

- **The Use of Liquid Ga and Li as Limiter Material in T-3M and T-11M Tokamaks**
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Main aims of liquid metals use in tokamaks

Melting, cracking, blistering, abnormal ion sputtering and low-cycles fatigue of solid PFC may occur in tokamak-reactor conditions.

It is believed, that tokamak solid PFC problem may be overcome when a liquid metal (LM) will be used as a permanent contact surfaces with plasma.

The idea to use LM as PFC material in tokamak attracted attention for a long time. In particular, a liquid Li films flowing on the divertor plate were proposed for one of the first project of tokamak-reactor UWMAK-1

Choose of metals

Two metals with low vapor pressure are most popular:

Li with $T_M=180^{\circ}\text{C}$ and boiling temperature $T_B=1358^{\circ}\text{C}$ (nuclei charge $Z=3$) and Ga with $T_M=32^{\circ}\text{C}$ and $T_B=2400^{\circ}\text{C}$. (Despite high $Z=31$)

However the simple evaporation is not a unique channel of liquid metal erosion and impurity flux to plasma. In principal we need take to account several known mechanisms:

- sputtering by all kinds of bombardment ions in plasma periphery and most dangerous-selfsputtering, if its coefficient surpasses 1-2,*
- liquid metal splashing as result of MHD-effects,*
- unipolar arcs,*
- local emission bursts (like carbon blooms),*
- development of micro-capillary waves at the boundary plasma-liquid metal,*

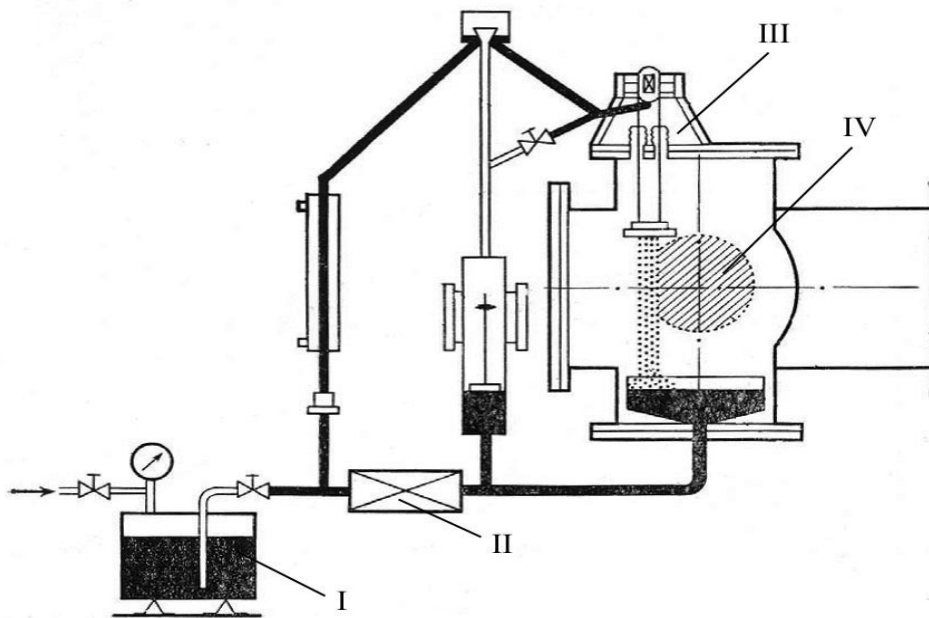
The special experimental program has been initiated in our country to reveal the advantages or disadvantages of LM plasma facing components in tokamaks.

1. Research work on flowing free lithium films was performed in Kurchatov Institute.

2. In parallel, the gallium-based liquid metal limiters have been designed and tested in T-3M tokamak (1989-92, NPO “Energy”. Unfortunately the first result of LM film limiter studies was an inference that from the alteration of tokamak magnetic fields it was practically impossible to make steady state homogeneously flowing LM- film.

3. A LM jet-drop curtain (E.V. Muraviev) appeared to be a more advanced option as eliminating the influence of ponder motive forces induced in liquid metal flowing in magnetic field. These experiments were successful.

