Tokamaks with LiWalls: what is interesting about them

Leonid E. Zakharov,

Princeton University, Princeton Plasma Physics Laboratory

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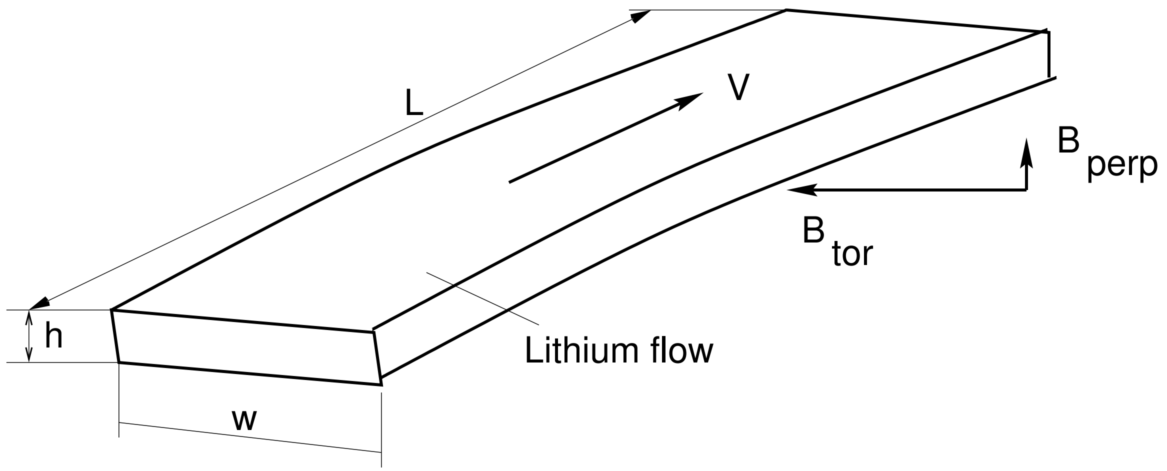
OUTLINE

- Magnetic propulsion of liquid lithium.
- Research results in physics
  1. TFTR lithium results, DIII-D QDBH mode
  2. Non-recyling LiWall (1998) and Sakharov's (1951) regimes.
- Power extraction from tokamaks and tokamak-reactors
  1. Absorbing and renewable plasma facing wall surface
  2. LiWalls and energy extraction from the plasma
  3. Effect on plasma energy confinement;
  4. Effect on plasma stability;
- Yacht Sail approach for the tokamak fusion reactor design:
  1. . . . , . . .
- Does the tokamak fusion has a path ?
  1. Consistency in DoE/Congress approach to fusion.
  2. Competence in research and our progress in fusion.
  3. Safety of future reactors
- Summary

1 Magnetic propulsion of liquid lithium

There 3 magnetic Reynolds numbers which control lithium MHD in tokamaks

$$
\begin{aligned}
\text{dynamics}: \quad & \Re_0 \equiv \mu_0 \sigma L V, \\
\text{electro-dynamics}: \quad & \Re_1 \equiv \mu_0 \sigma h V, \\
\text{dynamics}: \quad & \Re_2 \equiv \mu_0 \sigma \frac{h^2}{L} V, \\
& \mu_0 \sigma \simeq 4 \ \left[\frac{sec}{m^2}\right].
\end{aligned} \tag{1.1}
$$



Characteristic flow parameters:

$$
\begin{aligned}
V = 20\ m/sec &\rightarrow \rho\frac{V^2}{2} \simeq 1\ [atm], \\
B = 1\ T &\rightarrow \frac{B^2}{2\mu_0} = 4\ [atm], \\
B = 5\ T &\rightarrow \frac{B^2}{2\mu_0} = 100\ [atm].
\end{aligned} \tag{1.2}
$$

Dynamic pressure losses are determined by $\Re_0$ and $\Re_2$

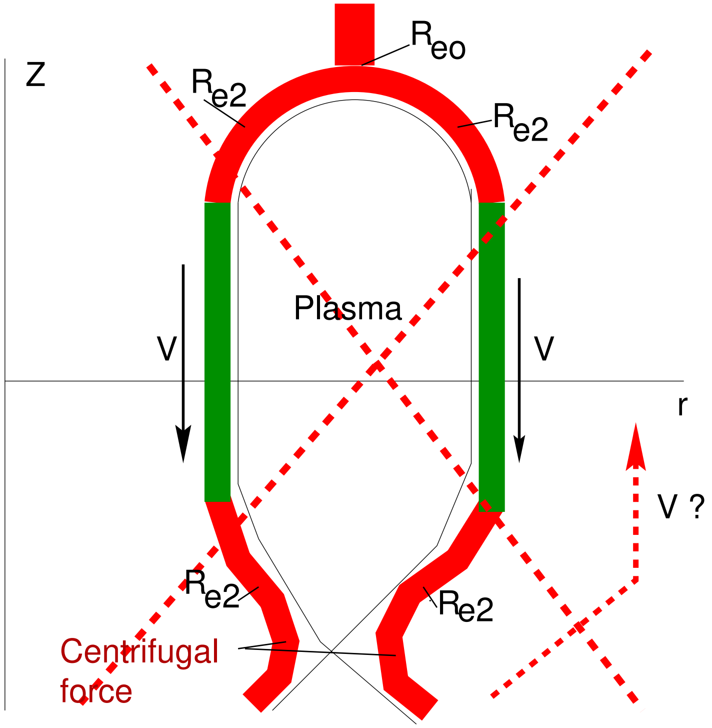
$$
\begin{aligned}
\Re_0 : \quad & \Delta\rho\frac{V^2}{2} = \mu_0\sigma L V \frac{B_\perp^2}{2\mu_0}, \\
\Re_2 : \quad & \Delta\rho\frac{V^2}{2} = \mu_0\sigma \frac{h^2}{L} V \Delta\frac{B_\parallel^2}{2\mu_0}, \\
& \mu_0\sigma \simeq 4\ \left[\frac{sec}{m^2}\right].
\end{aligned} \tag{1.3}
$$

