

TOFE-21, Anaheim, CA, USA, November 2014

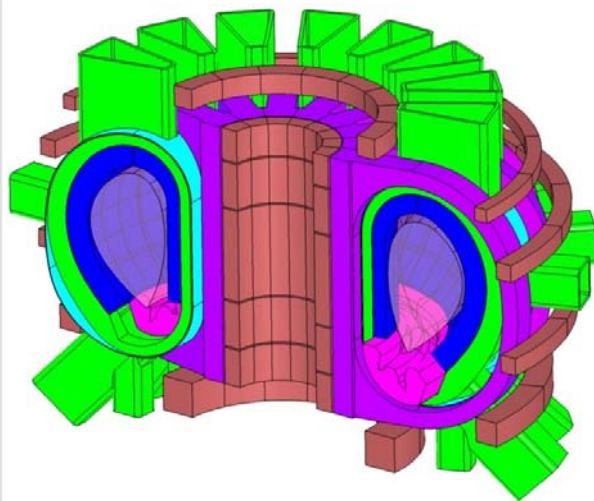
## Development of Sandwich Flow Channel Inserts for an EU DEMO Dual Coolant Blanket Concept

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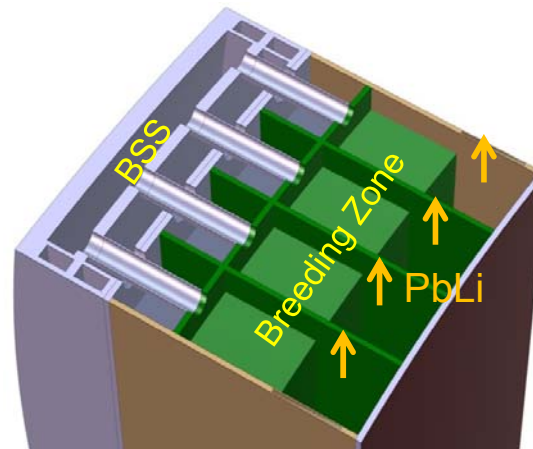
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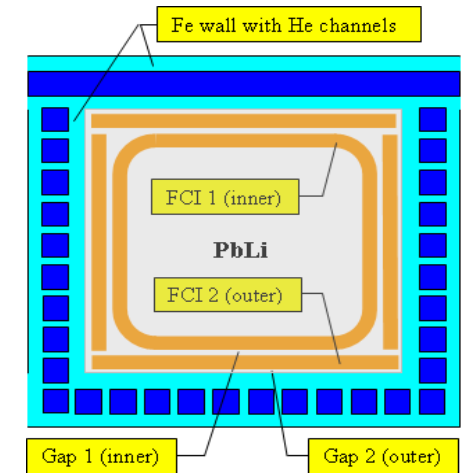
EU PPPT DEMO



DCLL 2014



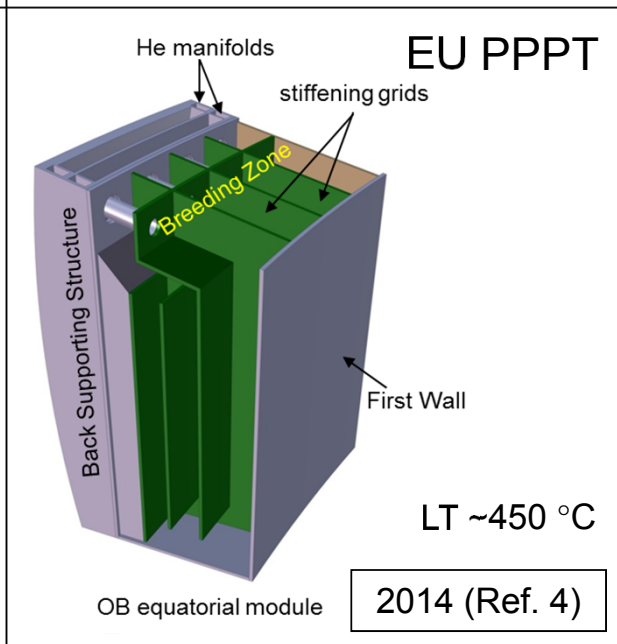
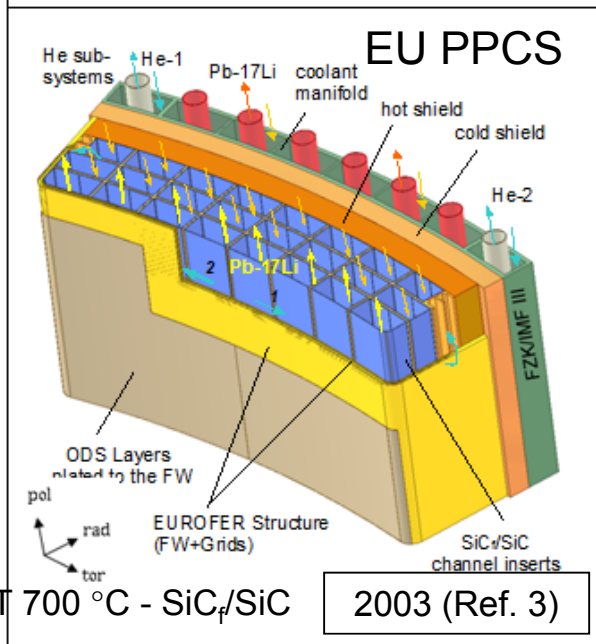
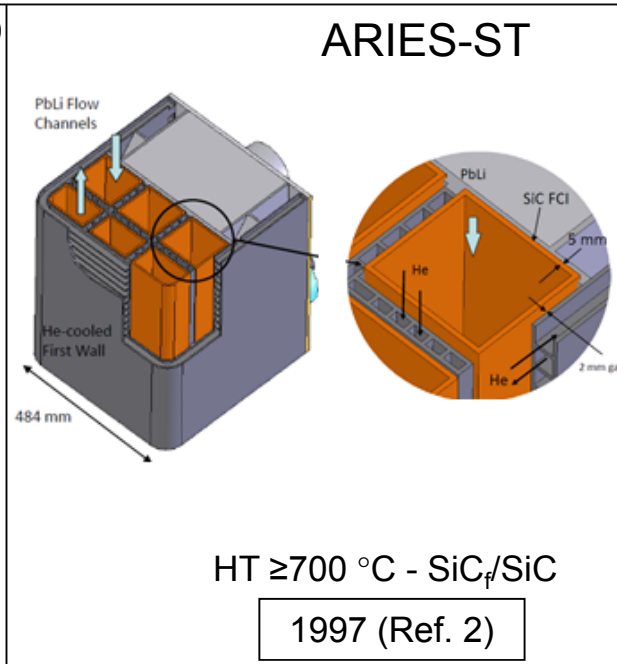
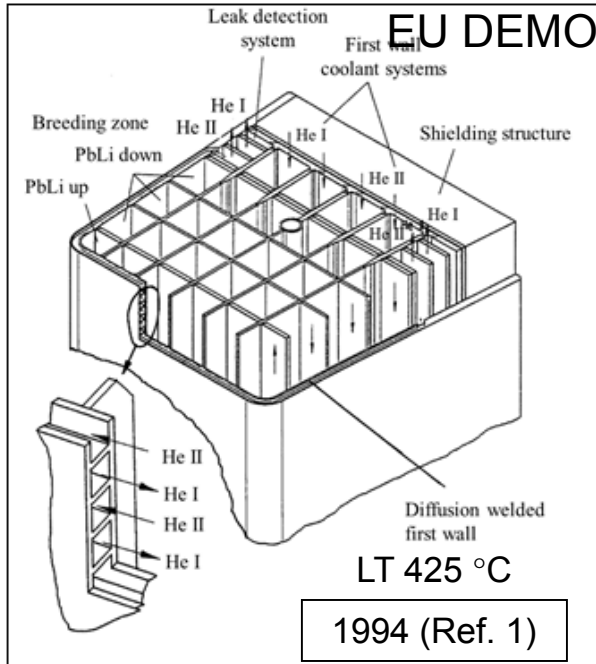
Integration in DEMO 2014



