Power extraction from tokamaks and tokamak-reactors

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INTRODUCTION

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.

INTRODUCTION

Magnetic propulsion (invented in Dec. 1998) put Intense Lithium Streams (20 m/sec) to the scope of the tokamak research and resulted in

a concept of LiWall tokamaks

LiWall concept introduced 2 new elements into the tokamak fusion

1. Absorbing and renewable plasma facing wall surface:
   (a) LiWalls and energy extraction from the plasma;
   (b) Effect on plasma energy confinement;
   (c) Effect on plasma stability;
2. Yacht Sail approach for the tokamak fusion reactor design:
   (a) . . . , . . .

Only one of key points, i.e., the power extraction from the plasma is addressed in this short presentation.

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

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

For an illustrative example they are

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

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.

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

For copper

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

$$d_{\text{“}skin\text{''},Cu} \simeq 10 \cdot 3\ mm \simeq d_{Cu}$$

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 LiWall tokamak-reactor can be done exclusively on machines, which experimentators are familiar with (starting with CIRCULAR cross-section tokamaks).

TFTR had

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

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

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

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.

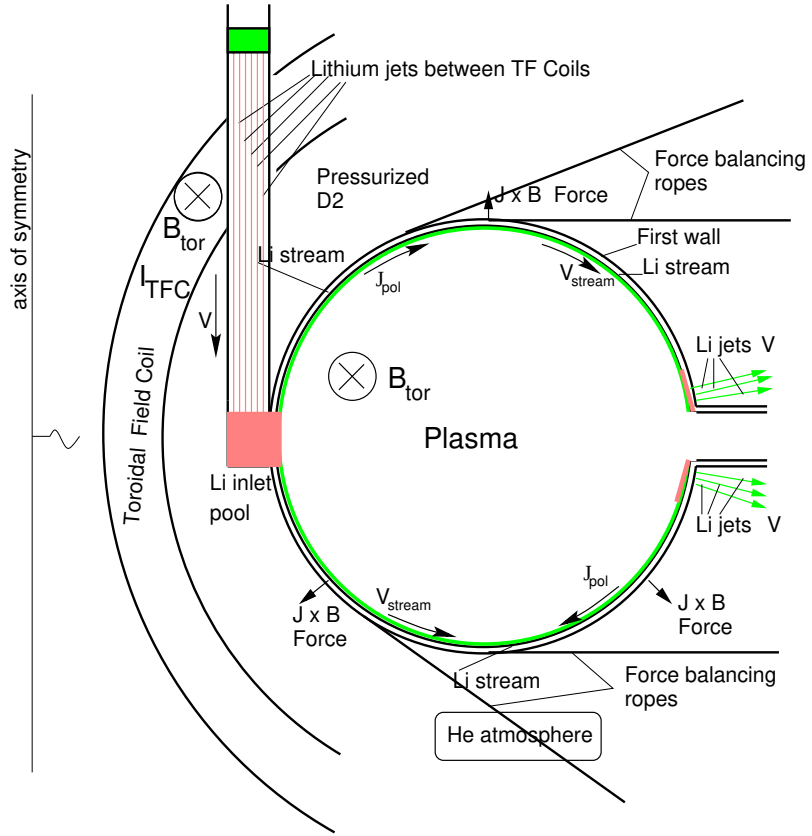
Thus, most of the physics of the burning plasma and calibration of our knowledge will be done in a reliable fashion.

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).

