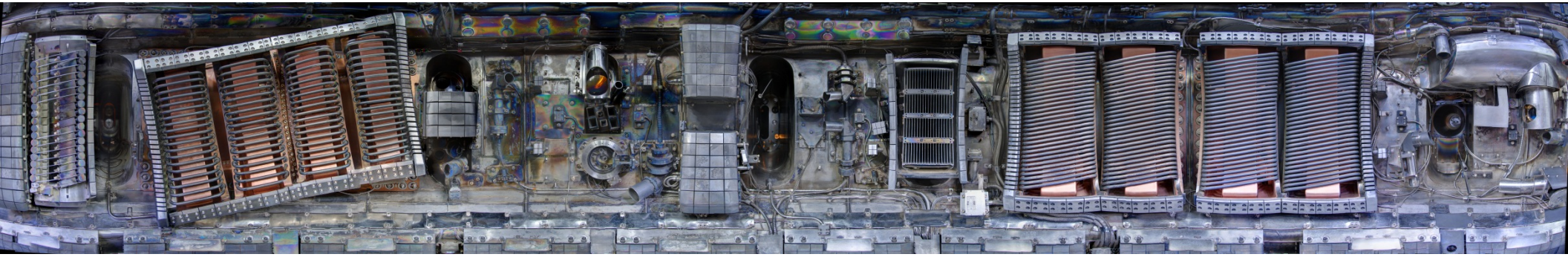


Successful Completion of Alcator C-Mod and Transition to a New, Advanced Divertor Facility

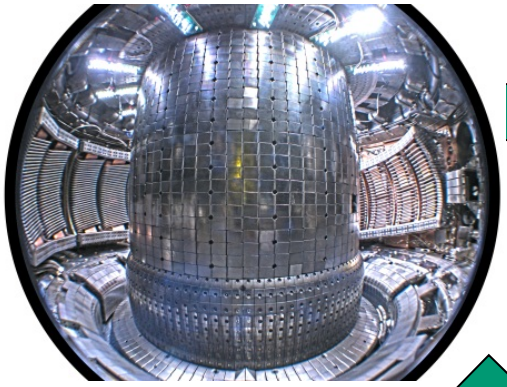
Maintaining World Leadership on the High Magnetic Field Path to Fusion

Earl Marmar for the Alcator Team

Presentation to FESAC Strategic Planning Panel, July 8, 2014

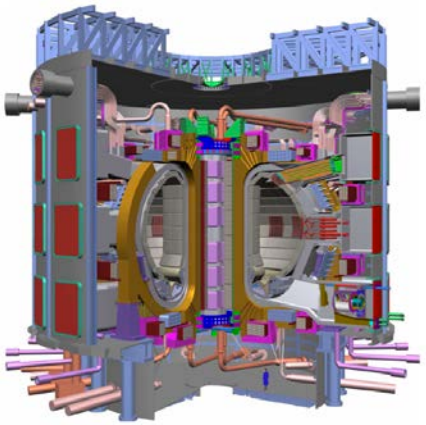
The High-Field Approach to Magnetic Fusion Energy

