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Scalable Flowing Liquid Lithium System (FLiLi) for tokamaks[1]

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In memory of a great man, John Timberlake

Theory Seminar

Nov. 03, 2011, PPPL, Princeton NJ

[1] This work is supported by US DoE contract No. DE-AC02-09-CH11466.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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- **How to implement the Flowing Liquid Lithium (FLiLi) ?**
- **Why do we need Liquid Lithium (LiLi) ?**

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Liquid Lithium (LiLi) data

Reference (LiLi) parameters

1.	*	A	6.941	Atomic mass	
2.	*	ρ	0.495 $\frac{g}{cm}$	Density	half water density
3.	*	T_m	180.54 ^oC	Melting temperature	
4.	*	T_b	1347 ^oC	Boiling temperature	
5.	*	Q_{melt}	0.432 $\frac{kJ}{g}$	Heat of fusion	larger than water
6.	***	Q_{vapor}	20.9 $\frac{kJ}{g}$	Heat of vaporization	
7.	*	c_p	4253 $\frac{J}{kg\cdot K}$	Thermal capacity	like water
8.	**	κ_T	47.6 $\frac{MW}{m^2}$	Thermal conductivity at 600^o K	$\frac{MW}{m^2}$ at $T' = \frac{210^o}{mm}$
9.	**	σ	3.4·10^6 $\frac{1}{\Omega\cdot m}$	Electric conductivity at 600^o K	1/17.5 of copper
10.	**	ν	0.42·10^{-3} $Pa \cdot s$	Viscosity ν at 600^o K	like water
11.	*	σ_T	0.339 $\frac{N}{m}$	Surface tension at 600^o K	

[*] “Handbook of Physical Quantities”, Ed. by Igor S.Grigoriev and Evgenii Z. Melnikov, Russian Research Center “Kurchatov Institute”, Moscow, Russia. CRC press, Boca Raton, New York, London, Tokio (ISBN 0-8493-2861-6)

[**] "Handbook of Thermodynamic and Transport Properties of Alkali Metals", Editor Roland W. Ohse, Blackwell Scientific Publications, Oxford, London, Edinburgh, Boston, Palo Alto, Melbourne (ISBN 0-632-01447-4).

[***] Internet

FLiLi system requirements

The typical particle flux to the wall in tokamaks can be assessed as

$$\frac{dN}{dt} = \frac{10^{22}}{s}. \qquad (0.1)$$

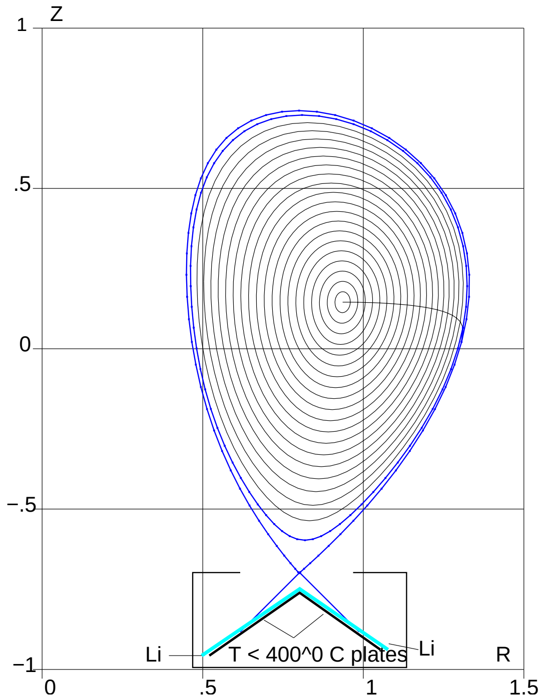
In the LiWF regime this number is expected to be 30-50 times smaller.

