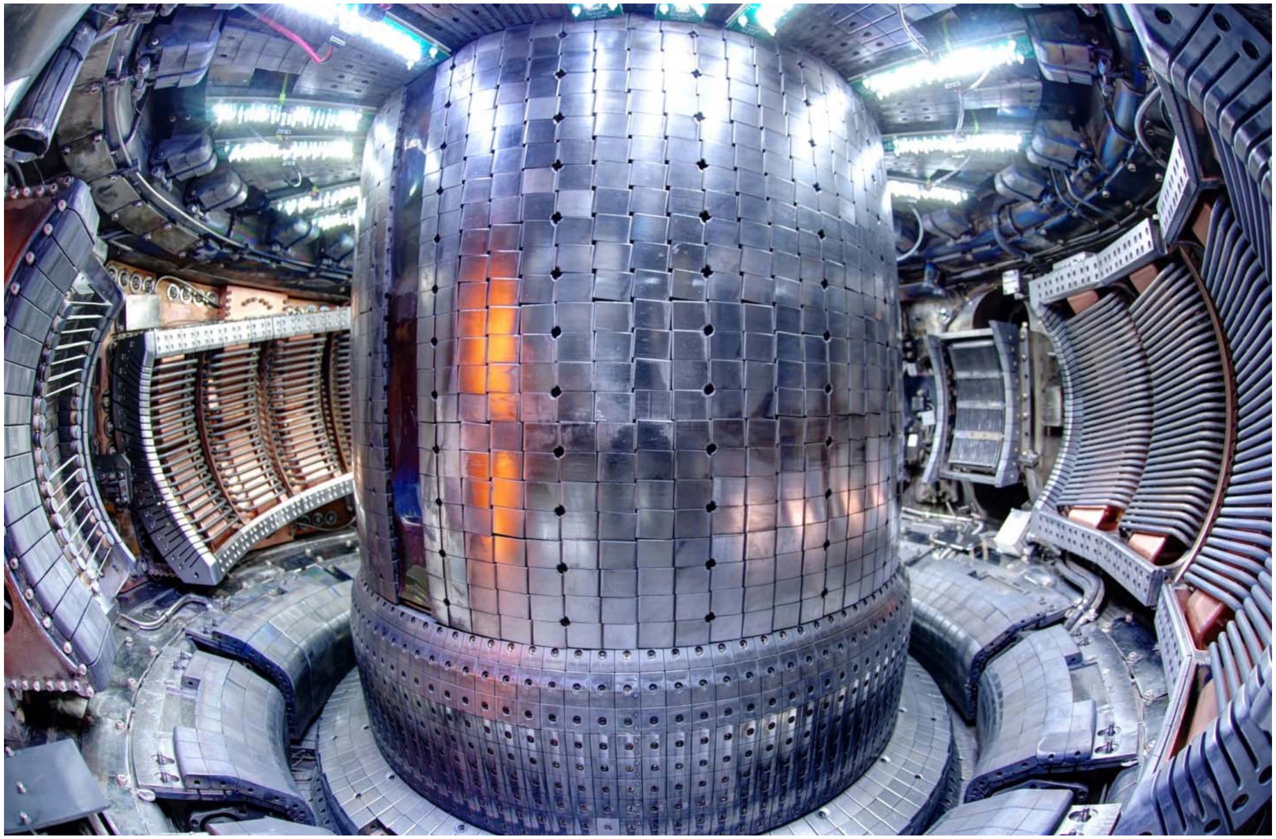
OV/2-5: Overview of Alcator C-Mod Results

Research in Support of ITER and Steps Beyond*



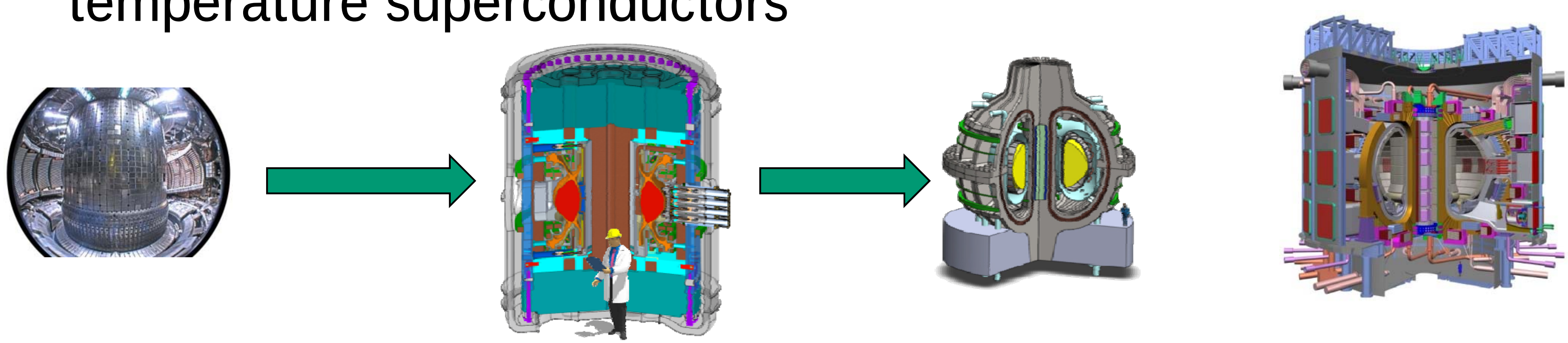
E.S. Marmar on behalf of the C-Mod Team

25th IAEA Fusion Energy Conference, Saint Petersburg, Russia, 13 October, 2014

*Supported by US Department of Energy, Office of Science

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

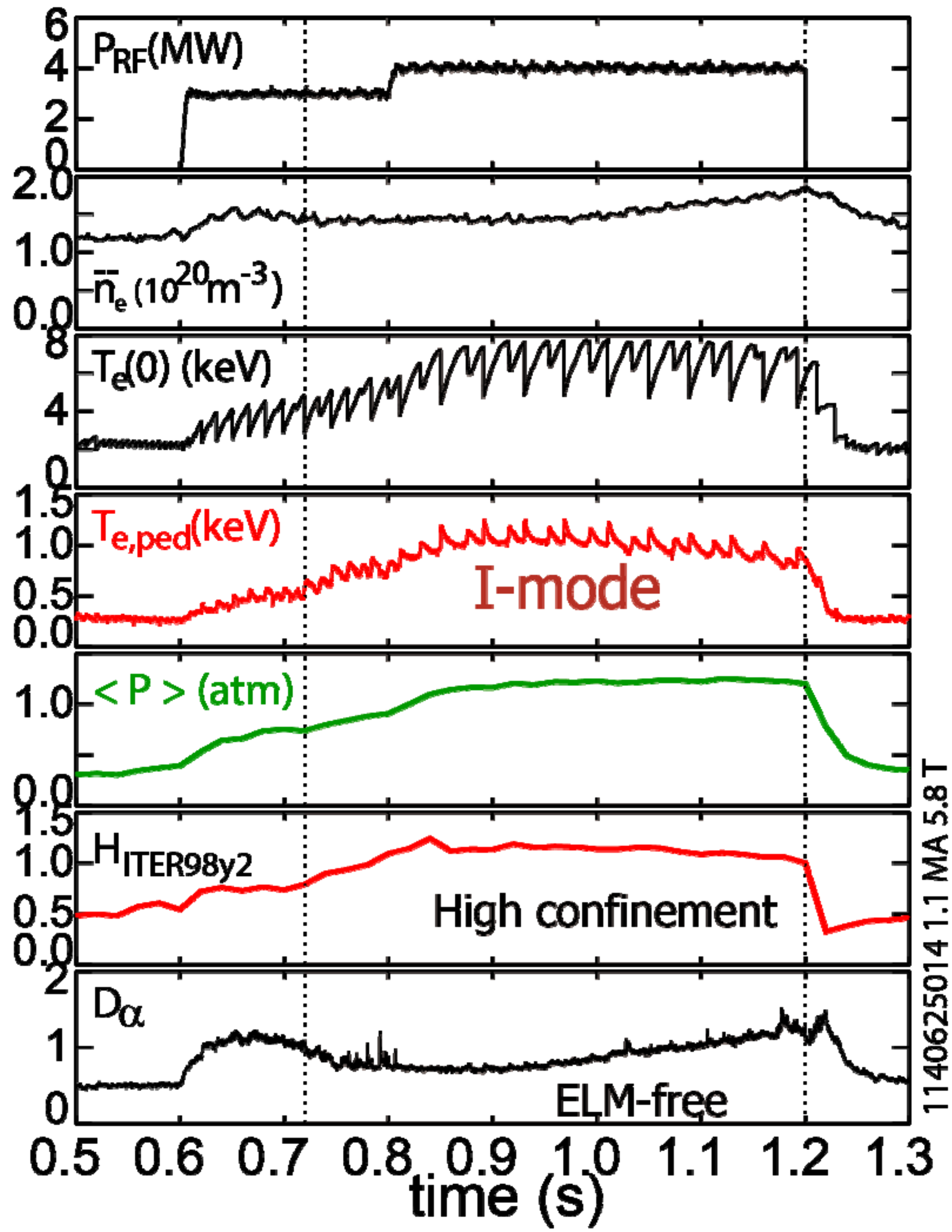


I-mode would be very favorable regime for burning plasma

- 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:

