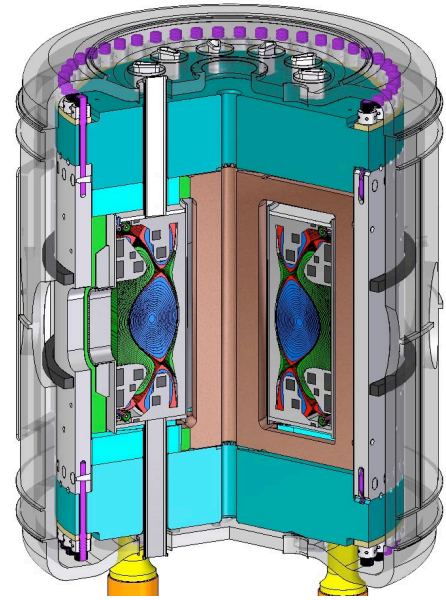


High Power Density Advanced Divertor Test Facility – Alcator DX

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Mission: Develop robust divertor concepts to solve power exhaust and material erosion challenges for steady-state plasma fusion reactors; explore core performance in plasma regimes otherwise inaccessible using conventional divertors; test reactor relevant ICRF and LH drivers that minimize plasma-material interactions.

Summary: Alcator DX is a compact, high power-density tokamak, designed specifically to test advanced divertor concepts for next-step fusion devices, such as FNSF and DEMO. The device uses the proven, high magnetic field technology of the Alcator design [1] combined with high-power ICRF heating to produce plasma pressures and power exhaust densities of a fusion reactor. A vertically extended vacuum vessel accommodates removable divertor cassettes, which contain the poloidal field coils required to explore a variety of advanced configurations, including the ‘snowflake’, ‘super X’ and a more recent innovation, the ‘X-point target’ divertor. The device will be unique in the world, advancing the development of high-power density power exhaust systems and yielding fundamental insights into the physics of divertor and boundary layer plasmas. Equally important, the synergy of these divertors with core plasma performance will be explored in a variety of confinement regimes (L-mode, H-mode, I-mode). The experimental platform will also enable the development of next-generation ion-cyclotron (ICRF) heating and lower hybrid current drive (LHCD) actuators, including the possibility for high-field side launch. This flexible, innovative and relatively inexpensive device will inform the conceptual development and accelerate the readiness-for-deployment of next step, steady state plasma fusion experiments (pre-FNSF, FNSF, DEMO).



- **Ability to contribute to world-leading science (2014-2024):** (a) absolutely central
- **Readiness for facility construction:** (a) ready to initiate construction

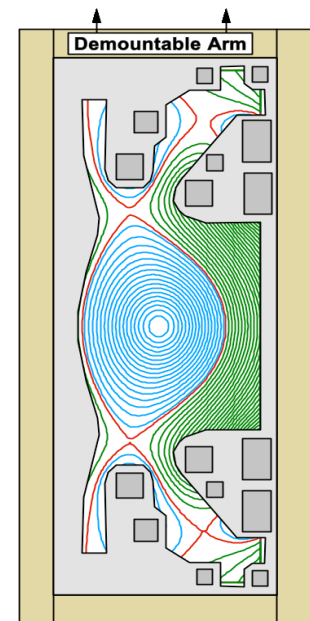
Critical Need: Magnetic fusion energy research is rapidly progressing towards its ultimate goal – the construction of a fusion power reactor (DEMO). ITER is an important step along that pathway. If successful, it will demonstrate the scientific feasibility of fusion, producing ~10 times more power out than in. Yet, one of the challenges facing ITER is in accommodating ~100MW of plasma exhaust; this power load will severely test the limits of its conventional divertor. For this reason, the world community recognizes that robust, high-power divertor concepts must be developed and tested before proceeding to next-step reactors, especially a DEMO – a device that is likely to have 4 times ITER’s power exhaust in a similarly sized machine. Promising new concepts been identified: ‘snowflake’ (SF), ‘super X’ (SXD) and the ‘X-point target’ (XPT) divertors. The use of liquid metal targets has also been considered. These concepts have the potential to resolve three key challenges

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facing next-step, steady-state fusion experiments: (1) how to safely handle the extreme plasma exhaust powers, (2) how to completely suppress material erosion at the divertor target and (3) how to do this while maintaining high core plasma performance. Advanced divertors may be the means to fully accommodate all these requirements – producing a fully detached, low temperature plasma in the divertor chamber while maintaining a hot boundary layer around a clean plasma core. The demonstration of such a regime would be a seminal achievement for magnetic fusion energy – a game changer for the development of plasma fusion reactors. However, no facility yet exists in the world to test these concepts at the power densities required to qualify them for an FNSF or DEMO-class device.

