Proposal on Lithium Wall Experiment (LWX) on PBX-M[1]

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OUTLINE

1. Mini-conference on Lithium walls and low recycling regime.
2. PBX-M Capabilities.
3. Motivation.
4. Physics background and significance.
5. Critical issues.
6. The goal of the proposal.
7. Multi-institutional involvement.
8. Summary.

1. Mini-conference at APS 2000

"Lithium covered walls and low recycling regimes in tokamaks".

APS meeting, October 23-27, 2000, Quebec, Canada,

Abstract Deadline: July 12, 2000

ORAL, Lithium wall mini-conference.

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The mini-conference will discuss the following topics:

(a) Experiments on suppressing recycling and lithium conditioning in tokamaks.

(b) Central fueling, particle and energy transport in the core plasma with low recycling edge.

(c) MHD stability with lithium walls (fixed plasma boundary conditions, stabilization by intense lithium streams).

(d) Edge physics of tokamaks with lithium walls (impurity accumulation, recycling, boundary layers, etc).

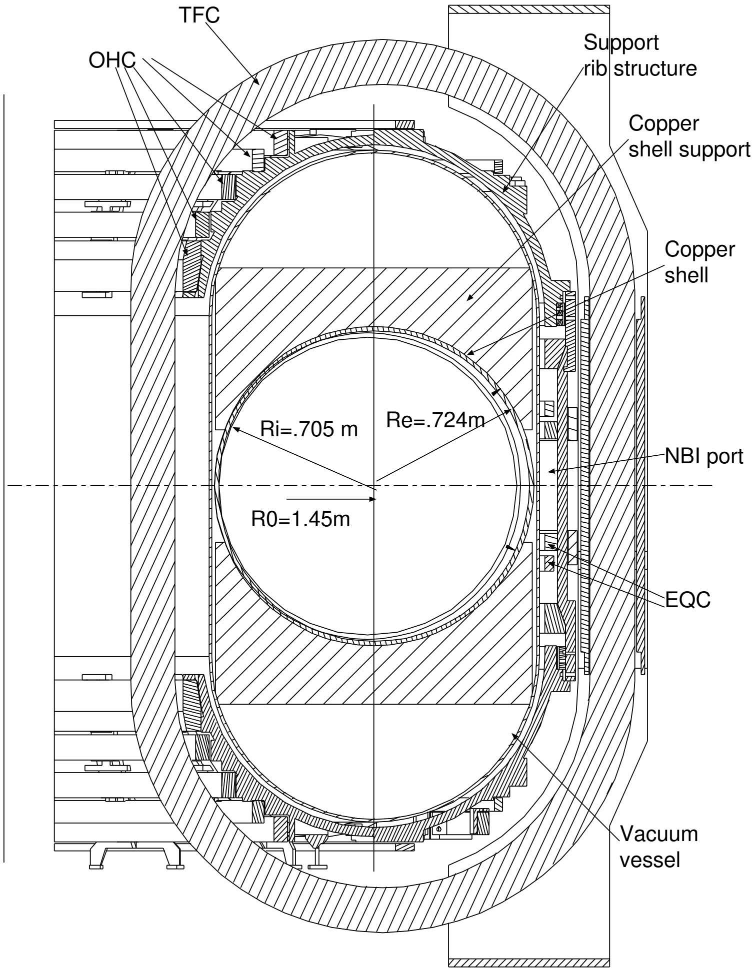
(e) Wall surface physics (heat, hydrogen retention, evaporation, sputtering, etc).

(f) Wall technology (Li pellets, sputtering, wet meshes, liquid walls, propulsion of intense lithium streams, etc).

(g) Helium exhaust from configurations with no divertor, retention in lithium and pumping.