Ga – droplet limiter experiment in tokamak T-3M

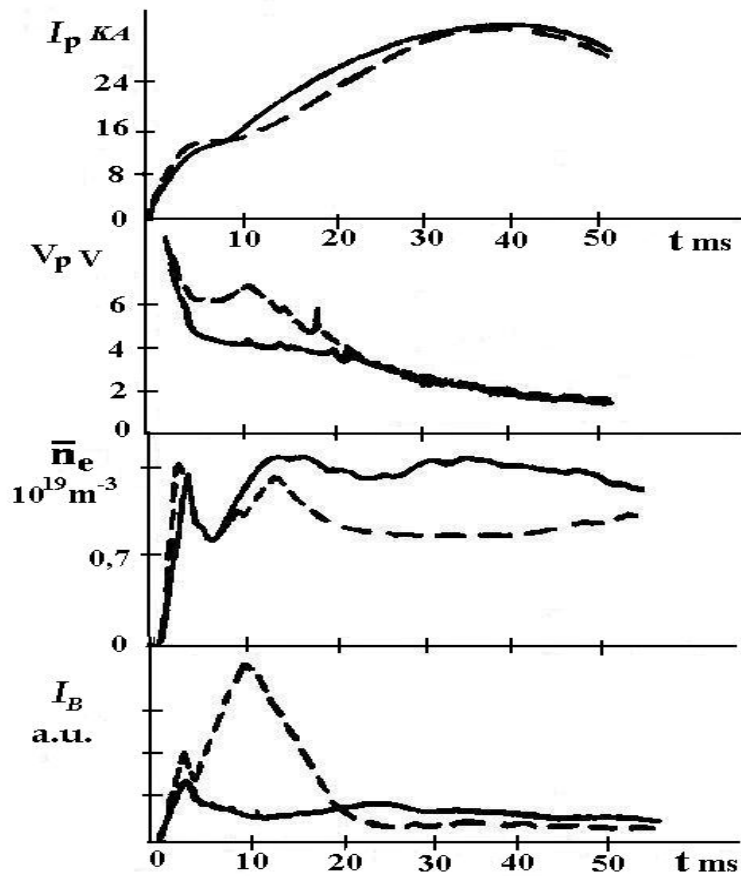


$B=1T, f=600Hz, V_{Ga}=1.8 \text{ m/s}$

I-Ga-reservoir, II-MHD-pump, III –MHD-shaper

The droplet stream in test stand

*The comparison of two discharges: with graphite
and Ga droplet limiters*



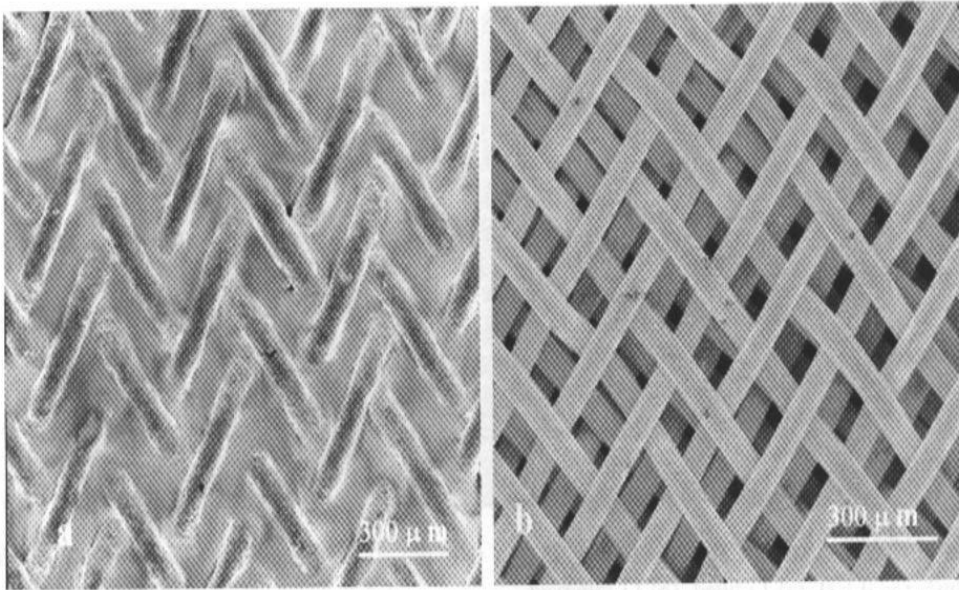
C-solid line, Ga-dotted line

- *The main results of T-3M experiments with liquid Ga are:*

- The droplet stream can be useful as method of LM injection in tokamak and Ga limiter can work as graphite limiter or better.

But film limiter experiments were unsuccessful

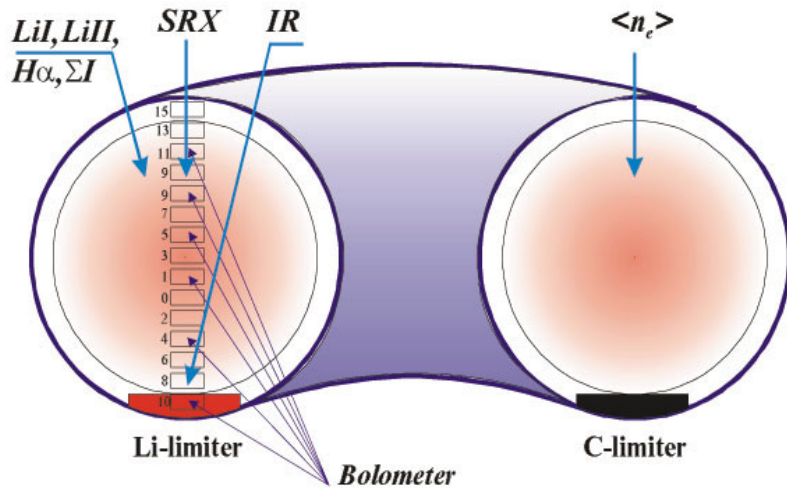
Capillary pore structure (CPS)