Path to attractive high-field, compact pilot plant/reactor*

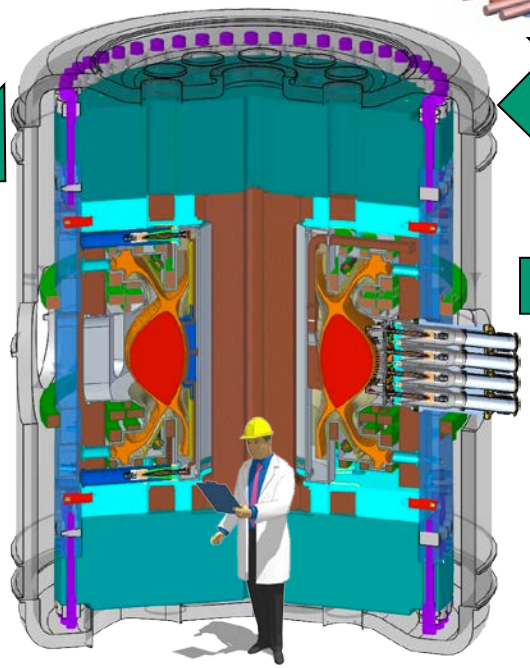


C-Mod

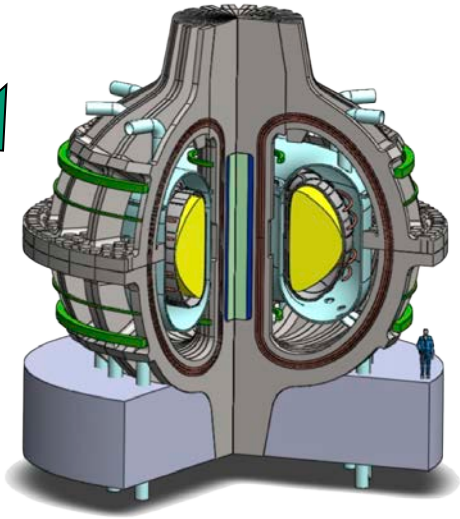
ITER



ADX



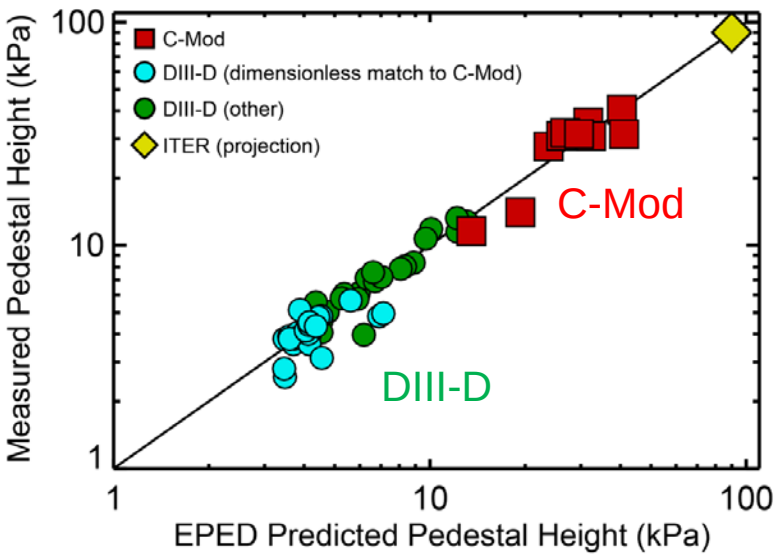
FNSF/ Pilot

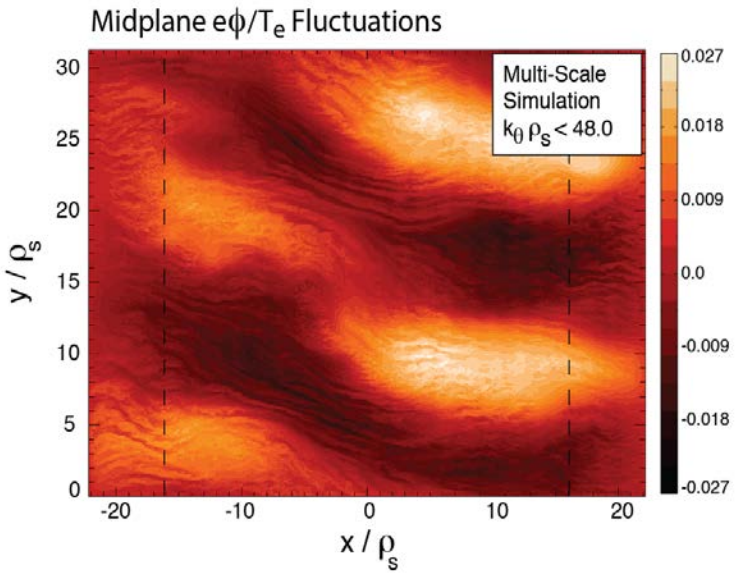


*D. Whyte, B. LaBombard, J. Minervini, FESAC Strategic Planning Presentations, June, 2014

