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


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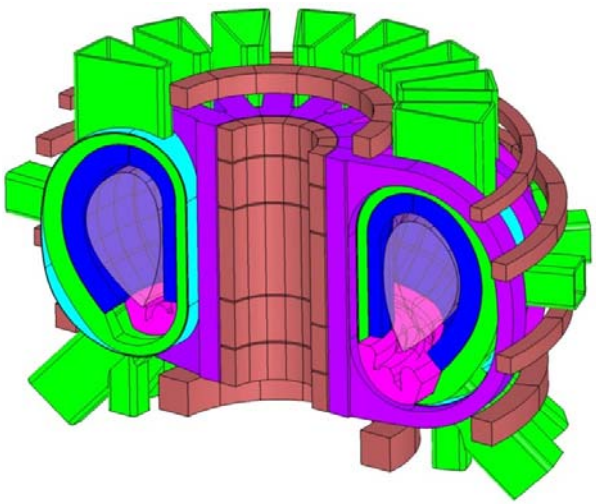
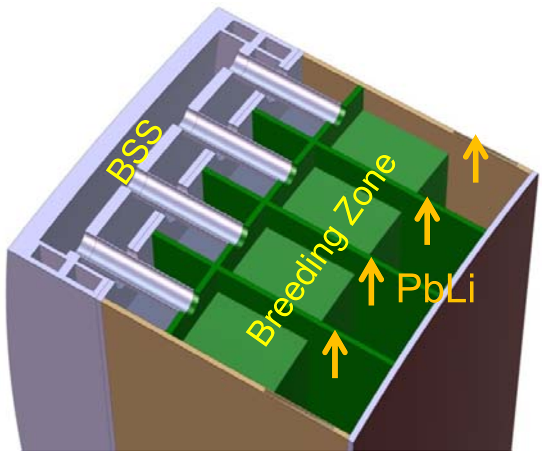
KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)