2 Yacht Sail approach for tokamak fusion reactors

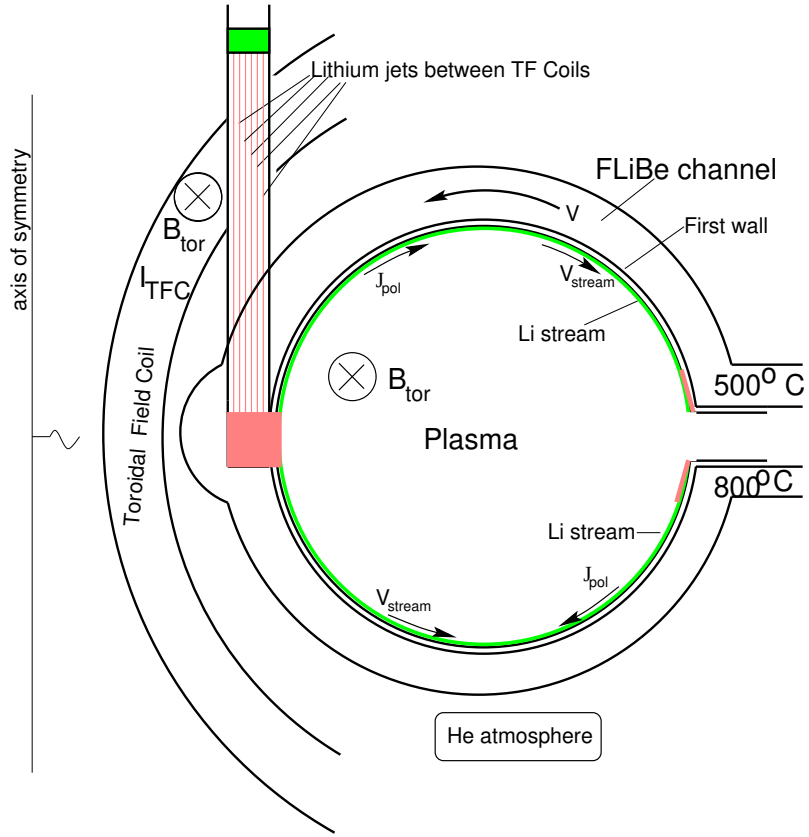
Intense Li Streams affect the very fundamentals of tokamak reactor desing.

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 electromagnetic 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

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

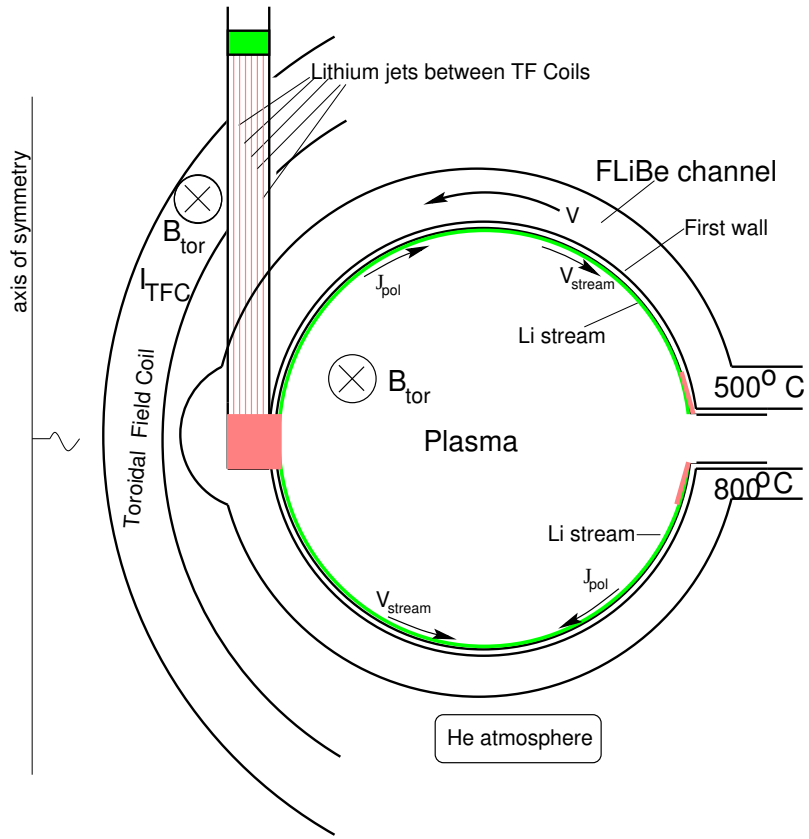
Independent of inner temperature in the chanell FLiBe has a solid boundary layer at the walls.

