Perspectives on Priorities for Fusion Energy Sciences and The Role of Alcator C-Mod

Presentation to FESAC Priorities Sub-Panel
July 18, 2012
Bethesda, MD

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Critical Scientific Issues
For Development of Fusion Energy

- Taming the Plasma-Wall Interface
  - We must develop a sufficient understanding of plasma-wall interactions to design robust material components that interface with the hot plasma
  - ITER plans solid tungsten, with high surface temperature (1000 ^{0}C), low bulk temperature (water cooled)
  - For DEMO and reactors, need to move beyond, to high bulk temperature (thermal efficiency, retention)
- Producing Steady-State High-Performance Plasmas
  - For practical fusion energy with the Tokamak device, we need to master the science and technology required to efficiently drive current in the plasma
  - High-power microwaves in the "Lower-Hybrid" frequency regime are the only solution proposed for a steady-state tokamak reactor
  - ITER plans to explore this problem in a second research phase

C-Mod Makes a Set of Indispensible Contributions

- Support for ITER design and operation – with unique facility capabilities and unique parameters for testing theory, codes and for comparing with other experiments
- Discovery of strong self-generated plasma rotation – critical for reactor stability and confinement
- Pioneering research on the role of boundary plasma turbulence in determining edge plasma dynamics, plasma heat loads on the wall and the plasma density limit
- Pioneering research with high-Z wall materials (Molybdenum, Tungsten)
  - Demonstration of techniques for reducing steady state heat load (impurity seeding), transient heat loads (I-mode and disruption mitigation)
  - Soon – the first studies with the wall at reactor relevant temperatures (1000°K) and the first in-situ measurements of wall erosion and fuel retention
- Development of unique field-aligned RF antenna – critical for controlling plasma impurities in future devices
- Development of Lower-Hybrid current drive science and technology – at reactor relevant field, density
- Student training – a major educator for the next generation of scientists and engineers

C-Mod has a World-Leading Program Critical to the Success of ITER and the Development of Fusion Energy

- Pioneered the vertical-plate divertor and solid high-Z plasma facing components
  - Both adopted for ITER: only viable solution for high power density, low retention
  - Now taking this to the next level with high temperature tungsten: best (only?) hope for FNSF/DEMO/Reactor
- Experts on RF for heating, current drive, flow drive - plasma control
  - Unique LHCD studies at fields, densities, frequency for ITER, FNSF, DEMO
    - Only proposed solution for steady-state tokamak reactor
  - Making rapid progress on the challenge of ICRF-induced impurities: Solution(s) within view
- Discovered and developing potential solution to the ELM problem: I-mode
  - At least as credible as RMP approach (in our opinion)
- In concert with MIT academic programs, C-Mod is a major educator of the next generation of plasma physicists and fusion scientists

C-Mod PMI research: Exploit its worldwide unique match to FNSF/DEMO divertor and SOL parameters

Parameter Description	FNSF / DEMO	Alcator C-Mod	DIII-D / AUG	EAST / KSTAR	JET
Global power density, P/S (MW/m^2)	0.9 - 1	~1	~0.3	~0.25	0.24
Magnetic field (T)	6-8	5.4 - 8	~2	~2	3
Divertor density@10 eV (10^{20} m^{-3})	10-20	10-20	1	1	3
Parallel heat flux@ 10 eV (MW/m^2)	500	500	50	50	150
Ambient divertor temperature (C)	> 500	25-600	25	25-?	200
Pulse length (s)	30,000,000	3	10	<1000	10

- **Due to its reactor power density and field, C-Mod accesses local divertor plasma parameters not available to any other tokamak or linear plasma in the world**
  - Reactor-level flux densities, recycling and short ionization MFP physics
  - Grazing B field with aligned high-temperature solid 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

*Whyte, et al. FED 2012; Stangeby et al NF 2011

2012 FESAC report: Tungsten PMI research at T>500 ^{0}C with "reactor-like plasma and temperature" conditions is high near-term priority