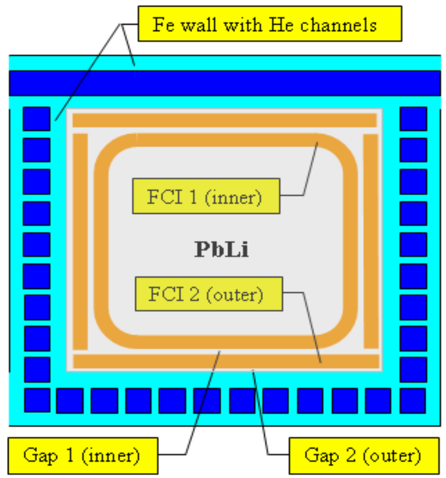


EU PPPT DEMO




DCLL 2014

Integration in DEMO 2014

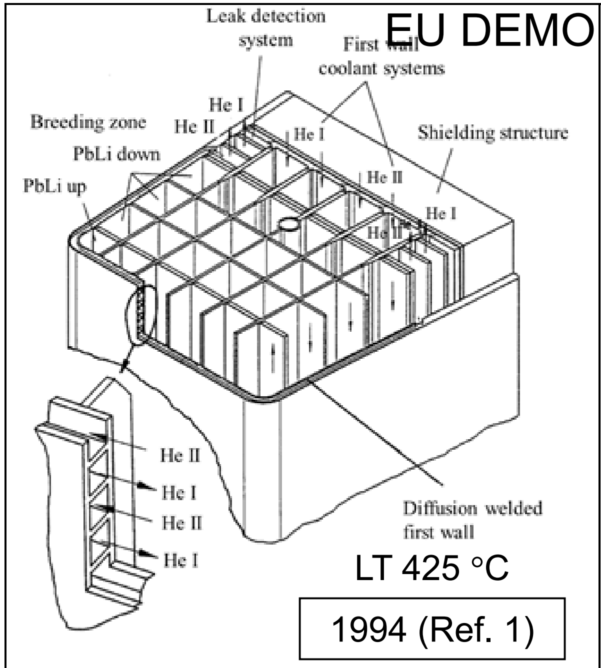


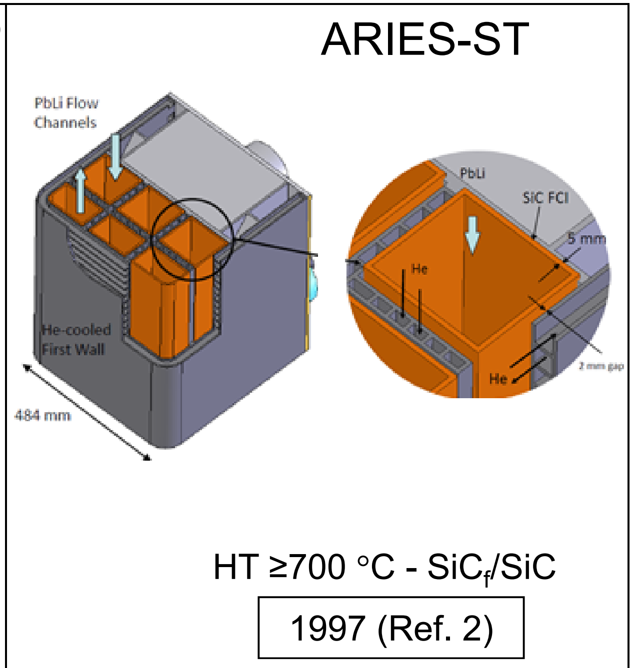

Nested FCI

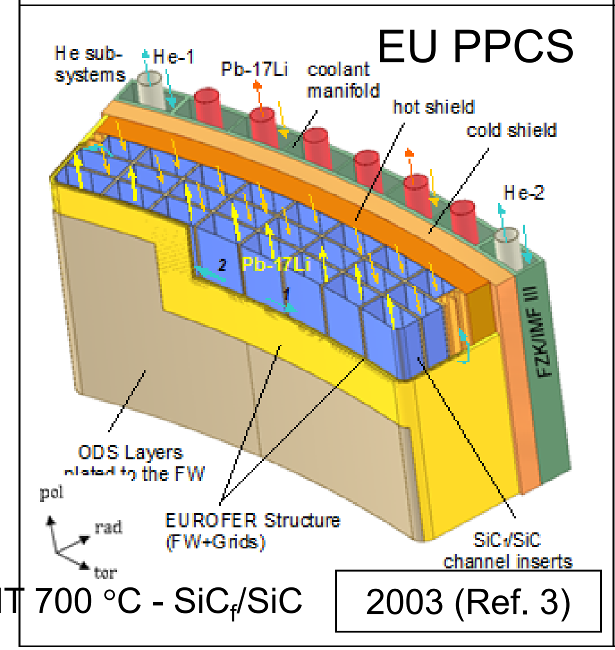
# Content

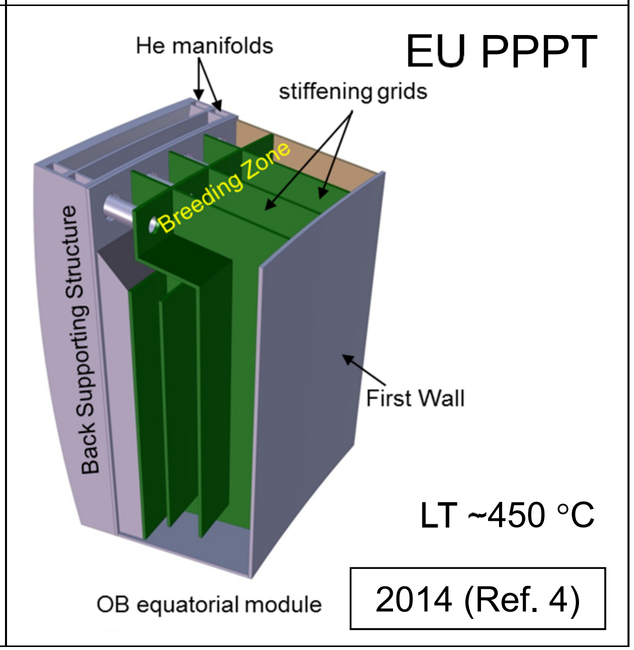
1. Why do we need flow channel inserts (FCIs)?
2. Basic design principles for FCI
3. Requirements for FCI materials
4. Selected materials and their major properties
5. Several different FCI design types (pros and cons)
6. Demonstration of manufactured FCIs
7. Investigations of starting materials and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

# DCLL Blanket Concept Evolution



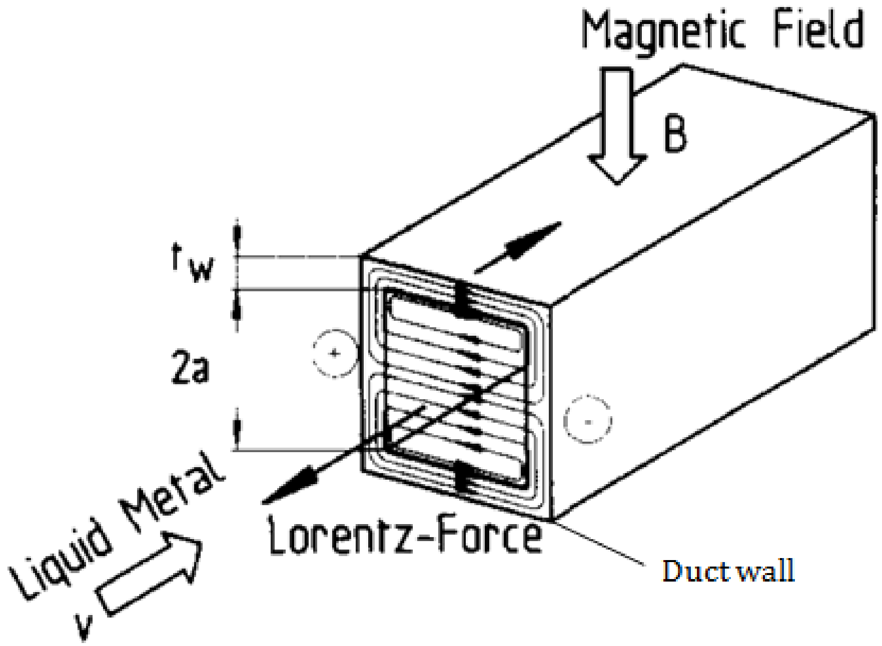




Some common features:

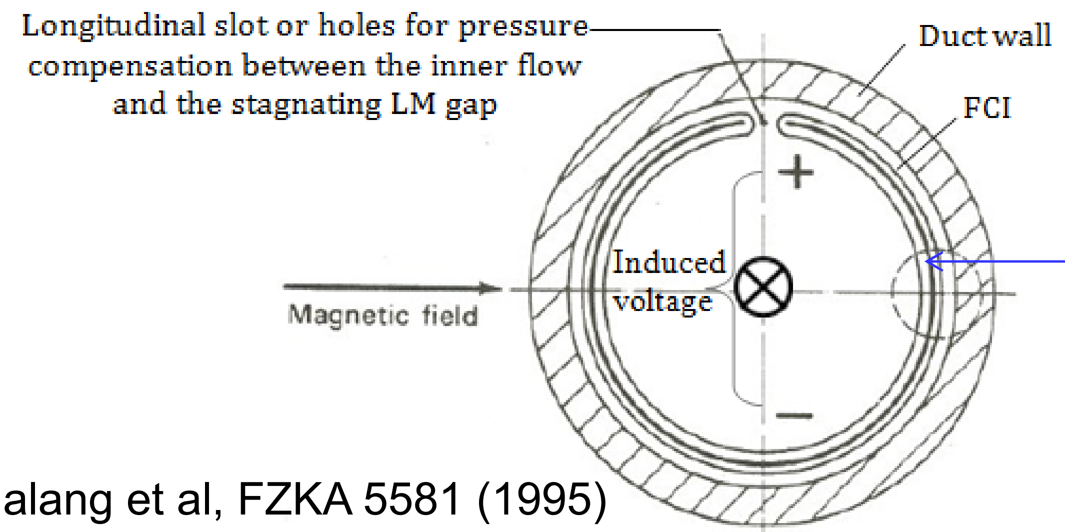
- Dual coolants:
  - He for cooling of structures
  - PbLi as breeder and self-cooling medium
- Poloidal PbLi flow ⊥ magnetic field