2. PBX-M Capabilities

B_{tor}	1.9 T for 1 sec, 1.5 T for 3 sec
Volt-sec	3 Volt-sec
NBI	7 MW, 0.3 sec
IBW	0.9 MW 0.1 sec
I_{plasma}	0.6 MA at 1.1 T
Flat-top	0.6 sec
Pellet Injector	8 / shot
T_e	1.8 keV
T_i	4.8 keV
n_e	$0.48 \cdot 10^{20}$
β_{tor}	< 6.8 %
$R_{vacuum-vessel}$	1.45m
$2a_{vacuum-vessel}$	1.45m



Modified PBX-M (LWX) facility with the copper shell and its support structure

It is envisioned

- to install inside the PBX vacuum vessel a copper shell of the circular cross-section

and use the existing PBX capabilities, such as

- NBI (< 8 MW)
- pellet injection for central refueling
- diagnostics and plasma control systems
- spacious vacuum vessel

to perform the experimental test of enhanced plasma performance

- with lithium pellet injection,
- lithium covered (by sputtering) walls
- and, possibly, with the wetted meshes of melted lithium surface.

No flowing lithium is projected on the physics stage of this proposal.

Target LWX (modified PBX-M) parameters (to be determined on design phase)

	DIII-D) (NCS)	DIII-D (VH)	PBX-M H-mode	FSX FSX	LWX
R	1.67	1.68	1.65	1.54	1.45
a	0.61	0.62	0.28	0.45	0.5-0.7
κ	2.15	2.0	1.7	1.87	1
δ	0.9	0.86	0.70		0
Vol, m^3	22		4.5		7.1-14
S, m^2					27-40
B, T	2.15	2.1	1.35	1.12	1
I, MA	2.25	1.6	0.34	0.66	0.6
β, %	6.7	2.9	5		10
τ_E, sec	0.400	0.340	0.034	0.070	0.1-0.2
T, keV	18	5.6	4.5		5
T_{edge} keV					2-5
$n,\ 10^{20}$		0.65	0.43	0.4	0.5
$N_{part},\ 10^{20}$					3.5-7
W MJ					1.67
t, sec					1

The intention is to submit in June of 2000 the application to DoE for

funding the design work and supporting research

to modify the PBX machine as the appropriate scale experimental facility for a new, multi-institutional program in fusion science, which will address the scientific and technological issues of tokamaks with the lithium covered walls.

The massive copper shell

- provides the MHD stabilization
- specifies the initial temperature of the lithium surface
- removes efficiently the heat from the plasma facing lithium surface during the discharge.

This allows to control and study the effects

- of lithium evaporation and
- electron emission

on the plasma performance starting from their negligible level until when these effects will be dominant.

With the PBX readiness for an earlier (not realized) proposal for a feedback stabilization experiment (FSX),