SF, SXD and XPT divertor physics: Snowflake (SF) is a first-generation advanced divertor concept; it has been found beneficial for reducing peak divertor heat loads. Yet, like conventional divertors, this concept may suffer a fundamental limitation: under the conditions of complete divertor detachment, the ‘thermal front’ initiated at the divertor plate tends to be spatially unstable; it ‘jumps’ to the X-point region, producing a cold, radiating ‘X-point MARFE’, which cools the separatrix and degrades core plasma performance. In contrast, SXD and XPT may avoid this fate; their thermal fronts are stabilized by magnetic field strength variation along field lines entering the divertor. XPT in particular aims to exploit this physics, producing a stable ‘X-point MARFE’ *in the divertor volume*. In this regime, heat transport to material surfaces occurs via atomic and molecular physics (line radiation, ion-neutral charge exchange, low energy neutrals/molecules), spreading heat loads over large surface areas and eliminating material erosion via ion bombardment. Linear plasma simulators cannot study this physics; it involves the interplay among magnetic topology, thermal front stability and external controls (gas puffing, seeding). Nor can they study the synergies with core plasma performance. A high-performance tokamak facility is required to test SF, SXD and XPT concepts.

Proposed Facility: Alcator DX builds on the high-field magnet technology currently employed by Alcator C-Mod. A LN₂ cooled, copper toroidal field (TF) magnet will produce field strengths of up to 6.5 tesla on axis (nominal pulse length ~3 s with 1 s flat-top). The demountable TF design is essential; it allows the vacuum vessel to be removable with upper and lower cassettes containing divertor poloidal field coils (PF) and target plate geometries. Tungsten and molybdenum plasma-facing components will be employed and designed for operation at elevated temperatures – as will be required for reactors. Magnetic topologies can be changed between discharges for direct performance comparisons; cassettes can be replaced between run campaigns with specialized divertor packages prepared off-line. Plasma heating is by 8 MW of ICRF and 2 MW LHCD (net). This combination of high magnetic field strength and high power ICRF heating has already been found to produce world-record absolute plasma pressures in Alcator C-Mod and to yield scrape-off layer heat flux densities that are comparable to



those expected in fusion reactors, $q_{||} \sim 1 \text{ GW/m}^2$. Alcator DX will also take full advantage of the world-leading expertise in divertor/boundary and RF physics at the MIT Plasma Science and Fusion Center that has developed through the Alcator C-Mod program.

	MAST Upgrade	NSTX Upgrade	DIII-D Upgrade	EAST Upgrade	Alcator C-Mod	Alcator DX	ITER	ARIES-AT
B_T / I_p	0.84/2	1/2	2.2/1.5	3.5/1.5	5.4/1.3	6.5/1.5	5.3/15	6/13
a / R	0.65/0.85	0.62/0.93	0.6/1.75	0.45/1.85	0.22/0.67	0.21/0.71	2/6.2	1.3/5.2
P_{tot} [MW]	7.5	16	39	36	6	14	150	388
$q_{ }$ [GW/m ²] (1) / (2)	0.07/0.08	0.19/0.21	1.0/0.97	1.8/2.0	1 / 1	2.9 / 2.4	2.4/0.23	10/1.3
$n_{20G} R$ ⁽³⁾	1.3	1.5	2.3	4.4	5.7	7.7	7.4	13
Divertor	C,SF,SXD	C, SF, L	C, SF	C, L	C	C,SF,SXD,XPT	C	C?

(1), (2), (3) – see text. Divertors: (C) conventional, (SF) snowflake, (SXD) super X, (XPT) X-point target; (L) Lithium.

Other facilities worldwide: MAST-upgrade will be the first tokamak in the world (~2015) capable of operating with a SXD. However, it will not access the parallel heat flux densities ($q_{||}$) nor the divertor opacity conditions (nL) of reactors. Although the physics that sets $q_{||}$ is uncertain at this time, the scaling of $q_{||}$ with device parameters can be bracketed by considering two candidate models for the heat flux channel width, λ_q : (1) an empirical scaling $\lambda_q \sim a^{0.42} B_p^{-0.92} R^{-0.38}$ (from the multi-machine, attached-divertor database) or (2) a ‘pedestal width’ $\lambda_q \sim a$. A comparison of projected $q_{||}$ values from fully-upgraded, high performance tokamaks is shown in the table above, normalized to $q_{||} = 1$ GW/m² for C-Mod. Divertor opacity can be scaled from Greenwald density (n_{20G}) times major radius, (3) $n_{20G} R$. **This table shows that Alcator DX’s simultaneous access to high $n_{20G}R$ and high $q_{||}$ make it ideal for advanced divertor testing.** Should $q_{||}$ scaling relationship (2) be found appropriate for dissipative divertors, then Alcator DX would closely simulate DEMO (ARIES-AT) divertor conditions.

