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Plasma-wall boundary control with lithium divertor and associated plasma confinement improvements in NSTX*

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Developing a reactor compatible divertor has been identified as a particularly challenging technology/physics problem for magnetic confinement fusion. While tungsten has been identified as the most attractive solid divertor material, many challenges including surface cracking and deleterious modification of the surfaces by the plasma must be overcome to develop robust plasma facing components (PFCs). Alternately, a possibility of plasma-wall boundary control with lithium divertor and associated plasma confinement improvements has been receiving increasing interest in the recent years [1-2]. On NSTX, the effects of lithium coatings (both in solid and liquid phases) have been investigated on the divertor in H-mode plasmas. A liquid lithium divertor plate system was tested with about 1300 g of lithium evaporated into the NSTX vacuum vessel. The overall NSTX lithium coating results suggest attractive opportunities for future magnetic confinement research including H-mode power threshold reduction, the control of Edge Localized Modes (ELM), electron energy confinement improvements, impurity control during non-inductive plasma start-up, and improving radio frequency wave heating and current drive efficiencies. Another intriguing result from NSTX is that the surprisingly low levels of lithium ions observed in the NSTX H-mode plasma core (below 0.1% dilution) compared to higher Z impurities (such as carbon) even when the plasma is essentially surrounded by the lithium coated walls. This observation bodes well for lithium based plasma facing component and divertor applications. Importantly, with lithium coating, measurements showed a significant ~ 50% reduction in heat load on the LLD, indicated by enhanced bolometric radiation above the divertor surface. Based on the experimental results from NSTX with its liquid lithium divertor (LLD) and experimental results from other devices and test stands, promising divertor solutions based on liquid lithium are emerging [2].

In terms of handling the very high heat flux expected on the tokamak reactor divertor strike point, a liquid lithium (LL) based closed radiative divertor concept (RLLD) has been recently proposed as shown in Fig.1 [3].

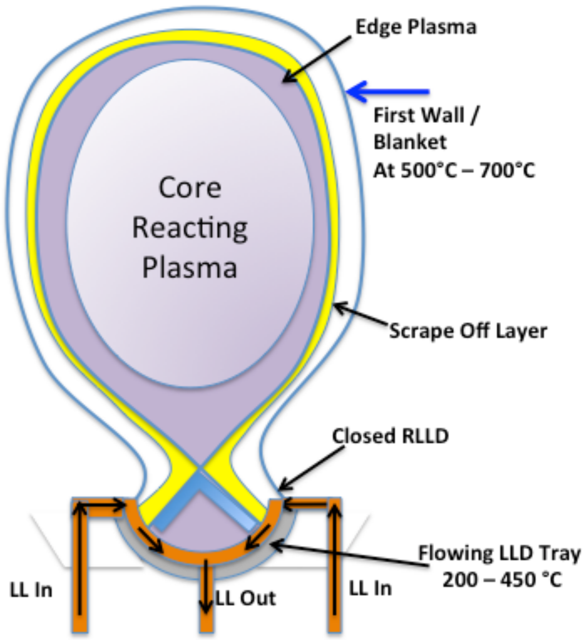

Fig.1. A possible RLLD configuration in a fusion power plant.

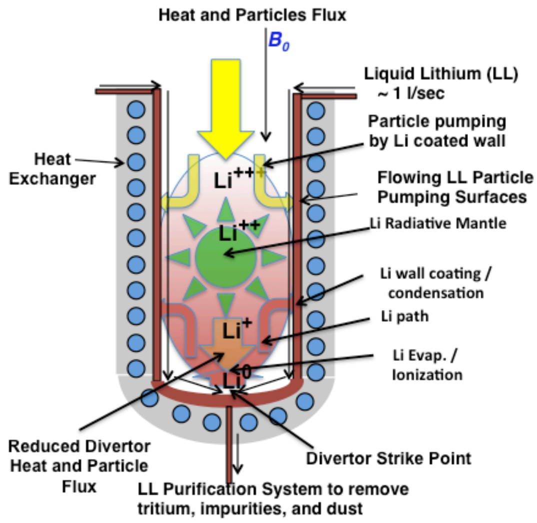

Fig. 2. A schematic for the RLLD concept.