Magnetic fields from the currents in the stream are determined by $\Re_1$

$$
\Re_1 : \quad B_{||out} - B_{||in} = \mu_0\sigma h V B_\perp. \tag{1.4}
$$

Lithium “water-falls” will not flow through the tokamak strong toroidal field

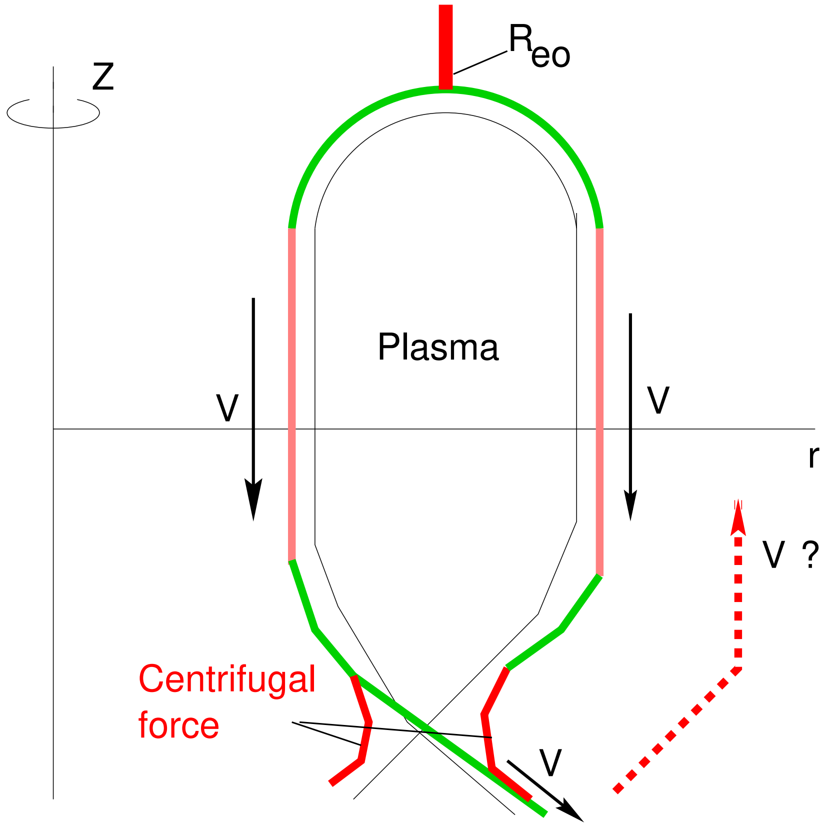
$$
\begin{aligned}
&h = 0.1\ m, \quad L_1 \simeq 0.2\ m, \quad L_2 \simeq 3\ m, \quad V > 2-5\ [m/sec],\\
&\Re_0 = 4L_1V => 1.6,\\
&\Re_2 = 4\frac{h^2}{L_2}V = 4\frac{h}{L_2}(hV) \simeq 0.01 - 0.025.
\end{aligned}
\tag{1.5}
$$



$$\boxed{\rho\frac{V^2}{2} \ll \Re_2\Delta\frac{B_{tor}^2}{2\mu_0}}$$

Momentum driven thin walls have many of unresolved problems in lithium MHD

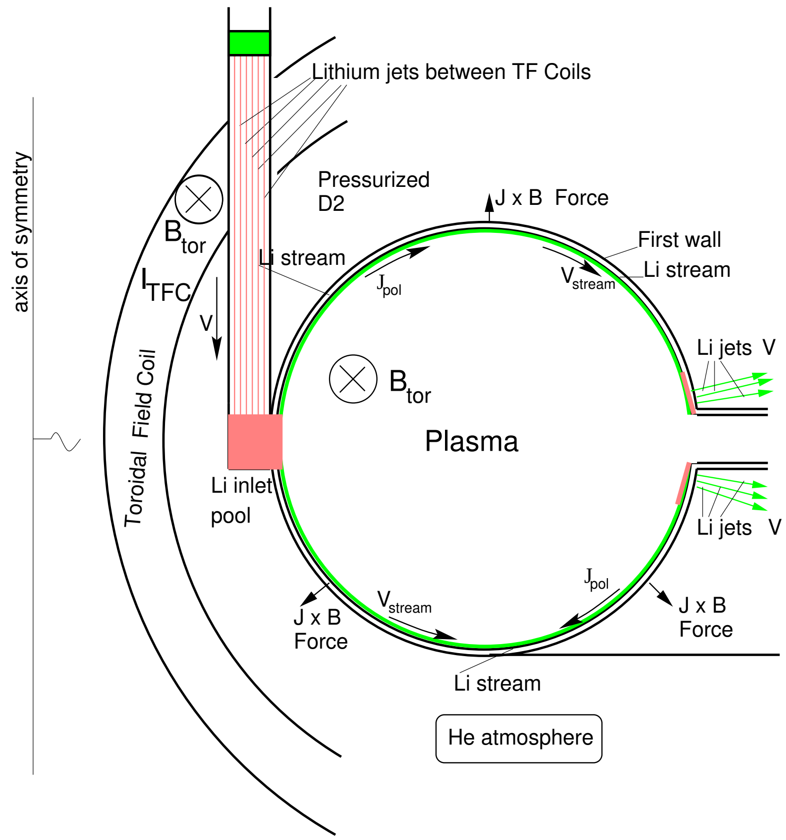
$$h = 0.01\ m, \quad L_1 \simeq 0.02\ m, \quad L_2 \simeq 3\ m, \quad V \simeq 20\ [m/sec],$$
$$\Re_2 = 4\frac{h^2}{L_2}V \simeq 1.3 \cdot 10^{-4}. \tag{1.6}$$



$$\boxed{\Re_0 = 1.6, \quad \rho\frac{V^2}{2} < \Re_0\frac{B_{pol}^2}{2\mu_0}}$$

Magnetic propulsion opens the possibility for intense plasma facing lithium streams in tokamaks

$$\boxed{p_{\mathbf{j}\times\mathbf{B}}\Big|_{inlet} - p_{\mathbf{j}\times\mathbf{B}}\Big|_{outlet} \gg \Re_2 \frac{B_{tor}^2}{2\mu_0}, \qquad \Re_2 \equiv \mu_0\sigma\frac{h^2}{R}V \simeq 0.0015}$$



- Driving electromagnetic pressure $\boxed{p_{\mathbf{j}\times\mathbf{B}}\Big|_{outlet} > 1\ atm}$

  $$\boxed{p_{\mathbf{j}\times\mathbf{B}}\Big|_{inlet} - p_{\mathbf{j}\times\mathbf{B}}\Big|_{outlet} \simeq 1.5 - 3\ [atm]}$$

- Flow parameters

  $$\boxed{V \simeq 20\ m/sec, \qquad h \simeq 0.01\ m}$$

- Magnetic Reynolds numbers

  $$\boxed{\Re_1 \equiv \mu_0\sigma h V \simeq 0.8, \qquad \Re_2 \simeq 0.0015}$$

- Stream are robustly stable due to centrifugal force

  $$\boxed{\rho\frac{\langle V^2\rangle}{2} > \frac{a}{2R}p_{wall}n_r}$$

2 Lithium Walls and tokamak plasma

Plasma facing surface is right at the critical place in the fusion reactor between the plasma and the neutron absorbing zone

