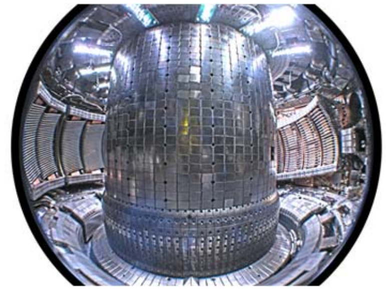
Alcator C-Mod National Fusion Facility

Alcator C-Mod Team†

<u>Ability of the facility to contribute to world-leading science</u> -
Grade: (a) – absolutely central

Mission: Compact high-performance divertor tokamak research to establish the plasma physics and engineering necessary for a burning plasma tokamak experiment and for attractive fusion reactors.



Interior view of Alcator C-Mod (R=0.67m, a=0.22m, $\kappa \leq 1.8$, $I_P \leq 2$MA, B=2 to 8T)

Summary: Alcator C-Mod is a flexible, high-field, high-Z metal wall, high power-density divertor tokamak located at the MIT Plasma Science and Fusion Center. C-Mod is unique in parameter space among all tokamaks world-wide, and with its exquisite diagnostic complement, provides data which are otherwise unobtainable. C-Mod, because of its unique combination of compact scale, high magnetic field, and high performance, provides extremely high leverage for coordinated cross-machine studies of energy, momentum and particle transport physics, plasma heating and sustainment, current drive, divertor physics and plasma-surface interactions. C-Mod, which pioneered the vertical-plate divertor and solid refractory metal plasma facing components, is now poised to install the world's first reactor-appropriate divertor, with active heating to 600 ^{o}C, to study effects on confinement and T retention. C-Mod is the only facility studying high power RF heating and μ-wave current-drive at reactor-relevant field and density (and thus plasma dielectric constant) conditions. Initial experiments with a newly installed field-aligned ICRF antenna are extremely promising, and could be a game-changer in solving the metal influx challenge with RF. With implementation of a new off-midplane LH launcher, C-Mod can develop efficient current drive for $n_e > 1\text{x}10^{20}$ m^{-3}. ELMy H-Mode, the standard high confinement tokamak operational regime for more than 30 years, faces significant challenges in ITER and reactors, including ELM-induced wall damage and impurity confinement; C-Mod is pioneering the ELM-free I-mode, which features H-mode energy confinement and L-mode particle confinement, a potentially revolutionary approach to solving one of ITER's most difficult challenges. C-Mod pioneered and continues to be world-leading on studies of self-generated rotation, critical for understanding stability in future experiments, where neutral-beam generated torque will be weak (ITER) or essentially absent (DEMO, reactors). C-Mod is currently uniquely using multiple simultaneous disruption mitigation gas jet injection locations, to study mitigation-induced toroidal asymmetries; this is directly relevant to the design of the mitigation system on ITER. C-Mod experimental results are used routinely to validate the predictive capability of simulations, thus improving those models and increasing confidence in their predictions for future steady state experiments, including ITER and FNSF. Alcator, situated on the campus of a world-leading science and engineering university, is a premier U.S. training facility for students, who will help lead the next generation of fusion scientists and engineers to operate ITER and develop fusion energy. In a Feb. 15, 2013 seminar at MIT, the US ITER Project Manager presented his 5 highest priority needs for critical research needed now in support of ITER: disruption mitigation; non-carbon divertor plates (Mo and tungsten); ELM control; experiment planning; and building the ITER research team. C-Mod is on the forefront of each. In the Rosner Panel's answer to their second charge, their first recommendation was that C-Mod should continue to operate for 3 to 5 years, with funding restored to the FY12 level. While C-Mod is strongly positioned to remain at the forefront well beyond that time horizon, the plans outlined here are consistent with those funding and operations assumptions. The remainder of this white paper

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briefly describes these plans, organized by research topic, and put in the context of recent FES planning documents.