Alcator C-Mod is Unique in the World

- Alcator C-Mod is the only tokamak in the world combining reactor-relevant parameters and tools:
  - Magnetic field to 8 T
  - Plasma density $5x10^{19}$ – $5x10^{20}$ m^{-3} (fully equilibrated electrons/ions)
  - All metal PFC's
  - High power density (P/S ~ 1 MW/m^2, PB/R~60 MW-T/m)
  - All RF auxiliary heating, current and flow drive
    - Electron dominant heating, low/no torque, no core fueling
- Due to its reactor power density and field, Alcator accesses local divertor plasma parameters not available to any other tokamak or linear plasma in the world
  - Extremely high flux densities, recycling and short ionization MFP physics
  - Grazing B field with aligned high-temperature tungsten divertor
  - Reactor-matched "drives" for erosion rate, redeposition, temperature effects
  - Covers unique parameters space for SOL/PMI in worldwide program
    e.g. heat width dependence, detachment, stability





The National Alcator Team is as Scientifically Productive as any in the World

- Publications/Citations (2009-2014):*

	Alcator C-Mod	Totals for the 3 Major OFES User Facilities
Articles	200	983
FY2014 Budget	22.3	159.8
Articles per $Million	**9.0**	6.2
Total Citations	1426	6983
per article	7.1	7.1
per $Million	**63.9**	43.7
External Citations	919	4343
per article	4.6	4.4
per $Million	**41.2**	27.2

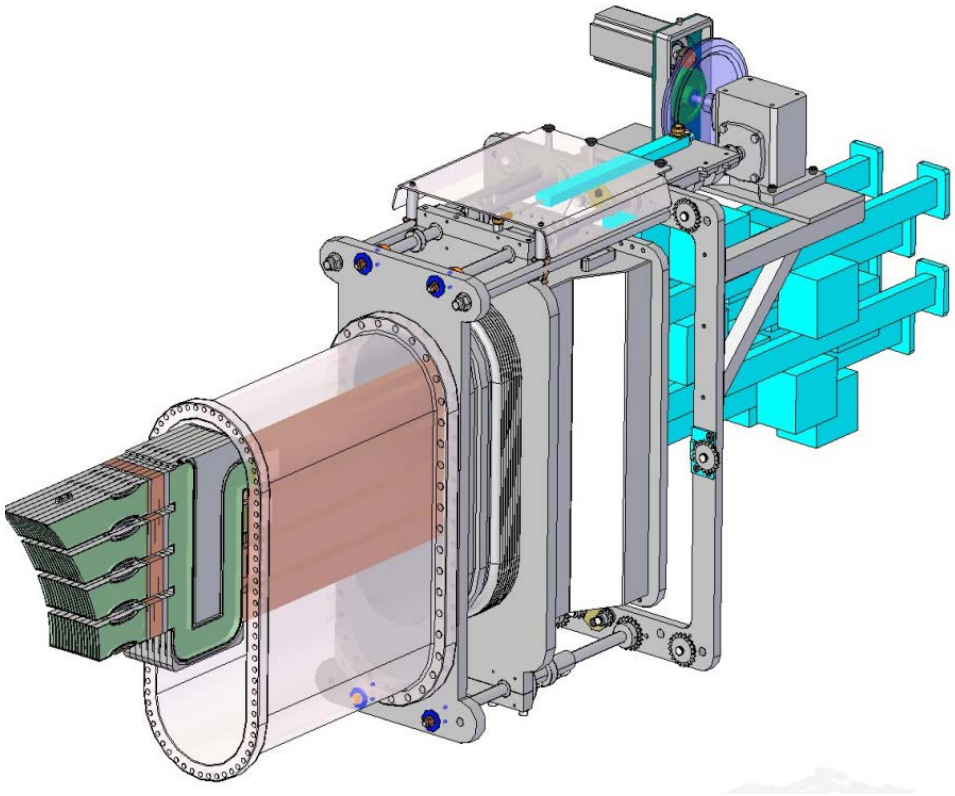
*Relevant articles were identified by searching the Web of Science database for items published in the past five years meeting the following criteria: Topic contains the facility name, and at least one author's address equals facility location (e.g., Topic="C-Mod", Address="Cambridge").

