Flowing PbLi corrosion of RAFM steels

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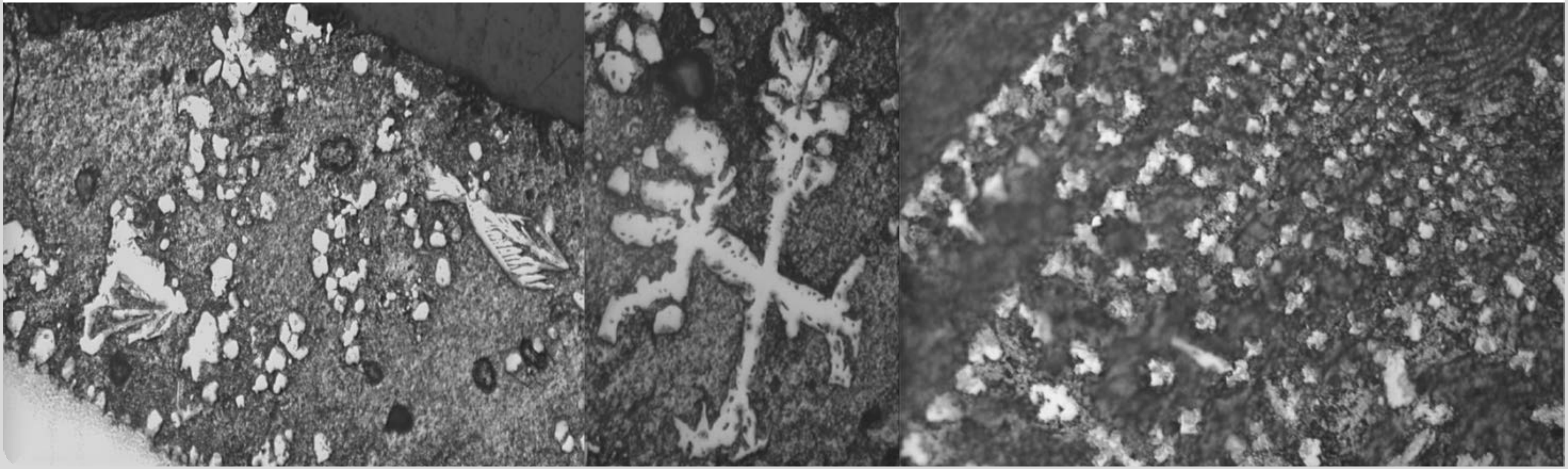
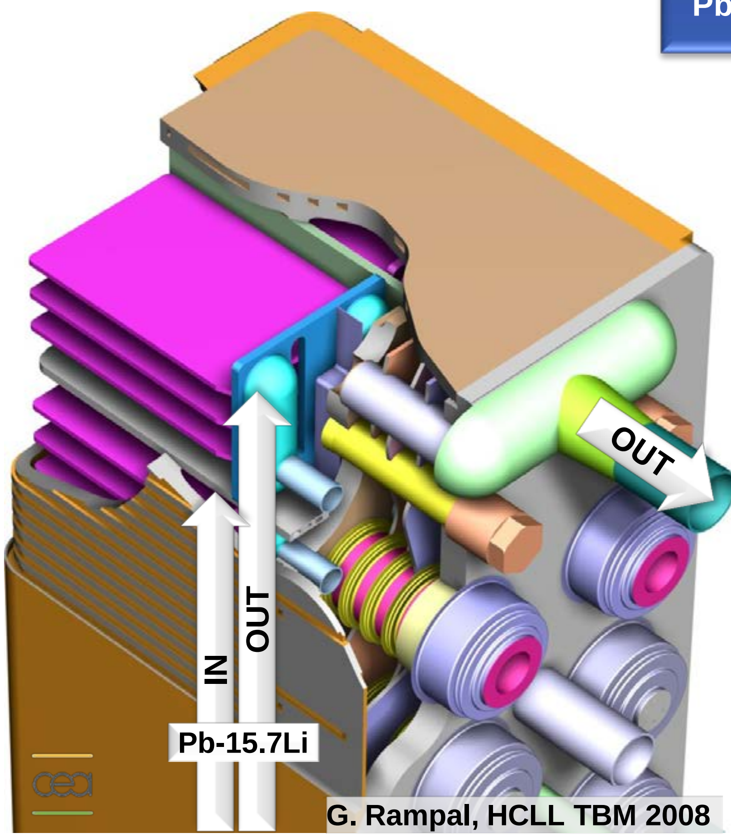


Outline

- Existing data at KIT for RAFM steels corrosion
  - Formation of metallic precipitates
- Corrosion test results
  - Campaigns at 22 and 10 cm/s
- Relevance of flow velocity for $DCLL_{mod.}$
- Modeling of corrosion/precipitation
  - Calculations and comparison with experimental data
- Conclusions

The HCLL (He-PbLi) TBM (and DEMO) blanket

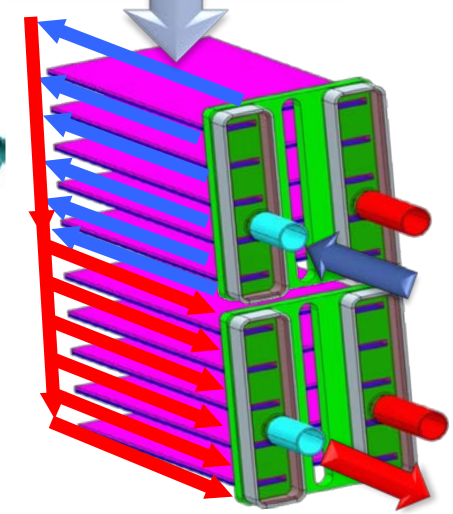
DEMO HCLL MAIN FEATURES
2m x 2m modules
RAFM steel (EUROFER)
He (8 MPa, 300-500°C)
Liquid Pb-15.7Li (eutectic) as breeder and multiplier
PbLi slowly re-circulating (10/50 rec/day)
90% ^{6}Li in PbLi Pb-Li velocities in breeding unit ~ 1 cm/s range
TBR = ≤1.15 with 550mm Breeder radial depth
Lifetime 7.5 MWy/m^2