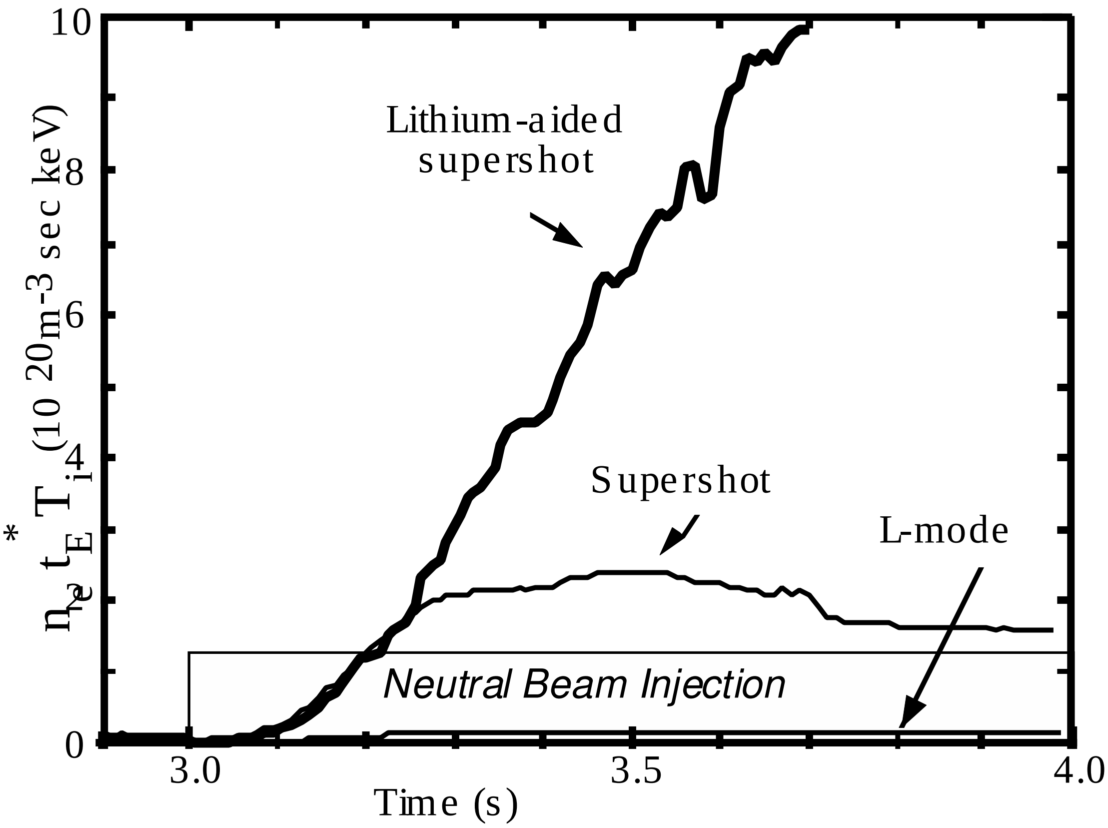
one-two years seems to be sufficient to prepare

a multi-institutional proposal to initiate a new research program on "Magnetic confinement with the lithium covered walls".

Existing or other facilities are considered as other options for the lithium wall program.

3. Motivation

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

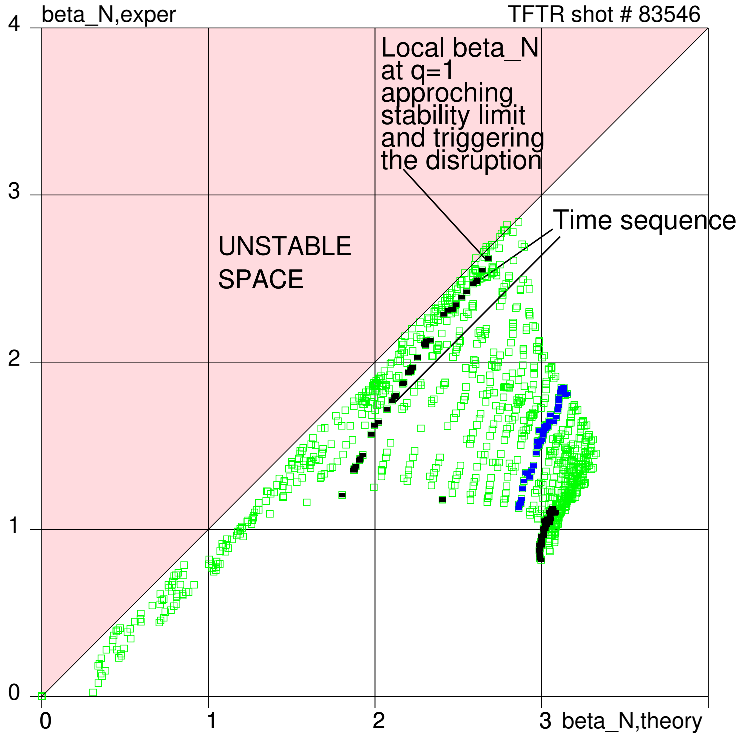


(TFTR # 83546 D.Mansfield, C.Skinner)

Increase in performance with an increase in amount of lithium at the plasma edge has not been saturated.

