Yacht-sail approach for the tokamak fusion reactor

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Abstract

Dynamically balanced design concept for the "first wall" for the tokamak fusion reactor will be described for MIT. The concept includes: (a) electromagnetically driven, plasma facing Intense Lithium Streams (ILiS), 20 m/sec, for the particle control and the power extraction from the plasma; (b) FLiBe neutron energy extraction blanket; (c) fabric-like guide wall, interfacing ILiS and FLiBe flow; (d) a set of ropes for balancing the toroidal component forces acting on the guide wall.

This design concept opens opportunities for nuclear engineers and technologists to express their creativity in development of acceptable and controllable tokamak fusion reactor.

Supporting material for the talk can be found on the web-page http://w3.pppl.gov/ zakharov

OUTLINE

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   - (a) Dynamic balancing.
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   - (c) Fabric-like vacuum chamber.
5. Summary.

1 Introduction. Where we are in magnetic fusion ?

Excellent review on progress in tokamaks was given by

R. D.Stambaugh “Progress in MFE science - tokamak research”

Presented at American Physical Society, DPP, Quebec City, Quebec, Canada, Oct.24, 2000

See, http://fusion.gat.com/presentations/

All sorts of “advanced” fusion reactor designes can be found on the web-site

http://ashley.ucsd.edu/ARIES/CAD/FIGURE/ARIES-RS

Is the situation so great ?

Despite a lot of enthusiasm among the active part of fusion physicists, there is much less enthusiasm outside fusion.

Fusion is not the plasma physics only. It is also, in fact, even in bigger proportions, about material science/technology, power extraction/conversion, activation/safety, reactor control/maintenance, acceptence by society, etc.

Present fusion program pays negiligible attention to the most of vital issues outside the plasma physics.

Is the situation, e.g., with the power extraction great ?
It is not when the only concept is a divertor.

In the reactor plasma:

- 20 % of energy goes into alpha-particles and finallly to the wall
- 80 % of energy goes to 14 MeV neutrons (for further conversion into electricity)

- without reliance on radiation from the divertor, the power loads on the plasma facing components will be more than an order of magnitude higher than the admissible level. E.g.,

$$R = 6\,m, \quad L = 0.1\,m, \quad S = 2\pi RL = 3.8\,m^2, \quad P \simeq 0.5\,GW$$

(L is the power deposition width) leads to the energy flux

$$q \simeq 130\,\frac{MW}{m^2}$$

On the other hand,

- reliance on radiation leads to:

  1. necessity of high plasma density at the plasma edge $\Longrightarrow$
  2. low plasma edge temperature $\Longrightarrow$
  3. inconsistencies in plasma profiles,
  4. internal instabilities (sawtooth oscillatoions)
  5. no ideas about reliable plasma control in the reactors
  6. . . .

  and to unaffordable fusion research program with billions $ device costs (e.g., ITER) for experimenting with plasma physics (and with little hopes for transferability to the reactor power scale).

Does the tokamak physics is so bad ? It is not.

Seeing the “stopper” problem in its real capacity suggests the proper path for the tokamak fusion program, i.e.,

distribution of the power over wall surface rather than its concentration in the divertor.

2 Lithium Walls and tokamak plasma

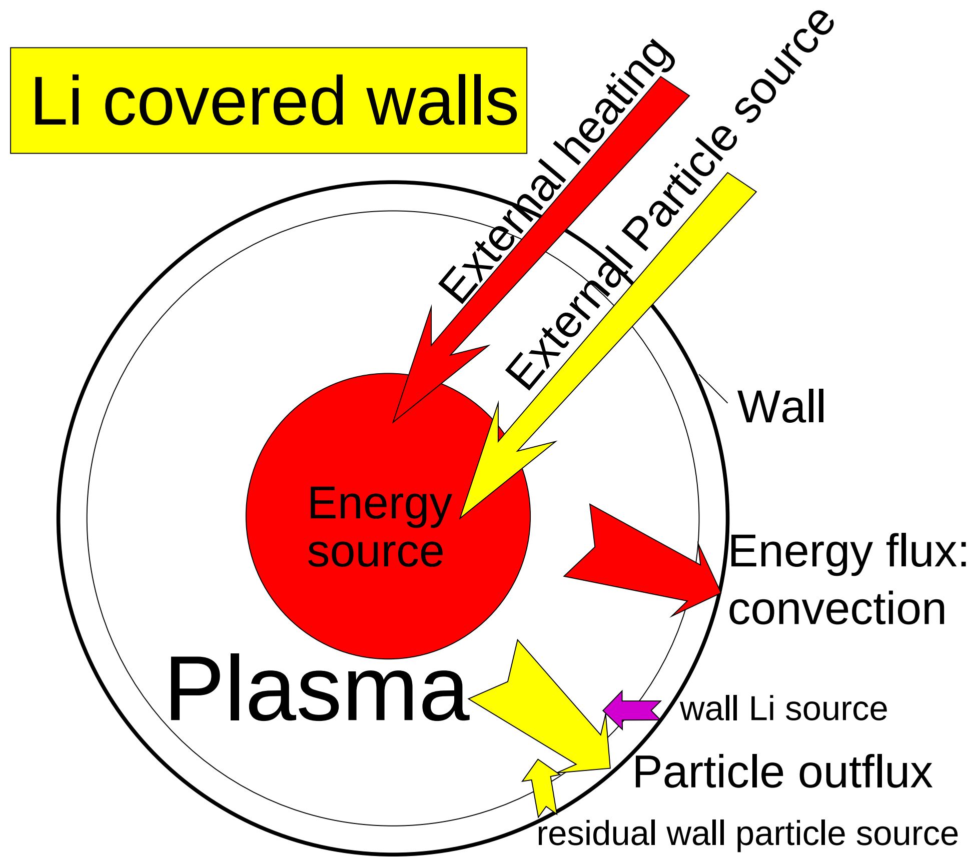
The first wall should be compatible with