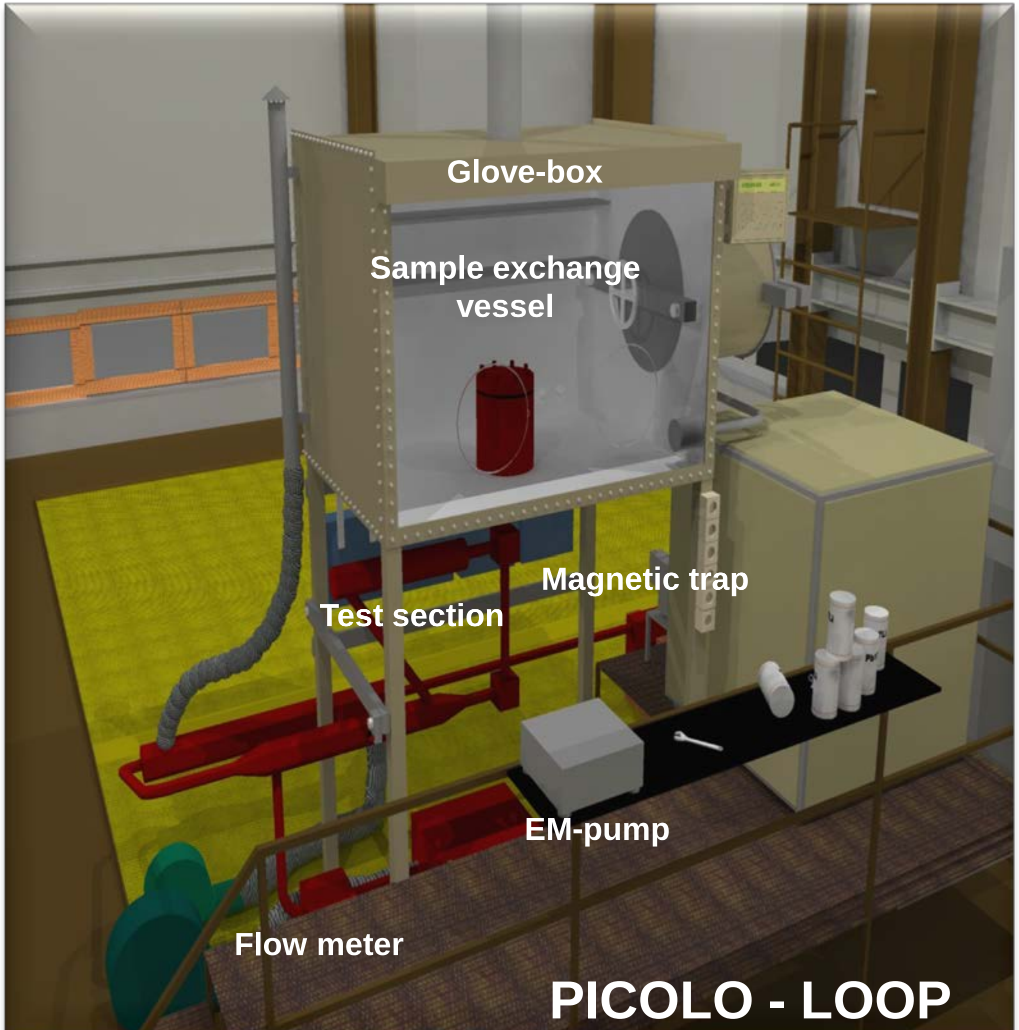
G. Rampal, HCLL TBM 2008

Corrosion of cooling and stiffening plates by PbLi and permeation of tritium from PbLi into He gas

PbLi flow velocity ~ 1 mm/s



Pb-15.7Li corrosion testing in PICOLO loop



Parameters of Pb-15.7Li Loop PICOLO

Test temperature:	480-550°C
Tmax in test section:	550°C
Tlow at EM-pump:	350°C
Pb-15.7Li volume:	20 litres
Flow velocity range:	0.01 - 1 m/s
Test velocity up to 2007:	0.22 m/s
Loop materials:	
Cold legs:	18 12 CrNi steel
Hot legs:	10 % Cr steel
Total loop operation:	
at 480°C	> 120,000 h
at 550°C	> 30,000 h

Test conditions since 2011

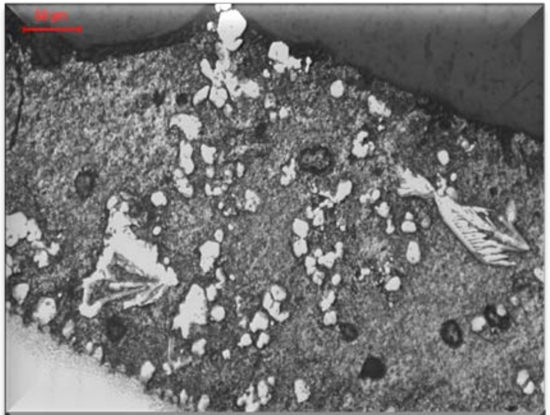
Pb-15.7Li velocity 0.1 m/s

Compromise to laminar / turbulent flow regimes, data for modeling and TBM requirements

