THE CONCEPT OF LITHIUM BASED PLASMA FACING ELEMENTS FOR STEADY STATE FUSION TOKAMAK-REACTOR AND ITS EXPERIMENTAL VALIDATION

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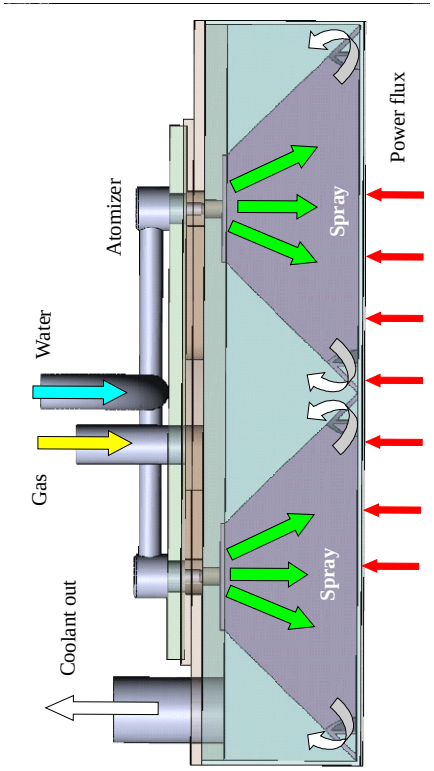
The most critical problem in the development of a stationary thermonuclear reactor is the design of its in-vessel plasma-facing elements (PFE). At present, it has become obvious that among the materials traditionally used for PFE there are no solid structural materials that would meet the requirements of long-term operation under the influence of a thermonuclear)14 MeV(neutron flow with a density of ~ 10^{14} cm^{-2} s^{1} and a heat flux with a density of 10-20 MW m^{-2}.
An alternative solution to this problem is to use liquid metals (LM) as plasma-facing materials with a low charge number Z or a high Z but low vapor pressure. This will create a long-lived, undamaged and self-renewing surface of the PFE, which does not have a polluting effect on the plasma

The concept of the CPS based PFE with liquid Li



- Plasma facing material – 0.5 mm thick of W felt based CPS with liquid Lithium. Li amount – 100 g/m^2

  2 *mm/s* Lithium flow rate for CPS filling, removal of trapped tritium and accumulated impurities
- PFE design - thin-wall structure with 2 mm thick of first wall
- First wall material - 67% W fiber+ 33% steel Eurofer composite with high heat conductivity (~90 W/mK) and mechanical properties (σ_y~ 480 MPa , σ_b~ 480 MPa)
- Main structure material – Eurofer type ferritic-martensitic steel
- Coolant - water / gas spray with 2 *bar* pressure,

  70-100 $kW\ m^{-2}\ K^{-1}$ heat transfer coefficient ,

  coolant consumption: water Gw~ 1 *liter / s* m^2 , gas G_{gas}~ 25 *liter* / s m^2
- Surface temperature - ~500 ^oC at power flux P=10 MW/m^2, ~700^oC at P=17 MW/m^2

Temperature limit of materials compatibility with LM

Structural materials	Temperature limit,°C	
	Li	Sn / Sn-Li alloy
Ferritic / ferritic-martensitic chromium steels	800	<400
Austenitic Cr-Ni steels	700	<400
V-Cr-Ti alloys	900	<700
Mo alloys	1200	1000
W alloys	1500	1200
Cu and alloys	incompatible >180	incompatible >230

Power flux limit of materials regarding surface temperature and available thermal stresses

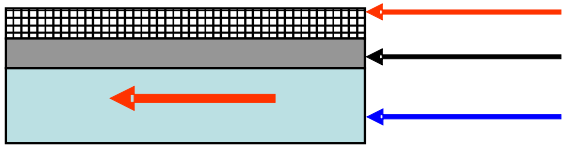
Material	Power flux, MW m^{-2}
Ferritic / ferritic-martensitic chromium steels	3
V-Cr-Ti alloys	9
67%W fiber+ 33% Eurofer steel	17
W	38

1 mm wall+0.5 mm CPS with Li , T surf = 650oC, water-das spray coolant

Main parameters and heat transfer coefficient of coolants

Coolant	Pressure, MPa	Flow rate, m s^{-1}	Temperature, °C	Heat transfer coefficient, kW m^{-2} K^{-1}
Liquid lithium	0.1	1	200	44
Liquid water	5	8	200	52 (swirl flow), 25 (normal flow)
Gas (helium)	15	135	200	20
Water-gas spray	0.2	40 $G_{gas}/G_{water}>0.06$ (ratio of mass flow)	20	70-100