[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



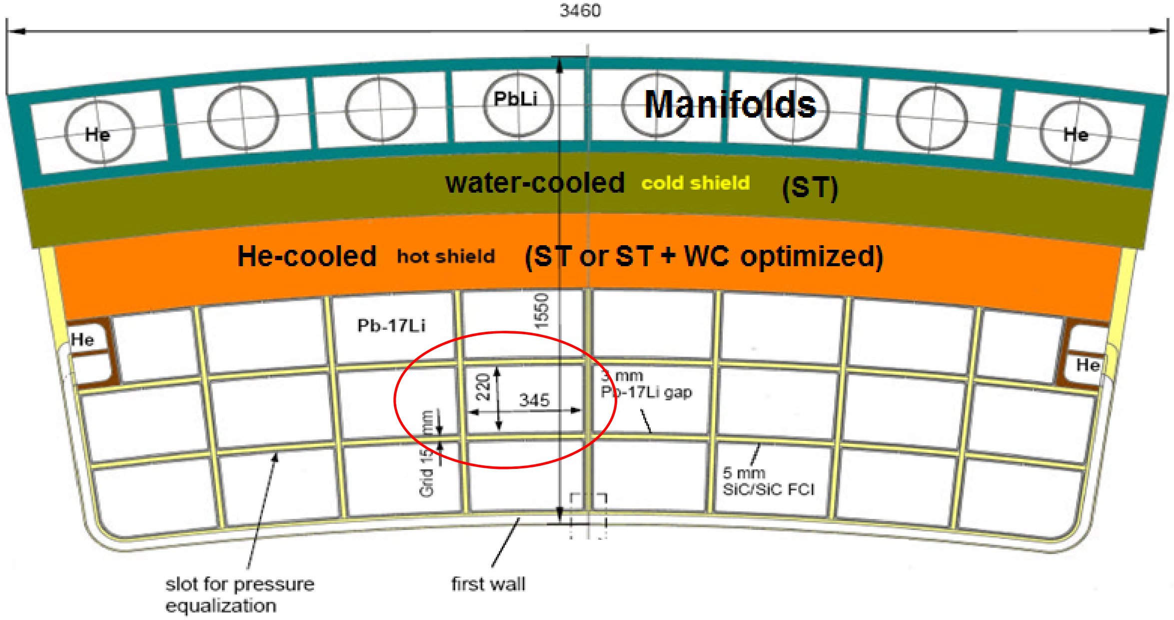

→ **MHD pressure loss !**



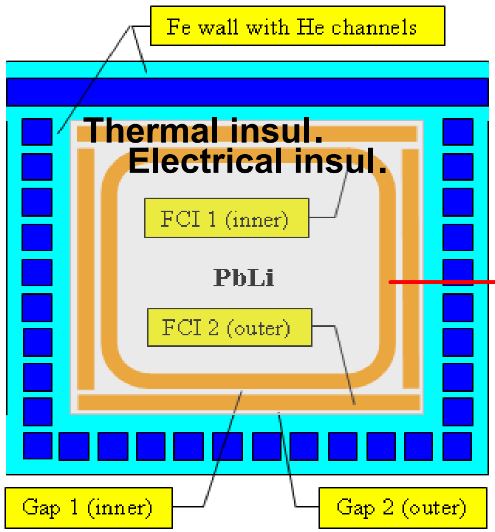

**Remedy by the use of FCI (e.g. of sandwich type)**

S. Malang et al, FZKA 5581 (1995)

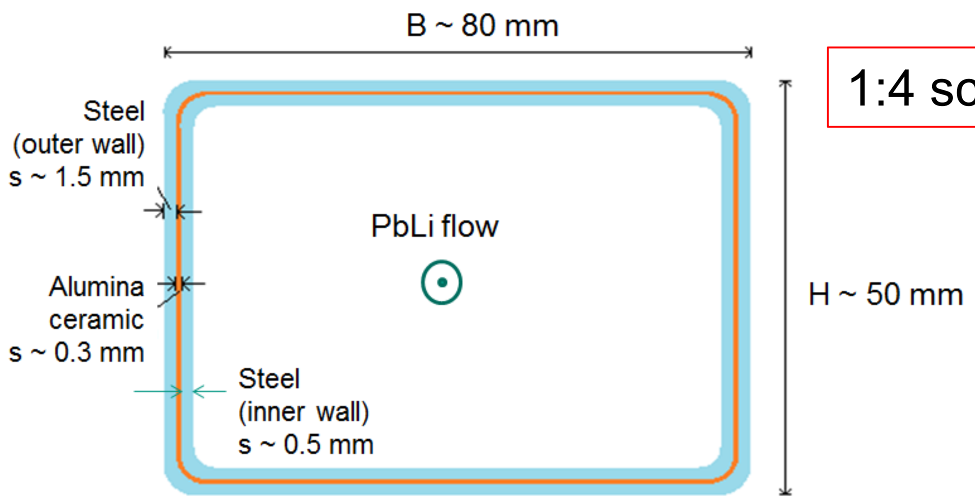
# Considerations about Sandwich FCI Design




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




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




1:4 scale

# FCI Design: Insulating Material

**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 $Al_2O_3$ and SiC ceramics materials.

$SiC_f$/SiC composites will be studied in future steps.

# FCI Design: Insulating Material

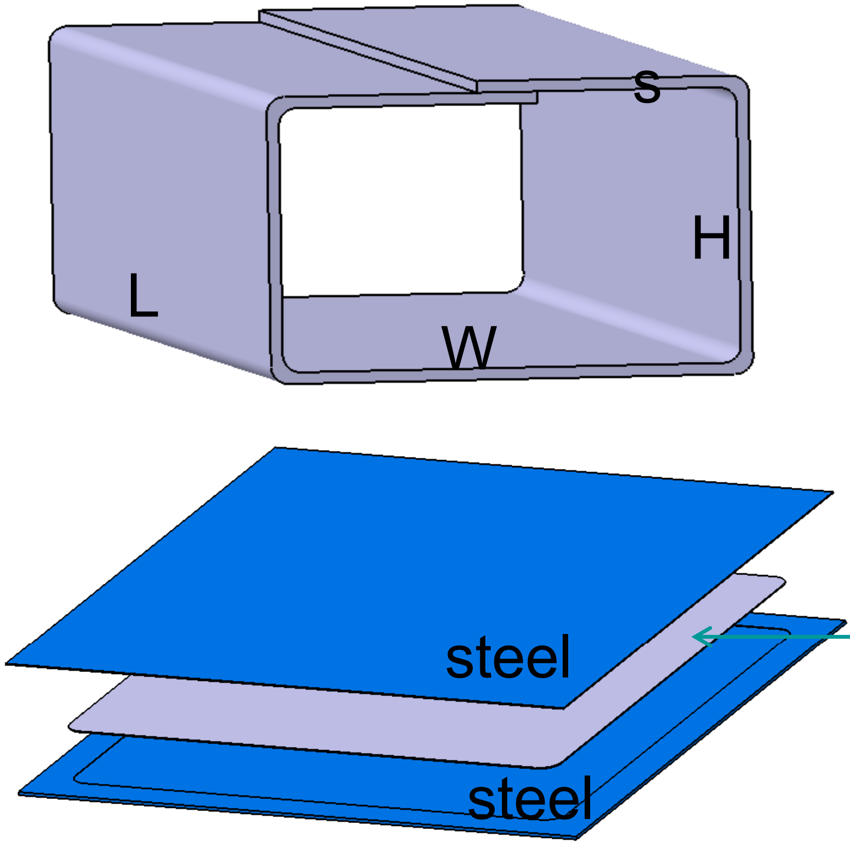
| Material | Electrical Resistivity (Ωm) | Electrical Dielectric Strength (MV/m) [1] | Heat conductivity (W/mK) | Bending Strength (MPa) | Thermal Expansion Coeff. ($10^{-6}$/K) | Tmax, LM corrosion (°C) |
|---|---|---|---|---|---|---|
| $Al_2O_3$ [1] | $10^{12}$ | 17 | 10 – 16 (80 %)<br>16 – 28 (95 %)<br>19 – 30 (> 99%) | 300 | 6 – 8 | 550 °C<br>(excellent purity is required) [3]) |
| SiC [1] | ~1 – $10^4$ [2] | 20 | 40 – 120 (Sintered)<br>20 (Recrystallized) | 500 – 800 | 4 – 5 | < 800 °C [4] |
| Eurofer* [6] | 0.5 – $1.1 \cdot 10^{-06}$ | | 26 (RT) – 29 (500°C) | Rm: 668 (RT) – 423 (500°C)<br>Rp02: 546 (RT) – 390 (500°C) | 10 (RT) – 12 (500°C) | 550 °C [5] |

