Robust, high-temperature divertor systems must be developed and demonstrated at reactor-level power-densities before a FNSF/DEMO can be considered.

C-Mod's unique capabilities should be utilized in this development pathway.

B. LaBombard

Massachusetts Institute of Technology, Plasma Science and Fusion Center,
175 Albany St., Cambridge, MA 02139 USA

The combination of power exhaust handling and pulse-length/fluence requirements for a DEMO divertor will far exceed anything that has been encountered in present day experiments, including that projected for ITER. Heat flux limitations for solid divertor target surfaces are well-established and fundamentally inalterable: ~20 MW m^{-2} steady state, ~0.5 MJ m^{-2} transient. In ITER, such limits already impose severe operational restrictions, with the potential to jeopardize its Q_{DT}=10 mission: ELMs must be eliminated, disruptions must be avoided and mitigated, and dissipative divertor regimes must be maintained at all times during high power operation. Although the present physics basis for projecting to DEMO conditions is quite poor (e.g., recent inter-machine scalings project to a power exhaust channel width in ITER that is factor of 5 times smaller than originally planned), the situation in DEMO will undoubtedly be much more severe than ITER: 4 times the power exhaust in the same sized package. Thus, even if ITER is able to demonstrate complete ELM and disruption suppression, steady-state heat fluxes into a standard-designed DEMO divertor system will be intolerable. Drastic, unrealistic restrictions would need to be imposed on DEMO's operational window, such as radiating ~90% of the output power. But this situation is not credible. Standard divertor solutions – which have been adequate for physics experiments up to now – simply do not scale to a DEMO-class device. Divertor lifetime issues stemming from erosion and neutron damage at high ion/neutron fluence are also potential show-stoppers. Divertor concepts must evolve to address these issues in an integrated way – and we must have access to high power density confinement devices to test them. Finally, and most importantly, the physics of boundary layer/divertor heat and particle transport must be understood in sufficient detail to enable predictive modeling and extrapolation to reactor conditions.

In order to address this critical need, the pathway forward must include: (1) development of new divertor/boundary concepts that can robustly handle the severe environment of FNSF/DEMO, (2) testing of current and new concepts in tokamak facilities at reactor-level power densities and at the high operating temperatures required of a DEMO (imposed by thermal efficiency and tritium retention considerations) and (3) development of the plasma/materials science to support this activity. Lacking this, a FNSF/DEMO cannot be realized, even if ITER's Q_{DT}=10 physics mission is wildly successful.

Conditions presently available in C-Mod, DIII-D, AUG and JET, and projected for EAST, KSTAR, FNSF and DEMO.

Parameter	Alcator C-Mod	DIII-D / AUG	EAST / KSTAR	JET	FNSF / DEMO
Power density, P/S (MW/m^2)	~1	~0.3	~0.25	~0.25	0.9 - 1
Magnetic field (T)	5.4 - 8	2-3	~2-3.5	3.5	> 6
Parallel heat flux (MW/m^2)	500	~20	~ 150	150	500
Divertor temperature (^{o}C)	25-600	25	25-?	200	> 500
Divertor material	Mo/W	Carbon	C /W	Be/W	W?
Pulse length (s)	3	< 30	<1000	10	3×10^7

The US fusion community presently leads the world in a number of key science areas: pedestal and boundary layer physics, divertor physics at reactor-relevant conditions, advanced divertor concept development, tokamak operations with liquid metal walls. With proper near- and long-term planning/guidance from FESAC and OFES, the US would also have the experimental facilities to maintain leadership through the ITER and DEMO eras – "with the chance to accelerate the time line to establish the scientific basis for fusion energy."

In this regard, Alcator C-Mod is unique in the world and particularly valuable to the world research effort, routinely accessing reactor-level power densities and parallel heat fluxes in its boundary plasma. In the near term, Alcator C-Mod will use these capabilities to test the viability of tokamak operations with a high-temperature, tungsten divertor target. This precision-aligned system will be configured in a single-null divertor with vertical-plate geometry – the best geometry to attain high poloidal flux expansion in a standard single-null divertor configuration. Extensive plasma and materials diagnostics are planned, including a novel in-situ 1 MeV ion beam to directly interrogate the first-wall and divertor material responses – a quantum step for plasma-wall interaction studies. In addition to being the first test of a high temperature divertor target in a tokamak, the information gained will help inform ITER operations, which is rapidly moving towards a tungsten target option.

While high-temperature tungsten is presently viewed as the first-tier option for near term materials development, it is already known to have serious limitations with regard to tokamak operations when used with a standard, vertical-target divertor configuration. Deleterious effects include core plasma contamination from tungsten sputtering (intrinsic and RF-sheath generated) and melt layer formation and splashing if maximum heat loads are exceeded. Thus, in its present form, a tungsten target divertor remains to be demonstrated as a viable solution to the FNSF/DEMO problem; alternative divertor configurations must also be sought with tungsten and/or with the development of new target materials that are compatible with reactor neutronics.

The ultimate divertor solution will be one that produces a controlled, fully-detached divertor condition (~no plasma sputtering) while maintaining high plasma temperatures 'upstream' at the last-closed flux surface – at the parallel heat flux density of an FNSF/DEMO. ***This vision should be the target of a US high-performance divertor development program.*** Recognizing the need to develop higher performance divertor options, the US fusion community has already identified some innovative schemes, including high flux-expansion topologies such as 'snowflake' and super-X divertor configurations. However, these concepts, which can significantly increase the complexity of a tokamak, need to be tested under reactor-level power densities against the performance of conventional, vertical-plate schemes. Perhaps a conventional divertor, deployed in a deep-slot configuration, with specially designed active feedback systems for divertor impurity seeding, could achieve this goal. Or perhaps a large volume divertor, akin to the original ASDEX divertor concept, might ultimately be required. One or more of these concepts, possibly combined with the use of high-temperature liquid metal targets to mitigate heat flux transients and erosion/neutron effects, may finally prove adequate for a FNSF/DEMO device.

Along this development pathway, a high power-density tokamak facility, such as Alcator C-Mod, is required to critically assess and test such concepts beyond their proof-of-principle stages. In the near term, C-Mod is configured to address the performance of a hot tungsten divertor in vertical plate geometry. Its extensive boundary physics expertise, which extends deep within the US and international fusion communities, will be used to unfold the plasma/material response. In the medium-to-long term, C-Mod could also be configured to investigate 'snowflake', deep-slot divertors and old ASDEX-style divertors with tungsten targets and high-temperature liquid metal target concepts (e.g. gallium). In additional to exploring boundary plasma physics for ITER, these experiments would provide timely guidance for new facilities (e.g., Vulcan, FNSF, DEMO,…).

In this era of highly constrained budgets, continued investment in research from Alcator C-Mod makes sense. C-Mod is already operating at power exhaust heat flux densities and divertor conditions (plasma/neutral densities) of a reactor, unequalled at other existing/planned experiments. Yet, it has the flexibility and low-cost associated with a small-sized experiment – all embedded within a world-class plasma science research center.