The experience of creating a PFE with active cooling

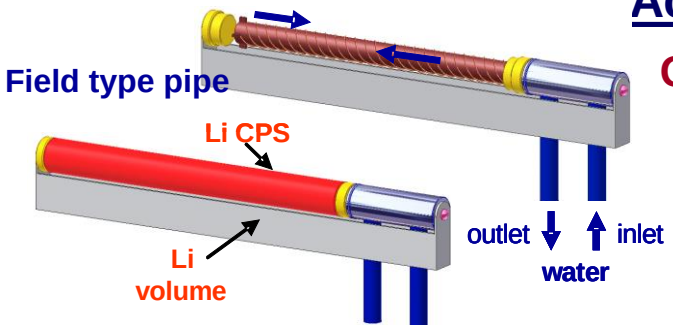


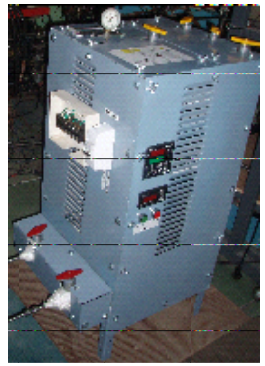
1 mm of Li CPS (SS, Mo, W)
1 mm of wall (SS, V alloy)
flowing coolant

Base structure of PFC surface

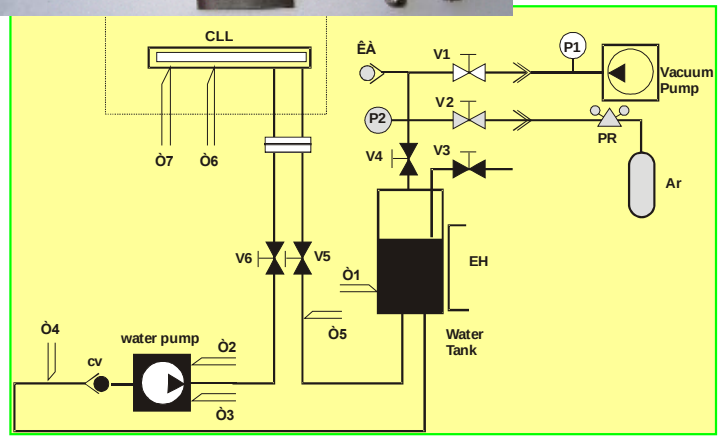
Active cooling Li limiter of T -11M

$Q \leq 10$ MW/m^2, t=0.2 s





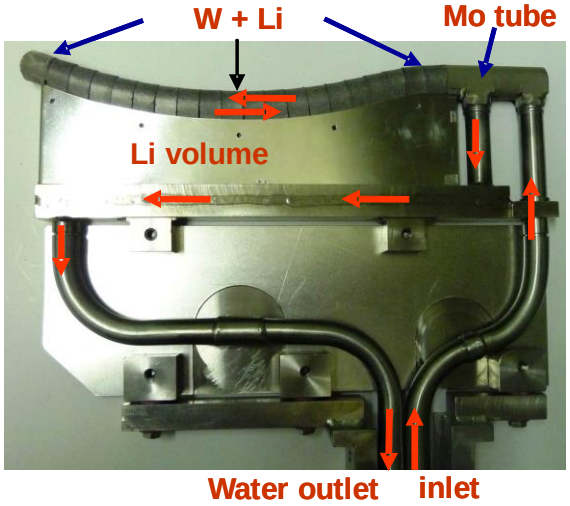
Li surface / coolant T_{min}	200°C
Li surface T_{max}	550°C
Surface area	40 cm^2
Power exhaust	20 kW
Heat-transfer agent	water
Agent pressure	up to 20 bar
Flow rate	0.05 l/s



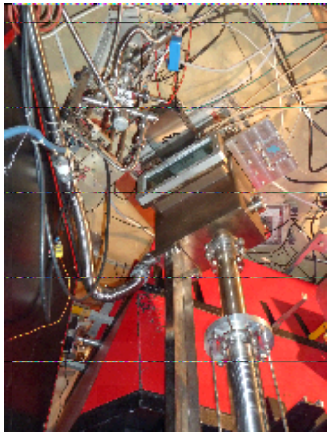
Active cooling Li limiter (CLL) of FTU (is under tests)

