Tokamaks with lithium covered walls

Leonid E. Zakharov,

Princeton University, Princeton Plasma Physics Laboratory

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"Lithium Walls and low Recycling Regimes in Tokamaks"

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SPECIAL THANKS

Many thanks to

Sergei Krasheninnikov, (UCSD)

for his idea to organize this meeting as a mini-coonference at APS 2000,

to

Allen Boozer, (Columbia U)

who accepted the idea and provided full assistence,

to

ALPS (R.Mattas, ANL) and APEX (M.Abdou, UCLA) DoE programs,

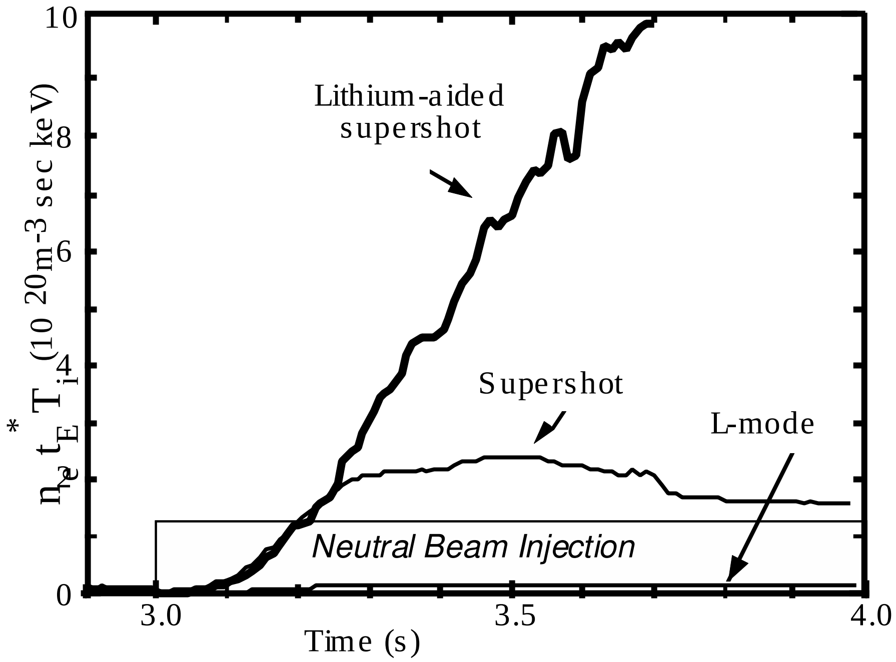
which behind the scene conduct and support lithium studies.

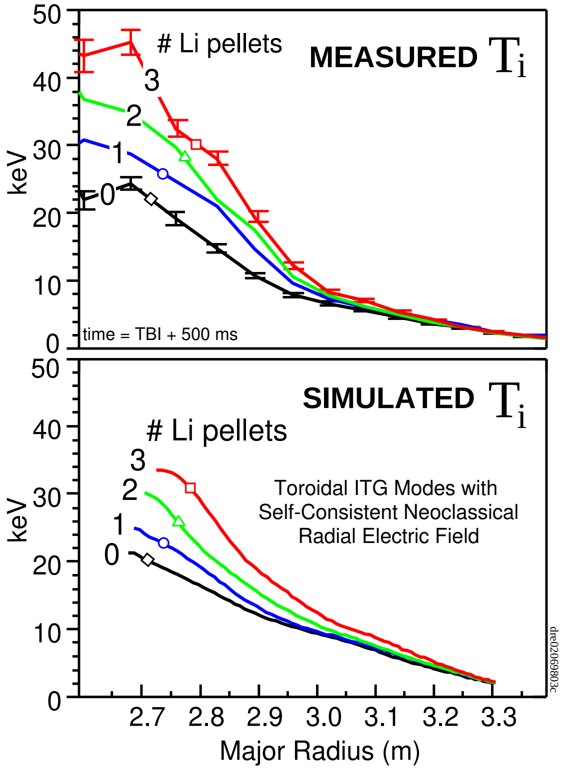
Web page

http://www.pppl.gov $\Longrightarrow$ Meetings $\Longrightarrow$ Lithium Walls 2000

Titles of the mini-conference talks hopefully
will contain links to
presentations and supporting stuff.

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



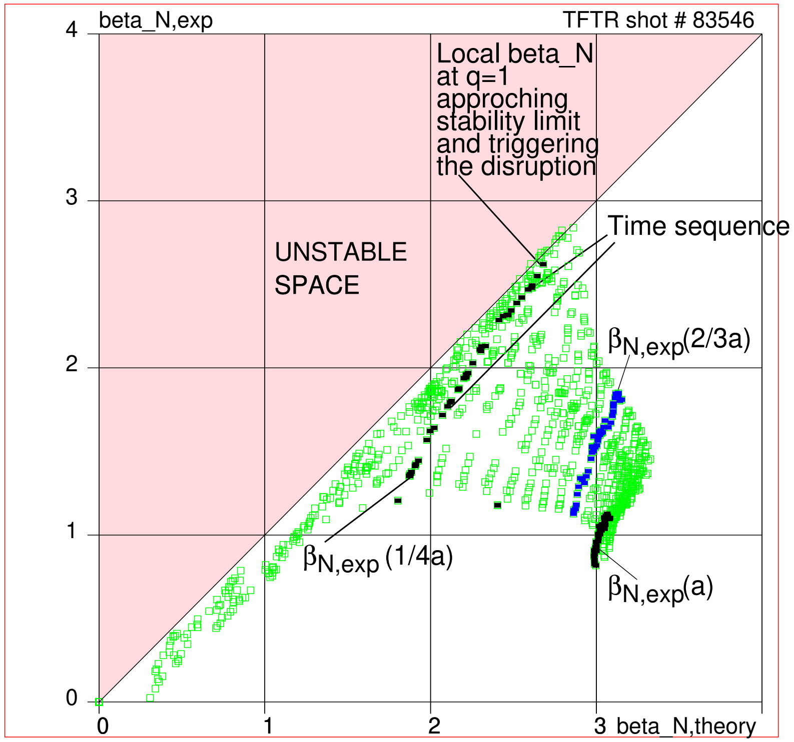


(TFTR # 83546 D.Mansfield, C.Skinner)

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

Instead, the performance was limited by disruptions

- pretty well understood in TFTR and
- related to some peculiar properties of supershots.



Local Troyon $\beta_N(r)$:

$$\beta_N(r) \equiv \frac{2\mu_0(<p> - p)|_r}{B_{tor}^2}\frac{r B_{tor}}{I_{pl}(r)}$$

Green points represent the time evolution during NB heating of local $\beta_{N,exp}$ at all minor radii in TRANSP simulations.

Black points correspond to $q(1/4a) \simeq 1$ and $q(a) \simeq 4$ surfaces.

Can use of lithium provide a new path for 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
...

Opportunity for studies of new plasma regimes and developing liquid lithium technology in a separate (parallel) manner.

