OAK RIDGE
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Perspectives of a DCLL blanket for a future strong magnetic field fusion device

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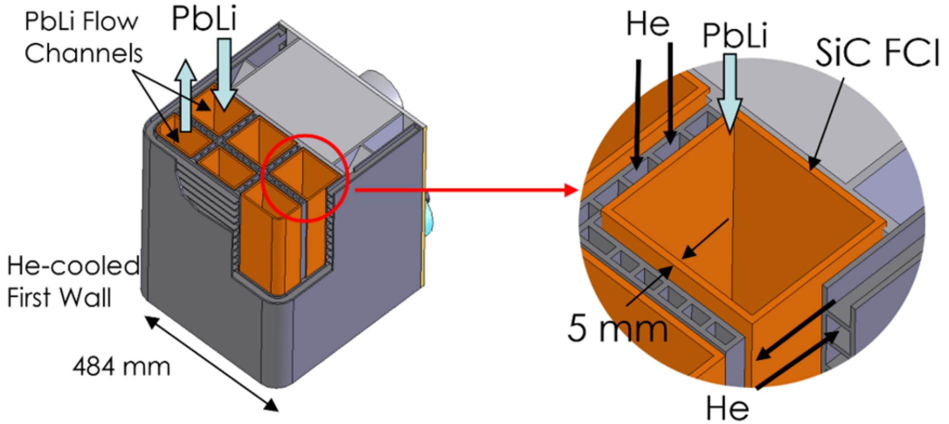
The main goal is to access feasibility of high magnetic field / high temperature DCLL blanket

- *Dual Coolant Lead Lithium* (DCLL) blanket is considered worldwide for implementation in future fusion devises
- High MHD pressure drop (1) and corrosion of RAFM (2) are the two feasibility issues. Both are strongly affected by a magnetic field
- In the US, a Fusion Pilot Plant (FPP) is considered as a near-term future machine aiming at net electricity production. Strong magnetic field B up to 20 T is envisaged
- All recent PbLi blanket studies are limited to B<5 T for outboard (OB) and B<10 T for inboard (IB)*

*S. Smolentsev et al., *MHD Thermohydraulic Analysis and Supporting R&D for DCLL Blanket in the FNSF*, Fusion Engineering and Design, 2018.



DCLL blanket concept

Solution towards high-temperature (T~700°C), high-efficiency (η>40%)

Reduced activation ferritic/martensitic (**RAFM**) steel as structural material

PbLi flows slowly (V ~ 10 cm/s) in large poloidal ducts (D ~ 20 cm)

A pressurized (~ to 8 MPa) **He gas** is used to cool the RAFM

SiC FCI is used to electrically and thermally decouple PbLi and RAFM

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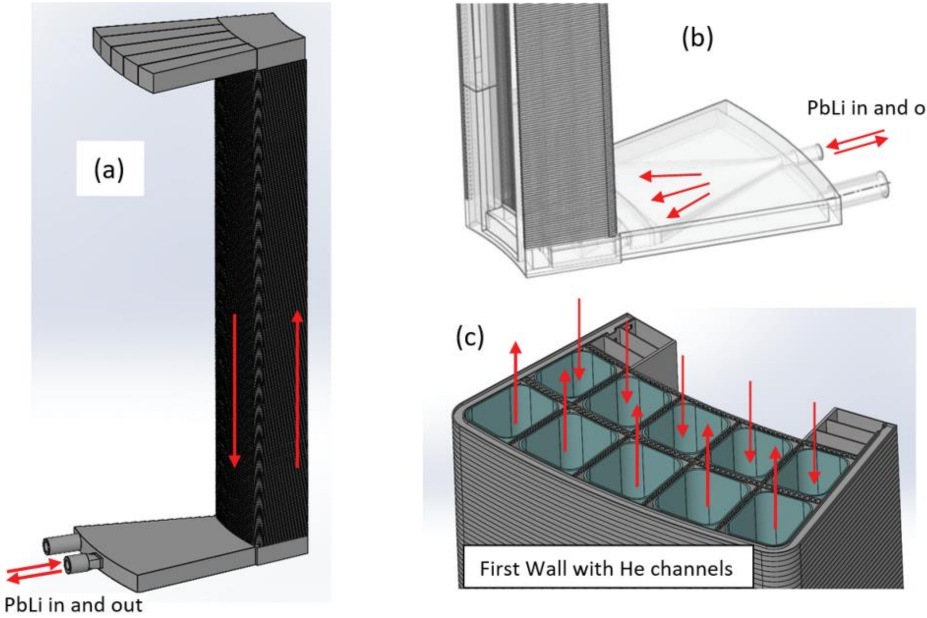
MHD flows, heat transfer and corrosion are accessed for the DCLL IB blanket in FNSF for B=10-20 T, and PbLi Tout=500-700°C