Three things are the most important:

1. power and particle extraction;
2. effect on core confinement

$$n_{DT} \cdot T_{DT} \cdot \tau_E > 5 \times 10^{21}\ m^{-3} \cdot keV \cdot s, \qquad n_{DT} \cdot T_{DT} \cdot \tau_E \propto \tau_E^2$$

3. effect on plasma stability.

$$Power_{fusion} \propto (n_{DT} \cdot T_{DT})^2 \propto \beta^2, \qquad \beta \equiv \frac{2\mu_0 \langle 2nT \rangle}{B^2}$$

3 Power extraction from the plasma

Plasma facing surfaces are positioned in the most crucial place in the quasi-stationary fusion (DT) reactor, i.e., between

- the plasma
- and the 14 Mev neutron energy absorbing layer.

The conceptual solution for the plasma facing surface affects control and robustness of both:

- plasma regime and
- the entire reactor.

4 Research results in physics

TFTR, DIII-D, T-11M, Li

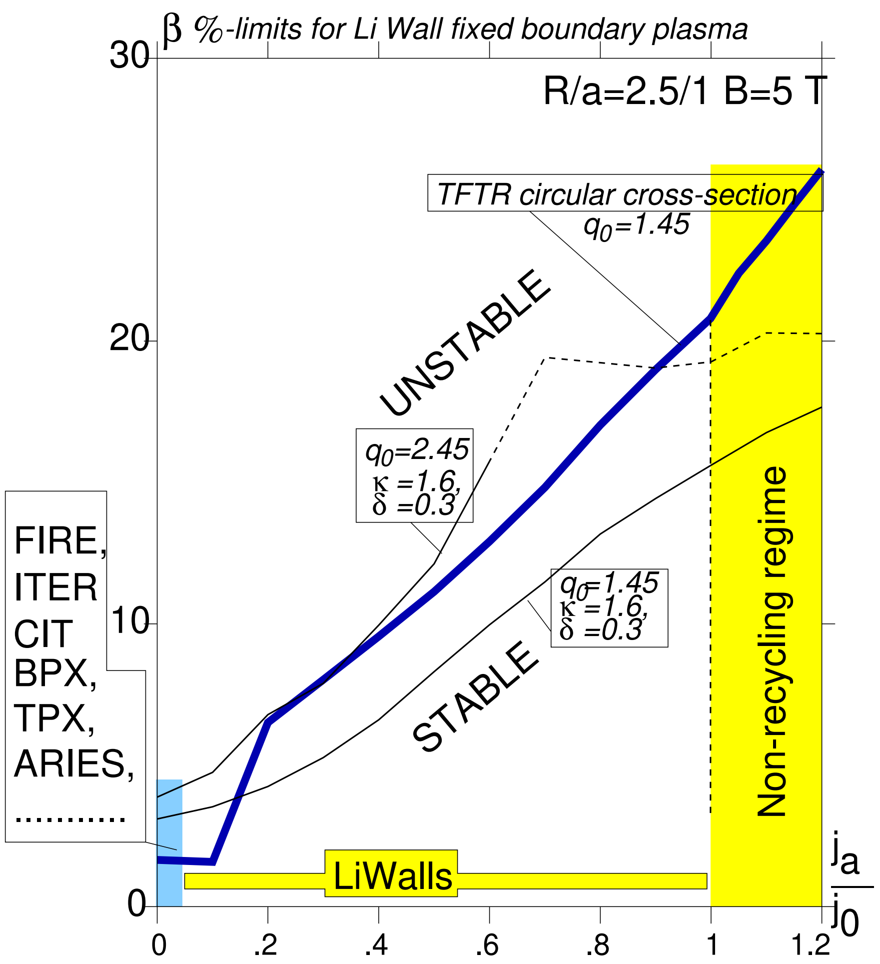
5 LiWalls and plasma stability

Intense lithium streams may create the best situation for the plasma stability control

$$Power_{fusion} \propto (n_{DT} \cdot T_{DT})^2$$

Goto Cbpu code.

Li walls allow much higher operational plasma pressures.