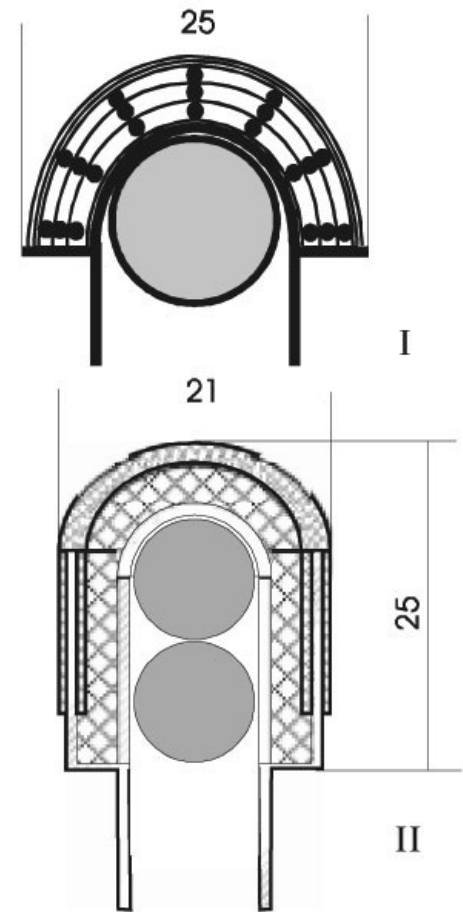
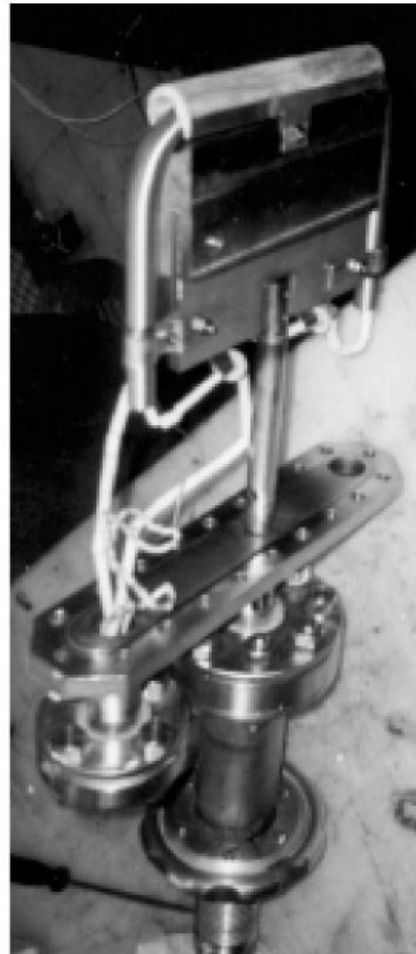
Mo-mesh with lithium filling and
without it

- *The idea to use LM in tokamaks as PFC was advanced basing on the surface tension forces in capillary channels that may also be used to compensate ponder- motive forces. These capillary channels (10-200mkm) may be realized in the form of so called capillary-pore systems (CPS) (V.A.Evtikhin etal.). Self-regeneration of liquid metal surface, contacted with plasma is an intrinsic property of such structures.*

Li-CPS limiter experiment in T-11M (TRINITI- "Red Star")