Experience from corrosion testing in PICOLO loop

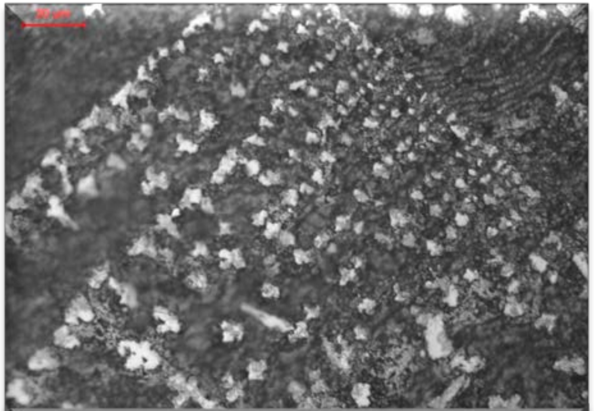
Precipitation and transport behavior of corrosion products

- Only rudimentarily data on transportation effects of corrosion products and their precipitation behavior are available.
- Only some small sections of PICOLO loop are analysed.
- But high risk was detected for loop blockages due to precipitations.
- New testing campaigns are extended to smaller flow rates towards mixed and laminar conditions with more TBM relevance.



Formed and transported precipitations

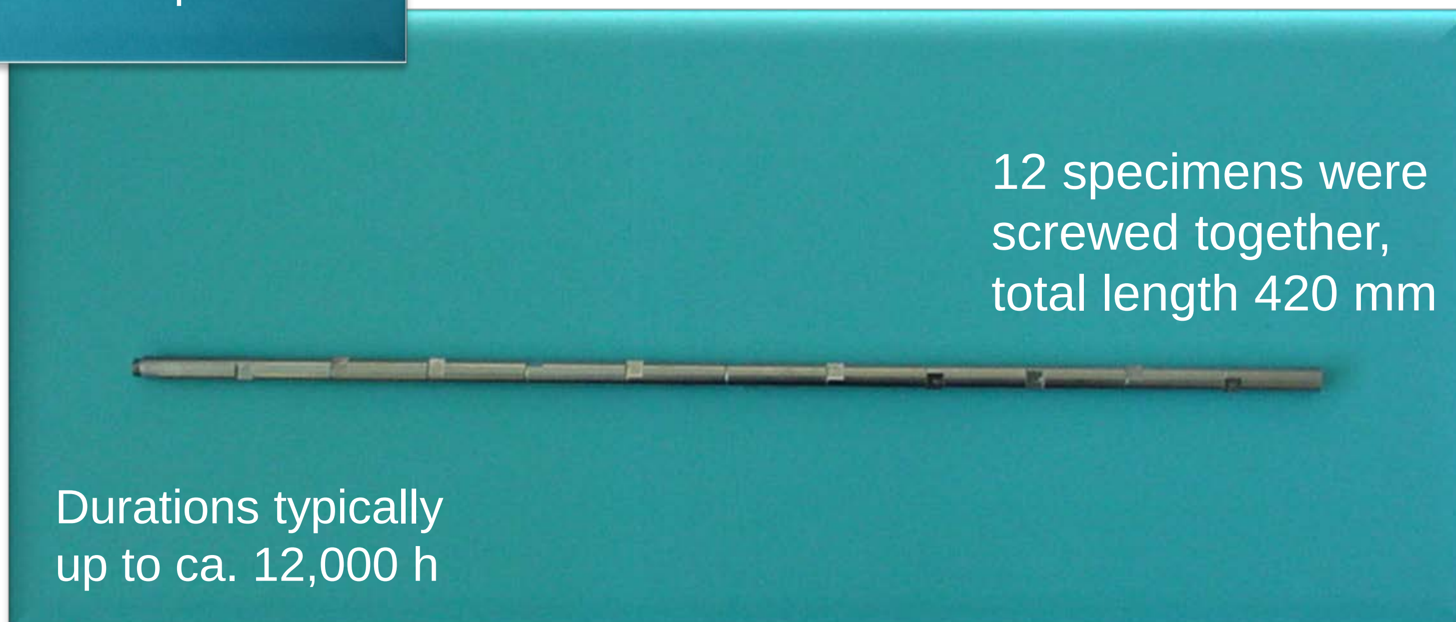
Precipitations in adherent Pb-15.7Li scale



