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Divertor Design for Low-Recycling Regime Tokamak: Concept, Experiments and Simulations

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We present a novel flowing lithium divertor design that allows low-recycling regime by handling ITER like reactor heat fluxes of $> 10MW/m^2$ with jxB induced flow speeds of centimeters per second, total lithium inventory of $100kg$, power consumption of $1MW$. Tritium in lithium is then concentrated as LiT crystals with small insitu cylindrical electromagnetic centrifuges without moving parts, reducing the power and mass requirements for tritium separation loop. We present the experimental results from prototypes placed in Liquid Metal eXperiment (LMX) at PPPL and numerical simulations of the system showing that the system is feasible. This system allows a breakthrough in comparison to the systems requiring high inventory/power lithium divertors for low-recycling regimes [1].

Fusion reactor operation in a low recycling regime has many possible advantages over the standard reactor designs with high recycling [2]. To achieve low recycling, a reactor would need a divertor covered with lithium without evaporation. Given the reactor heat fluxes, this can only be achieved with a recirculating flowing liquid metal (LM) divertor. The major studies in the field show that lithium flow over the divertor requires thick >m/s velocity flows. Moreover, in these designs, the separation of tritium embedded in lithium is solved by pumping the entire liquid mix out of the reactor for distillation, which requires long piping. Under these conditions, the lithium inventory easily exceeds tonnes and the tritium distillation purity requirement becomes excessive, introducing many engineering challenges that rightly yield skepticism about the feasibility of such a system. These challenges can be broadly listed as: 1) Safety issues related to a high lithium inventory; 2) The power requirement for pumping of the lithium against MHD drag; 3) The stability of open channel LM flow in high speeds under MHD forces; and 4) Separation of tritium from LM.

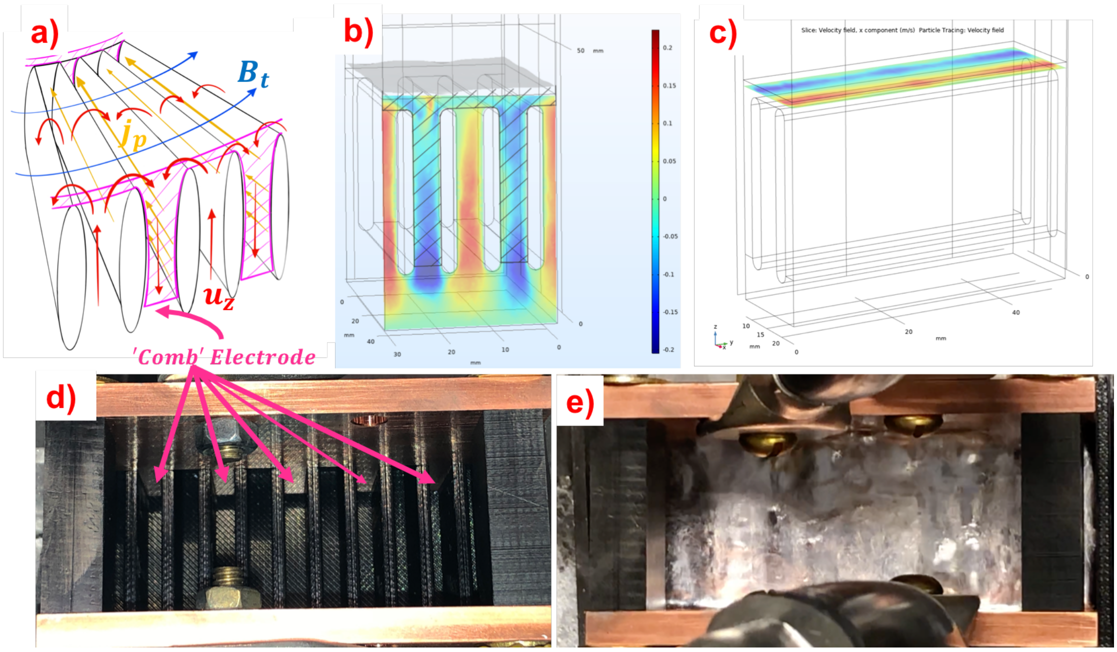

Figure 1: a) Sketch of "radiator"divertorlet concept. Comb shaped electrode allows poloidal current (from the inner radius to outer radius of the divertor) to run in the LM in even channels and on the surface. Downwards jxB allows LM on the surface and even channels to be pushed down. Mass conservation pushes the LM up in odd channels. b,c) COMSOL simulation of divertorlet at LMX with MHD and open surface showing stable surface, and vertical/horizontal flow velocity in m/s (>10 cm/s circulation speed). d) Prototype divertorlet section on LMX (comb structure visible). e) Divertorlets LM flow in LMX with surface shape similar to simulations above.

In this presentation, we introduce the alternative concept of "divertorlets", Figures 1, and in situ tritium concentration, Figure 2, then show how these concepts can alleviate the aforementioned issues by reducing the velocity, inventory and power requirements.

