Summary

FESAC Facilities Panel Meeting

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for the Alcator Group

C-Mod Unique in World and US Among High Performance Divertor Tokamaks

Alcator C-Mod

Unique in the World:

- Only high field, compact, high performance divertor tokamak
- All metal high-Z plasma facing components
- Highest pressure and energy density plasmas
- Particle and momentum source-free heating and current drive
- Equilibrated electron-ion coupling
- ITER level Scrape-Off-Layer Power Density
- Approach ITER neutral opacity, radiation trapping

Exclusive in the US :

- ICRF minority heating
- Lower Hybrid Current Drive
- Premier US Facility for Graduate Student training

Complementarity gives experimental breadth; Enables critical tests through coordinated studies

Parameter*	***C-Mod***	***DIII-D***	***NSTX***
Size: R/a (m), κ	0.67/0.21, to 1.9	1.67/.67, to 2.3	0.85/0.67, to 2.6
Magnetic Pressure	250 bar	16 bar	1 bar
<Plasma Pressure>	2 bar	1 bar	0.3 bar
Dominant Heating	ICRF, LH	NBI, ECH	NBI, HHFW
Current/Flow Drive	LH, ICRF, MC	NBI, ECCD, FW	NBI, CHI, EBW
P/S (MW/m^2)	0.7	0.2	0.2
First Wall Material	Molybdenum	Carbon	Carbon
Pulse Length, $\tau_{L/R}$	3 s, 2 s	10 s, 20 s	1 s, 20 s
ν^* range	0.06 – 1	0.007 – 0.2	0.1 – 2
$1/\rho^*$	220	180	70
Wall Stabilization	Distant	Close	Close

*Values are meant to be typical

Loss of C-Mod Would Leave Significant Gaps in Experience and Understanding Needed for ITER

Issue	***Dominant Contributions to ITER Databases***	***C-Mod***	***ITER***
Plasma facing materials	Low Z (carbon)	High Z	High Z?
Parallel SOL heat flux	<0.1 GW/m^2	0.5 GW/m^2	1.0 GW/m^2
Driven toroidal rotation	strong	none	weak
Ion-electron equilibration	weak	strong	strong
Dominant heating	Positive NBI	ICRF Minority	α-particle, NNBI, ICRF, ECRF
Current drive	NBI, ECCD, FWCD	LHCD, MCCD, FWCD	ECCD, FWCD, NNBI, LHCD?
Current relaxation	$\tau_{pulse} < \tau_{CR}$	$\tau_{pulse} > \tau_{CR}$	$\tau_{pulse} > \tau_{CR}$
SOL: neutral penetration; Ly α,β Radiation transport	transparent	opaque	opaque

Large Number of Significant Research Opportunities Would be Lost without C-Mod

- Many rely on facility capabilities that are unique in the world
- Others tied to joint experiments (domestic and international) where C-Mod provides unique high-leverage contributions because of size, field, power density, plasma density, …

Research on C-Mod is very cost effective

ITER-Critical Studies with All-Metal High-Z PFCs

- With ITER prototypical power and particle flux conditions Investigate:
  - Hydrogenic (tritium) retention and removal
  - Particle/fueling Control
  - Power Handling
  - Divertor physics (neutrals and detachment)
  - Disruption robustness
  - Wall conditioning
  - PFC material migration (impurity transport)
  - Impact of high-Z PFCs on core radiation and dilution
- C-Mod is the only test-bed for ITER- and reactor-prototypical solid tungsten Plasma Facing Components

C-Mod is Pursuing Disruption Mitigation at High Absolute Plasma Pressure

- Disruption Mitigation must be developed to safeguard ITER PFCs/structures
- Use of triggered massive gas jets is the leading approach
  - Must be extended to conditions of high absolute plasma pressure/energy density
    - Jet penetration likely most difficult at high plasma pressure
    - Dissipation of stored energy through radiative processes challenged at high energy density
- C-Mod has highest plasma pressure/energy density (comparable to ITER; at the ITER field and therefore β)

Many ITER-Critical Divertor Physics Studies Can Only be Carried out on C-Mod

- C-Mod divertor approximates ITER divertor conditions most closely in
  - Absolute neutral and plasma density
  - Mean free paths for neutrals and Lyman series radiation (JET is a factor of 2 farther from ITER than C-Mod)

- ITER divertor predictions utilize codes that have not been validated against such conditions. This gives rise to:
  - Uncertainties in detached divertor threshold and behavior
    - Required for power handling
  - Uncertainties in absolute plasma conditions and He ash removal

