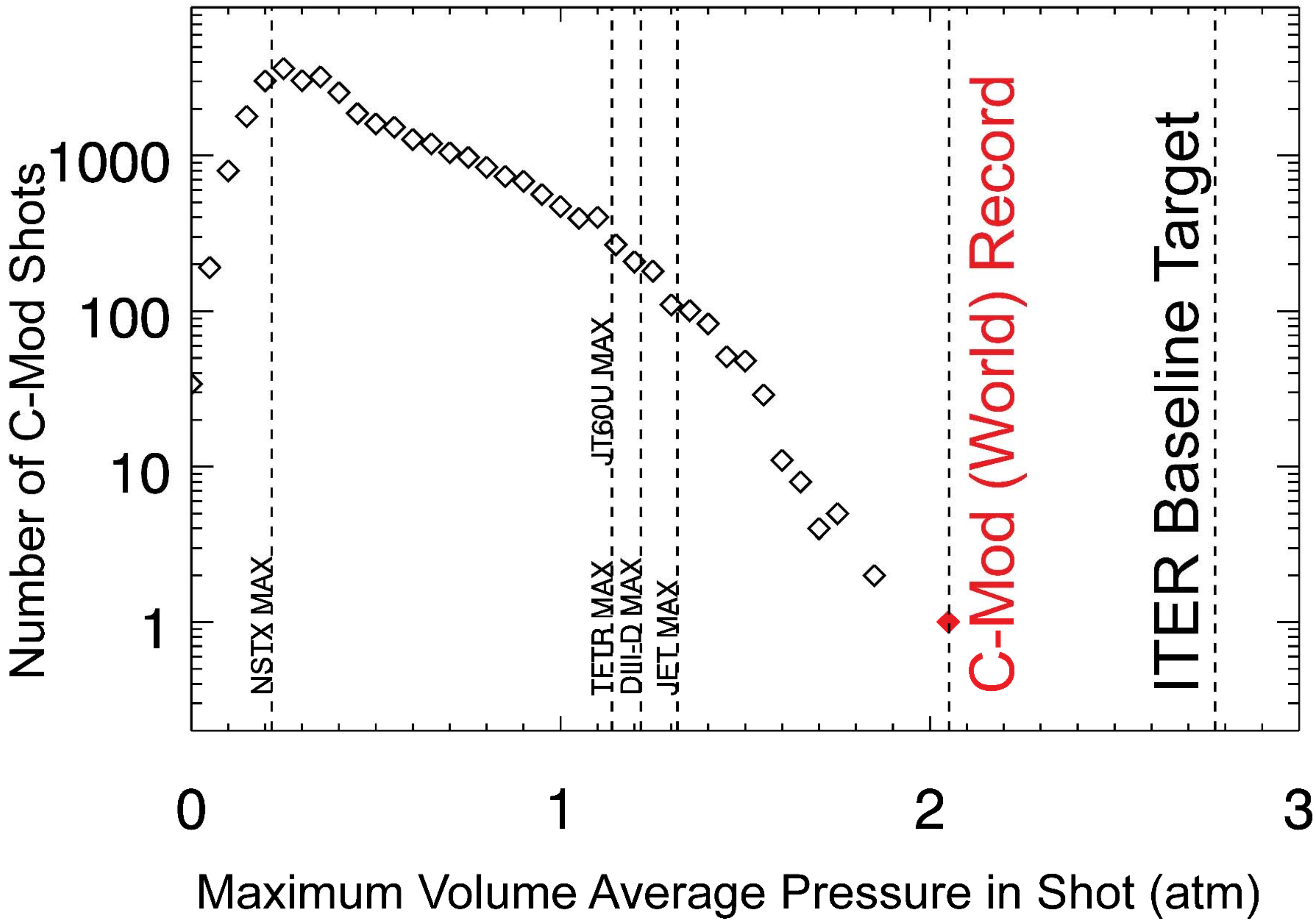
Alcator C-Mod

- 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



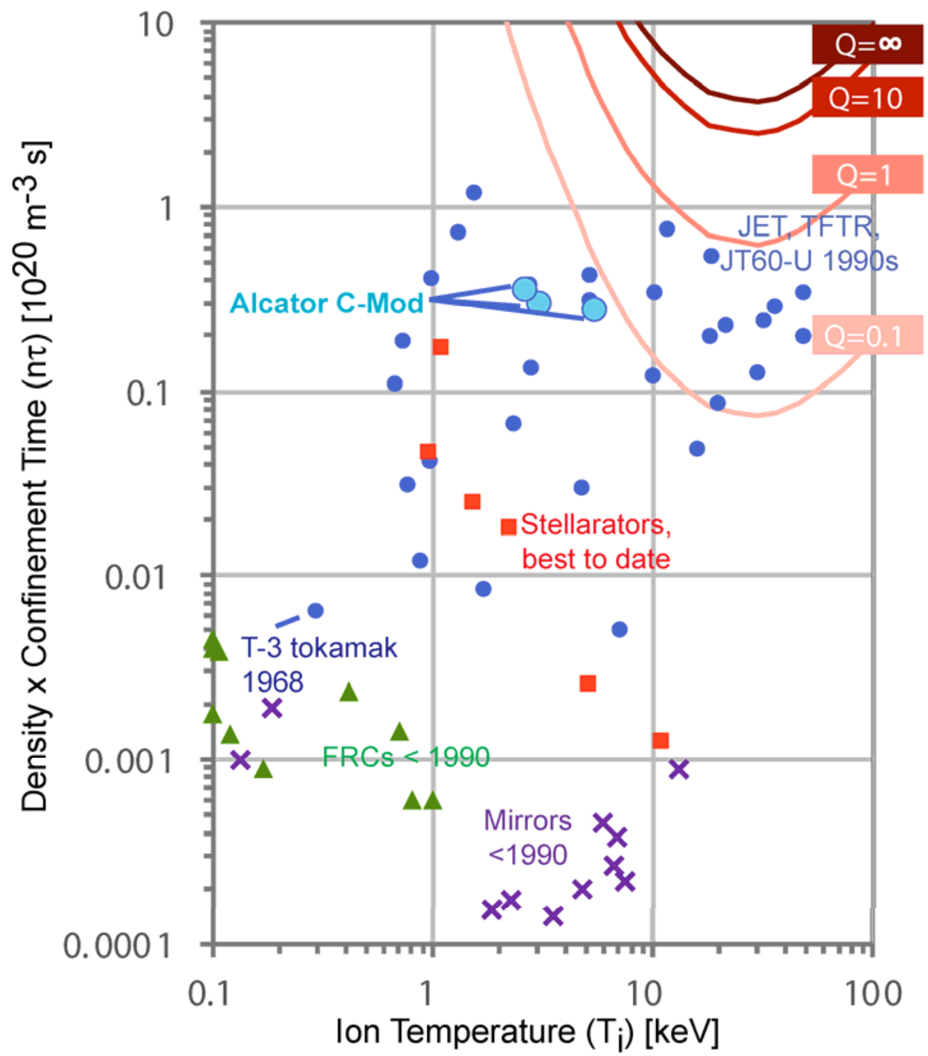
Histogram of Maximum <Pressure> from the Entire C-Mod Database



Alcator C-Mod has proven the tokamak physics at high magnetic field

Alcator C-Mod

- R=0.67, B=8T, I_p=2 MA
  - *100 x times smaller volume than the JET tokamak*
- C-Mod holds world's record for average plasma pressure in a tokamak
  - > 2 atmosphere at temperature of 35 million degrees Kelvin)
  - Pressure $\propto B^2$
  - Fusion power/volume $\propto$ Pressure$^2 \propto B^4$