  $$P_{L\text{-}I}<P<P_{I\text{-}H}$$

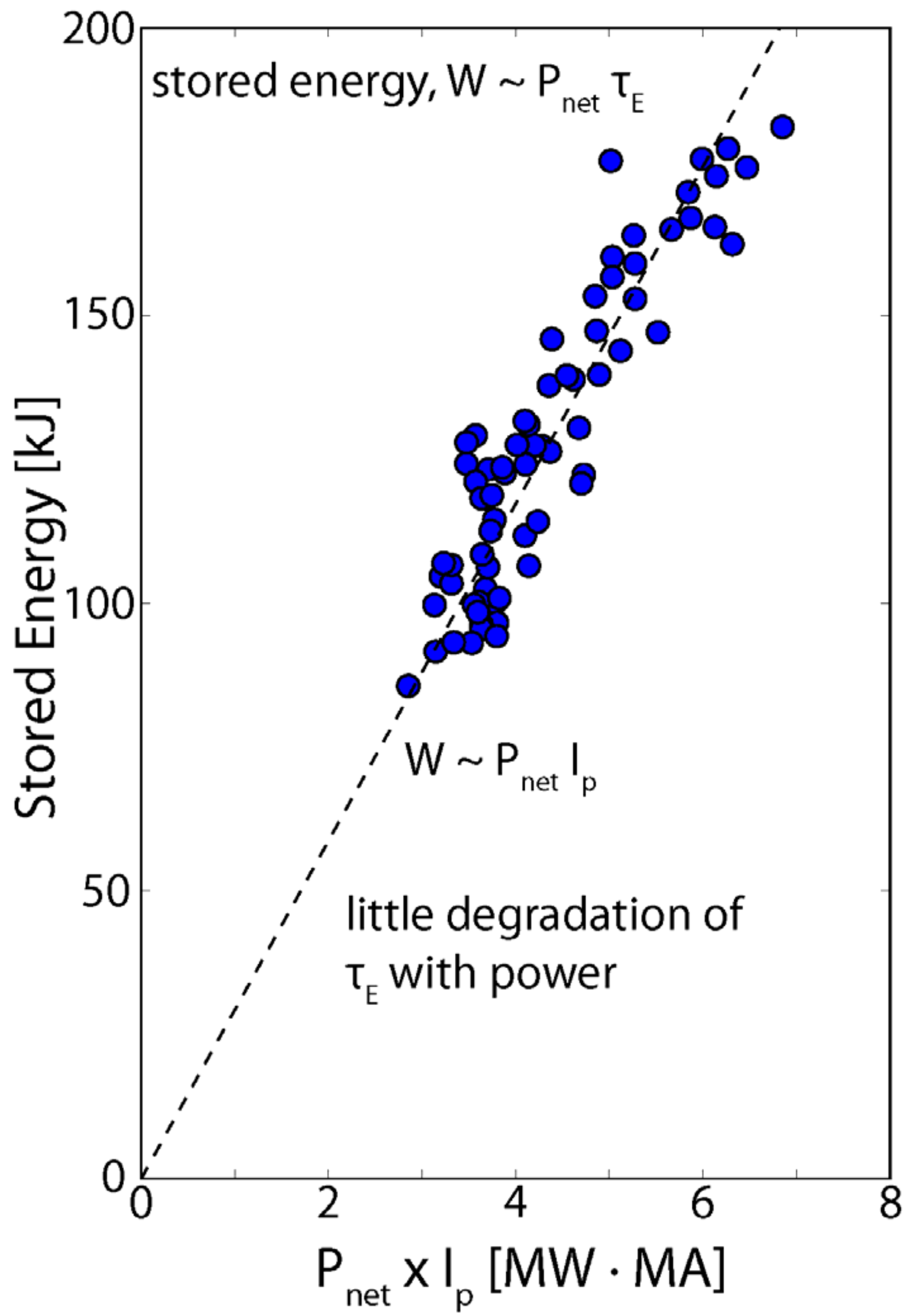
  - window expands with **B**x∇B drift away from X-point



A.E. Hubbard, et al., EX/P6-18

I-mode: Confinement does not degrade with input power

- C-Mod experiments show $P_{L\text{-}I} \propto n$, τ_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