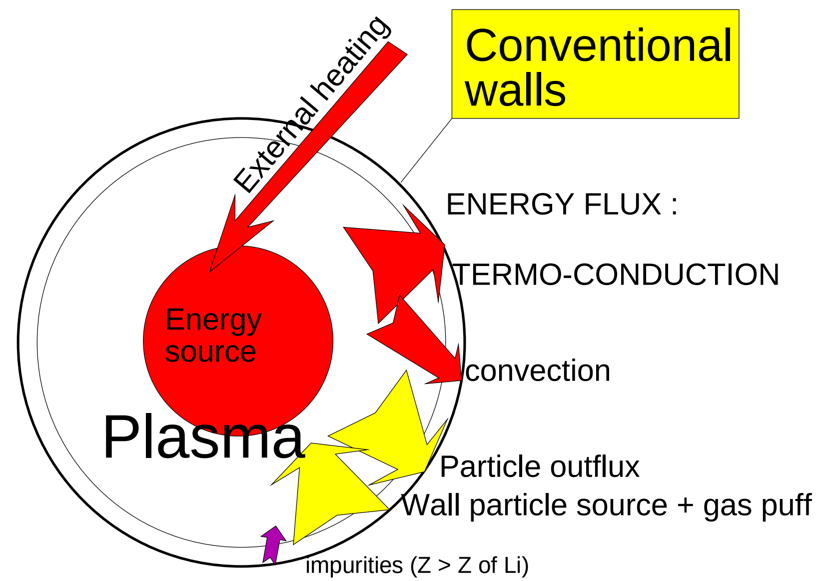
1. power extraction
2. control of the plasma particles (fueling or pumping)
3. plasma confinement and stability regimes
4. helium ash exhaust (in the tokamak reactor)
5. high 14 MeV neutron flux

Lithium plasma facing wall surface satisfies all this requirements according to the present understanding the plasma physics and the lithium properties (ALPS/APEX DoE technology programs).

3 Lithium Walls and tokamak plasma.

Li is an excellent getter for the hydrogen plasma particles.





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

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

$$\Delta T_{max} = q_{wall}\sqrt{\frac{4t_{exposure}}{\pi\kappa\rho c_p}}, \quad d_{skin} \equiv \sqrt{\frac{\kappa t_{exposure}}{\rho c_p}}$$

For copper

$$\kappa_{Cu} > 10\kappa_{Li}, \quad (\rho c_p)_{Cu} \simeq (\rho c_p)_{Li}$$

For a limited time

$$t_{exposure} \simeq 3.25\ sec, \quad \Delta T_{max} \leq 200^o\ C$$

such a Li coated copper shell can tolerate the reactor-relevant total power flux

$$q = 3.5\,\frac{MW}{m^2}, \qquad S \simeq 500\ m^2, \qquad qS > 1\ GW$$

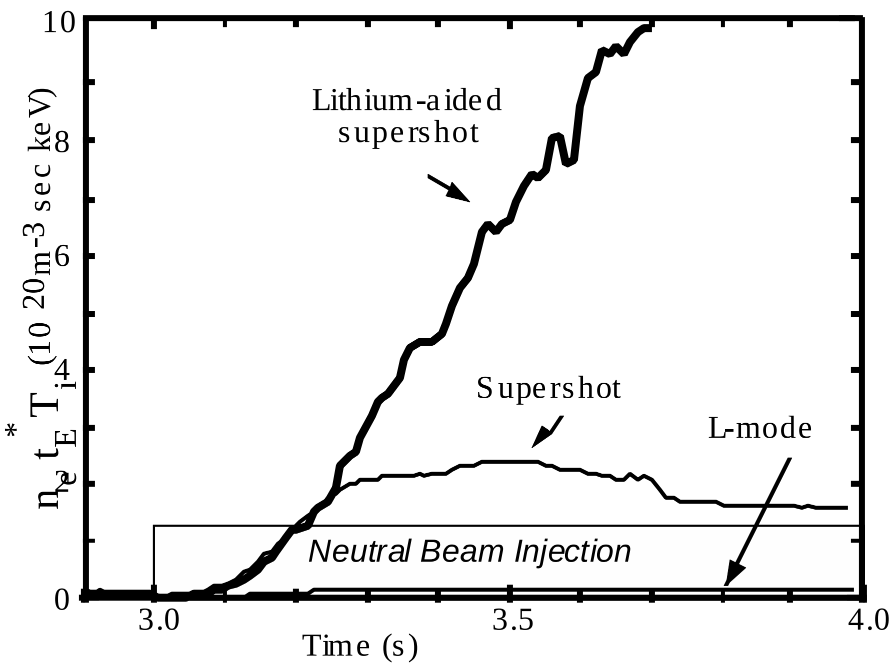
In the Test Fusion Tokamak Reactor (operated in PPPL till 1996) such a flux would be only $0.5MW/m^2$ with 50x3.25 sec (instead of 1 sec) of the pulse duration at 40 MW of the heating power.