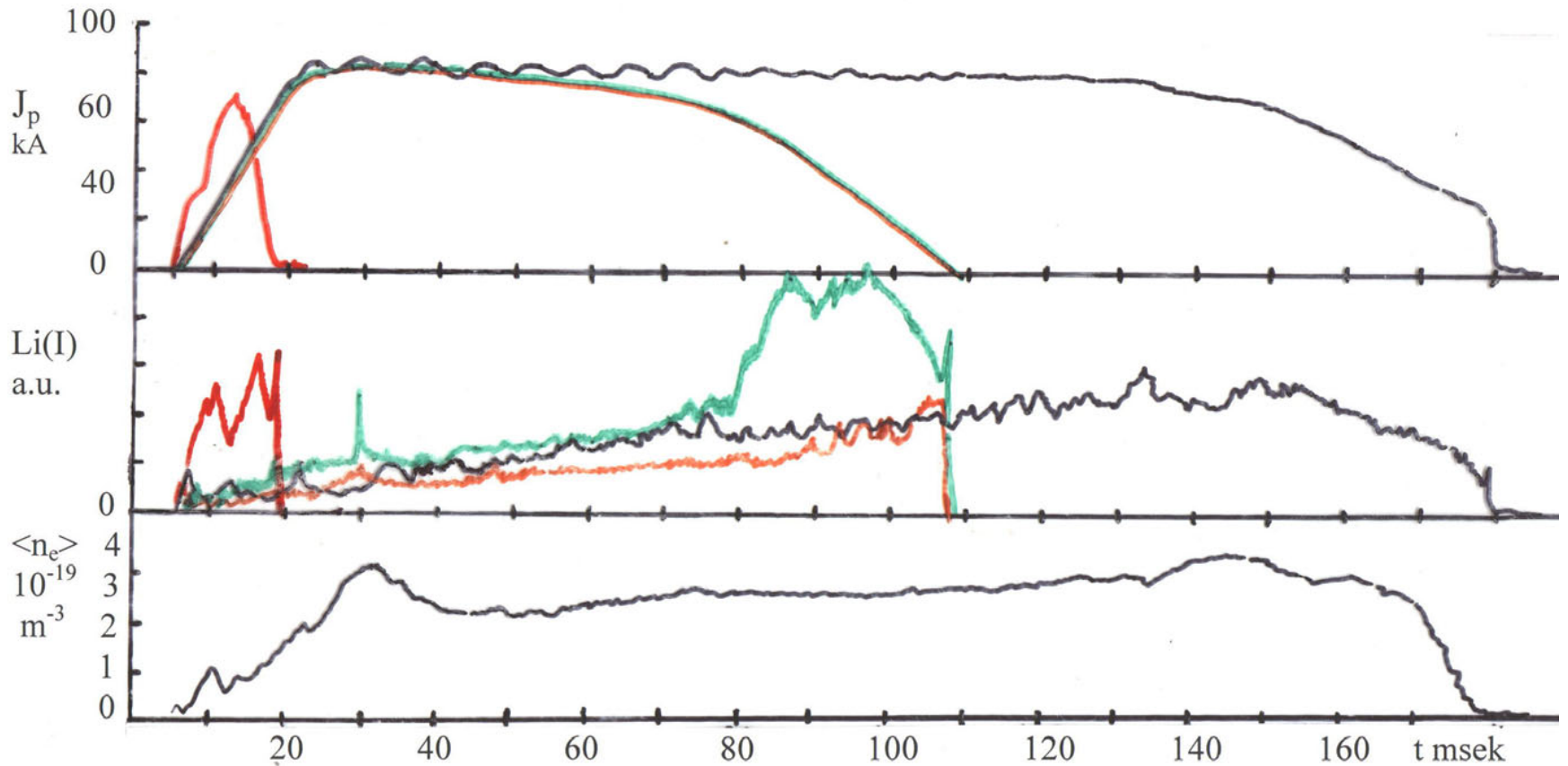


Schema of T-11M experiment



Time development of T-11M Li experiment

— T-11M (2002) $T_0=200^{\circ}\text{C}$ # 16883
— T-11M (1999) $T_0=200^{\circ}\text{C}$ # 10775
— T-11M (1999) $T_0=300^{\circ}\text{C}$ # 10784
— CDX-U (2000)



Lithium erosion, as function of limiter temperature

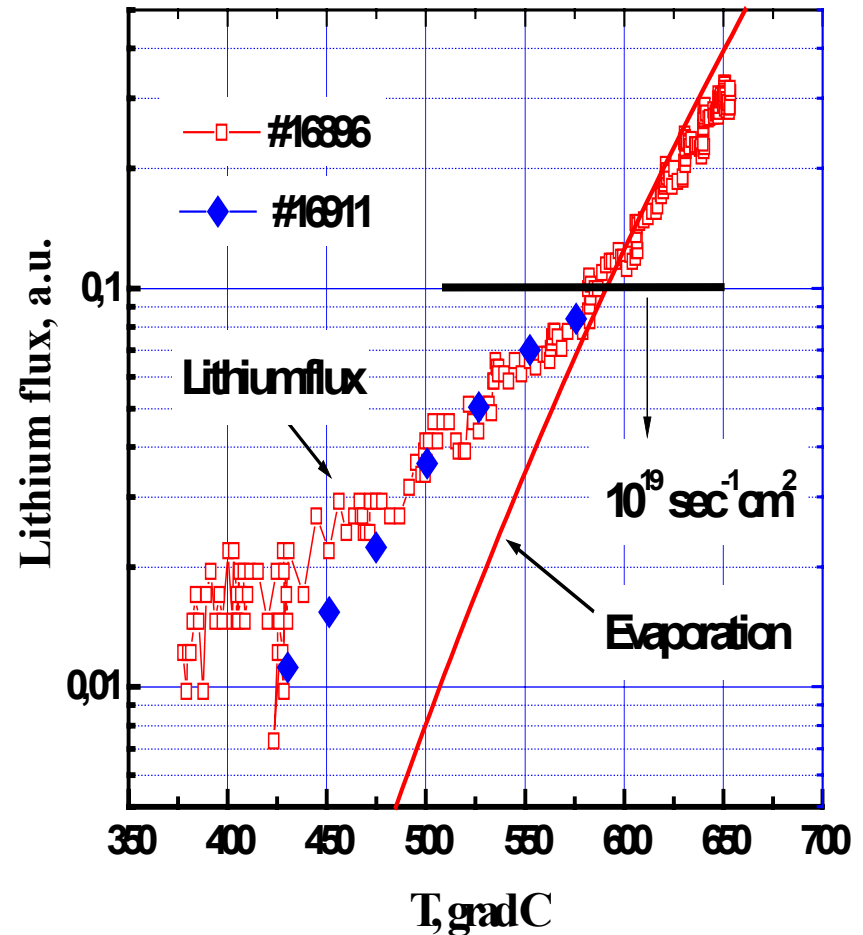
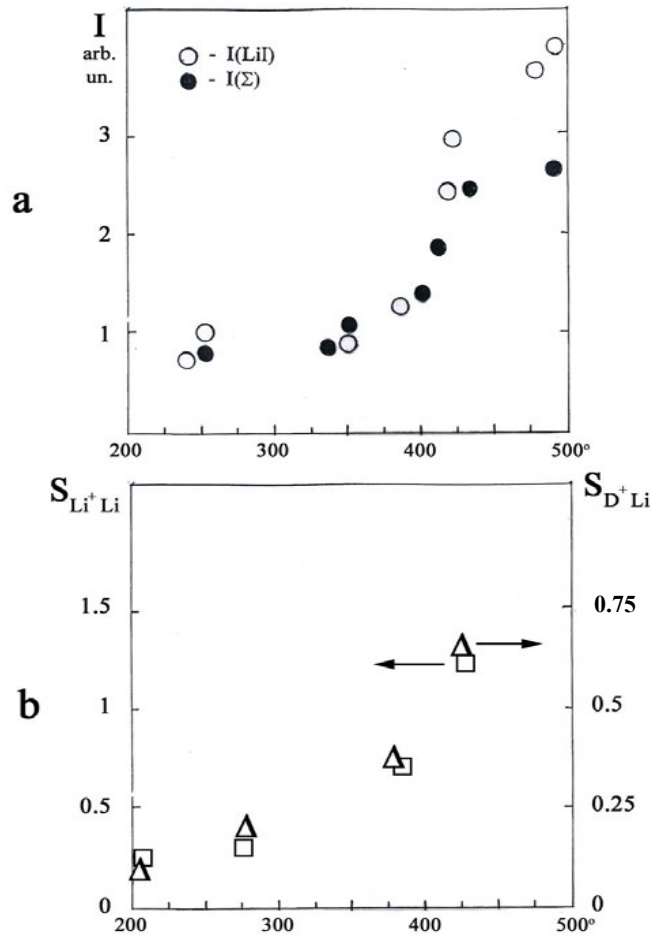
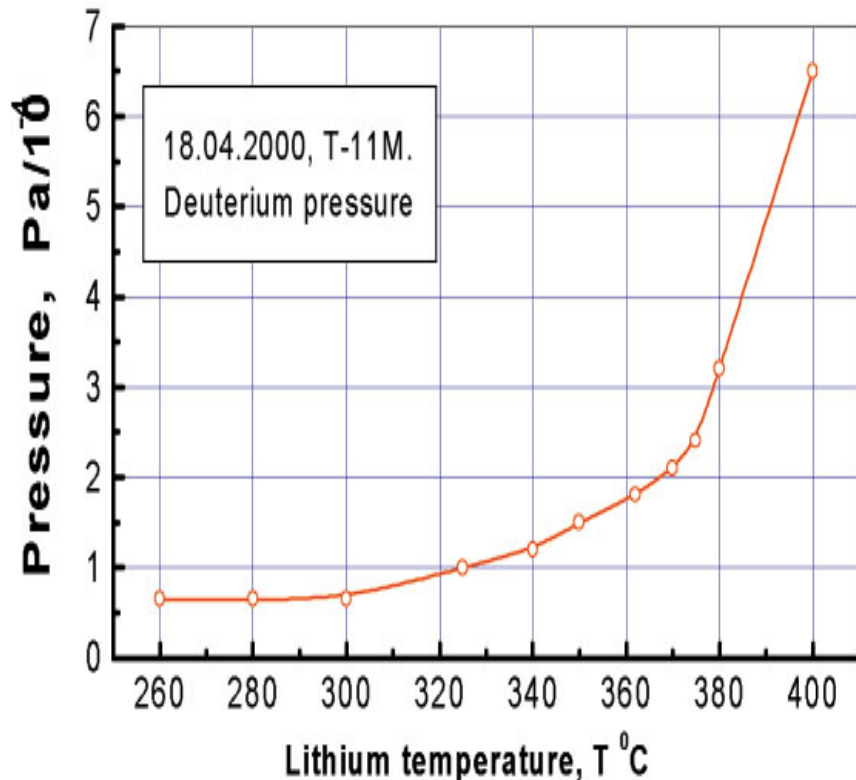


