IN-BORE TOOLS FOR BLANKET REPLACEMENT IN THE DEMO FUSION REACTOR

J. Rey[1], C. Köhly[1], P. C. Polixa[1], J. Reimann[1]

[1] Forschungszentrum Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany
e-mail contact of the main author: joerg.rey@iket.fzk.de

Abstract

Studies for the integration of a blanket in a fusion reactor have been performed during the last year in FZK. In these investigations a maintenance concept based on the replacement of large blanket modules and a lay-out for a helium coolant manifold has been addressed [1]. The proposed concepts assume that about 350 blanket modules with a weight limit of about 10 t have to be replaced through the equatorial ports of the reactor [2]. This paper describes the design of the He cooling pipe system and the requirements and strategies for the in-bore welding and cutting tools for (re-)placing a blanket module.
The Helium cooled fusion reactor requires a pipe system inside the Vacuum Vessel (VV) which has to be welded, cut and re-welded with in-bore tools. The overall length of one pipe section and thus the distance the tool has to pass, could be larger than several x 10 m. The pipes are fixed radial behind the shield modules which are lifetime components and constitute the segmentations for the pipes compensators. Additional requirements are path detection and position detection as well as inspection of the weld. Therefore different in-bore tool modules are required to execute such different tasks.

1. Introduction

To realise the replacement of blanket modules *only* with the combination of in vessel remote handling and in-bore tool design, the requirements for pipe connections, compensation strategy and the possible tool tasks had to be observed. Also the scenarios of weld seam design and joining process is close depending from the observation and space tasks of in-bore tools. The maintenance time for the pipe connections between lifetime components and replacement to the process methods will be shown in the status of material dependence.

2. Overview of In-vessel Blanket, Shield and pipe integration

In the present studies of the reactor integration process for Demo it is foreseen to fix the pipes of the Blanket cooling system on the shield segments. These segments are fixed to the vacuum vessel by remote handling tool. The system of the **H**elium **C**ooled **P**ebble **B**ed (HCPB) consist out of the *Inboard* $D_{internal}$ 150 mm pipes with 10mm wall thickness and the *Outboard* $D_{internal}$ 200 mm pipes with 15mm wall thickness. Also a purge system is foreseen with about $D_{internal}$ = 70 mm pipes which is not realized yet in the design [3].
Fig 1 shows the Outboard and the Inboard pipe system of a poloidal segment of the reactor.
The operation data for the calculation of the thermal expansion of the pipes depends from the max. ΔT between the water cooled shield and the max. in-bore He temperature. The shield is fixed to the VV and so these reactor parts are foreseen to be in a temperature range about 150°C. The inlet temperature of the He system to the blanket modules is about 350°C. After the heating up in the First Wall (FW) and after passing the Breeder Units (BU) the outlet temperature of the HCPB is about 500°C. So the thermal gradient for the calculation of the pipe expansion is about ΔT = 350°C.