The National Alcator Team is as Scientifically Productive as any in the World

- Two of the 4 most recent Nuclear Fusion Journal awards for outstanding paper went to C-Mod first authors:
  - 2013 – Dennis Whyte, et al., *I-mode: an H-mode energy confinement regime with L-mode particle transport in Alcator C-Mod*
  - 2010 – John Rice, et al., *Inter-machine comparison of intrinsic toroidal rotation in tokamaks*
- Anne White, 2014 winner of the APS-DPP Katherine E. Weimer Award *For fundamental contributions to the understanding of turbulent transport in tokamaks through development and application of electron cyclotron emission diagnostics and insightful comparison of plasma fluctuations with gyrokinetic simulation predictions.*
- Miklos Porkolab, 2013 winner of the EPS Hannes Alfven Prize *For his seminal contributions to the physics of plasma waves and his key role in the development of fusion energy*
- **In concert with MIT academic programs, Alcator C-Mod is a major educator of the next generation of plasma physicists and fusion scientists**
  - **Trained over 170 graduate students to date**

Near-term C-Mod Upgrades: Answer Key Questions for ITER and FNSF

- With addition of off-axis LH launcher (incremental) , and installation of new klystrons (ARRA-funded) many important new investigations enabled
  - Double available coupled power
  - Enable fully non-inductive operation across wider range of n_e and I_p (e.g. 1 MA at $5x10^{19}$ m^{-3})
  - Explore predicted quasi-linear damping synergy between different $n_{||}$ launched from the 2 arrays
- $800k required to complete ($2.5M already spent)
- Operation in FY16

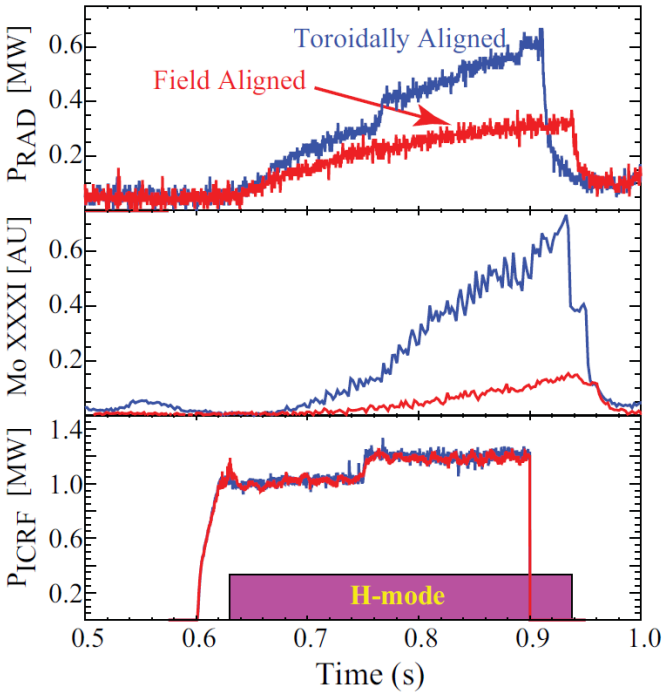


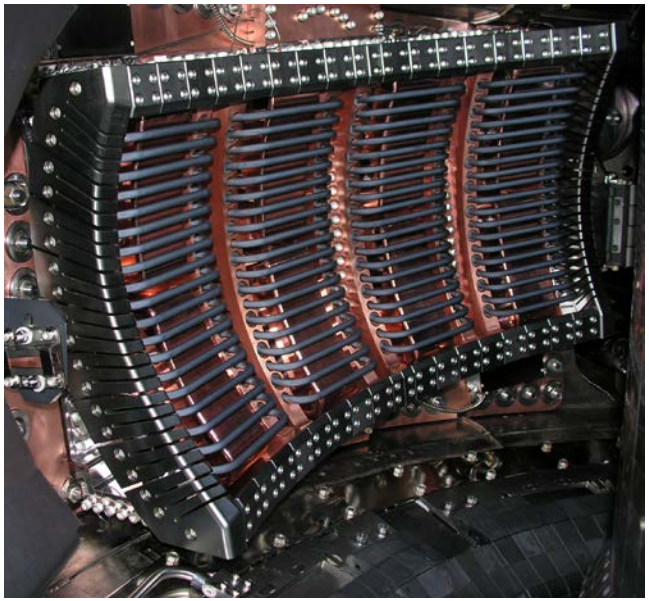
Near-term C-Mod Upgrades: Answer Key Questions for ITER and FNSF