Nested FCI

- 1. Why do we need flow channel inserts (FCIs)?**
- 2. Basic design principles for FCI**
- 3. Requirements for FCI materials**
- 4. Selected materials and their major properties**
- 5. Several different FCI design types (pros and cons)**
- 6. Demonstration of manufactured FCIs**
- 7. Investigations of starting materials and post-examination of mock-ups**
- 8. Conclusion and outlook**

# DCLL Blanket Concept Evolution

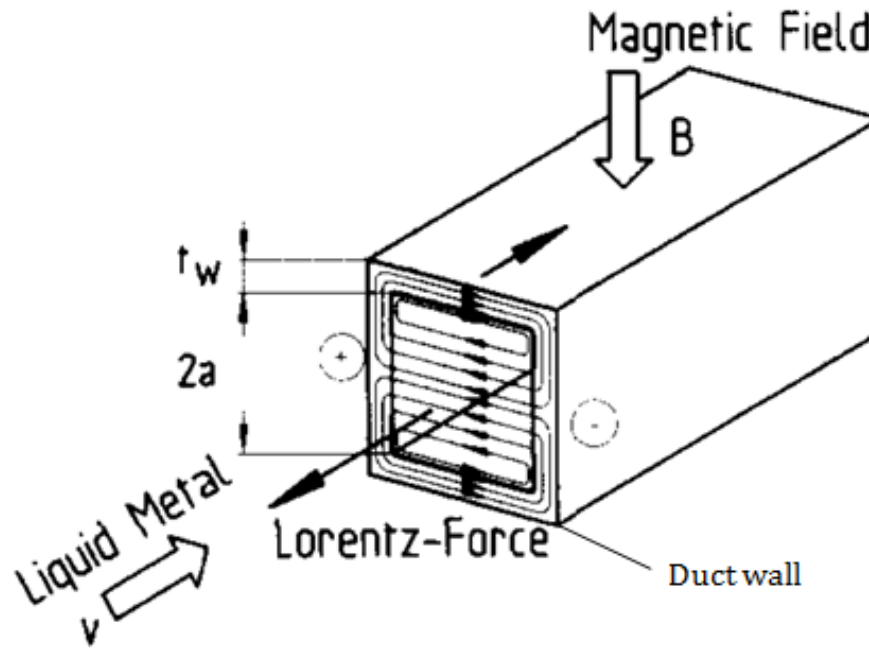


Some common features:

- Dual coolants:
  - He for cooling of structures
  - PbLi as breeder and self-cooling medium
- Poloidal PbLi flow  $\perp$  magnetic field

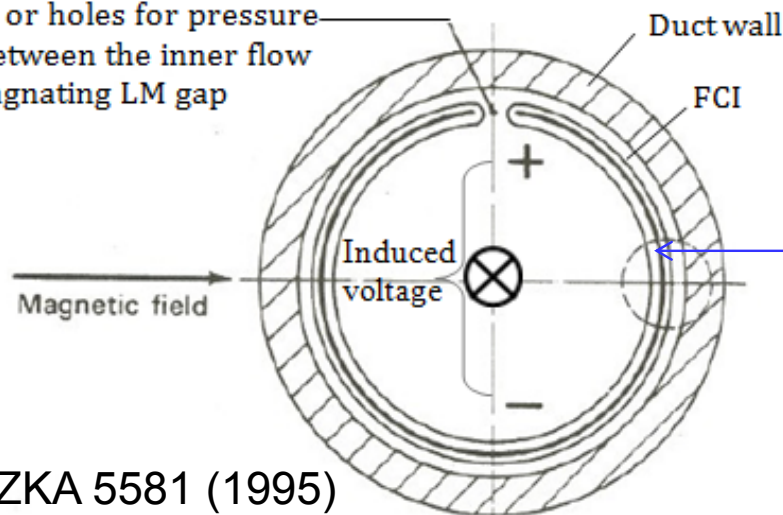
[1] S. Malang et al., FZKA 5581, 1995.  
 [2] D. K. Sze et al., Fus Eng Des, 48, 371 (2000).  
 [3] P. Norajitra et al., FZKA 6780, 2003.  
 [4] I. Fernández, D. Rapisarda, et al., this conference.