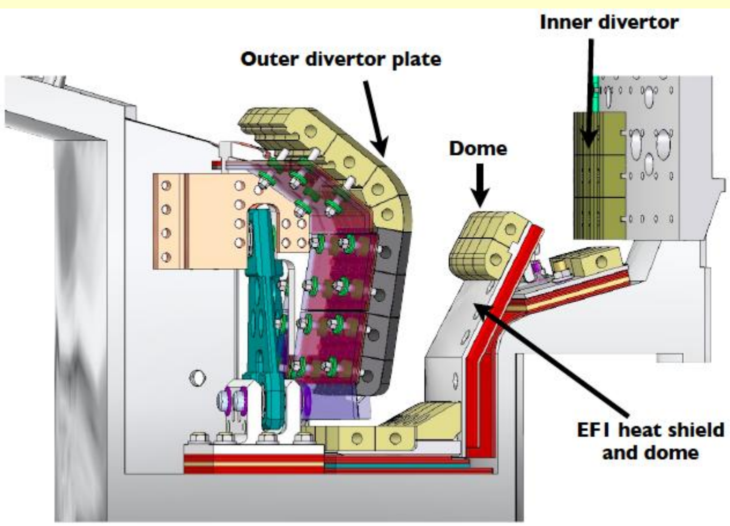
"The leading FNSF/DEMO candidate solid material to meet the variety of PFC material requirements is tungsten due to its projected erosion resistance, high melting temperature and high thermal conductivity."

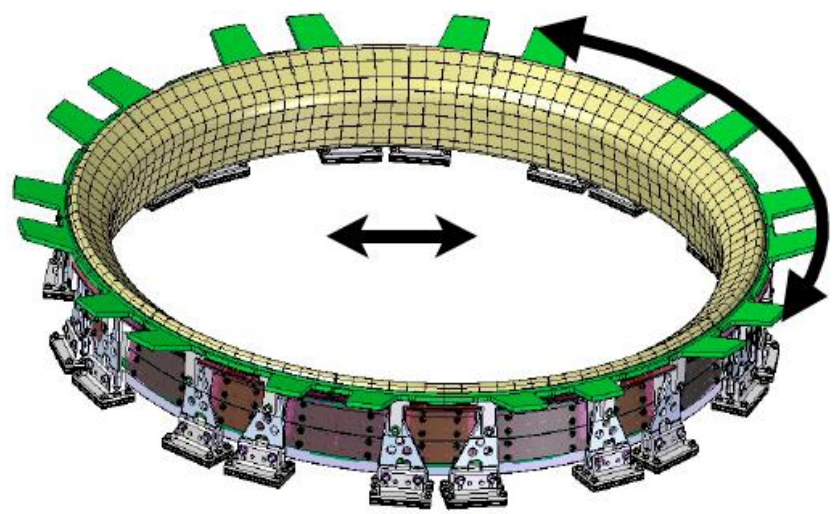
"Initiatives with the following objectives are required…characterize tungsten-based materials in appropriate plasma, thermal and radiation damage environments"

"Important considerations are the impact on the core plasma via impurities, their response to plasma particle bombardment,… their thermal performance under high heat flux and operating temperatures above 500^{o}C."

The new hot-divertor on C-Mod will provide first of a kind studies of tungsten PMI in the reactor-relevant plasma + thermal environment

Install FY13, Operate FY14





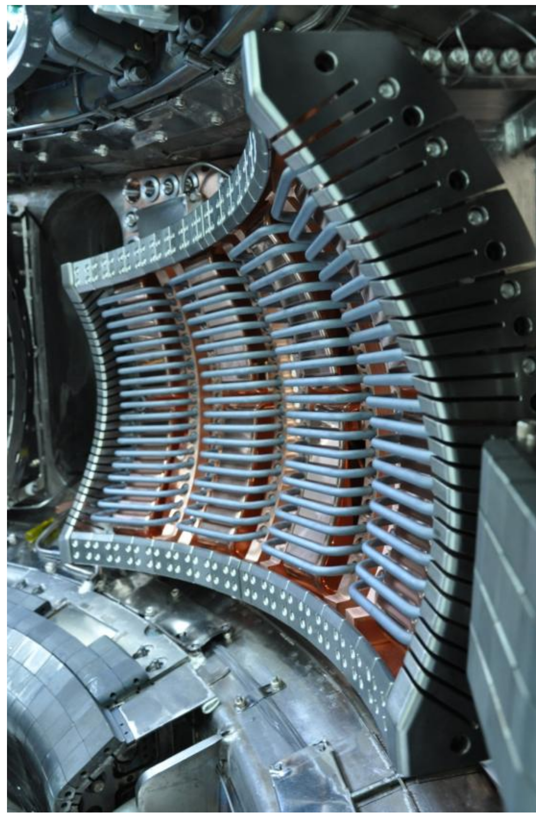
ICRF is currently one of the required heating methods for ITER and FNSF/reactor