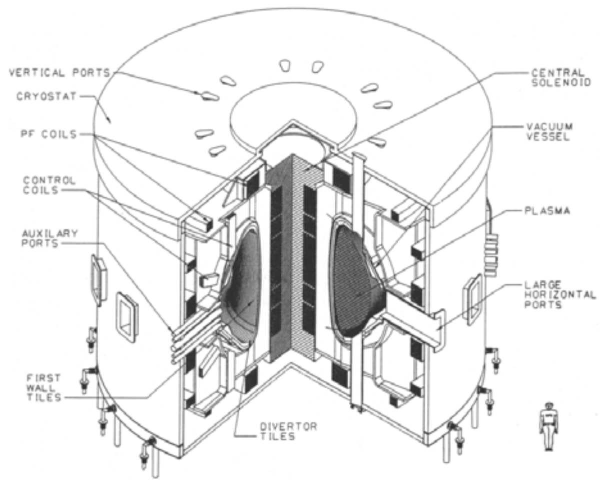


High-Field Tokamaks Long Recognized as an Expedient Approach to Study Burning Plasmas

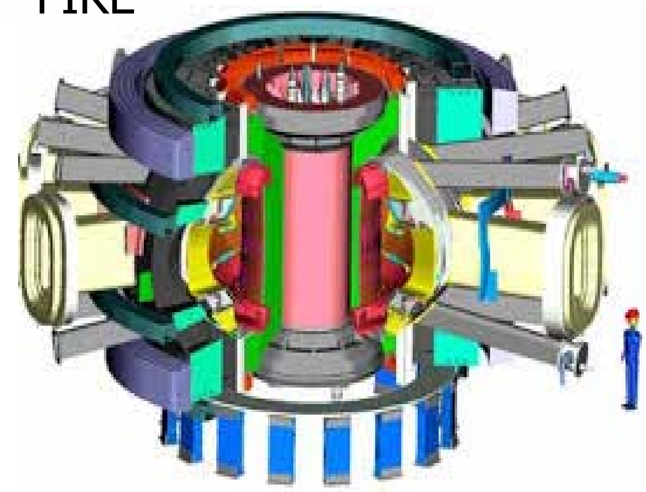
Alcator C-Mod

- Compact copper-magnet designs, including Ignitor, Zephyr, CIT/BPX, FIRE
  - Demonstrate and study alpha-dominant heating regimes, in pulsed operation
  - Since the required magnetic fields were not achievable with conventional superconductors, deemed by some to be a "dead end"