Precipitations in the center of the magnetic trap parallel to field lines

Experimental

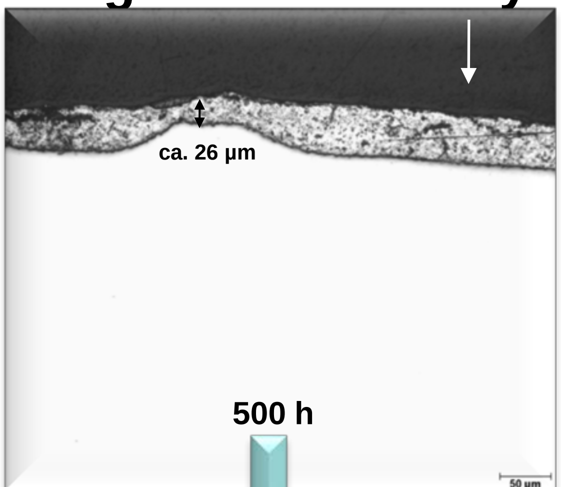
Diameter: 8 mm
Length: 35 mm

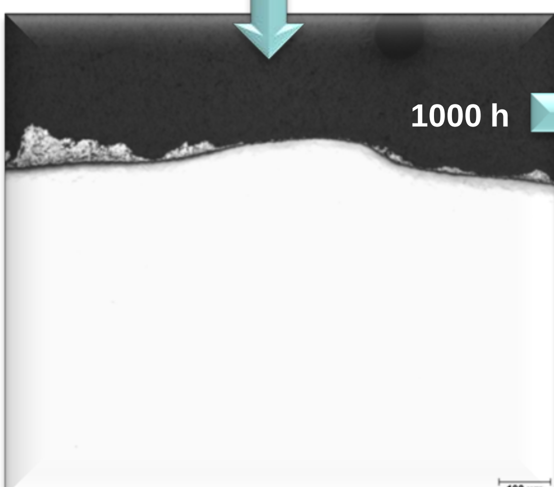


Results of corrosion testing in PICOLO loop EUROFER steel exposed to Pb-15.7Li at 550°C

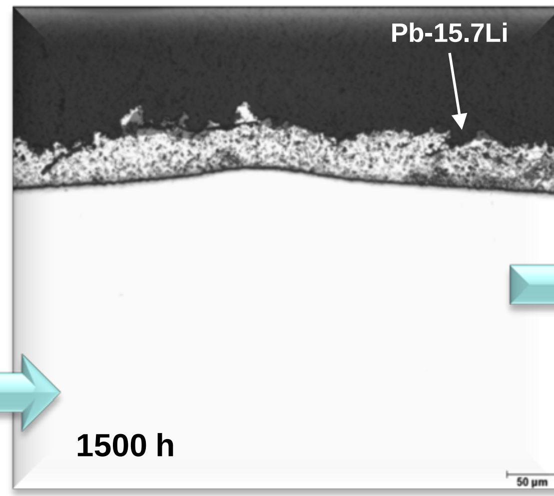
- “high“ flow velocity -

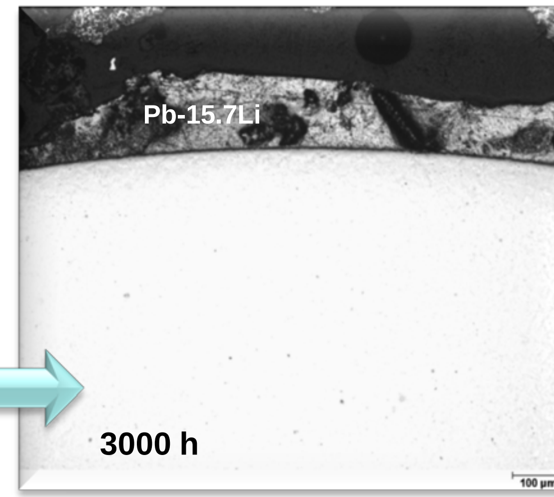
Severe corrosion!!