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

FLiBe

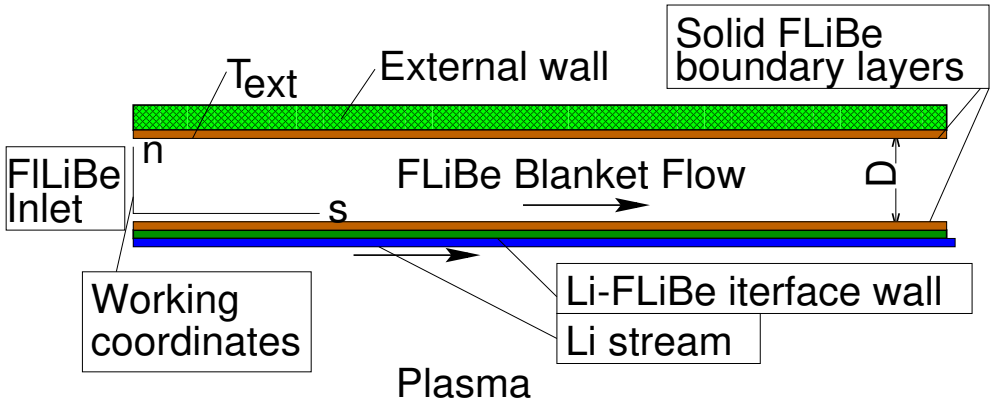
$$(LiF)_n(BeF_2)$$

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

$$\begin{aligned} \rho c_p V \frac{\partial T}{\partial s} &= \kappa T''_{nn} + S, \quad T > T_{melt}, \\ 0 &= \kappa T''_{nn} + S, \quad T < T_{melt} \end{aligned} \tag{2.1}$$

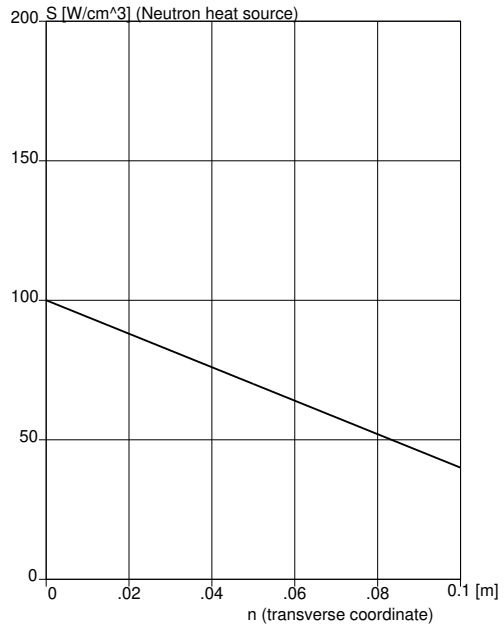
together with the matching conditions determines the temperature distribution in the flow.

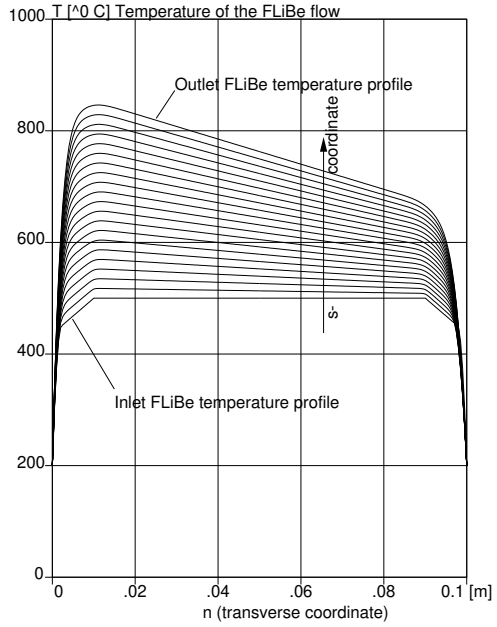
Here, ρ is the mass density of FLiBe, c_p is the heat capacity, V is the velocity of the flow, κ is the thermo-conduction.

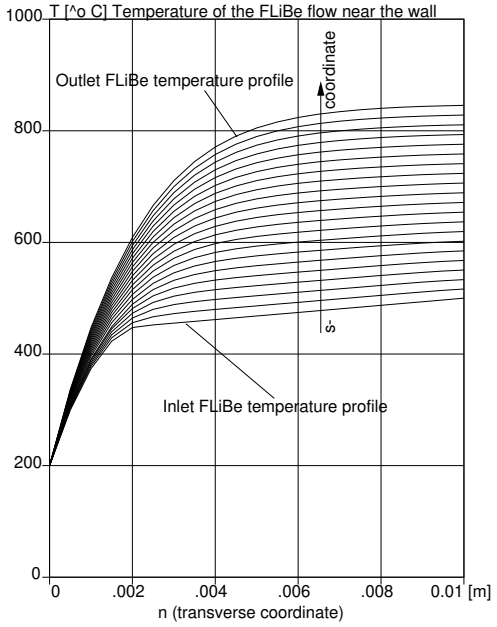
Thickness of the solid layer is determined as an eigenvalue of the problem in a self-consistent way.