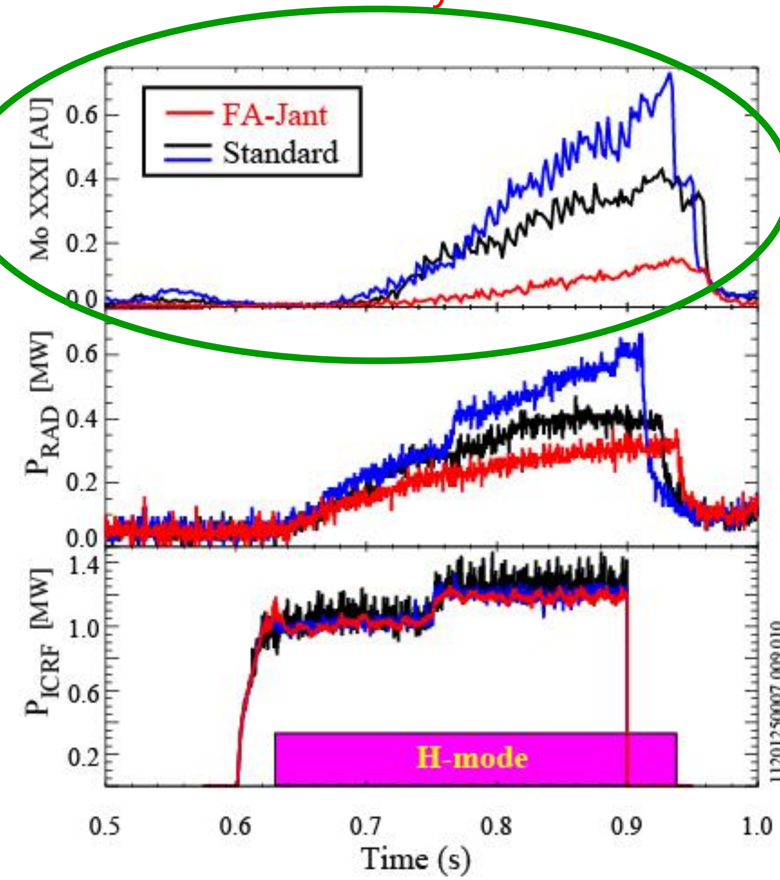
There is a long history of unacceptable high-Z impurities accompanying ICRF & no evident solution

- **C-Mod is only divertor tokamak in the world that relies primarily on ICRF for heating**
  - **Strongest tokamak team with substantial ICRF development program in the U.S.**
- **C-Mod leads the charge to understand the science and find solutions**
  - **Direct measurements of ICRF waves, plasma potential, impurity sources**
  - **Detailed comparisons with state of the art models**

The PSFC and collaborators leading efforts worldwide in understanding the underlying physics – along with model validation

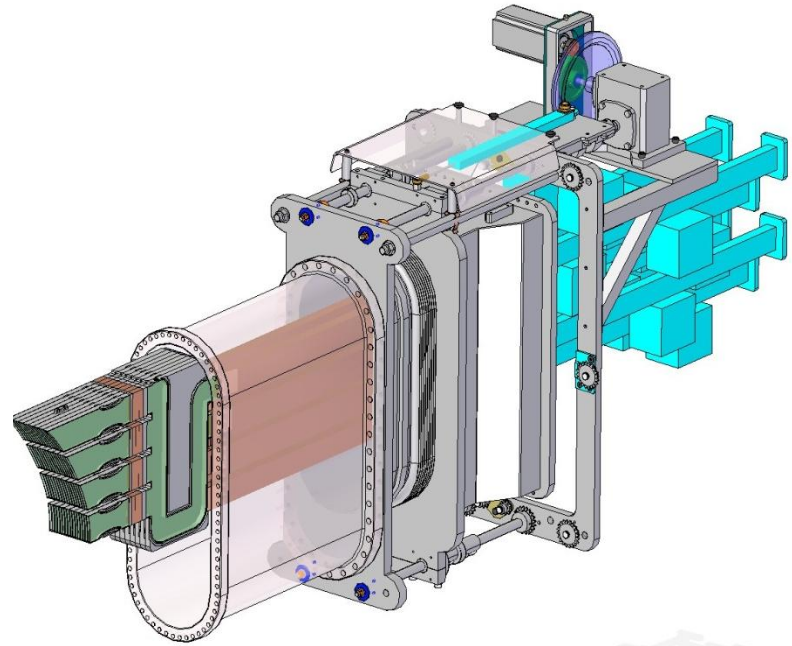
Field-Aligned Rotated Antenna: First significant reduction of ICRF impurity contamination in the last 20 years

