ReNeW White Paper: Severe divertor issues on next step devices, and validating the Super-X divertor as a promising solution

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Motivation

The divertor bottleneck could severely constrain the future of the US and world fusion program beyond ITER, so development of innovator divertors is a must [1,2]. Next step devices complementary to ITER (e.g., CTF, DEMO or fission-fusion hybrids) present unprecedented divertor challenges. These will almost certainly have several times higher upstream parallel heat fluxes than ITER, and small devices (CTF and hybrid) will also have much shorter line lengths. Conventional understanding and simulations indicate that such parameters are outside the envelope of conventional divertor solutions [2]. A simple example will suffice. ITER has 120 MW of heating power P_h and an assumed core radiation fraction of 50%. Proposed reactors (e.g. ARIES RS) have a P_h/R which is 5 times higher (P_h =500MW, R = 5.6m), so with a core radiation fraction of 50%, the upstream parallel heat flux should be expected to be in the range of 5 times higher. To attain a parallel heat flux equal to ITER, the core radiation fraction would have to be about 90%. Analysis from the viewpoint of confinement, helium exhaust, thermal stability, and disruptivity indicated that such high core radiation fractions are very unlikely to be tolerable with acceptable reactor performance [2]. Hence, innovative divertor solutions are needed that can handle several times higher upstream parallel heat flux than ITER.

Challenges from high upstream heat fluxes include 1) both steady state and transient heat fluxes on PFCs 2) very high plasma temperatures (and thus low densities) at the PFC leading to severe erosion and plasma impurities, and also leading to 3) low divertor neutral pressure with very poor helium pumping. These problems are made all the more intractable since divertor PFCs in a DEMO/CTF are exposed to over an order of magnitude higher neutron fluence than ITER, potentially seriously degrading their capabilities. A successful divertor must solve all these issues *simultaneously*.

Tasks

- Simulations and analysis of SXD and other innovative divertors using existing code suites for projected CTF, DEMO and hybrid parameters.
- Collaborations with edge groups to improve the physics of models.
- Development of experimental tests of innovative divertors on US and world tokamaks, e.g., on MAST (where the SXD is slated to be part of MAST-upgrade).
- Low cost tests of innovations on US experiments (e.g. DIII-D, NSTX, Pegasus) i.e., test as well as possible for little cost
- Diagnostic upgrades to measure key quantities as needed, and simulation, analysis and interpretation of experimental results
- Major hardware upgrades (i.e. for NSTX or DIII-D) for more complete implementation of the innovative divertors on US devices. In the case of NSTX, PF coil modifications and possibly vacuum vessel shape modifications might be required for the SXD. Simultaneous tests with

lithium would be particularly significant. For DIII-D, additional PF coils and internal baffling might be needed. Finally, implementation on future devices, e.g. NHTX/Vulcan, CTF, etc.

Discussion

A new divertor magnetic geometry, the Super-X Divertor (SXD) has recently been devised. Among all proposed magnetic divertor geometries (including snowflake, plate tilting, etc.), it uniquely reduces *parallel* heat fluxes at the plate *purely geometrically*, by expanding the exhaust to larger major radius. This leads to comprehensive advantages: reducing heat fluxes at the plate within engineering limits for plate tilt, sharply reducing plasma temperatures (and increasing density) at the plate to reduce erosion and plasma impurities and facilitating further radiative dissipation, and enabling much higher neutral pressures for helium pumping. In addition, the geometry can uniquely reduce neutron fluence on the divertor material, potentially easing material development requirements.

Efforts to investigate the SXD should be part of a larger effort to examine alternative magnetic geometries and comprehensively examine their relative merits and advantages for CTF, hybrid and DEMO parameters. Various innovations should be considered, such as the snowflake divertor, liquid metal PFCs, etc. Investigations should include comprehensive modeling and analysis of such geometries for CTF and DEMO parameters, for heat flux, erosion, plasma impurities, and helium pumping, to provide guidance for how different concepts need to be improved to meet the requirements.

Modeling can start today with existing codes such as SOLPS, UEDGE, REDEP/WBC, etc. For transient phenomenon (ELMs and disruptions), the HEIGHTS code package can be used. There are additionally US models/codes for such areas as dust formation/transport, atomic and molecular processes, liquid metal surface properties, and the like. Such modeling will be very helpful in guiding the development of innovations to advance to the point where they appear likely to meet projected needs for DEMO/CDT/hybrid. Modeling will also be a crucial tool to developing appropriate experimental tests, and interpreting results.

This modeling will be essential to evaluating the full magnitude of advantages, in comparison with likely requirements. For example for the SXD, can the new geometry enable more heat spreading by magnetic or possibly ExB drifts, supersonic transitions, etc. - with opportunities to increase volumetric losses. Getting the targets away from the core plasma makes it easier to shield it from divertor impurities (e.g. Li evaporation). The magnitude of engineering advantages such as easier divertor access for maintenance and pumping could be considerable and also needs assessment.

When modeling divertor performance on future devices, uncertain parameters such as the SOL width, ELM duration, etc. can be varied within the likely range. Other thrusts will improve our understanding of the physics, and hence improve the models used in simulations. Obviously ongoing advances from those thrusts will inform the analysis of this thrust. However, the magnitude of the divertor challenge on devices beyond ITER appears so large that it is clear that major divertor innovations will very likely be needed, even given the uncertainties in our present understanding. Since the SXD can potentially solve so many problems simultaneously, it should be intensively investigated.

In addition, experimental testing of the innovations is needed, with comparisons to modeling. Diagnostic upgrades may be needed to measure all the quantities relevant to satisfactory divertor operation with acceptable erosion and helium pumping: divertor heat flux, plasma temperature and density, neutral pressures, spatial radiation distribution, etc. By testing in new geometries, general divertor physics might be clarified- e.g. the new innovations can lead to significant changes in magnetic shear, line length, SOL temperature, SOL instability (with the potential for greater spreading of the heat), etc.- with possible illuminating effects on detachment, H-L thresholds, etc.

Experimental investigations should be pursued on US tokamaks, as well as via international collaborations with other experiments. The SXD is already slated to be tested on reduced size plasmas on DIII-D in 2010, it is being implemented on MAST (EU) and SST (India), and there is interest at TCV (EU). It is slated for testing in NSTX's 10 year program. High power devices can examine heat flux issues. Lower power experiments (including possible tests on US devices such as Pegasus) could test important physics aspects such as the predicted sharp reduction in plasma temperature at the plate with the SXD, the increase in divertor neutral pressure (for helium pumping and density control), simultaneous tests with lithium gettering (LTX and NSTX), etc.

At present, almost no major experiments in the world are dedicated to innovator divertor development to overcome expected challenges on devices beyond ITER (the implementation of the SXD on MAST being one of few exceptions to this.) Hence, this is a crucial area where the US can take decisive leadership in the world fusion program-in the near term with dedicated analysis and simulation to find likely solutions for future devices (CTF, hybrid, DEMO), then with inexpensive testing on present experiments. In the longer term, promising innovations need testing on existing devices with major upgrades and implementation on future devices, e.g., NHTX, CTF, hybrid, DEMO.

Finally, systems analysis of the both the benefits of the SXD and the requirements for its practical implementation are needed. The benefits of reduced core and edge radiation requirements allowed by innovative permeate throughout the device, and give major advantages by allowing lower edge density (and hence higher current drive and bootstrap current) with major effects on MHD stability, attainable confinement, disruptivity, etc. More systematic evaluation of these benefits is needed through integrated modeling. In addition, costs and difficulties associated with the new geometry need to be assessed through systems level engineering evaluations.

Reference

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