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A Tokamak Reactor with Lithium Walls

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Background: *A recently discovered mechanism of magnetic propulsion of a liquid metal in the toroidal magnetic field of tokamaks (December of 1998) enables intense stationary liquid lithium (Li) streams covering the plasma facing surface of the vacuum chamber. There are several attractive properties of such a regime. These are presented, together with the possible issues, experimental foundations and the necessary R & D.*

Li streams: The streams are about 1 cm in thickness and are held to the surface by the $\mathbf{I}_{pol} \times \mathbf{B}_{tor}$ electromagnetic force, where $\mathbf{I}_{pol}$ represents the externally driven electric current through the streams. In the strong tokamak magnetic field this force can be so large (3 orders of magnitude larger than in the momentum or gravity driven liquid walls) that the liquid Li is capable of withstanding the possible electromagnetic forces during potential disruptions.

Electro-magnetic propulsion: The intrinsic inhomogeneity of the $\mathbf{I}_{pol} \times \mathbf{B}_{tor}$ force drives the liquid Li along the walls (see Fig. 1) from the inner, strong magnetic field, side to the outer side of the torus, where the toroidal field is smallest. The velocity of the Li streams due to magnetic propulsion is of order 10-20 m/sec and should easily compensate all associated viscous losses. The magnetic Reynolds number for such a streams should be about $0.2 - 0.4$ in order to satisfy the power absorption requirements. The diamagnetic drag force is negligible given the small thickness of the streams. For a tokamak-reactor with $R \simeq 5\ m$ and $a = 1.5\ m$ with the modest cost of about 20 MW of electric power for driving the streams, the magnetic propulsion allows the propulsion of more than 2 T/sec of Li. This ammount is capable of absorbing 1 GW of power and will also enable its transmission out of the device, while keeping the temperature of the Li in the range of $300 - 350^o\ C$.

On one hand, the relatively small temperature of the Li stream, does not allow efficient conversion of the energy coming from the α-particles to electricity i.e., 20% of the total fusion power. On the other hand, the low temperature of the Li streams with a continuously refreshed plasma facing surface allows us to utilize the unique properties of Li to absorb the D and T particles (by producing Li hydrate molecules). With such an absorption environment at the plasma edge, the discharge may go into a new, non-recycling regime in tokamaks, which overcompensates the unavoidable loss of the 20% of the fusion power.

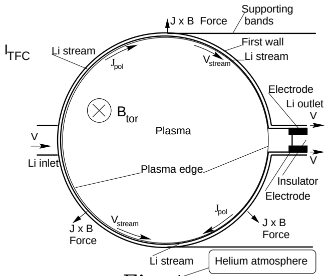

Fig. 1

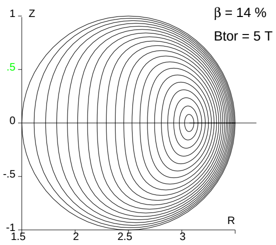

Fig. 2a

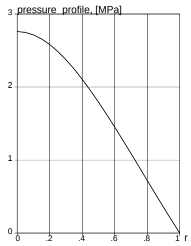

Fig. 2b

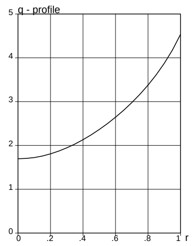

Fig. 2c

Basic physics of the non recycling confinement regime.

Fuelling: With the complete absorption of the plasma particles by the Li walls, refuelling would rely on DT pellet injection into the central core of the discharge.

Transport: In the situation, where the particle and the energy sources are concentrated near the core and assuming the sources of DT and Li at the plasma boundary are negligible, the high temperature of the core would essentially extend up to the Li walls, where particles are absorbed and their energy is converted into the heating of the Li stream. The outflux of the plasma from the center continuously drives back the Li particles coming from the wall, thus, providing $Z_{eff} \simeq 1$ in the body of the plasma.

The resulting, flat plasma temperature profile with $T \simeq 15 - 20\ keV$ at the plasma edge has a dramaticaly reduced ion temperature gradient, which results in the *elimination* of the anomalous energy transport, which at present limits the energy confinement time in the big tokamaks. The profile is only flat on average since the pellet injection causes temperature oscillations in the core.

MHD stability: From the MHD point of view, the flat temperature profile corresponds to a flattened stationary current density profile with the safety factor q in the plasma signficantly above 1, which corresponds to a continuous second stability zone with no conventional ballooning stability limitations.

Another important factor is that the intense Li stream also helps to suppress the fast growing ideal free boundary MHD modes, by reducing their growth rate to the level of the resistive wall modes, which can be stabilized by feedback system or *by the same Li streams*, if the magnetic Reynold number of the flow will be lifted to the value above 1.