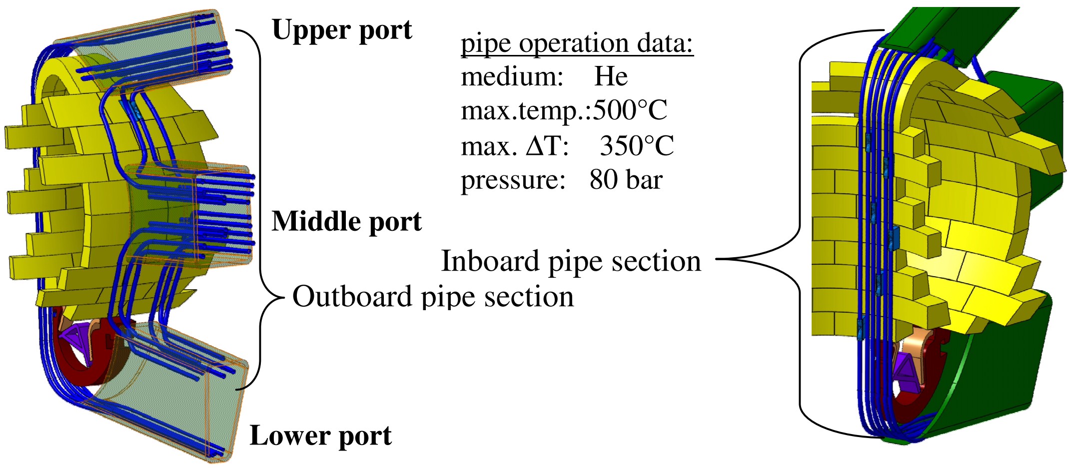


Fig.1 Outboard and inboard He cooling pipe system for Demo Reactor

The shield segments are welded with equidistant poloidal He pipes. This shield segments are fixed to the internal Vacuum Vessel (VV) by a Remote Handling (RH) tool. The strategy for the replacement of the Helium Cooled Pebble Beds (HCPB) canisters uses a reactor rail system with 4 manipulators each one for a section of 90° of the reactor as shown in M&R I. The canisters are realized with a weight less than 10 tons. To allow a cutting of the pipe ends in the range of shield and VV, the HCPB canister is instrumented with 2x pipe bending ends and a short straight pipe end. This also guarantees that replacement welds are in the range of the shielded backside of the HCPB as shown in Fig. 2.

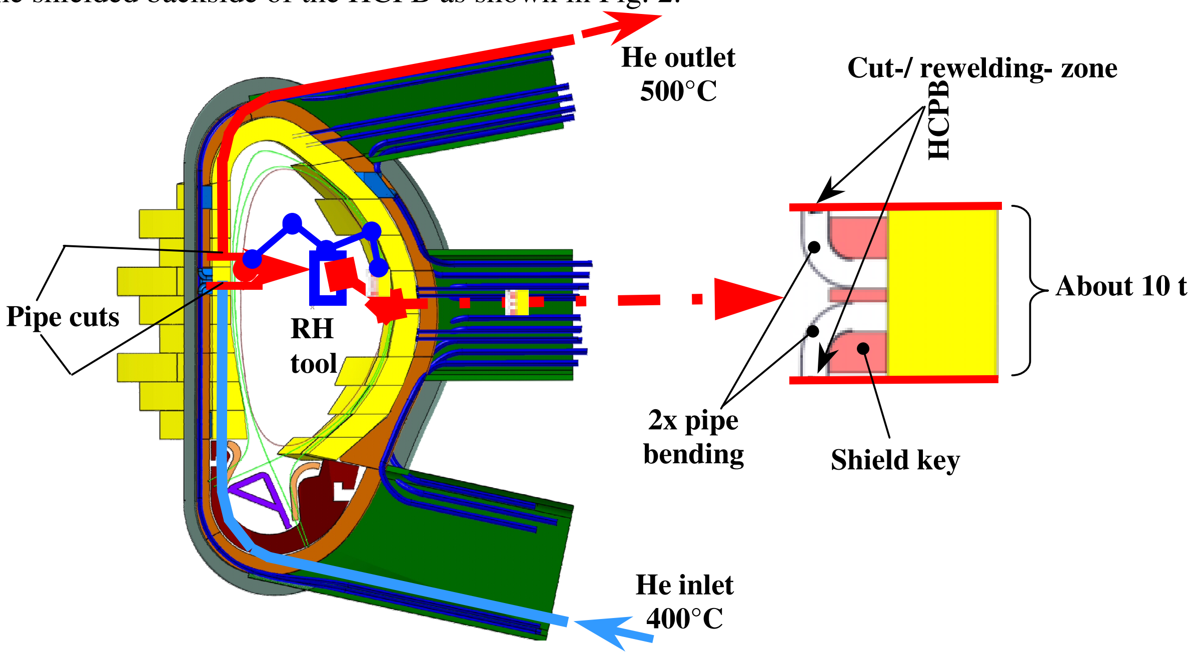


Fig.2 (Dis-)assembling strategy for HCPB Blankets

3. Outboard and Inboard pipe requirements

The strategy of the displacement of only the HCPB and the two pipe bending without the poloidal pipe system makes it necessary to have a lifetime for this pipe component for the whole operation time. Stress analysis showed that in dependence of the present material 1.4919, which is an austenitic steel, it in not possible to avoid a compensation system. Also in

addition to the assembly strategy, it is necessary to foresee intermediate pipe fixing points in the range of the shield segmentation. In the case of a static reactor operation in the last 6 months in FZK a design for 20.000 load alternation was observed to be acceptable for this requirement. Further material research to calculate the fatigue resistance in lifetime will be necessary to raise this load alternation power up.
The design of a compensation system *in vessel* makes it necessary to reduce the radial volume of the waves as far as possible. The goal is a modular compensator with no further radial reinforcements of the waves. The assembly of compensator always needs pre welded short pipe ends which are joined with the plies in a high precision *pre*-process. Also the use of in-bore tools makes it necessary to use internal telescope pipes to allow the passing of the tool. These telescope pipes are also useful to reduce pressure drops in these modules.
The inboard compensators are realized for the 8 MPa operation pressure for the He system with 10 plies and a foil thickness of 0.7mm for each wave segment (Fig. 3).