LiLi absorbing capacity as 10 % (atomic) would determine the system parameters

$\frac{dLiLi}{dt}$	$> 2 \cdot 10^{-3}$	$\frac{L}{s}$	*rate of replenishment*
h_{LiLi}	$\simeq 0.1$	*mm*	*thickness of the LiLi*
V_{LiLi}	$\simeq 0.2$	$\frac{cm}{s}$	*flow velocity, gravity driven* $V_{cm/s} = 4.8\frac{h^2}{0.1^2}\sin\theta$
	No MHD drag force, no complications		
$\Re_0$	$\simeq 2 \cdot 10^{-3} \ll 1$		$\Re_0 \equiv \mu_0\sigma L V_{LiLi} = 4LV_{LiLi}$ - *Magnetic Reynolds number for* $B_\perp^2/2\mu_0$
$\Re_1$	$\simeq 10^{-6} \ll 1$		$\Re_1 \equiv \mu_0\sigma h V_{LiLi} = 4hV_{LiLi}$ - *Magnetic Reynolds number for* $\tilde{B}$
$\Re_2$	$\simeq 10^{-10} \ll 1$		$\Re_2 \equiv \mu_0\sigma\frac{h^2}{R}V_{LiLi} = 4\frac{h^2}{R}V_{LiLi}$ - *Magnetic Reynolds number for* $\nabla B_{tor}^2/2\mu_0$

Reduced by good confinement, heat flux should be absorbed by the heat sink with no great challenge.

Thin LiLi layer on the top of a heat sink



Thin LiLi layer at the surface of actively cooled target plates

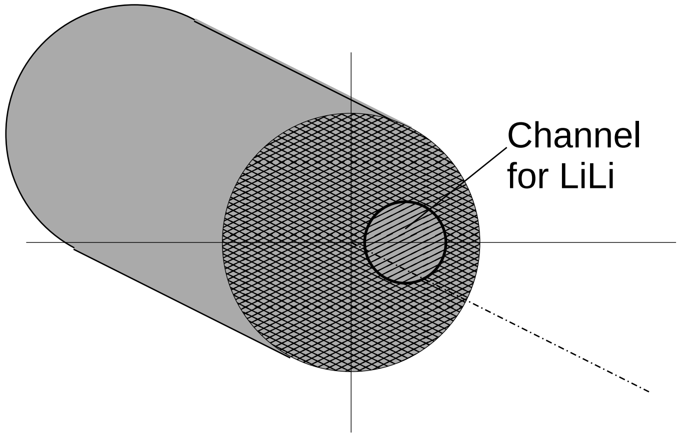
The surface $T_{LiLi} < 400^o$ C with LiLi $h \simeq 0.1$ mm does not limit heat extraction from the plasma.

In fact, it opens opportunities to use Copper (with an interface SS, Be, or Mo layer) for high flux extraction either by

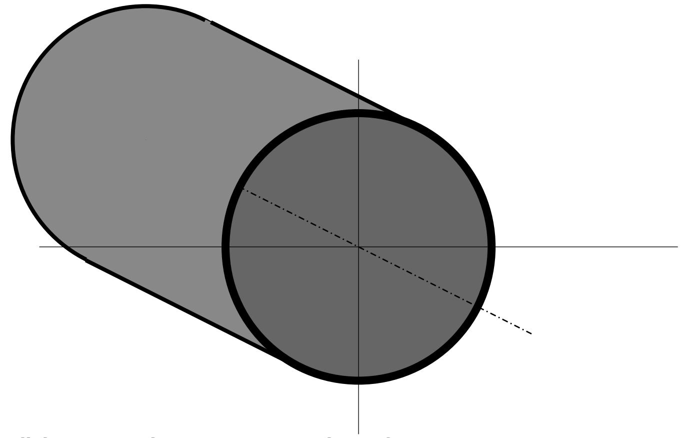
- *by water or*
- *by He (at the record rate of 20 MW/m^2)*

The issue is how to design a reliable system, which would be compatible with the tokamak divertor environment and plasma unknowns.