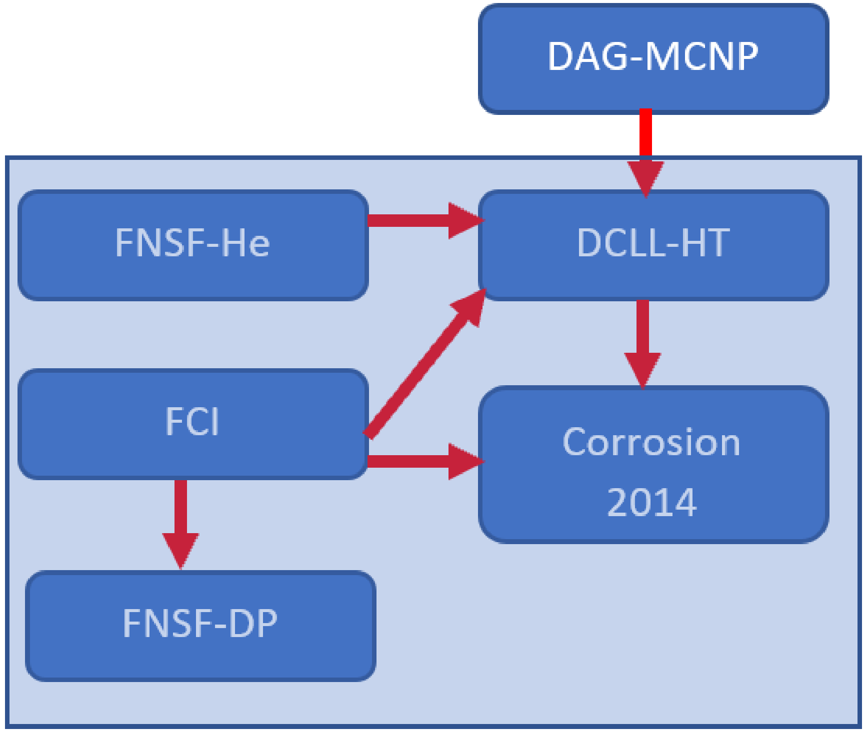
- The **Fusion Nuclear Science Facility** (FNSF)* is a tokamak-based machine with 518 MW of fusion power, a 4.8-m major radius, a 1.2-m minor radius, and a machine average neutron wall loading of ~1 MW/m^2.
- IB blanket features:
  - ✓ 5 front ducts facing the plasma with PbLi flowing upwards
  - ✓ 5 rear ducts with PbLi flowing downwards
  - ✓ 180° turn at the top
  - ✓ PbLi inlet and outlet manifolds at the bottom
  - ✓ He-cooled RAFM structure, including the FW
  - ✓ All PbLi ducts have SiC FCI

ORNL design for the DCLL IB blanket in FNSF



*C. Kessel et al., *Overview of the Fusion Nuclear Science Facility…*, Fusion Engineering and Design, 2018

Integrated modeling using custom-made FORTRAN codes



FNSF-He: He flows and heat transfer in the cooling channels in the FW and blanket RAFM structure (correlations, analytical solutions)

FCI[1]: 2-D computations for fully-developed PbLi poloidal flows with SiC FCI (finite-difference)

DCLL-HT[1]**:** 3-D computations of temperature field in the poloidal ducts (finite-difference)

FNSF-DP[2]: $\Delta P = \sum_{i=1}^{N} \Delta P_i\,,\ \ \Delta P_i = k_i(Ha_i, Re_i, N_i)\frac{\rho U_i^2}{2}$ (correlations)

Corrosion 2014[3]: 2-D and 3-D computations for corrosion of RAFM and transport of corrosion products in PbLi (finite-difference)

DAG-MCNP: Volumetric heating[4]

1. S. Smolentsev et al., *Magnetohydrodynamic and Thermal Issues of the SiCf/SiC Flow Channel Insert*, Fusion Science and Technology, 2006.
2. S. Smolentsev et al., *MHD Thermohydraulics Analysis and Supporting R&D for DCLL Blanket in the FNSF*, Fusion Engineering and Design, 2018.
3. S. Smolentsev et al., *Numerical Study of Corrosion of Ferritic/Martensitic Steels in the Flowing PbLi with and without a Magnetic Field*, Journal of Nuclear Materials, 2013.
4. T. Bohm, University of Wisconsin, *Private communication*, June 2020.

Computations are performed for central front/rear duct

- **RAFM wall: 4 mm**
- **SiC/SiC FCI: 5 mm, σ=10 S/m, k=5 W/m-K**
- **PbLi gap (between SiC and RAFM): 2 mm**
- **PbLi bulk flow (inside the FCI box): 29.7 cm (tor) x 20.0 cm (rad)**
- **Poloidal length: 7.04 m**
- **NWL: 0.86 MW/m^2**
- **Surface heat flux: 0.16 MW/m^2**
- **He flow: "He-1" (one circuit), "He-2" (two circuits)**

☐ **PbLi Tout=500-700°C**

☐ **B=10-20 T**

DESIGN GOALS and LIMITATIONS:

PbLi Tout as high as possible

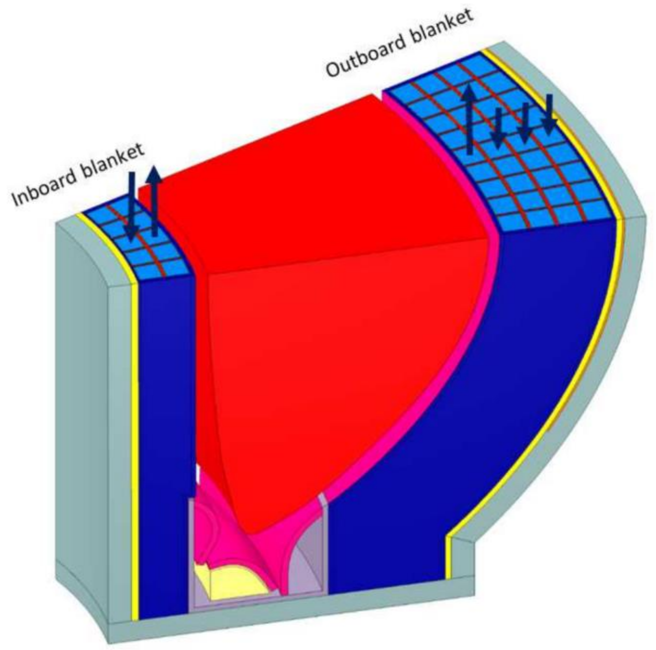
FW RAFM T < 550°C

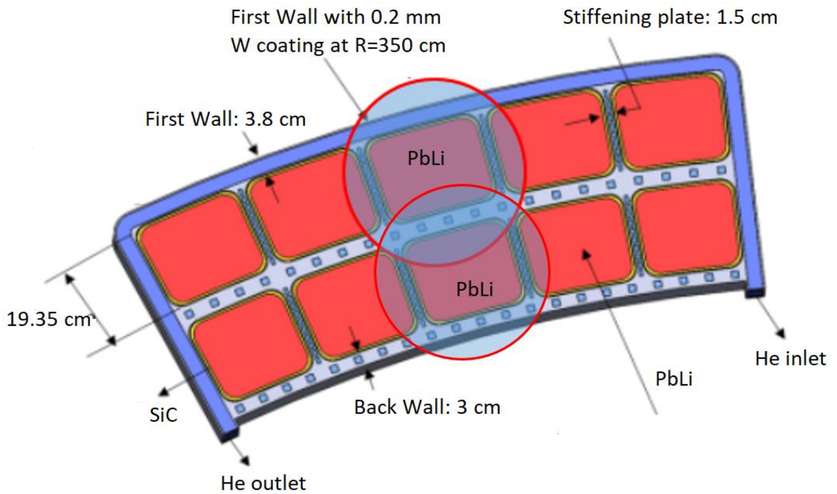
Blanket PbLi MHD ΔP < 2 MPa

RAFM-PbLi T < 470°C

RAFM wall loss < 20 μm/y

FCI ΔT < 150 K



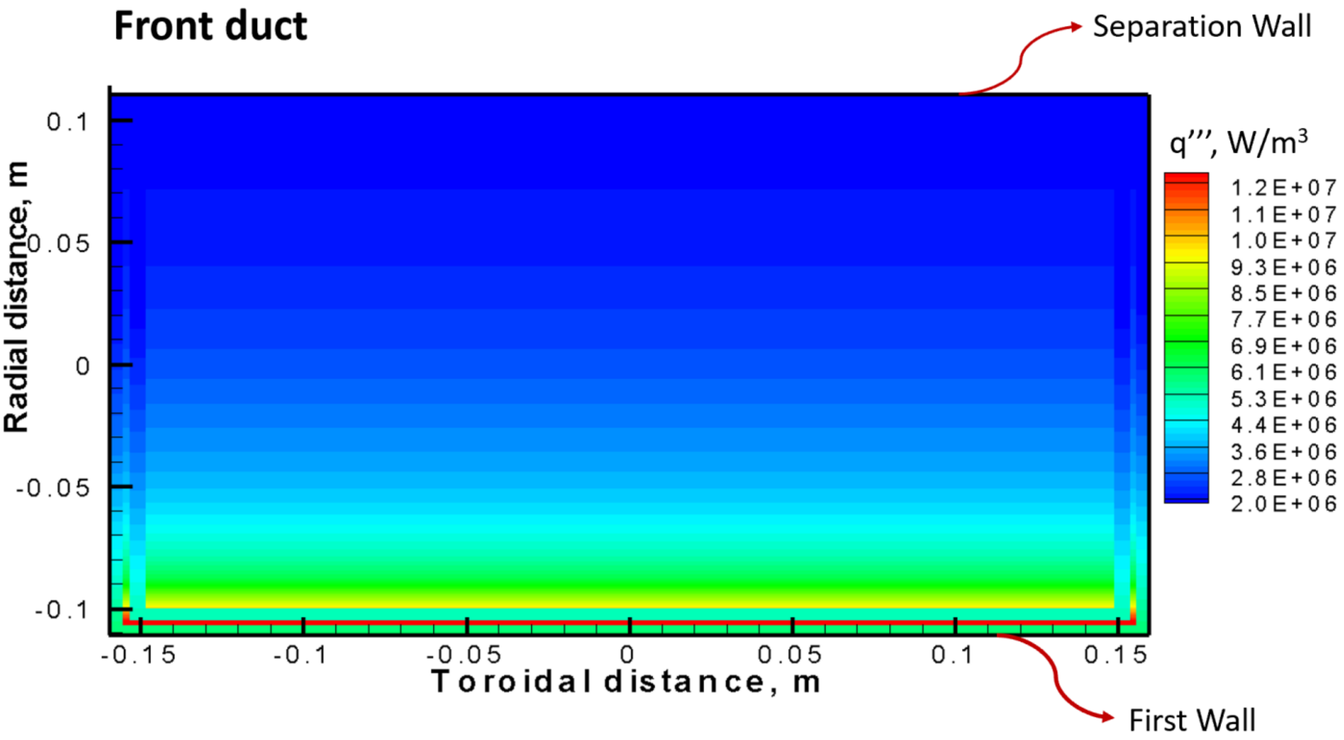


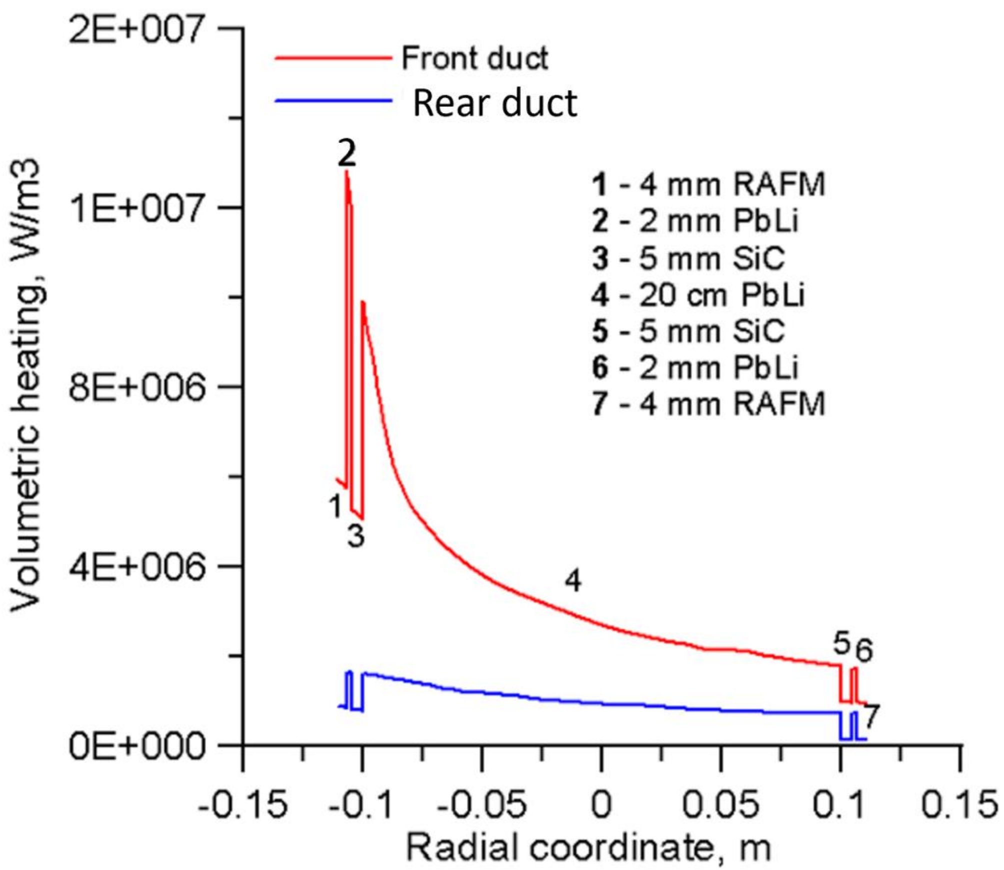
