Evaluation of conservative and innovative manufacturing routes for gas-cooled TBM and breeder blanket first walls

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Institut für Neutronenphysik und Reaktortechnik

Design, Analysis and Fabrication

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Content:

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Conclusions

Introduction

In 2017/2018 study to identify „DEMO Cost Drivers“ was performed by Ariane Group
Goal: Cost estimation + identification of main factors for reference route

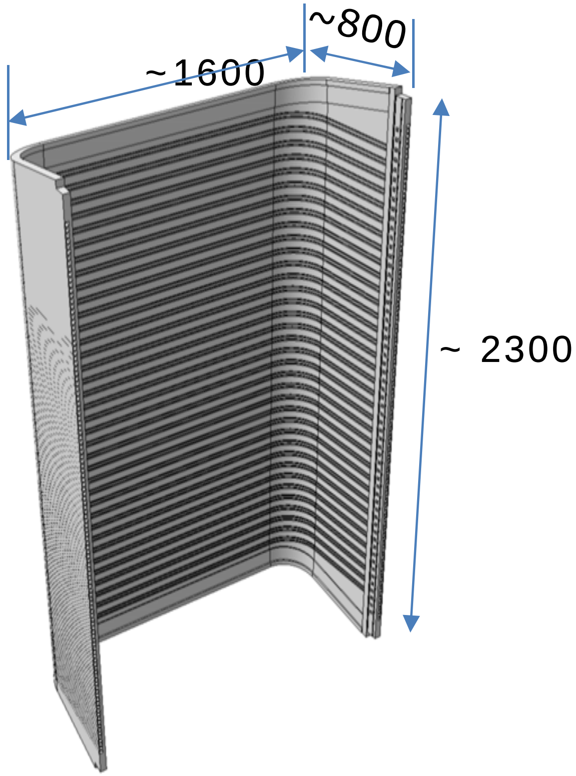
Conclusions: HCPB First Wall (report p. 40): ~ 3 M€
Similar numbers also for HCLL

Basis for the study:

- „Typical“ Breeder Blanket (BB) [REF-a]
- HCPB reference manufacturing route: Electrical Discharge Machining (EDM) + Forming [REF-b], details later...

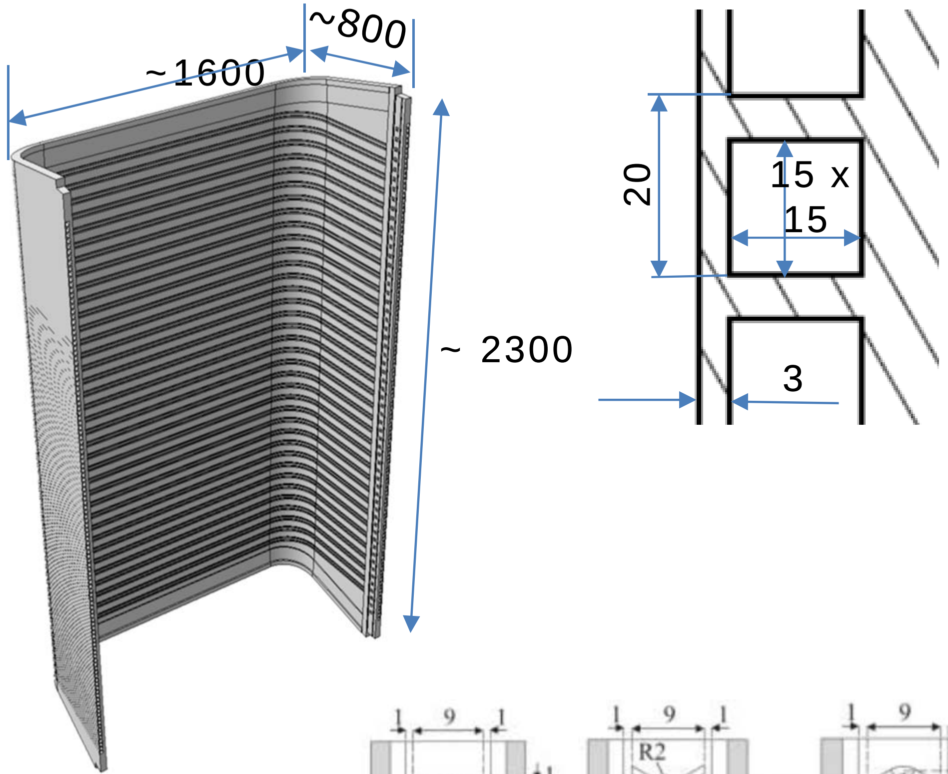
Results of study underline necessity to:

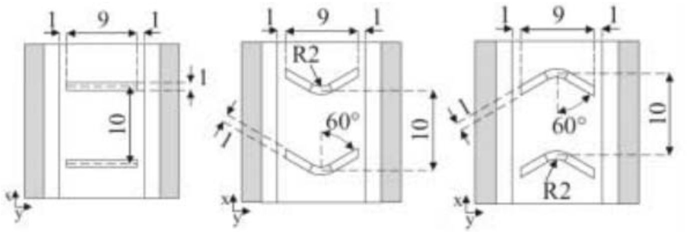
- Re-consider existing manufacturing routes
- Development of new and innovative concepts, e.g. Additive Manufacturing (AM)



Requirements on a typical BB First Wall

- Shape and external dimensions
  - Plane plate with 2 bends
  - straight length ~ 2.6 m
  - Total front surface: 2.6 x 2.3 = 6 m^2
  - Plasma facing portion: ~ 50 %
  - 3D-curvature + edges ?
- Internal channel structure
  - e.g. 15 x 15 mm^2 Cross Section
  - Length-to-diameter ration ~ 200
  - Typical pitch = 20 mm
  - FW cover layer = 3 mm
  - Heat Transfer (HT) enhancement structures [REF-c] ?
- Requirements triggered by licensing:
  - No weld on plasma facing side
  - Total number of welds ALARA [REF-d]





Criteria for evaluation of different manufacturing routes

Procurement cost

- **On basis of past procurements**
- **Estimations for new technologies**

Dimensional deviation:

- External form deviation
- Channel Cross section (Area/shape)
- Thickness of FW cover layer

Maturity level

- Number of % of FW demonstrated
- Availability of equipment in industry
- Development effort from now on

Licensing effort

- Acceptance of technologies in C&S (RCC-MR)
- Total number of welds (meters/BB FW)

Suitability for HT- enhancement structures

- Surface roughness
- Arrowheads, etc.

HCPB FW routes considered in presentation are:

A) Conventional process chains
Developments started ~ 2010, even before

A1) Reference concept for HCPB: EDM + Forming + Machining
A2) HIP for assembly of FW by pipes and grooved shells [REF-e]

B) Innovative process chains (based on Additive Manufacturing)
Developments started ~ 2017

B1) Selective Laser Melting based concept (FW- Stripes)
B2) Metal Powder Application (Hermle AG)

Forthcoming slides show

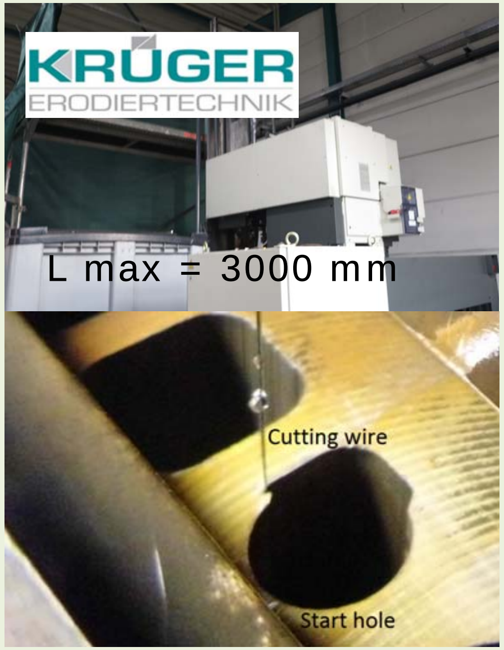
- Main process steps to build FW according to routes for HCPB
- Largest demonstration mock ups for each route
- Activities launched in order to overcome limitations
- Finally, evaluation criteria are quantified to make a comparison