Field-Aligned (F-A) ICRF antenna – may solve ICRF impurity challenge

Initial results with first F-A antenna show dramatic decrease in metallic impurity sources, core contamination and radiated power

- 2nd F-A antenna nearly complete
  - $250k remaining costs
- Installation for FY15 operation:
  - full power for optimal heating and flow drive



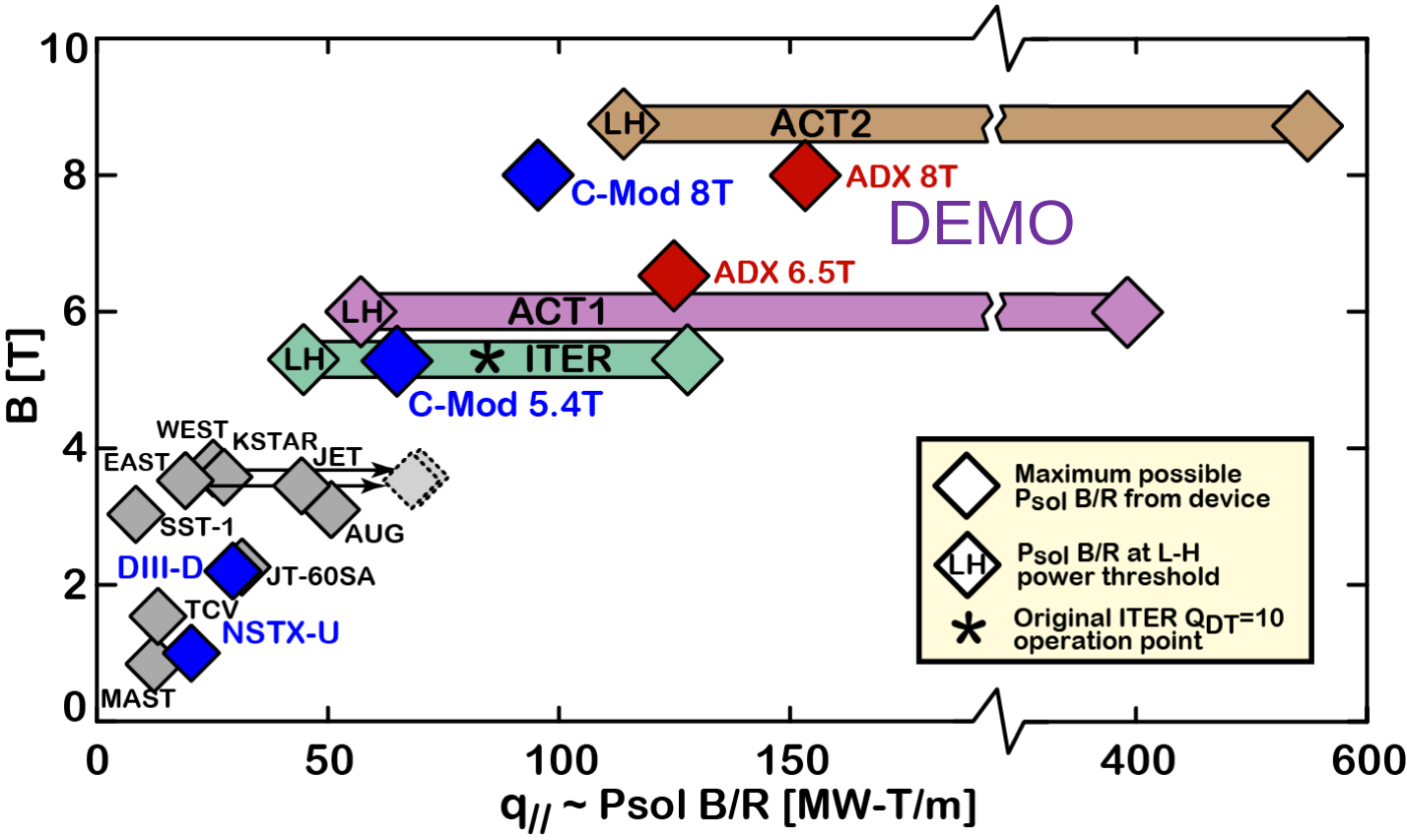


Near-Term C-Mod Research to Answer Key Questions

- Divertor/PMI
  - Full exploitation of vertical target high-Z solid metal target (ITER)
    - — Power handling, retention, erosion, impurity sources, detachment
  - Direct comparison of vertical target/snowflake (ADX, FNSF)
- RF heating, current drive, flow drive
  - Full exploitation of advanced field-aligned ICRF (ADX, FNSF)
    - — heating, flow drive, confinement
  - Addition of off-axis Lower Hybrid launcher (ITER, ADX, FNSF)
    - — full power capability, fully non-inductive at 1 MA & reactor density, exploit synergy of on- plus off-axis launch physics
- ELM free pedestal physics (ITER, ADX, FSNF)
  - Full exploitation of naturally ELM-suppressed confinement regimes
- Disruption mitigation, runaway electron dynamics (ITER)
  - at ITER density, field, plasma pressure

Two Highest Priority Issues* for FNSF/Pilot: **PMI and Steady-State Sustainment**
Requires New Facility — ADX

- Since 2007, we've learned that the **PMI** challenges have gotten even bigger
- New results imply $q_{||}$~PB/R
- As envisioned DEMO needs to handle PB/R between 100 and 300 (c.f. 60 on C-Mod)
- Zero net erosion requires divertor plasma temperature below 5 eV (or liquid metal PFCs)