Synergies with core plasma performance: SXD/XPT divertors in particular have the potential to enhance core plasma performance by a large margin, reducing or eliminating the need for impurity seeding for heat flux control, and enabling clean, hot core plasmas. These concepts will enable higher temperature, lower collisionality fusion regimes to be explored, including advanced, ELM-free core plasma regimes, such as I-mode and QH mode. The operational space available for enhanced core performance with advanced divertors is not clear, however. Conditions required for access to H-modes and I-modes, and plasma operation near the density limit need to be reexamined. Experience obtained in Alcator DX will therefore define the landscape for next-step fusion reactor concepts.

Innovation platform: While SXD/XPT concepts may solve divertor heat flux and erosion challenges, techniques must also be developed to mitigate plasma-material interactions (PMI) on main-chamber components, such as ICRF antennas and LH launchers. Alcator C-Mod’s new field-aligned antenna has proven successful in this regard and will be employed in Alcator DX. The roles that ICRF and LHCD will play in fusion reactors will hinge on the development of robust, PMI-tolerant antennas and launchers. A potential game-changer is to locate these components on the high-field side, where the boundary plasma is quiescent and boundary profiles there can be actively controlled by X-point flux balance. Reactor studies envision this possibility for efficient LHCD with low PMI. Alcator DX is an innovation platform; its vacuum vessel is designed to accommodate inner-wall launch LHCD and ICRF. Low-PMI, reactor-prototypical LHCD systems will be explored with up to 2 MW net power. Non-inductive plasma scenarios with LHCD, which favor moderate density

discharges, may especially benefit from SXD/XPT divertors. This experience will be critical for informing the development of compact, steady-state LHCD-driven reactor concepts.

Alignment with OFES Priorities: The mission of Alcator DX is specifically targeted to address high priority elements in the OFES roadmap for fusion.

ReNew (page 87):

Potential “game changers” What new areas can provide innovative solutions to some of the more uncertain issues in the high-performance fusion plasma regime? ...The exploration of advanced divertors, including liquid metal approaches, should be pursued to understand their potential for handling the high particle and power loads in a fusion power plant as well as the particle control and material evolution issues...

Greenwald Panel Gaps (page 15):

G-2: Demonstration of integrated, steady-state, high-performance (advanced) burning plasmas, including first wall and divertor interactions.

G-7. Integrated understanding of RF launching structures and wave coupling for scenarios suitable for Demo and compatible with the nuclear and plasma environment.

Rosner Priorities Panel – Highest priority ReNew thrusts (pages 6,10,11):

3.1.3 Thrust 9: Unfold the Physics of Boundary Layer Plasmas

- *Fundamental understandings of cross-field transport mechanisms, including the relation between the SOL and the region inside the separatrix*
- *Innovative ideas for improved divertors*
- *Explore the detailed effects of RF heating on the boundary plasma*

Alignment with International Priorities: Alcator DX is essentially the ‘Divertor Tokamak Test’ facility, called for in the EFDA roadmap for fusion. It will therefore lead world science in this critical research area and be a central hub of international collaboration.

EFDA Roadmap to Fusion (page 1):

A reliable solution to the problem of heat exhaust is probably the main challenge towards the realisation of magnetic confinement fusion. ... an aggressive programme on alternative solutions for the divertor is necessary. ... a dedicated test on specifically upgraded existing facilities or on a dedicated Divertor Tokamak Test (DTT) facility will be necessary.

Schedule: 5 year construction period. Alcator DX will not require the development of new technology. Robust design concepts developed for Alcator C-Mod will be employed: coaxial feeds to electro-formed terminals, sliding joints, extremely strong super-structure, and support of PF and OH coils by a rigid vacuum chamber.

Construction Costs: \$93M; \$48M for hardware, not including contingency (superstructure, magnets, power supplies, RF systems, upgrades to prime power/buildings); \$45M over five years for engineering, design and construction team. Estimates are based on procurements and staffing for construction of Alcator C-Mod. Alcator DX will utilize the extensive infrastructure at MIT presently supporting Alcator C-Mod – a \$200M facility.

Annual Operating Costs: \$30M total research facility operation costs.

Co-Signatories: expressing very strong support of the Alcator DX research facility

Dr. Nobuyuki Asakura (JAEA)

Dr. Matt Reinke (ORISE)

Prof. Peter Stangeby (U. Toronto)

Dr. David Brower (UCLA)

Dr. William Rowan (UTA)

Dr. Mike Ulrickson (SNL)

Dr. Luis Delgado (PPPL)

Dr. Steve Scott (PPPL)

Dr. Stewart Zweben (PPPL)

[1] Bibliography: http://www.psfc.mit.edu/research/alcator/program/Alcator_DX_Bibliography.pdf