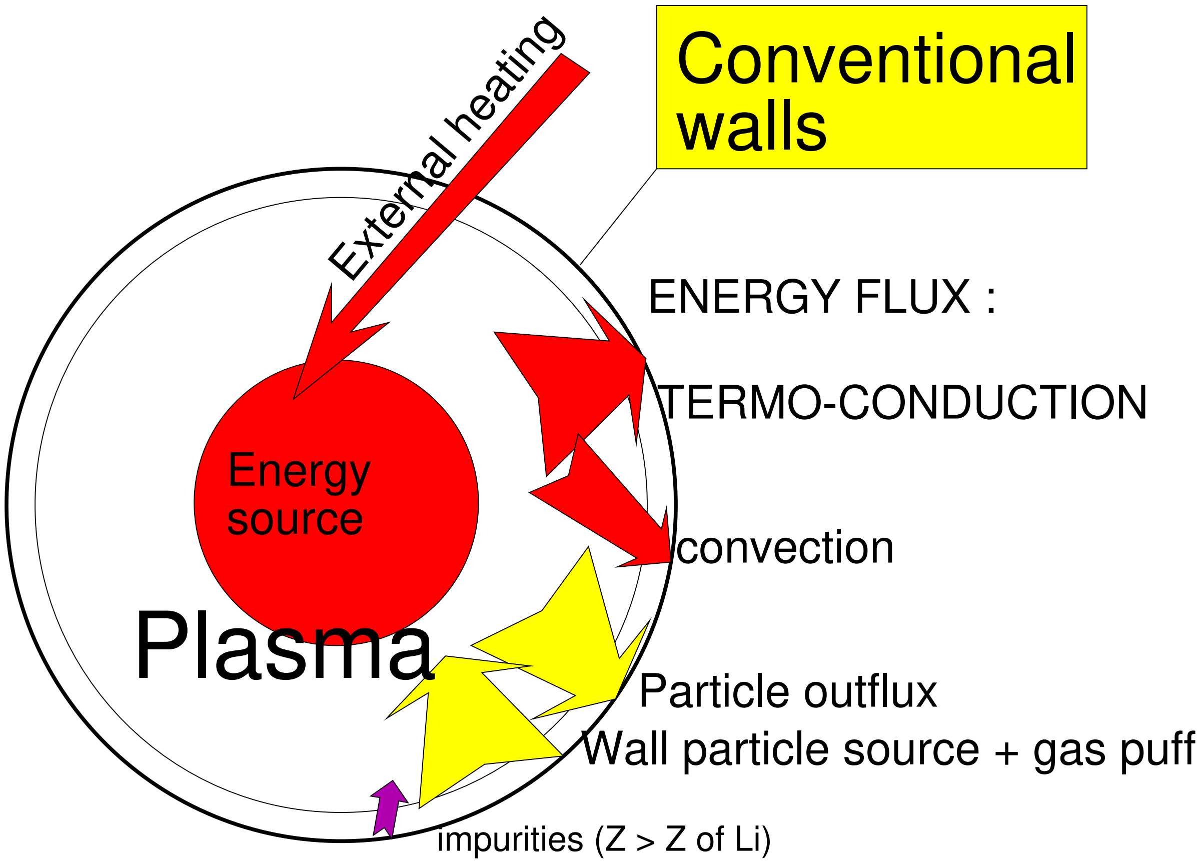
OUTLINE

1. Low recycling regime and necessity in a dedicated tokamak experiment.
2. Intense lithium streams and reactor aspects of lithium walls.
3. Summary.
4. Topics for discussion.

1 Low recycling regime

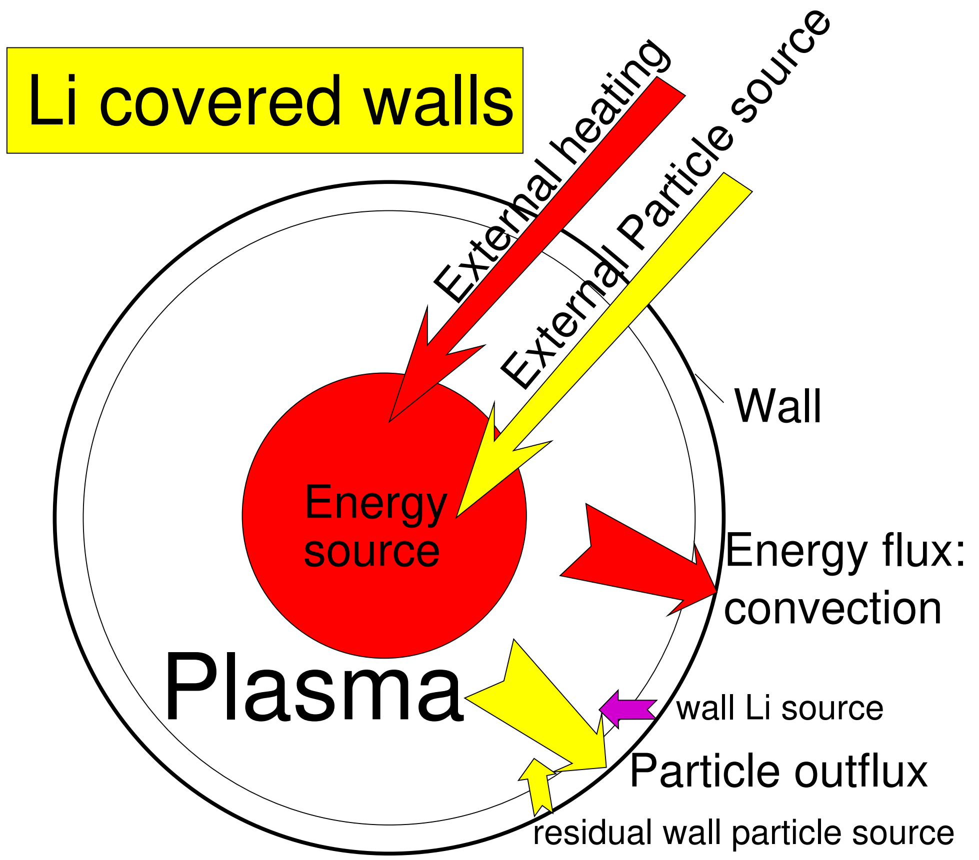
Common wisdom:

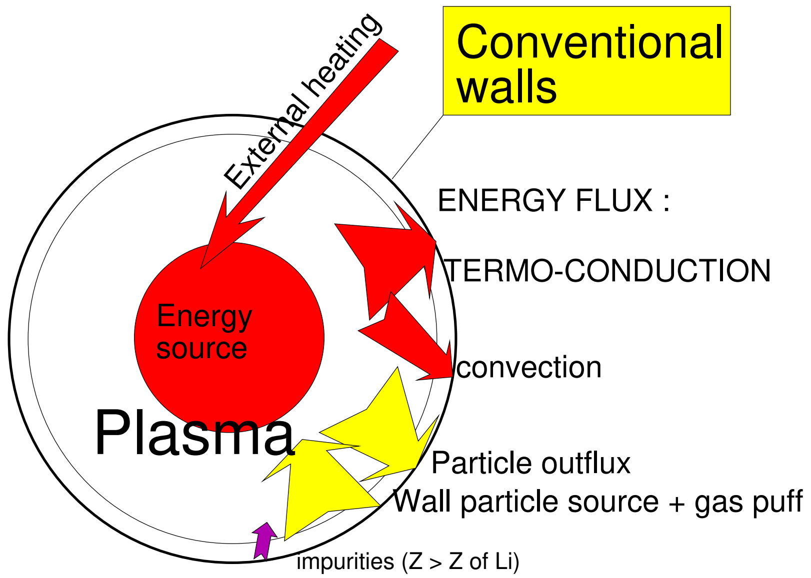
Plasma boundary provides boundary conditions for internal transport



Believes (and some data, e.g., T-11) are that:

Li is an excellent getter for the hydrogen plasma particles.