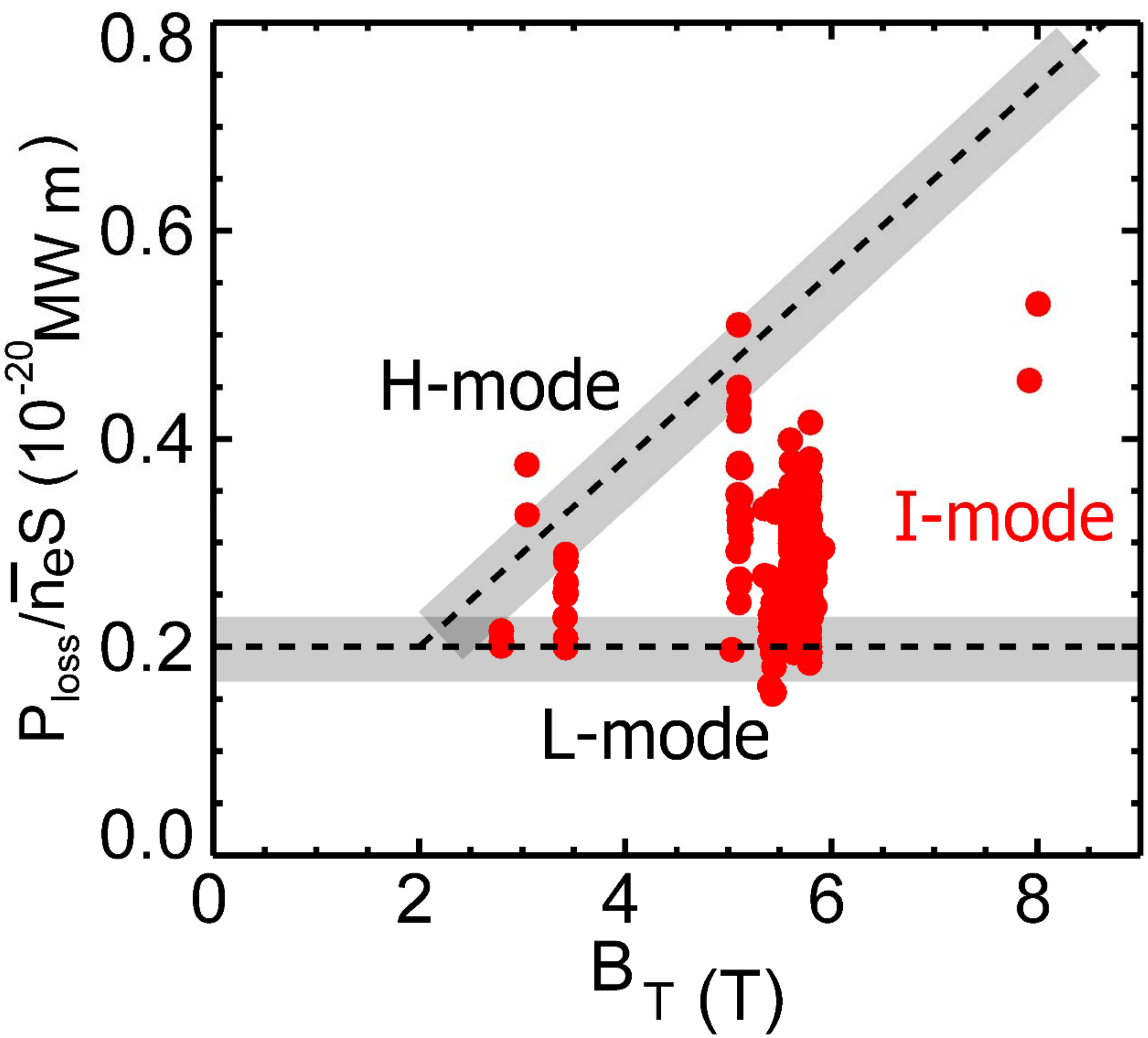
A.E. Hubbard, et al., EX/P6-18

I-mode: Threshold independent of B; power window widens at high fields

- Overall approximate threshold scaling

  $P_{L\text{-}I} \sim n \times S$

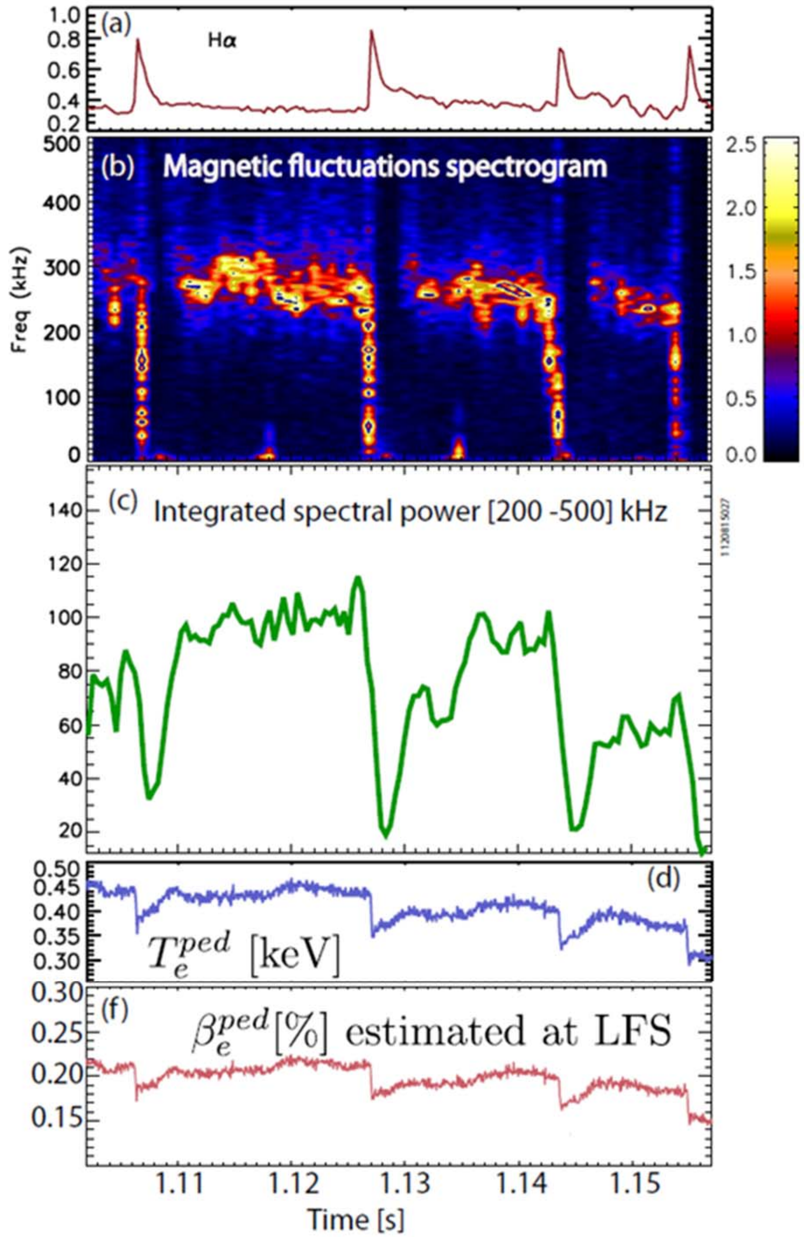
- C-Mod data indicate $P_{L\text{-}I}$ ~independent of B
- H-mode threshold increases with B
  - Strongly favors high B for I-mode
- May help explain narrow I-mode power windows on DIII-D and AUG
  - also seen at 2.8 tesla on C-Mod
- Favorable for prospects on ITER (B=5.3 T)



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



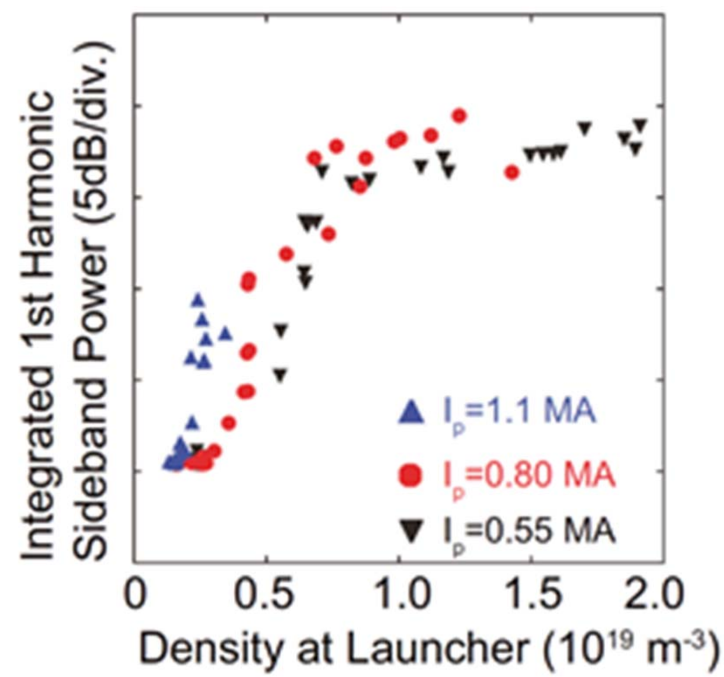
*P. Snyder, et al., Physics of Plasmas, 9 (2002) 2037

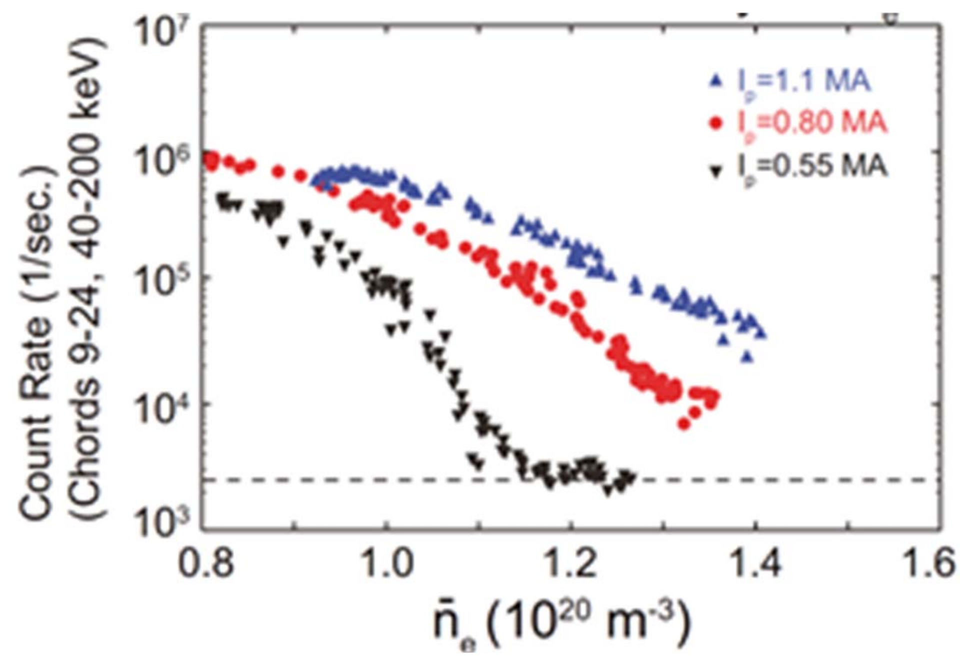
A. Diallo, et al., EX/3-2

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

Alcator C-Mod

- For n_{ave}~$0.5x10^{20}$ m^{-3}, LH current drive efficiency, $\eta = n_{20}IR/P = 0.25$ A•m/W, in line with simulations
- Fast electron production and η 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]