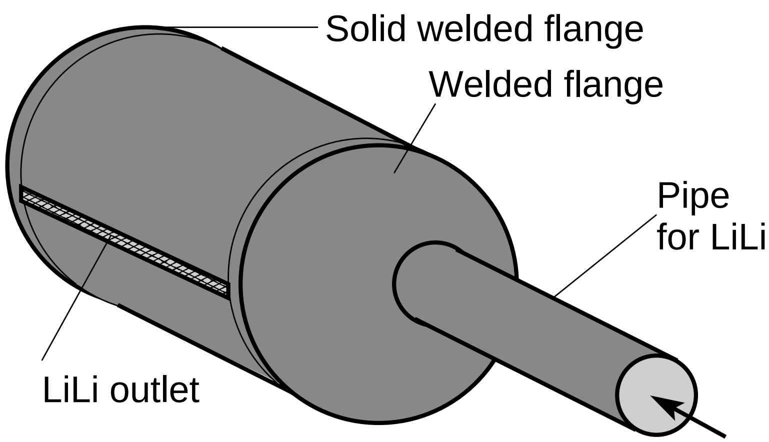
Sintered SS filter based FLiLi system



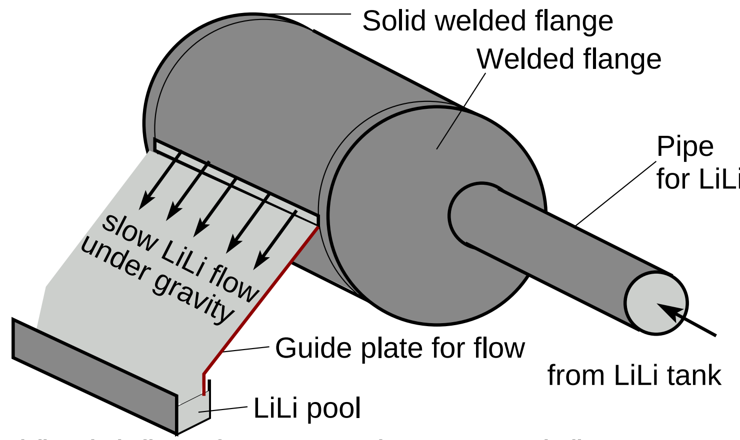
(a) A cylinder from Sintered (porous) Stainless Steel (SSS)



(b) SS tube as a casing for SSS



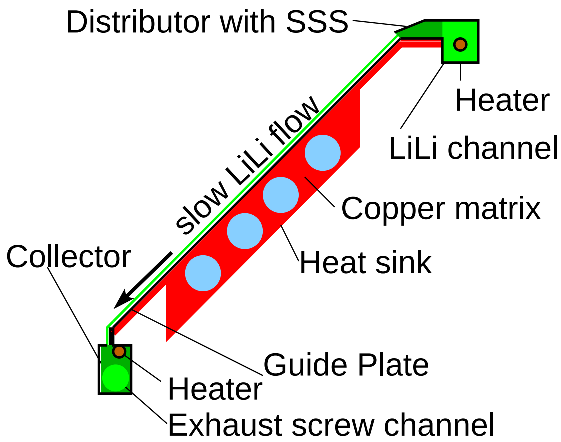
(c) SS tube as a casing for LiLi supply to the SoL target surface



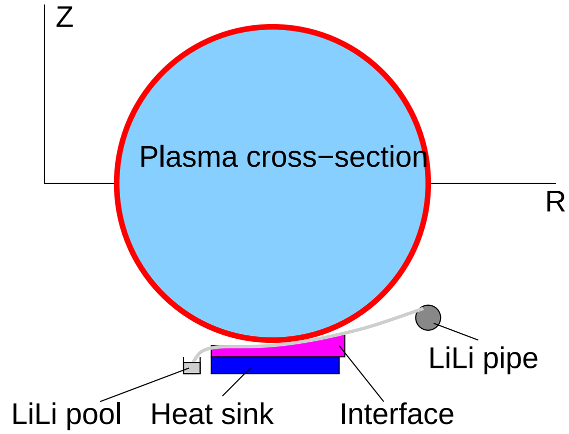
(d) LiLi flow from a tank to a pool (heaters not shown) (workbench prototype)

Heaters should be engineered, everything else is straightforward.