Two He-cooling schemes

He-1: He flows in FW at Tin/Tout=350/450 °C, then proceeds to the blanket RAFM structure in the breeding zone

He-2: Two independent He circuits, 1st is the FW at Tin//Tout=350/450°C, 2d is RAFM at Tin=350 °C

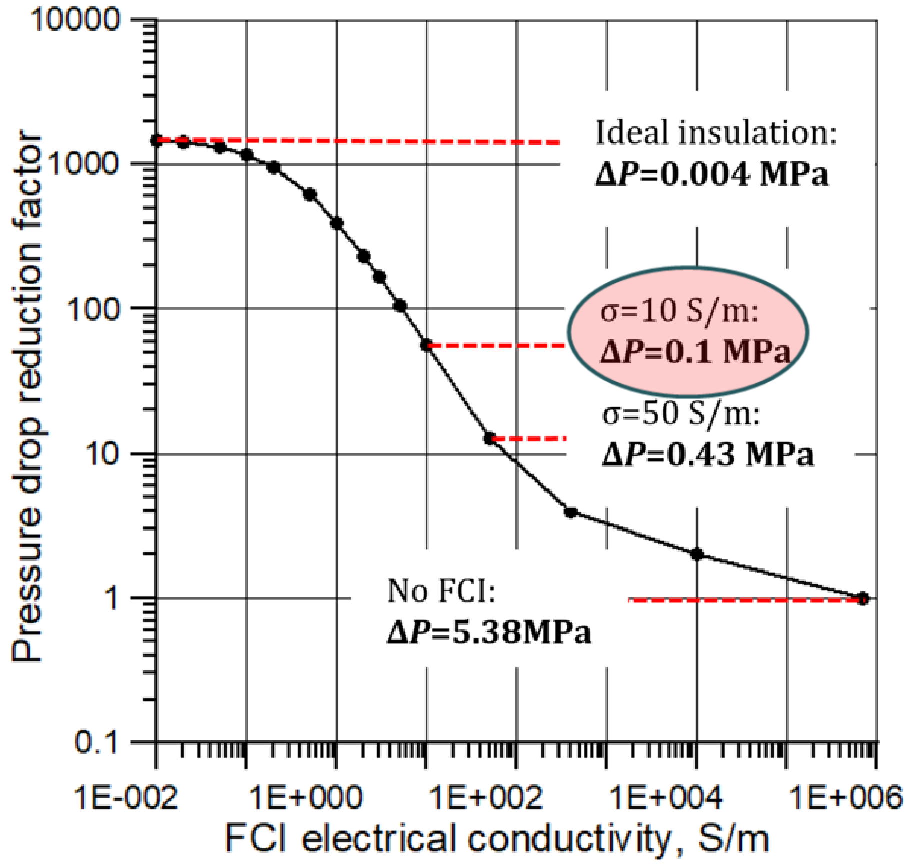
Volumetric heating computed with DAG-MCNP