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

$$\rho c_p V \frac{\partial T}{\partial s} \simeq S, \quad T > T_{melt}, \tag{2.2}$$

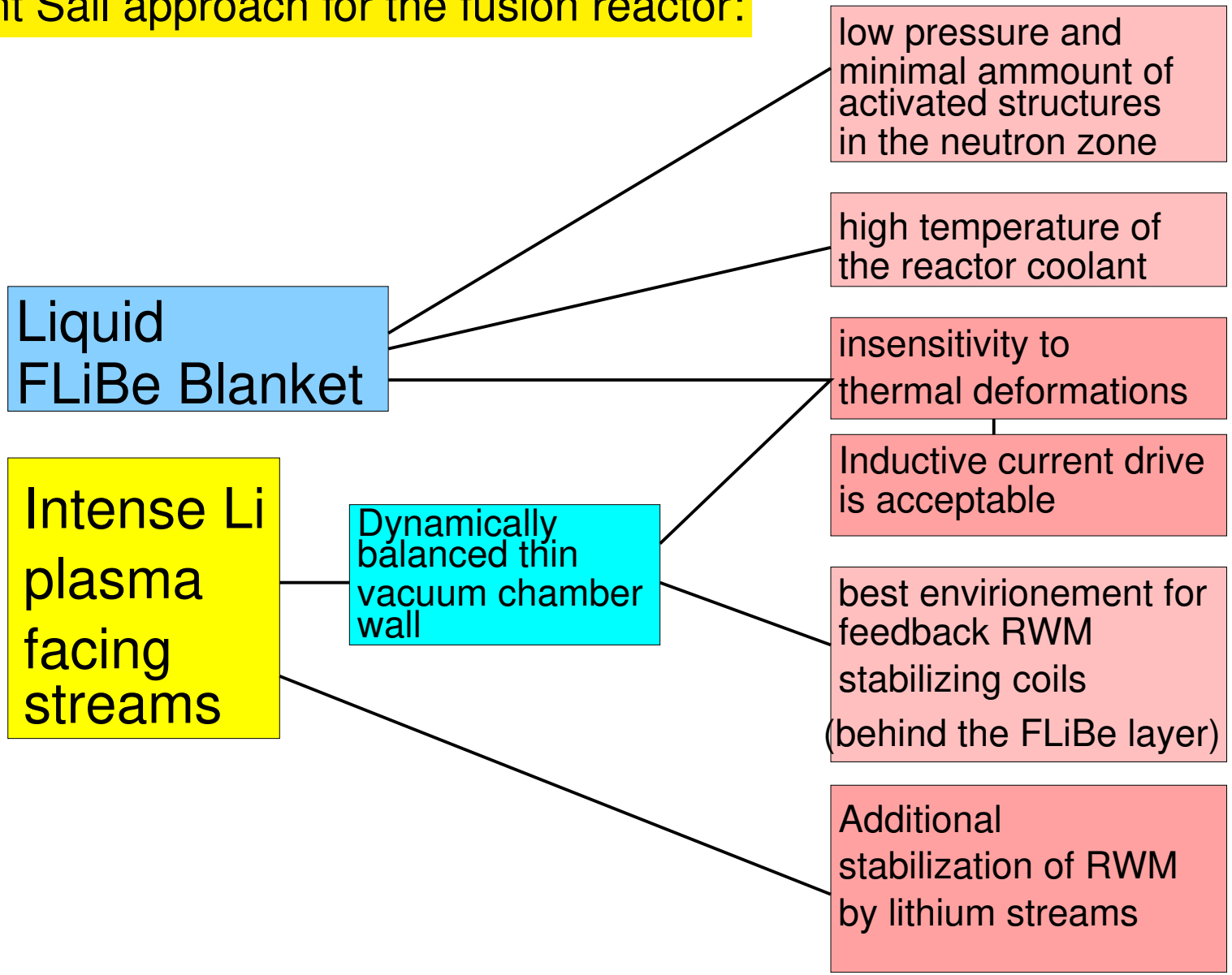
not by thermo-conduction losses.

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:



3 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
- . . .

4 Does the tokamak fusion have a path ?

Yes. Technology (both nuclear and general) seems to suggests this.