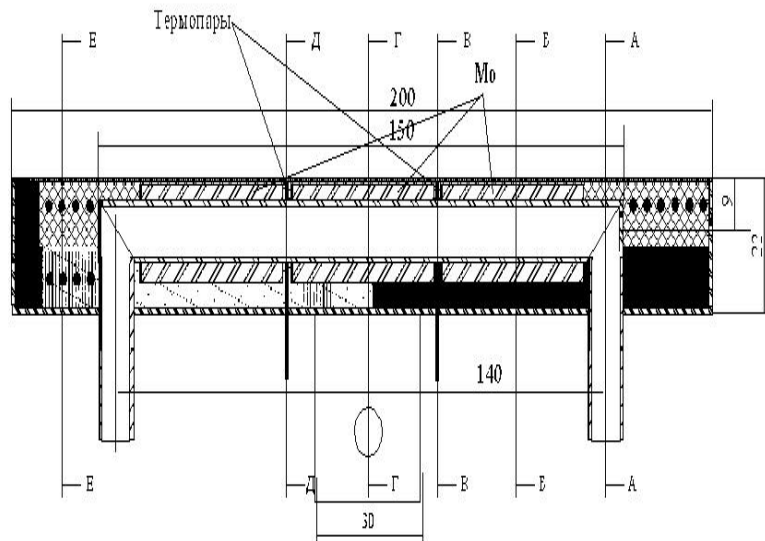
Fig.3. a) behaviour of Lithium and total light during experiment with lithium limiter heating;
 b) behaviour of spattering coefficients during experiment with lithium limiter target.
 Δ - Allain J.P., Ruzic D.N., Hendricks. J.Nucl.Mat. 290-293, p.180. D^+Li
 \square - Allain J.P., Ruzic D.N., Hendricks. J.Nucl.Mat. 290-293, p.180. Li^+Li

Deuterium extraction from Li



- The Li-limiter heating after experiments to 450°C shown a desorbtion of the captured deuterium from lithium at temperatures higher than 320°C. Lithium hydrides are supposed to decompose at temperatures about 600°C. Therefore, one may conclude that considerable part of deuterium was captured by lithium not in the form of deuteride but it was only dissolved in lithium.*