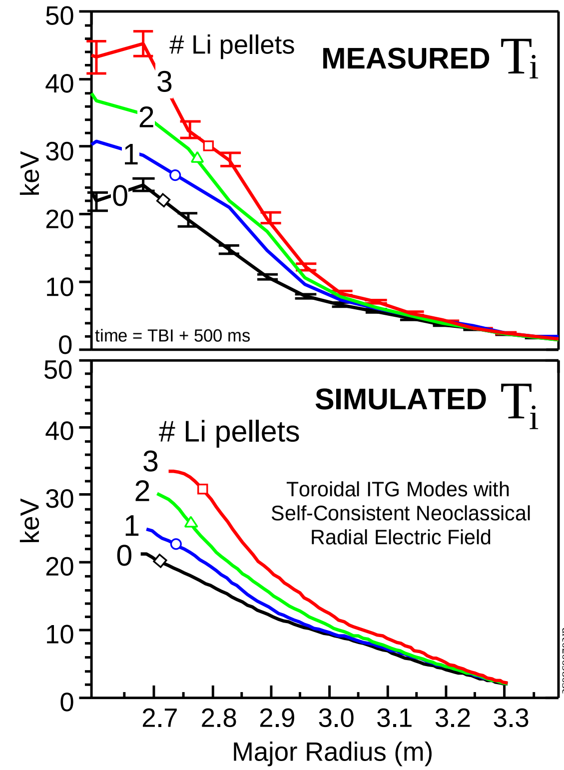
TFTR and then T-11M (TRINITI, Troitsk, Russia) shown perfect compatibility of plasma facing lithium with the edge and core plasma.

All TFTR best regimes have been obtained with the lithium conditioning

T-11M demonstrated immense particle gettering capabilities of the Li surface, for both Deterium and Helium (!!!).

TFTR discovered and demonstrated that Lithium conditioning was the most important factor in its performance

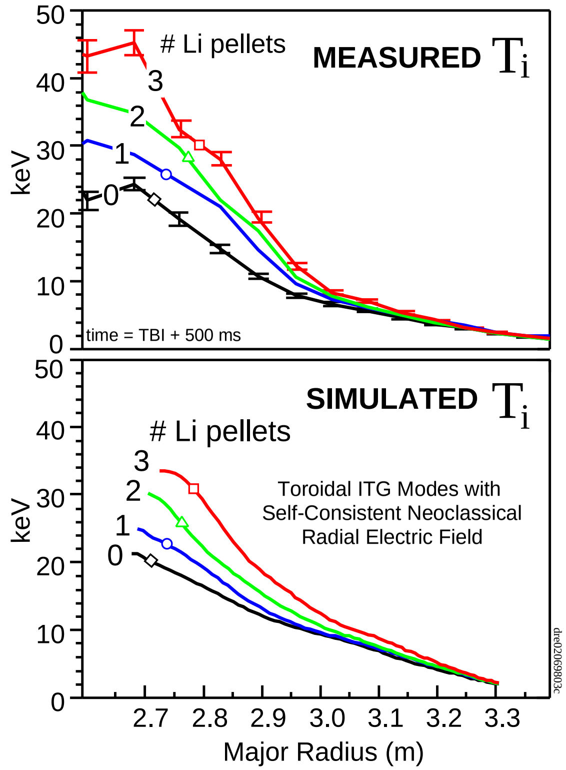


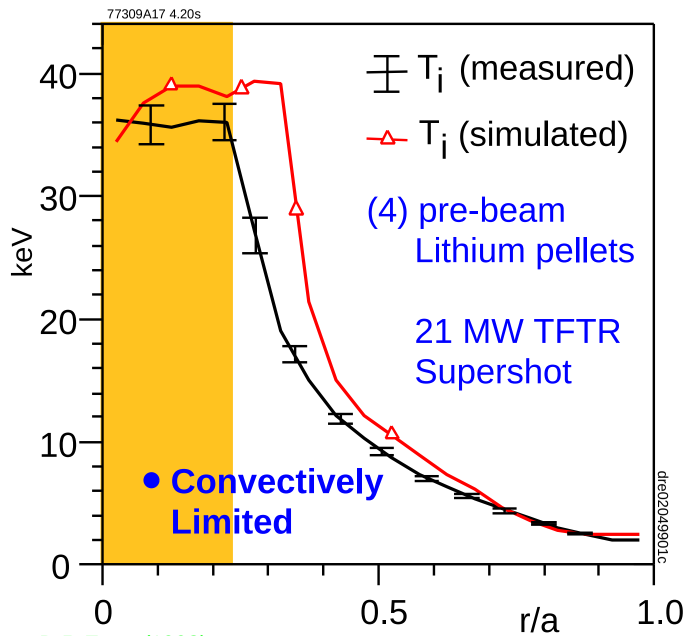


(TFTR # 83546 D.Mansfield, C.Skinner)

The increase in performance with increase in amount of lithium at the plasma edge has never been saturated.