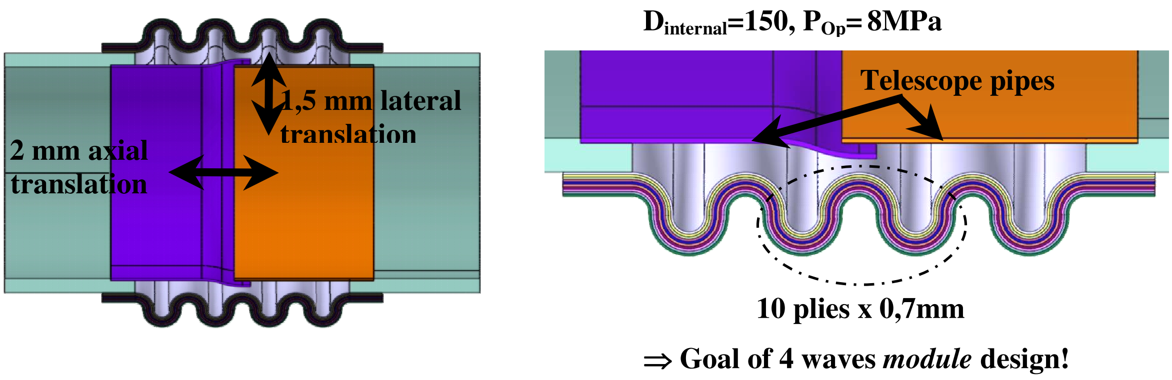
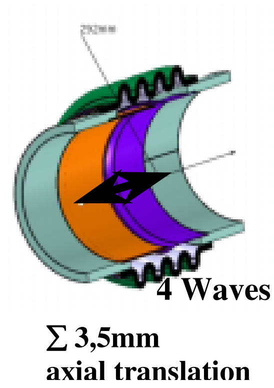
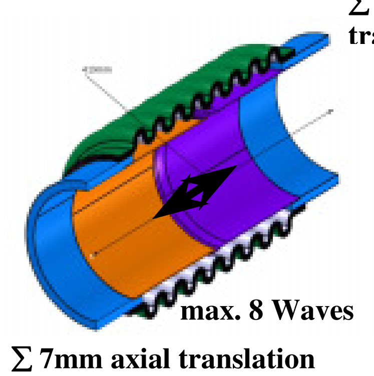


Fig 3 Modular axial and lateral wave movements

A compensation system in the quantities of the foreseen 350 blanket module system makes it necessary to avoid the danger of a wrong assembly of compensation modules. Also the aspect of production costs makes it necessary, to think about a universal kind of compensator module. Such modules I, II, III for the present calculated inboard section are shown in Fig.4 to Fig.6.





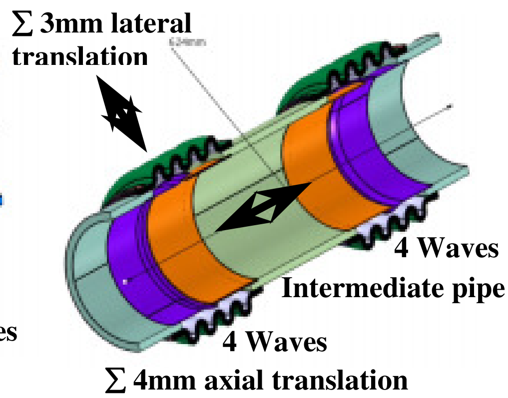


Fig. 4 Short axial module I *Fig.5 Long axial module II* *Fig.6 Axial / lateral module III*

It is an important fact to regard the forces coming from the internal pressure of 8 MPa and the *spring rate* of the compensator waves. The axial elongation of a compensator causes an axial wave displacement force F_{ax} . In the case of the shown $D_{internal}$ = 150mm pipes $\sum F_{ax}$ = 11kN (dependent from the ply structure). Every kind of pipe bending with an internal high pressure produces in the projection screen of the bending zone an operation force F_{op}. The whole force flux and the resulting compensation line of the contact zone of the HCPB blanket module could be seen in Fig.7. The about 90° bending radius of the pipe is foreseen to be a combined sliding fix point. Magnetic operation forces and the lateral internal pipe pressure forces are absorbed in the shield key of the HCPB in the force vector F_{F2}.