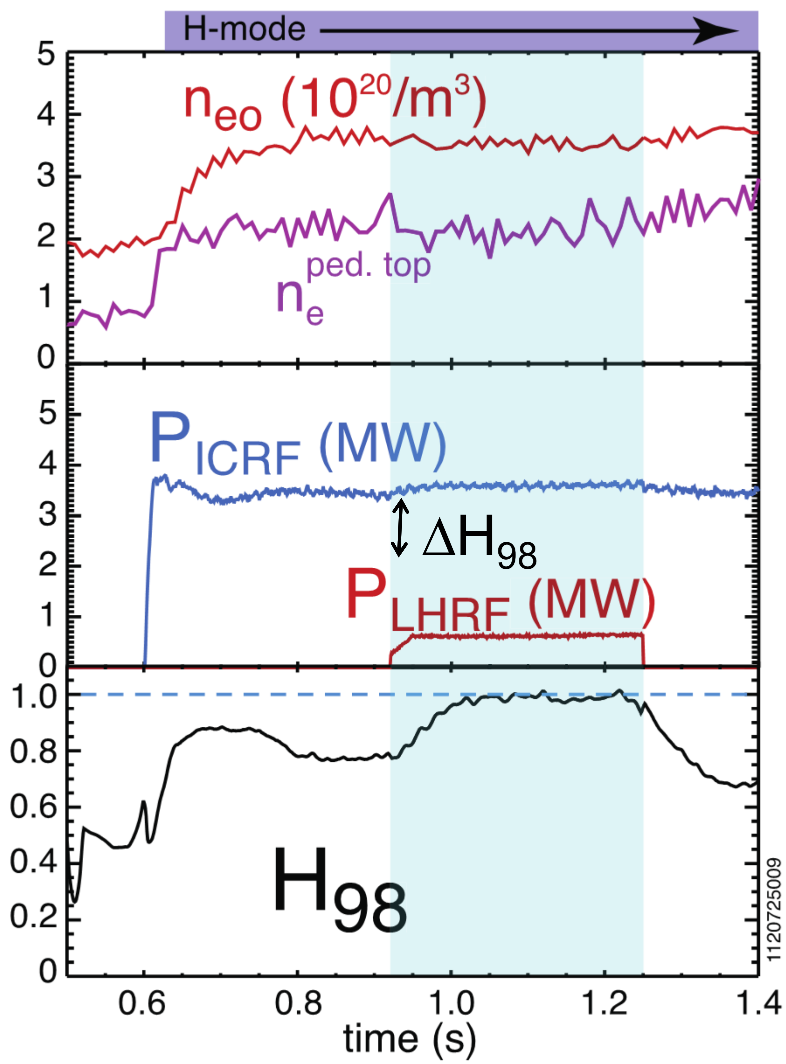
[1] *R. Parker, et al., EX/P6-17*

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

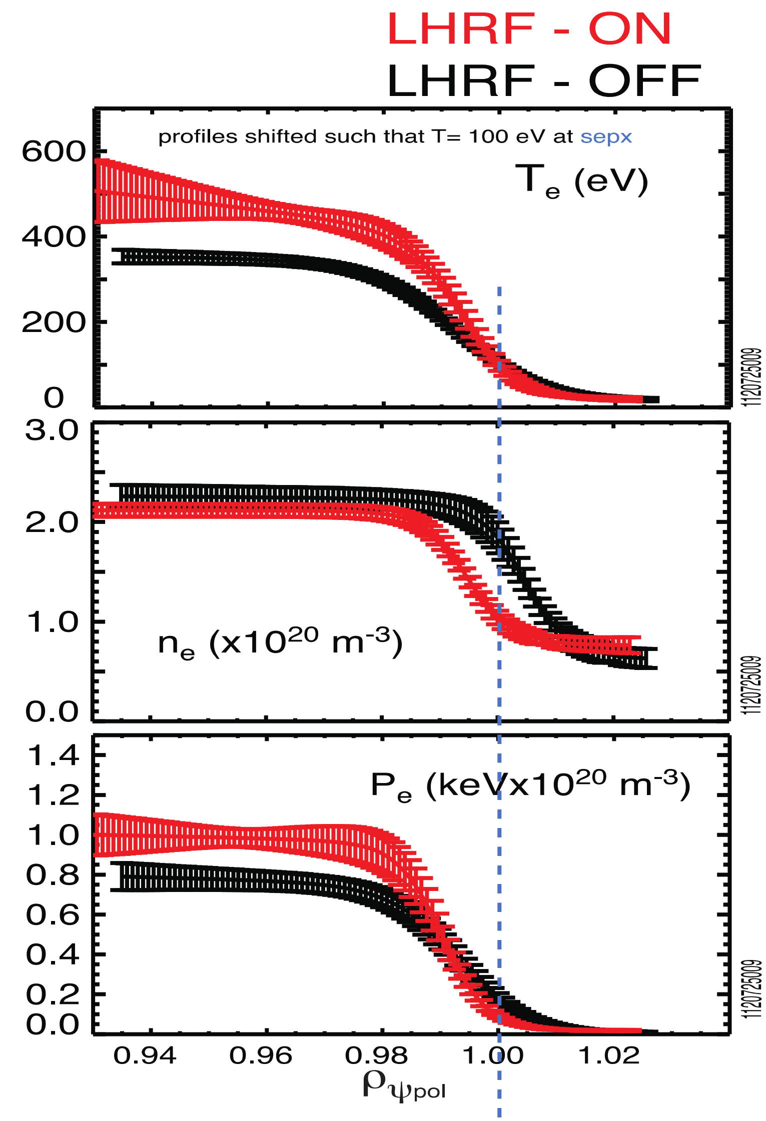
Confinement improves with injection of LHRF into high-density H-modes