Thin CPS-limiter experiment

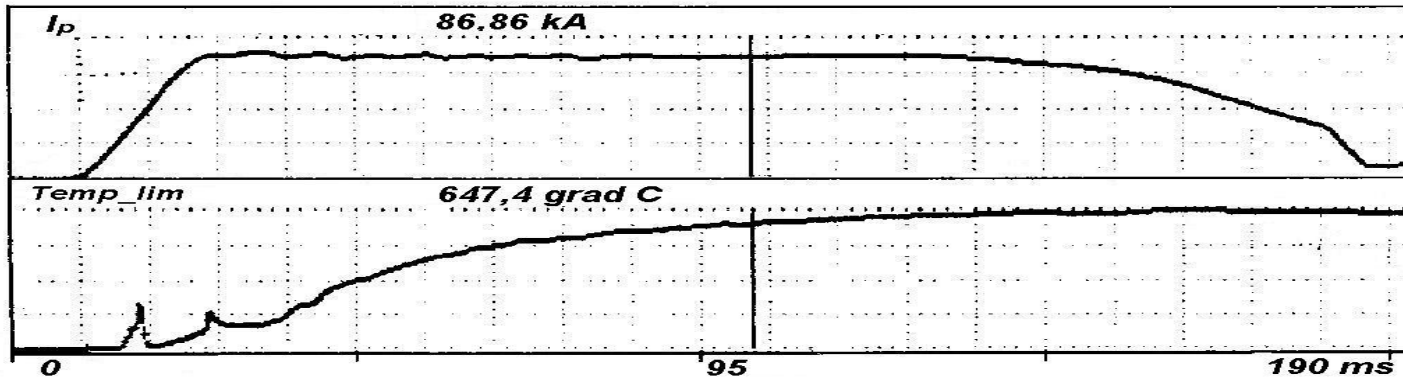


Schema of thin CPS-limiter

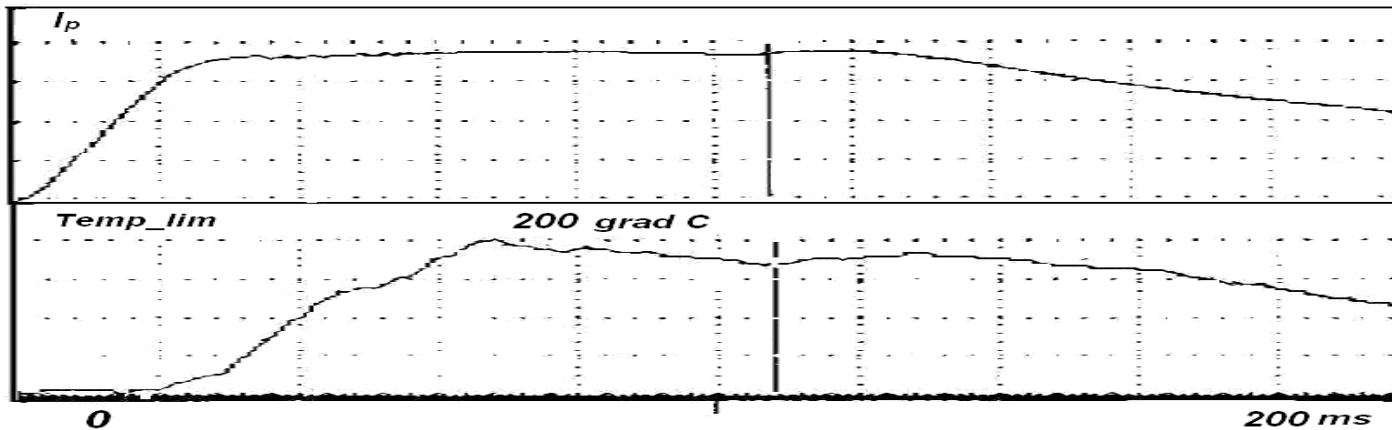
- The ends of CPS should sink in Li-reservoir so that it works as steady-state Li-wick. Then the main heat flux should go across thin CPS layer to cooled bed and lithium can flow to limiter surface along wick.*

Experiment with thin CPS limiter

A

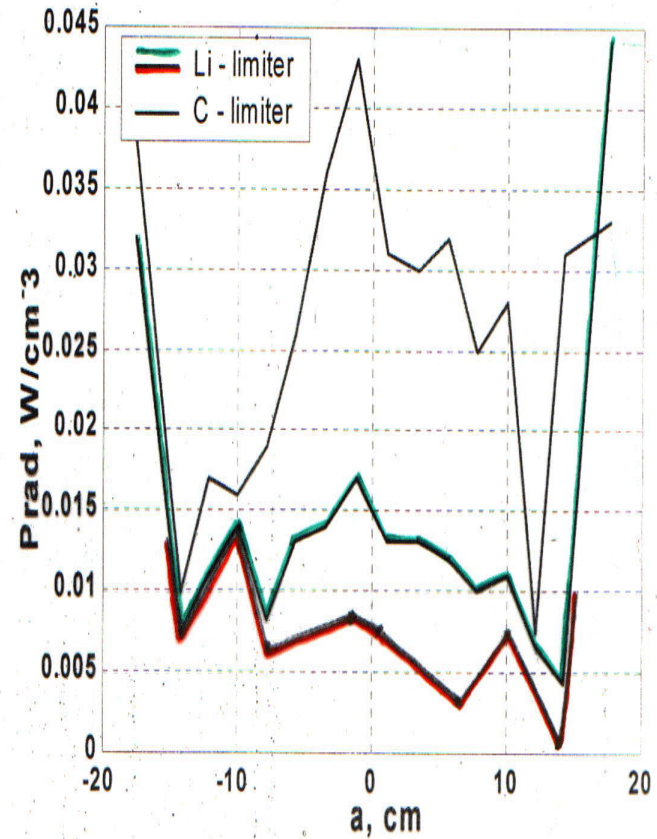
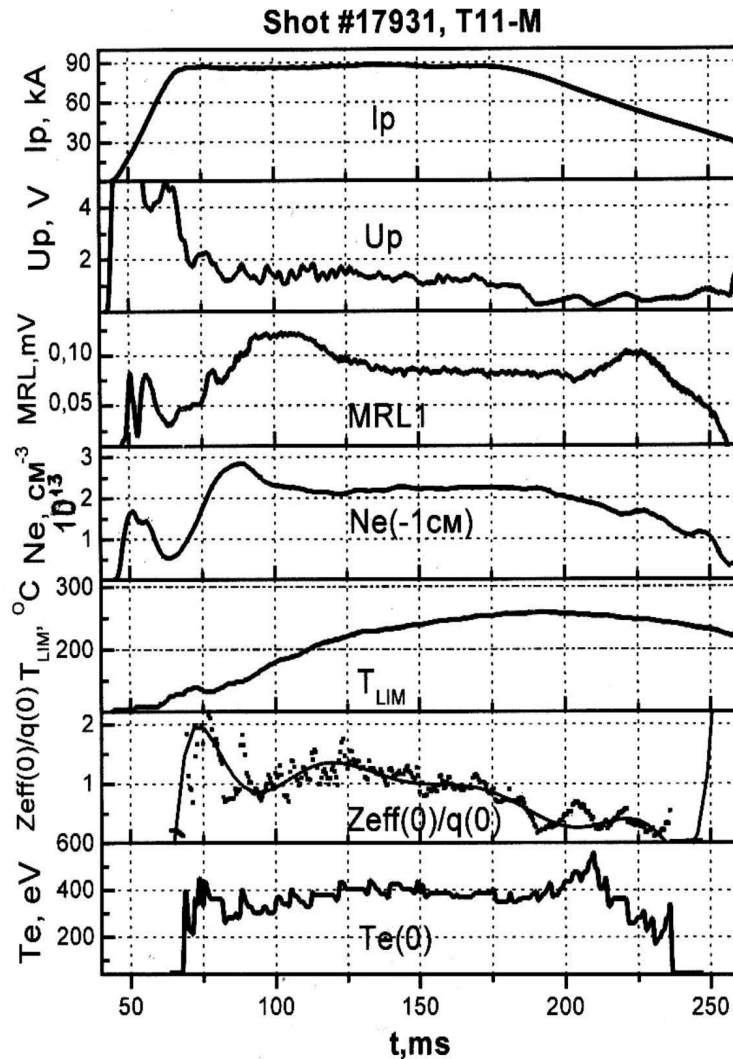