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

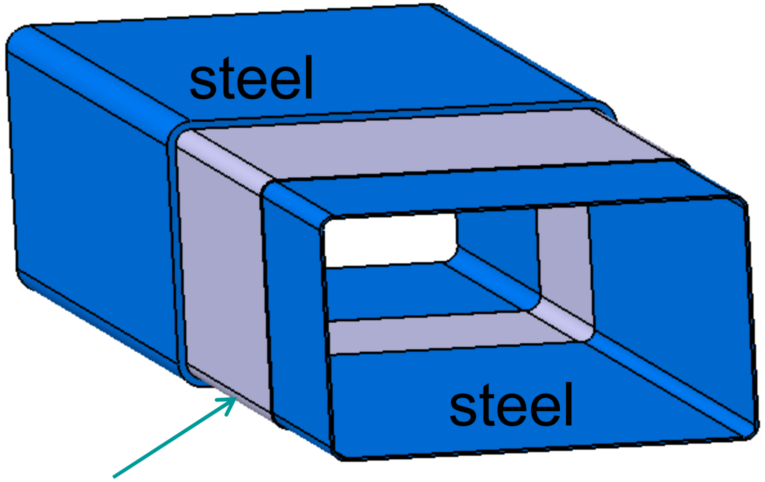
[1] http://www.keramverband.de/keramik/englisch/fachinfo/eigenschaften.htm
[2] http://accuratus.com/silicar.html
[3] W. Krauss et al, Journal of Nuclear Materials, 455, 522 (2014)
[4] C.P.C. Wong et al, Journal of Nuclear Materials, 367–370, 1287 (2007)
[5] J. Konys et al, Journal of Nuclear Materials, 417, 1191 (2011)
[6] RCC-MRx DMRx 10-115 A3.Gen et A3.19AS Eurofer

# Two Bent-Tube Design

## Bent-Tube Design



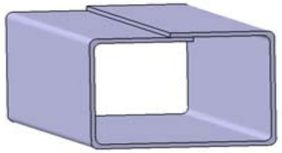

## Tube-in-Tube Design




$Al_2O_3$ (or SiC)
Ceramic Inter-Layer
s ~ 0.1-0.3 mm

Dimensions:
W = 80 mm, H = 50 mm, L = 250 mm,
s ~1-1,5 mm

# Manufacturing Study for Bent-Tube FCI (Step 1)



**Advantages:**

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

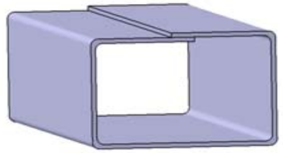
**Disadvantages:**

- 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)