# Fundamental Problem with LM Flow Through the Magnetic field



→ MHD pressure loss !

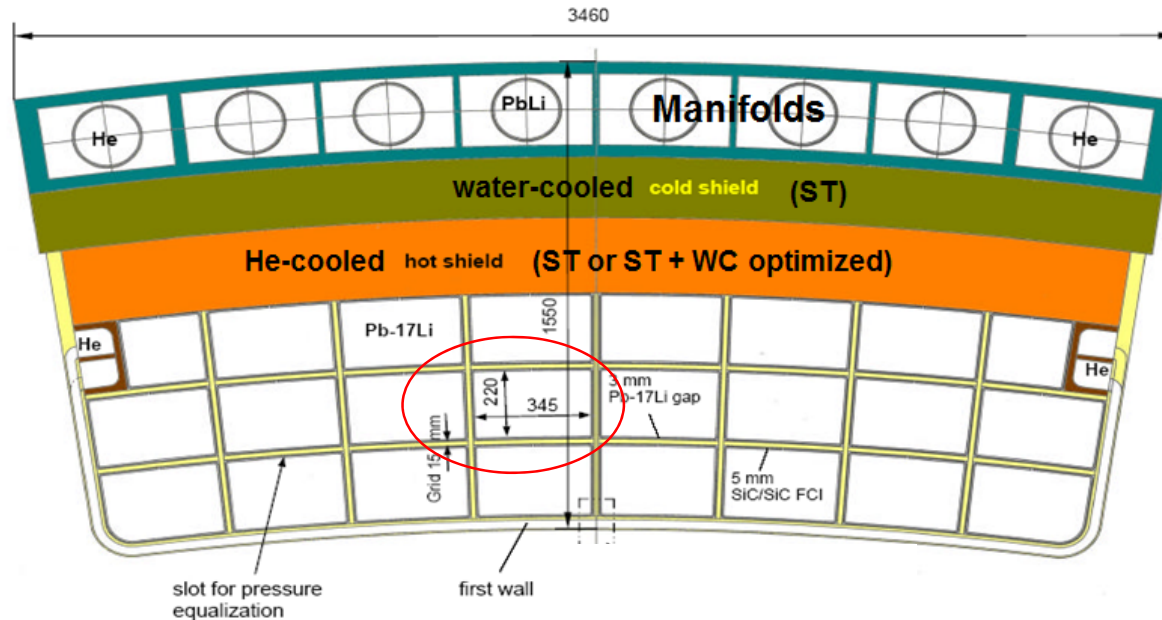
Longitudinal slot or holes for pressure compensation between the inner flow and the stagnating LM gap



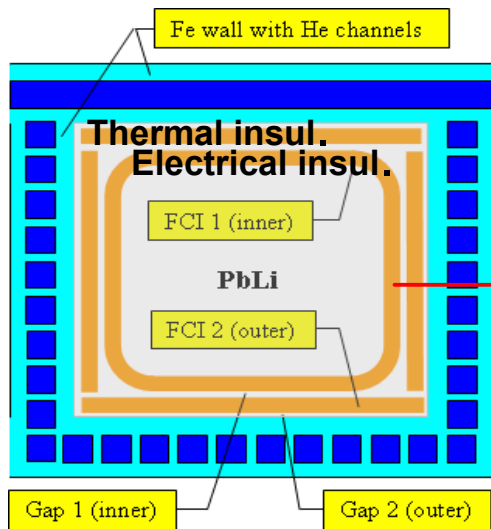
Remedy by the use of FCI (e.g. of sandwich type)

S. Malang et al, FZKA 5581 (1995)

# Considerations about Sandwich FCI Design

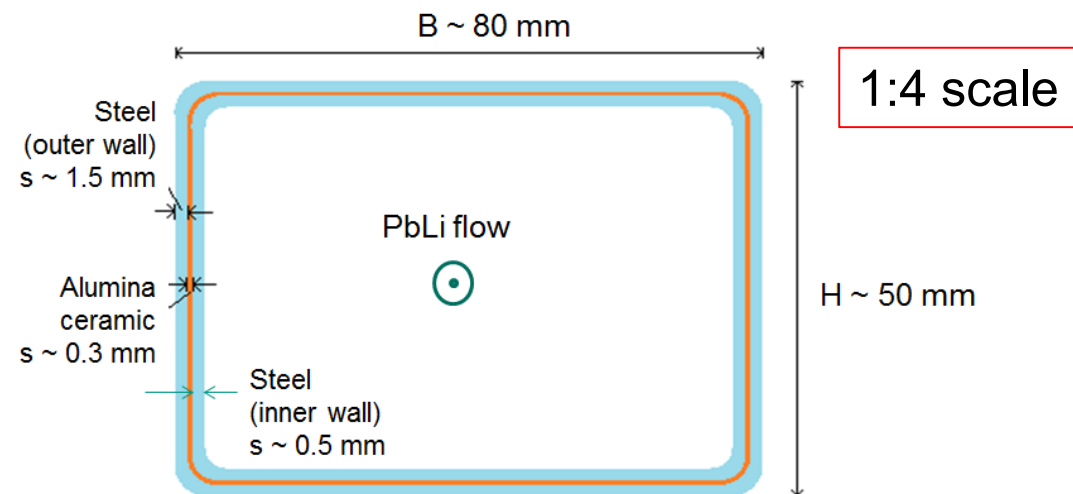


[P. Norajitra et al, EU PPCS-C, FZKA 6780, 2003]



**Nested FCI**

[S. Malang et al, FS&T, 60, 249 (2011)]



## Requirements:

- High electrical resistance (FCI inner part)
- *Good thermal insulation (poor thermal conductivity) (FCI outer part)*
- High LM corrosion\* resistance
  - \* f (LM velocity, contact temp., grade of insulating material)
- No seeping of liquid metal through insulation material (LM tightness)
- As low as possible activation

## Note:

The following investigation focuses on commercially available Al<sub>2</sub>O<sub>3</sub> and SiC ceramics materials.