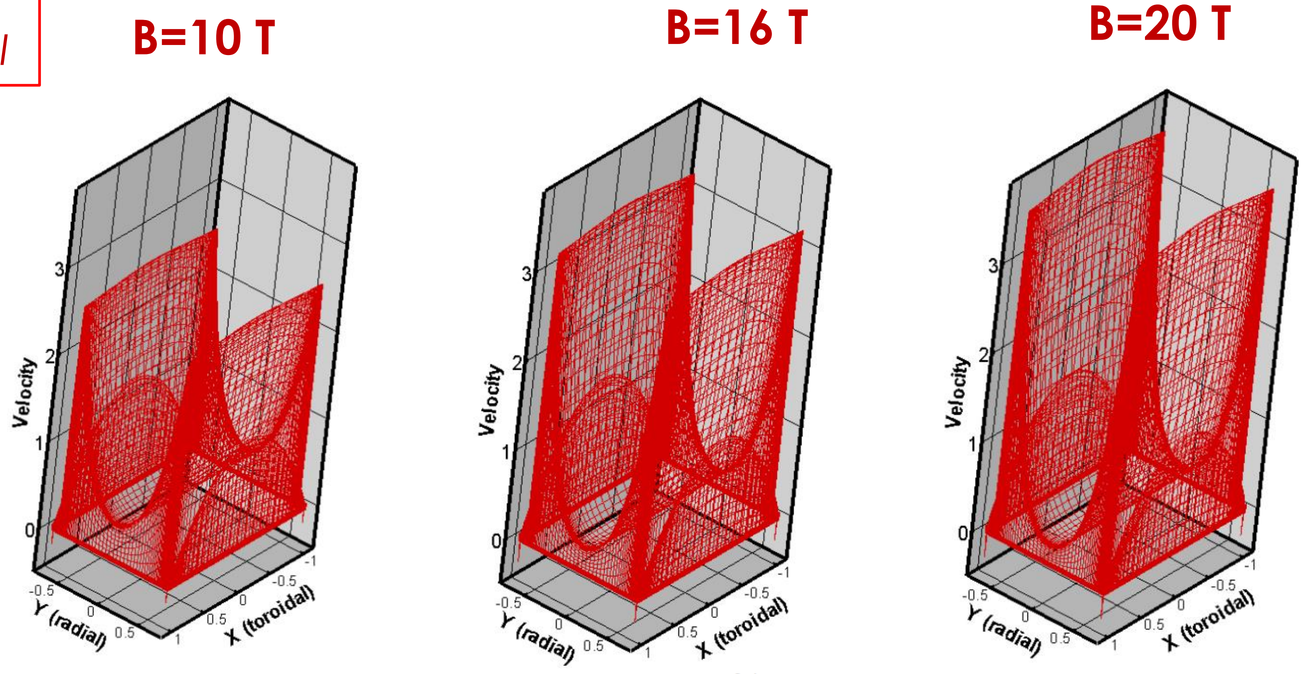


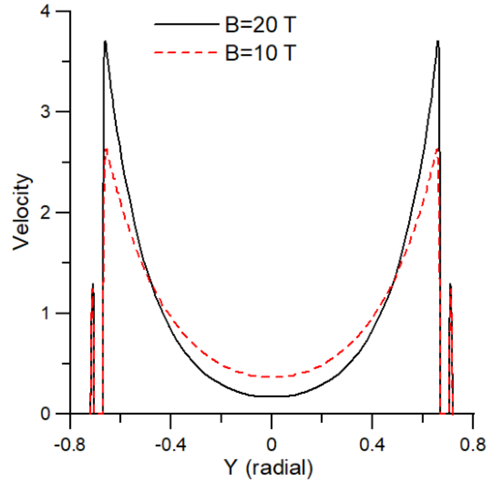
PbLi MHD flows in poloidal ducts - MHD pressure drop can be reduced to ~ 0.1 MPa with 5 mm SIC FCI at σ=10 S/m

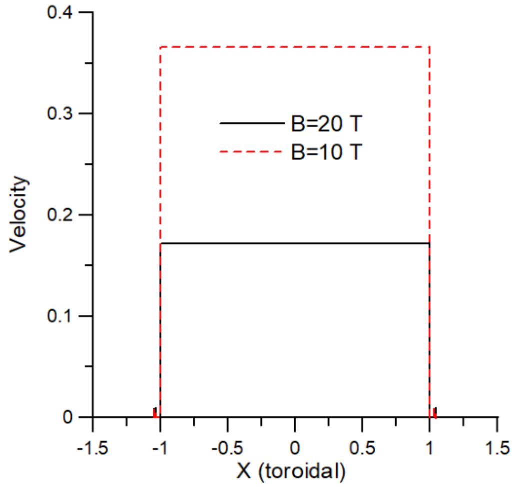
Pressure Drop Reduction Factor =
Pressure drop without FCI / Pressure drop with FCI