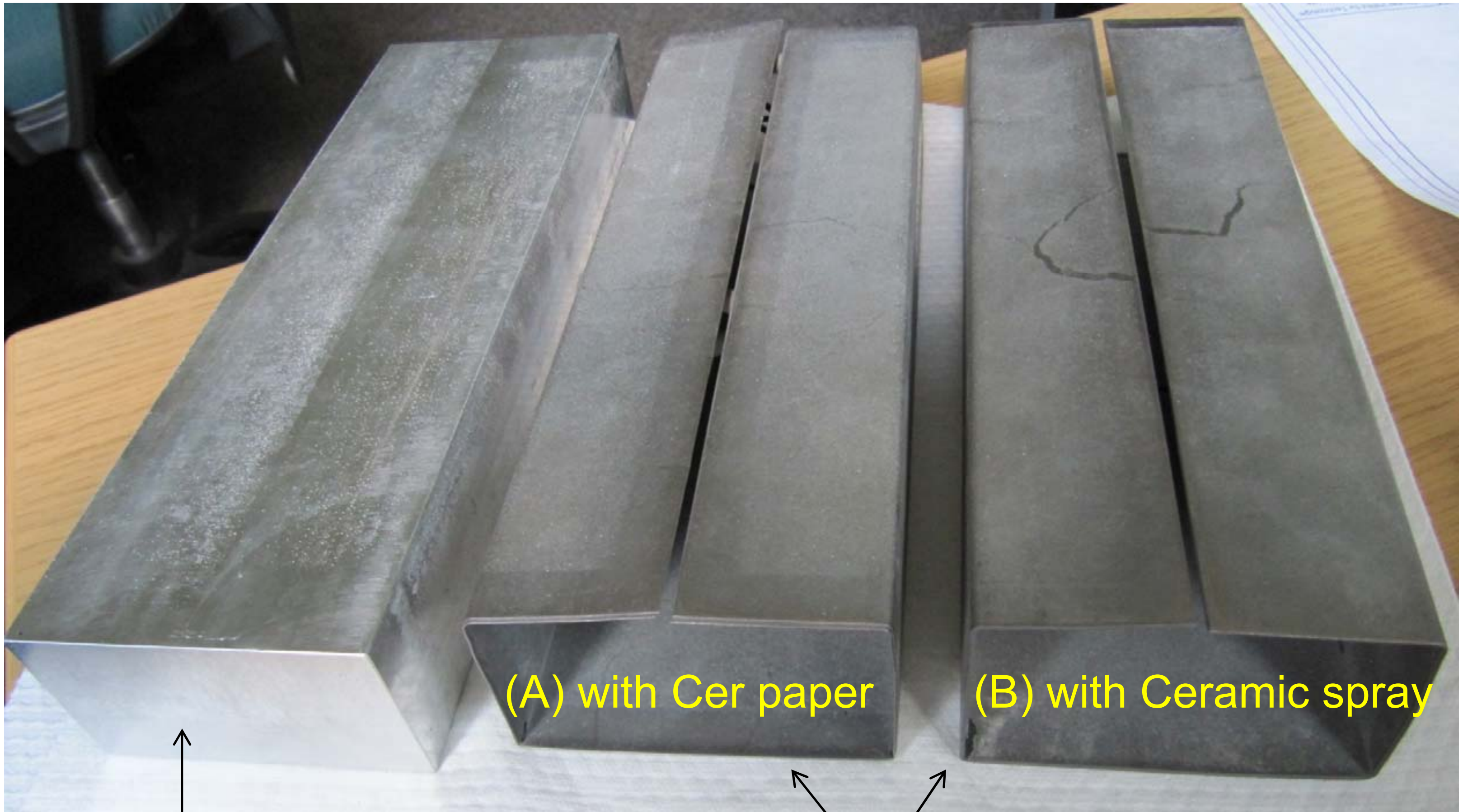


In cooperation with KIT/IMVT

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

Diffusion bonded sandwich sheet (example)

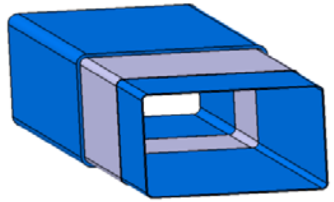
# Manufacturing Study for Bent-Tube FCI (Step 3)




Aluminium bending core

Sandwich FCIs bent after diffusion bonding step

# Manufacturing Study for Tube-in-Tube FCI (Design 1)

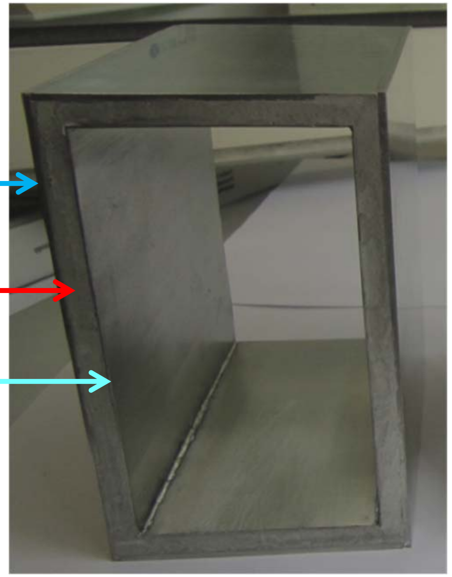


## A) Closed design variant

– Outer Steel Tube

– Ceramic (Alumina)

– Inner Steel Tube



In cooperation with KIT/TID

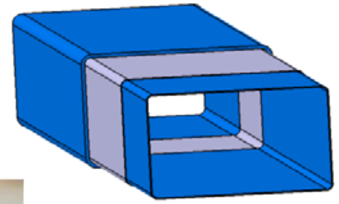
**Advantages:**

- 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 ~ 550 °C.

# Manufacturing Study for Tube-in-Tube FCI (Design 2)



KIT Karlsruhe Institute of Technology

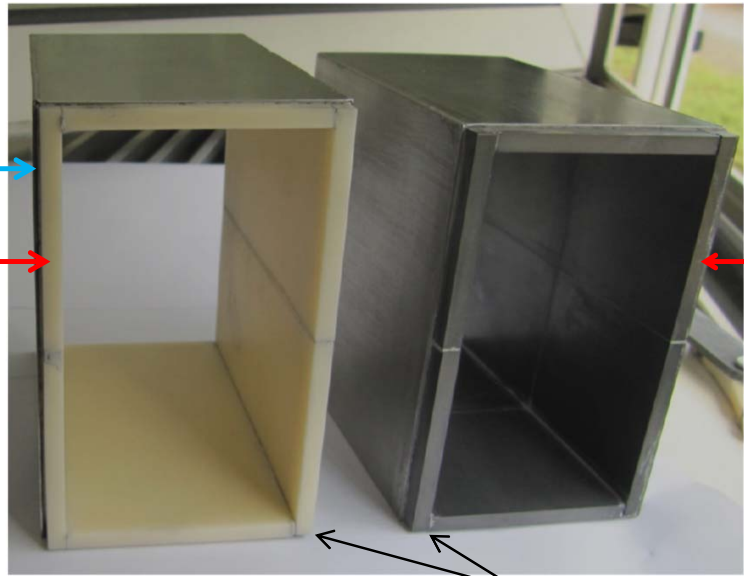
**B) Semi-open variant**

– 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)