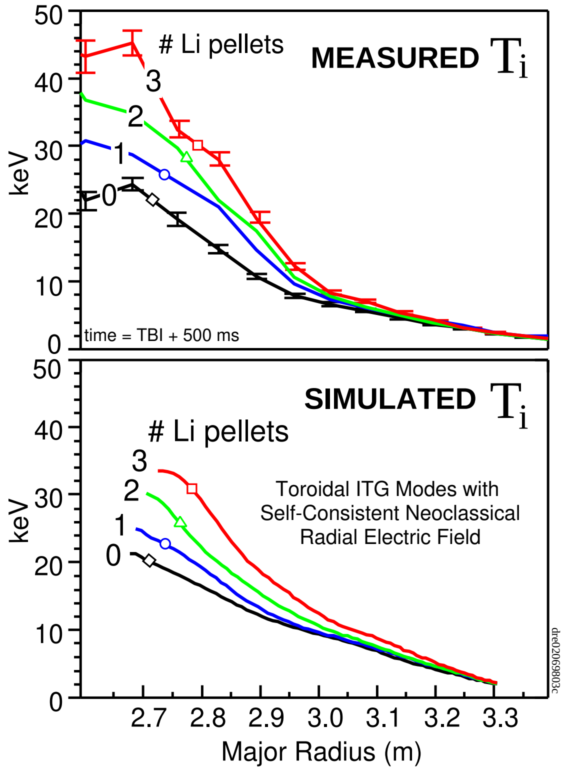
Instead, the performance was limited by disruptions

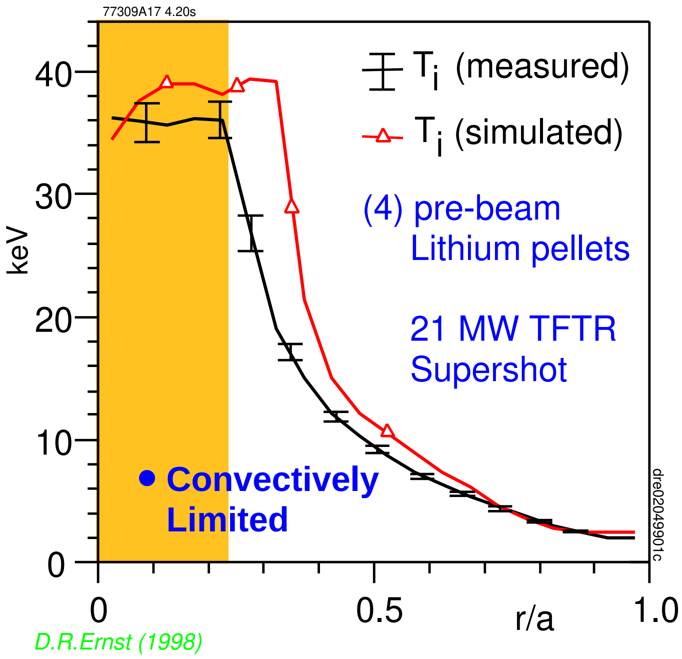
- pretty well understood in TFTR and
- related to some peculiar properties of supershots.



$$\beta_N(r) \equiv \frac{2\mu_0[<p> - p(r)]}{B_{tor}^2} \frac{rB_{tor}}{I_{pl}(r)} \tag{3.1}$$

Li pellets at the plasma edge affected the central ion temperature





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

With 4 pellets the TFTR started to develop a flat themperature profile in the central core.

Second, the interest to lithium came from the technology side, where lithium is one of the options for new power extraction schemes based on liquid walls for fusion reactors.

Motivation for a proposal came from realizing

- potentially revolutionary role of the lithium edge conditioning which may extend far beyond the TFTR results,
- its consistency with new power extraction scheme,
- growing interest in the community to lithium wall tokamak regimes,
- possibility of making a real breakthrough in enhencing confinement and β in tokamaks

4. Physics background and significance

Lithium walls can act as a powerful hydrogen pump situated right at the plasma edge suggesting

(a) necessity in the central refueling.