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

What implications are ?

At the most basic level,

plasma profiles are determined by the particle continuity equation

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

and by the energy balance

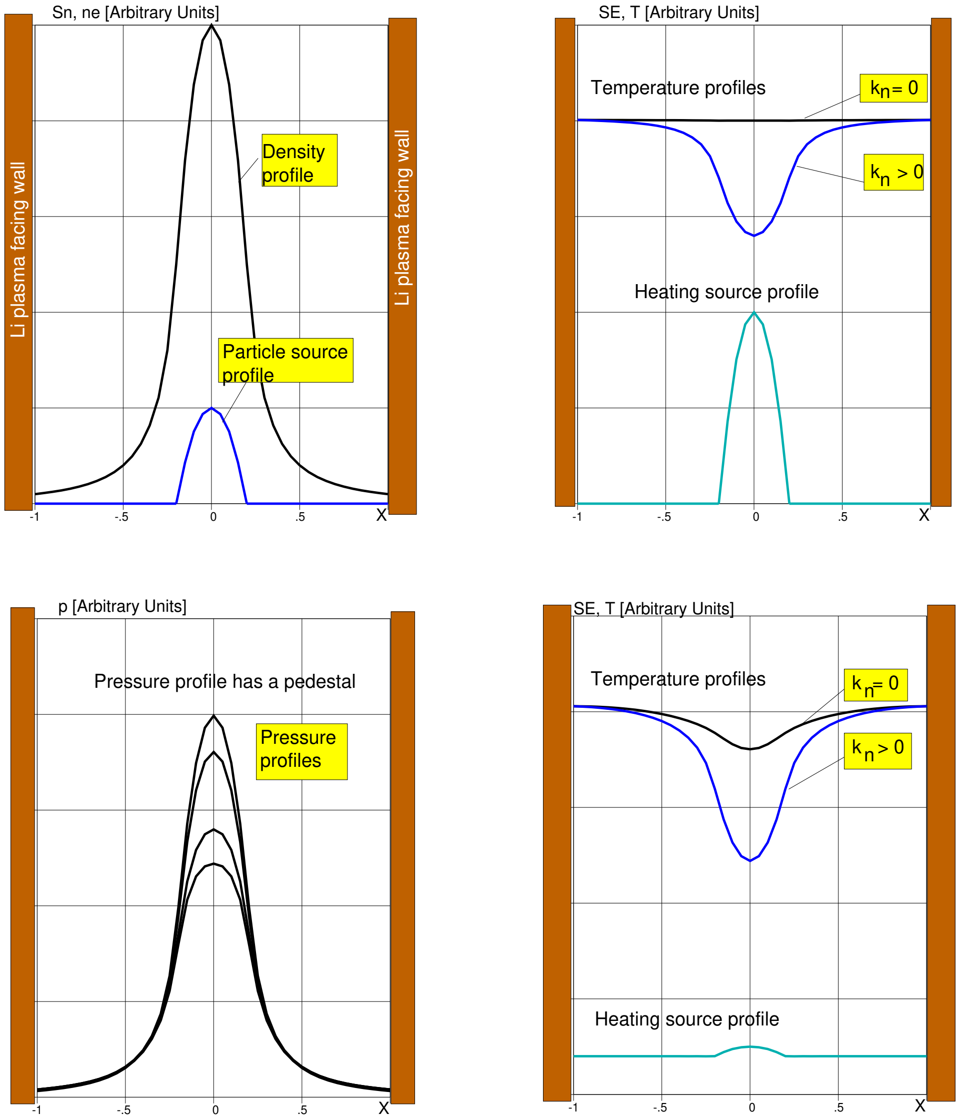
$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P_E dv$$

Boundary conditions for the perfectly absorbing walls

$\left(\frac{5}{2}\Gamma T\right)_a = \int_0^a P_E dv \quad P_E-$ heat source in the plasma.

Energy confinement is determined solely by the particle confinement (S. Krasheninnikov).

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.

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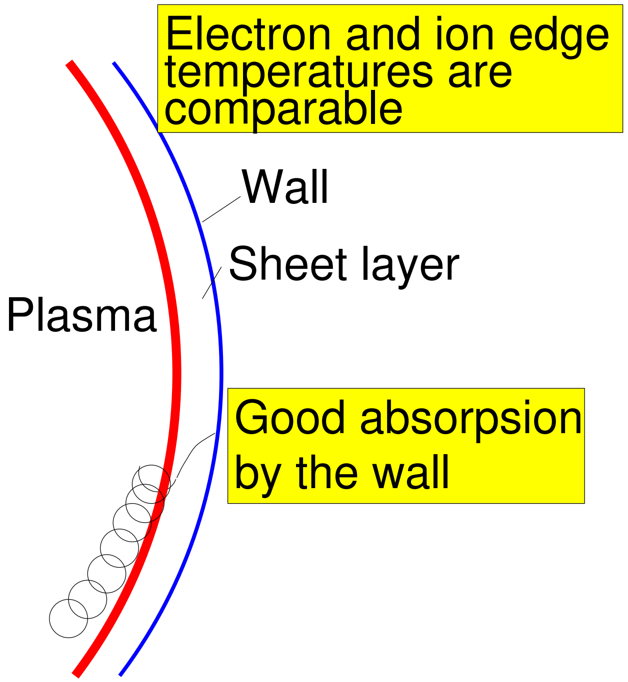
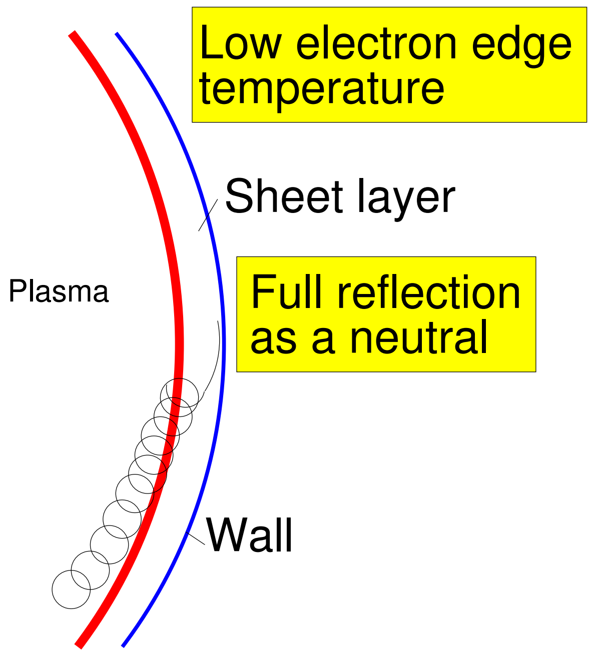
Crucial issues:

- Properties of the lithium. For solid Li they are very attractive, e.g., 1 keV D-ion penetrates hundreds of monlayers of lithium (D.Ruzic, UL).
- Sheet potential near the walls. Is determined by the electron energy, $E \simeq 3T_e/\rho_i$.