B

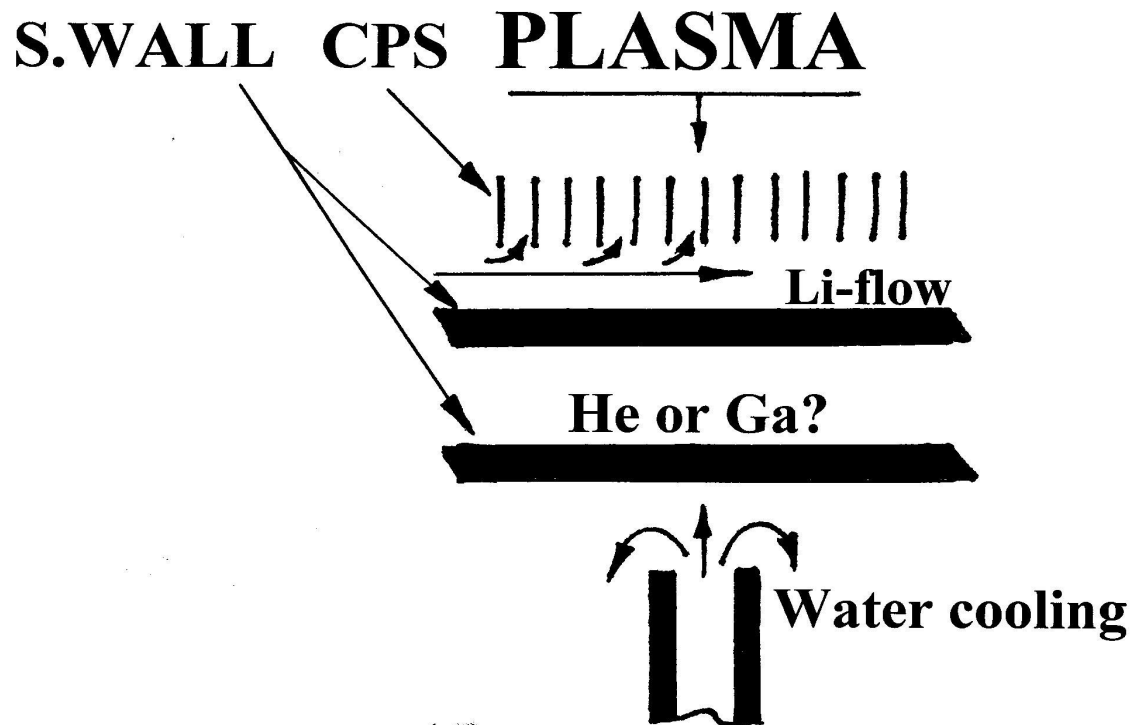


- A- without cooled backing,
- B- with cooled backing
- (Mo-tubes)