Divertorlets emerged out of the multi-year effort of our group in LM behavior control by running electric current in the LM under different divertor setups [3,4,5]. To first order approximation, LM evaporation start time is $t_{crit} = (T/2q)^2$ π k ρ c_p, which is constant for a given LM and heat flux [3]. For lithium ΔT, the temperature rise, is ~200 [°C] to avoid evaporation, and a choice of heat flux of $q = 10MW/m^2$, gives t_{crit} $0.05[s]$.. Thus, velocity,$v = L/t_{crit}$, requirement for LM divertor increases linearly with flow length reaching >m/s in reactor designs with 10s cm of divertor. To overcome this scaling, we divide the flow along the divertor into many uniquely shaped small divertorlets, which allows for non-evaporative flow at much lower velocities with a separate cooling system. The challenge is to figure out a way to circulate the LM flow in these small divertorlets where high flux is present on top disallowing many standard options. In our design, the LM is circulated with Lorentz force achieved via novel electric current flow setups (and the magnetic field already available in the reactor) with negligible power requirements compared to the power plant balance. There are a few divertorlets concepts developed, experimental setup and numerical simulations for "Radiator" divertorlet with ~1 cm channels is shown in Figures 1. Electrodes are placed every other divertorlet and on top where LM touches the plasma in a "comb"setup. The poloidal current thus the jxB_t in the divertorlet with the electrode is higher than divertorlet next to it. This pressure gradient allows LM to circulate. The jxB on the top of the divertorlets push the flow downward keeping the LM flow thin and high speed on top. Flow speed can be calculated by setting the jXB force difference to MHD drag which dominates over viscous terms giving $v = \eta/C_{MHD}(V/LB_t)$. Here V is the applied voltage, η is efficiency of pumping i.e. ratio of the current in divertorlet with electrode over the current in divertorlet without electrode, and C_{MHD} is the ratio of MHD drag to ideal closed conductive walls. C_{MHD} is <0.1 for this setup based on simulations and measurements. η starts at 1 close to the electrode where we expect the highest heat and reduces to around 0.5 midway. This approximation matches with the measured >10 cm/s flow recirculation speeds at LMX (with $> 10MW/m^2$ heat uptake capacity and with COMSOL shown in the figure. Scaling LMX system to ITER would require LM inventory ~100 kg, and the power requirement to around a megawatt.

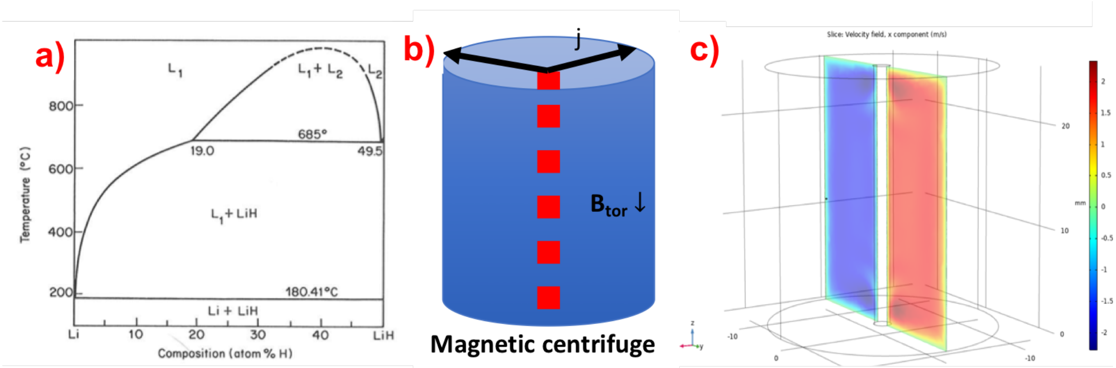

Figure 2: a) Li, Li-Hydride composition curve. Showing that at reduced temperatures Hyrogen and its isotopes forms crystals in LM Lithium [7]. b) Sketch of the magnetic centrifuge. Current is run from a rod (red line) at the center to the edge of the cylinder. Along with toroidal B forms jxB force which rotate the LM in high speed. c) Numerical simulation of the magnetic centrifuge showing >m/s flow and thus centrifugal force (>g) can easily be achieved in a reactor with high magnetic field. This force concentrates the LiD/LiT crystals at the edge which can be pumped out of the reactor for separation.

A larger part of the lithium inventory and power requirement is due to the long piping of the LM out of the reactor for tritium separation. Tritium inside the liquid lithium forms LiT crystals with twice the density of lithium when slightly cooled [6]. A few small cylindrical electromagnetic centrifuges along toroidal direction (∥ to B_t) with current emanating from center rod to the outer radius induces fast rotation due to jxB_t as shown in Figure 2. High magnetic field inside the reactor allows these centrifuges with no moving parts to operate with minimal currents and power requirement to concentrate the LiT to very high levels. Only this concentrate is piped out for separation reducing inventory and pumping power by orders of magnitude. Even though the challenges of a flowing lithium system are substantial, the novel approaches described in this presentation may reduce the engineering issues to reasonable levels and enable exploration of the advantages that a low-recycling regime brings to plasma performance and fusion reactor design.

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References:
[1] M.A. Abdou, et al., FED 54, 181–247 (2001)
[2] D.P. Boyle, et al., PRL 119, 015001 (2017)
[3] E. Kolemen, et al., NME, Vol. 19, 524-530 (2019)
[4] A. Fisher, et al., NME, Vol. 19, 101-106 (2019)
[5] M. Hvasta, et al., NF 58 016022 (2018)
[6] R. Majeski, E. Kolemen, Patent Disclosure M-924, PPPL (2017)
[7] Y. Sato, et al., Molten Salts Chemistry, 451-470 (2013)

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