  Electrons in tokamaks are capable for any unpleasant surprise.
- Plasma edge alignement with the wall surface (hot spots, electron emmision). Circular machines are the only first step option.
- Edges of the ports in walls (hot spots, electron emmision).





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At present, it is universally accepted with many experimental evidences:

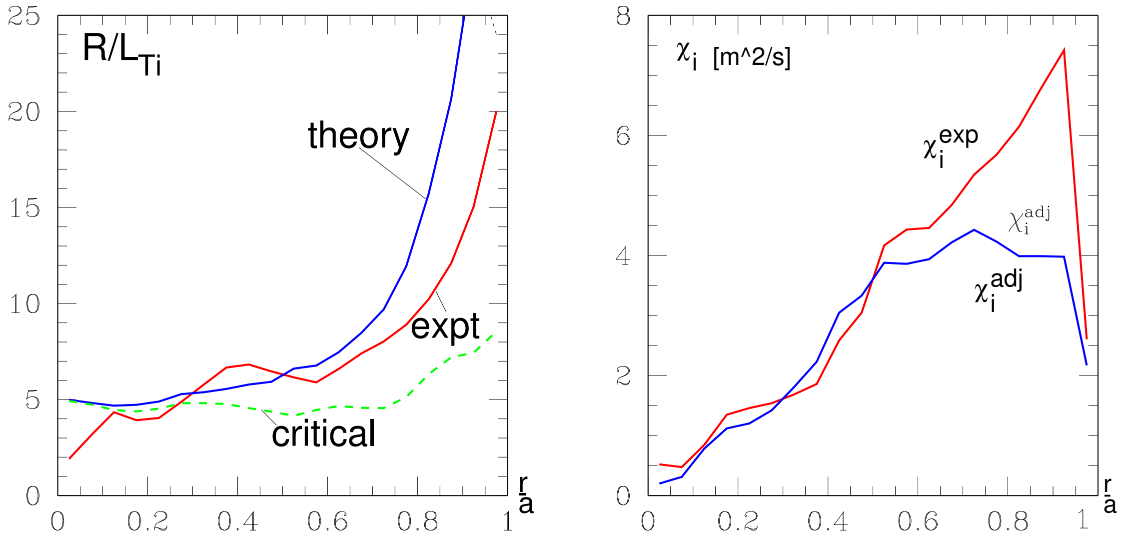
Boundary is the key for the CORE confinement.

(e.g., high edge temperature pedestal results in improved confinement)

Contemporary theory of the turbulent transport (Dorland 1994 et al.)

$$\chi_i \simeq \frac{\rho_i^2 V_{ti}}{R}\left(\frac{R}{L_{Ti}} - \frac{R}{L_{Ti}^{crit}}\right), \qquad \frac{R}{L_{Ti}} \simeq \frac{RT_i'}{T_i}$$

relates the rate of the turbulent transport with the temperature gradient.



left: $\frac{R}{L_T}$ vs r/a

right: χ_i vs r/a

IFS-PPPL model for TFTR thermo-conductivity

Turbulent trasport is highly sensitive to the edge temperature pedestal.

Even without eliminating thermo-conduction completely, Lithium walls may eliminate the turbulent transport.

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Lithium covered walls affect the very fundamentals of tokamak fusion

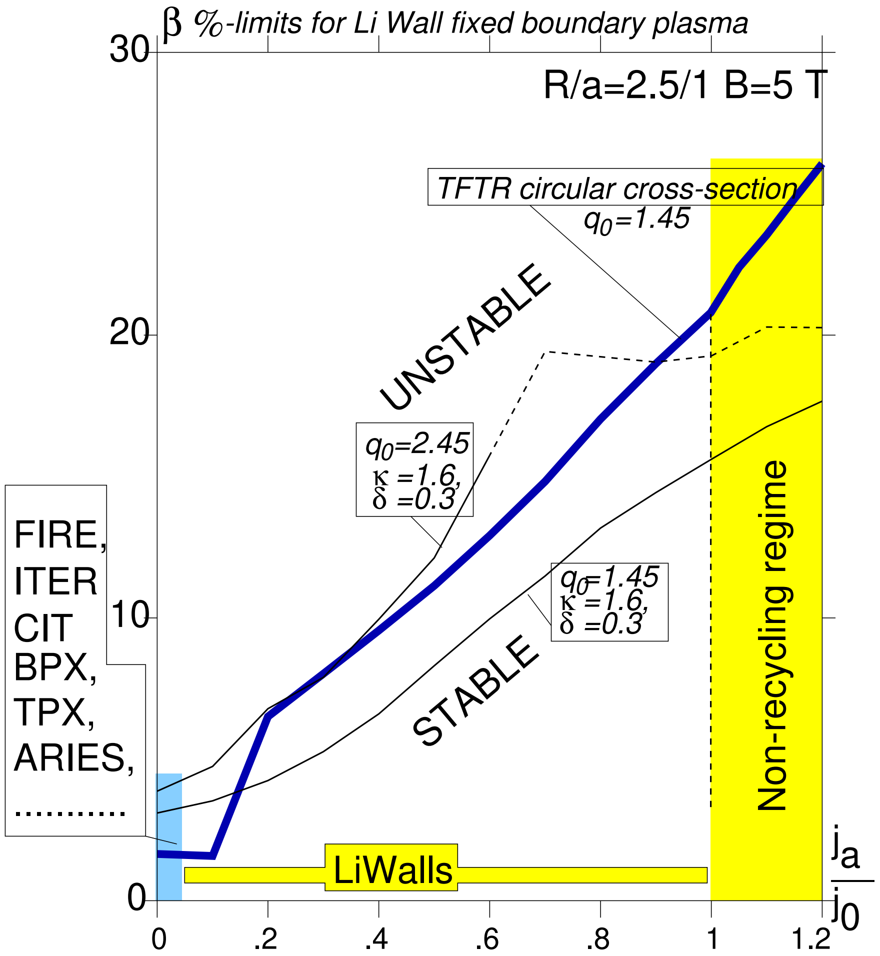
Absorbing walls (solid or liquid)

- High temperature pedestal
  - suppression (DIII-D) (elimination) of thermo-conduction
  - elimination of sawteeth (NTM)
  - Elimination of Troyon limit (second stability regime) -> high beta
- Conducting walls at the plasma boundary
  - With an additional feedback - fixed boundary MHD conditions -> high beta

Intense lithium streams

- Additional stabilization of RWM

Fix boundary plasma + edge temperature pedestal introduce the edge current density pedestal as a parameter into MHD stability.