Manufacturing routes in detail

A) Conventional process chains
A1) Reference concept for HCPB: EDM + Forming + Machining

Developed since ~ 2010, route includes 3 main manufacturing steps:

1) EDM Wire cutting



2) Forming of edges:
3000 T press (automotive)

Press + staff hired, equipment KIT property

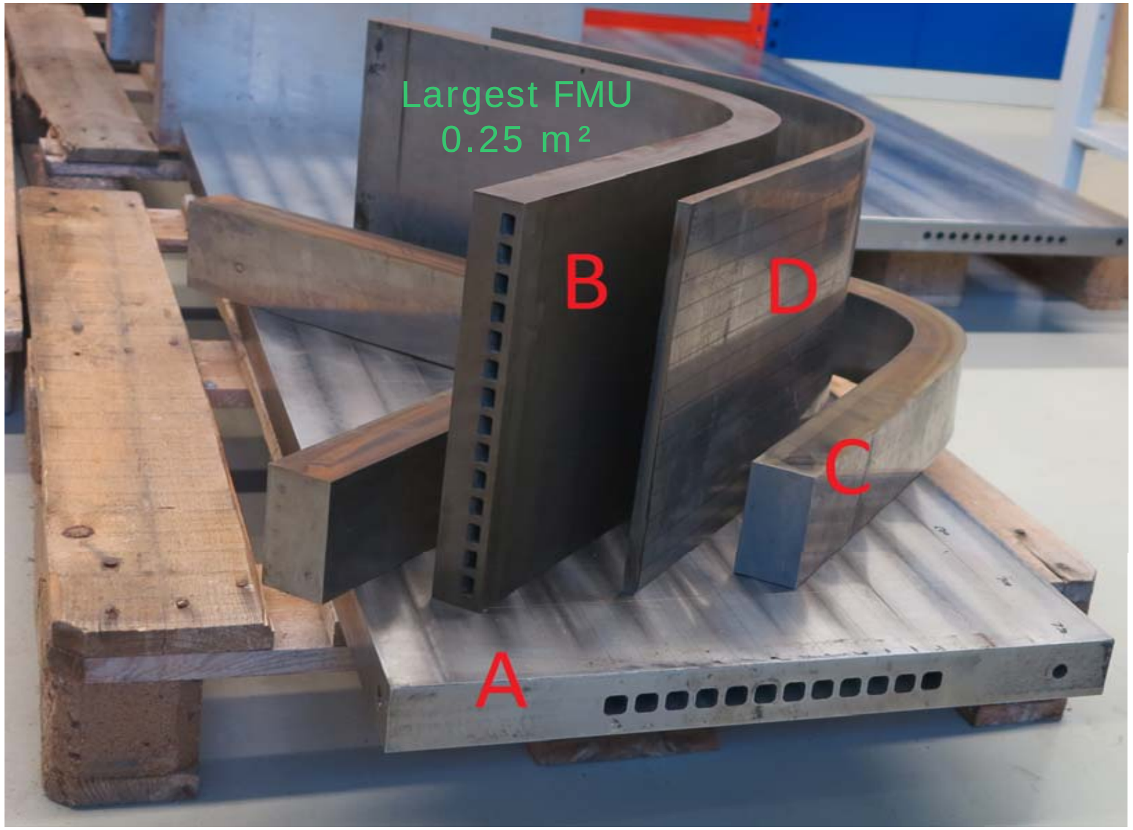
3) Final machining, EDM wire cutting

Manufacturing routes in detail

A) Conventional process chains

A1) Reference concept for HCPB: EDM + Forming + Machining

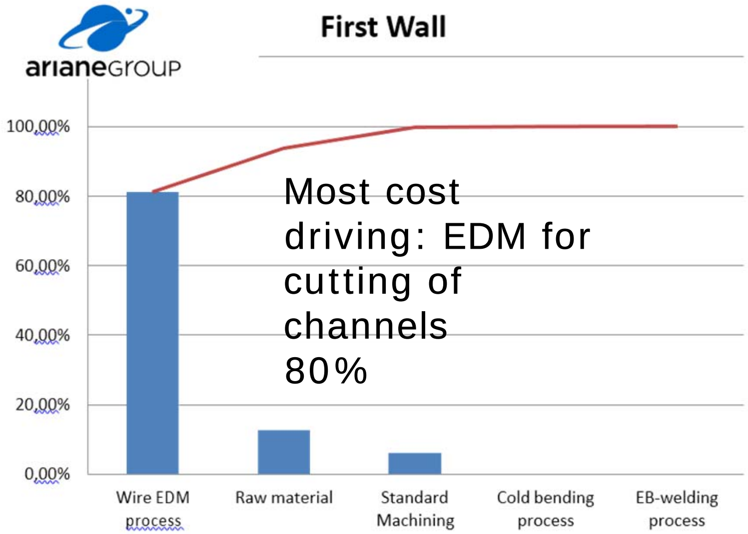
Largest demonstrator 0.25 m² (B) / to be Completed in 2019: 0.4 m², 2 x 90° bends (A)



Cost estimation for typical full scale BB:

EDM wire cutting channels: ~ 2.5 M€
Forming into U-shape: ~ 0.25 M€
Final machining (EDM): ~ 0.25 M€

→ **~ 3 M€ (Ariane-Study)**
→ **0.5 M€ / m² front surface**



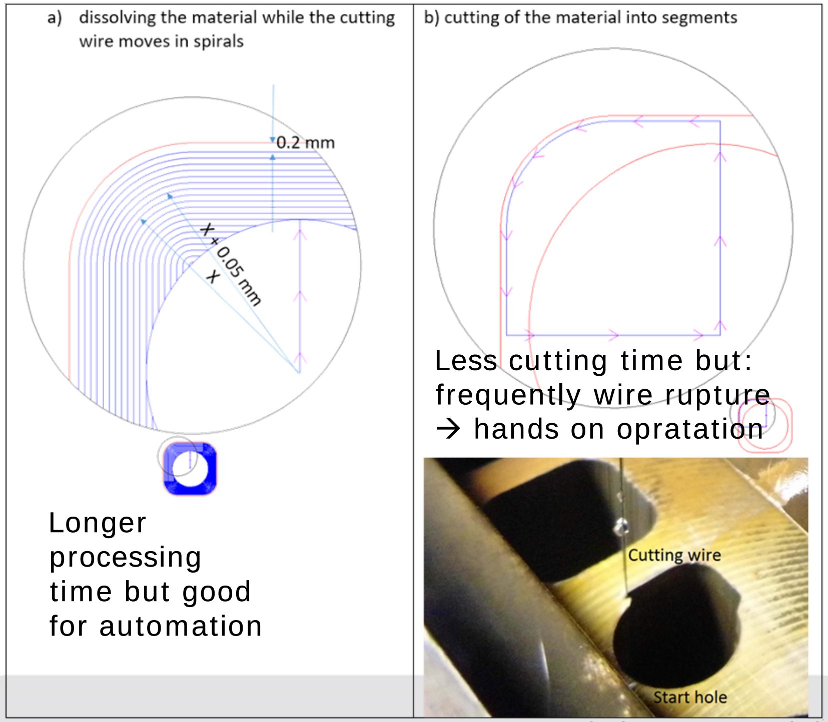
Manufacturing routes in detail

Karlsruhe Institute of Technology

A) Conventional process chains
A1) Reference concept for HCPB: EDM + Forming + Machining