This property changes the most fundamental aspects of magnetic confinement, resulting in

(a) low recycling condition at the plasma edge
(b) high temperature pedestal at the plasma edge and flattened or (even hollow) temperature profiles
(c) suppression (or effective elimination) of the thermo-conduction energy losses

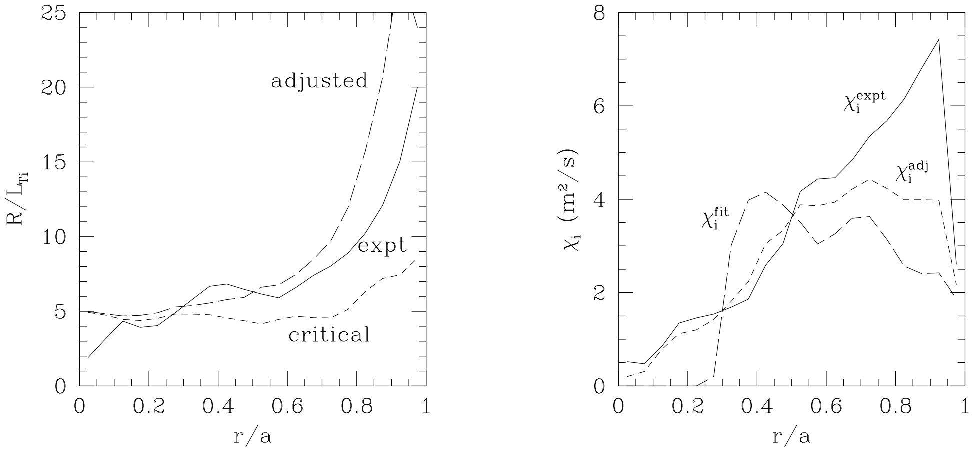
$$\Gamma_{energy} \simeq \frac{5}{3}\Gamma_{particles}T \tag{4.1}$$

(d) flattened plasma current density distribution.

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

$$\chi_i \simeq \frac{\rho_i^2 V_{ti}}{R}\left(\frac{R}{L_{Ti}} - \frac{R}{L_{Ti}^{crit}}\right), \quad \frac{R}{L_{Ti}} \simeq \frac{RT_i'}{T_i} \tag{4.2}$$