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

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

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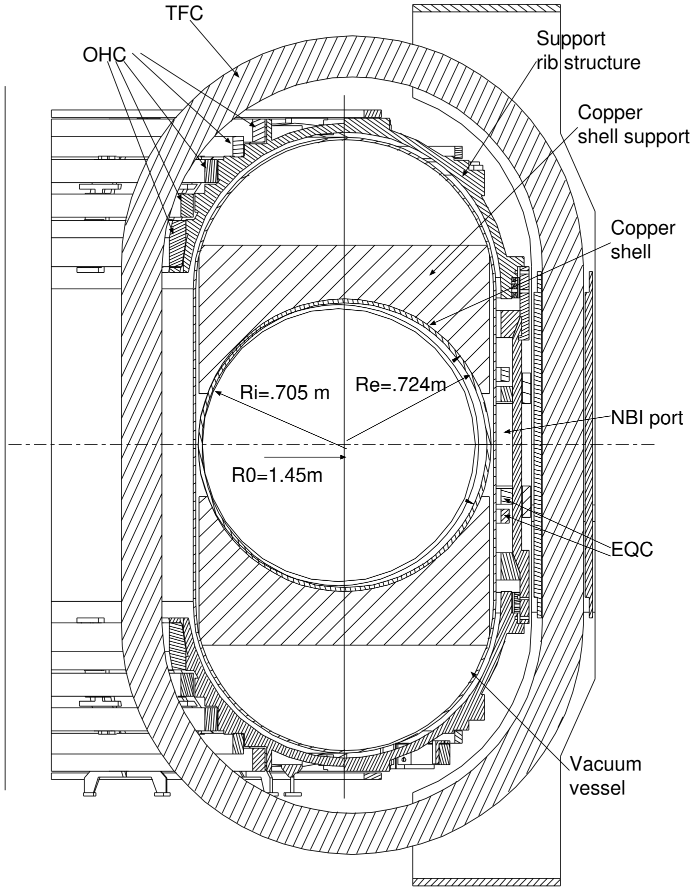
PPPL has everything to desing and conduct lithium (solid) walls experiments



- people who discovered the lithium effect on TFTR;
- authors of the turbulent transport theory;
- PBX facility with
  1. 7 MW x 0.3 sec NB + 0.9 MW 0.1 sec IBW heating
  2. 8/shot Pellet injection
  3. 1.9 T x 1 sec Btor
  4. 0.6 MA x 0.6 sec Iplasma
  5. 4.5 keV Ti achieved, . . .

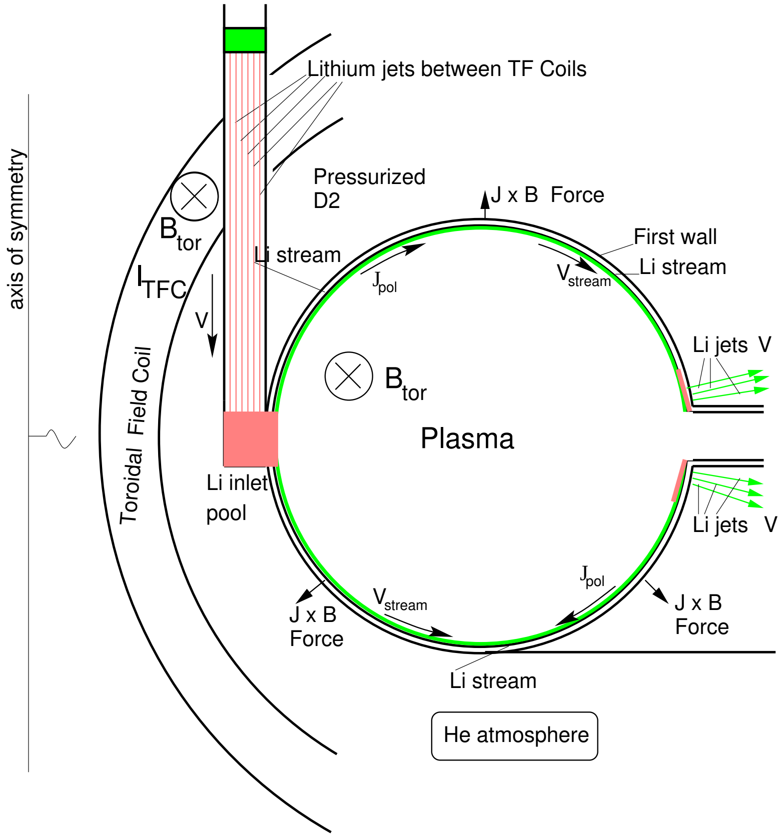
Many Universities and technology groups would be interested in designing and participating in those experiments.

Physics issues to be addressed during the design phase

- Resistive wall mode stabilization (PPPL, Columbia, GA, LANL, . . .)
- Core transport in the low-recycling regime (PPPL, UMD, UT, . . .)
- Lithium influx to the plasma (PPPL, UCSD, LANL, ORNL, UMD, . . .)
- Plasma edge physics (PPPL, UCSD, MIT, GAL, LLNL, ORNL, UMD, . . .)
- Lithium sputtering (U of Illinois, . . .)
- Hydrogen retention in Li (UCSD, U of Illinois, APEX, ALPS, . . .)
- Electron emission (UCSD, ...)
- . . .

2 Intense lithium streams

Magnetic propulsion makes MHD of intense lithium streams compatible with tokamaks $\boxed{p_{\mathbf{j}\times\mathbf{B}}|_{inlet} - p_{\mathbf{j}\times\mathbf{B}}|_{outlet} \gg \Re_2 \frac{B_{tor}^2}{2\mu_0}, \quad \Re_2 \equiv \mu_0\sigma\frac{h^2}{R}V \simeq 0.0015}$