SiC<sub>f</sub>/SiC composites will be studied in future steps.

Material	Electrical Resistivity ( $\Omega\text{m}$ )	Electrical Dielectric Strength (MV/m) [1]	Heat conductivity (W/mK)	Bending Strength (MPa)	Thermal Expansion Coeff. ( $10^{-6}/\text{K}$ )	Tmax, LM corrosion ( $^{\circ}\text{C}$ )
$\text{Al}_2\text{O}_3$ [1]	$10^{12}$	17	10 – 16 (80 %) 16 – 28 (95 %) 19 – 30 (> 99%)	300	6 – 8	550 $^{\circ}\text{C}$ (excellent purity is required) [3])
SiC [1]	$\sim 1 - 10^4$ [2]	20	40 – 120 (Sintered) 20 (Recrystallized)	500 – 800	4 – 5	< <u>800 <math>^{\circ}\text{C}</math></u> [4]
Eurofer* [6]	$0.5 - 1.1 \cdot 10^{-06}$		26 (RT) – 29 (500 $^{\circ}\text{C}$ )	Rm: 668 (RT) – 423 (500 $^{\circ}\text{C}$ ) Rp02: 546 (RT) – 390 (500 $^{\circ}\text{C}$ )	10 (RT) – 12 (500 $^{\circ}\text{C}$ )	550 $^{\circ}\text{C}$ [5]

\*Stainless steel 1.4404 was used as a substitute for Eurofer due to the better availability.

[1] <http://www.keramverband.de/keramik/englisch/fachinfo/eigenschaften.htm>

[2] <http://accuratus.com/silicar.html>

[3] W. Krauss et al, Journal of Nuclear Materials, 455, 522 (2014)

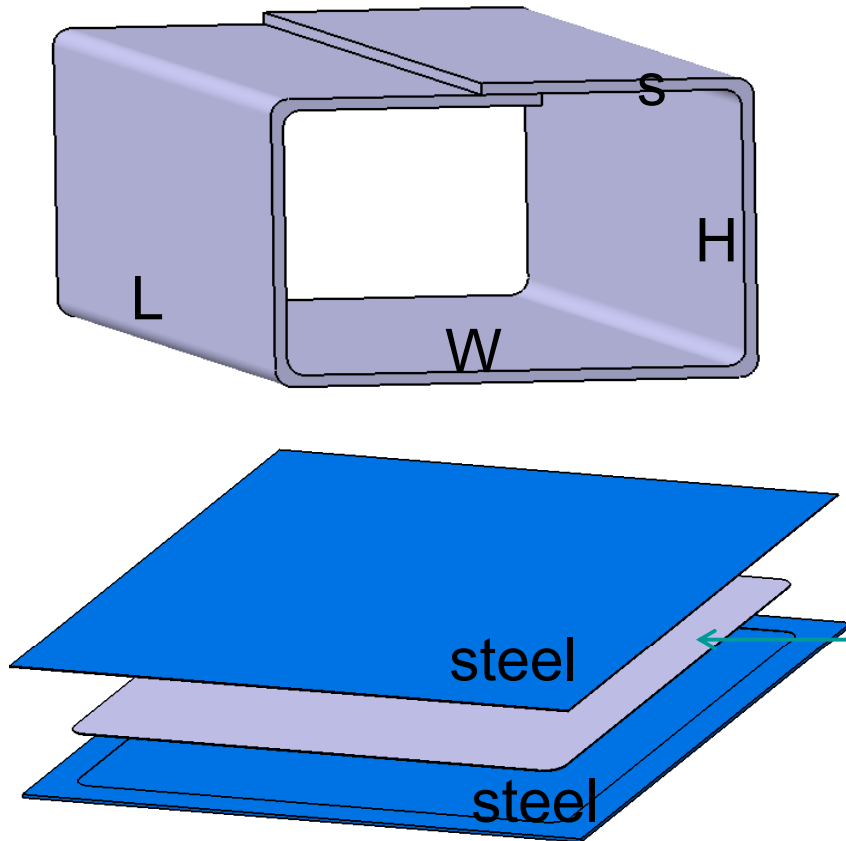
[4] C.P.C. Wong et al, Journal of Nuclear Materials, 367–370, 1287 (2007)

[5] J. Konys et al, Journal of Nuclear Materials, 417, 1191 (2011)

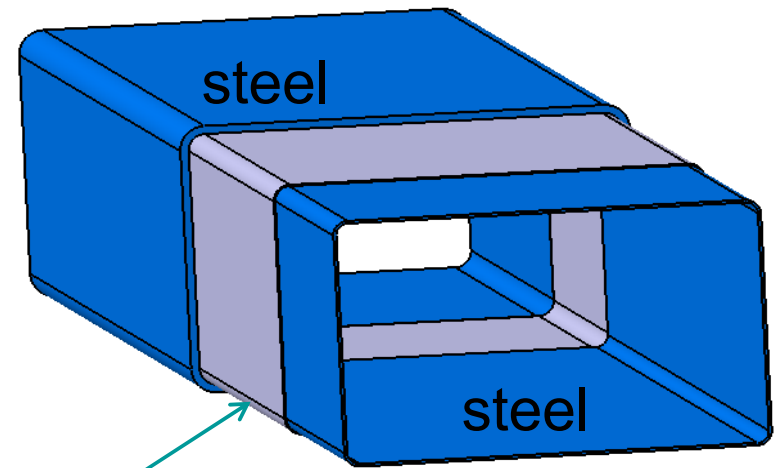
[6] RCC-MRx DMRx 10-115 A3.Gen et A3.19AS Eurofer