Start of corrosion attack



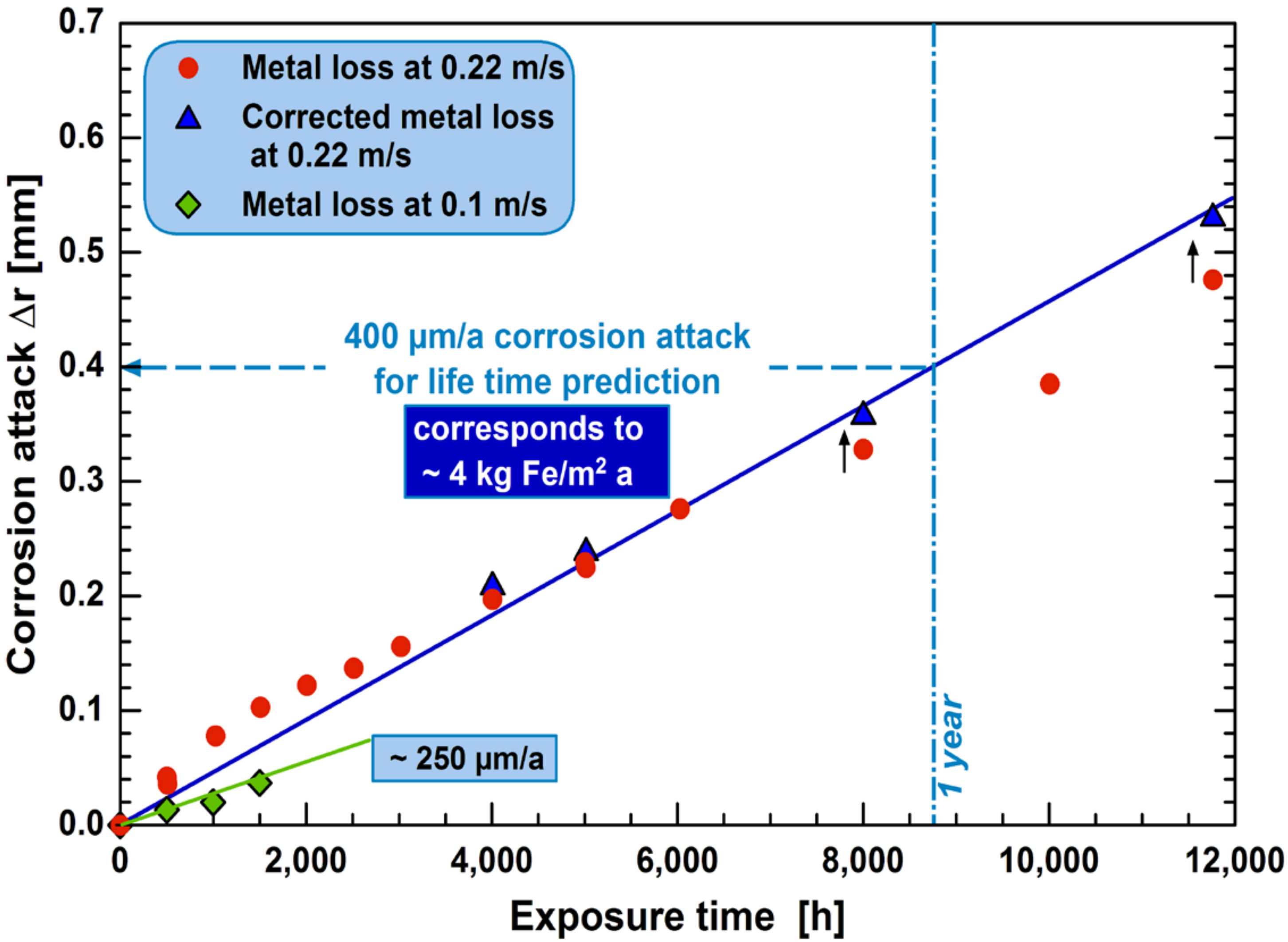


Homogeneous attack for long-term exposure

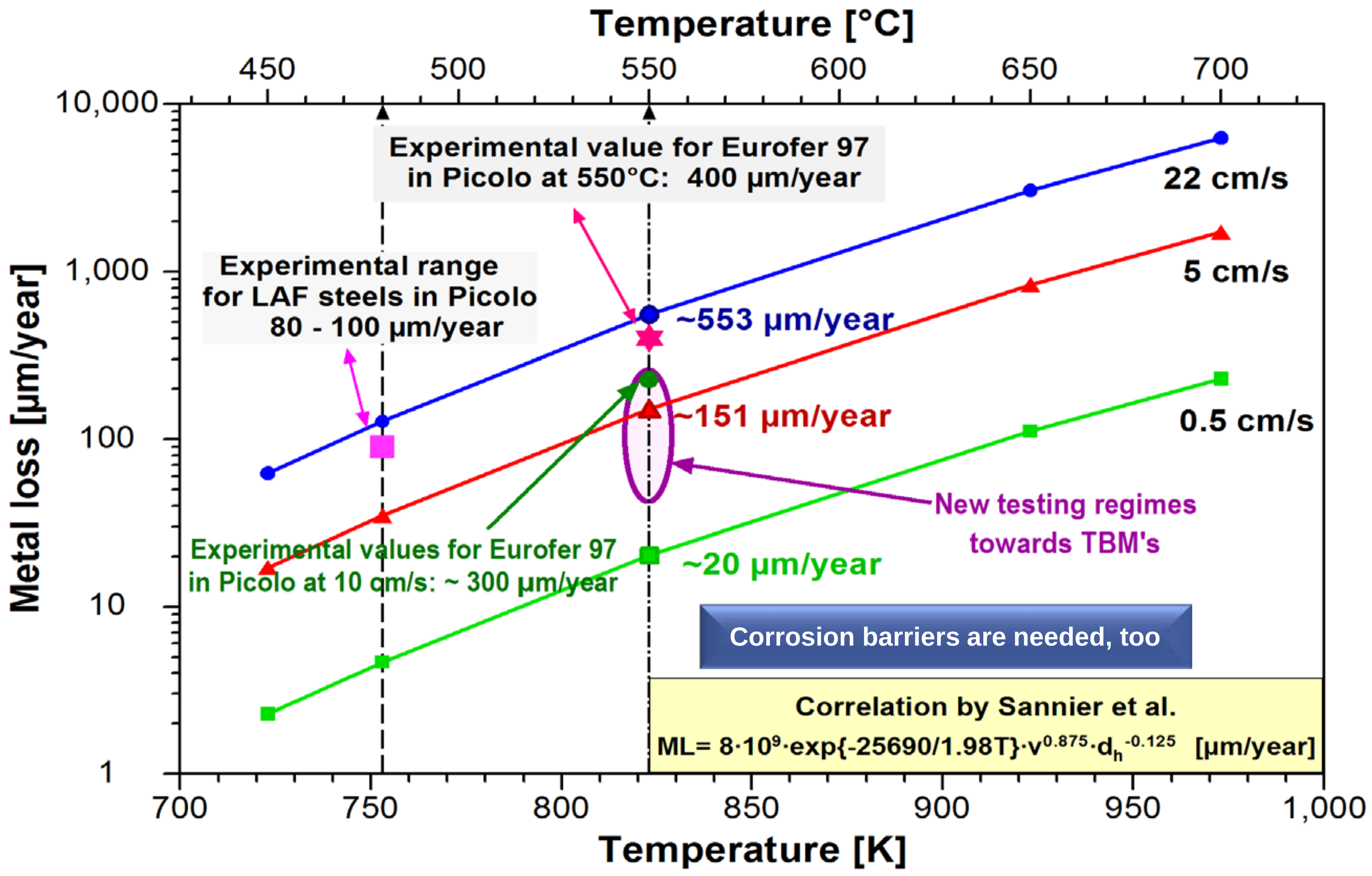
CHEMICAL COMPOSITION OF INVESTIGATED STEELS (WT.-%)