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_{tot}

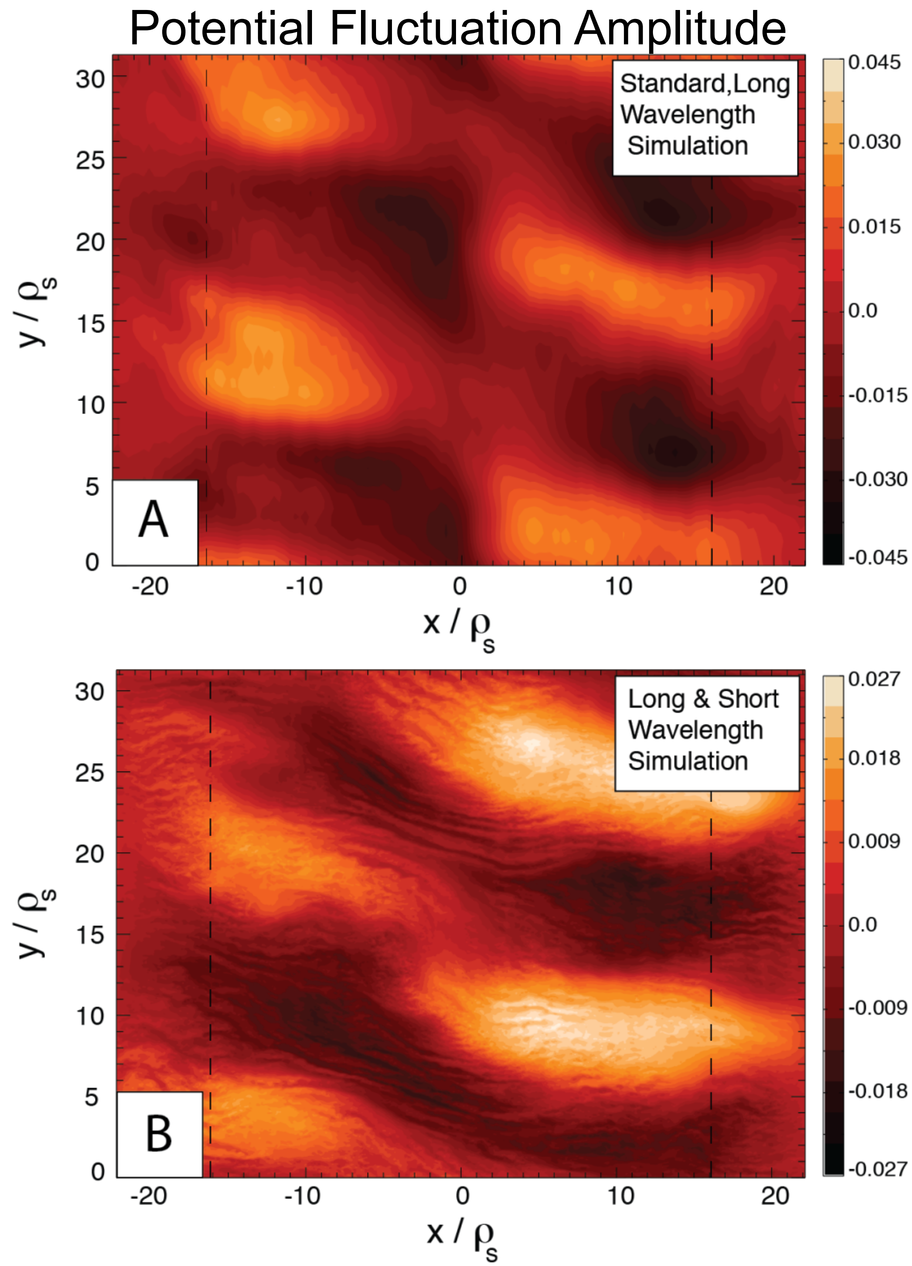


Pedestal Profiles



Electron Scale Turbulence Coexists with Ion Scale Eddies

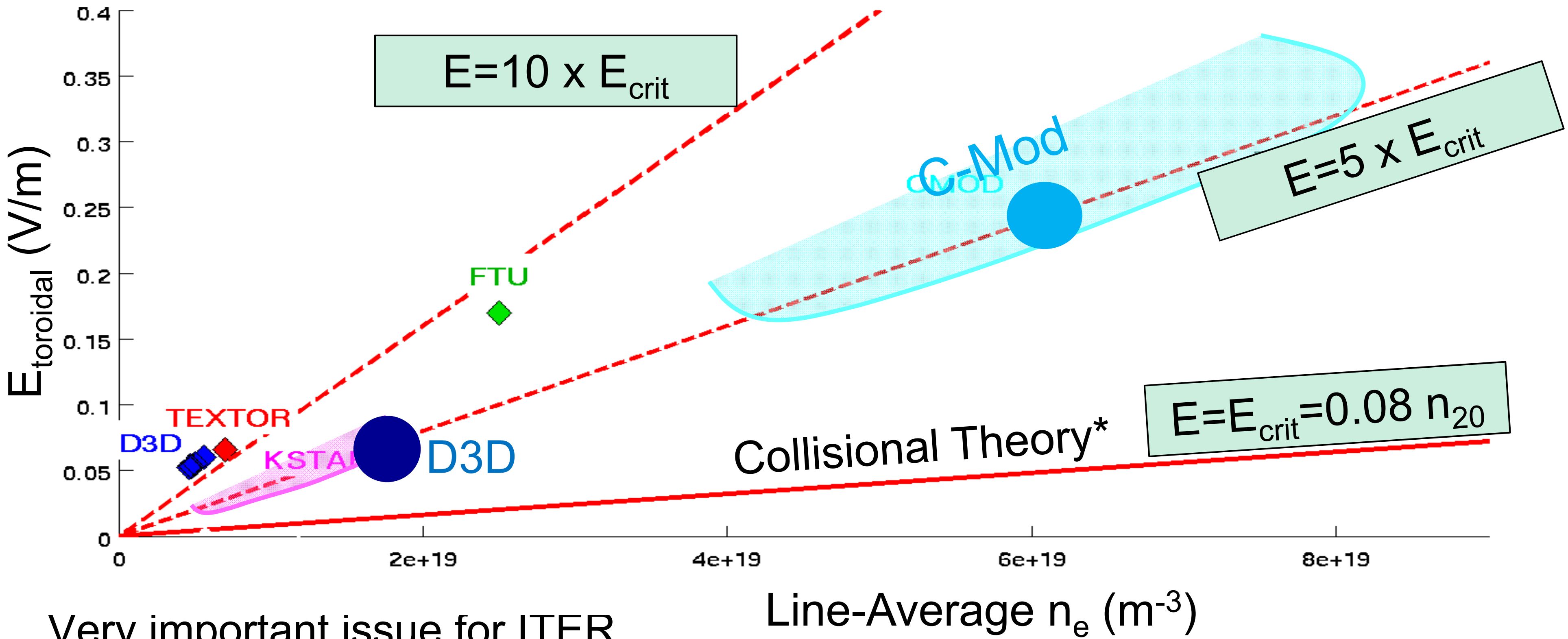
- Core electron heat transport still not well understood
  - very important for ITER and reactors
- Gyrokinetic simulations can underpredict χ_e
- First GYRO simulations using realistic experimental profiles & mass ratio, with both ion and electron spatio-temporal scales, show:
  - electron scale turbulence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



N.T. Howard, et al., Submitted to Phys. Plasmas (2014)

Runaway electron suppression requires much less density than expected from collisions

Alcator C-Mod

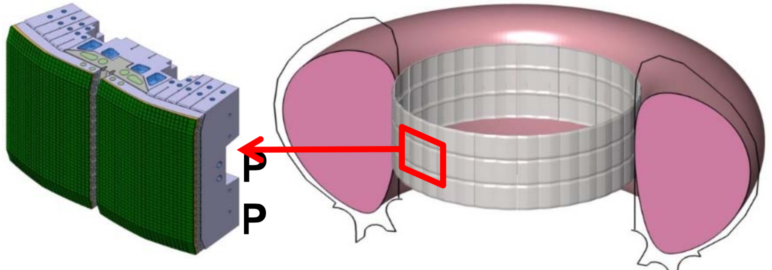


- Very important issue for ITER
  - Runaways must be quenched during disruptions
  - Reaching densities required for collisional suppression challenges mitigation technologies and pumping system
- ITPA joint experiments indicate challenge may be reduced
  - Anomalous loss process(es) dominate (~5x reduction in required density)
  - Mechanism(s) not yet identified

