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The Lithium Vapor Box Divertor

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Abstract

It has long been recognized that volumetric capture of the plasma efflux from a fusion power system is preferable to its localized impingement on a material surface. Volumetric capture mitigates both the anticipated very high heat flux and intense particle-induced damage. Recent projections to a tokamak demonstration power plant suggest an immense upstream parallel heat flux, of order 20 GW/m^2, implying that fully detached operation may be a requirement for the success of fusion power. Building on pioneering work by Nagayama et al. and by Ono et al., we present here a concept for a lithium vapor box divertor, in which lithium vapor extracts momentum and energy from a fusion-power-plant divertor plasma, using fully volumetric processes. At the projected powers and pressures this requires a high density of vapor, which must be isolated from the main plasma. Isolation is achieved through a powerful differential pumping scheme available only to metal vapors. The preliminary calculations are encouraging, but much more work is required to demonstrate the practical viability of this scheme.

1. Motivation

It has long been recognized that volumetric capture of the plasma efflux from a fusion system is preferable to its localized impingement on a material surface, in order to mitigate the anticipated both very high heat flux and intense particle-induced damage. This is the fundamental motivation behind the "gas-box" divertor concept[1], in which recycling DT fuel is to provide momentum balance with the upstream plasma, through charge-exchange and collisional friction, allowing the divertor plasma to detach from the material target. Full detachment, however, often results in the high-neutral-density detachment region moving to the magnetic x-point[2], and in deterioration of plasma confinement and increased impurity levels. Projections to a demonstration power plant[3], furthermore, suggest an immense upstream parallel heat flux, of order 20 GW/m^2, so fully detached operation may be a requirement for the success of fusion power. Building on earlier work by Nagayama et al.[4] and by Ono et al.[5], we present here a concept for a lithium vapor box divertor. In Section 2 we describe a means for confining a high pressure of lithium vapor in the path of a divertor plasma, with minimal lithium efflux to the main plasma. In Section 3 we develop a simplified model of particle and power balance including plasma entrainment, and in Section 4 look at a less simplified model for power balance. In Section 5 we consider further simulations and experiments that are needed to establish the practicality of this scheme, and draw conclusions.

2. The Lithium Vapor Box

In pioneering work, Nagayama et al.[4] suggested that evaporative cooling could be used to accept the heat efflux from a fusion power plant. If we imagine that such a device produces 2500 MW of fusion power at $Q_{plasma} = 25$, the plasma will be heated by 500 MW of α power and 100 MW of auxiliary power. Following the prescription used for ITER, let us then assume that 200 MW (1/3 of the total heating power) will travel to the outer divertor leg. The heat of vaporization of lithium is 19.6 MJ/kg, so about 10 kg/sec of lithium would need to be evaporated at the divertor strike point and recondensed over a much broader region. Nagayama et al. recognized that only a very small fraction of this lithium could be allowed to escape to the main plasma without extinguishing it, and he developed a two-chamber differential pumping scheme to attempt to reduce the flux to the plasma from the lithium-surfaces region. However it is uncertain if his result of 120g/sec is realistic, could be tolerated by the main plasma, or could be cleaned out of the main chamber as rapidly as required to avoid unacceptable accumulation. It is also problematic that the evaporating lithium would be locally ionized and immediately returned to the divertor surface, substantially weakening the cooling effect at a given lithium surface temperature. Indeed this could even be a mechanism for accelerating heat deposition from the plasma.

Recognizing some of these issues, Ono suggested that lithium be injected into the plasma as it approaches the strike point, and that power be dissipated by radiation rather than by evaporation. The heat of vaporization of lithium is only 1.4 eV per atom, so one should be able by such a scheme to significantly reduce the required amount of lithium.

Our approach can be viewed as a combination of the two earlier ideas. We propose to use a series of surface-pumped "vapor boxes" to isolate a high pressure of lithium vapor from the main plasma chamber. This powerful differential pumping scheme is only available to condensable vapors, not conventional gasses. In the extreme case, the lithium can provide pressure balance for full detachment from the main plasma. Alternatively, a lower vapor pressure can radiate enough power from the plasma that it should recombine and then pressure balance would be achieved between the flowing lithium plasma and its recombined vapor (Section 3).