Steel	Cr	Ni	C	Mn	V	W	Mo	Ta
EUROFER	8.82	0.02	0.11	0.47	0.20	1.09	-	0.13
OPTIFER	8.5	-	0.11	0.57	0.23	1.16	-	0.16
MANET	10.6	0.87	0.13	0.82	0.22	-	0.77	-
F82H-mod.	7.7	-	0.09	0.16	0.16	1.95	-	0.02

Results of corrosion testing in PICOLO Loop at different flow velocities



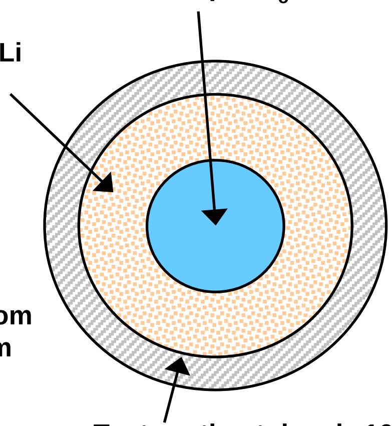
Flow rate dependent corrosion of FM steels in Pb-15.7Li



TBM test conditions concerning corrosion

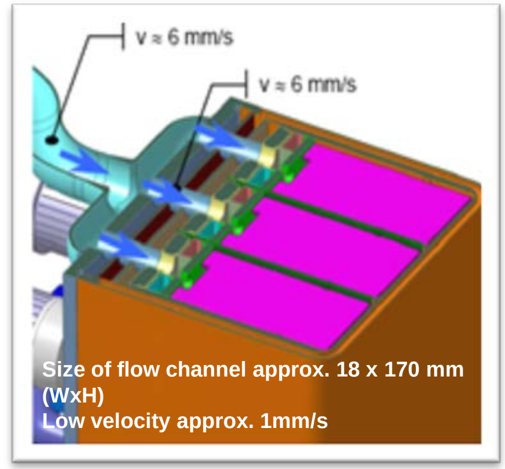
Figures of merit for TBM/DEMO derived from PICOLO tests

Geometry of test section Picolo	Geometry of TBM



t=0 h: d = 4 mm
t=12,000 h: ca. 5 mm
V(Pb-Li) = 0.22 m/s

Increase of gap width from s=4 mm (t=0) to ca. 5 mm after 1 year



The flow in pipes is laminar up to a Reynolds number of ca. 2,300 and it becomes fully turbulent at a Reynolds number of e.g. 10,000.

Hydraulic diameter Picolo	Hydraulic diameter TBM
d_{hyd} = 4A/U = d − d0 = 2s d_{hyd} = 0.8 cm	dhyd = 4A/U = 4 (WxH) /2 (W+H) dhyd = 3.25 cm

TBM test conditions concerning corrosion

Envisaged Reynolds number for TBM Re = some 100 in accordance with MHD calculations of L. Bühler, KIT

	PICOLO 22 cm/s	PICOLO 10 cm/s	PICOLO 1 cm/s	TBM 0.1 cm/s
Reynolds $Re= u_{fl}\ d_{hyd}/\nu_{fl}$	22 * 0.8 / $0.105 * 10^{-2}$ = (17.6 /10.5) $*10^{4}$ = 16,800	10 * 0.8 / $0.105 * 10^{-2}$ = (8 /10.5) $*10^{4}$ = 7,620	1 * 0.8 / $0.105 * 10^{-2}$ = (0.8 /10.5) $*10^{4}$ = 762	0.1 * 3.25 / $0.105 * 10^{-2}$ = 0.325/10.5 * 10^{4} = 310 100<Re<1000
	turbulent	Main part turbulent	laminar	laminar
Schmidt $Sc = \nu_{fl} / D$	$0.105 * 10^{-2}$ / $1,185 * 10^{-6}$ = 860	= 860	= 860	= 860
Sherwood number for laminar flow in Picolo is assumed to be 3.66 “Inlet” corrections have to consider the Graetz number : G = Re Pr d / l				