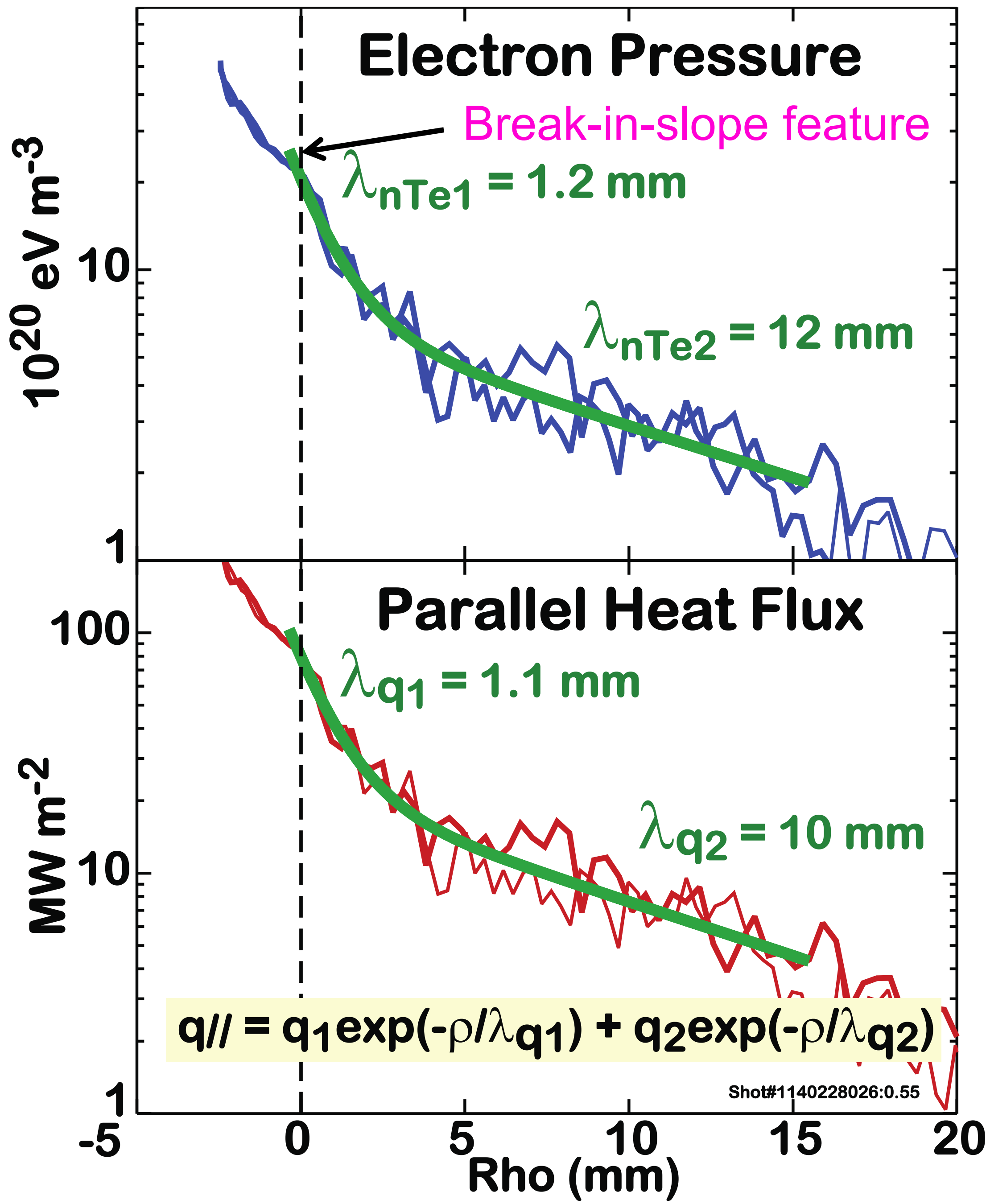
*J.W. Connor, R.J. Hastie, Nucl. Fusion **15** (1975) 415

R.S. Granetz, et al., EX/5-1

ITER inner-wall redesigned to deal with very narrow near SOL λ_q



- ITER inner wall originally designed assuming λ_q = 50 mm
- Measurements (JET, COMPASS, TCV, DIII-D) indicate narrow λ_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 λ_q<2 mm
- ITER has redesigned inner wall PFC tile shape to accommodate

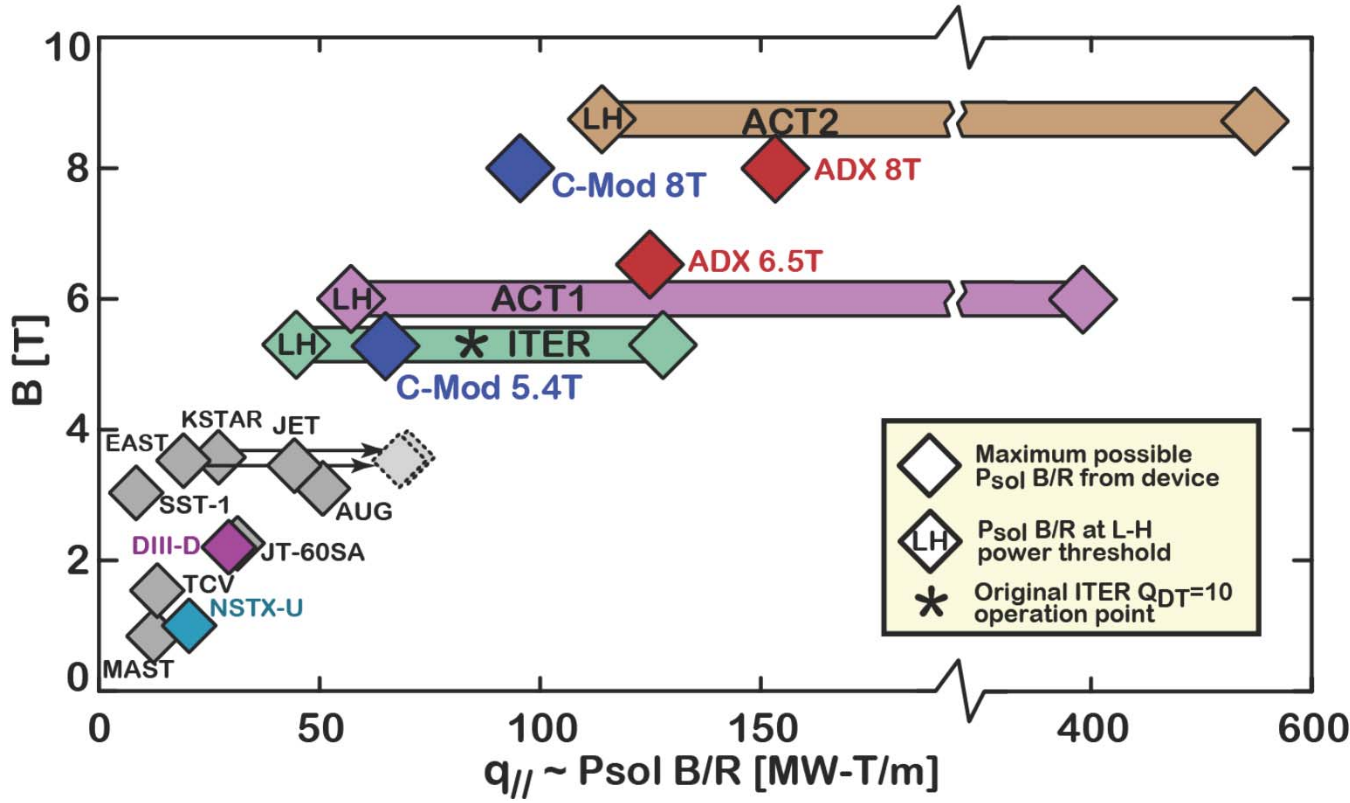


T. Golfinopoulos, et al., EX/P6-19

Key Challenges for the Future: Linked to High Magnetic Field (High Density, Power, Current Drive)

Alcator C-Mod

- **Exhaust/PMI**
  - Recent results project to very narrow power exhaust channel (~1 mm in ITER and DEMO)†
  - $q_{||} \sim P_{SOL} B/R$
  - DEMO ~4x$q_{||}$ 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)**