Jaworski[6] has noted that lithium in evaporation/condensation equilibrium with a wetted surface at ~900° C has a pressure in the range of thousands of Pascals. The upstream pressure in the demonstration power plant discussed above is estimated[3] at 6300 Pa. Figure 1 shows a cartoon of the basic idea of using the pressure of the vapor to balance that of the plasma. The density of lithium in this case is in the range of $10^{23}/\mathrm{m}^3$, however, and clearly must be isolated from the main plasma chamber. We cannot rely on plasma plugging for this purpose because the heat flux channel is projected to be quite narrow, and room will be required to allow for imperfect plasma control.

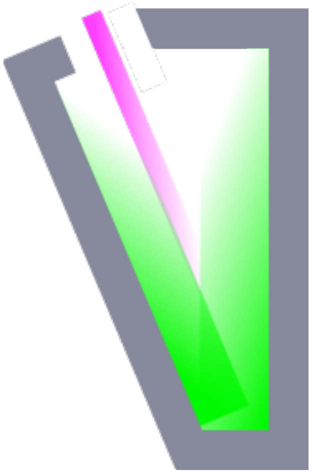

Figure1: Cartoon of vapor-box divertor.

We propose therefore a chain of vapor-filled boxes whose inner walls are covered with capillary-porous material holding liquid lithium, schematically shown in figure 2. The hottest box, at 950C, is located furthest from the plasma, with progressively cooler boxes towards the plasma, arriving finally, in this case, at 300C. This chain of vapour boxes forms a powerful differential pumping system, whose properties we can estimate simply.

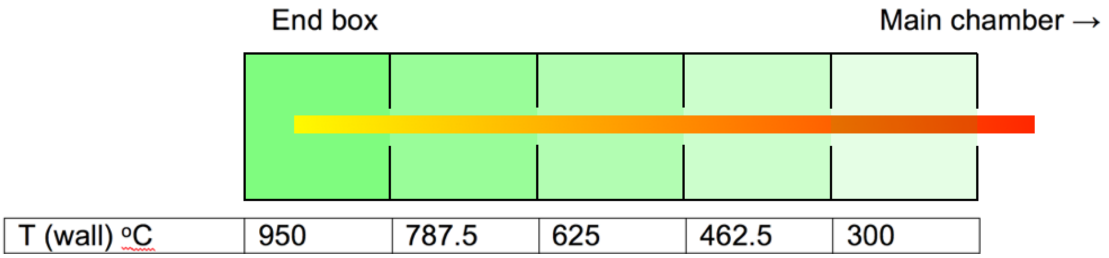

Figure 2. Schematic of differentially pumped vapor box chain.

Consider this schematic chain of five boxes of width and height 0.4m, connected by slots of width 0.1m. We assume that each slot allows ideal-gas choked nozzle flow, $\Gamma = 0.6288n\sqrt{kT/m}$, from a higher density box to the next in the chain, and we assume Langmuir flux, $\Gamma = n\sqrt{kT/2\pi m}$, to and from the walls. If we further assume uniform density and temperature in each box, due to the complex shocks that will form in the box downstream of the supersonic nozzles, we can set up the mass balance equation for this system:

$$0.6288\sqrt{\frac{k}{m}}\left(A_{noz,i-1}n_{i-1}\sqrt{T_{vap,i-1}} - A_{noz,i}n_{i}\sqrt{T_{vap,i}}\right) + \sqrt{\frac{k}{2\pi m}}A_{wall,i}\left[n_{eq}\left(T_{wall,i}\right)\sqrt{T_{wall,i}} - n_{i}\sqrt{T_{vap,i}}\right] = 0$$

A_{noz} represents the area of the nozzle, and A_{wall} the area of the wall. We can also set up the enthalpy balance equation:

$$\begin{aligned}&0.6288\sqrt{\frac{k^3}{m}}\frac{5}{2}\left(T_{vap,i-1}A_{noz,i-1}n_{i-1}\sqrt{T_{vap,i-1}} - T_{vap,i}A_{noz,i}n_{i}\sqrt{T_{vap,i}}\right)\\&+\sqrt{\frac{k^3}{2\pi m}}\frac{5}{2}A_{wall,i}\left[T_{wall,i}n_{eq}\left(T_{wall,i}\right)\sqrt{T_{wall,i}} - T_{vap,i}n_{i}\sqrt{T_{vap,i}}\right] = 0\end{aligned}$$

Note that the supersonic flow at each nozzle means that the upstream vapor properties are not influenced by those downstream, making this a particularly easy system of equations to solve. The result is given in table 1.