# Two Bent-Tube Design

## Bent-Tube Design



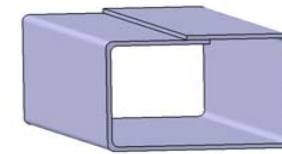
## Tube-in-Tube Design



$\text{Al}_2\text{O}_3$  (or SiC)  
Ceramic Inter-Layer  
 $s \sim 0.1-0.3 \text{ mm}$

Dimensions:  
 $W = 80 \text{ mm}$ ,  $H = 50 \text{ mm}$ ,  $L = 250 \text{ mm}$ ,  
 $s \sim 1-1,5 \text{ mm}$





## Advantages:

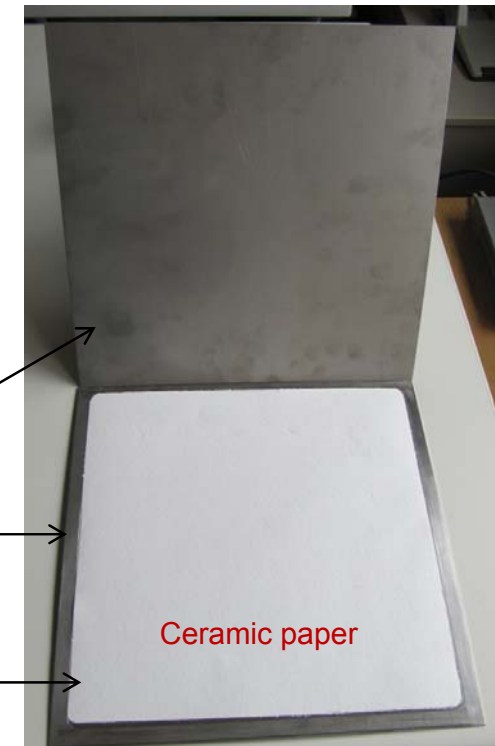
- Flexible choice of insulation material (e.g. ceramic paper)
- No contact between ceramic interlayer and liquid metal.
- Flexible design, no high accuracy required.

## Disadvantages:

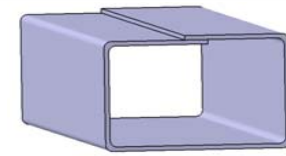
- Bare steel sheet edges provide some bridge for "dirty" current.
- No cutting of the mock-ups possible (falling out of loose interlayer)
- → Functional testing and qualification only feasible in a liquid metal loop.

## FCI Components:

- 2 steel sheets, 0.5 mm thick (for wrinkle-free bending)
- Two options for intermediate layer
  - A) Ceramic paper (~0.3-0.5 mm, KAGER)
  - B) Ceramic spray / paste (Dr. Stephan Rudolph)



## Manufacturing Study for Bent-Tube FCI (Step 2)



In cooperation with KIT/IMVT

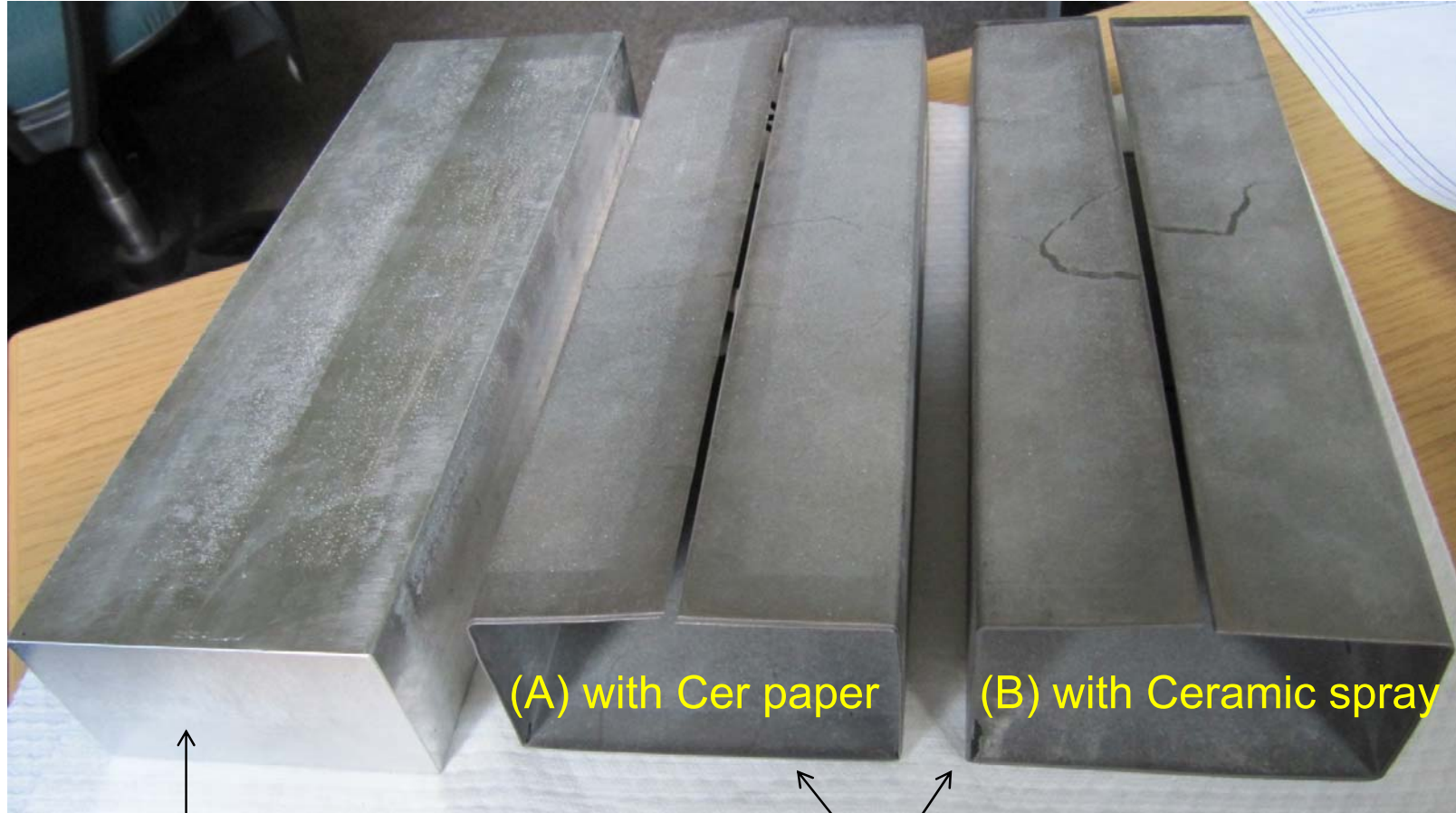
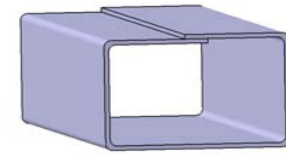