With an LL coating, the lithium is evaporated from the divertor strike point surface due to the intense heat as the lithium evaporation increases rapidly with the surface LL temperature. The evaporated lithium is readily ionized by the plasma due to its low ionization energies, and the ionized lithium ions can radiate strongly, resulting in a reduction in the divertor heat flux. A schematic of the RLLD concept is shown in Fig. 2. This radiative process has the desirable function of spreading the narrowly focused divertor heat load to the entire divertor chamber, which facilitates the divertor heat removal. Since the projected Li radiation can be very high (i.e., ~100 MJ / mole of Li ions), it should be readily feasible to provide an adequate amount of LL in the high heat flux divertor region even for steady-state operation. For example, to radiate an estimated 200 MW of influx power into divertor for a 1 GW-electric class fusion power plant, it would only take about two moles of Li per sec to handle the divertor heat load. One can readily provide higher evaporation rate if necessary. A 1-D model calculation of RLLD has been performed with a two-point model in a cylindrical geometry [3]. With Li radiation level of 10^{-26} W-cm^3, which assumes relatively poor confinement of $n_e\tau = 10^9 - 10^{10}$ in the divertor region, the model predicts only ~ 10^{18} Li particles would be needed for an ST-based FNSF with R= 1.5 m and ΔR = 2 cm. If the Li radiative mantle could reduce the direct divertor heat flux down to the vicinity of 5 MW /m^2, then the solid substrate material (perhaps made out of tungsten) could become viable as long as it is coated with Li. The LL surface can also provide a "sacrificial" surface to protect the substrate solid material from transient high heat loads such as the ones caused by large ELMs. If the transient heat flux is high, that much more Li would be evaporated and ionized, which would then increase the radiative cooling until an equilibrium condition is reached. For example, in an ITER scale tokamak reactor, with the enhanced radiative process, only a modest amount (~ 1cc) of LL is needed in principle to radiate the expected heat pulse of ~ 10 MJ for an exceptionally large ELM event.

The closed radiative LLD concept has the following additional attractive features: 1. Some degree of shielding for LL is provided from fast disruptive events. Placed within the chamber, even if LL is "splashed", it can be largely contained within the chamber. 2. Particle partition is provided from the main plasma chamber due to the strong divertor lithium retention. 3. Strongly divertor pumping action is provided from the divertor chamber wall as the vaporized and ionized lithium ions coat the entire divertor chamber wall. The strong pumping would access a low recycling regime for advanced high performance plasma operations. 4. Lastly, by operating the divertor lithium condensing surfaces at lower temperature (200-450°C) than the first wall (500-700°C), the LLD can serve as a purifying / pumping system for the entire reactor chamber as impurities generally migrate toward lower temperature surfaces in addition to the natural divertor flow action. To maintain the LL purity, a closed LL loop system with only a modest circulating capacity (~1 liter/sec for ~ 1% level "impurities") will be needed in a steady-state reactor operation. A schematic for a possible LL purification loop is shown in Fig. 3.

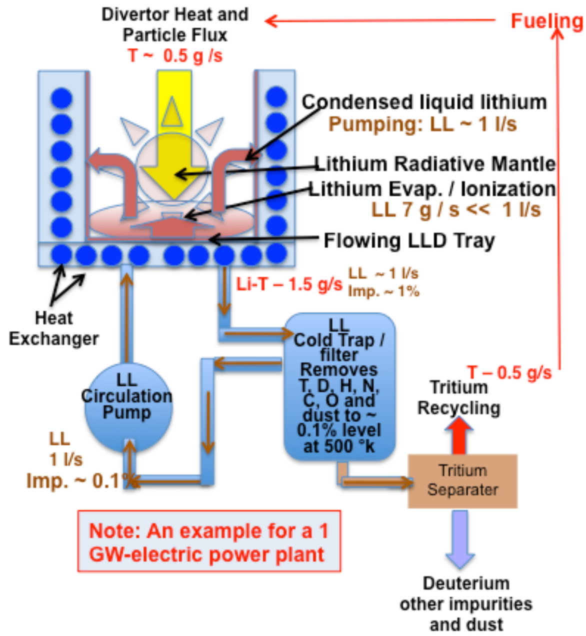

Fig.3. A schematic for the RLLD purification loop.

Finally, it should be emphasized that Li application should be quite compatible with various divertor geometry and magnetic confinement configurations providing the same benefits of Li. Application of Li may also be considered for protecting the tungsten based solid PFC surfaces such as the ones for ITER, as long as a means to purity/refresh LL can be provided. In summary, a radiative mantle based LL divertor solution have the exciting prospect of providing a cost effect flexible means to improve the fusion reactor performance, while providing a practical solution to the highly challenging divertor heat handling issue confronting steady-state magnetic fusion reactors.

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References:

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