Scrape-Off-Layer (SOL) Physics and Plasma Material Interactions (PMI): The edge plasma, and plasma-material interface, have been repeatedly identified by multiple community and FESAC studies as being critical in the near term for ITER, as well as on the path to next step devices (FNSF and DEMO). These studies include the Gaps and Opportunities Report, ReNew (thrusts 9, 10, 11, and 12), and the 2013 Rosner Panel Report; the latter identifies SOL and PMI as 2 of the 5 highest priority near-term topics from ReNeW (Thrusts 9 and 10). C-Mod's divertor studies have shown that detachment can be accessed at ½ the density of flat-plate divertors, leading ITER and other tokamaks to convert to that shape. ITER, and reactor conditions of parallel heat flux ($q_{||}$), absolute density and normalized mean free paths for multiple processes, are only reproduced in the C-Mod divertor, making such data the definitive test of divertor models essential to the planning of ITER. C-Mod's broad research program has elucidated crucial aspects of SOL transport and flows, blobs, main chamber recycling, SOL $q_{||}$, the mutual interaction between RF waves and the boundary plasma, the role of the boundary on the density limit, and of the close connection between the pedestal dynamics and the near-SOL. This productive science will continue with additional attention given to how far impurity seeding can be pushed at the ITER $q_{||}$ consistent while maintaining compatibility of the divertor solution with clean, high-performance core plasmas. C-Mod, with a heated (to 600^{o}C) tungsten divertor, is poised to directly address the critical question of fuel retention in a reactor, where high temperature surfaces are advantageous for thermal efficiency and material properties. The 2012 Zinkle Report identifies hot solid tungsten as the leading candidate, urgently requiring experiments. The design and prototyping of the actively heated tungsten divertor for C-Mod is almost complete, with first operation scheduled ~one year from now. At that point, C-Mod's parameters and diagnostics will enable it to provide unique input to not only ITER, but to an FNSF. C-Mod has recently implemented the world's first, and only, inter-shot divertor and first-wall diagnostic system, which interrogates, in real time, the surface evolution of impurities and retained deuterium. Using this, in concert with C-Mod's unparalleled, comprehensive scrape-off-layer and divertor diagnostics, we anticipate that major advances in both fundamental understanding and practical knowledge will be accomplished in this PMI research during the next few years.

Pedestal Research in H-mode and I-mode: Pedestal research on Alcator C-Mod focuses on the physics of pedestal formation and sustainment. C-Mod pioneered the study of H-mode access in a device with metal walls, high edge opacity, and ITER-relevant divertor geometry. C-Mod's parameter space provides critical extensions of pedestal data sets, needed for a broad array of model validation, both for predicting pedestal structure and for turbulence-driven transport. This satisfies a clear need noted by both the 2007 Gaps report and ReNeW Thrust 6 (Rosner Report, high priority). Significant research opportunities are being explored in the area of pedestal control, specifically via changing particle transport while maintaining high energy confinement, applying both lower hybrid waves and high-k magnetic perturbations (Gaps report, A6).

C-Mod has pioneered and leads the exploration of the I-mode regime, which is highly attractive for fusion, combining the high energy confinement of H-mode with the low particle and impurity confinement of L-mode, eliminating impurity accumulation and the danger of ELMs (a key aspect of high priority ReNeW Thrust 2). Focused efforts in recent campaigns have made great progress, increasing the I-mode power range up to the 6 MW available. Experiments late in the

FY12 campaign indicated that the operational space in density and power can be further expanded within our present capabilities. The ITER team has encouraged research on I-mode, recognizing its promise in removing ELMs and reducing core impurity levels. We aim to determine whether the regime is indeed accessible for ITER, and/or future fusion devices; open questions which will be addressed include power thresholds, edge stability at higher pressure, and compatibility with dissipative divertors. This research also promises key insights into edge transport barrier formation and the separate responses of thermal and particle channels. I-Mode is an excellent example of innovative research made possible with a relatively small facility and team, which gives flexibility to adjust campaign schedules to capitalize on unexpected discoveries.

Core Transport Studies: C-Mod is the *only* existing experiment which can investigate multi-channel transport under reactor like conditions: similar magnetic field, density, power density and neutral opacity, with equilibrated electrons and ions (which is *not* the same as $T_i = T_e$), without core particle or momentum sources (the latter is *not* the same as having balanced input torque), purely RF driven and with high Z metal walls. C-Mod therefore is the *single* most relevant device to address transport issues for ITER and DEMO, directly aligning with the recommendations in the Gaps report. C-Mod's flexibility (magnetic field between 2 and 8 T, electron density from $1x10^{19}$ to $1x10^{21}/m^3$, ability to run D_2 and He plasmas, and tunable ICRH) enables contributions to all phases of ITER scenario development. Advanced instruments, including a world leading high Z spectroscopy suite and turbulence diagnostics (PCI, CECE, TCI and reflectometry), provide the only platform for simultaneous multi-channel (heat, momentum *and* high Z impurity) transport studies for validation of gyrokinetic simulations under reactor relevant conditions. Such validation is a necessary component for demonstration of predictive capability and addresses the highest level FESAC gap G-1, and ReNeW Thrusts 4 and 6. C-Mod is the world-wide leader in studies of intrinsic rotation, RF ITB formation, I-mode and ICRF mode conversion flow drive. These capabilities enable C-Mod's active contribution to 13 out of the 15 currently active ITPA Transport & Confinement Joint Experiments.