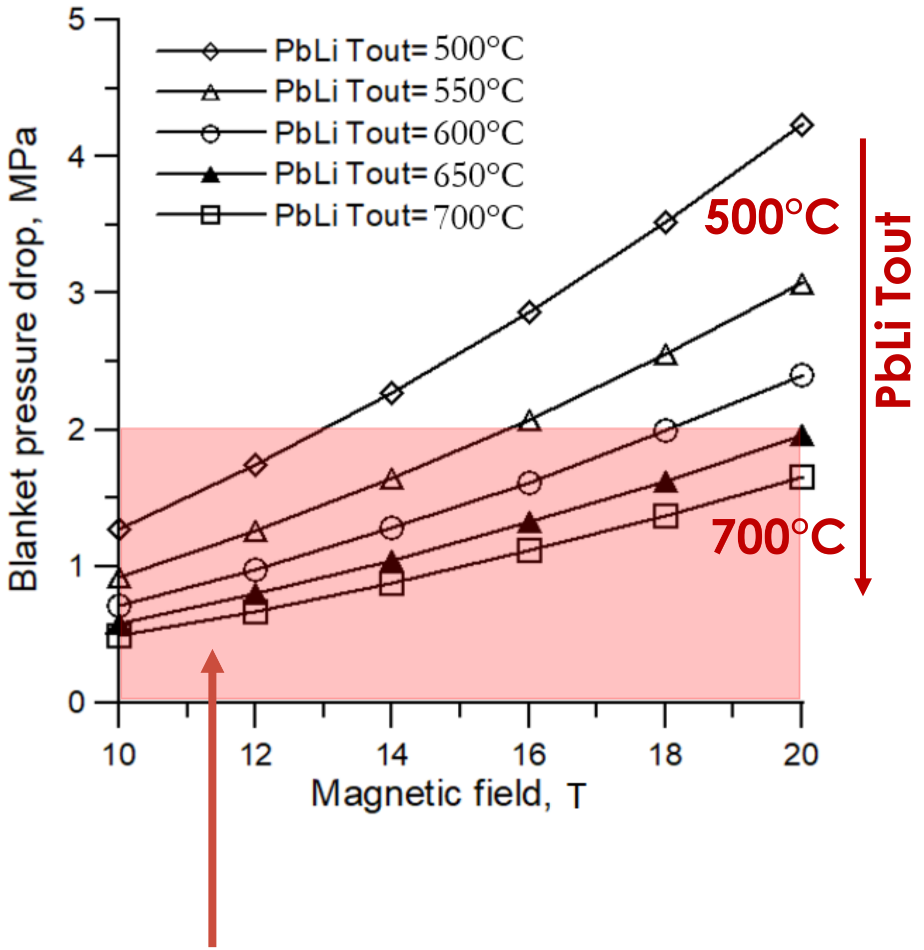
B=20 T   PbLi Tin/Tout=350/550°C


B=10 T   **B=16 T**   **B=20 T**





Blanket pressure drop – *HT DCLL has lower MHD pressure drop because of lower PbLi flow rate. High B-field DCLL is feasible*



“DESIGN Window” , blanket Δ*P*<2 Mpa

$$\Delta P = \Delta P_{Man} + \Delta P_{Pol} + \Delta P_U + \Delta P_{Rad}$$

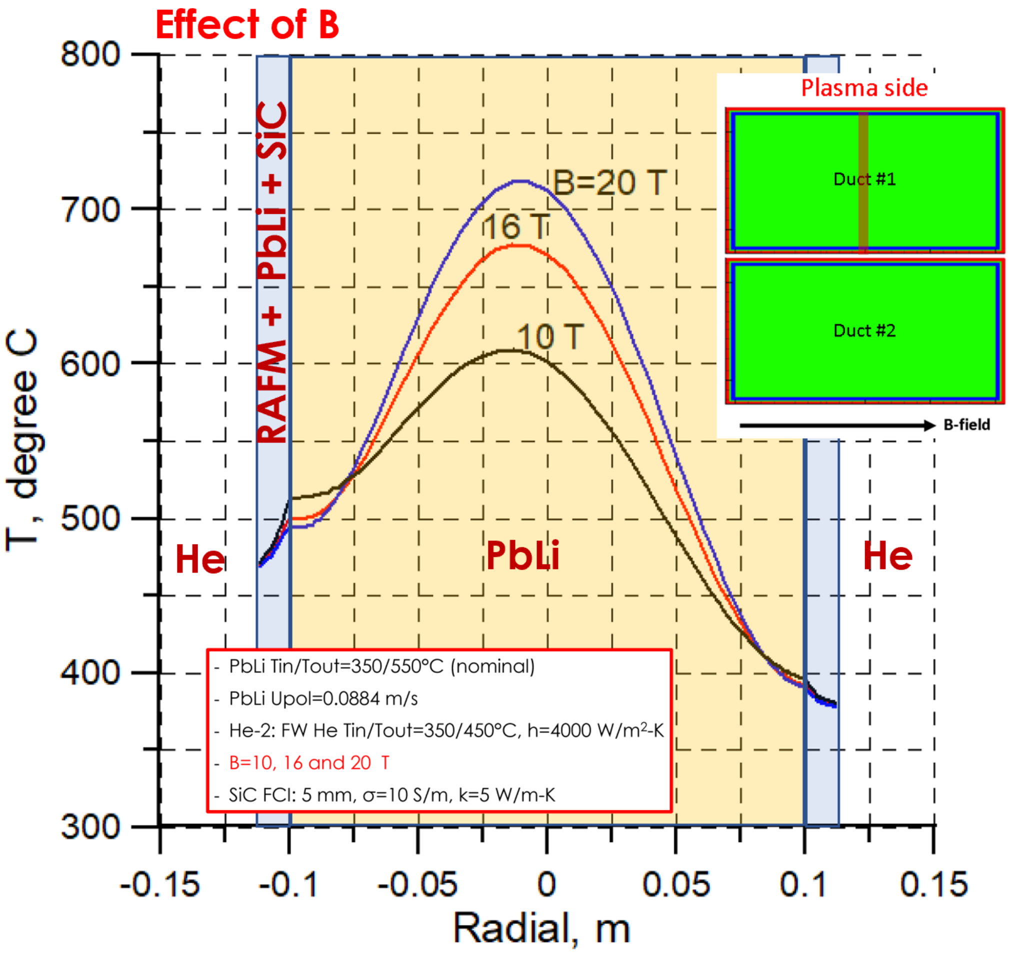
ΔP_{Man} – Inlet and outlet manifolds
ΔP_{Pol} – Poloidal ducts
ΔP_U – U-turn at the top
ΔP_R – Radial ducts