Li Walls concept deffers in details from TFTR results but is consisitent in basic tendencies to flat the temperature in the core by reducing recycling at the edge





D.R.Ernst (1998)
J. D. Strachan, et al., EPS Inv. (1994).

Lihtium coated walls provide the RESEARCH path for the magnetic fusion program up to demonstration of ignition and burning plasma.

At least, 4 of the “first-wall” functions can be fully explored in this way

1. power extraction
2. control of the plasma particles (fueling or pumping)
3. plasma confinement and stability regimes
4. helium ash exhaust (as in the tokamak reactor)

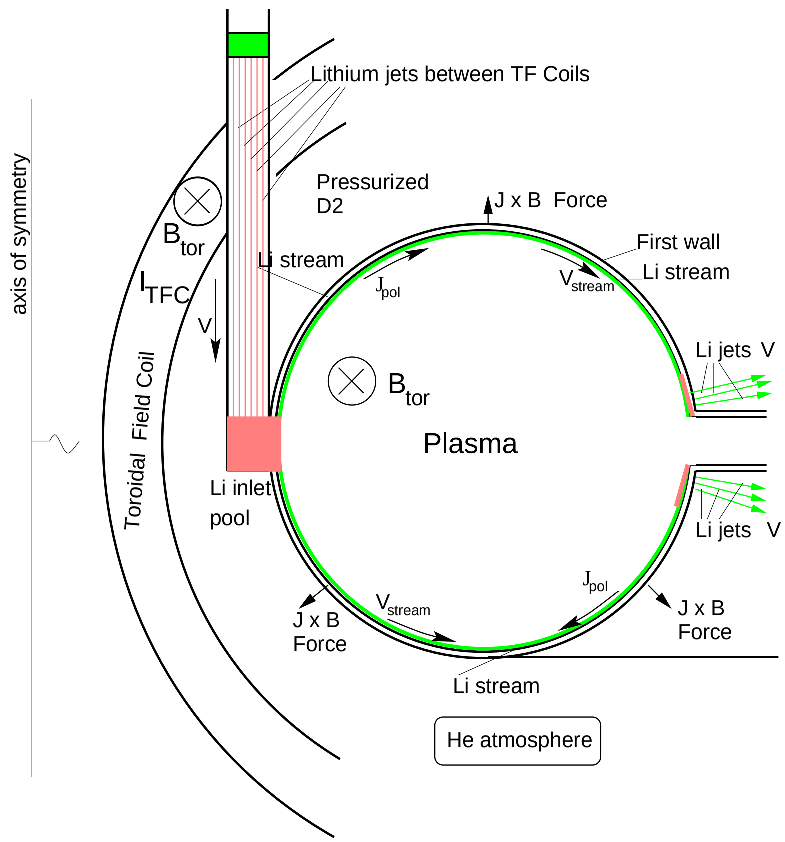
4 Magnetic propulsion of liquid lithium

Demonstration of relevant plasma physics is not yet the demonstration of its relevance to fusion reactor application.

In this regard, it is remarkable that liquid lithium can be propelled electro-magnetically in the tokamak magnetic field (invented in Dec. 1998).

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

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



- Driving electro-magnetic pressure

$$p_{\mathbf{j}\times\mathbf{B}}|_{outlet} > 1\ atm$$

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

- Flow parameters

$$V \simeq 20\ m/sec, \quad h \simeq 0.01\ m$$

- Magnetic Reynolds numbers

$$\Re_1 \equiv \mu_0 \sigma h V \simeq 0.8, \quad \Re_2 \simeq 0.0015$$

- Stream are robustly stable due to centrifugal force, if

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

Intense lithium streams have reactor relevant power extraction capabilities

$$\Delta T_{max} = q_{wall}\sqrt{\frac{4t_{transit}}{\pi\kappa\rho c_p}}, \quad d_{skin} \equiv \sqrt{\frac{\kappa t_{transit}}{\rho c_p}}$$

$$R = 6\ m, \quad a = 1.6\ m, \quad q_{wall} \simeq 3.5\,\frac{MW}{m^2}, \quad P_{wall} = 4\pi^2 Ra q_{wall} \simeq 1.3 GW$$