Disruption Mitigation: Disruption issues continue to be one of the most urgent areas of concern for ITER and beyond, as recognized in the ReNeW Thrust 2 (Rosner, high priority) and FESAC gap (#5) reports. Disruption characterization, prediction/warning, and mitigation are all crucially important, and our understanding of these issues have benefitted from research on many different devices, as well as from theoretical and modeling efforts. Initial C-Mod experiments with multiple gas jets to study mitigation-induced toroidal asymmetries yielded unexpected results, commanding reassessment of existing models, and further experiments and modeling are clearly required. Looking beyond ITER, to FNSF and DEMO, more extreme disruption power mitigation will be required. The plasma thermal energy in a reactor is so high (of order 1 GJ), that a 1 ms thermal quench will likely exceed the tungsten melt limit. At very high densities ($>10^{22}$ m^{-3}) and low temperatures (< 0.8 eV), D_2 could become a blackbody radiator, effectively increasing the radiation time and assuring spatial uniformity. We will use massive D_2 injection to study radiation energy transport in unparalleled opacity conditions.

Ion Cyclotron Heating and Flow Drive: C-Mod provides the US with its only opportunity to investigate ICRF physics and technological issues in a device with all-metal plasma facing components, at magnetic fields and densities which are prototypical of ITER and burning plasmas. These investigations are facilitated by a flexible ICRF system, access to sophisticated ICRF simulation codes through the RF-SciDAC initiative, and advanced RF diagnostics. C-

Mod's unique combination of experiment and modeling expertise in this area is critical to developing the physics and technological basis required for ICRF utilization in future devices. ICRF (8 MW source, 6 MW coupled) is our primary heating source, and the C-Mod group has demonstrated that it can be made robust and reliable. We provide ongoing support for ITER through experimental validation of wave propagation and absorption simulation (ReNeW Thrust 6). To address impurity contamination linked to ICRF antenna operation, C-Mod has implemented a novel field-aligned ICRF antenna to experimentally investigate whether this can reduce impurity contamination and impurity sources (ReNeW Thrust 9, Gap #10). The results challenge the existing models for ICRF impurity contamination; impurity sources and core contamination were reduced, but the measured RF enhanced potentials were unmodified. C-Mod has pioneered and is a world leader in the use of ICRF mode conversion flow drive, and is uniquely positioned to determine the mode conversion flow drive physics. Although the empirical results are convincing and the process appears to be a promising candidate for external control of plasma rotation and shear, the underlying physics understanding and ability to predict the flow drive in future experiments and devices requires more experiments along with theory and modeling (ReNeW 5, Gap 6). Our comprehensive complement of novel RF diagnostics will allow for stringent testing of core absorption, flow drive, and RF antenna simulations.

Lower Hybrid Current Drive: LHCD research on C-Mod advances understanding of the physics of steady-state regimes and RF wave-interaction with the SOL. Steady state operation was identified by the Rosner Report as a "*cross-cutting*" research topic with "*connections to each of the high priority thrusts*", emphasizing that "*development of these [steady state] operating scenarios is prerequisite to ITER's steady-state mission, to a long-pulse FNSF, and indeed to the ultimate goal of fusion energy*". ReNeW Thrusts 5 and 6 also highlight the need for research on profile control and steady state, and recent studies conclude that LHCD in particular will be critical for ITER steady state scenarios. LHCD research on C-Mod investigates current profile modification and control under conditions (magnetic field, plasma density, LHCD frequency, magnetic geometry) nearly identical to those anticipated in ITER, as well as those expected for steady state tokamak reactors. C-Mod is the only facility in the US studying LHCD, and no other facility in the world matches all of these ITER LHCD physics parameters. C-Mod has demonstrated non-inductive operation by LHCD for several current relaxation timescales at $n_e \sim 0.5\times10^{20}$ m^{-3}. Velocity space synergy between the mid-plane launcher and the planned off-mid-plane launcher should result in strong single-pass absorption of the LH waves (as predicted for ITER), expanding our non-inductive operational space to high performance, reactor-relevant density (~1.5×10^{20} m^{-3}), with significant bootstrap current. C-Mod will continue to enhance our understanding of the interaction of RF waves with the SOL (ReNeW Thrust 9, high priority) by investigating edge turbulence suppression with LH waves and the impact of the SOL on current drive at high density.

Facility value, operating costs: The estimated value for the current Alcator C-Mod facility is $200M. The annual operating budget (FY12, 19 weeks of research operation) is $28.5M.