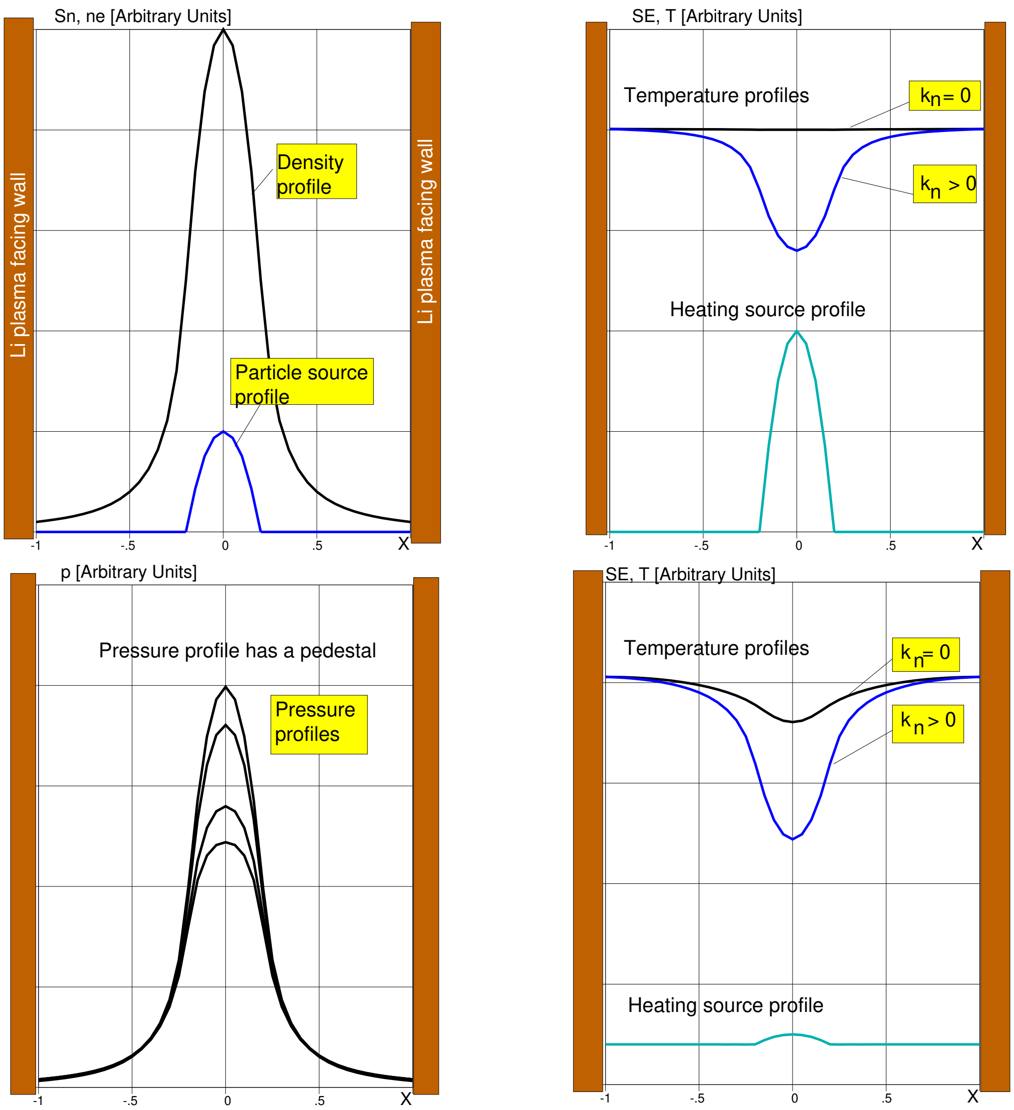
suggests crucial importance of the temperature gradient for the rate of the turbulent transport and sensitivity to the edge temperature pedestal.



IFS-PPPL model for TFTR thermo-conductivity

Absorbing wall would eliminate turbulent transport.

$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P dv \qquad (4.3)$$



density and pressure temperature profiles

in the non-recycling regime

Neutralization of the plasma ions during the first tangential hit of the lithium wall can be the major problem in utilizing pumping properties of the lithium walls.

VFTRIM-3D results on Total Yield = Reflection + D Sputtering (produced by D.Ruzic group) at 1 keV for D on D-saturated solid lithium

- 10 degrees: 0.921
- 30 degrees: 0.335
- 45 degrees: 0.156
- 60 degrees: 0.086
- 80 degrees: 0.047

With high sensitivity to the angle, everything depends on kinetics of plasma particles.