T (wall) (C)	950	787.5	625	462.5	300
T (vapor) (C)	950	866	820	812	812
n (vapor) (m^{-3})	1.51E+23	3.25E+22	4.17E+21	4.33E+20	4.38E+19
Pressure (Pa)	2.55E+03	5.11E+02	6.29E+01	6.48E+00	6.56E-01
Mass flow (kg/s)	4.98	1.04	0.131	0.0135	0.00137
Latent heat flow (W)	9.77E+07	2.04E+07	2.56E+06	2.65E+05	2.68E+04
Enthalpy flow (W)	1.83E+07	3.55E+06	4.27E+05	4.39E+04	4.44E+03

Table 1: Properties within and flows out of each vapor box, in the absence of plasma.

The cooler lithium-coated surfaces function as efficient pumps for the hot dense lithium vapor flowing out of the hotter boxes, with the result that the drop in density from box to box is approximately given by the area of the slot divided by the surface area of the box, about one order of magnitude. Since the pressure drops similarly, the assumption of choked flow is well justified. The mass efflux also drops by about an order of magnitude per box, with the result that the efflux from the total system to the main plasma chamber is reduced to about 1.4g/sec. Thus this differential pumping system has met its goal of isolating a high density of lithium vapour from the main plasma chamber.

Interestingly, the mass flow from the bottom box is about 5 kg/sec, whose latent heat of vaporization represents about 50% of the total divertor power. The enthalpy flowing with the vapor raises the energy loss through flow to about 60%. The pressure achieved in the hottest "bottom" box is somewhat less than the projected upstream pressure, but it is certainly acceptable to project that the pressure width of the divertor plasma would be at least 2 or 3 times greater than its extremely narrow, ~1mm, upstream width.

3. Particle Balance and Power Balance including Plasma Entrainment

Next we consider that the divertor plasma, as it flows downstream from the main chamber, will entrain ionized lithium just as DT is entrained in a high-recycling divertor. To estimate this in a rough manner, we assume that because of its very low ionization potential, all of the lithium that enters the plasma (from both sides) via the Langmuir flux is ionized and travels downstream to the bottom box. We carry with this lithium its enthalpy, and release both in the bottom box. In addition, we release the 200 MW of divertor power into the vapor in the bottom box, as if all power were absorbed by ionization and recombination takes place only in the bottom box. (This is conservative, as some power will certainly be released upstream as radiation.) These physical effects now couple upstream vapor parameters with downstream ones, but the equations can be solved iteratively very quickly. The result is shown in table 2.

T (wall) (C)	950	787.5	625	462.5	300
T (vapor) (C)	2443.9	1756.5	1533.9	1499.1	1498.6
n (vapor) (m^{-3})	1.15E+23	1.80E+22	1.74E+21	1.23E+20	8.21E+18
Pressure (Pa)	4.30E+03	5.04E+02	4.33E+01	3.00E+00	2.01E-01
Mass flow (kg/s)	5.3605	0.7124	0.0643	0.0045	0.00037
Latent heat flow (MW)	1.05E+08	1.40E+07	1.26E+06	8.81E+04	5.89E+03
Enthalpy flow (W)	3.92E+07	3.75E+06	2.95E+05	2.02E+04	1.35E+03
Wall heat flux (W/m^2)	9.85E+05	2.40E+06	3.06E+05	2.74E+04	1.91E+03

Table 2. Properties within, flows out of, and wall heat flux onto each vapor box, including plasma entrainment and power deposition into the bottom box.

We see that the heat flux into the bottom box has greatly increased the vapor temperature and somewhat increased its pressure. The heat efflux from the bottom box is now about 140 MW. The particle flux from the system is reduced to 370 mg/sec, due to the plasma entrainment. Most encouragingly, the heat flux to the walls of the bottom box and that just above it are 1 MW/m^2 and 2.4 MW/m^2 respectively. A parallel heat flux of 20 GW/m^2 has been mitigated by a factor of ~10^4.

4. Power Balance including Plasma Cooling

When lithium atoms are introduced into a plasma, energy is inevitably extracted from the free electrons. Some of the extracted energy is committed to ionization of lithium, but line and continuum radiation are also emitted from the plasma, assuming it is optically thin. The resulting cooling is generally expressed in terms of L_Z, defined by the equation for the volumetric cooling rate: $p_{cool} = n_e n_Z L_Z$. For a collisional-radiative model (as opposed to a coronal model), one takes into account nonlinear density effects such as multi-step ionization, three-body recombination and collisional de-excitation. In this case, L_Z becomes a function of both T_e and n_e. In order to consider the case where lithium has a finite residence time at fixed plasma temperature and density, the lithium is introduced as neutral atoms that evolve in their charge-state distribution over time, while all states are steadily depleted with time constant τ_z. We have evaluated $L_Z(T_e, n_e, \tau_Z)$ using the ADAS database, with the results shown in figure 3 for τ_z = 100 μsec.