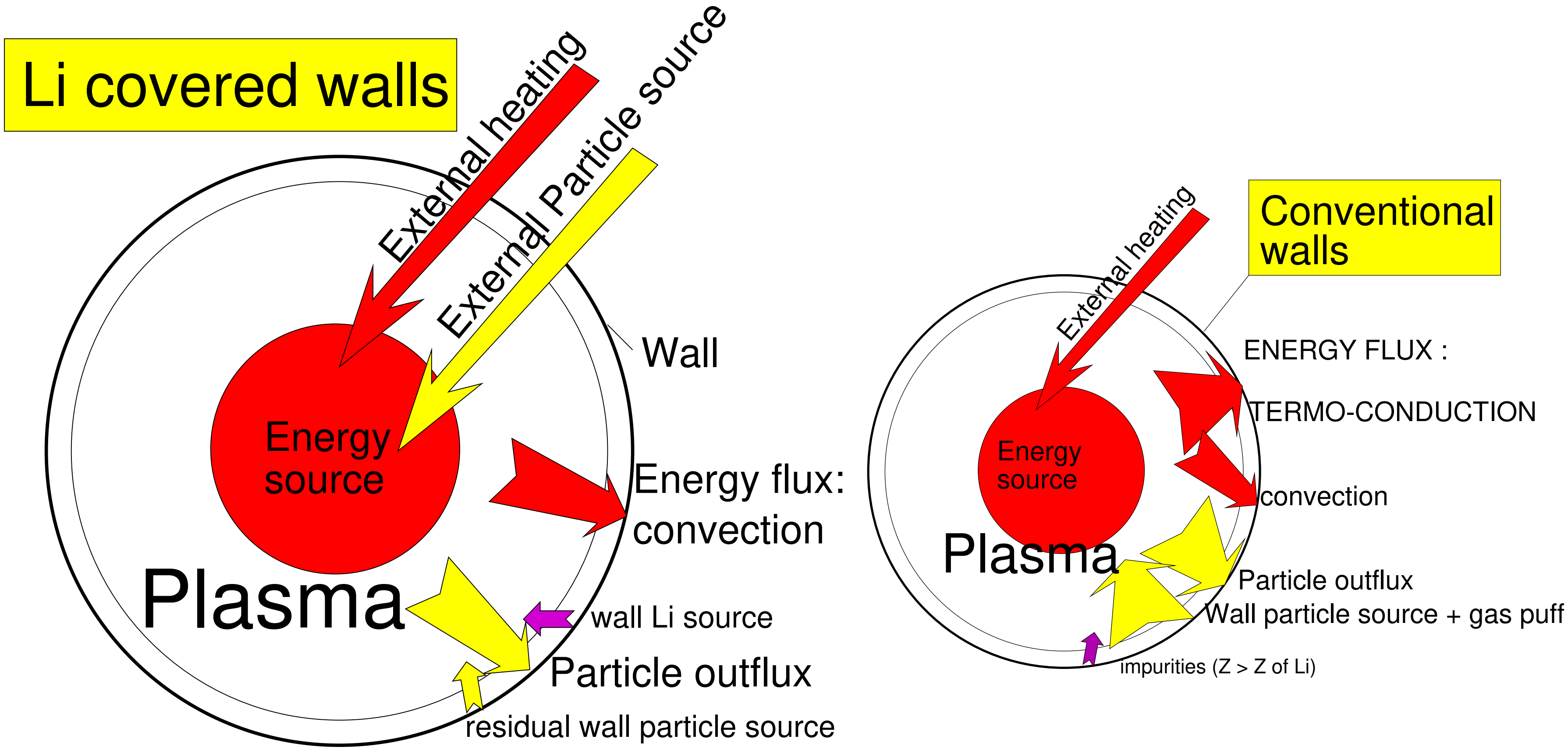


β - limits for the second stability regime

- fixed boundary plasma
- n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON)
- current density with an edge pedestal

$$\mathbf{j}_{\parallel} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$

Li is an excellent getter for the hydrogen plasma particles.



Lithium can be propelled along the walls
for power and particle extraction.

Improved energy confinement is extremely for igniting the plasma

$$n_{DT} \cdot T_{DT} \cdot \tau_E > 5 \times 10^{21}\ m^{-3} \cdot keV \cdot s, \quad n_{DT} \cdot T_{DT} \cdot \tau_E \propto \tau_E^2$$

Plasma profiles are determined by the particle continuity equation

$$\Gamma \equiv Snv = const = (\Gamma)_a$$

and by the energy balance

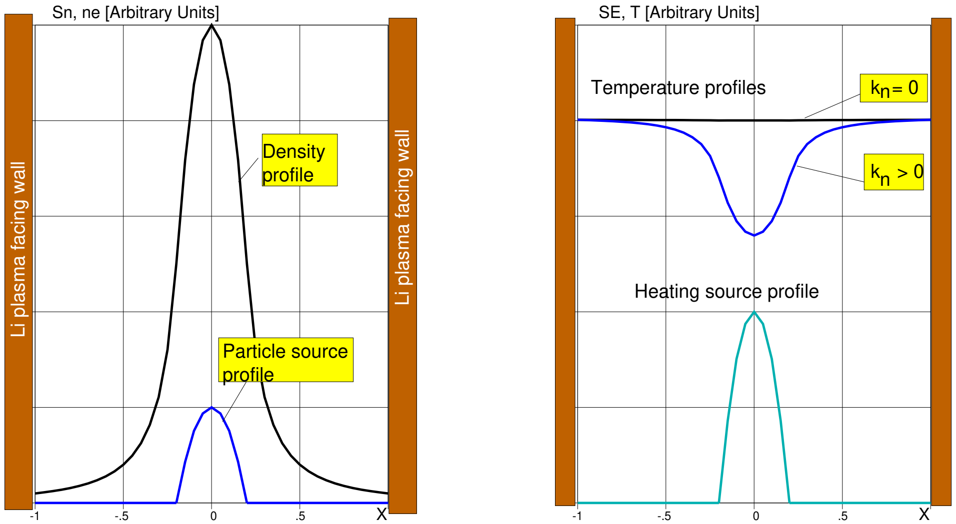
$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P_E dv$$

With perfectly absorbing walls plasma does not know the temperature of the (cold) walls and leaves no room for thermo-conduction

$$\left(\frac{5}{2}\Gamma T\right)_{edge} = \int_0^a P_E dv, \quad T_{edge} = \frac{\int_0^a P_E dv}{\frac{5}{2}\Gamma} \quad P_E - \text{ heat source.}$$

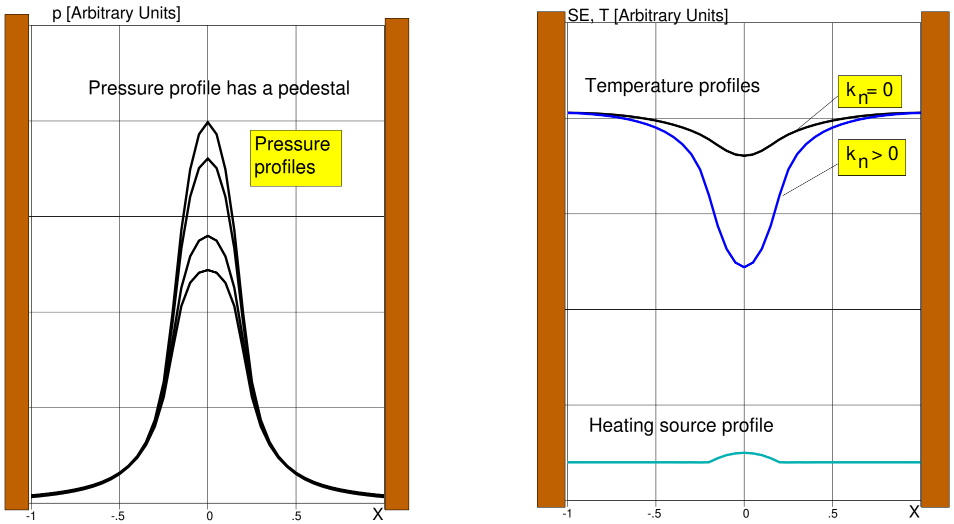
Thus, the major energy loss channel, i.e., thermo-conduction, can be eliminated with this absorbing wall boundary condition (S. Krasheninnikov, PFSC at MIT, now at UCSD).

In non-recycling regime $\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P dv$



DENSITY profile (left) is predetermined by the central fueling.

TEMPERATURE profile (right) adjusts itself in order to ELIMINATE the thermo-conduction.



PRESSURE profile (left) has a jump at the plasma boundary.

TEMPERATURE profile (right) eliminates the thermo-conduction irrespective to the heat source profile.