Analyses of ITER-TBM tests vs. state-of-the-art

Karlsruhe Institute of Technology

Deficits towards ITER-TBM testing and modeling

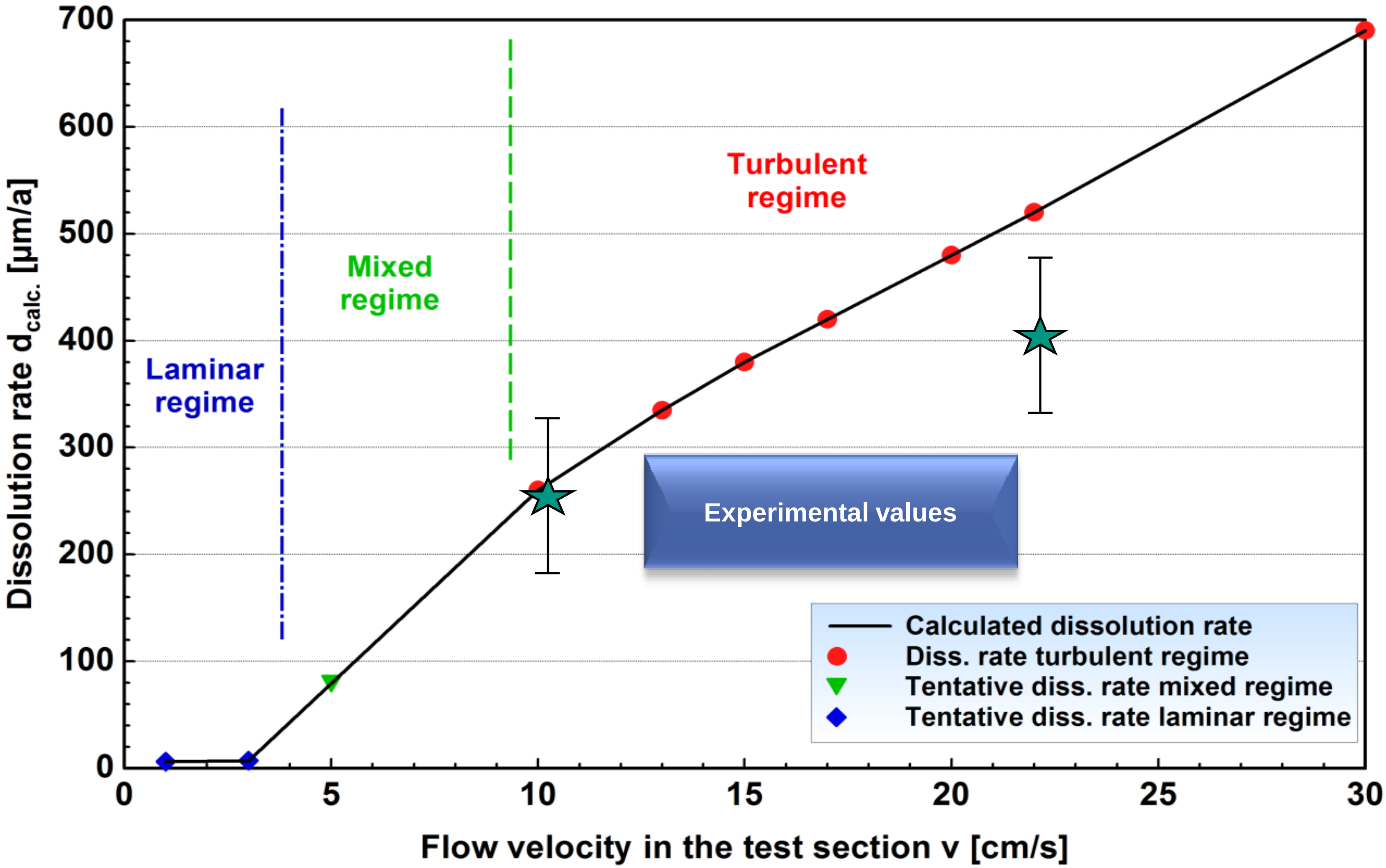
Generally:
Quantitative corrosion-testing in dynamic lead-lithium eutectic at TBM- and DEMO-relevant conditions

Detailed deficits and/or key issues:

- Channel configuration different to all loop tests
- Corrosion in TBM geometries and flow velocity profiles “unknown”
- Influence of magnetic field on corrosion
- Retention of precipitates inside of TBM
- Effects of impurities in Pb-15.7Li on corrosion/precipitation
- Composition changes of Pb-15.7Li during operation
- H_2-effects on corrosion and precipitation behavior
- Effective purification system
- Stability of barriers under TBM conditions
- Validation of modeling tools and codes
- Risk assessment for system blocking

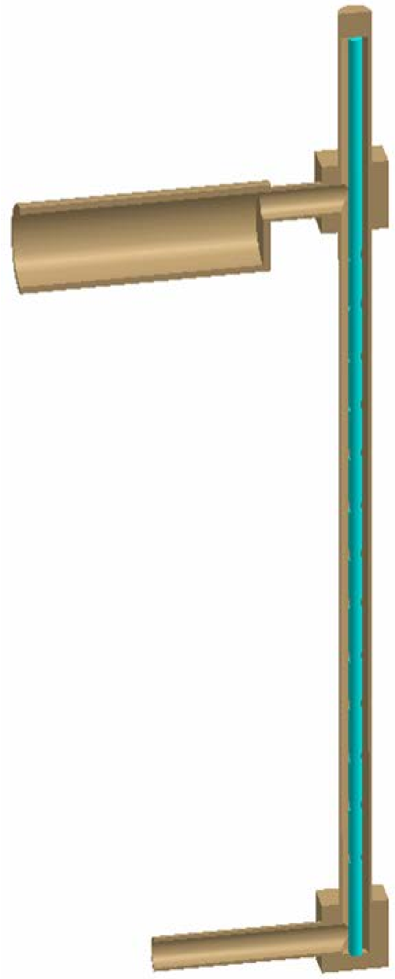
➔ **Definition of activities for development towards DEMO**