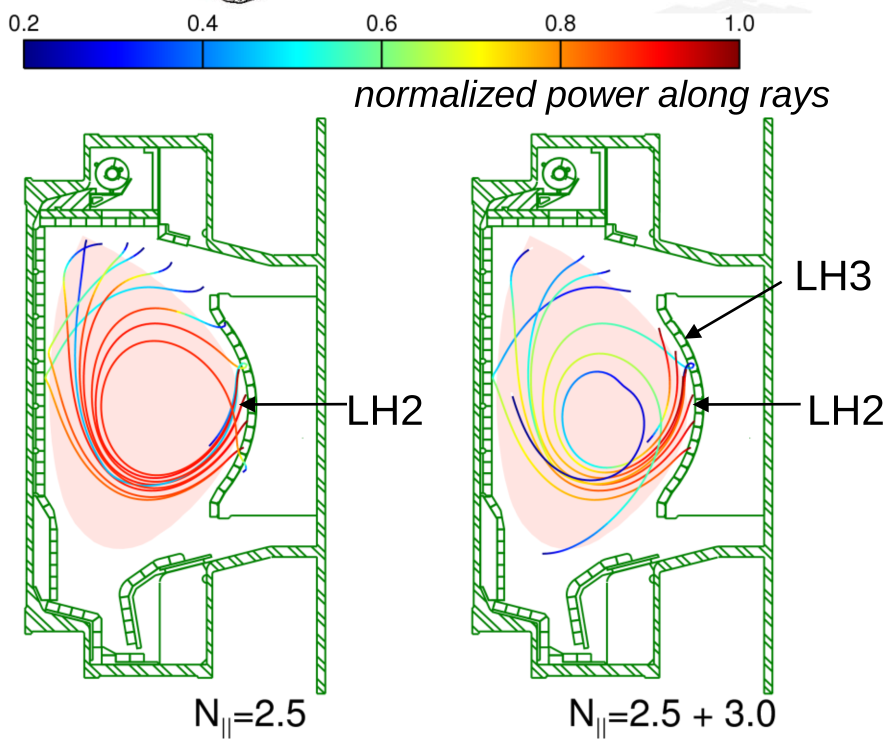




C-Mod is uniquely positioned to answer whether ITER/FNSF/DEMO can achieve steady-state

- C-Mod is the only facility world-wide with the right parameters for ITER and FNSF/DEMO relevant LHRF
  - Density (1-3 x 10^{20} m^{-3})
  - Magnetic Field (5-8 Tesla)
  - SOL density/opacity
  - RF frequency and physics
- Will also inform LHCD on EAST & KSTAR
- Critical for success of steady-state tokamak reactor