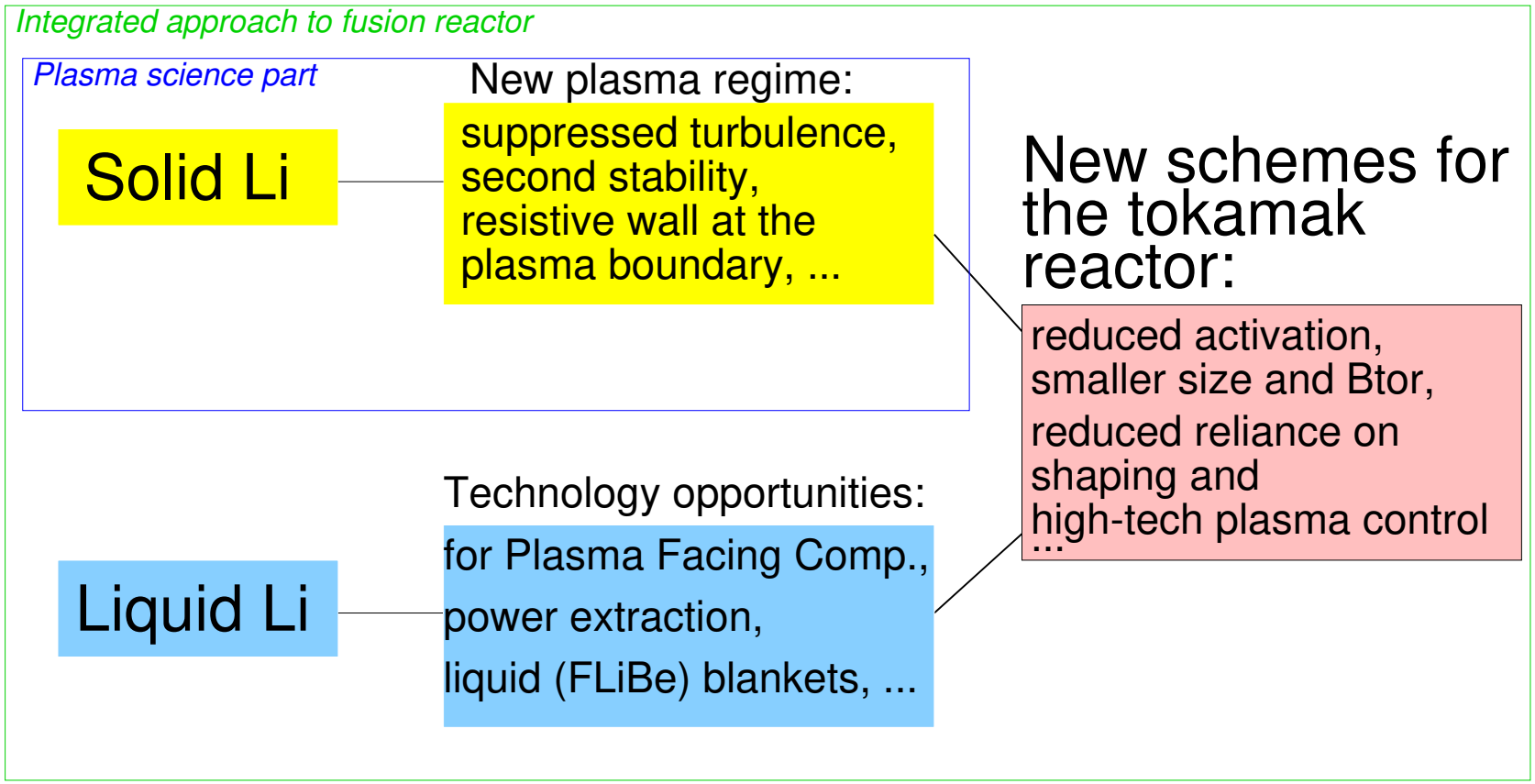
Inside the fusion, we, fusion physicists and technology people, should, first, realize the deep meaning of what Sean Connery said about the tokamak fusion technology

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

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

(S. Connery, TWENTIETH CENTURY FOX and REGENCY ENTERPRISES film “Entrapment", 1999)

Our physics colleagues outside fusion, being consultant of the funding Agencies, should always remind us to be on the right track, and to be driven by technology needs in the great endeavor to make the tokamak working in our life time limit as a commercial power reactor.


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
...