Q =10 MW/m^2, t ~1.5 - 5 s

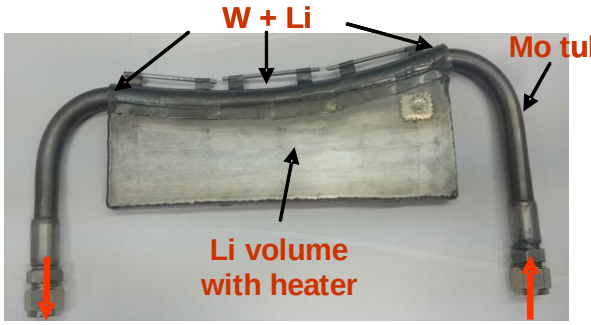
CLL with Field type pipe

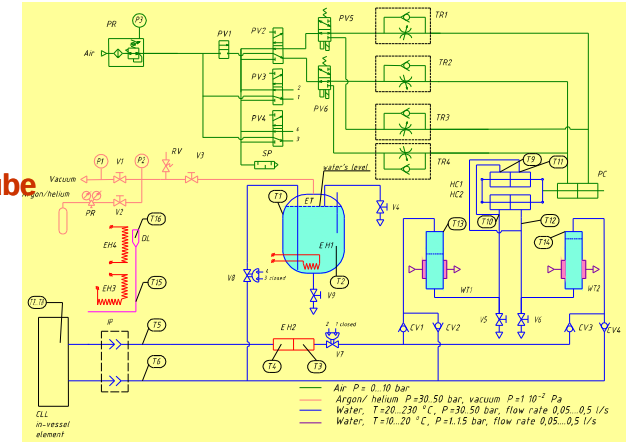


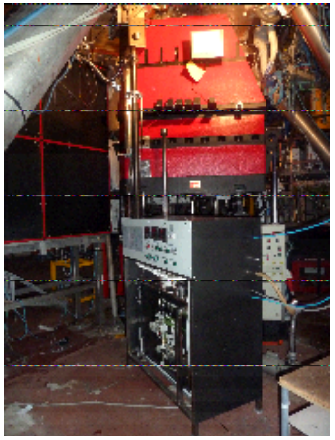
Li surface / coolant T_{min}	200-230°C
Li surface T_{max}	550°C
Surface area	100 cm^2
Power exhaust	100 kW
Heat-transfer agent	water
Agent pressure	up to 40 bar
Flow rate	0.05-0.5 l/s