Composition of the MHD pressure drop for PbLi Tout=550°C, MPa

B	10 T	16 T	20 T
ΔP_{Man}	0.401	0.768	1.042
ΔP_{Pol}	0.023	0.057	0.076
ΔP_U	0.068	0.175	0.274
ΔP_{Rad}	0.426	1.074	1.669
ΔP	0.918	2.074	3.061

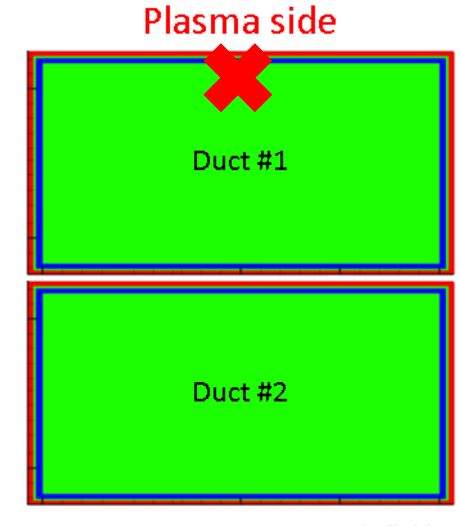
Summary of the 3-D temperature computations

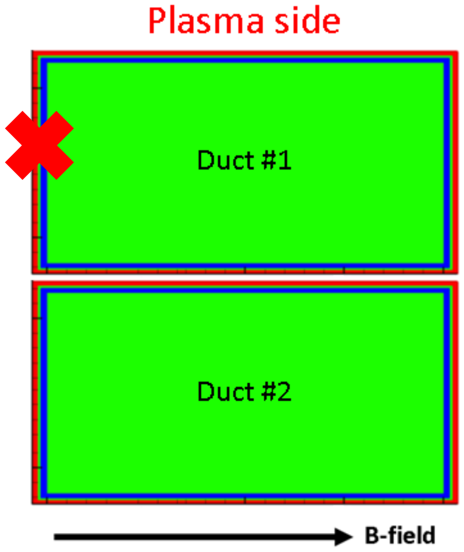
- Temperature variations in all directions with the highest temperature gradient in the radial direction in the front duct
- About 80% of PbLi ΔT in in the front duct
- Significant heat loss from PbLi into He. Example: Nominal PbLi Tout=550°C, computed Tout=540°C (He-1) and 510°C (He-2). More heat loss at higher Tout
- Strong effect of B in the PbLi bulk flow and lesser effect in the RAFM/PbLi gap/SiC
- Strong impact of He flow on RAFM/PbLi interfacial temperature
- He-1: higher corrosion / lower heat leakage
- He-2: lower corrosion / higher heat leakage

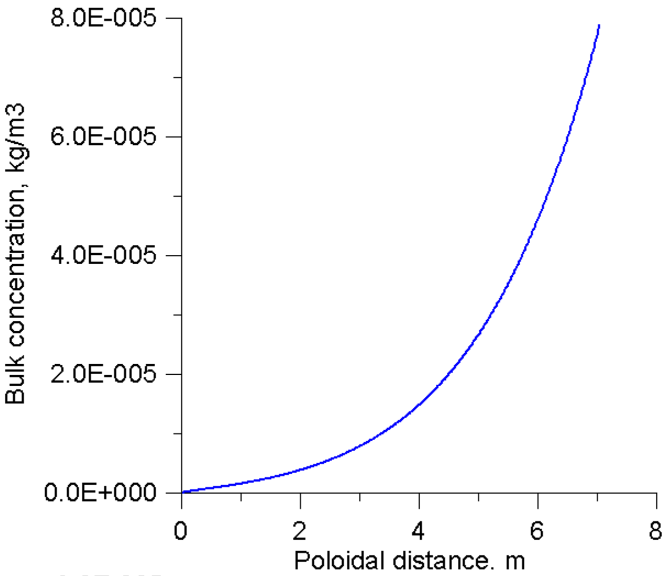


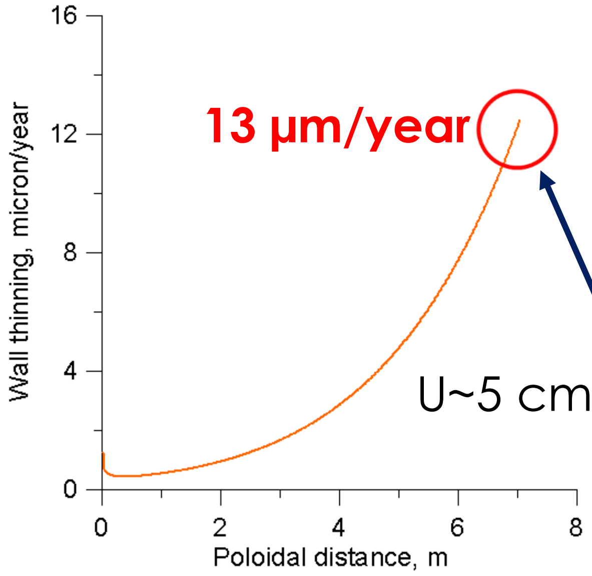
- PbLi Tin/Tout=350/550°C (nominal)
- PbLi Upol=0.0884 m/s
- He-2: FW He Tin/Tout=350/450°C, h=4000 W/m^2-K
- B=10, 16 and 20 T
- SiC FCI: 5 mm, σ=10 S/m, k=5 W/m-K

Example of corrosion computations – *higher corrosion in the side-wall gap, lower in the Hartmann-wall gap*