Diffusion bonding by axial pressing in vacuum furnace (10 MPa, 1000 °C, 6h)



Diffusion bonded sandwich sheet (example)

# Manufacturing Study for Bent-Tube FCI (Step 3)

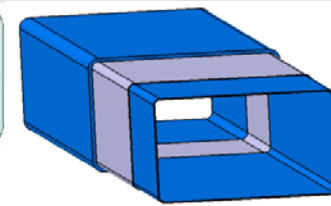


(A) with Cer paper

(B) with Ceramic spray

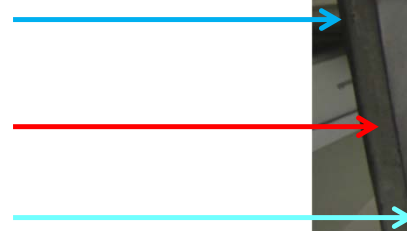
Aluminium bending core

Sandwich FCIs bent after diffusion bonding step



## A) Closed design variant

- Outer Steel Tube
- Ceramic (Alumina)
- Inner Steel Tube



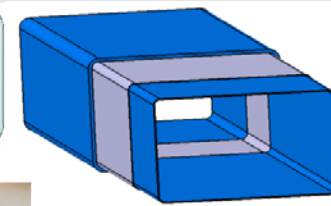
In cooperation with  
KIT/TID

## Advantages:

- No contact between ceramic and liquid metal (completely sealed).
- No high purity of ceramic required (wrt LM corrosion), the poorer the quality the better.
- No electrical “bridges”.
- Accurate pre-defined geometry for a plug-assembly of FCI individual parts.

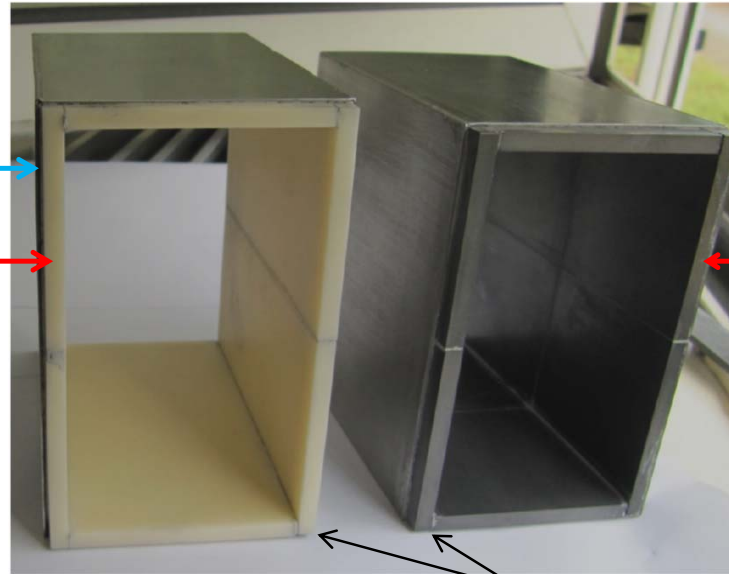
## Disadvantages:

- Higher production costs for fit precision parts.
- Ceramic parts can not be mechanically reworked due to high hardness.
- No cutting of the mock-ups possible.
- Functional testing and qualification only feasible in a liquid metal loop.
- Applicability of this design version is dictated by Eurofer/PbLi corrosion at  $\sim 550$  °C.



## B) Semi-open variant

- Outer Steel Tube
- Ceramics: Alumina  
(Tmax ~ 550°C wrt LM corr.)
- No Inner Steel Tube



In cooperation with  
KIT/TID

or SiC Interlayer  
(Tmax ~ < 800°C)

### Advantages:

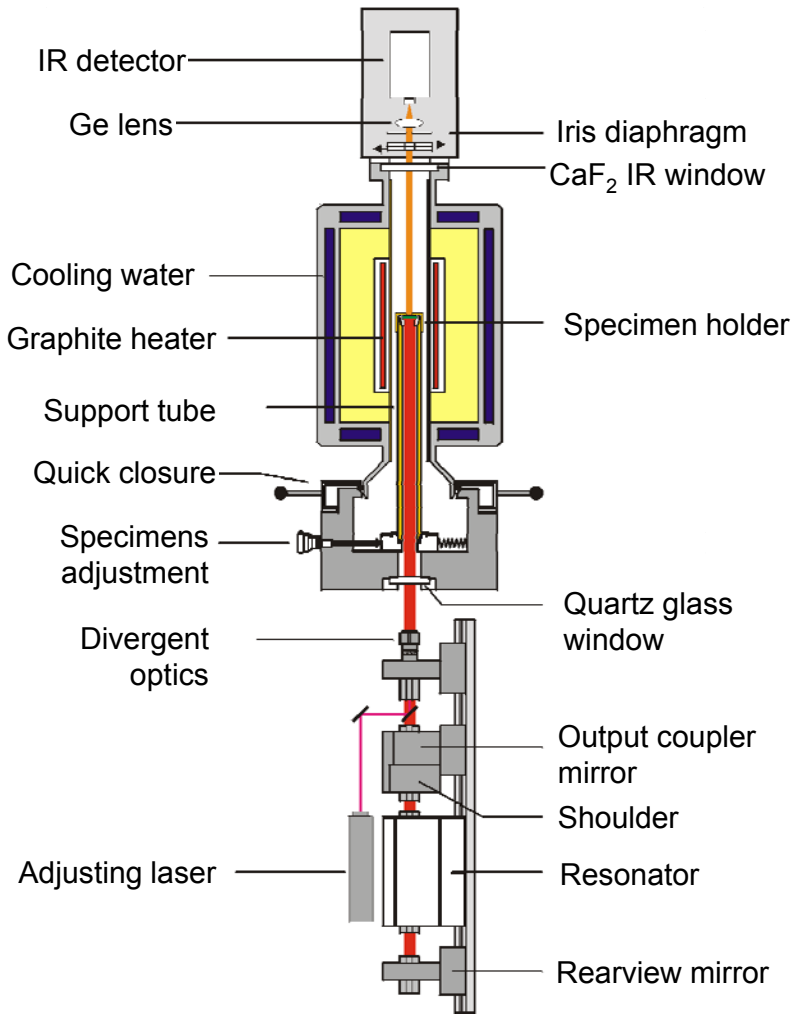
- Simpler manufacturing than “closed” variant.
- *No electrical “bridges”.*
- *Accurate pre-defined geometry for a plug-assembly of FCI individual parts.*