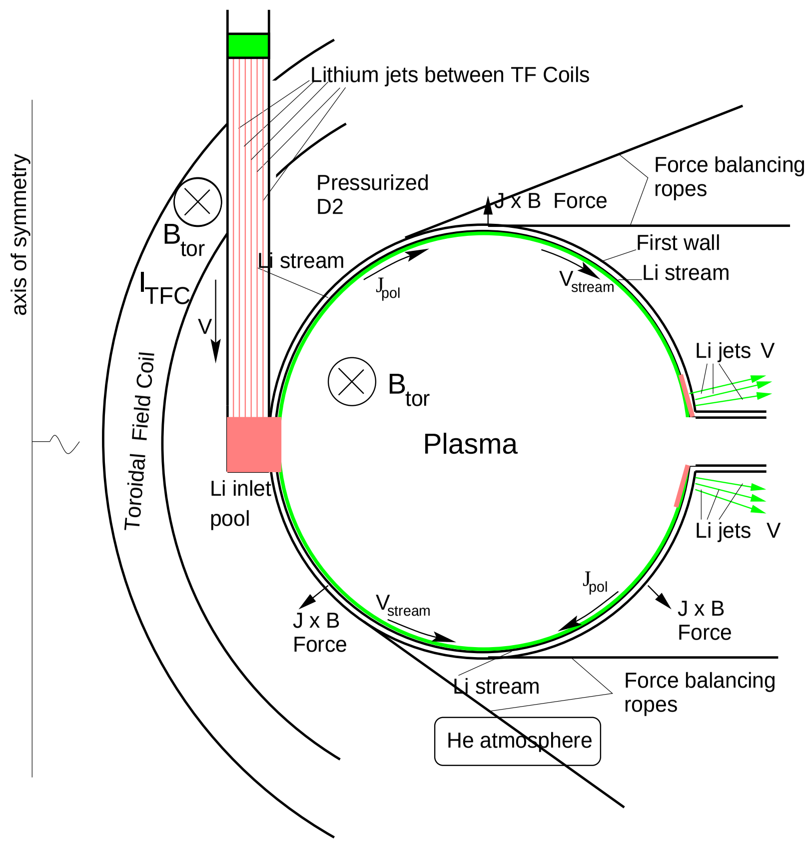
even with no reliance on the vortices in the streams.

Intense lithium streams can keep wall temperature low (250-300^o C) at the neutron wall loading $> 10\ MW/m^2$.

5 Yacht Sail approach for tokamak-reactors

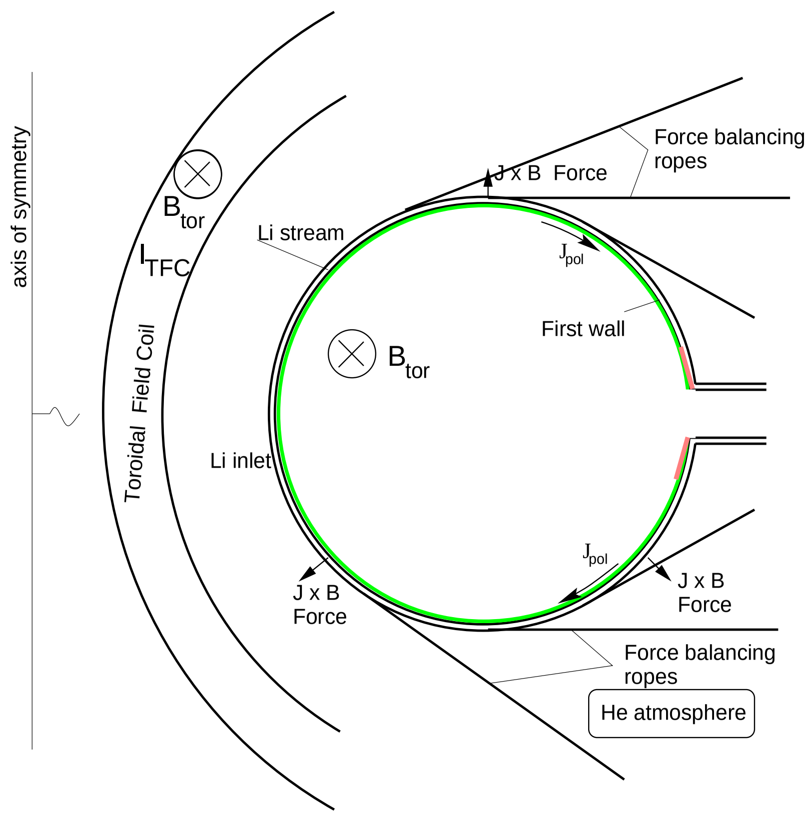
Intense Li Streams affect the very fundamentals of tokamak reactor desing.

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).
- 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).

Dynamic gives a real 3-D design puzzle.



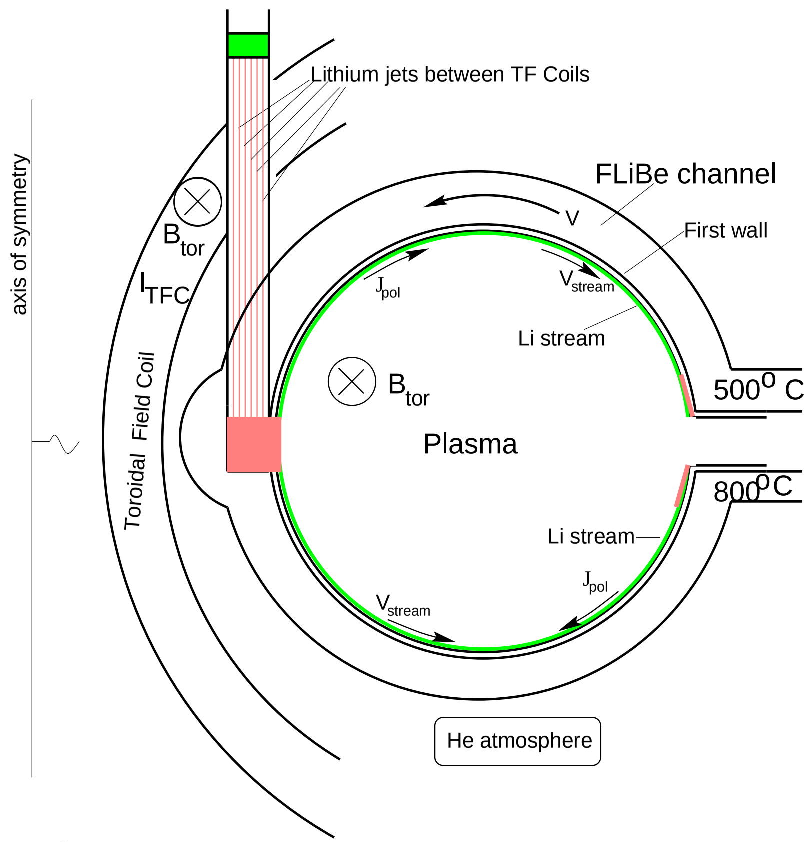
- Toroidal component of the electro-magnetic force can be balanced by the set of external wire ropes