2017: Qualification of innovative technology Part I – EDM
a) experiments for parameter optimization
b) Increase of efficiency (parallel processing)

2 cutting strategies:
Scooping out channel vs. cutting in segments



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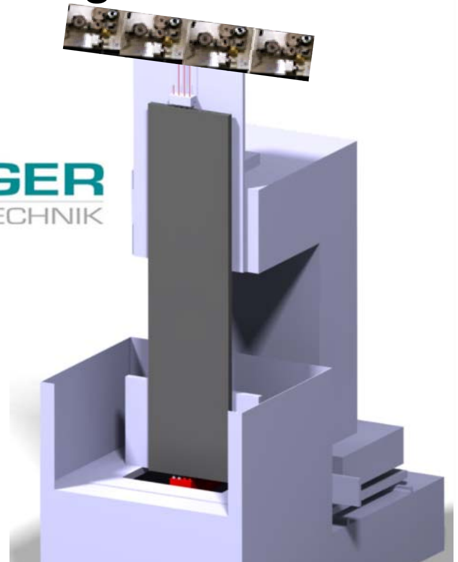
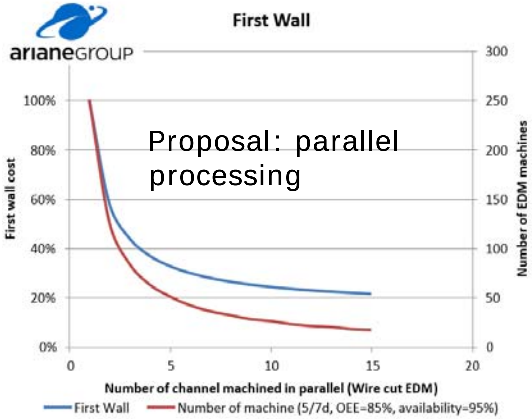
Existing 3 m cutting length as basis of study



Parallel processing of 4 channels
Engineering study

arianeGroup



Total cost reduction to be expected ~ 40 %

→ 1.8 M€/First Wall
→ ~ 0.3 M€/m² FW front surface in future

Manufacturing routes in detail

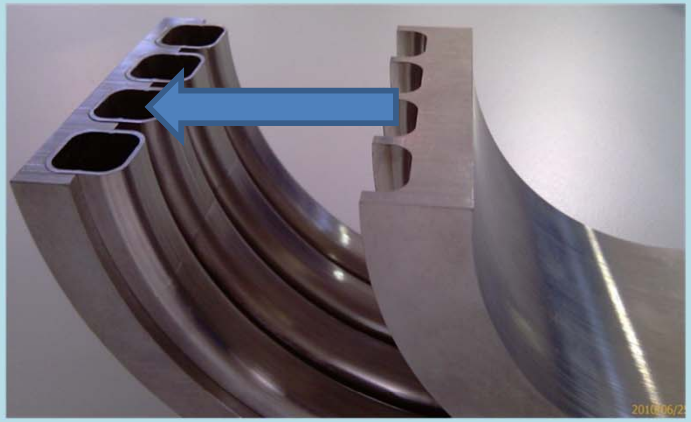
A) Conventional process chains

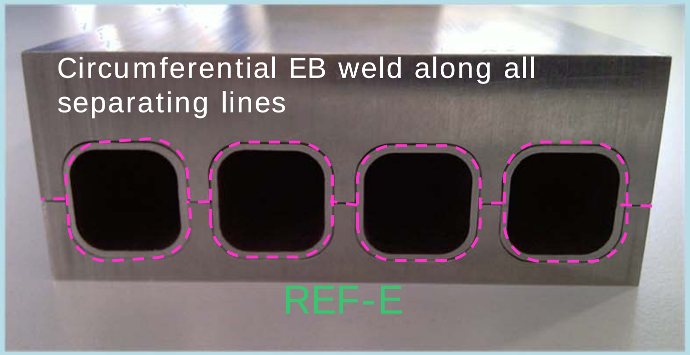
A2) HIP for assembly of FW by pipes and grooved shells [REF-e]

Developed in KIT IAM, route includes 3 main manufacturing steps:

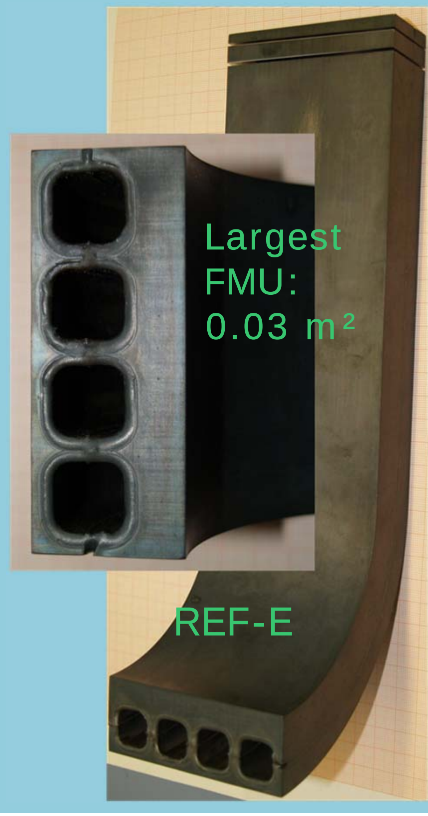
1) Build rectangular pipes + suitable external and internal shells

2) Pre-assembly + tacking by Electron Beam welding (in vacuum)





3) Joining into one cohesive body by HIP-process



Manufacturing routes in detail

A) Conventional process chains
A2) HIP for assembly of FW by pipes and shells

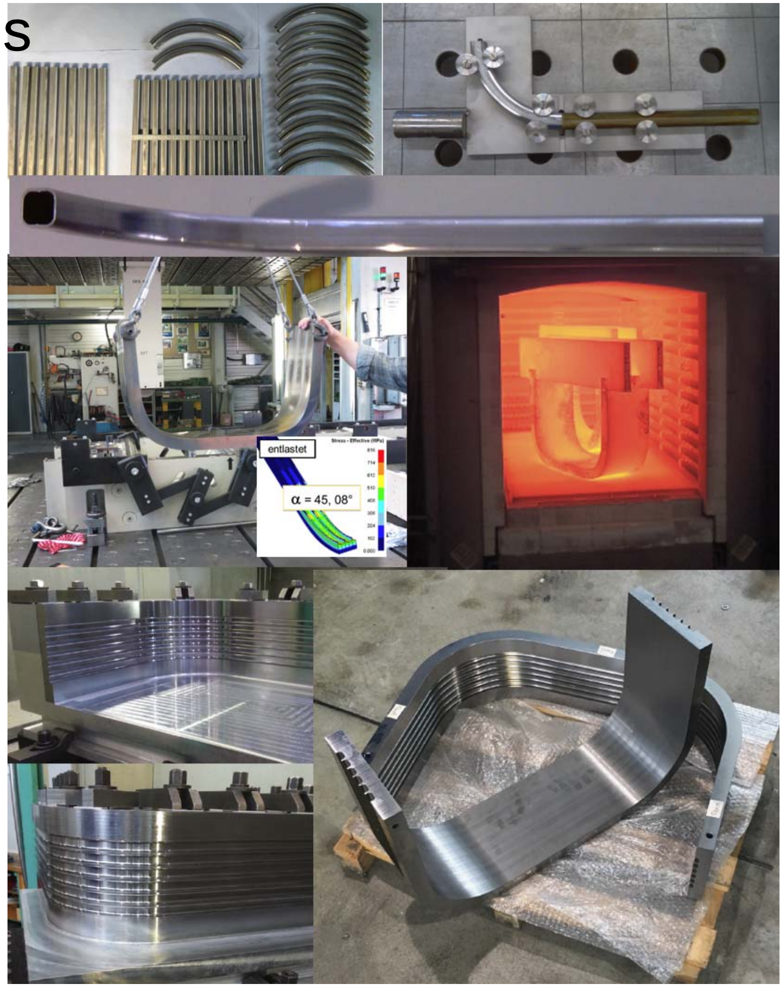
2016: BB-7.1.3-T003-D002: First Wall via HIP: Engineering study to estimate the effort to complete a medium-scale demonstrator from semi-finished parts already built in 2015