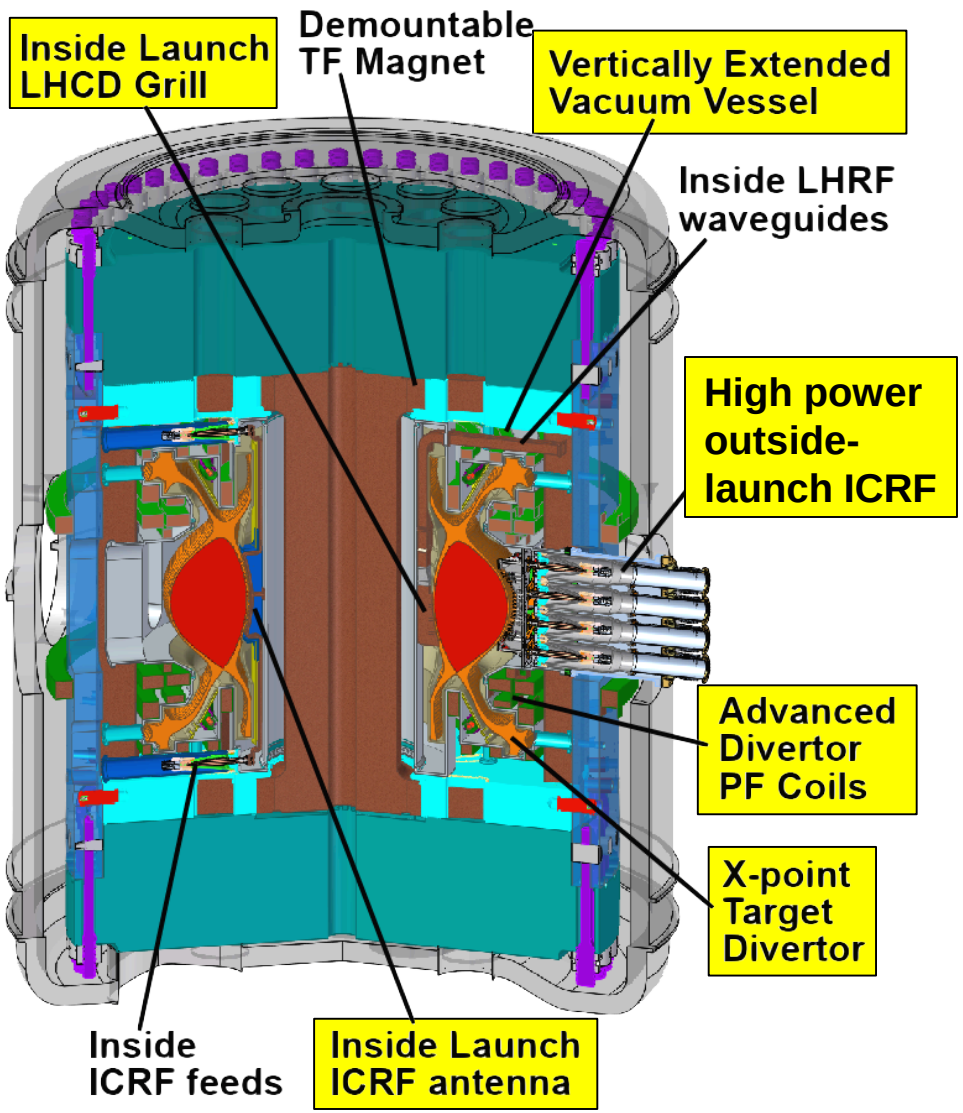


- Need reactor compatible actuators (not beams) for **steady-state sustainment** (or 3D/stellarator configurations)
- Inner-wall launch RF is an attractive candidate, that needs to be proven

*Priorities, Gaps and Opportunities, FESAC, Oct. 2007

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

Advanced Divertor Experiment

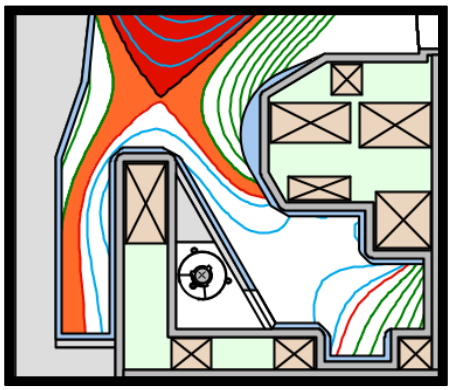


- Development platform for Advanced Divertors
- Reactor-level $q_{||}$, B, plasma pressures

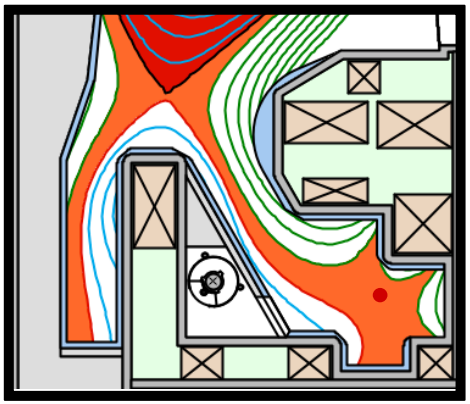
  P_{sol} *B/R ~ 125*
  => above ITER, Q_{DT}=10 operating point (90)

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

Vertical Target



X-point Target



Transition from C-Mod to ADX

- Highest priority C-Mod research can be completed in the next few years
- In parallel, we are ready to begin ADX engineering design now
  - 2 year activity, prior to start of construction
  - cost is $1.5m/year
- Construction estimates (based on C-Mod experience)
  - 4 years @$17M/year (hardware + personnel)
- During construction, MIT scientists (and some students) can expand participation in domestic and international collaborations
- Operations (first plasma 6 years after start of engineering design) @$25M/year (including national collaborations)
  - Need continuous transition, or risk permanent loss of engineering expertise
- No increase in funding (relative to FY2012) required
- Continue critical ITER support aimed at operations
- Train students for the US ITER team (needed ~2025 and beyond)

Specific Recommendations

- Fund Alcator C-Mod for near-term high priority research
  - Funding sufficient for at least 15 weeks of operation per year, and implementation of targeted upgrades and diagnostics to complete its mission ($23M/year, including collaborations)
- Complete the ADX engineering design (@$1.5M/year for 2 years), starting in FY15
- Begin construction of ADX when Alcator C-Mod completes operations
- Related presentations and white papers:
  - Whyte: *Exploiting high magnetic fields from new superconductors for a faster, more attractive fusion development path*
  - LaBombard: *A nationally organized, advanced divertor tokamak test facility is needed*
  - Goldston: *A strategy for resolving problems of plasma-material interaction for FNSF*
  - Catto: *Unique opportunities to advance theory and simulations in the Advanced Divertor Experiment*
  - Parker: *RF actuators for steady-state tokamak development*
  - Minervini: *Superconducting magnets research for a viable U.S. fusion program*