$$\left(p_{\mathbf{j}\times\mathbf{B},outlet}\frac{r^2_{outlet}}{r^2} - p_{atm}\right)\frac{r}{r_{inlet}} = Td,$$

where T is the tension of ropes, $d(r)$ is the total height as the function of position of the touch point.

- Ropes are the best solution to with-stand plasma disruptions.
- Ropes can be made from Be (non-activatable).
- Ropes can be replaced during reac-tor operation.

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

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

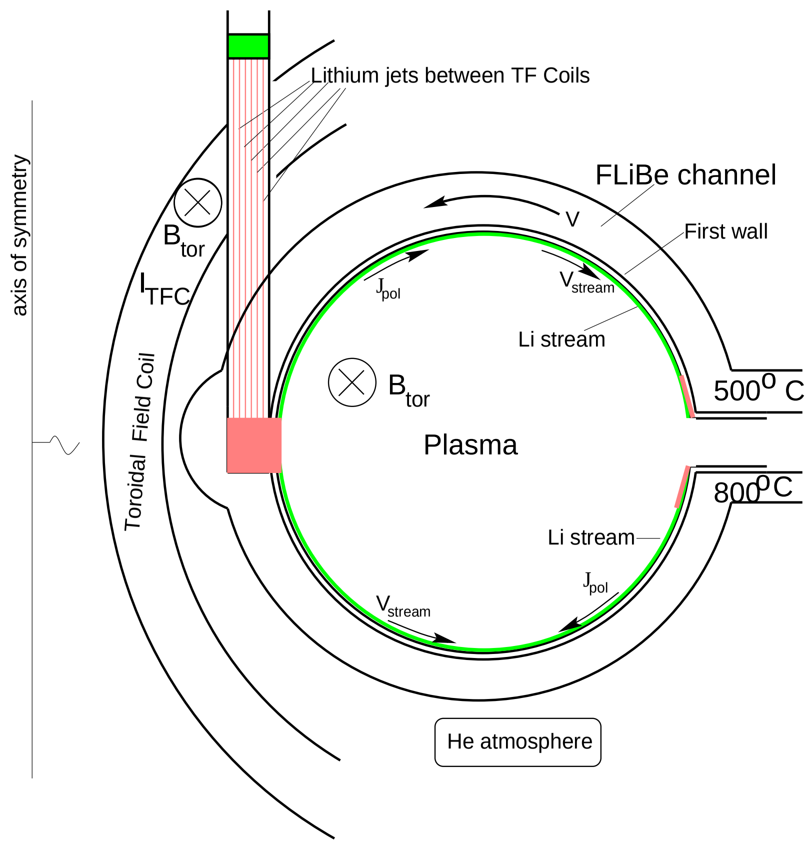
Independent of inner temperature in the chanell FLiBe has a solid boundary layer at the walls.

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

FLiBe

$$(LiF)_n(BeF_2)$$

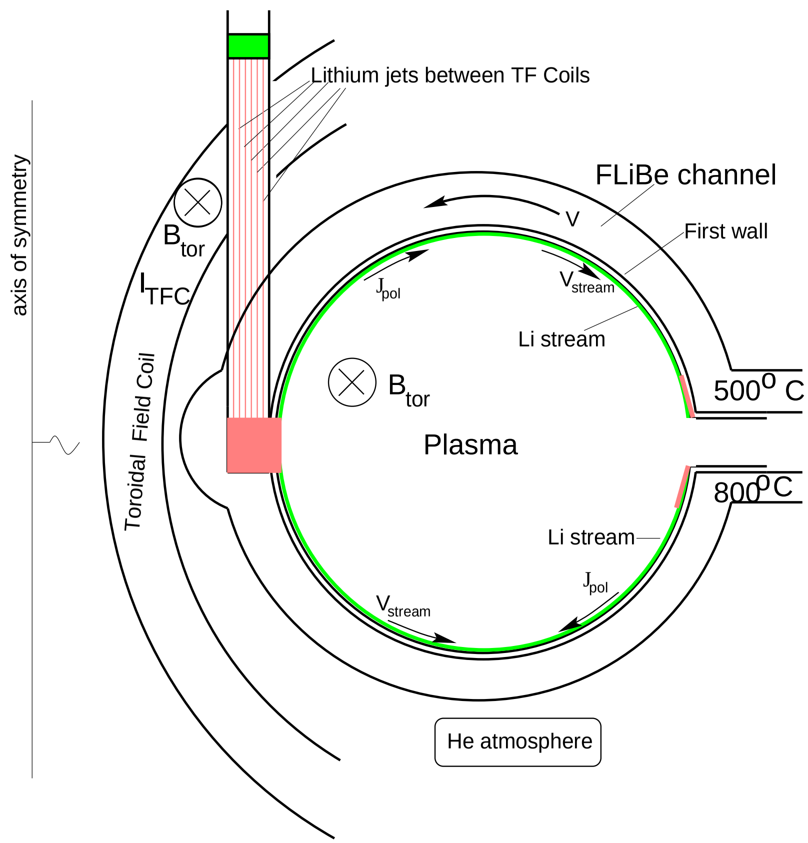
It would be not crazy to think about making the vacuum chamber from the wire mesh