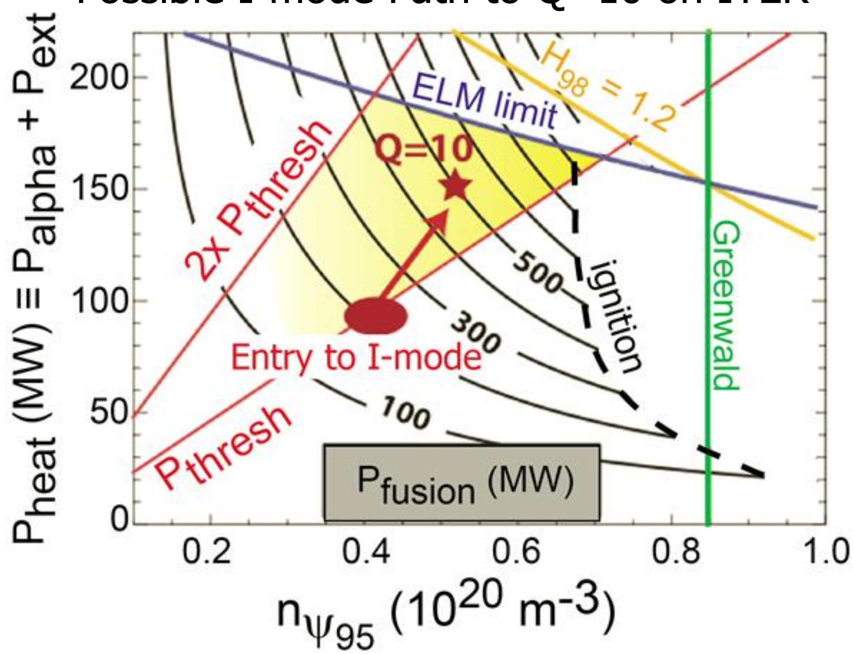




C-Mod developing I-Mode as a steady, robust alternative to type I ELMy for ITER

- The critical need to develop **high performance scenarios without transients** is a key finding of 2012 FESAC FNS & Materials Report, as well as the focus of the FY13 JRT
- **Energy confinement reaching or exceeding H-mode**
- **L-mode particle transport**, so no impurity accumulation, compatible with high Z PFCs and seeding.
- **NO ELMs required**, or usually observed.
- Maintained in **steady state** (> 10 τ_E)
- I-Mode **compares favorably to RMP ELM** stabilization
  - Does not require costly add-on coils
  - Smaller confinement penalty
- Possible application to ITER being evaluated
  - Requires more experiments on C-Mod and other facilities (FY13 JRT planned to focus on this and related issues)

Possible I-mode Path to Q=10 on ITER



ITER and Burning Plasma Physics

- Understanding dominantly self-heated fusion conditions is broadly accepted as a critical next step on the path to developing fusion energy
- ITER was endorsed by US community at Snowmass II
  - envisioned as ~$5B project, with US contributing 10%, D-T operation in early 2020's
- Budget has now grown dramatically (~x5), and schedule is slipping continuously (serious D-T operation now envisioned in late 2020's, at the earliest).
  - Must question whether this is still the right path for the US program
  - ITER can only be a success for the US if it is tightly linked to a strong, vibrant domestic program
- FY13 DoE budget request is a disaster for the domestic program (notably for C-Mod, but damage would be deep and lasting across the entire program), and also apparently would not meet US commitments for ITER

International Collaborations are an Important Adjunct; They do not Supplant the Need for Strong Domestic Program

- New Facilities in China and Korea, and planned ones in India and Japan, offer prospect of very long pulse operation
  - US collaborations will expedite their development
  - Opportunities for cutting-edge research are, in many cases, still years away
- We should (and are) expanding our international collaborations
  - Must recognize that international collaboration does not, by itself, offer path forward to advancing US interests in developing fusion
  - Will be optimal only when combined with strong, complementary domestic facilities (as clearly stated in recent FESAC report)

C-Mod Central and Critical to "10 year vision"

OFES *Vision* for 2021	Critical C-Mod Contributions
ITER	1) Maximize ITER's chance of success (tungsten divertor, disruptions, ELM-free scenarios, RF heating and current drive); 2) Workforce development.
Fusion materials science	1) Erosion, tritium retention, formation of nano-structures, in reactor temperature tungsten divertor; 2) World-leading diagnostics; 3) Close collaboration with MIT Surface Science Center
Extend the reach of plasma control science and plasma-wall interactions	1) ITER and reactor-relevant RF control tools (heating, current-drive, flow-drive); 2) Plasma-wall interactions at reactor-relevant particle- and power-densities, with solid high-z materials; 3) Unique DEMO-like actively heated tungsten divertor
Validated predictive capability	1) Extremely well-diagnosed experiments; 2) Tight coupling to world-leading theorists and modelers (in-house and through collaborations); 3) State of the art computational models and codes.