7 LiWalls and energy extraction from the plasma

Intense Lithium Streams (20 m/sec) have extraordinary power extraction capabilities

$$\Delta T_{max} = q_{wall}\sqrt{\frac{4t_{flight}}{\pi\kappa\rho c_p}}, \quad \Delta T_{max} \le 200^o\ C, \quad t_{flight} \simeq 0.25\ sec, \quad d_{skin} \equiv \sqrt{\frac{\kappa t_{flight}}{\rho c_p}} \simeq 3\ mm$$

For an illustrative example they are

$$R = 6\ m, \quad a = 1.6\ m, \quad q_{wall} \simeq 3.5\ \frac{MW}{m^2}\ \left(14\ \frac{MW}{m^2}\right)_n, \quad P_{wall} = 4\pi^2 Raq_{wall} \simeq 1.3GW$$

even with no reliance on vortices in the streams.

Intense lithium streams can keep guide-wall temperature low (250-300^o C) at the neutron wall loading $> 10\ MW/m^2$, thus, making wall surface compatible with the FLiBe blanket. (This important reactor issue is out of the scope of this presentation).

Li coated copper wall (1–3 cm) has extraordinary power extraction and RESEARCH capabilities.

$$\boxed{\Delta T_{max} = q_{wall}\sqrt{\frac{4t_{exposure}}{\pi\kappa\rho c_p}}, \quad d_{skin} \equiv \sqrt{\frac{\kappa t_{exposure}}{\rho c_p}}, \quad (t_{flight} \simeq 0.25\ sec, \quad d_{skin,Li} \simeq 3\ mm)}$$

For copper

$$\boxed{\kappa_{Cu} \simeq 10\kappa_{Li}, \quad (\rho c_p)_{Cu} \simeq (\rho c_p)_{Li}, \quad t_{exposure} \simeq 10 t_{flight} \simeq 4\ sec, \quad \Delta T_{max} \leq 200^o\ C}$$

$$\boxed{d_{``skin'',Cu} \simeq 10 \cdot 3\ mm \simeq d_{Cu}}$$

It is a misinterpretation that I ever suggested a tokamak experiment with the flowing lithium. Litium should be deposited on a surface with a massive copper behind it. Copper serves two purposes: (a) as a stabilizer of the plasma facing temperature and (b) as a temporary stabilizer of MHD modes.

Most of physics and technology research as well as training for the Li-Wall tokamak-reactor can be done exclusively on machines, which experimentators are familiar with (starting with CIRCULAR cross-section tokamaks).

TFTR had

$$\boxed{S_{wall} \simeq 90\ m^2, \quad P_{heat} \simeq 40\ MW, \quad q_{walls} \simeq 0.5\ MW/m^2}$$

PBX-M (modified for the Li/copper wall physics/technology studies, including continuation of what was terminated by the TFTR shutdown), will have practically the same wall loading as future LiWall based tokamak reactor

$$\boxed{S_{wall} \simeq 30-40\ m^2, \quad q_{walls} \simeq 1-1.3\ MW/m^2}$$

if moved to the TFTR cell (assuming same power of NBI will be reinstalled).

DD equivalent of Lawson criterion, upon the results on PBX/DIII-D class of machines, may be demonstrated on tokamaks similar to TFTR (might be slightly non-circular) with no divertors and with

the Li coated COPPER walls.

Then, if allowed, a very limited N of DT shots might be designed by the theory/exper. community (as Fu/Nazikian did successfully on TFTR) and fired in order to measure everything possible about the alpha-driven instabilities in the burning plasma.

LiWall concept is not sensitive to the energetic particles deposition. Nevertheless, because the alpha particle instabilities will be intrisically in the tokamak fusion reactor, it is important to learn about them as much as possible during the pre-reactor level of limited DT experiments.

For the reactor itself, (with Intense Li streams), nothing seems to be "dangerous" in an unexpected energetic particle deposition.

With the energy confinement time being not a challenging problem for the reactor if it works in one of the best tokamak regimes (TFTR lithium conditioned regimes, DIII-D QDB H-mode, low recycling LiWall regime), high energy alpha particle losses might be tolerable or even good for the additional He pumping.

"First hand" information on physics of energetic particles (and associated instabilities) from the burning plasma might be crucial for optimization the reactor operation.

Within the concept of LiWalls, the development toward the burning plasma relies solely on experiments with lithium coated solid walls (e.g., copper with an intermediate material, compatible with the thin Li layer) and

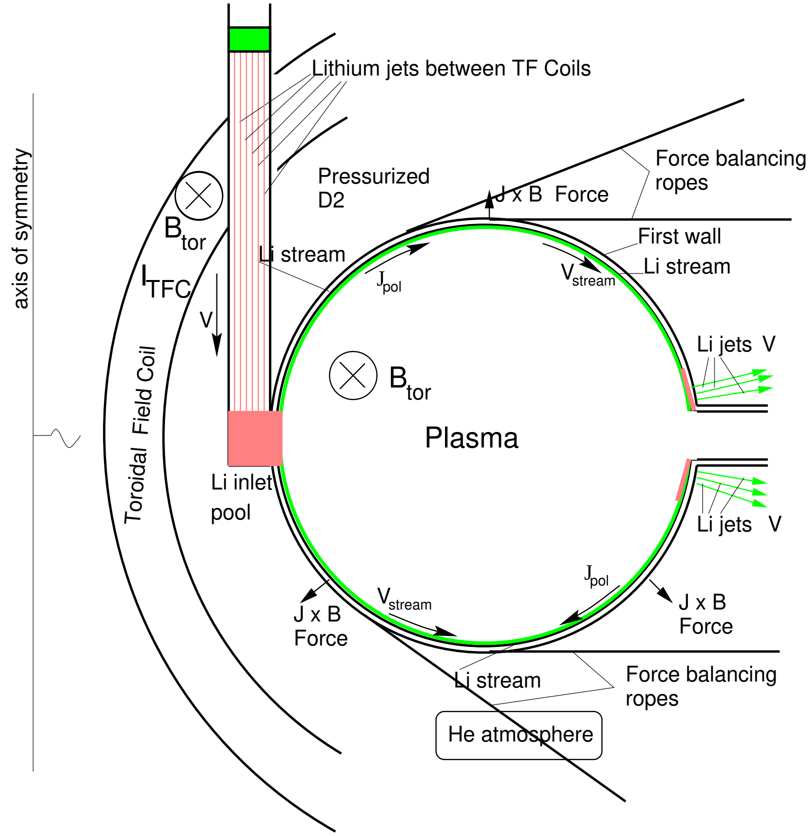
- with recoating Li surface between discharges (which would give several seconds for demonstrating burning) or by continued Li pellet injection or with a DOLLOP-like facility (for extended length of the discharge).
- with MHD stabilization of free-boundary modes at high betas by the copper shell with an assistance of feedback system.