- 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);

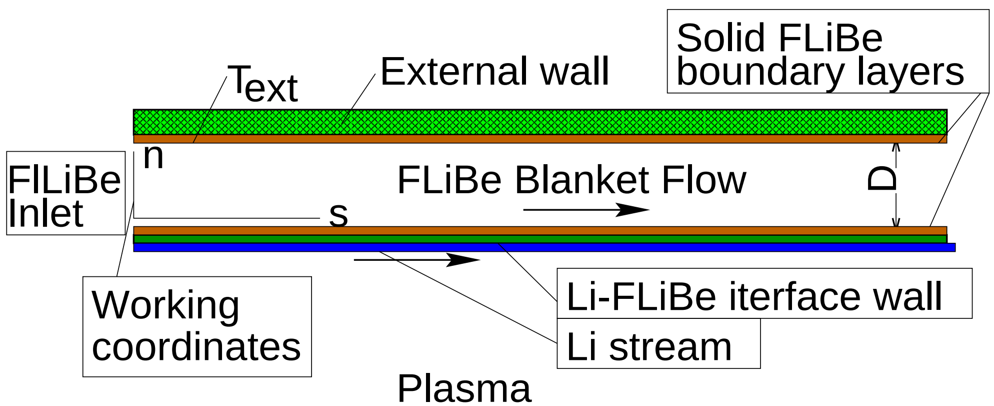
Tokamak is no longer a hostage of the requirement to be stationary!

5 Yacht Sail approach for tokamak-reactors. Fabric-like vacuum chamber. (cont.)



- wire wall, presumably, can withstand the high neutron flux;
- activation is minimum in the neutron zone;
- feedback plates are protected 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

$$\begin{aligned} &\rho c_p V \frac{\partial T}{\partial s} = \kappa T''_{nn} + S, \quad T > T_{melt}, \\ &0 = \kappa T''_{nn} + S, \quad T < T_{melt} \end{aligned} \tag{5.1}$$

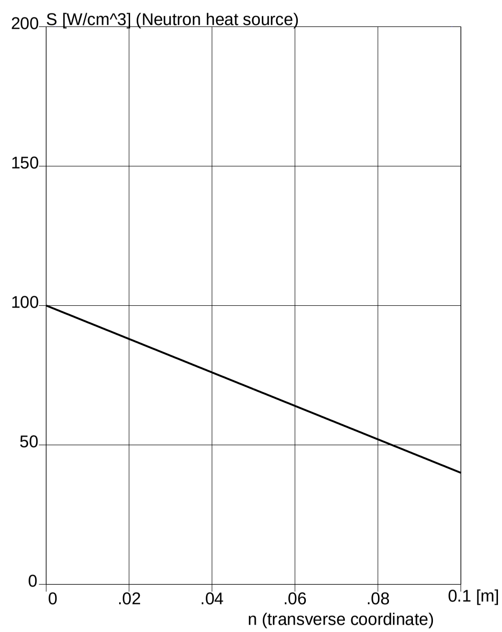
together with the matching conditions determines the temperature distribution in the flow.

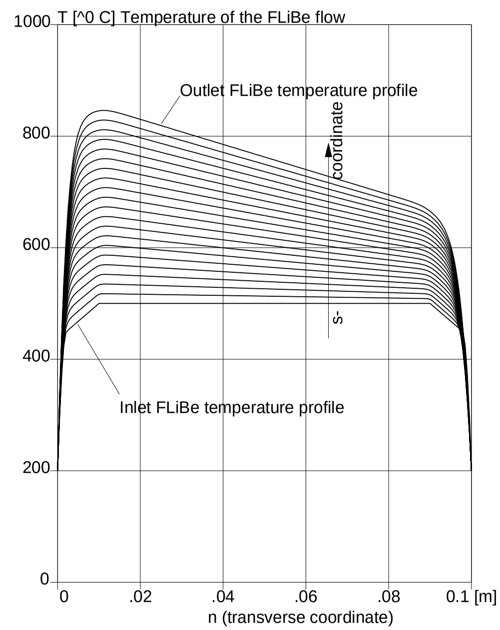
Here, ρ is the mass density of FLiBe, c_p is the heat capacity, V is the velocity of the flow, κ is the thermo-conduction.