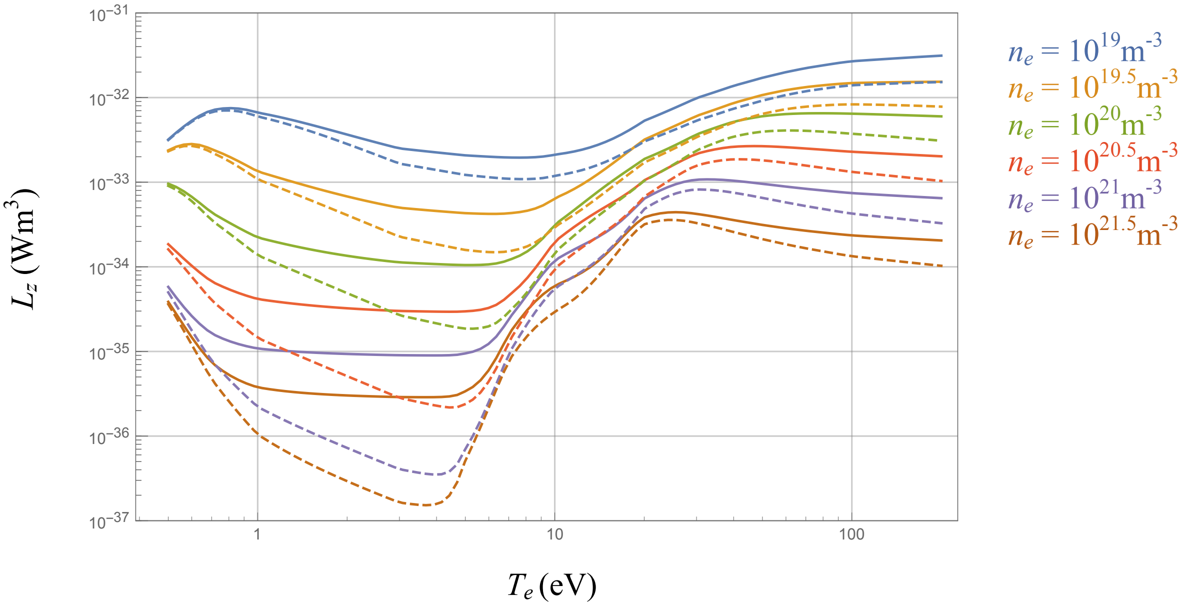

Figure 3. ADAS-based collisional-radiative L_Z vs. T_e for $\tau_Z = 10^{-4}$ sec. Dotted lines are for radiation losses only, solid lines include power committed to ionization.

If we take S to be the rate of particle introduction, in #/sec, we can relate n_Z to S by $n_z = \tau_z S/V$, where V is the volume into which the particles are introduced. This allows the total energy loss per particle introduced to be calculated as:

$$\frac{p_{cool}V}{S} = \left.\frac{\Delta E}{\#}\right|_{cool} = n_e \tau_Z L_Z\left(T_e, n_e, \tau_Z\right)$$

Near its minimum at $T_e \sim 5$ eV, it can be seen that L_Z varies as $1/n_e$ and calculations varying τ_z between 1 μsec and 1 msec show that L_Z varies as $1/\tau_z$ in this temperature range. Together these scalings indicate that the total energy loss per particle introduced at $T_e \sim 5$ eV is roughly constant at about 6.2 eV. From comparing the dotted and solid lines, it is evident that this cooling is mostly due to ionization.

We cannot be confident that fresh lithium neutrals will penetrate to regions where $T_e > 10$ eV, nor are we primarily concerned with regions below 1 eV, where the temperature required for recombination has already been reached. For conservatism, therefore, we will assume that each injected lithium atom causes an energy loss of 10 eV from the free electrons in the divertor plasma. This appears to be more conservative than the approach taken by Ono et al., in which L_z was approximated as fixed at 10^{-32} Wm^3, within a solution based on a segmented 2-point model.