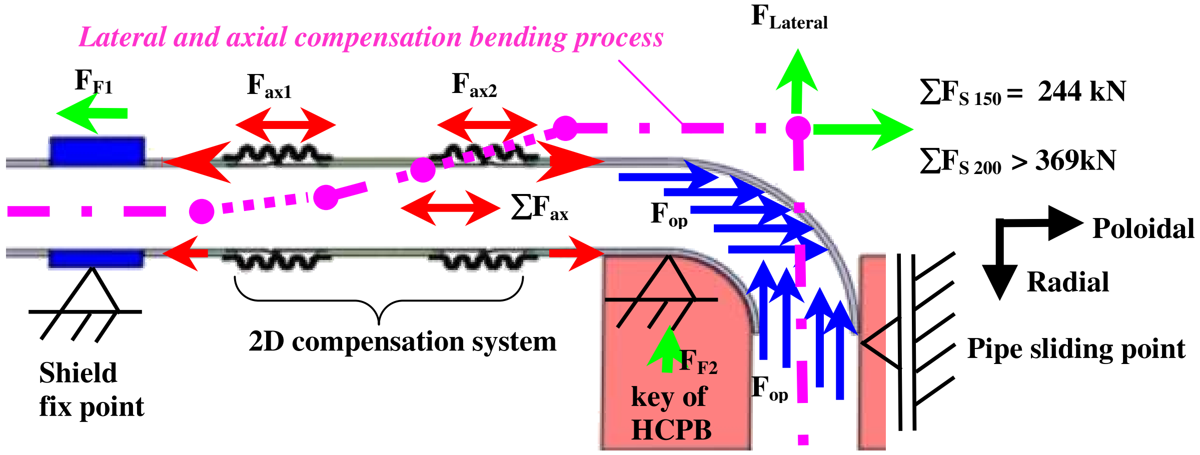


Fig.7 Balance of structural pipe forces in the contact zone of the HCPB compensation

In the $D_{internal}$ = 150mm pipes this total force is $\sum F_{s150}$ = 244kN. In the case of the outboard pipe $D_{internal}$ = 200mm pipes this force is growing to more than $\sum F_{s200}$ = 369kN. In dependence of the design rule in the example of the European Directive 97/23 EG the test pressure is about 14MPa and therefore $\sum F_{s200}$ = 369kN as shown in TABLE I.

TABLE I: Selective pipe forces in operation and test scenario

$D_{internal}$ [mm]	Axial wave displacement F_{axial} [kN]	Internal pipe force *in operation* 8MPa *scenario* F_{OP} [kN]	Internal pipe force *in test* 14MPa *scenario* F_{Test} [kN]
150	4x 2,7 [kN/mm] =10,7	233	407
200	—	369	646

The segmentation of the compensation makes it necessary to limit all modules with fix points which are shown in Fig.7 in the force position F_{F1}. The total poloidal inboard segmentation with the use of fix points is demonstrated in Fig.8. The blue blocks had to be welded construction elements at the shield.