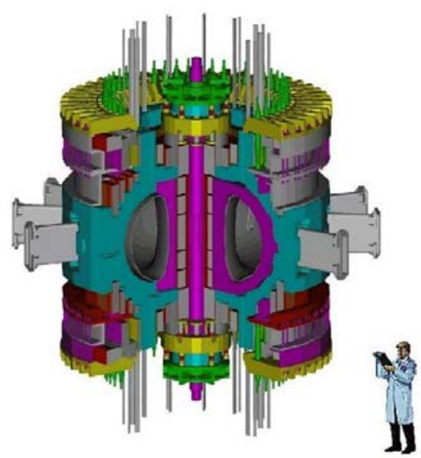
BPX



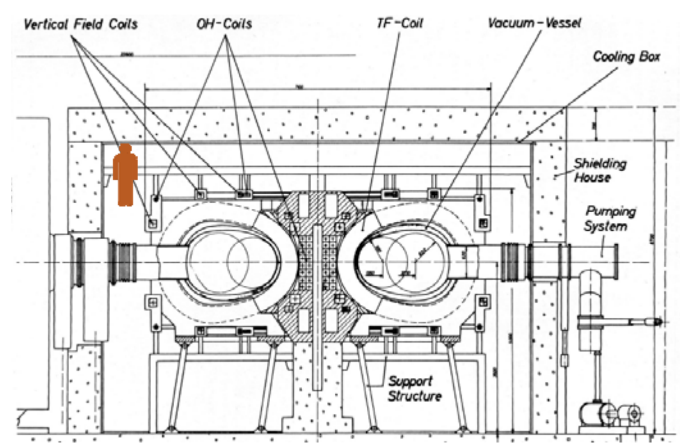
FIRE



Ignitor

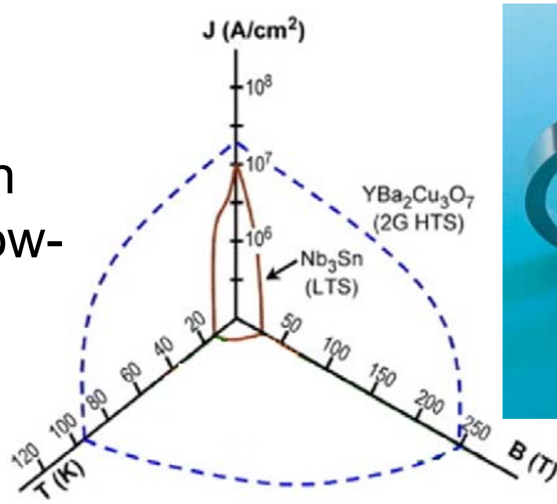


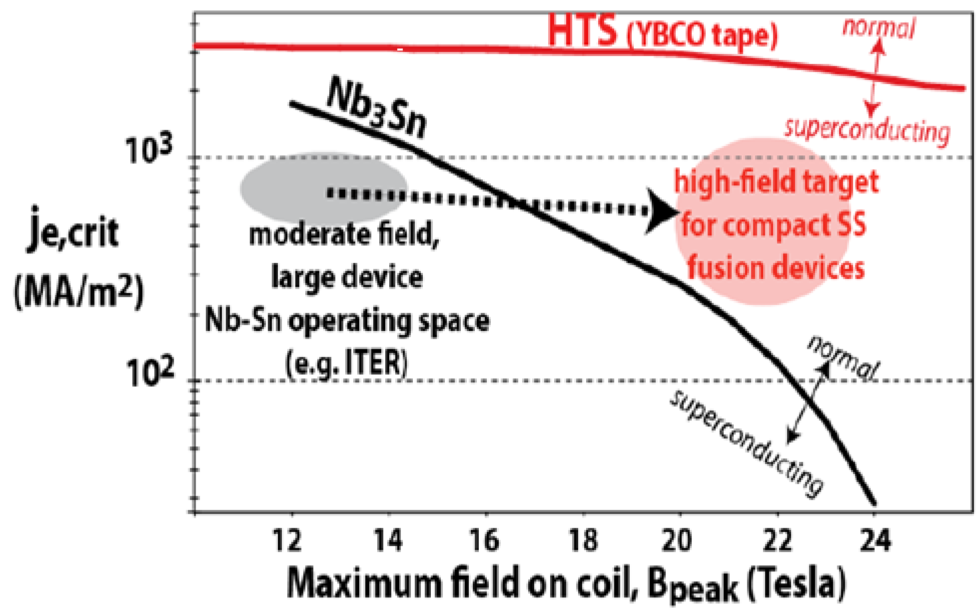
Zephyr



A disruptive technology - High Temperature Superconductors
- Operate at very high magnetic field (>30 Tesla):
Enables compact high field tokamak reactors

- High Temperature Superconductors (HTS) represent a step-change in magnet technology over low-temperature superconductors (LTS)
  - Enable much higher magnetic fields
  - Operation at higher temperature
  - Stronger materials
  - Higher current densities
- The next superconducting tokamak should be made from these!