Modeling of corrosion with MATLIM code for 550°C



Simulation models of test section in PICOLO

3-D model of test section



Boundary Conditions

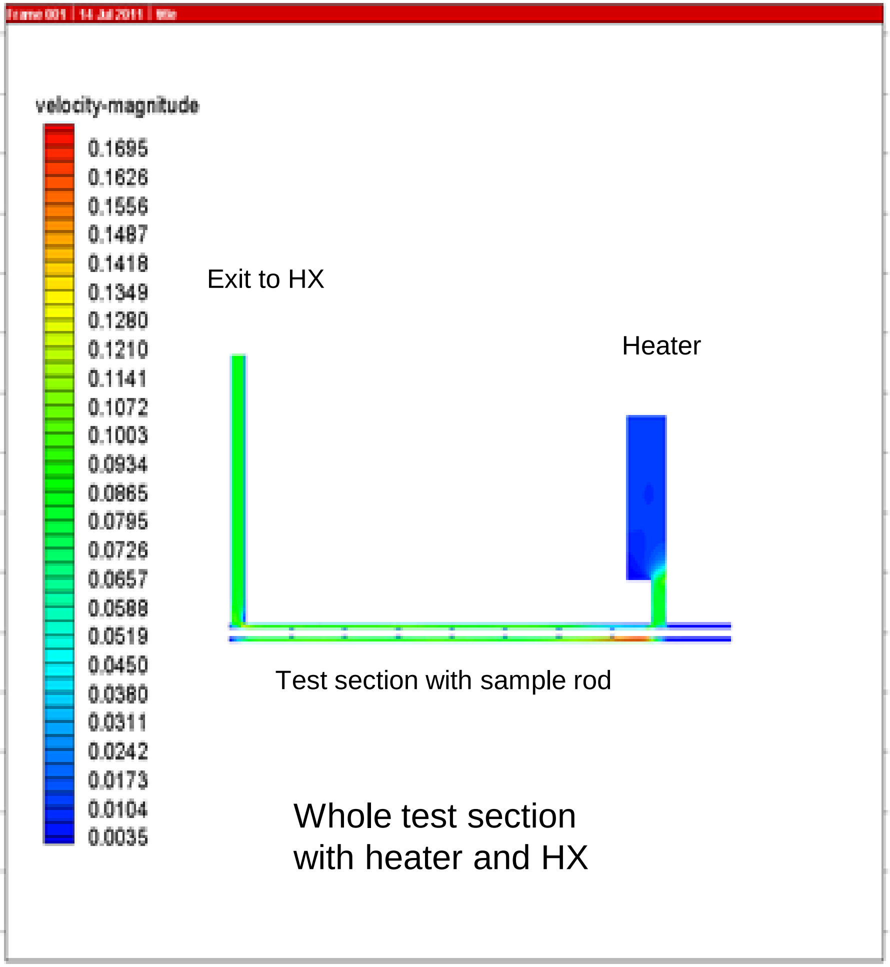
Input Conditions

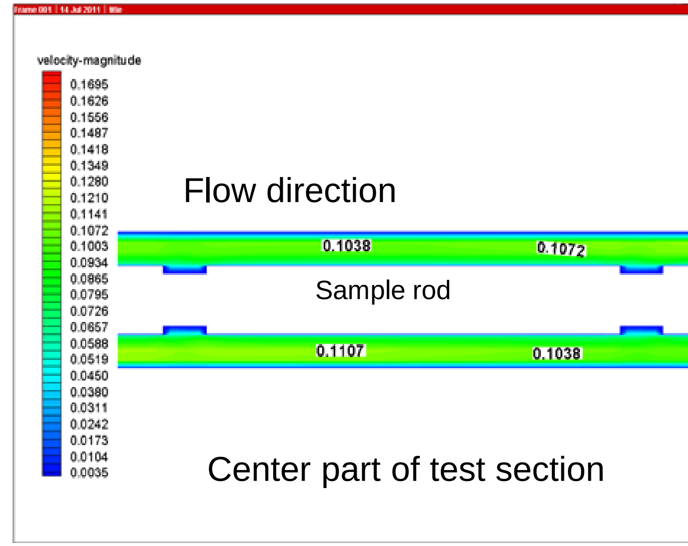
- V = 55 l/h (or ~ 0.1 m/s), T = 550°C
- definition of inlet, outlet and wall (heat insulation)
- thermo-hydraulic parameters: density, specific heat, thermal conductivity, viscosity

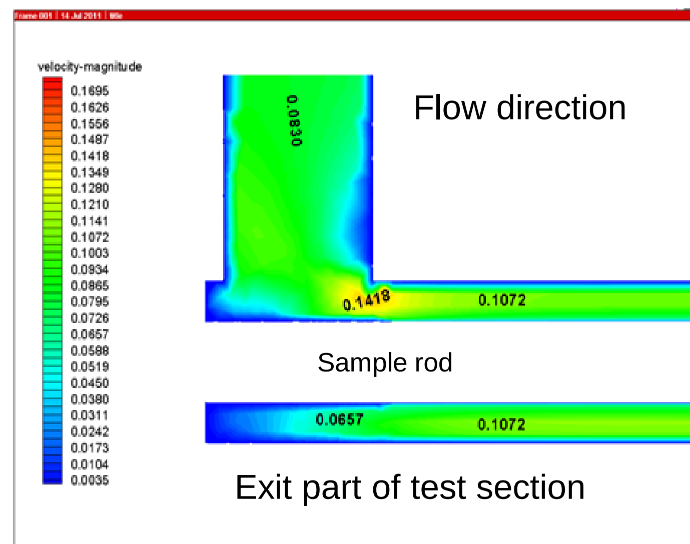
Solutions

- the flow field distribution along the test section
- the pressure drop between input and output
- the average flow velocity across the section in gap
- the flow velocity around samples

Results of simulation of test section in PICOLO







Conclusions and open issues

Conclusions

- The corrosion rate of RAFM steels in PbLi depends strongly on temperature and flow velocity. At ”high” flow velocity (22 cm/s) and ”lower” temperature (480°C), ca. 80 µm/year, whereas at ”lower” flow velocity (10 cm/s) and ”higher” temperature (550°C), ca. 250 µm/year can be reached.
- Al-based coatings on structural components can minimize the corrosion attack in liquid Pb-15.7Li up to 550°C very successful.
- Modeling tools to describe the corrosion behavior of RAFM steels in flowing PbLi under different thermo hydraulic and/or magnetic field conditions are available.

Open issues

- Screening impact of impurities on corrosion issues
- Testing under TBM relevant conditions with steep thermal gradients
- Development of sensors and sampling systems for qualification
- Validation of modeling codes by TBM relevant test values
- Work on extrapolation towards DEMO