CLL with direct type flow



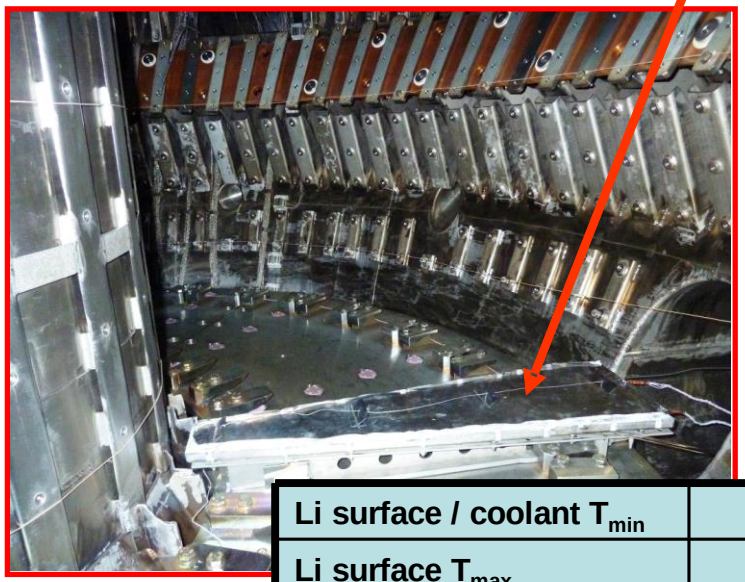




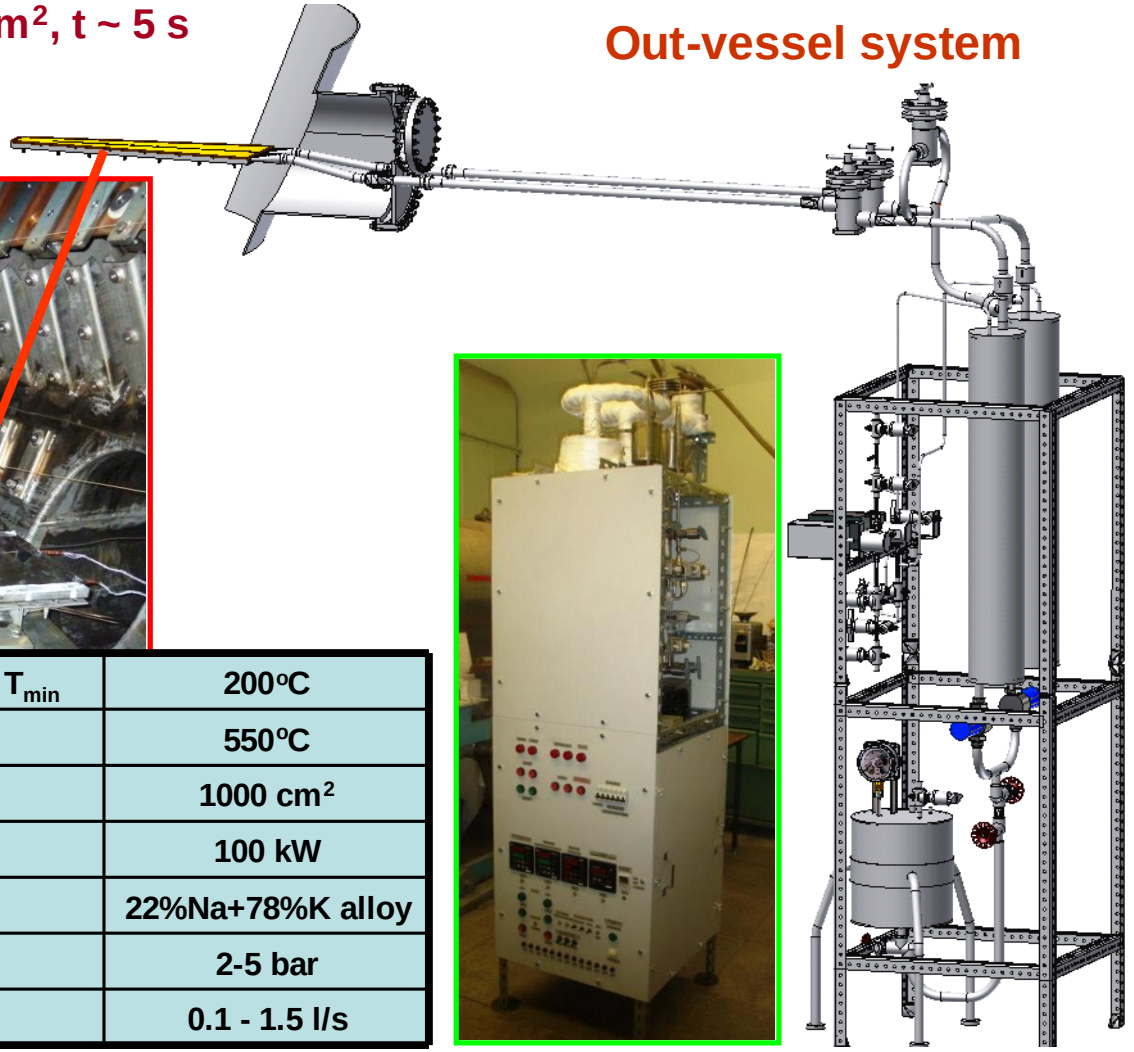
Lithium divertor module of KTM (standby mode)

Q =10 MW/m^2, t ~ 5 s

PFC



Out-vessel system

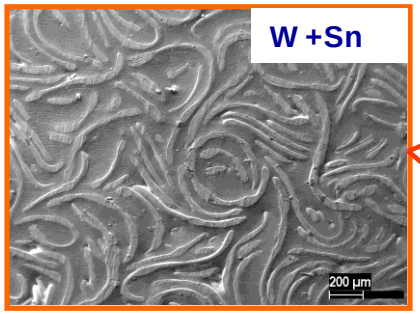


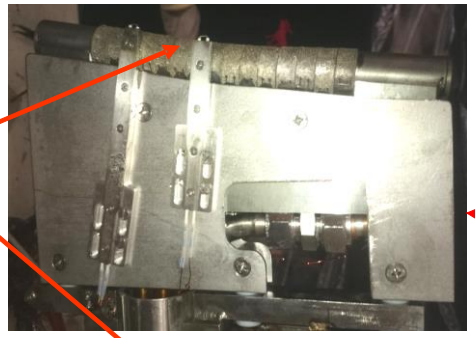
Li surface / coolant T_{min}	200°C
Li surface T_{max}	550°C
Surface area	1000 cm^2
Power exhaust	100 kW
Heat-transfer agent	22%Na+78%K alloy
Agent pressure	2-5 bar
Flow rate	0.1 - 1.5 l/s