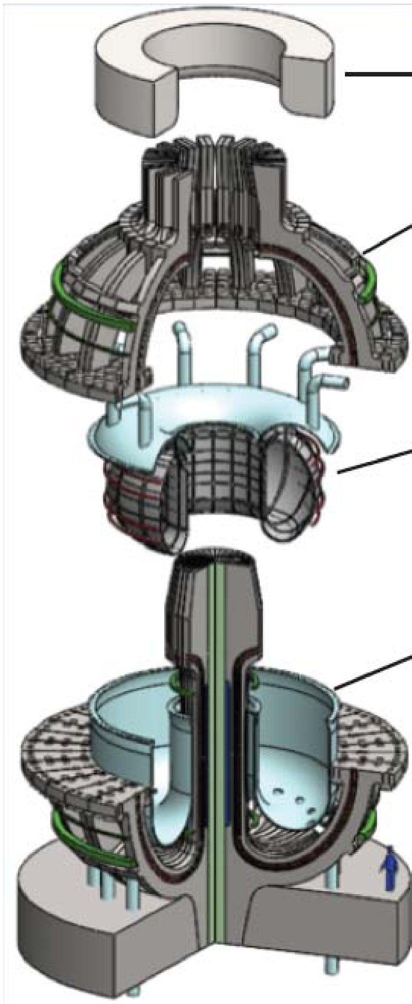


High B HTS Superconductors: New Technology Opens Pathway to Higher Field Reactors

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*

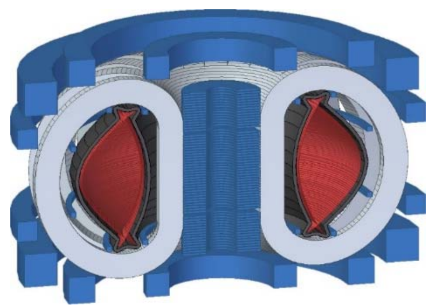


*Sorbom, et al., Fus. Eng. Des. 100(2015)378

Can we demonstrate net energy production in very near term (<10 years), at smallest possible scale?

DIII-D (San Diego):
R=1.66m, 2.1T, 2 MA
Water cooled copper coils

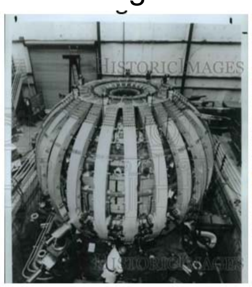
Combine established physics with HTS to achieve Q>2



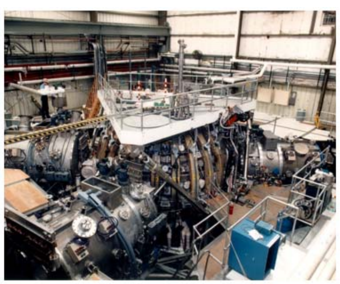
MIT Concept
R=1.65m, 12T, 7.5 MA
Cryogenic HTS