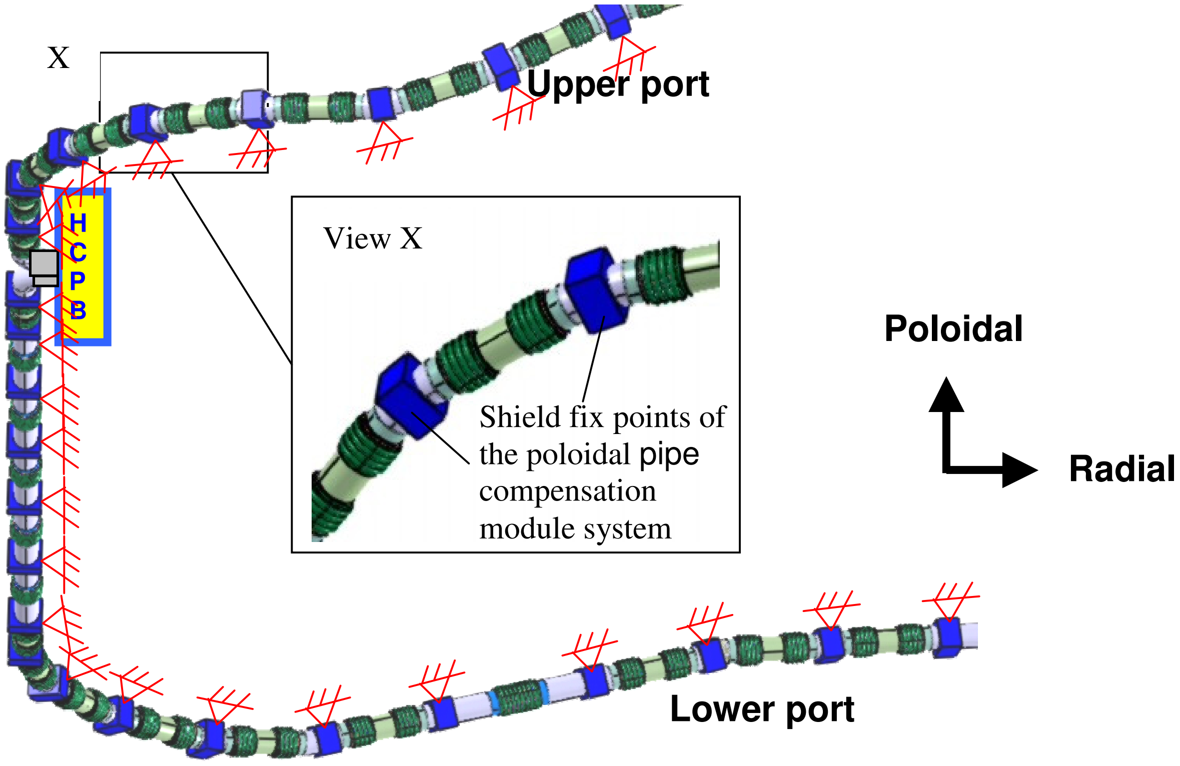


Fig.8 Complete inboard compensation system $D_{internal\ 150}$

4. In-Bore Tool design tasks

There are different tasks which had to be realised with 100% in bore tool processes:

4.1. Path reference
4.2. Pipe cutting
4.3. (Re)-welding
4.4. Inspection

Path references need to be realised in all further measures. Cutting, welding and inspection processes need to be positioned in the head module of the in-bore train. Therefore these tasks need to have three different tool trains.

4.1. Path reference

The path reference of in-bore tools uses in the present nuclear maintenance micro optical camera systems and also the 1D tire roll motion. The mainly poloidal radial pipe system of the FUSION reactor design needs also an observation of the 3D course of the pipe. There are to systems which are able to detect 3D pipe loops. One is the 3D gyroscope system. It consists out of three goniometers and three accelerators. The examination in the difference of phases in the influence of the gyroscope leads to the 3D path examination. With this system it is in the moment possible to detect in-bore positions of underground pipe loops. The precision of the system had to be increased in the further R&D of FZK-IAI to be in the range of fewer millimeters. The present 3D LASER systems are able to detect from different positions the outside dimensions of loops. Also here further R&D is necessary to realise this in in-bore tool design.

4.2. Pipe cutting

The He inboard / outboard pipe system for cooling HCPB needs the highest internal purgation. So the only foreseen cutting method is the LASER technique. A fiber optic wire for the contact to the in-bore train head is necessary to separate the extensive energy production from the tool head. A 3D adjustable torch with a reflector and an optical focus refractor allows an in-bore 90˚ adjusting to the radial cutting zone. Fig.16 of a future R&D for a LASER hybrid torch shows also this process. Instead of the arc torch the use a separate radial torch for an inert gas blow-out is used to allow the material cutting. Additional an internal vacuum system reduces further dust. A definition of the possible remaining dust is not calculated yet but it had to be clear that this fact will be not avoidable.
The internal cutting seam of the lifetime component is proposed to be rectangular. Only the replacement component needs an angular preparation.