Lithium covered walls may change significantly existing MHD considerations

(a) by eliminating q=1 surface, sawtooth oscilations and the Troyon limit

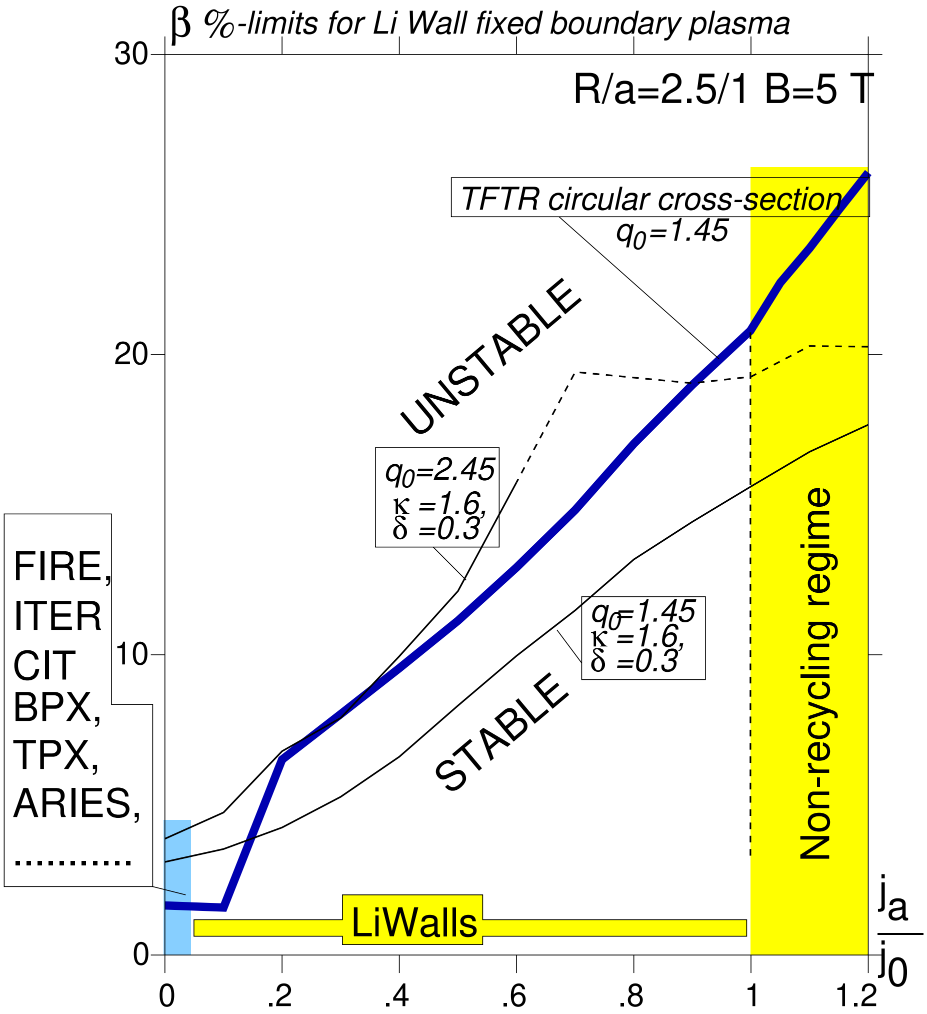
(b) by opening access to the second stability regime

(c) by opening opportunity of using highly conducting wall at the plasma boundary for controlling stability

(d) by giving assess to the high-$\beta > 10\%$ in tokamaks
- with the simple (e.g., circular) shape of the plasma cross-section and equilibrium control
- with conventional ($R/a = 2 - 5$) aspect ratios and inductive current drive

(e) by making realistic profile control inside the plasma

New regimes with high temperature, low recycling at the plasma edge and wall stabilization



may open a new dimension of opportunities for tokamaks.

Preliminary studies suggest that there is little marginal in physics which would question the possibility of the new regimes.

- Sputtering of lithium is completely acceptable
- Evaporation of lithium can be easily controlled by the temperature of the lithium surface
- Electron emission is less significant than the effect of evaporation
- With central refueling, penetration of the lithium into the core can be made not essential

The goal of the design work is to implement the new regime in a real device.

5. Critical issues

The wall temperature is determined solely by the energy flux

$$\Delta T_{LiWall} = 200^o \frac{\Gamma_{energy}}{3.5\ MW/m^2}\sqrt{\frac{t_{exposure}}{0.25 sec}\cdot\frac{\kappa_{lithium}}{\kappa_{wall}}} \tag{5.1}$$

For LWX

$$\begin{aligned} &\Gamma_{energy} = \frac{6-9\ MW}{30-40\ m^2} = 0.2 - 0.45\ \frac{MW}{m^2}, \\ &\kappa_{copper} \simeq 10\kappa_{lithium} \end{aligned} \tag{5.2}$$

the copper shell would provides a reliable control of the wall temperature.