ASDEX-U (Germany):
R=1.65m, 2.5T, <1.6 MA
Water cooled copper coils

Assembling DIII-D

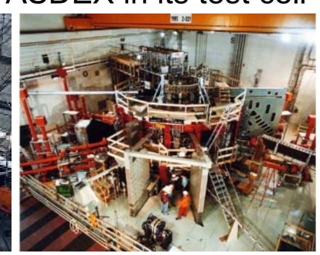


DIII-D in its test cell



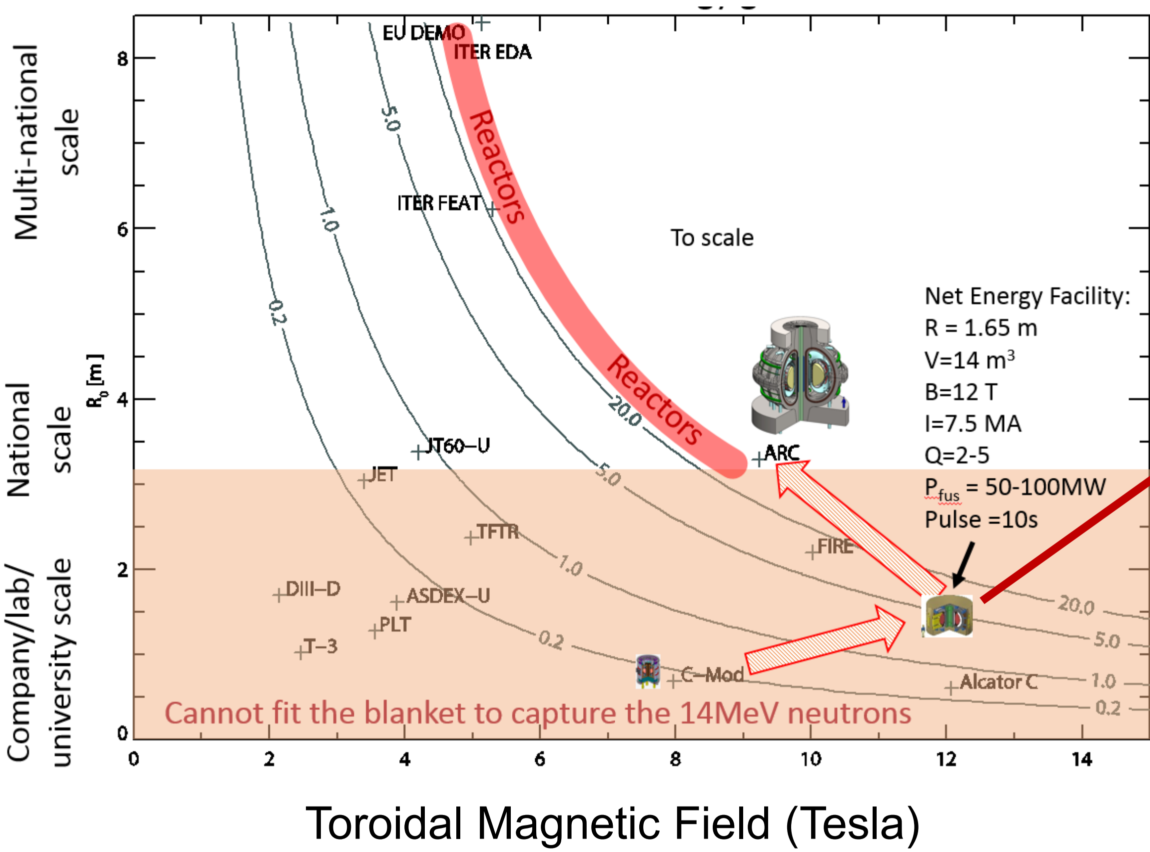
Assembling ASDEX

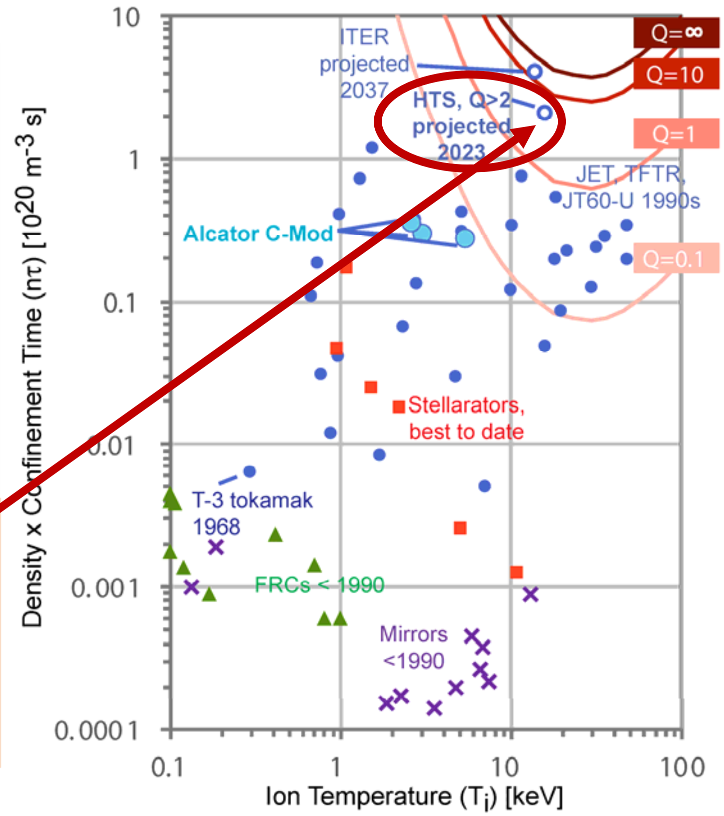
ASDEX in its test cell



Can we demonstrate net energy production in very near term (<10 years), at smallest possible scale?

We believe the answer is yes!





Plans

- Much analysis of C-mod 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 a faster path to fusion energy