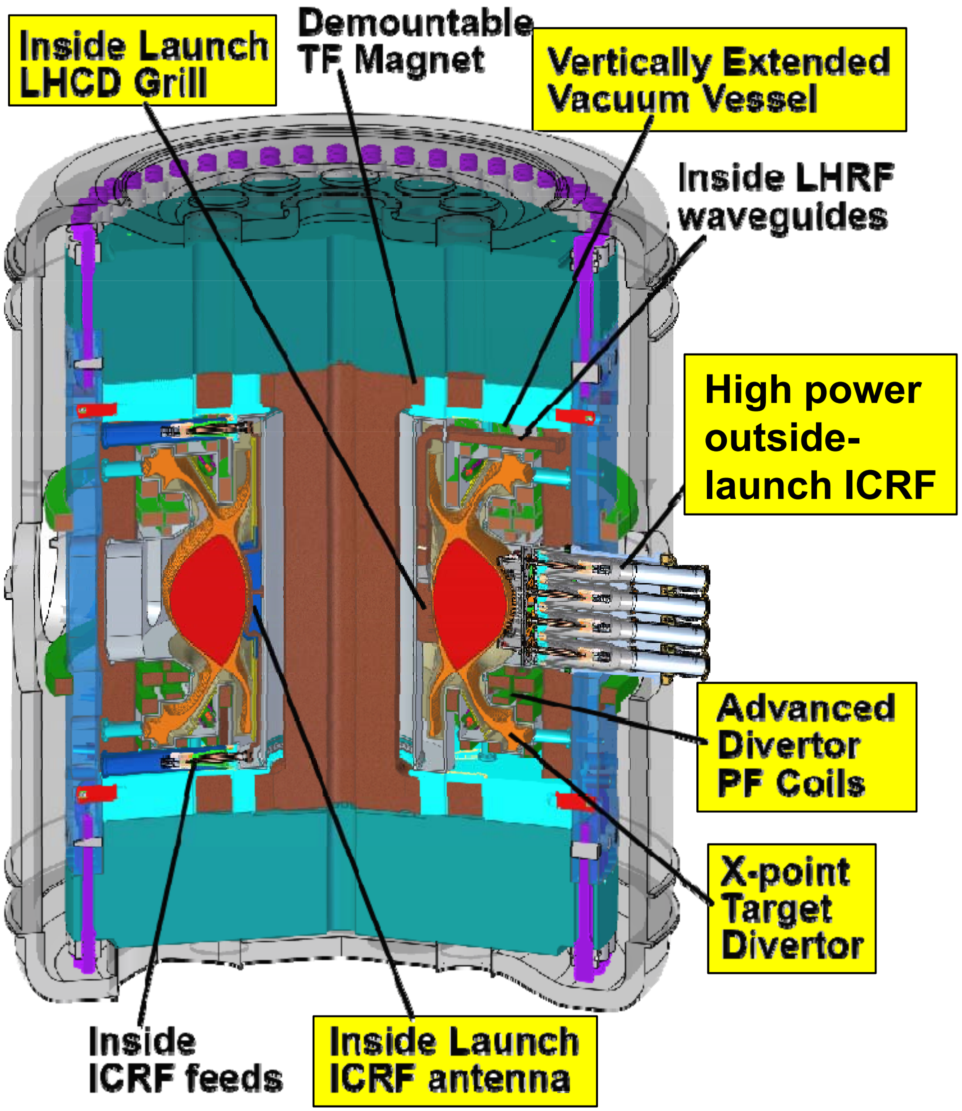
**B. LaBombard, et al., FIP/P7-18*

***R. Parker, et al., EX/P6-17*

†T. Eich, et al., J. Nucl. Mater. **438**(2013)s72.

ADX -- *A high-power, advanced divertor national test facility, using Alcator magnet technology*

Advanced Divertor Experiment



$B = 6.5$ T

$I_p = 1.6$ MA

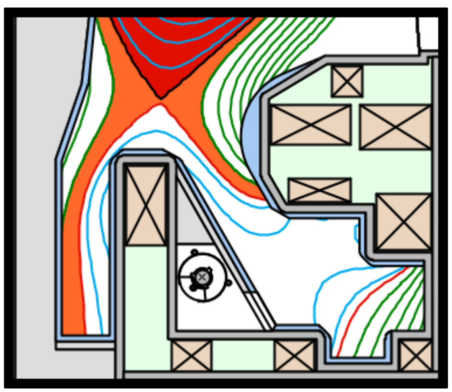
$R/a = 0.7/0.2$ m

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

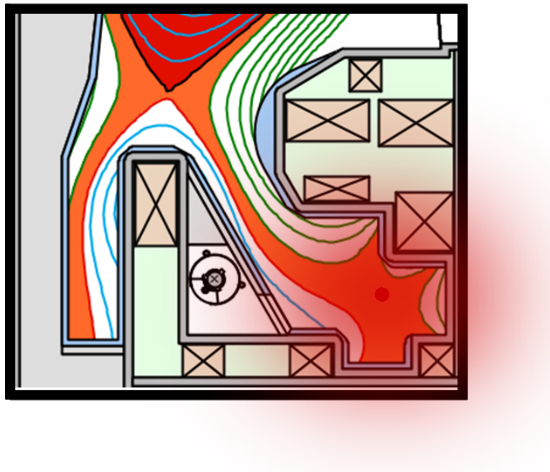
  P_{sol} B/R ~ 125
  => above ITER, Q_{DT}=10 operating point (90)

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

Vertical Target



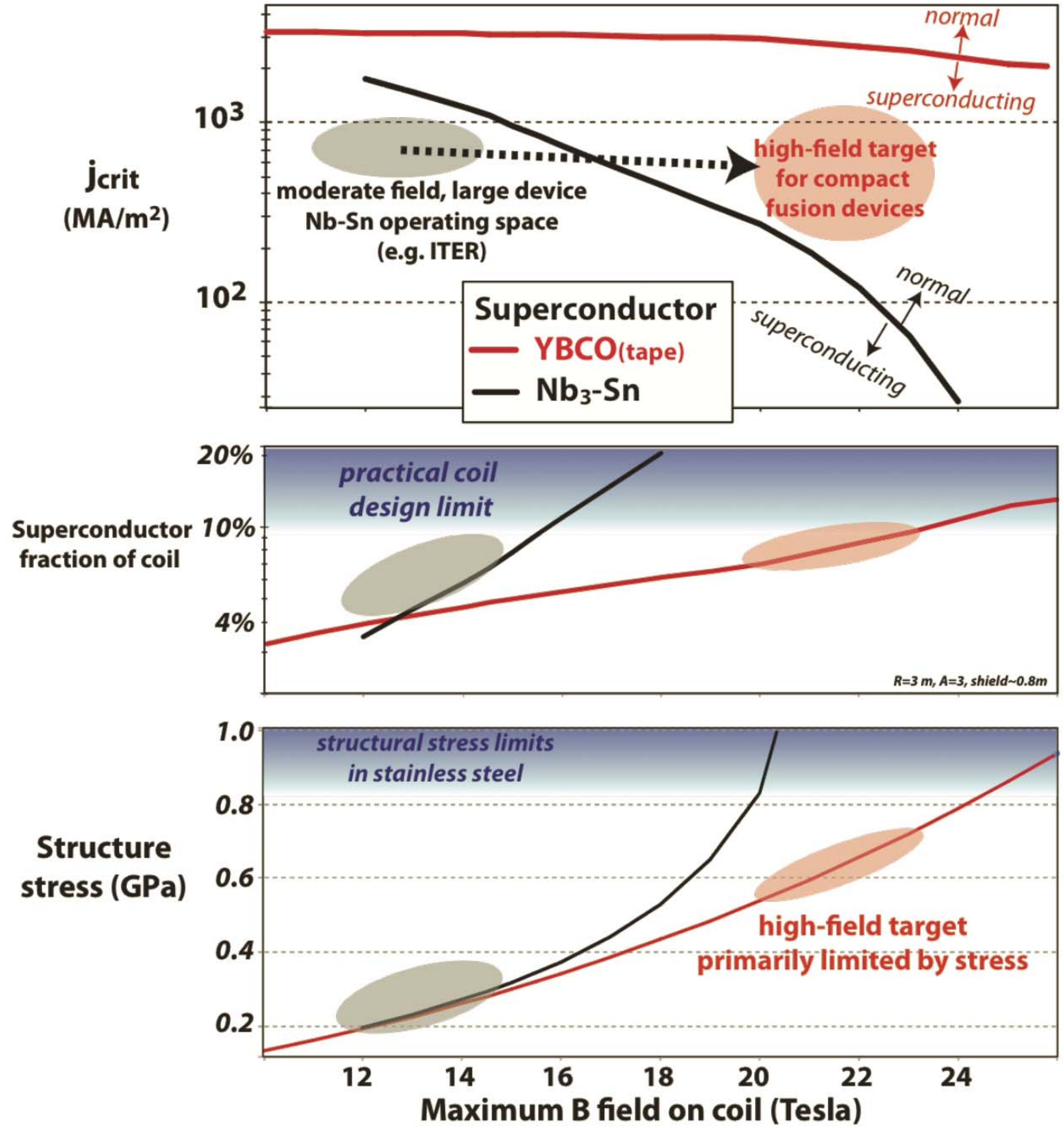
X-point Target



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

High Temperature/High Field Superconductors: Game-Changer for Fusion Energy Development