Thus, most of the physics of the burning plasma and calibration of our knowledge will be done in a reliable fashion.

For the future tokamak demo- and, then, commercial-reactors this approach is consistent with merge of the plasma physics with the technology of the Intense Li Streams being developed at some stage in a parallel way (without tokamaks).

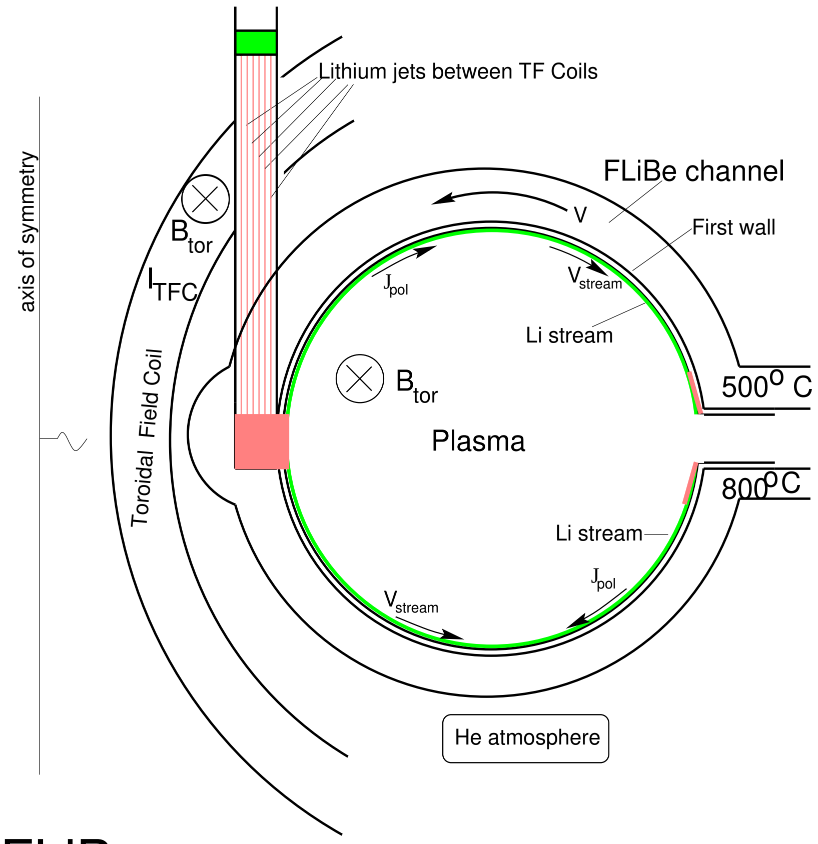
Intense Li Streams affect the very fundamentals of tokamak reactor desing.

Electrodynamic pressure creates a stable situation for the first wall.



- Guide wall works against expansion $\Longrightarrow$
- Guide wall can be made as a thin shell (like a car tire).
- Toroidal component of the electro-magnetic force can be balanced by the set of external wire ropes.
- Inner surface is sealed by the lithium streams (insensitive to cracks) $\Longrightarrow$
- Vacuum barrier can be moved to the plasma boundary (giving access to the neutron zone).

Intense lithium streams + FLiBe make an excellent FW/blanket combination (S.Zinkle, B.Nelson, ORNL)



Lithium streams keep the wall temperature below melting point of FLiBe

$$\boxed{T_{wall} \simeq 200^o - 250^0 < T_{melt,FLiBe} \simeq 450^o}$$

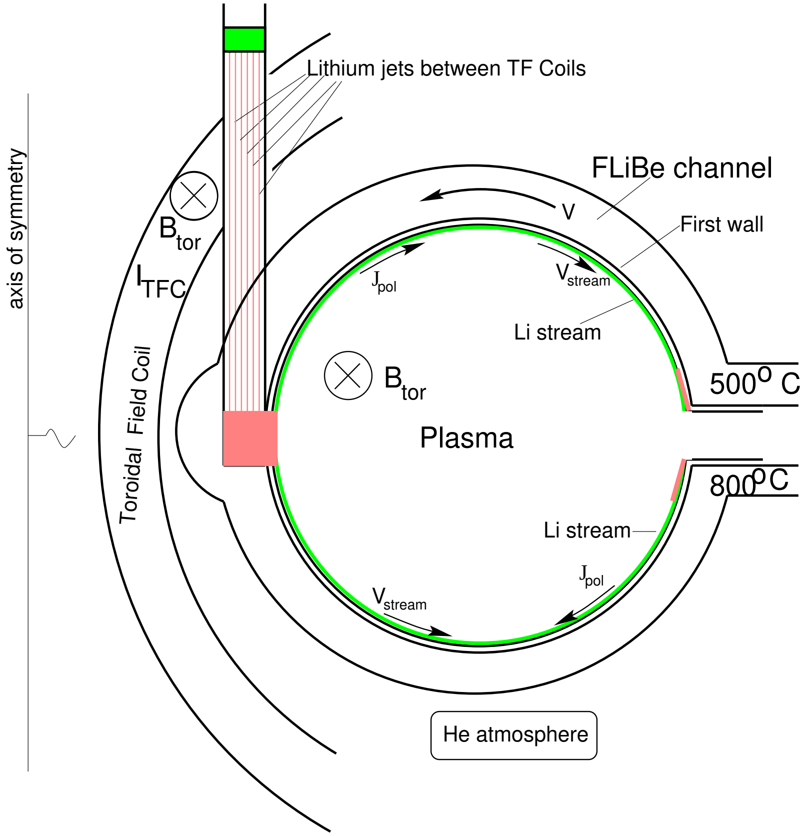
Independent of inner temperature in the chanell FLiBe has a solid boundary layer at the walls.

Even with $\boxed{T_{FLiBe}\big|_{outlet} = 800^o\ C}$ energy losses on the side walls are $\simeq 4\%$.