A preliminary analysis of the MHD stability shows, that even with the simple circular cross-section at the aspect ratio of 2.5, the plasma is stable to ballooning and to the n=1,2,3,4 global modes with a fixed boundary up to $\beta = 14\%$, $\beta_N = 13\%$ ($q_0 = 1.7$, $q_a = 4.5$), (Fig. 2a,b,c).

Ignition: The enhancement in the confinement time τ_E by a factor H (which can be reasonably expected to be at least $4-5$) with no limitation on the plasma β, the fusion ignition parameter $n\tau_E$ increases by a factor of H^2 at the same temperature, and, therefore opens the possibility of achieving ignition in tokamaks with a simple magnetic geometry, reduced size and lower toroidal magnetic field.

Necessary absorption capacity of the Li streams:. For a fusion reactor with a 1 GW power in the α particles, assuming the burning rate of the DT fuel at 2% , the total plasma particle flux dN_{DT}/dt to the wall is $1.8 \cdot 10^{23}$ sec^{-1}. With the Li density $n_{Li} \simeq 0.5 \cdot 10^{23}$ cm^{-3} and propulsion of 1 T/sec of Li in a 1 cm thick stream this implies that the number of mono-layers K, which should be converted into LiD and LiT, is 64.

This number corresponds to the saturated distance $d_{LiDT} \simeq 1.7 \cdot 10^{-6}$ cm, which should be compared with the penetration length $\lambda_{D,T}$ of the incident D,T ions in the liquid Li $\lambda_{D,T}$ $cm \simeq 2.3 \cdot 10^{-6} T^2$ $(keV)^2$. For the edge plasma temperature of $T = 10$ keV, $\lambda_{D,T} = 135 d_{LiDT}$ and increases with the temperature.

It is possible to conclude, that the magnetic propulsion can provide an adequate rate of refreshing of the Li surface in order to absorb all D,T ions, coming from the plasma.

Evaporation of Li: With a tokamak reactor surface area of $S < 500$ m^2, the plasma particle flux will be $dN_{DT}/Sdt = 3.6 \cdot 10^{20}$ $sec^{-1}m^{-2}$, while the evaporation rate is $0.4 \cdot 10^{20}$ at 350^o C and $0.04 \cdot 10^{20}$ at 300^o C, falling exponentially with a decrease in the temperature. Intense magnetic propulsion allows us to keep the Li temperature low enough ($\simeq 300^o$) so the evaporation will be negligible, compared to the plasma particle flux.

Sputtering and other sources of Li errosion:. The sputtering and erosion as mechanisms for plasma edge cooling and contamination by Li impurities is *the critical issue that needs to be resolved* for achieving this low recycling regimes. Without numerical simulations in the edge boundary physics in tokamak in the Li wall environment it is impossible to assess its effect at this point. The general favorable factor is that D,T penetration length $\lambda_{D,T}$ rises with the temperature as T^2, thus, presumably reducing the Li erosion.

Tokamak-reactor implications. Having identified the crucial physics issues associated with Li walls, we note that this approach challenges many fundamental aspects of physics of tokamak-reactors. On the science side, it indicates the possibility for

1. suppression of the anomalous transport;
2. extension of the MHD limits (including the resistive wall modes) to the level of $\beta > 10\%$, well beyond the conventional Troyon limit or MHD limits for the free boundary MHD modes;
3. comprehensive plasma current and temperature profile control by pellet injection;
4. achieving ignition conditions in machines with a simple magnetic geometry of the size of TFTR.

The regime with the flat temperature is also not sensitive to the possible neoclassical tearing modes. On the reactor side, the confirmation of these scientific possibilities by appropriate numerical simulations and experiments, together with independent development of the magnetic propulsion technology for Li, would result in

1. a more simple magnetic configuration of the plasma;
2. an efficient use of the toroidal magnetic field at the 5-6 T level;
3. efficient plasma profile control through refuelling;
4. extended optimization space and flexibility for designing the tokamak fusion reactor.

The perspectives for R & D. Besides the necessary detailed numerical simulations of the plasma/Li wall interactions and the non-recycling regimes, the issue seems to be so complicated that experiments on the real tokamaks should be done for the real assessments. Fortunately, the Li properties, such as thermal conductions, specific heat of melting, surface tension, allows us to conduct the relevant experiments on big machines even with solid Li.

E.g., for the TFTR parameters and 40 MW of the heating power, the solid Li (covering all the inner wall) will melt at the rate of 2 mm/sec (with no significant increase in the temperature above the melting point). Thus, at least for the limited but sufficient time of the order of 1-2 sec, the non-recycling regime can be achieved. While being limited by MHD stability at the level of $\beta_N = 2$ in the supershot regimes with the conventional limiter and walls, with the Li walls this machine will acquire stability up to the unachievable level of $\beta_N \simeq 10$ with the realistic possiblity of surpassing the Lawson ignition criterion.

Although the full scale experiments require the higher plasma temperature of about 10-20 keV, further theoretical studies of the issue may identify the milestones achievable in smaller experiments.