4.3. (*Re-*)welding of blanket He pipe system

In-bore tool application needs the use of a welding torch which is able to pass the entire bending pipe radius. The possible radius of present in-bore tools is about $r \geq 1.5 \times D_{internal}$. To allow all adjusting motions, it is necessary that welding torches need a three axis translation and of the orbital seam also a rotation bearing. In this moment torches allow only the weld of straight pipes. A welding torch is shown in Fig.10. The torch length is about 1.2m also Fig. See. To reach the bending radius of $r_{150} \geq 225$ for inboard pipes and $r_{200} \geq 300$ for outboard pipes tool manufacturers had to reduces these translation bearings for this task. The scenario for the passing of in-bore tools for inboard assembly is presented in Fig.9

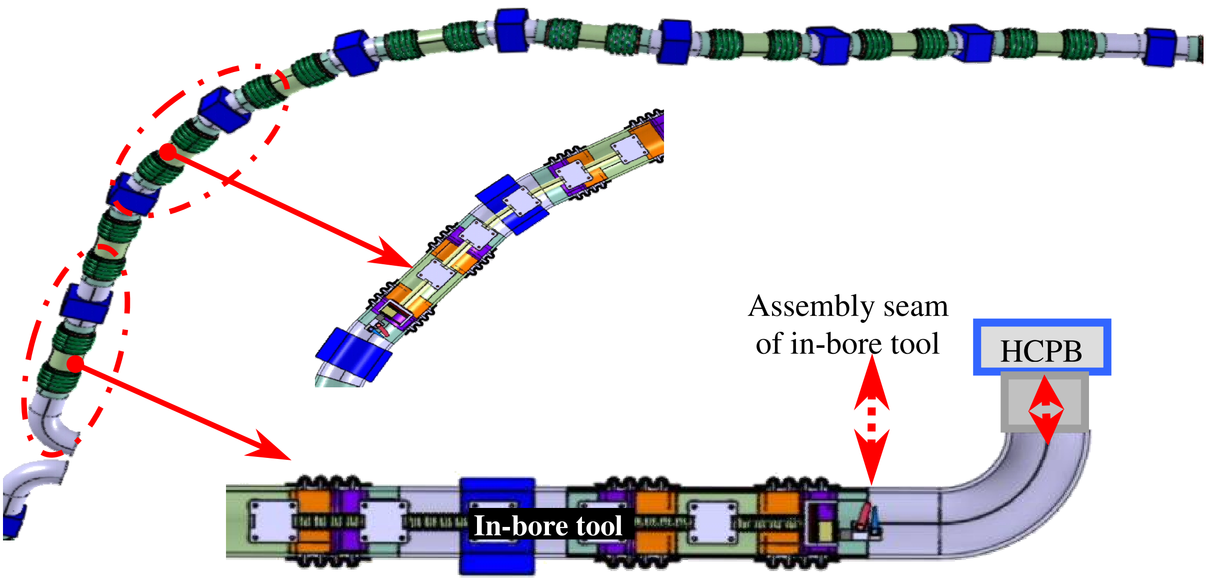


Fig.9 Inboard pipe from upper port with in-bore tool

4.3.1. Aspect of joining process and gap bridging

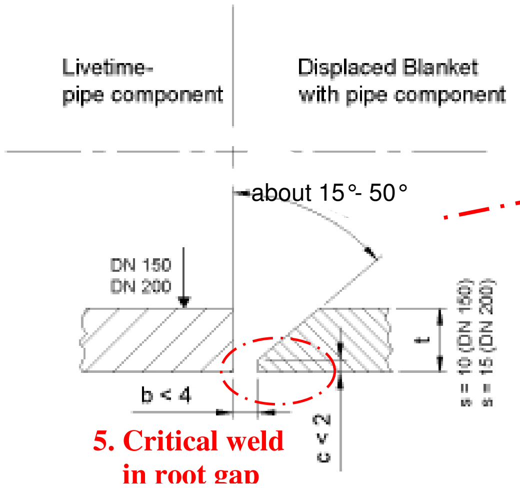
The pipes of the shield- and the blanket modules cannot be positioned with constant gaps accurate to a few millimeters. Thus the tool must be able to build these gaps up in order to realise a seam forming. In addition to this problem the welding must be in the quality for pressure containment design and He leak tightness. TABLE II gives an overview of in-bore welding techniques. In comparison from energy beam techniques, the arc welding joining is the only method to realize the aspect of gab bridging. Standard LASER or EB welding techniques need a gab tolerance of less than 0.3 mm. In order to minimize flange defects also Metal Shield Gas (MSG) welding method is not foreseen for in-bore tools