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

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

- Flow parameters

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

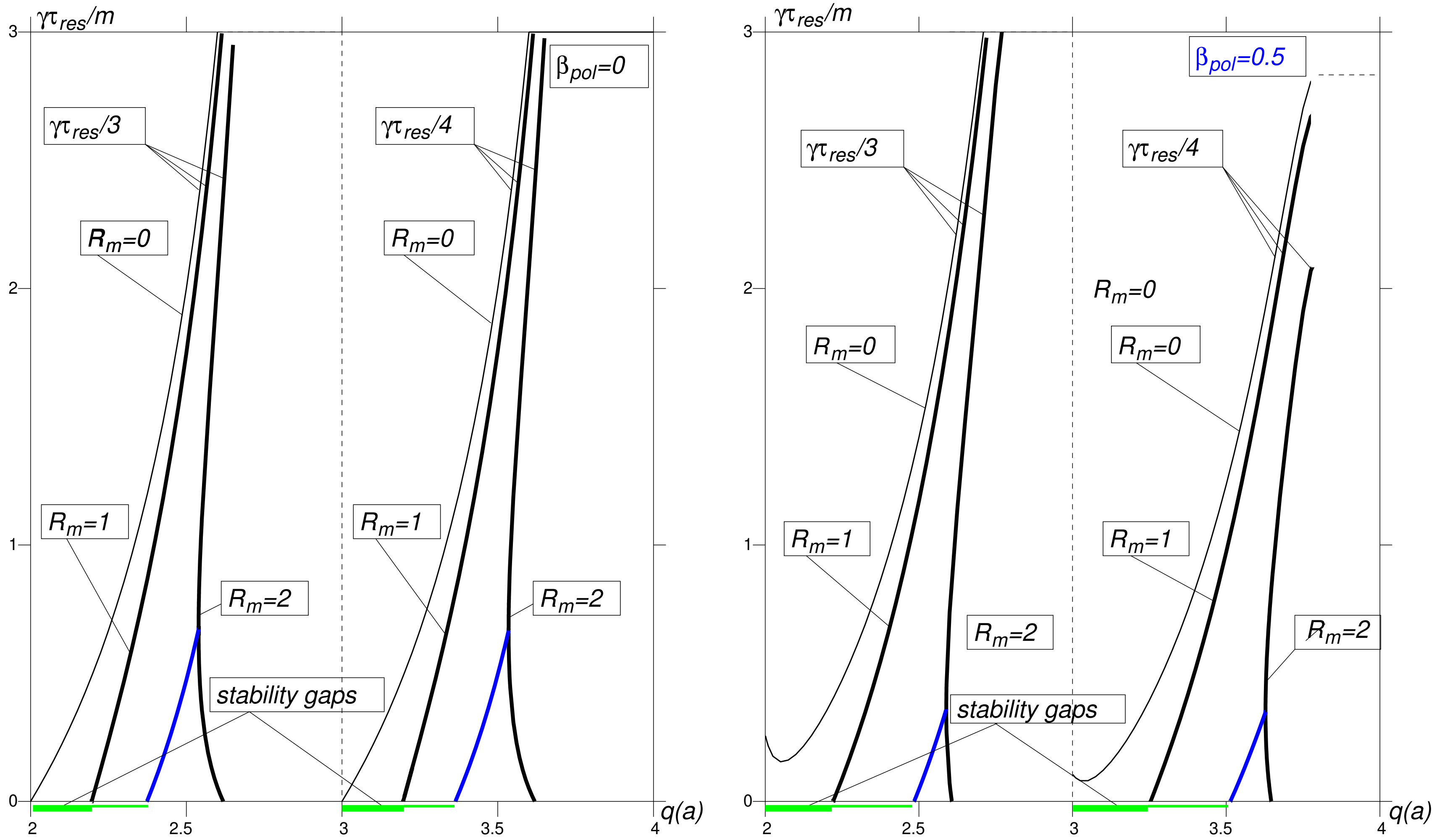
- Magnetic Reynolds numbers

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

- Stream are robustly stable due to centrifugal force

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

Intense stream contribute in plasma stabilization in the whole frequency range



Stability gaps are not sensitive to m-number. Finite β can be stabilized.

Power extraction capability of lithium walls fits well reactor relevant wall loadings, $> 10\ MW/m^2$ in neutrons (distributed over the wall surface)

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

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

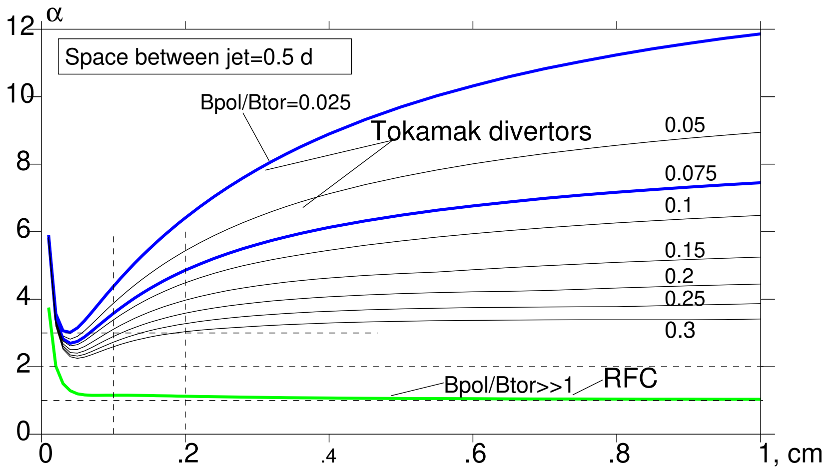
even with no reliance on the vortices in the streams.

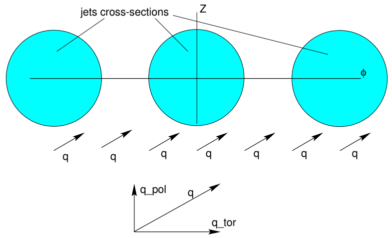
It is at least 1 order of magnitude higher than that of Li or LiSn jets in the divertors

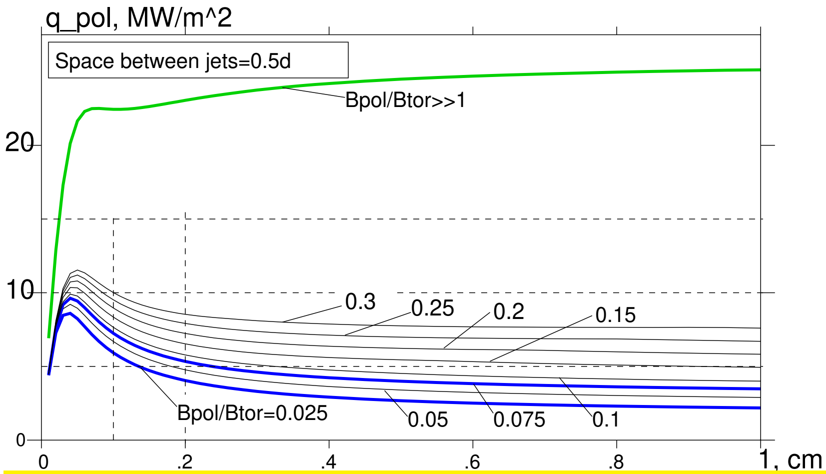
$$\Delta T_{max} = \alpha \left(\frac{d}{d_{skin}}\right) q_{pol}\sqrt{\frac{4t_{transit}}{\pi\kappa\rho c_p}}. \tag{2.1}$$

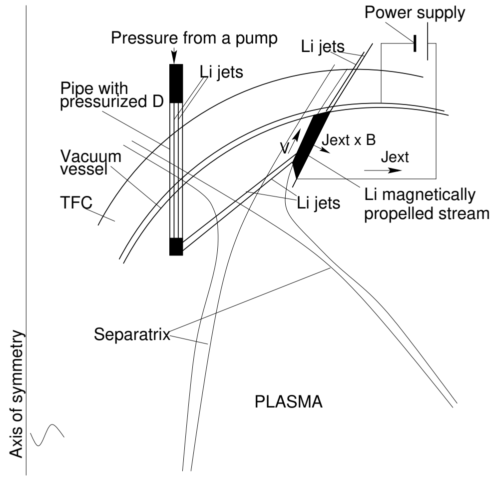
(For gallium ΔT_{max} is not yet determined.)