→ Pipes, external and internal grooved shells were built in KIT central workshop (BMBF-03FUS0011)

- Dedicated report is concluded
- The demonstrator will be completed in 2019

Cost estimated for medium scale demonstrator:

- Total 0.24 M€ for 2015 configuration (0,15 m^2 front surface)
- > 1 M€/m^2 front surface
- Significant cost reduction potential: fabricate seamless rectangular pipes (> 50 %)

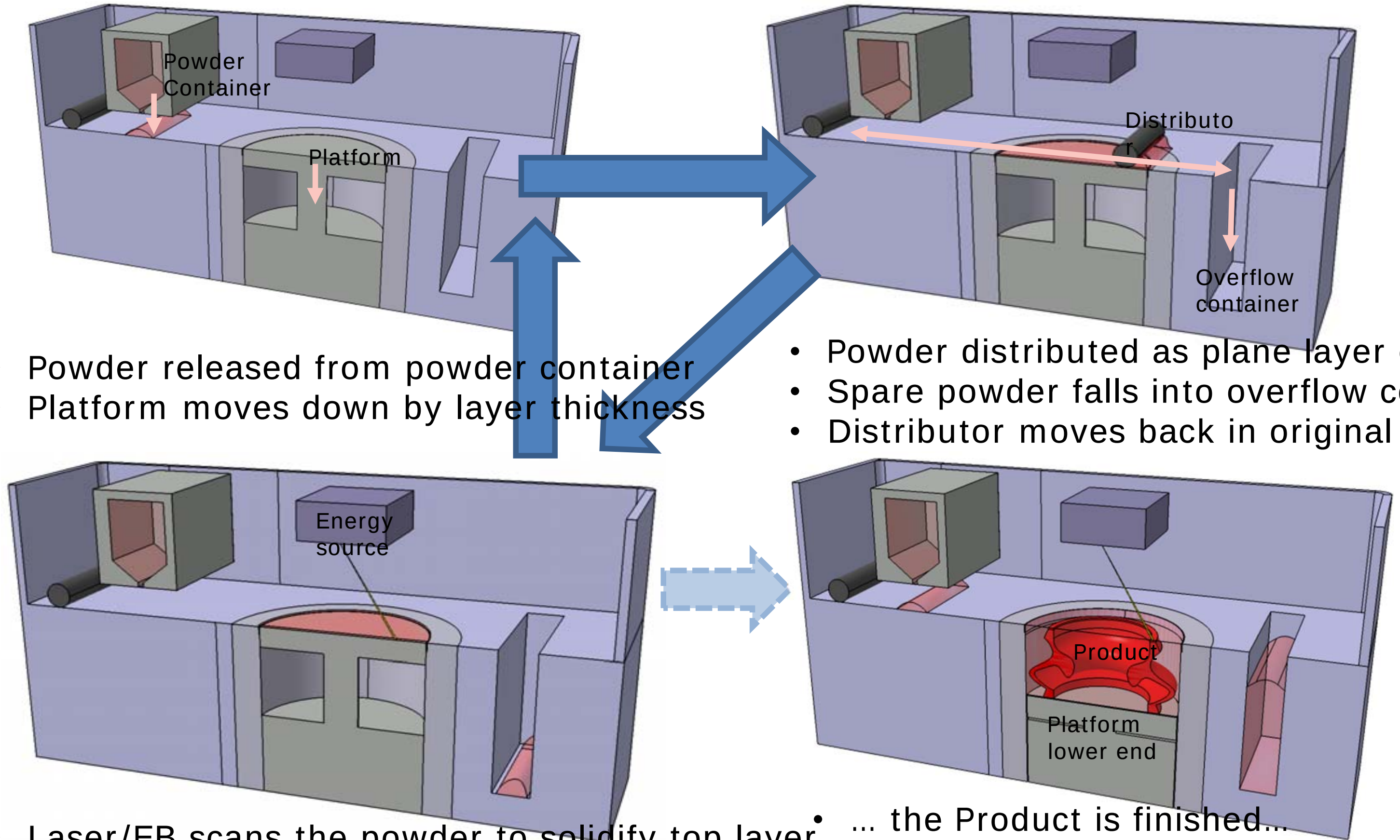


a) pipe segments (machining), b) assembly of segments by EB, c) forming of external and internal shells, d) heat treatment, e) machining of grooves for pipe installation, f) external and internal shell completed

Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

Selective Laser Melting builds a part layer by layer, schematic view below:



- Powder released from powder container
- Platform moves down by layer thickness

- Powder distributed as plane layer on platform
- Spare powder falls into overflow container
- Distributor moves back in original position

- Laser/EB scans the powder to solidify top layer
- Repeated on and on, until…….

- … the Product is finished…
- …or the platform has reached lower end

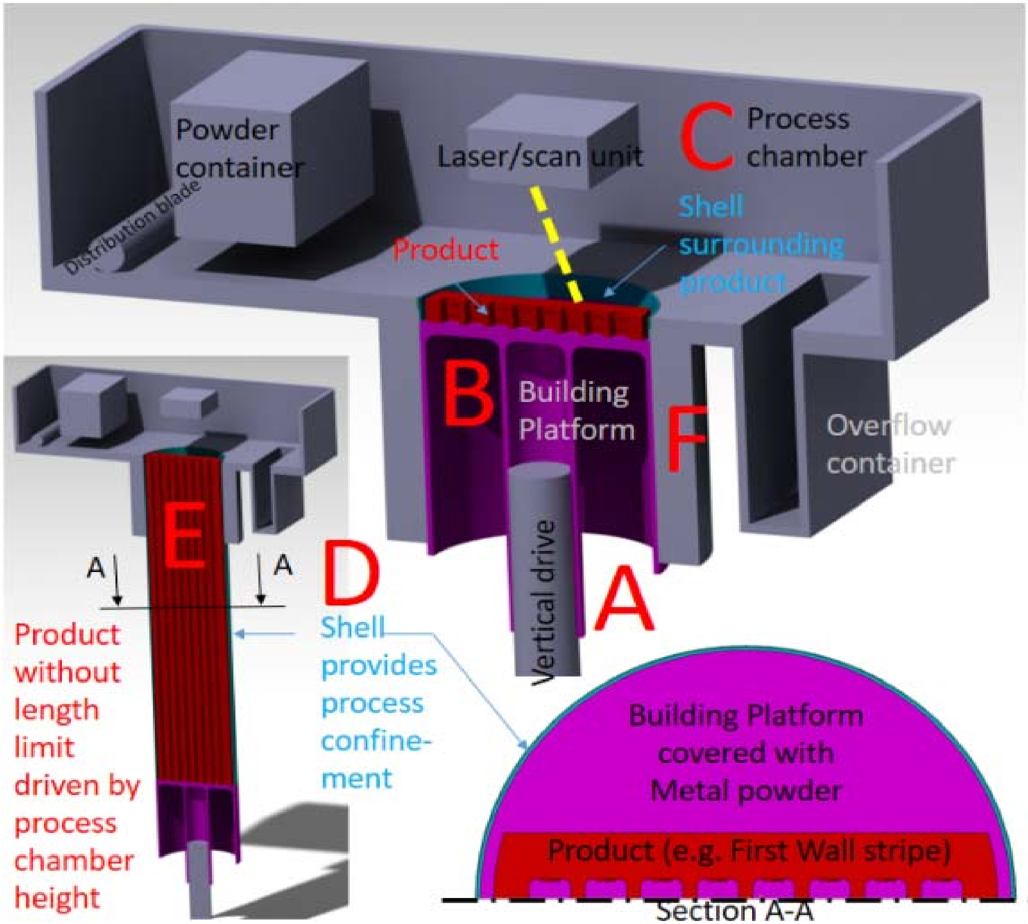
Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