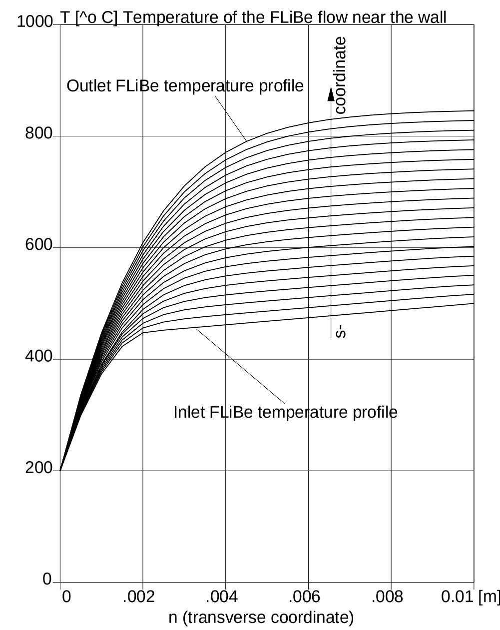
Thickness of the solid layer is determined as an eigenvalue of the problem in a self-consistent way.

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

$$\rho c_p V \frac{\partial T}{\partial s} \simeq S, \quad T > T_{melt}, \tag{5.2}$$

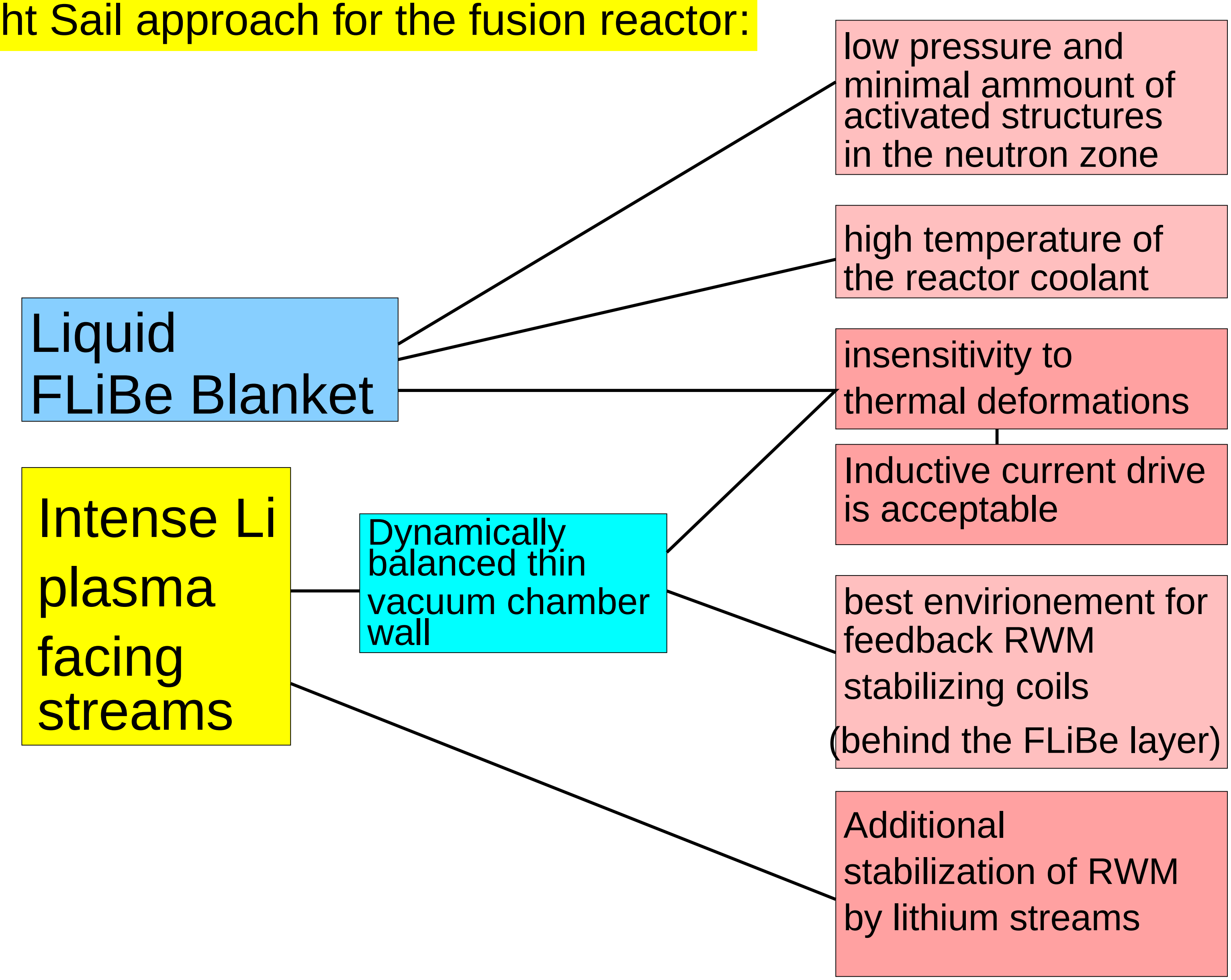
not by thermo-conduction losses.

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:



6 Summary

Tokamak fusion program has now a consistent tokamak-reactor LiWall concept developed by the plasma physics/technology community during the last 2 years.

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,

LiWalls, 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
- . . .

After more than 30 years of intense research and accumulating a great experience with the plasma physics, the tokamaks seem to have found an approach for a fusion reactor.

It is evident that a lot of work has to be done.

Now, it is a proper time for the plasma physics program to break its apearant isolation and to be with the broad physics community in such a great endeavor as to make the tokamak working as a commercial power reactor within our life time limit.