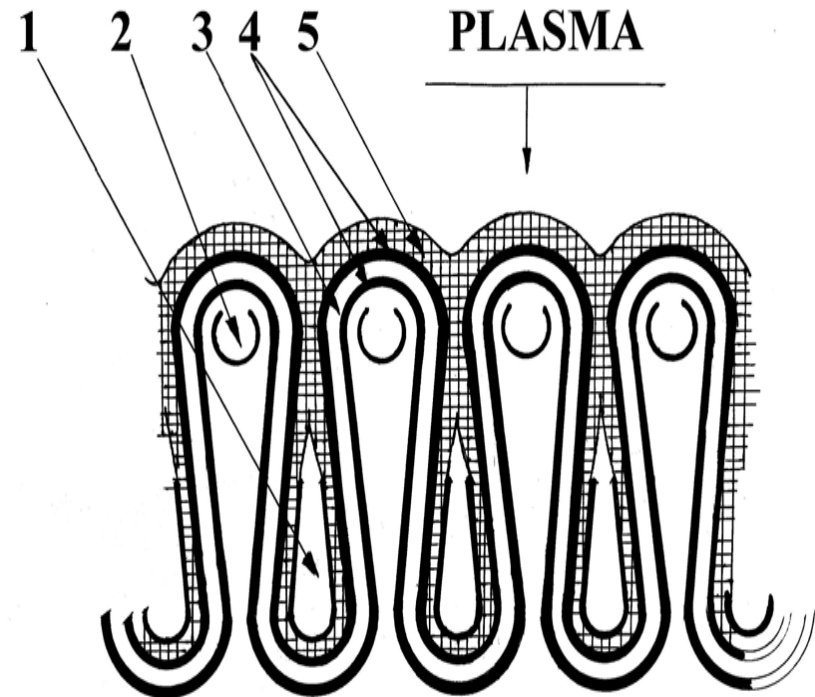
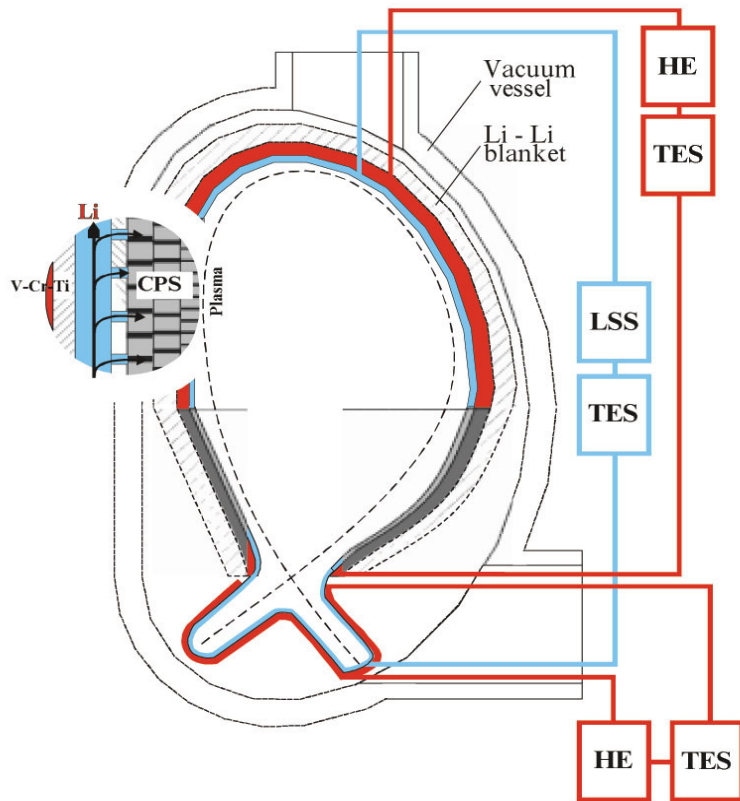
“Steady-state” experiment with thin limiter



Schema of double first wall of Li-tokamak-reactor with water cooling



Lithium-tokamak-reactor



- - first wall and divertor lithium heat removal system;
- - CPS lithium supply dynamic system;
- HE - heat exchanger; TES - tritium extraction system;
- LSS - lithium supply system.

Summary

Ga results:

- 1. The droplet stream can be useful as method of LM injection in tokamak, but film limiter experiments were unsuccessful.*
- 2. Ga – droplet limiter can be used in short pulse and probably steady – state tokamaks.*

However, $Z=31$ may be serious obstacle for using Ga, as PFC in tokamak reactor.

The experience of Ga use in big tokamak is absent today

Li results:

- 1. Lithium, as lowZ-material, is compatible with plasma of small and large tokamaks (TFTR, T-11M, CDXU).*
- 2. The surface tension forces in CPS may be used to solve the problem of pondero-motive forces (splashing suppress) and regeneration problem of PFC.*
- 3. Experiments with hydrogen (deuterium) and helium plasmas on T-11M tokamak with Li – CPS limiter have shown:*
 - No spontaneous bursts of lithium ejection under heat flux to limiter at the level about 10 MW/m^2 have been observed.*
 - Total lithium erosion close to level of hydrogen and lithium ions sputtering has been measured.*
 - The lithium radiation protected the limiter from high power load during disruptions.*
 - The solid basis of CPS limiter had no damages after more than $2 \cdot 10^3$ of plasma shots.*
 - The recovery temperature of hydrogen isotopes from Li is $320\text{-}500^\circ\text{C}$ (for helium $50\text{-}100^\circ\text{C}$). Therefore, at high PFC temperatures ($400^0\text{-}500^0 \text{ C}$) a tritium capture can be minimized.*
 - It should be provided, that separation of helium and hydrogen isotopes will be possible in lithium circuit with lower PFC temperatures.*

These results are making a convincing basis for the advance of the liquid lithium PFC for steady state Li-tokamak. The following problems of such tokamak might be decided:

- wall and divertor plates erosion,*
- “dust” accumulation and redeposition,*
- tritium recovery,*
- low $Z_{eff}(0)$,*
- heat removal in stationary conditions and during disruptions.*

The progress of the considered approach needs further experimental, calculation, design research and technological developments.

We assume, the lithium ITER-like tokamak will be the next step toward tokamak-reactor after ITER .