Circular cross-section simplifies the power deposition control.

The most crucial condition is ability of the lithium walls to absorb hydrogen particles.

Essential conditions for the high edge plasma temperature pedestal are

- small ionization losses and high plasma temperature at the edge

$$T_{i,e} >> E_H(\simeq 30\ eV),\ E_{Li}(\simeq 100\ eV) \tag{5.3}$$

  (E_H, E_{Li} - ionization costs for the H and Li atoms),
- small Li wall sputtering

$$\Gamma_{Li} = Y_{Li}\Gamma_{Li} + Y_H\Gamma_H \tag{5.4}$$

  (Y_{Li} - self-sputtering yield, Y_H sputtering by H). It is crutial that with lithium wall aligned with the plasma surface only neutral atoms really counts.
- small rate of Li evaporation (independent on the plasma flux to the wall)

$$\Gamma_{Li} \simeq 3 \cdot 10^{18} \cdot 10^{\frac{(T-300)^oC}{50}} \frac{1}{m^2 sec} \ll \frac{1}{1-Y_{Li}}\Gamma_H. \tag{5.5}$$

In PBX-M

$$\Gamma_H > 5 \cdot 10^{19} \tag{5.6}$$

with wall temperature controlled by the copper shell.

TFTR routinely had the plasma egde temperature of $1-2$ keV in the stationary conditions.

Most crucial issues to be determined during the design phase

- Copper shell design, assess to interior, sectioning (PPPL, . . .)
- Copper shell stabilization requirements for both LWX and other machines (PPPL, Columbia, GA, . . .)
- Lithium-copper interface (APEX, ALPS, Sandia, . . .)
- Lithium surface maintanence (PPPL, APEX, ALPS, Sandia, . . .)
- Requirements for the plasma surface alignment (LLNL, UCSD, UCLA, ORNL, . . .)
- Lithium handling in tokamak environment (PPPL, GA, . . .)
- Diagnostics for the lithium layer monitoring (PPPL, . . .)
- . . .

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, ...)
- . . .

Except to the specifically lithium related issues, the conversion of PBX-M into LWX does not represent significant chellenges.

6. The goal of the proposal

At present there is a growing recognition (consistent with the basic theory) that the edge conditions play a key role in confinement.

The long term scientific goal of the proposal is to

- affect, suppress (or, probably, eliminate) the core turbulent thermoconduction as the dominant mechanism of the energy losses from the plasma.
- achieve high $\beta \simeq 10\%$ in the wall-stabilized plasma
- check and calibrate the plasma core confinement theory by using edge temperature pedestal as the most significant experimental parameter
- develop and calibrate the edge plasma model for the lithium wall at the edge

This objectives will prepare the physics background and justification for developing the techology of intense lithium streams for the tokamaks for future steady state operation.

The short term (the current stage) of the proposal is to preform a consistent technology and physics research (including experiments on existing tokamaks)

- for designing the LWX facility as well as
- for consideration of capabilities of existing machines

to make a decision on experimental facility for the lithium wall program.

7. Multi-institutional involvement

The proposed program is intrinsically multi-institutional with no dominant party.

It is evident that the role of different groups of experts (MHD stabilization, confinement, heating and refueling, plasma edge interaction, technology of the lithium walls and their maintanence, etc) is absolutely crucial for the success.

At the personal level, this initiative gives the opportunities to everybody to be a leader at any level and in any aspect in the lithium wall program and, thus, encourage the active participation.

Also, other options (other than PBX) can be considered and compared.

8. Summary

There is a strong motivation in initiating a new, lithium wall program in magnetic fusion.

This program has a chance to significantly advance the plasma science and magnetic fusion by relying on a new physics and technology.

Existing PBX-M represents practically perfect facility for both short and long term lithium covered wall studies.

Now, it is a good time for a new initiative which challenges the most fundamental issues of magnetic fusion and can unify physics and technology community by involvement into these chellenges.