TABLE II: Overview of in-bore welding techniques

Welding technique	**Additional wire**	**Seam design**	**Gap bridging ability**	**Acceptance for in-bore**
TIG (standard) TIG narrow gap	yes	HV gap about 15°- 50°	Max. 4 mm	high
MSG	yes	HV gap about 30°- 50°	Max. 4 mm	risk of flange defects
LASER (standard)	no	II	0 to 0.3 mm	no
LASER Hybrid	yes	II	Max. 1mm	further research
EB	no	II	0 to 0.3 mm	no

Fig. 10 In-bore TIG welding head with marked translation and rotation torch

Possible seam scenarios of the Tungsten Inert Gas (TIG) joining method are demonstrated in Fig.11. The Figure uses seam angles from about 50° (standard TIG) to the specialized narrow gap weld about 15°.
It is much more supposable that a seam scenario is more like a mixture of Fig. 12. The critical aspect is always the quality of the root gap and root flanges.



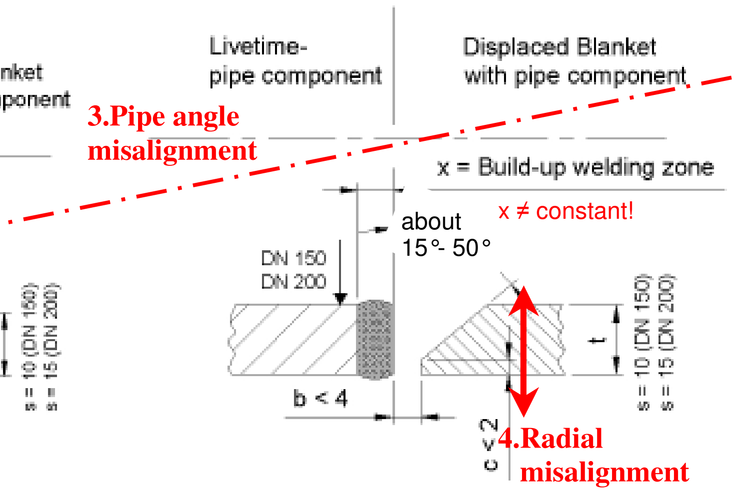
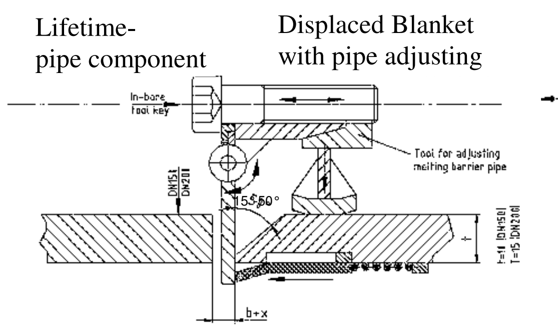


Fig. 11 Standard TIG HV-seam

Fig. 12 TIG HV-seam + X-gap

In all TIG joining the root weld needs additional inert gas shielding. The fatigue resistance of this welds needs to have a defined forming of this root gap. Therefore a sagging of the root must be avoided. The design for this problem uses a dynamic gap barrier Fig. 13. In the replacement of HCPB this barrier is flush with the pipe end. An inserted tool which is put out with an in-bore tool key allows that this barrier closes the gap after the finished assembly in Fig. 14.