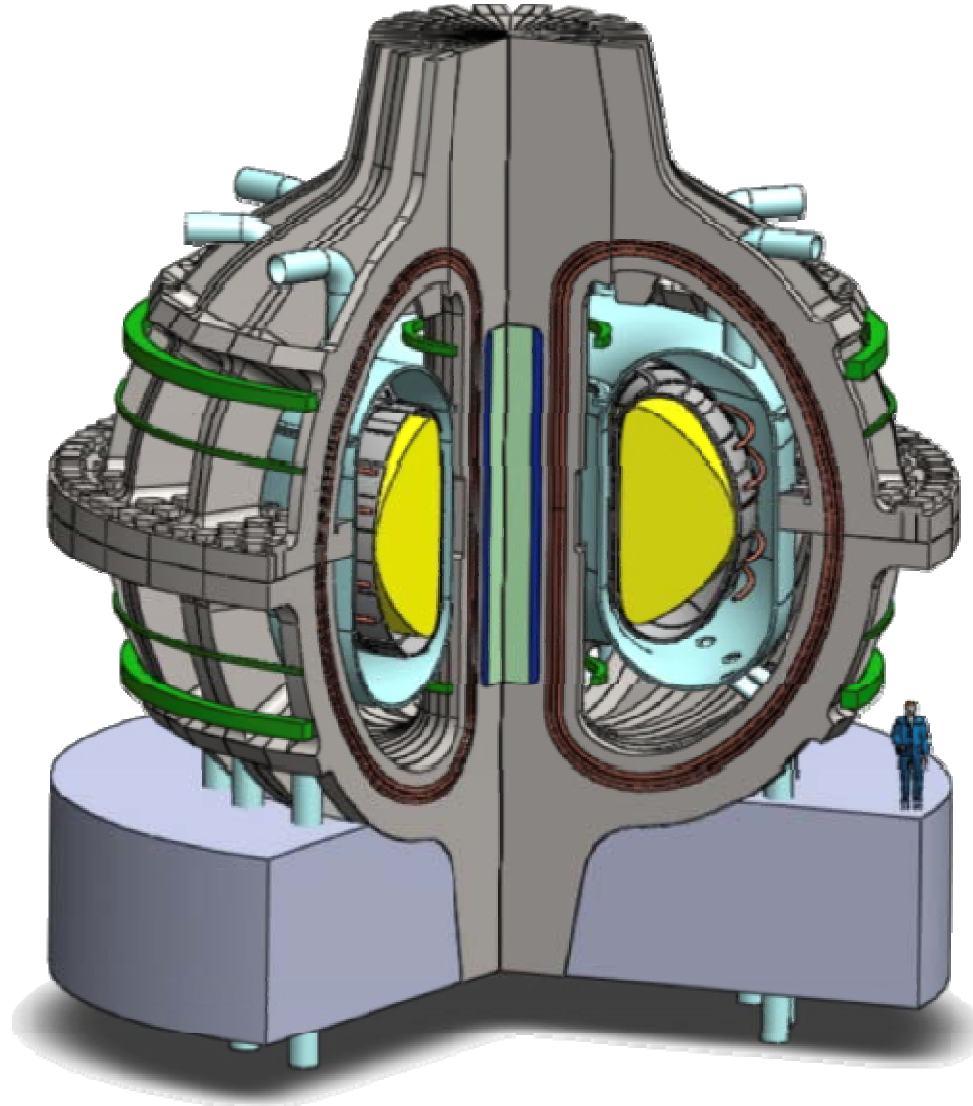
- Conventional (Nb_3Sn) superconductors limit field at the coil to ~14T
  - implies large burning plasma (and DEMO) designs, with B~5T at plasma
- Recent developments in high-temp SC technology (e.g. YBCO) dramatically opens the design space
- Doubling the field allows for smaller reactor design
  - more economical, and tractable steps



ARC*: 10 tesla superconducting FNSF/Pilot

Alcator C-Mod

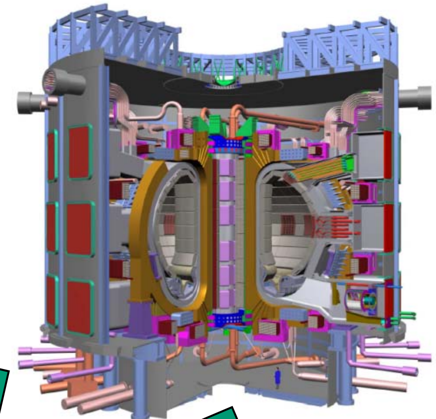
- Emerging Technology
  - Combines high-field, high temp. YBCO SC technology with liquid blanket
- Superconducting JET at 10 tesla
  - Net electric production ~200 MW ($Q_{eng.}$~4)
- 20 ^{0}K magnet operation
  - Can incorporate joints with acceptable thermal losses
- Demountable coils
  - Eases maintenance,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

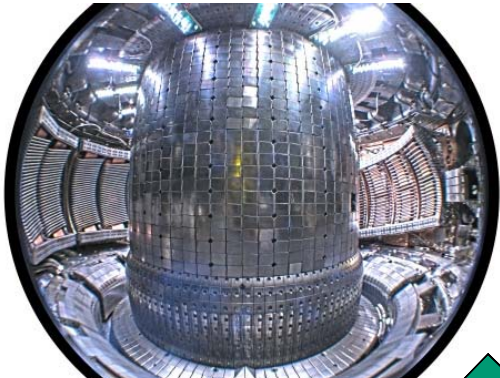


*B. Sorbom, et al., *ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets*, Submitted to Fus. Eng. Design, Sept, 2014.

High-Magnetic Field Development Path

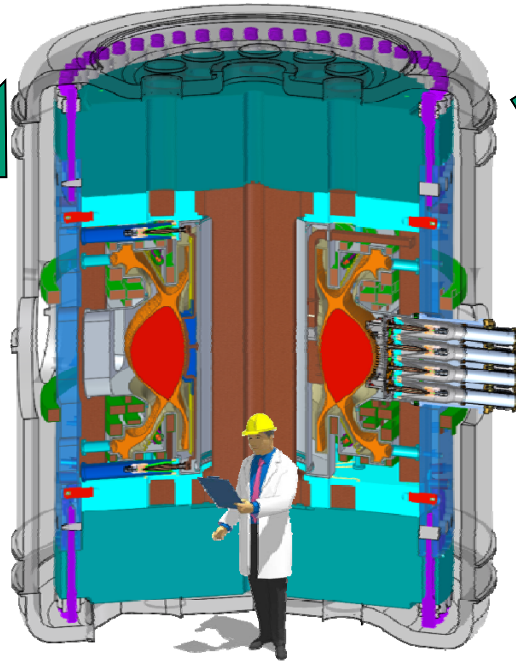
ITER

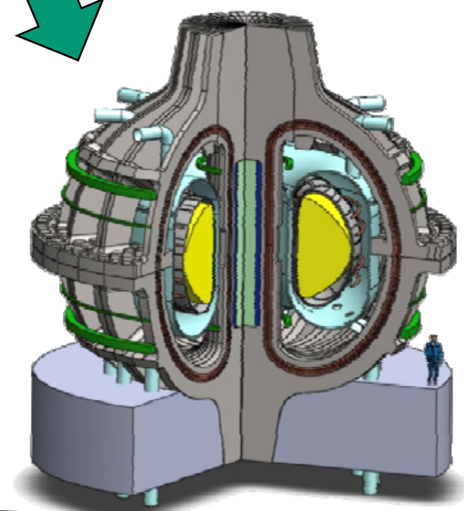




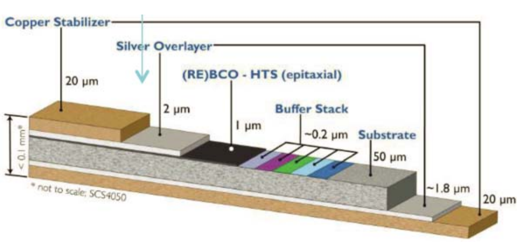
C-Mod

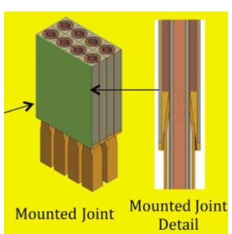
ADX





FNSF/
DEMO





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