### Disadvantages:

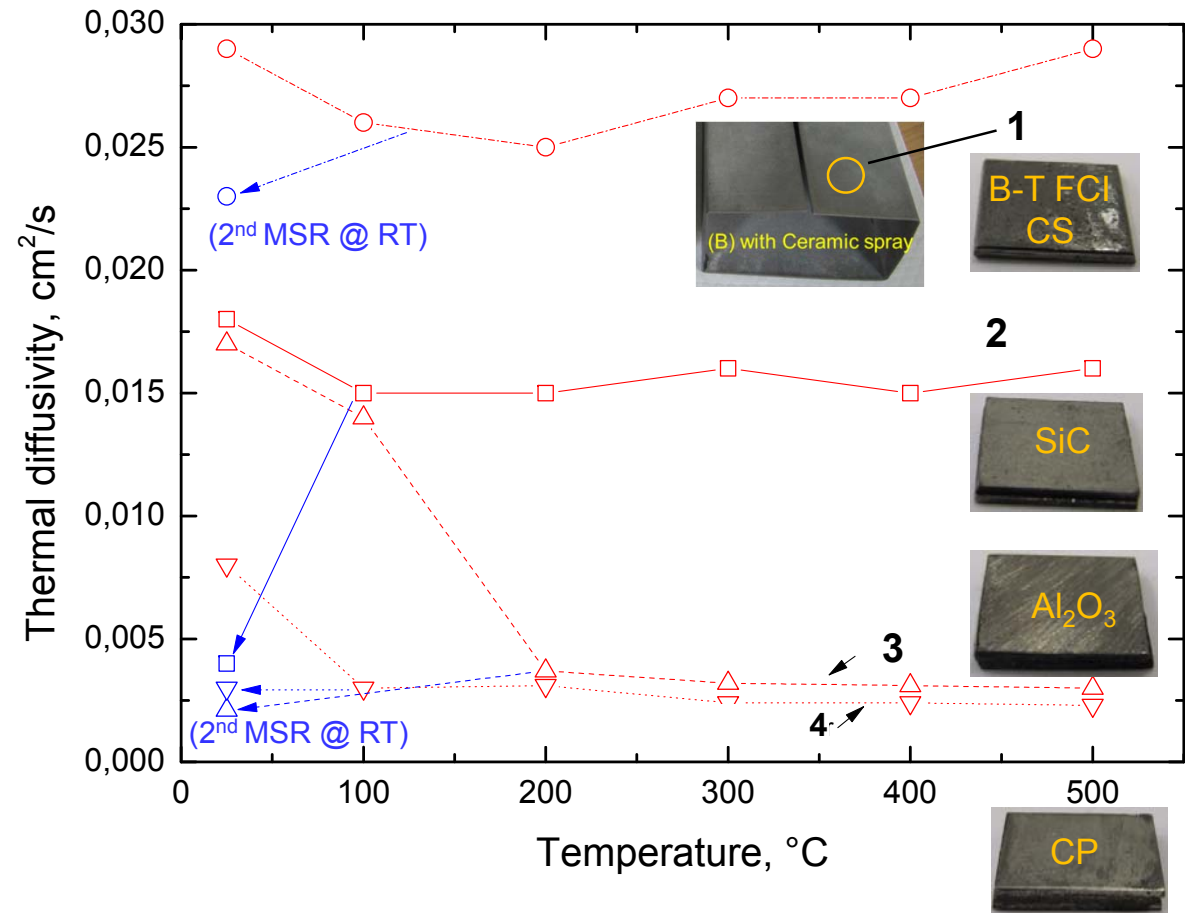
- High purity of the ceramic is required (wrt LM corrosion).
- *Higher production costs for fit precision parts.*
- *Ceramic parts can not be mechanically reworked due to high hardness.*
- *No cutting of the mock-ups possible.*
- *Functional testing and qualification only feasible in a liquid metal loop.*
- Max. oper. temp. of this design is dictated by Cer/PbLi corrosion at ~ 550 – < 800 °C.