When considering SLM for First Wall applications one issue shall be considered:

- No SLM machine on the market is available for parts > 2 m length
- Idea: Use existing machine and operate in continuous production mode
- Brief description of required modifications here, (for details see [REF-f])
  - Gate (A) below building platform (B) is installed
  - A shell (D) is built coincidently on top of the building platform together with the product (E)
  - The shell shrouds the product and provides process confinement
  - A powder and gas retaining system (F) prevents interaction in between ambient conditions and the process chamber (C)

SLM machine in continuous operation



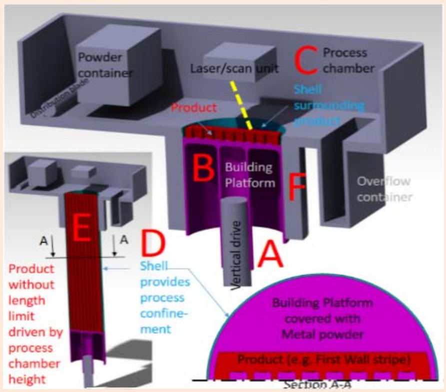
Manufacturing routes in detail

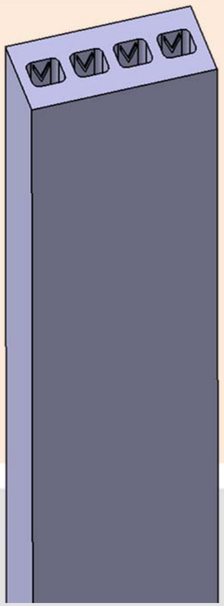
Karlsruhe Institute of Technology

B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

FW manufacturing from SLM-stripes consists of 5 main manufacturing steps:

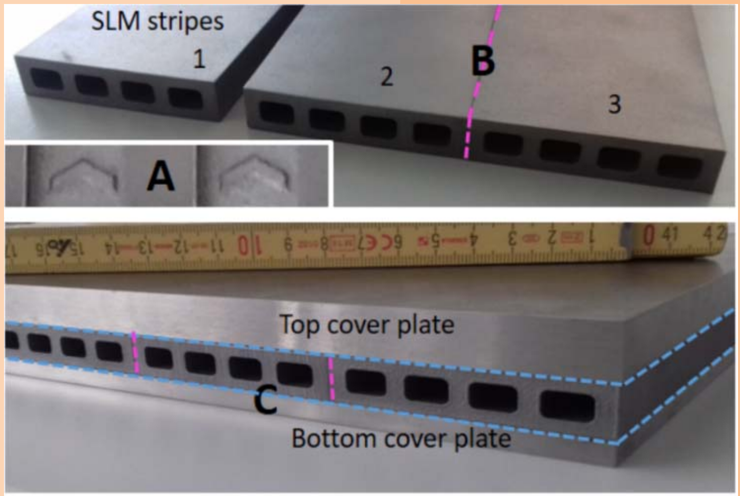
1) Build FW Stripes by SLM





2) Pre-assembly by EB-welding

3) HIP-process



4) Forming + 5) Final machining

...as shown for conventional route

Cost estimated from 2018 demonstrator parts:
350 k€/m² front surface

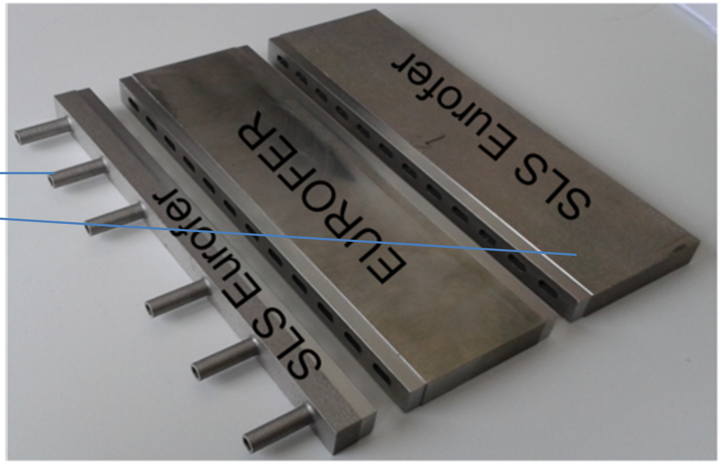
Next step:

- complete demonstration part from three 0.2 m long stripes
- qualification, material tests, comparison to EUROFER-97

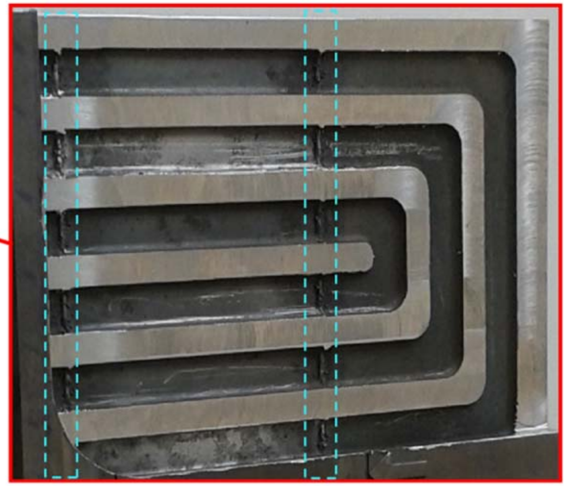
Manufacturing routes in detail

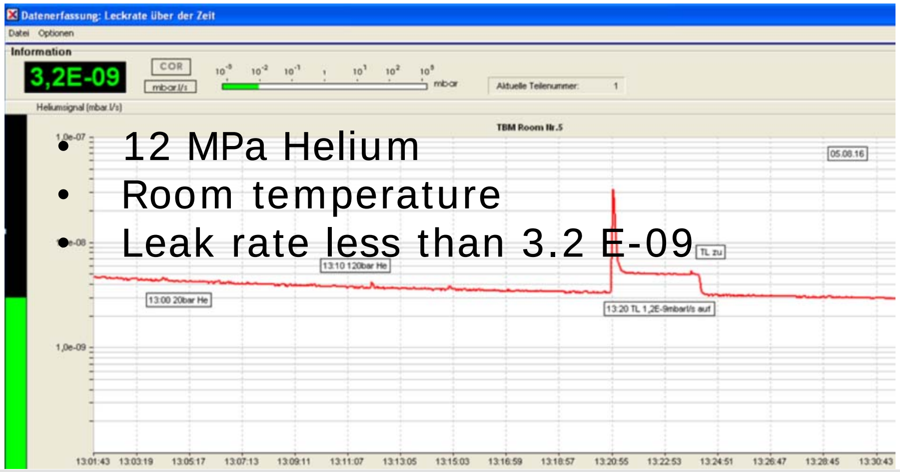
B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

