Potential impact of low recycling equilibria and lithium walls on reactor design

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Introduction

The initial phases of spherical tokamak research in the U.K. and the U.S. were motivated by a desire to reduce the scale and complexity of tokamak fusion systems. Advances in liquid metal wall technologies, coupled with the potential confinement advantages of low recycling walls, could further reduce the scale and cost of component testing, and prototype development fusion systems.

For a small D-T spherical tokamak to produce 0.2 ~ 0.5 GW fusion power output, on the order of what is projected for ITER, advances in two areas are required. First, a compact ST system requires energy confinement beyond what is currently accessible. Even modest improvements in electron confinement would permit construction of fusion systems at reasonable scale. Very significant advances in confinement could result in very compact, driven-burn systems of high enough gain, and small enough scale, to make significant alpha particle heating unnecessary. Secondly, a compact ST fusion device requires a first wall capable of enduring high power density. Because the erosion rate for a solid first wall in a high power density ST would be prohibitive, this last requirement probably mandates the use of a renewable liquid metal first wall. For an ST-based system, operation near the ideal no-wall limit stability limit can produce sufficient fusion power output for a compact facility for nuclear testing, or for implementation of hybrid fusion-fission systems.

Both high confinement and a renewable wall may be provided by liquid lithium PFCs. The research path necessary to determine the feasibility of compact D-T STs for fusion development is well defined, and tractable well within the ITER time frame.

Confinement

Numerous analytical and experimental papers have indicated that a liquid lithium plasma-facing surface should produce minimal recycling. This work dates back to McCracken[1], and extends to more recent results from T11-M, PISCES, CDX-U,[2] FTU,[3] and NSTX[4]. Other systems (e.g. cryopumped divertors) reduce recycling, but typically by no more than 5-10% - not to the level where wall fueling is unimportant. Analyses further indicate that low recycling (certainly less than 50%, but the required level is not yet certain), in combination with strong core fueling, will produce very high edge electron temperatures;[5] a result which is supported by observations of high edge electron temperatures with lithium wall conditioning in TFTR. Numerical simulation codes such as ASTRA, UEDGE, and TSC all indicate that the electron temperature gradient in the core will be greatly reduced by low recycling walls and core fueling. The lack of a significant electron temperature gradient in the core plasma is predicted to reduce energy transport, since eliminating the electron temperature gradient removes the largest free energy source for instability drive in the system. In the only spherical tokamak experiment ever operated at <50% recycling, CDX-U, the observed confinement exceeded ELMy H-mode scaling by a factor of 2-3.[2] Enhanced energy confinement times are predicted in the follow-on to CDX-U, the Lithium Tokamak eXperiment (LTX).[6] Confinement may be limited by ∇n driven turbulence, but in the absence of an edge

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particle source, the density profile can be determined by the fueling profile. It remains to be seen whether ∇n driven modes will be significant, or whether in any case a region of very good core confinement be constructed in a tokamak, by appropriate tailoring of the fueling profile. Control of the fueling profile is valuable in itself, and a cross-cutting issue with Theme II, (High Performance Steady-State Plasmas). Low edge densities would also improve current drive efficiency and increase bootstrap current, and thus allow greater ability to control the current profile, and thereby ameliorate beta-limiting instabilities at any given β_N.

First Wall

A renewable liquid metal first wall is one of the few alternatives to a solid tungsten first wall for a reactor. Liquid metal wall concepts have been advanced which employ high recycling metals, and implementations considered range from fast flowing jets to slow capillary flow of liquid metals embedded in porous metal substrates. Startup and other issues are simplified if the liquid lithium PFC consists of a slowly flowing thin layer, cooled from behind, embedded in a porous metal substrate, and restrained by capillary forces. This wall construction is similar to the structure of liquid lithium limiters used on T11-M and FTU, and to the design of the liquid lithium divertor system now under construction for NSTX, as well as the lithium-coated wall in LTX. The development of liquid metal PFCs has a separate importance to the fusion program, which is further discussed in a white paper submitted to Theme III (Plasma-Material Interface).