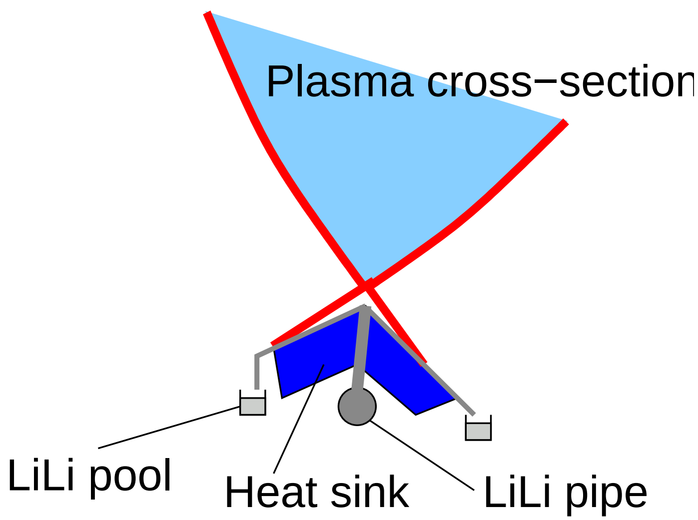
FLiLi R&D path



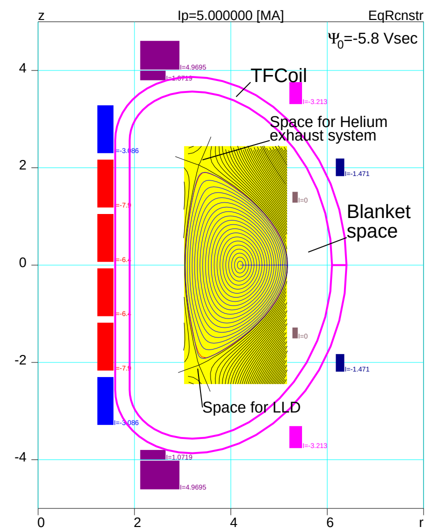
(a) Cross-section of the system



(b) Toroidally extended SSS-FLiLi on HT-7



(c) FLiLi for EAST



(d) From EAST to 100 MW FFRF

SSS-based FLiLi is practical in all aspects

For magnetic fusion the thin layer FLiLi addresses all basic requirements:

- *Opens a way to the best possible (diffusion based) confinement regime;*
- *Improves macroscopic plasma stability (in both core and at the edge);*
- *Provides stationary plasma-wall conditions;*
- *Is insensitive to electro-magnetic forces;*
- *Improves overall plasma control;*

*Unlike 5-fusion, **the heat extraction from the plasma is not an issue** in the resulting LiWall Fusion regime.*

The SSS-based FLiLi has a clean step-by-step R&D path:

- *Technologically simple (compact, no leading edges in flow, flushable, etc).*
- *can be developed starting with a small-size prototype (5-10 cm in linear dimensions);*
- *is scalable in size in both toroidal and poloidal direction;*
- *is scalable from a workbench to HT-7, and from HT-7 to EAST;*
- ***requires minimal flow rate and in-vessel inventory of LiLi;***

HT-7 has unique pioneering mission in developing FLiLi system for fusion

One of the reasons why fusion needs LiLi

4 Summary

Disruptions are too complicated to be completely understood

Still significant progress was made:

- ***Two new key players (WTKM and Hiro currents) were identified.***
- ***The situation with our (lack of) understanding of disruption became much more clear.***
- ***New realistic objectives for theory development are identified as***
  1. ***transition to adaptive MHD 3-D simulations;***
  2. ***realistic simulations of in-vessel components (ITER case corresponds to exa-scale HPC)***
  3. ***creation of a model for the plasma edge in disruptions***
  4. ***creation of a reasonable model of the plasma-wall interactions in disruptions***
  5. ***modeling generation and loss of energetic particles (including RE).***
  6. ***motivation of dedicated to disruptions measurements in experiments***