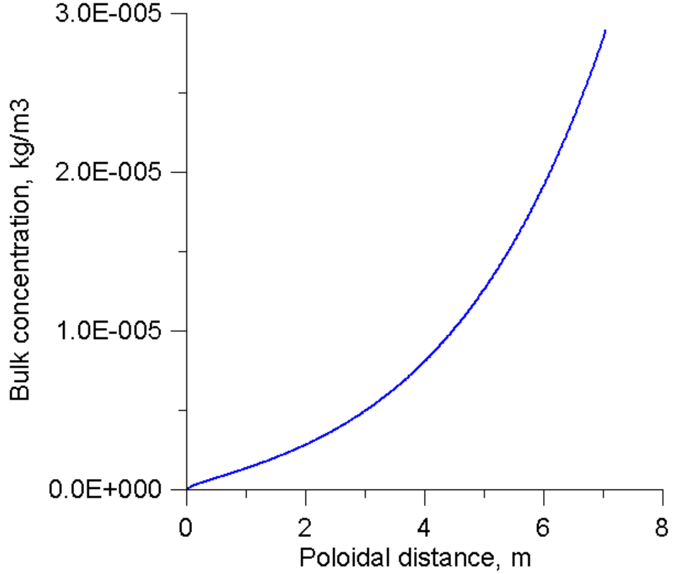


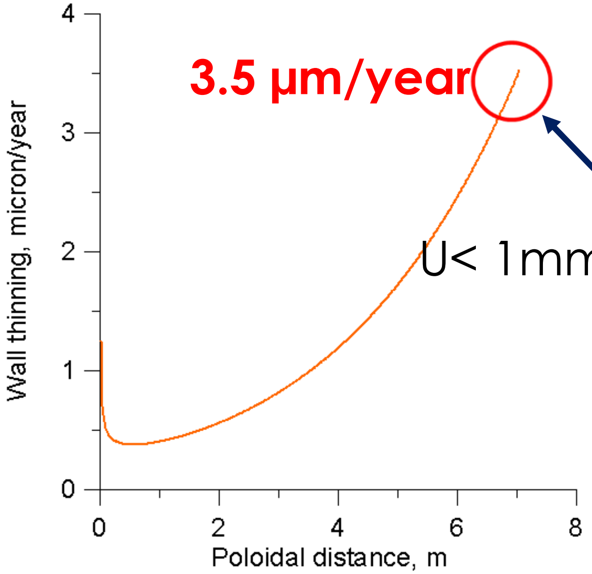




13 µm/year

U~5 cm/s

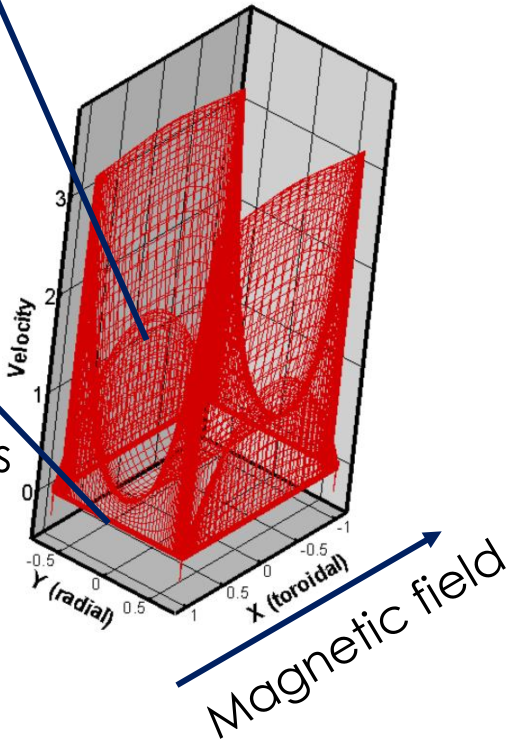




3.5 µm/year

U< 1mm/s

PbLi Tin=350°C
PbLi Tout=550°
B=16 T
He-2
FCI σ=10 S/m
FCI k=5 W/m-K



Summary of the computed results

PbLi T_{out} (°C) (nominal)	**PbLi U_{pol} (m/s)**	**ΔP (MPa)**		**FCI ΔT (K)**	**Max $T_{RAFM/PbLi}$ (°C)**		**Max corrosion loss (μm/year)**	
		16 T	**20 T**		**He-1**	**He-2**	**He-1**	**He-2**
550	0.088	2.07	3.32	< 150	487 (rear)	468 (front)	< 20	< 20
600	0.071	1.62	2.40	< 150	503 (rear)	474 (front)	> 20	<20
650	0.059	1.32	1.96	< 150	512 (rear)	480 (front)	> 20	<20
700	0.051	1.11	1.66	<150	522 (rear)	487 (front)	> 20	<20

CONCLUSIONS

Feasibility of high-B/high-T DCLL blanket has been accessed for the first time

- The maximum allowable magnetic field B_{max} increases with PbLi Tout. HT DCLL has lesser ΔP than LT DCLL allowing for higher B_{max}
- For LT DCLL (PbLi $T_{out} < 500°C$), B_{max} is 13 T
- For HT DCLL, B_{max}=16 T for PbLi T_{out}=550°C and B_{max}=20 T for PbLi T_{out}=650°C
- A high B-field DCLL blanket design might be feasible, providing corrosion limitations are met
- A DCLL design at B=16 T and PbLi T_{out}=550°C was found feasible from both the pressure drop and corrosion viewpoint
- The feasibility of HT DCLL blanket at PbLi temperatures higher than 550°C is still questionable because of high heat losses from PbLi into He and corrosion losses
- An effective He-cooling scheme and low thermal conductivity FCI are two important design considerations as the He flow controls the RAFM-PbLi interfacial temperature and both the He flow and the FCI affect the heat loss from PbLi

THANK YOU !

QUESTIONS ?