Stability and Beta limits

The ST is suitable for this development because of its high beta limits. It is even possible that a compact, low recycling ST can serve as the basis for a reduced or intermediate scale DEMO. But the low recycling, liquid metal wall may be most attractive for a power reactor when incorporated into a more conventional aspect ratio, superconducting tokamak, since the lithium-walled tokamak should provide higher ideal with-wall beta limits.

Several features of a low recycling, lithium-walled tokamak may provide access to β_N values in excess of the no-wall limit. First, the plasma-wall separation can be very small with lithium walls. Conducting walls at $r<1.05a$ are feasible. Stability analyses for LTX, which is designed with a conformal lithium coated conducting (copper) shell or wall at $r/a \sim 1.02$, indicate that the close proximity of the conducting wall significantly extends the stability boundaries for both low-n and peeling-ballooning modes, from a no-wall limit of $\beta_N \sim 3\text{-}4$ to a stable $\beta_N \sim 8\text{-}10$, with the shell. Access to high stable β_N during startup might be complicated by unstable regions at integer values of the edge q. These conditions would allow an evaluation of the stability needs for DEMO-levels of β_N - the required plasma rotation profile and magnitude generated by momentum input from neutral beam injection, and the needs for active control of resistive wall modes and mitigation of ELM transients.

In a long-pulse or continuously operated system, the requirement for continuous first wall cooling might also be satisfied by replacing the passive copper shell with a hollow shell, filled with a liquid lithium coolant, flowing along field lines. If the flow of lithium coolant is sufficiently fast, then it will provide MHD stabilization. Wall stabilization produced by a fast flowing liquid metal is expected to be active as long as the flow persists, with no resistive decay of the stabilizing effect. A very preliminary analysis of the LTX equilibrium with a flowing shell of liquid lithium, ~ 1 cm thick, indicates that the stability limit will be extended significantly beyond the no-wall value. These studies are still in an early stage; the liquid metal flow pattern has not been optimized.

Research Thrusts

Modeling - Integrating a low recycling wall model into a code which deals with tokamak confinement has so far only been attempted with ASTRA. While the ASTRA modeling is very helpful, other codes exist or are under development, which are intended to provide a comprehensive and detailed linked plasma core-edge-wall model. Initial modeling of MHD stabilization with a layer of fast flowing liquid metal at the plasma edge has been performed with the AEGIS code (U.T. – Austin), but the array of possible flow patterns and velocities is large, and when multiplied by the possible plasma equilibria, presents a large number of possible solutions for optimization. The transport of a liquid metal along a porous metal PFC has not been modeled. Fast flowing liquid metals in ST-relevant magnetic fields, input/outlet manifolds, etc. require an extensive modeling effort, although this task may be shared with any general development effort for liquid metal PFCs.

Experiment - There is appreciable work now underway on the effects of lithium walls and coatings on confinement in LTX and NSTX. However, both devices currently rely on gas puffing for most fueling, which simply replaces one edge localized gas source with another. Core fueling capabilities on these devices are needed. Stability limits could in principle be explored on LTX, but sufficient auxiliary power is lacking. NSTX has ample auxiliary heating, but plans call for replacing only a fraction of the carbon PFCs with liquid lithium systems over the next few years. Broader tests of the effects of lithium walls are desirable not only from the point of view of the research thrust advanced in this white paper, but for the purpose of increasing the performance of small ICC devices which are now dominated by edge charge-exchange losses.

An expanded research thrust into the general area of liquid metal walls could provide the technology required for the implementation of low recycling walls, but of course has broader applicability, and is advocated in conjunction with the ReNeW panel on PMI issues.

A concerted effort to determine the confinement in low recycling tokamaks could yield enough data to design a next-step device within a few years. Positive results from such an experimental program could significantly reduce the scale size of high performance tokamaks and STs, and the cost of a component test facility.

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