Power extraction by the jets of Lithium, LiSn, Ga, crossing the X-point region in the tokamak.



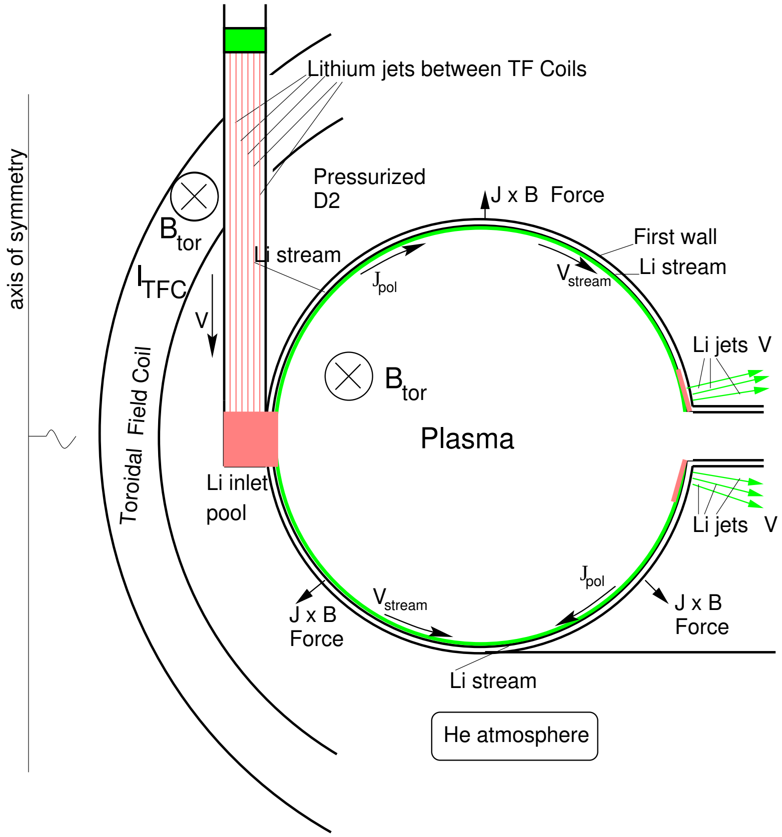






Any concentration of the power deposition is highly unfavorable

Stable force balance in the vacuum chamber walls



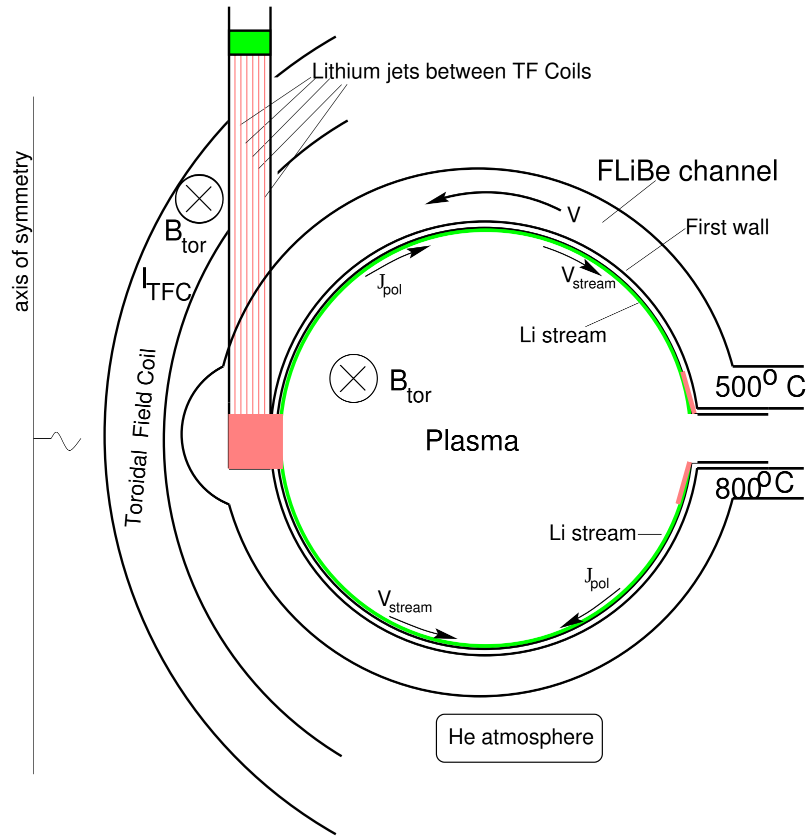
Electro-magnetic force $\mathbf{J}_{pol} \times \mathbf{B}_{tor}$ makes vacuum chamber work against expansion, not compression.

Vacuum chamber wall can be thin like a car tire.

Lithium provides a vacuum sealing.

Outside the first wall is the atmosphere (He).

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

How crazy if would be to think about making the vacuum chamber from the wire mesh

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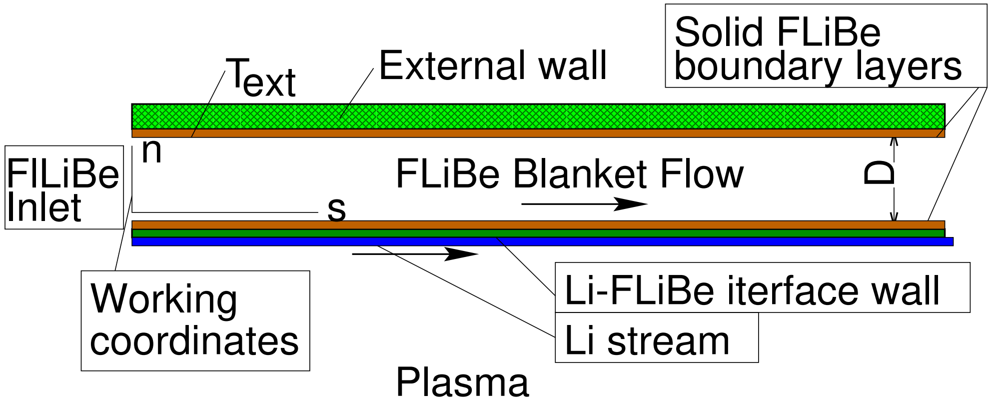
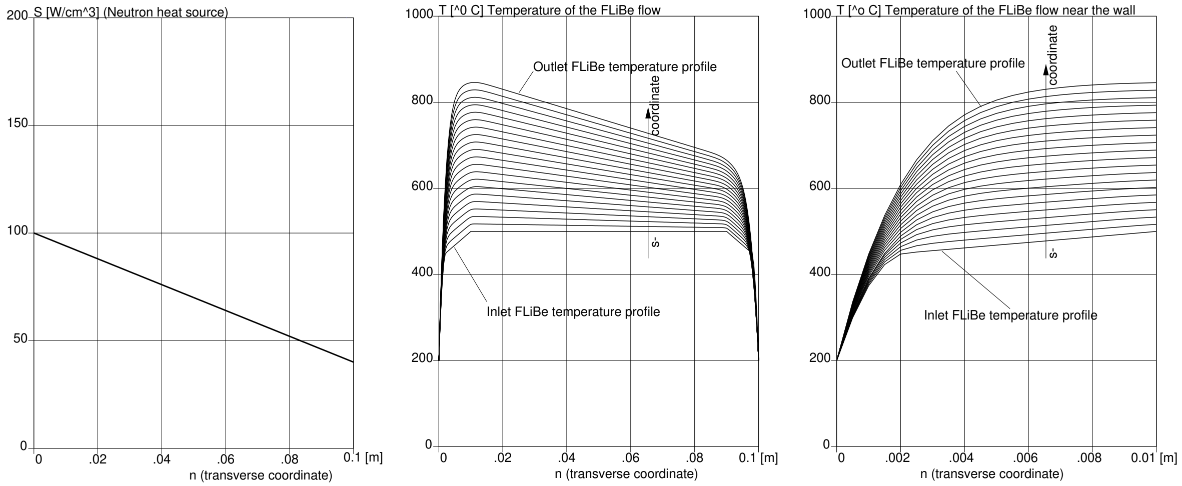
Stratified geometry of the FLiBe Blanket/Lithium streams