FLiBe

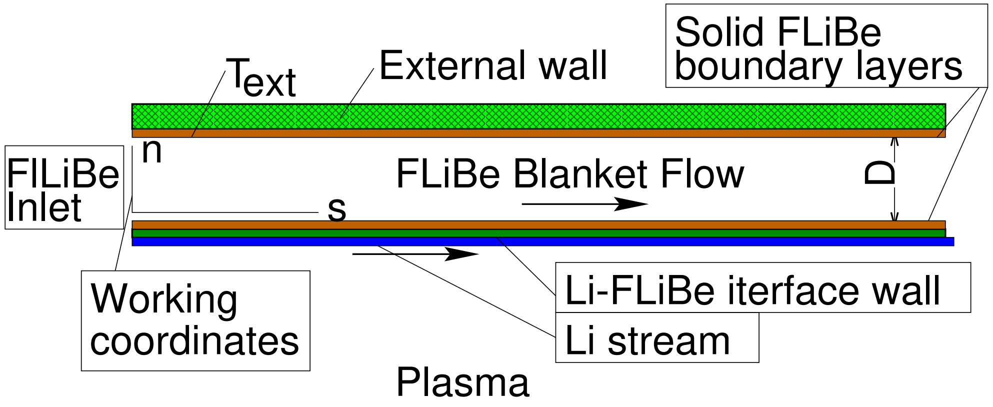
$$(LiF)_n(BeF_2)$$

It would be not crazy to think about making the vacuum chamber from the wire mesh



- wall becomes insensitive to thermal deformations $\Longrightarrow$ pulsed regime is acceptable (no high-tech for the current drive);
- deformations of the wall can be corrected on the fly (Yacht sail approach);
- wire wall presumably can withstand high neutron flux;
- minimum activation in the neutron zone;
- protection of feedback plates by the FLiBe layer with still excellent coupling with the plasma;

Stratified geometry of the FLiBe Blanket/Lithium streams



D	m	0.1
L	m	10
V	$\frac{m}{sec}$	0.5
$S(n)$	$\frac{W}{cm^3}$	100-40
$T_{side\ \ wall}$	C^o	200

The radial thickness D of the channel is assumed to be much smaller than the length L of the channel. Plasma side wall temperature is kept constant by a fast Lithium flow.

Heat source S corresponds approximately to 10 MW/m^2 in neutrons.

The walls of the channel are kept below the melting point of FLiBe, so two solid salt layers are formed on the walls of the channel.
The stationary heat diffusion equation

$$\begin{aligned} &\rho c_p V \frac{\partial T}{\partial s} = \kappa T''_{nn} + S, \quad T > T_{melt}, \\ &0 = \kappa T''_{nn} + S, \quad T < T_{melt} \end{aligned} \tag{8.1}$$

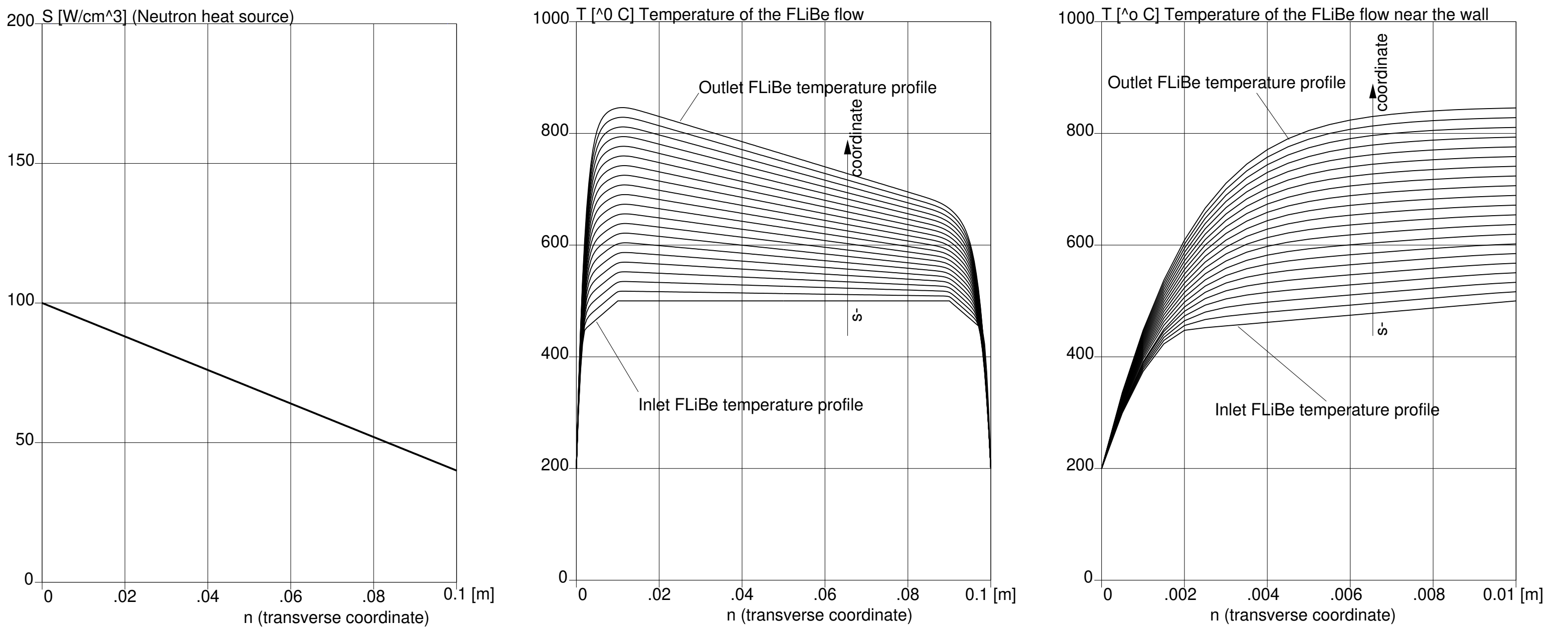
together with the matching conditions determines the temperature distribution in the flow.

Here, ρ is the mass density of FLiBe, c_p is the heat capacity, V is the velocity of the flow, κ is the thermo-conduction.

Thickness of the solid layer is determined as an eigenvalue of the problem in a self-consistent way.