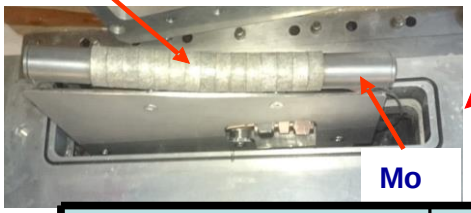
Active cooling liquid Tin limiter (TLL) of FTU (is under tests)

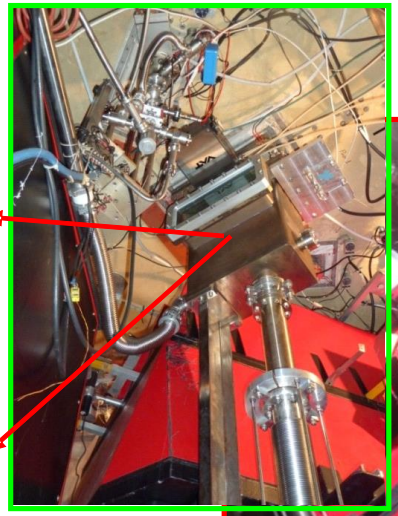
Q =10 MW/m^2, t ~ 5 s

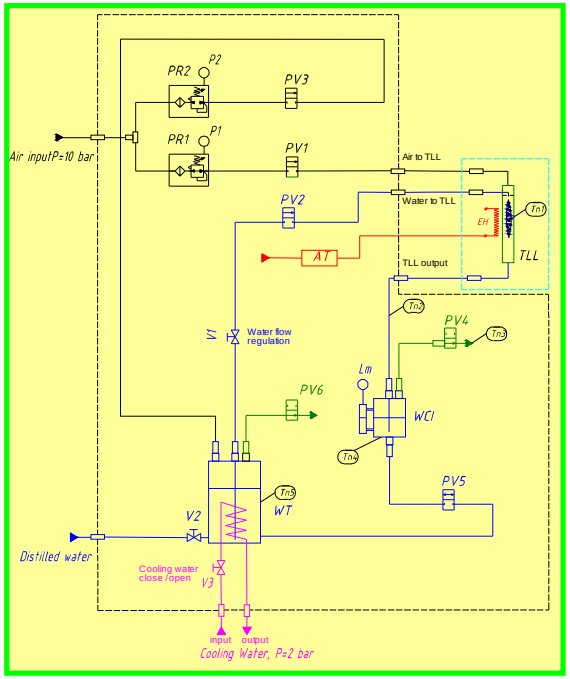
Prototype of new PFC generation







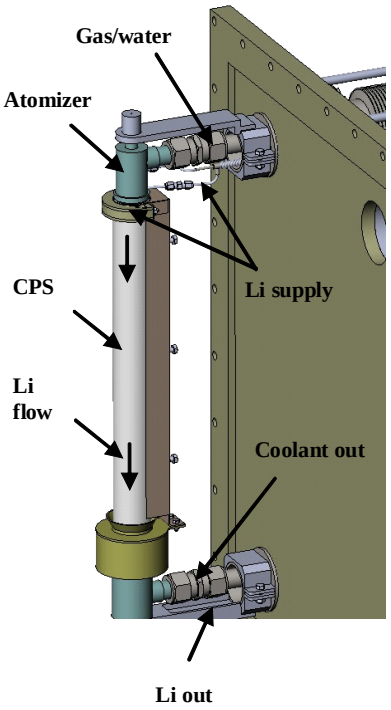


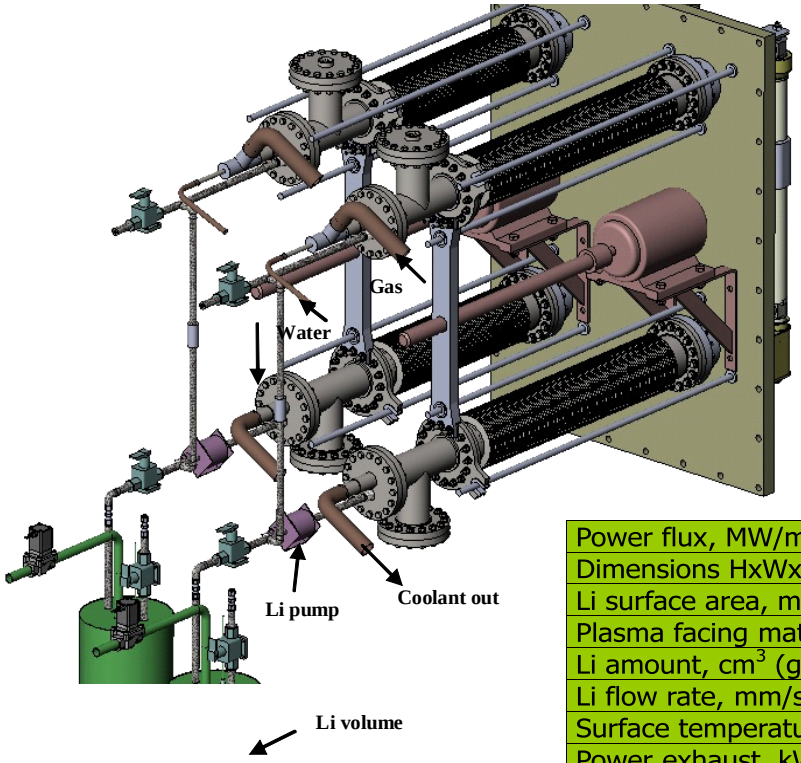


Li surface/coolant T_{min}	240°C
Li surface T_{max}	900°C
Surface area	85 cm^2
Power exhaust	85 kW
Heat-transfer agent	Water spray
Agent pressure	up to 2 bar
Flow rate	0.05 l/s

Design of liquid lithium limiter for T-15 tokamak

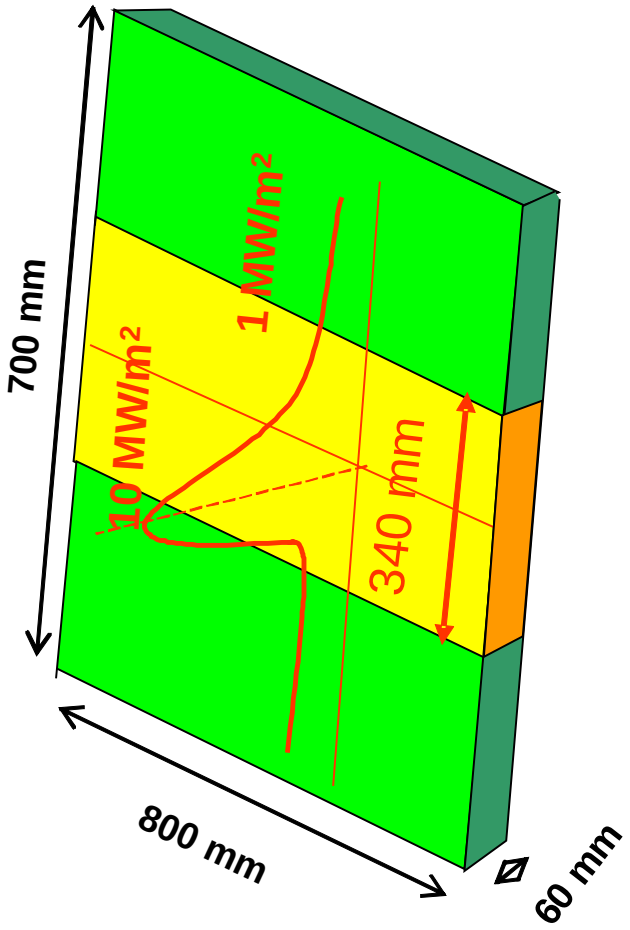
The limiter is designed for stationary operation at a power flux of 10 MW m^{-2}. Such a limiter can operate in tandem with a similar one, acting alternately as an "emitter" or "collector" of lithium, thereby ensuring the closed circuit of the circulation of lithium atoms in the tokamak chamber, which prevents the accumulation of lithium on the walls of the tokamak in the process of long-term operation.Lithium renewal in CPS is supposed. Temperature stabilization is provided by water/gas cooling system.





Power flux, MW/m^2	up to 10
Dimensions HxWxD, m	0.75x0.1x0.05
Li surface area, m^2	0.1
Plasma facing material	1 mm thick of W felt+Li
Li amount, cm^3 (g)	700 (350)
Li flow rate, mm/s	2
Surface temperature, °C	180-600
Power exhaust, kW	230
Coolant	Water / gas
Coolant pressure, MPa	0.2-0.3
Coolant flow rate, l/s	0.5