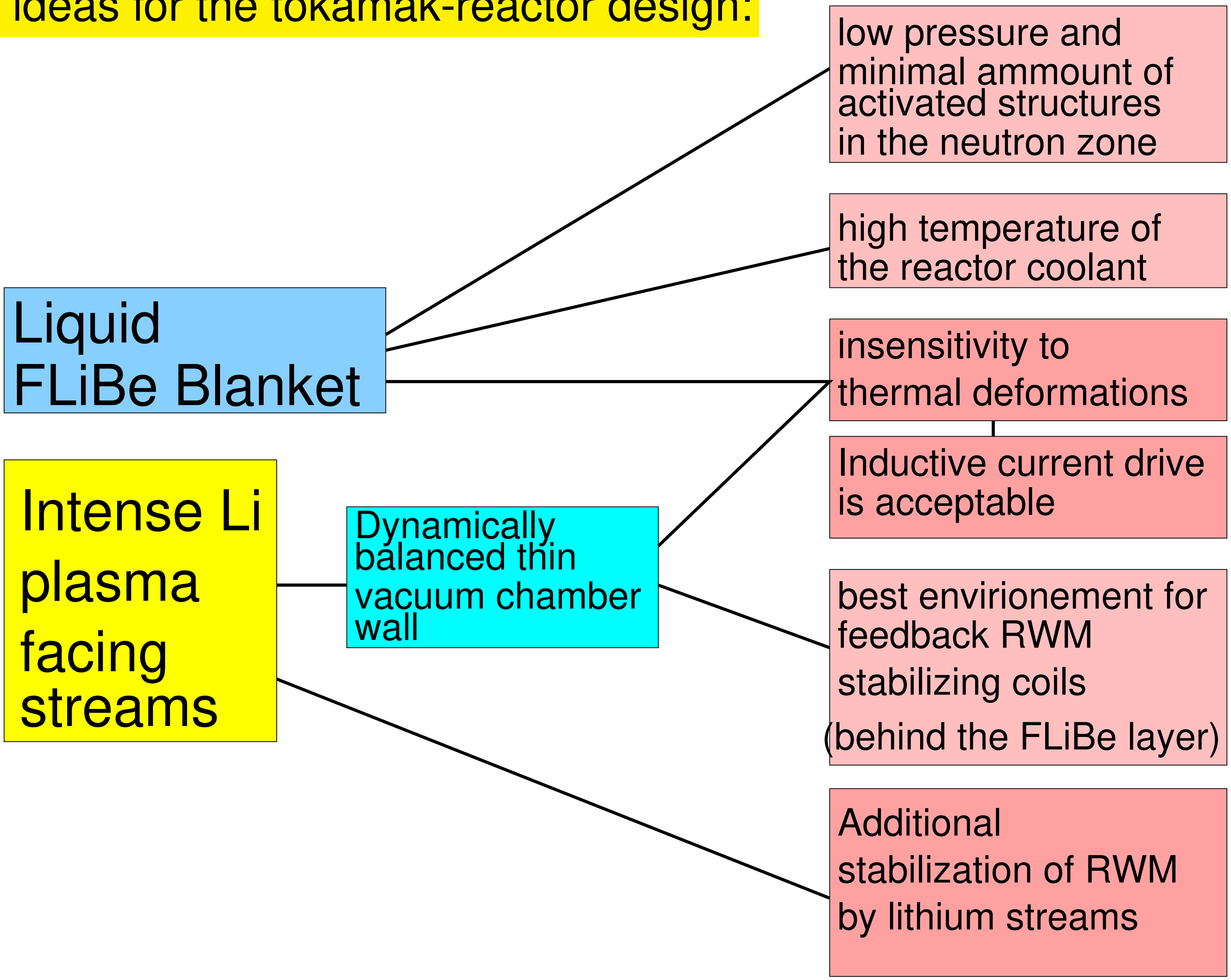


D	m	0.1
L	m	10
V	$\frac{m}{sec}$	0.5
$S(n)$	$\frac{W}{cm^3}$	100-40
$T_{side\ wall}$	C^o	200

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



New ideas for the tokamak-reactor design:



3 Summary

What was presented is just a motivation for the research in this new area of tokamak physics and technology.

Typically, major problems arise at the interface between different areas of physics and technology.

This idea of lithium walls is an attempt to make several fundamental things in fusion, i.e, plasma physics, first wall, neutron zone and activation, compatible with each other at least at the conceptual level. This area is full of unsolved problems where new ideas are possible and the most valuable.

As a practical step for further development, an experiment on a circular machine which would have the lithium coated walls and would be capable to produce

1. $T_i > 1$ keV at the plasma edge;
2. high electron temperature $T_e \simeq T_i$;
3. precise control of the plasma surface alignment with the wall;
4. full control of the wall surface temperature;

is the first priority goal.

Even for this minimal, but reasonable goal an extensive technology and design research should be performed.

Topic for discussion

The mini-conference will discuss the following topics:

1. Experiments on suppressing recycling and on lithium conditioning in tokamaks.
2. Central fueling, particle and energy transport in the core plasma with low recycling edge.
3. MHD stability with lithium walls (fixed plasma boundary conditions, stabilization by intense lithium streams).
4. Edge physics of tokamaks with lithium walls (impurity accumulation, recycling, boundary layers, etc).
5. Wall surface physics (heat, hydrogen retention, evaporation, sputtering, etc).
6. Wall technology (Li pellets, sputtering, wet meshes, liquid walls, propulsion of intense lithium streams, etc).
7. Helium exhaust from configurations with no divertor, retention in lithium and pumping.