Examples of KIT work for AM [REF-i]
2015: First batch of EUROFER, hybrid components, weld-ability

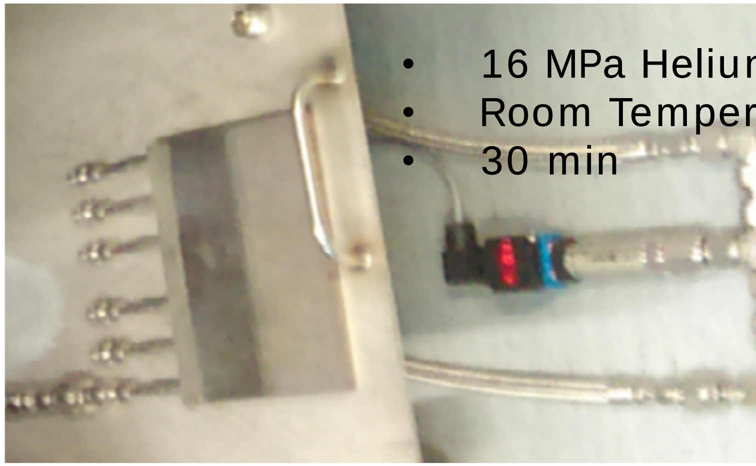


EB welds





- 12 MPa Helium
- Room temperature
- Leak rate less than 3.2 E-09

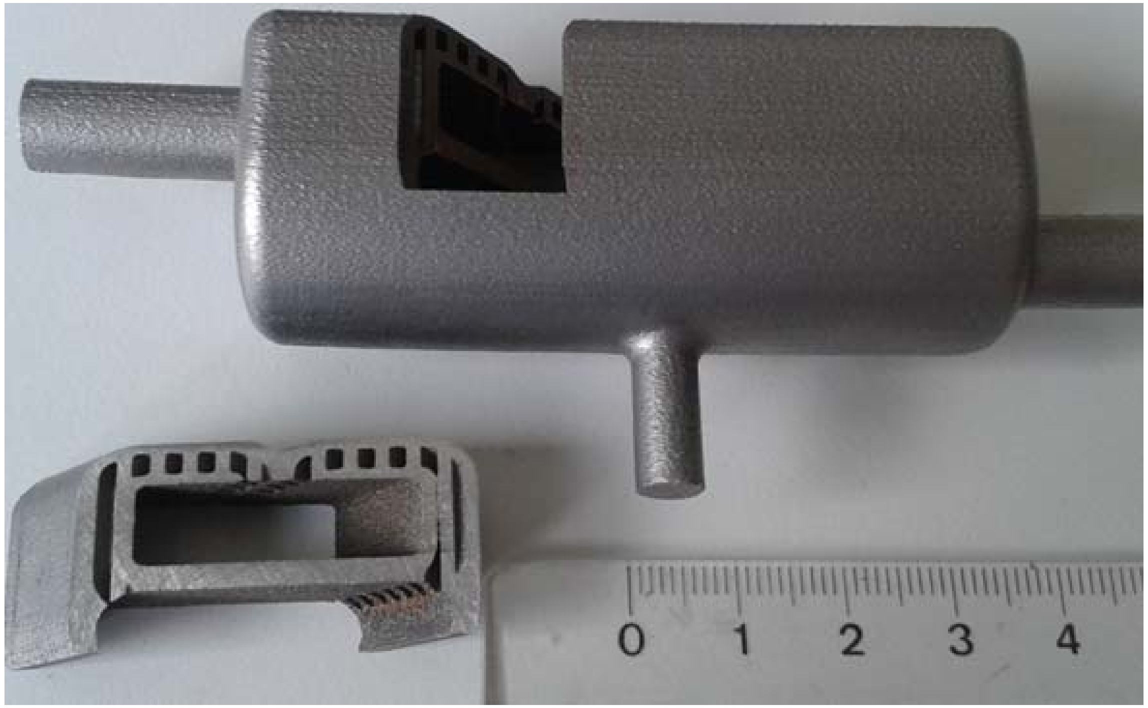


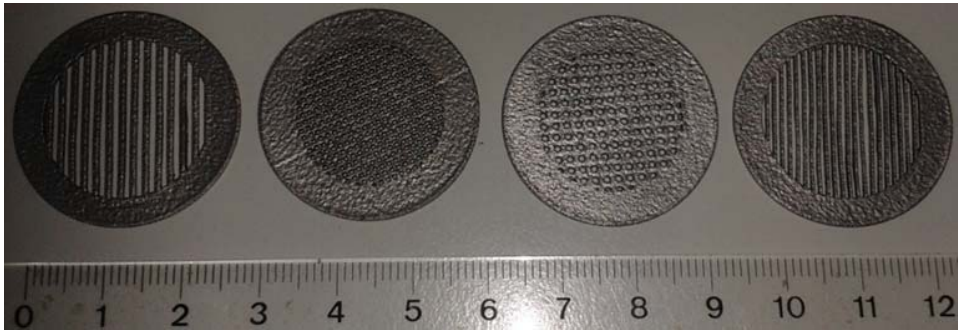
- 16 MPa Helium
- Room Temperature
- 30 min

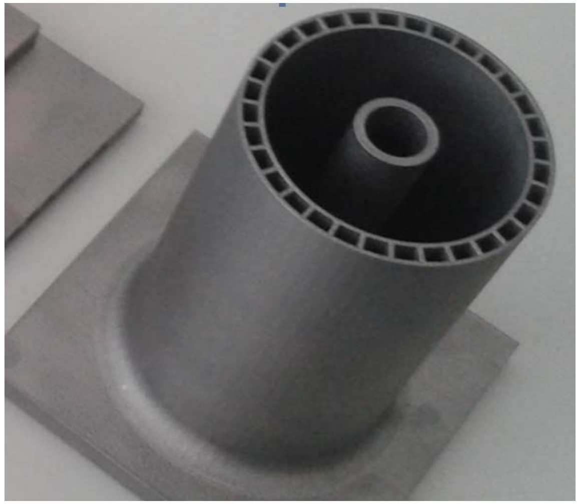
Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

Examples of KIT work for AM
2016: second batch of EUROFER





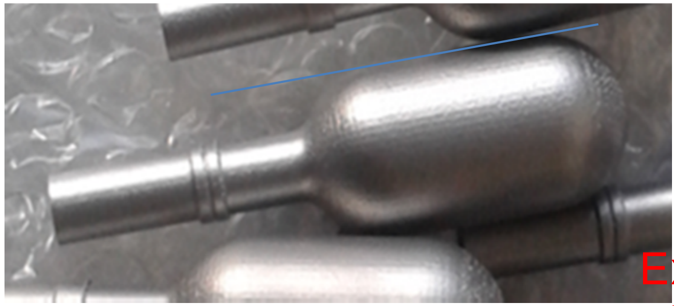


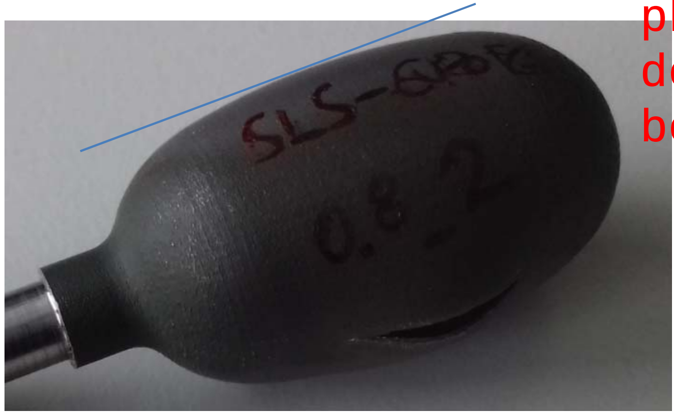
Small CS channels, gas penetration structures, qualification parts

Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

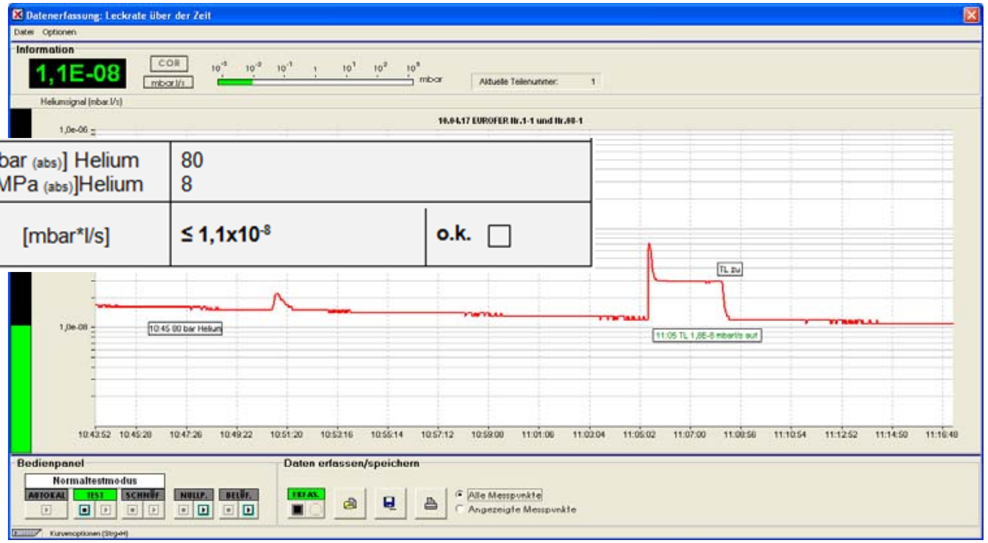
Examples of KIT work for AM
2017: second batch of EUROFER, burst tests





After burst
Dark color comes from HIP/Q/T

Excessive plastic deformation before burst



Prüfdruck/ Test pressure	[bar (abs)] Helium [MPa (abs)]Helium	80 8	
Leckrate/ Leak rate	[mbar*l/s]	**≤ 1,1x10^{-8}**	**o.k.** ☐

Burst pressure 48 MPa
S = 0.8 mm
> 90 % Ult. Stress comp. to EUROFER-97 with comparable HT

Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

Examples of KIT work for AM

2017: second batch of EUROFER, double wall components + CP-lateral parts

Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B1) Selective Laser Melted based concept (FW- Stripes)

2018: latest material parameter results of MIXED EUROFER powder (be published by Ludek Stratil, IPM Brno, Cz in material journal)

Short summary: parts manufactured with 2 sets of SLM process parameters manufactured from mixed EUROFER powders were tested

Different heat treatment procedures were applied

Best results from mechanical tests (compared to EUROFER-97):

- DBTT, Rm, Rp0.2 ~ 90 %
- USE ~ 90 %, DBTT - 90 °C

Micro-structure tests are carried out

Creep/Fatigue are soon completed

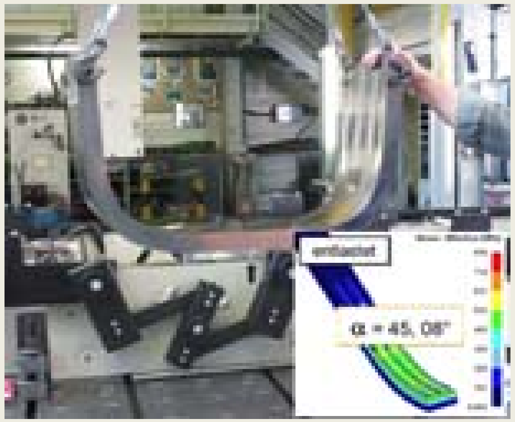
Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B2) Metal Powder Application (Hermle AG)

Total number of 6 process steps, 1 – 3:

1) Pre-forming of blank part

Plane, Bended, 3D-shaped, forged, Etc.

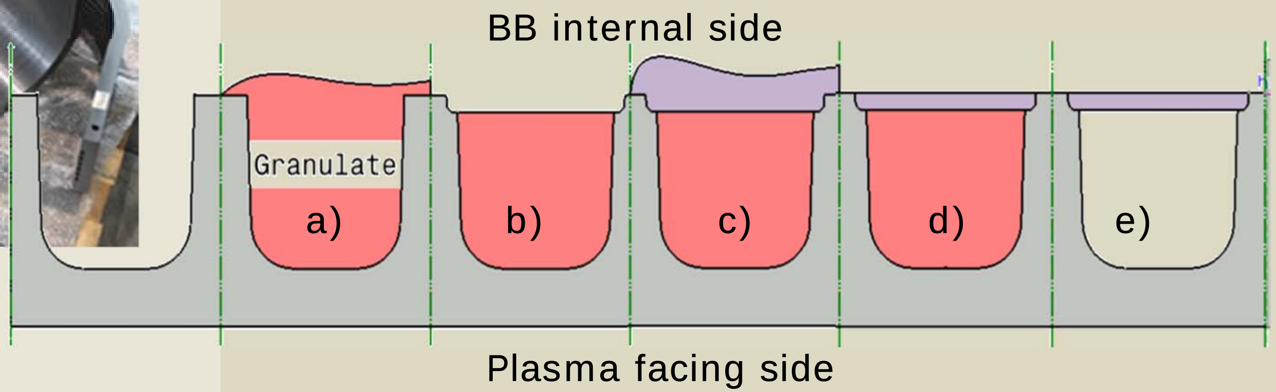


2) Machining of channels

Grooves are machined into blank part used as substrate plate

3) Covering of channels [REF-g]

a) Grooves are filled with granulate
b) Surface is flattened by machining
c) Metal powder is applied as accelerated particles
d) Surface is flattened again
e) Granulate is rinsed by water



Manufacturing routes in detail

B) Innovative process chains (Additive Manufacturing)
B2) Metal Powder Application (Hermle AG)

Total number of 6 process steps, 4 – 6:

4) Preparation of cover plate

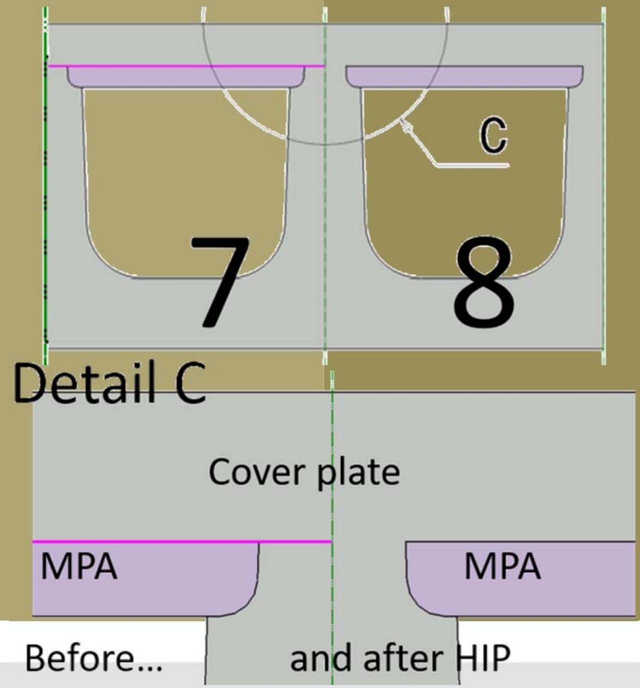
- precise geometry of substrate plate surface is recorded by laser scanning
- A cover plate is prepared by machining accordingly