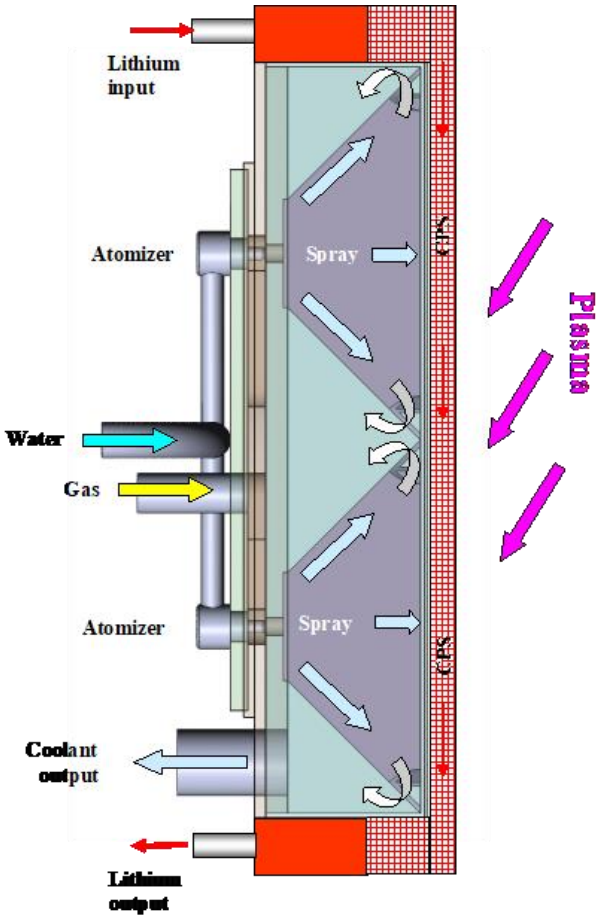
Development of a prototype of DEMO divertor



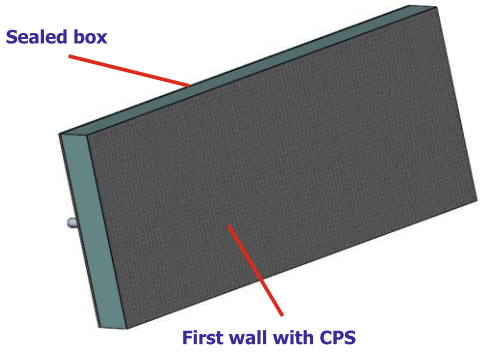
Target design: 3 modules of cellular structure with thin-wall flat cooling channel
Plasma facing material: 0.5 mm thick W felt + liquid Li
First wall material: 2 mm thick composite 67% W fiber + 33% Eurofer steel
Main material: Eurofer steel

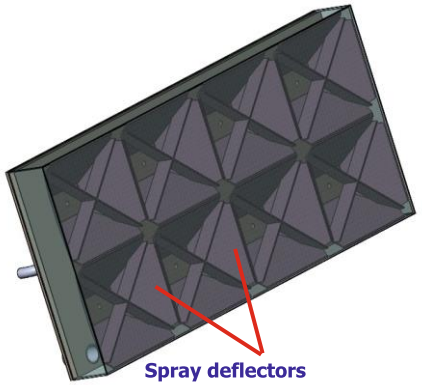
Main parameters of LMDT for DEMO reactor	
Target dimensions HxWxD, m	0.7 x 0.8 x 0.06
Li surface area, m^2	0.56
Lithium volume/weight, l /kg	0.1 / 0.05
Li flow rate, m/s	0.002
Maximal T concentration in Li, at %	2.8
Surface temperature, ^oC	430
Power flux, MW	10
Coolant	Water / gas spray
Coolant pressure, MPa	0.2
Water / gas consumption l/ s	0.5 / 14