offset of ~ 20 mm for plug-in

**Advantages:**

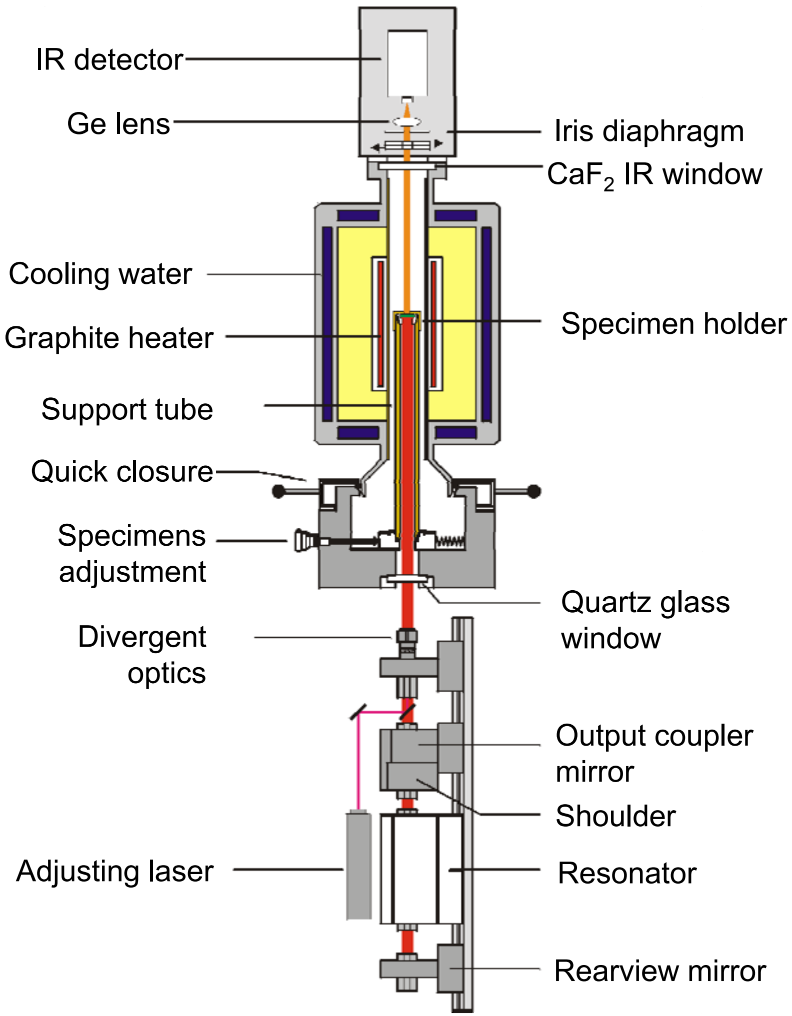
- Simpler manufacturing than "closed" variant.
- *No electrical "bridges".*
- *Accurate pre-defined geometry for a plug-assembly of FCI individual parts.*

**Disadvantages:**

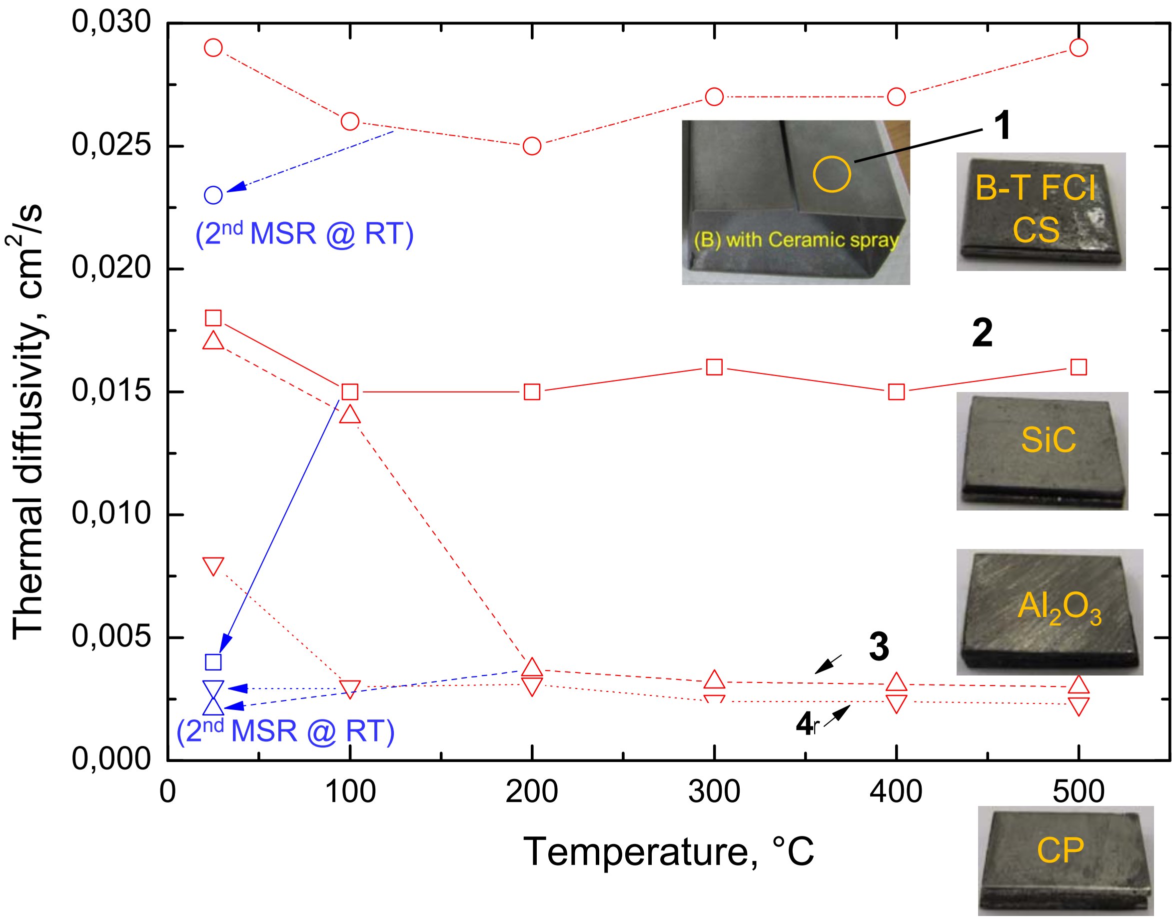
- High purity of the ceramic is required (wrt LM corrosion).
- *Higher production costs for fit precision parts.*
- *Ceramic parts can not be mechanically reworked due to high hardness.*
- *No cutting of the mock-ups possible.*
- *Functional testing and qualification only feasible in a liquid metal loop.*
- 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)