5) Installation of cover plate (EB)

- Cover plate is placed on top of substrate plate
- Circumferential EB welding is applied

6) Joining of cover plate by HIP

- One solid cohesive body is created
- MPA provides sealing during HIP
- No Structural function of MPA
- Direct contact in between cover and substrate plate is established



Manufacturing routes in detail

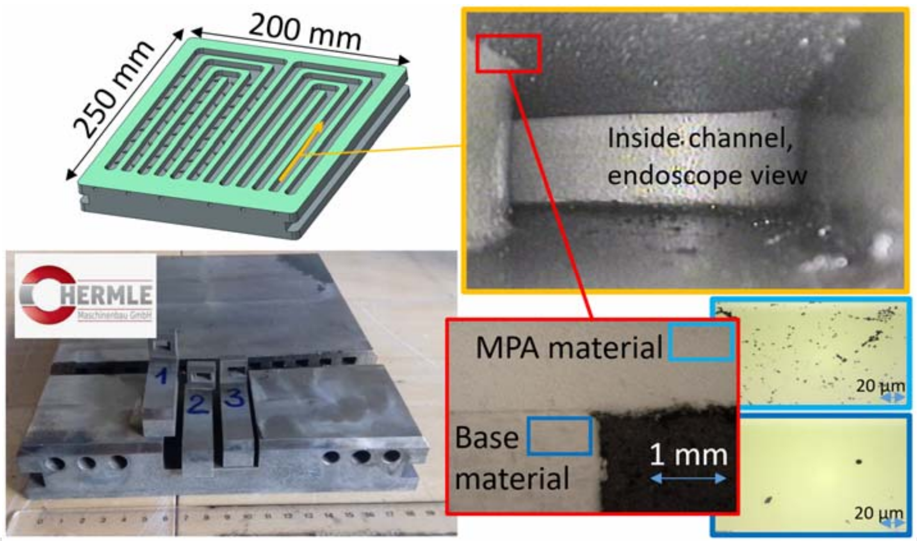
B) Innovative process chains (Additive Manufacturing)
B2) Metal Powder Application (Hermle AG)

Cost estimated from 2018 demonstrator parts:

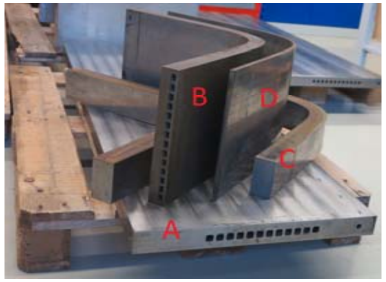
- BB internal structure with meandering channel structure
- FW relevant structure

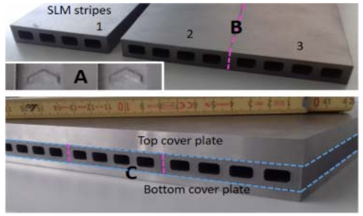
150 k€/m² FW front surface, MPA + cover plate + HIP

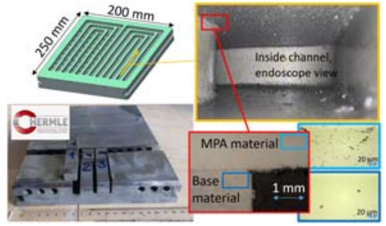
Next step:
- Complete demonstrators (cover installation, EB + HIP), Qualification/material tests



Direct comparison among concepts







Process	EDM + forming	HIP assembly	SLM stripes	MPA + HIP
Cost [M€]/m² (now)	0.5 M€/m²	> 1 M€/m²	0.35 M€/m²	0.15 k€/m²
Estimated cost reduction potential ~ 10 years	40 % (parallel processing)	> 50 % (using seamless pipes)	10 % (parameter optimization)	20 % (parameter optimization)
Deviation FW cover layer	+/- 0.5 mm	+/- 0.25 mm	+/- 0.5 mm	+/- 0.1 mm
% of BB FW full size built	4 % (7 % end of 2019)	1 % (2.5 % end of 2019)	1 % by end of 2019	2 % by end of 2019
% of key dimension (total channel length) demonstrated	> 80 % (2.5 m)	40 % (1.2 m end 2019)	7 % (0.2 m)	15 % (0.4 m) Increase of length feasible without development effort
Licensing effort, [ranking 1 (low) – 4 (high)]	1 (route qualified for HCPB TBM CP , [REF-h]), no welding	3	4	2 (MPA material has no structural function in operation)
Feasibility to implement HT enhancement structures [yes/no]	Yes, demonstrated for 0.6 m, 1.6 m are presently envisaged	Yes	Yes	Yes

Conclusions

Conventional route of EDM + forming is the most developed for HCPB

- Largest demonstrator built ~7 % of BB total size at 65% channel length relevance
- All equipment is available, licensing was done for comparable fabrication route
- No welding is applied to build a formed plate with channels
- Measures for cost reduction are identified and are realistic to be realized

Innovative routes using Additive Manufacturing

- Increased precision level is possible by machining of channels after forming (MPA)
- Variety of possibilities exist to implement Heat Transfer enhancement structures
- Cost reduction potential is high (especially MPA)
- SLM in continuous production should be considered also for thin walled high complex structures, double wall parts or tubes, etc.

One final Example:

0.15 M€/m² for MPA process (status now) vs.
0.5 M€/m² for EDM + forming now → reduction by 70 %
0.3 M€/m² for EDM + forming (incl. parallel processing) → reduction by 50 %

Strong interest to further develop innovative routes in parallel to the conventional ones

References

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b) H. Neuberger, Overview on ITER and DEMO blanket fabrication activities of the KIT INR and related frameworks, DOI: 10.1016/j.fusengdes.2015.06.174

c) Sebastian Ruck, Heat transfer and pressure drop measurements in channels roughened by variously shaped ribs on one wall, DOI: 10.1080/08916152.2017.1410506

d) Tonio PINNA, D.N. Dongiovanni, Probabilistic evaluation of safety and RAMI concerns for the different blanket models of DEMO reactor, 26th European Fusion Programme Workshop, (November 2018 in Bad Dürkheim, Germany)

e) Michael Rieth et.al., Cost effective fabrication of a fail-safe first wall, https://publikationen.bibliothek.kit.edu/230081118

f) Karlsruher Institut für Technologie, 2019. Generative Fertigungsanlage und Verfahren zur Herstellung von Bauteilen mittels dieser generativen Fertigungsanlage, DE 10 2017 118 065 A1 2019.02.14

g) http://werkstoffwoche.de/fileadmin/user_upload/Hermle_Praesentation__Additive_Fertigung_mit_der_MPA_Technologie.pdf

h) M. Zmitko, The European ITER test blanket modules: Progress in development of fabrication technologies towards standardization, DOI: 10.1016/j.fusengdes.2015.10.029

i) H. Neuberger, Selective Laser Sintering as Manufacturing Process for the Realization of Complex Nuclear Fusion and High Heat Flux Components, Fusion Science and Technology, Volume 72, 2017 - Issue 4: Selected papers from the Twenty-Second Topical Meeting on the Technology of Fusion Energy—Part 2