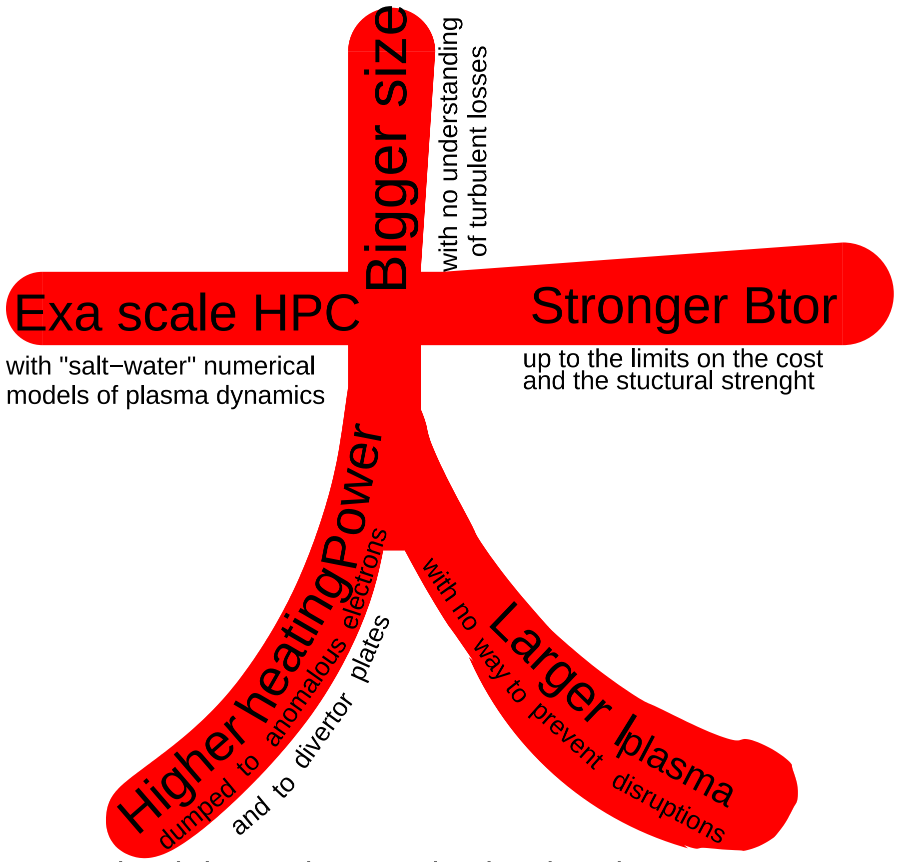
Only cooperation of three equal partners: theory, simulations, and experiment (no one perfect) can address the problem in an acceptable way.

The real approach for solving the disruption problem is in development and implementation of the LiWall Fusion regime, the best possible in confinement and stability (no sawteeth, ELMs, density limit), with NBI controlled plasma, and stationary plasma-wall interactions.

We are moving in this direction in China.

But this is another story

Reliance on 5 “Bigs” of present 大-fusion is exhausted



Every “Big” creates additional plasma physics and technology problems.

The approach has been essentially exhausted at the level of TFTR and JET.

Can we still go forward ?
What kind of reserves are still not utilized ?

+ Massive (Big # 6 !) Gas Injection (MGI)
+ Big promises of fusion power to the grid in 2035, presumably from the ocean water (according to NY Times)

++ The cost of 大 is not simply Big. It is **astronomical**.

Chinese character “Big” 大 has no enough legs for all “Bigs” of magnetic fusion:

Potential applications of FLiLi

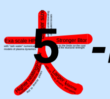
Sintered metal based FLiLi is applicable for

- ***IFE chamber (C. Gentile)***
- ***FRC***
- ***mirror machines***
- ***stellarators***
- ***even tokamaks with disruptions, and***
- ***everything which needs pumping of hydrogen isotope atoms or ions in vacuum***

Invention of a FLiLi represents the final step in the LiWall Fusion concept, completing its plasma physics part.

1 Summary

Of course, FLiLi is not as sexy as "fusion" from the ocean water or Boozer's concept of "confinement by a single magnetic surface" (presented to public as a "quasi-symmetric" stellarator), which 10 years ago overexcited Ray Orbach (Director of the DoE Office of Science), caused devastation of fusion research in PPPL, and still continues damaging the US fusion program.

We expect from FLiLi only a modest thing, i.e., to open the door from the present  ***-madness to the science based fusion R & development.***