ADX: A compact, high-field, high power density Divertor Test Tokamak (DTT) and RF Sustainment Test Tokamak (STT) for fusion energy development

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Summary

- The vision of a high-field pathway for fusion energy [1, 2] – made possible by high-temperature superconductors (HTS) [3] – is shifting critical research towards finding solutions for the support systems of a tokamak pilot plant: (1) advanced divertors to handle order-of-magnitude increases in power density over present experiments while completely suppressing divertor erosion and damage; (2) efficient RF systems for steady-state current drive and heating that can survive the plasma-materials interaction (PMI) onslaught in a DT reactor long enough to be economically viable.
- Recent research has uncovered new ideas to potentially solve these challenges; some of them may be truly transformative: long-leg divertors with embedded secondary x-points [4], enabled by demountable magnets [5] and liquid immersion blankets [6]; high-field-side RF launch combined with operation in near double-null magnetic configurations [7].
- However, no facility presently exists in the world (or is being planned) that can test these and other innovative ideas under the conditions needed to qualify them for consideration in a pilot plant design.
- ADX (Advanced Divertor and RF tokamak eXperiment) [8] is conceived as a compact, high-field, high power density Divertor Test Tokamak (DTT) and RF sustainment test tokamak (STT) specifically designed to fill these gaps in the world fusion research program; it has a large, flexible divertor volume with the ability to deploy RF launchers on the high-field side; its access to high performance, reactor prototypical core plasma conditions with short current relaxation times make it an ideal platform for exploration of reactor-relevant RF wave physics and current drive actuator development.
- World research has established that boundary heat flux widths are independent of machine size and scale inversely with poloidal magnetic field [9], and that pedestal pressures scale with poloidal magnetic field squared [10]. These scalings enable an ADX – operating at the poloidal field, plasma pressure and exhaust power density of a pilot plant – to perform divertor identity experiments. This capability is a very powerful research tool. If a divertor solution is proven in an ADX, its performance could be projected with low risk to a pilot plant.
- The US is presently in a position to be the lead in this area with the construction of a dedicated Divertor Test Tokamak (DTT), as recognized in the FES 2015 PMI workshop report [11]: “In our judgment, the development of this science and technology is the most critical issue for advancement to DEMO, and the country that leads here will be in a leading scientific and technological position for the future.”

Scientific and engineering opportunities

The tokamak is the most promising magnetic plasma confinement device ever devised. Based on the confidence gained from decades of research, ITER is projected to produce 10 times more power out than in. Moreover, taking advantage of recent developments in HTS magnetics, this same core physics could lead to a compact electricity-producing pilot plant (e.g. ARC) [12] that is the size of JET. However, for any pilot plant design, order-of-magnitude improvements in the performance of key support systems are required – robust systems for power/particle handling, erosion control, and steady state RF current drive – and these systems must be shown compatible with attaining a burning plasma core and capable of operating in the severe neutron environment of a DT reactor.

Exciting new ideas for order-of-magnitude improvements in power exhaust/erosion handling have been identified. For example, modeling has shown that tightly-baffled, long-leg divertors with secondary x-points may attain this while also attaining a passively-stable, fully detached divertor state over a wide power range [4, 13, 14]. With the development of demountable HTS magnets [5] and liquid immersion blankets [6], these schemes may be implemented in the neutron environment of a reactor with no impact

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on available core plasma volume [15]. Transformative ideas for efficient, low plasma-material interaction RF actuators for heating and current drive have also been identified. For example, high-field side RF launch combined with operation in near double-null configurations takes advantage of the ‘quiescent scrape-off layer’ at this location to reduce PMI and provide unprecedented external control of local conditions at the antenna-plasma interface. Most importantly, RF wave physics is highly favorable with high field side launch. Lower hybrid waves may penetrate to mid minor radius and at the same time attain a 40% or more improvements in current drive efficiency [7]. A host of other potential benefits accrue as well, including the elimination of energetic particle loads, ELM heat pulses and runaway electron damage on launch structures. These are the kinds of approaches needed to make fusion energy a reality. Unfortunately, no facility presently exists in the world that is able to test these ideas at the plasma conditions needed to qualify them for a reactor.

It is widely accepted that a Divertor Test Tokamak (DTT) will be required to determine which divertor concepts, if any, can accommodate reactor-level conditions [11, 16]. Until recently, it was thought that such a device would not be practical, requiring a reactor-scale tokamak. But recent measurements of boundary heat flux widths in multiple devices indicate otherwise; remarkably, the widths are found to be independent of machine size (varied by a factor of 5 between C-Mod and JET) and to scale inversely with poloidal magnetic field [9]. In addition, it is well established that plasma pressure in the pedestal region scales as poloidal field squared [10]. This means that a compact, high field, high power density tokamak (similar to an Alcator class device) could be used as a DTT – producing the same boundary plasma pressure, magnetic field, plasma exhaust heat flux densities and divertor heat flux widths as a reactor. The recently proposed ADX device [8] is based on this idea.

Proposed strategic element

ADX (or a similar DTT device) is a necessary element of a sensible strategic plan for U.S. fusion energy development. Such a purpose-built device can function as both a DTT and an RF sustainment test tokamak (STT). Its small size (and modest cost) would have the flexibility needed to rapidly assess reactor worthiness. “Through the process of experiment-driven science and discovery, a DTT would rapidly advance fundamental understanding, stimulate game-changing innovations, and facilitate U.S. world leadership in these most important science areas.” [11]

Most importantly, the ability to produce reactor-level conditions in a full-scale divertor mockup is not only practical but essential for developing reliable physics models. If a divertor solution is proven in ADX, its performance could be projected with confidence to a pilot plant – simply make the magnetic and physical divertor geometry (in cross-section) the same. Similarly, a tokamak with the ability to implement high-field side RF launch systems at reactor parameters is essential. It would help determine if RF sustainment is in fact technically viable for a tokamak.

1. Ensuring U.S. leadership in a field of plasma physics and/or fusion development

An ADX would build on US expertise in advanced divertors, divertor physics, plasma-material interactions, liquid metals, RF actuators and RF wave physics. It would provide critical information for next-step reactor designs and ensure US leadership in these areas now and in the future.

2. Impact on present and future international activities and collaborations by U.S. scientists

An ADX would be an attractive platform for international collaborations, hosted by U.S. scientists.

3. Impact on the health of domestic fusion research at universities, national labs, and industry

An ADX would reinvigorate the domestic fusion program; it would be a national facility of excellence with participation from university, national lab and industrial partners.

4. Impact of/from unanticipated events or innovations requiring programmatic re-direction

Recognizing potential technological advancements and breakthroughs, it is important that ADX have the flexibility to test a wide variety of new ideas as they reach appropriate levels of maturity. At the highest level, a programmatic re-direction of magnetic fusion energy research may be required – for better or for worse – depending on outcomes from an ADX. This highlights the need to test tokamak divertor concepts and RF sustainment technologies early in the strategic plan – at reactor-level conditions.

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