- In initial comparisons with C-Mod experimental results, the codes have failed

- Only C-Mod has the plasma conditions and diagnostics required to validate the codes and improve predictive capability for extrapolation to ITER

Importance of SOL Transport Brought to World Attention by C-Mod

- Main chamber particle fluxes can approach the level of divertor fluxes
  - Discovered on C-Mod, confirmed on ASDEX-U, DIII-D & JET
  - Significant implications for main chamber surface lifetime and impurities in ITER
- C-Mod continues to lead the world research on this topic
  - Analysis both at the basic turbulence level and empirical scalings
- SOL opacity to neutral penetration may be the determining factor in predicting the level of particle fluxes
  - Like pedestals, another case where neutral and transport physics intersect
  - Only C-Mod can achieve ITER-like SOL neutral opacities

C-Mod Investigating Pedestal Physics in Unique Regimes

- H-Mode pedestal strongly influences core plasma
  - Pedestal height can determine energy confinement (marginal stability $\Rightarrow$ profile stiffness)
  - Particle transport across the barrier required to prevent impurity accumulation

- Giant ELMs regulate pedestal pressure and impurity transport in the vast majority of H-modes studied world-wide
  - Ultra-high ELM power loading poses significant risk for ITER
  - Many approaches being explored on C-Mod, including EDA (pioneered on C-Mod) and small ELM regimes

- ITER will have unique pedestal: high plasma and neutral density (like C-Mod) and lower collisionality (like DIII-D, ASDEX-U, JET, JT60-U)
  - Combination not achievable on any current experiment
  - Require dedicated C-Mod experiments and coordinated experiments with other facilities to unfold the physics and increase the accuracy of extrapolation to ITER

C-Mod is the only US Tokamak Pursuing Minority ICRF

- ITER plans major ICRF minority heating system
- US is likely to provide about half of the ICRF system for ITER
  - Without C-Mod, lose important opportunities for research and prototyping in support of this task
- If the US is to benefit from leadership in the physics aspects of ICRF on ITER when it becomes operational, need expert tokamak ICRF physicists
  - C-Mod is an ideal place where they are being trained and will gain experience
- ICRF decouples major heating from particle and momentum sources (as in ITER)
  - C-Mod is without peer for investigations of source-free particle transport and natural rotation
    - Characteristic of reactors, and to a very large degree, ITER

C-Mod is only US Facility Investigating LHCD

- To access quasi-steady Advanced Tokamak regimes, ITER must have efficient far off-axis current drive
  - Lower Hybrid is the most efficient tool
- LHCD is being considered as an upgrade for ITER
- C-Mod experiments have unique combination:
  - ITER magnetic field (ω_c), ITER density (ω_p), ITER LHRF frequency (~5 GHz)
  - ITER shape, q, β_N
  - Potential to sustain for many current relaxation times at high T_e, low Z_{eff}, up to the no-wall limit
- Results from C-Mod will:
  - strongly influence the ITER LHCD implementation decision
  - provide significant increase in the US role in any ITER AT program.

C-Mod is the Only Divertor Tokamak Routinely Operating in the Equilibrated Ion-Electron Regime

- Strong electron-ion coupling will prevail in ITER and in ignited reactor plasmas
  - Influences broad range of plasma properties, particularly turbulent transport
  - Transport barrier dynamics can be fundamentally different

- Studies of energy, particle and momentum transport under these conditions provide insights that are difficult or impossible to obtain otherwise
  - Extend the validation of transport models into unique, reactor relevant parameter ranges

C-Mod Provides Unique High-Leverage Points for Dimensionless and Dimensional Scalings

- Four important examples which have changed ITER predictions:
  - H-Mode Confinement
  - Disruption Halo Currents
  - Error-Field Induced Mode Locking
  - H-Mode Threshold
- In the world portfolio of operating high-performance conventional aspect ratio divertor tokamaks:
  - Two facilities are medium scale
  - Two facilities are large scale
  - C-Mod is the sole high-performance compact tokamak
- Without C-Mod, the highest leverage points for all future scaling studies would be lost

C-Mod is the Premier US Facility for Training Students

- C-Mod has by far the largest number of graduate students of the major US fusion facilities, and strong participation of undergraduates

- We expect ITER to begin operations in about 10 years
  - Over the subsequent 10 to 20 years of ITER research, there will be a critical need for highly qualified and experienced US scientists and engineers
  - Without C-Mod's major contributions to educating these experts, the US ability to benefit from the enormous investment in ITER hardware will be substantially weakened

C-Mod is Unique

- In the coming years, vitally important research, including many critical ITER R&D tasks, can and will only be accomplished on Alcator C-Mod.

- **There is no other high field, compact, high performance divertor tokamak in the world program**