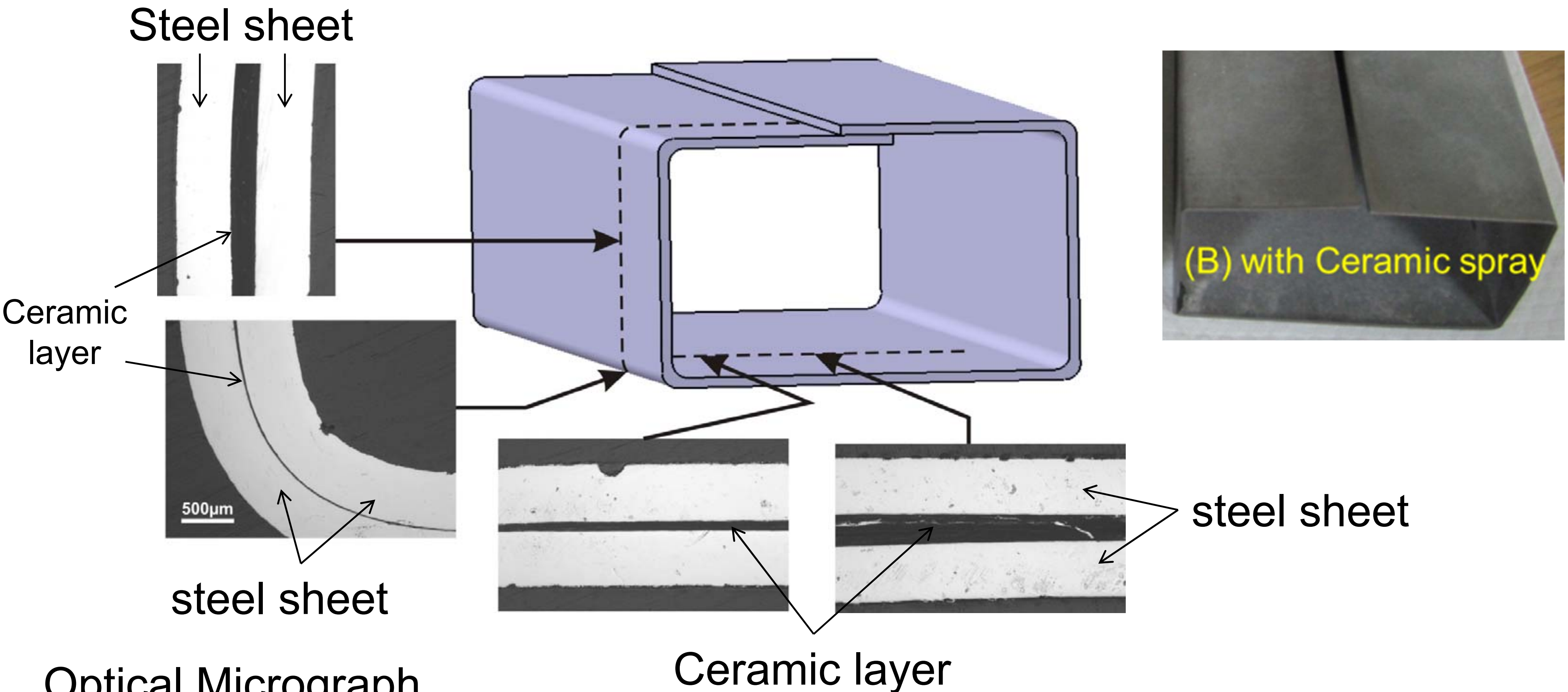
2: Steel – SiC adhesives – Steel

3: Steel – $Al_2O_3$ adhesives – Steel

4: Steel –ceramic paper (CP) – Steel, glued with $Al_2O_3$ 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.

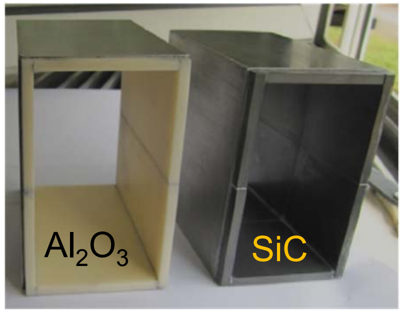
# Preliminary Resistivity Data for Produced Tube-in-Tube FCI Mock-Ups

In cooperation with CIEMAT

• 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).

| | $Al_2O_3$ | SiC |
|---|---|---|
| **mean resistivity (ohm.m)** | $4 \pm 2 \times 10^{11}$ | $0.1 - 10^2$ |




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**

# Conclusions

- Requirements for the ceramic material for use in FCI design were summarized, material data for selected $Al_2O_3$ 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 $SiC_f$/SiC composite material.
- Influence of n-irradiation on the properties of ceramic material, in particualr radiation-induced electrical degradation (RIED).

Thank you for your attention!