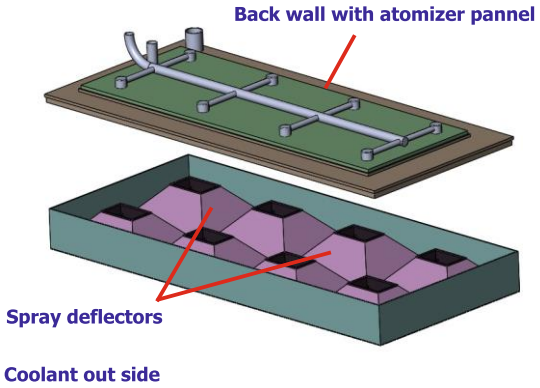
Main design scheme

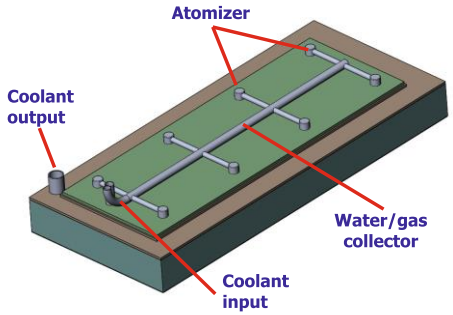


Central module design scheme



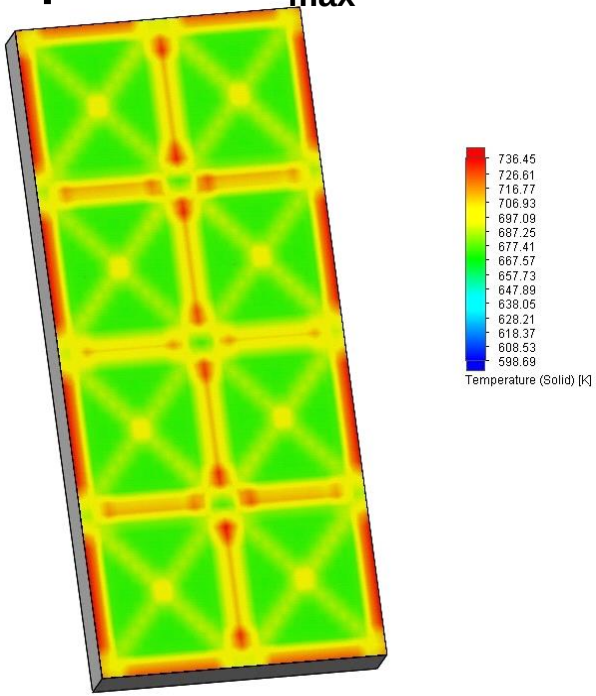






Temperature and stress analyses at 10 MWm^{-2}

Temperature T_{max}<500°C



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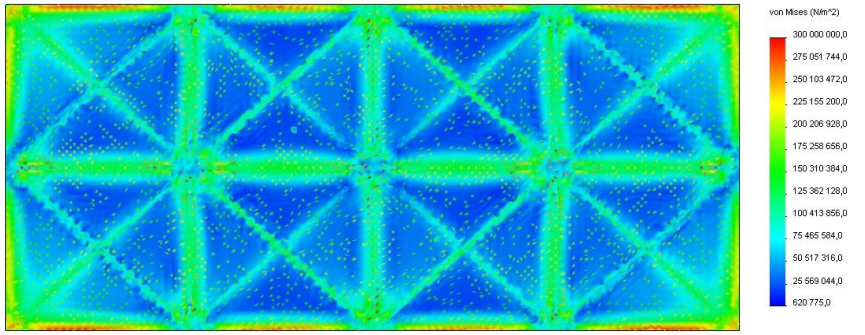
Stress, S_{max}=250 MPa



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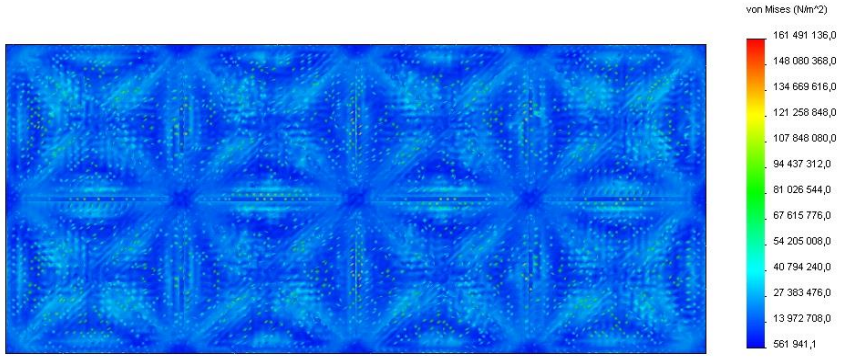

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Conclusion

The developed concept and the hands-on experience in steady-state operating LM PFE creation and tests allows the solving a number of critical issues in the development of appropriate PFE design that meet the requirements for long-term operation at DEMO type tokamak conditions.

Tungsten fiber based CPS with lithium provides PFE surface protection and renewal under expected power flux. Thin-walled cooling system ensures maintenance of LM surface temperature at an appropriate level preventing plasma pollution. The new composite structural material (67%W fibers + 33% Eurofer steel) for the PFE first wall is presented to meet requirement in radiation stability, thermal and stress capabilities. New type of coolant based on water-gas spray is considered and proposed as more convenient coolant for lithium-containing PFE that meet temperature limit and safety demands. All these points allow to elaborate promising design of the DEMO divertor target plate.