# Thermal Diffusivity of Starting Materials

In cooperation with  
KIT/IAM-AWP



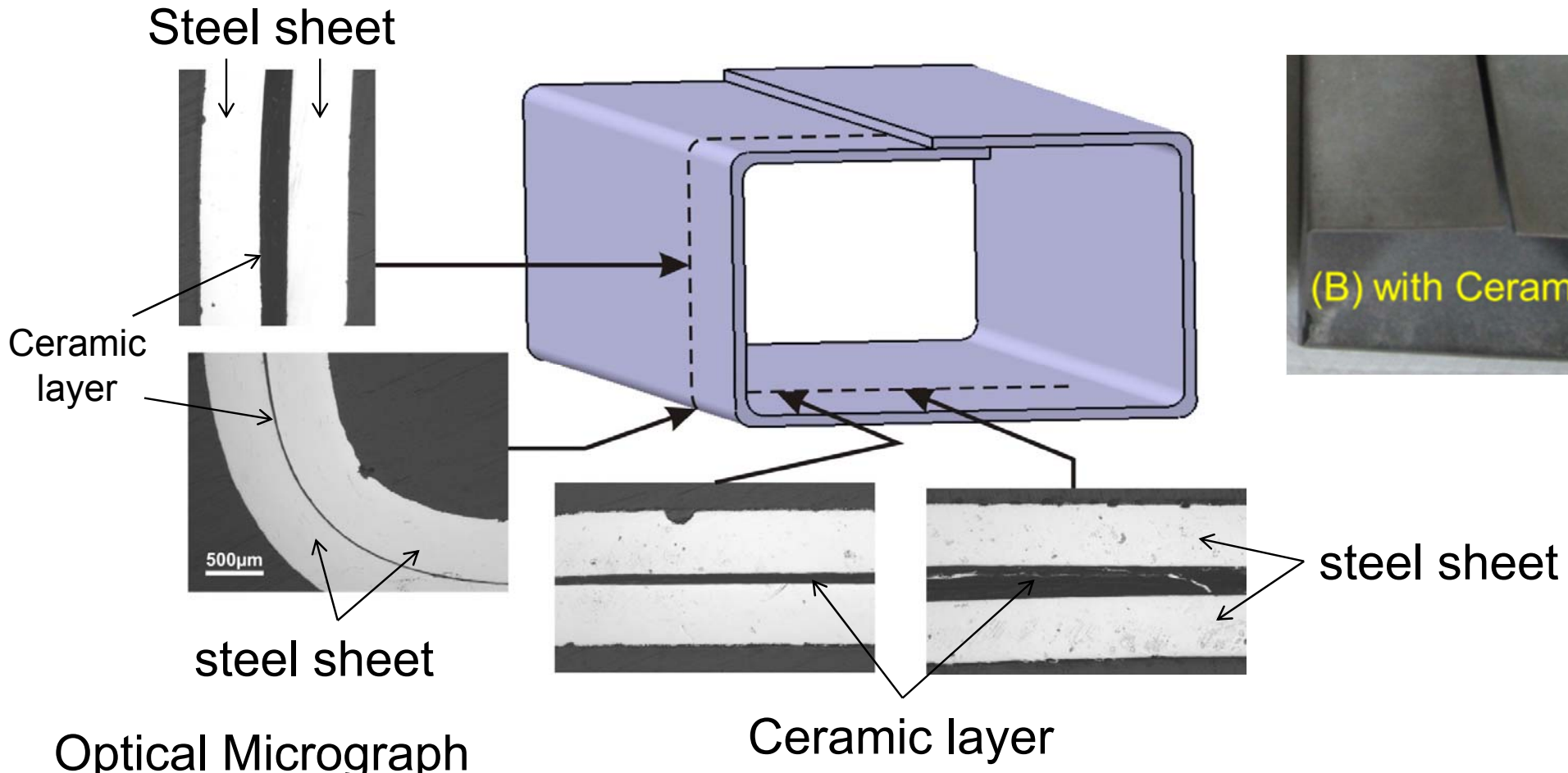
Laser flash thermal measurement device



- 1: Cut sample from bent-tube FCI with cer spray (CS)
- 2: Steel – SiC adhesives – Steel
- 3: Steel – Al<sub>2</sub>O<sub>3</sub> adhesives – Steel
- 4: Steel – ceramic paper (CP) – Steel, glued with Al<sub>2</sub>O<sub>3</sub> adhesives

# Post-Examination of Produced Bent-Tube Mock-Ups (with Ceramic Spray)

In cooperation with  
KIT/IAM-WBM



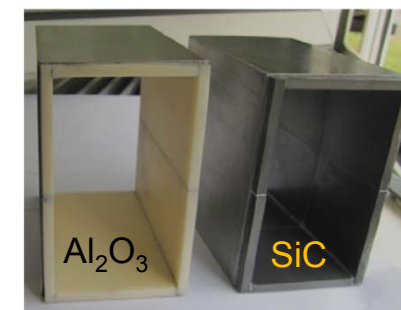
## Optical Micrograph

- No wrinkles formation observed.
- Despite strong bending at corners, no contact between the steel sheets, i.e. no short circuit.
- No constant insulation thickness.

## Preliminary Resistivity Data for Produced Tube-in-Tube FCI Mock-Ups

- Surface resistivity was calculated from the resistance measurement between two electrodes on the surface of the insulating material, taken into account electrode dimensions.
- Measurements were performed on the tube-in-tube, semi-open mock-ups with alumina and SiC insulator (Table).

	Al <sub>2</sub> O <sub>3</sub>	SiC
mean resistivity (ohm.m)	4 ±2 x 10 <sup>11</sup>	0.1 – 10 <sup>2</sup>



### Overall results:

- ✓ Good agreement with literature reported data.
- ✓ High dispersion in resistivity values indicates the presence of defects, impurities, low grade or poor homogeneity of dopant in ceramic insulator.



**Testing on  
small sample  
recommended**



- Requirements for the ceramic material for use in FCI design were summarized, material data for selected  $\text{Al}_2\text{O}_3$  and SiC presented.
- Two design variations Bent-Tube and Tube-in-Tube were presented.
- The latter with subdivision in Closed- and Semi-open designs.
- Their advantages and disadvantages were discussed.
- Manufacturing studies conducted with 1:4 scale mock-ups have confirmed the feasibility and manufacturability for all design variants.
- Measurement of starting material properties and post-examination of produced mock-ups show good agreement with literature.

Open issues for future R & D are:

- Transferability to a 1:1 full scale mock-up has to be checked.
- Study on 3D printing technology.
- Function tests and characterization of FCIs under real magnetic conditions in a PbLi loop.
- Manufacturing study for an advanced FCI with  $\text{SiC}_f/\text{SiC}$  composite material.
- Influence of n-irradiation on the properties of ceramic material, in particular radiation-induced electrical degradation (RIED).

**Thank you for your attention!**