We can now proceed to evaluate the energy loss from the free plasma electrons (non-self-consistently) for the model used in section 3, whose results were shown in table 2. This gives us the energy loss per box shown in table 3. We do not evaluate this for the bottom box, where our assumption is that recombination dominates resulting in net heating of the free electrons.

T (wall) (C)	950	787.5	625	462.5	300
Radiated power (W)	–	5.363E+08	4.886E+07	3.423E+06	2.289E+05

Table 3: Non-self-consistent cooling power in each vapor box, assuming 10 eV per injected lithium atom.

This result, albeit based on the simplified assumptions of the collisional-radiative, finite-life model, suggests that the plasma might be extinguished part way into the next-to-bottom box, since the total cooling power by that point would be greater than the assumed total input power. Because lithium radiates very effectively at low temperature and high density, presumably the system would recombine there. Momentum balance would in this case be achieved between the flowing, largely lithium, plasma and the lithium vapor through collisions and recombination. The resulting flowing lithium vapor would transfer its momentum to the walls of the box. Perhaps the "bottom" box would not be required at all. Or with greater radiative efficiency than conservatively assumed here, even the second-from-bottom box might not be necessary. Conversely it might be advantageous to retain a bottom box with a thick lithium-filled capillary porous region at its extreme end to withstand transient events such as large ELMs or disruptions. This would avoid damage to any material surface and avoid enhanced particle efflux into the main chamber. One could also add another box at the colder end, to reduce the lithium efflux further.

However, as discussed in the next section, while this is an encouraging result, much more work is required to assure its practicality and optimize its performance.

5. Future Work and Conclusions

Clearly the analyses presented here are highly simplified. The lithium vapor in this system is highly collisional, so it would be appropriate to undertake a complete classical fluid dynamics calculation, including the shocks generated by the supersonic nozzles. The dimension of 40cm for the distance between 10cm apertures was chosen with an eye towards avoiding direct flow from one aperture to the next, but a narrow fan shock could focus the flow. On the other hand, it may be possible to position reflecting surfaces, perhaps chevrons, to enhance mixing. The apertures might be directed at an angle of 45^o to one another[7]. Furthermore, the vapor-box chain shown in figure 2 does not account for realistic tokamak physical and magnetic geometry. Obviously surfaces would need to be smoothed to handle heat fluxes associated with startup or loss of position control. Intriguingly, it may be possible to test and even optimize this concept using a simple scale model chain of lithium-filled vapor boxes[8].

Another interesting question is the degree to which a system such as this can or should pump deuterium and tritium. In the sections with $T_{wall} > 500$ eV, hydrogenic species are not expected to be retained in lithium. However one can choose the temperature of the colder end of the vapor box chain at will, since the lithium density and flow speed is insensitive to the temperature of the surfaces. These essentially only serve as lithium vapor pumps, as can be seen from the constant vapor temperature. The ability to vary their surface temperature may provide flexibility to pump hydrogenics at a desired rate. Impurities such as oxygen will certainly be pumped very effectively.

To understand these effects and in general to provide a more realistic power balance, it will be necessary to couple a realistic 2-D plasma model to the model for the vapor. It will be particularly important to determine if any flow reversal occurs, bringing high-density lithium back to the main chamber via plasma flow.

From a practical point of view, it will be necessary to determine the best means to return the lithium that is pumped at the top of the system back to the bottom. The geometry we are using is reminiscent of a heat pipe (albeit with the heat deposited from the inside!) but even more of a thermosiphon, where the liquid is returned by gravity. Perhaps TEMHD can also be harnessed for this task[8]. Rapid return is desirable to minimize the lithium inventory in the system. Some fraction of the circulating lithium should be extracted from the torus for removal of impurities and extraction of deuterium and tritium. Ultimately it will be necessary to recollect the lithium that escapes from the vapor box chain. If, as anticipated in a fusion power plant, the first wall is everywhere above 500^o C, one would not expect build-up of lithium on these surfaces, nor any associated tritium retention in the chamber. Conceptually, a colder element located where lithium is likely to be deposited could be used to capture and channel the lithium out of the system. This clearly would require experimental validation.

In conclusion, it appears that we have identified a promising concept for capturing the plasma escaping from a fusion reactor volumetrically, which would be a welcome development for the practicality of fusion power. This concept builds on very valuable pioneering analyses by Nagayama et al., and by Ono et al. However much more work is required to demonstrate the viability of any of these new concepts.

Acknowledgments

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