FLiBe parameters		
ρ	$\frac{kg}{m^3}$	2240
c_p	$\frac{J}{kg \cdot C^o}$	2380
κ	$\frac{W}{m \cdot C^o}$	1
T_{melt}	C^o	450

Profiles of the (neutron) heat source and T in the FLiBe channel



FLiBe thermo-conduction is so small that the temperature inside body of the flow is determined solely by the heat source power

$$\rho c_p V \frac{\partial T}{\partial s} \simeq S, \qquad T > T_{melt}, \tag{8.2}$$

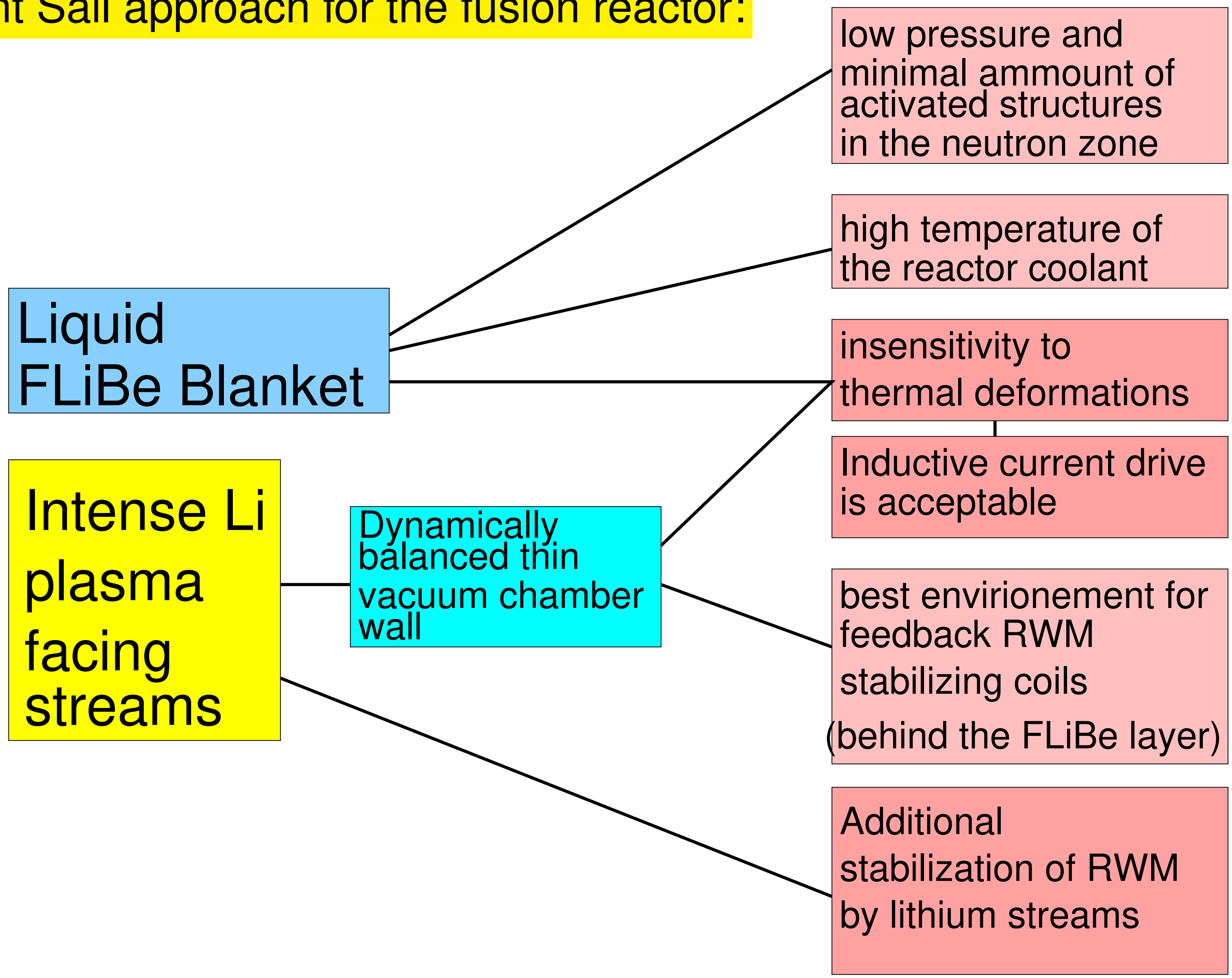
not by thermo-conduction losses.

Two boundary layers of the order of 1-3 mm are formed near walls of the channel. Inside, each of them contains a sublayer of a solid FLiBe.

In the example the averaged energy losses are $0.26\ MW/m^2$ through the plasma side wall and $0.16\ MW/m^2$ through the Toroidal Field Coil (TFC) side of the wall, which constitute approximately 4 % of the incoming neutron flux energy.

FLiBe seems to be a perfect coolant for the tokamak-reactor

Yacht Sail approach for the fusion reactor:



9 Does the tokamak fusion have a path ?

The answer is Yes. Just the path to the practical fusion tokamak-reactor.

goto netscape

- Competence in research
- Freedom of communications

are a key for security of our progress in fusion.

Safety of future reactors depend solely on new generation of physicists. Nobody can guarantee the fast success in developing the commercial reactors. But,

- any kind of covering up the present reality from students is 100 % guarantee of future failures with fusion reactors

10 Summary

From the very first presentation to PPPL (PS&T seminar, Jan. 08, 1999), the idea of a tokamak with lithium covered walls was presented as a consistent tokamak-rector concept.

For the first time, the renewable and absorbing plasma facing walls were introduced into the tokamak research.

From the plasma physics side, lithium walls may provide

- a low recycling regime (best possible for energy confinement);
- low-Z plasma facing surface (with a central plasma fueling and surface impurities source);
- rector relevant power extraction capabilities from the plasma
- wall conditions, which are not sensitive to the edge plasma temperature as soon as it exceeds a certain level (about 1 keV).
- slowing down free-boundary MHD instabilities,
- etc,

Li Walls, for the first time, introduce the “Yacht Sail” approach for the fusion reactor design, which may provide

- insensitivity of the structure to thermal/electro-magnetic perturbation;
- best environment for both internal and external plasma stability control;
- elimination of (unrealistic) requirement for the stationary regime;
- efficient power extraction from the neutron zone with a high temperature (FLiBe) coolant;
- minimizing the content of activated structural elements;
- simplification of the entire reactor control and maintainence scheme
- ...

Inside the fusion, we, fusion physicists, should, first, realize the deep meaning of what Sean Connery said about the tokamak fusion

"It is impossible *(in the conventional way, LZ)*",

". . . but doable *(if we follow the way of physics, LZ)*"

(S. Connery, the Fox movie “Entrapment", 1999)

Now, we are already on the track leading to a practical fusion.

Integrated approach to fusion reactor

Plasma science part

Solid Li

New plasma regime:

suppressed turbulence,
second stability,
resistive wall at the plasma boundary, ...

Liquid Li

Technology opportunities:

for Plasma Facing Comp.,
power extraction,
liquid (FLiBe) blankets, ...

New schemes for the tokamak reactor:

reduced activation,
smaller size and Btor,
reduced reliance on shaping and
high-tech plasma control
...