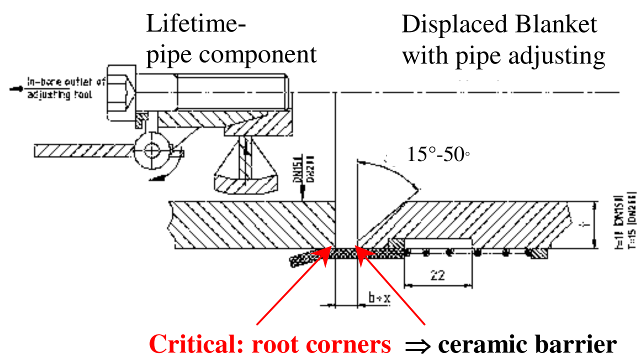


Fig. 13 Possible in-bore pipe assembly scenario

Fig. 14 Adjusted seam root and tool outlet

4.3.2. Thermal joining aspects and process-time reliability

In a present calculation for an inboard weld with 1.4919 material the following data are necessary to realize the weld. Thermal In-bore Arc welding seam composition aspects $D_{internal}$ = 150mm pipes and a wall thickness of 10mm it is proposed to make a 12 plies joint with TIG technique. In the first 3-4 plies it is possible to weld without interrupting the process. Up to ply 5 in the Heat Affected Zone (HAT) of the join the temperature is growing higher than 200℃. Therefore the danger of thermal cracks is the consequence. To avoid these defects it is necessary to re-cool the weld in a temperature range of 150°C < t_{HAT} < 200°C. To accelerate this process an additional gas cooling is not very efficient. So the re-cooling time depends mostly from the material and is in the range of 2x $f(t_{join})$ as mentioned in TABLE III.

TableIII: Total welding process time

Process	Tool velocity	Process time [min]	Remarks
In-bore module positioning	≈ 200 [m / h]	2 x 10 + 10 = 30	path detection inclusive, without tool reference
Join process	≈ 6 [min / ply]	≈ 72	without cooling sequence
Re-cooling	—	**2 x f (join)** = 144	accompanying to the join process, depending from number of plies

In conclusion the total process time for one join in $D_{internal}$ = 150mm pipes is about more than 4h. The process time in $D_{internal}$ = 200mm pipes is therefore about more than 6h. This calculation did not include weld torch defect times which in such cases make it necessary to remove the whole tool for one time.

4.4. In-bore tool inspection systems

There are three different methods to get information of the general in-bore and especially the welding seam qualification. The first is a visual micro camera test which is able to detect surface defects. The present camera standards are in the range of a diameter less than 5mm which makes it possible to get a 3D effect of the detection zone.
The Eddy current test uses an electro magnetic effect to detect surface cracks.
At last the almost known ultrasonic test is leading to a total detection especially in the important root zone of the weld. Sagging of welds in the root zone in the range of 2-4mm is a standard effect and so never a critical point to disallow the seam. In the detection of welds unfortunately the US technique is not able to detect between standard sagging signal and the very critical root flange defects. Fig. 15 is presenting these less different of the signals which make therefore a differentiation impossible. The root barrier from Fig. 14 also allows a plane melting shrinkage and allows therefore this detection without further mechanical work. In the present the R&D for this barrier is not determined.

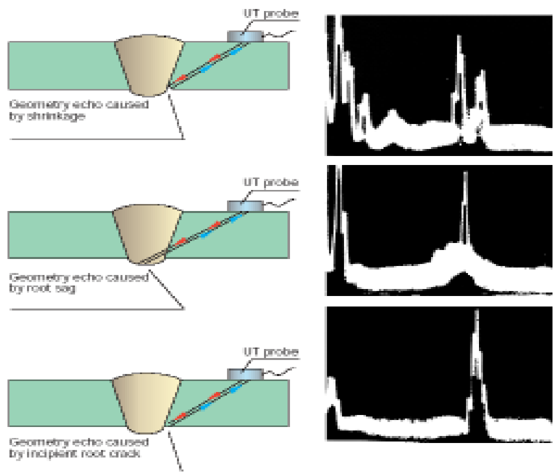


Fig. 15 Ultrasonic detection of root flange defects in comparison to the sagging signal

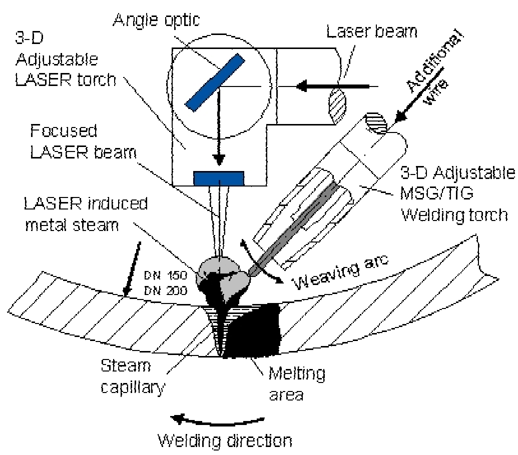


Fig. 16 LASER hybrid joining technique with an additional arc weld process

5. Overview of present and further R&D for join tool design

In addition the effect of thermal energy inlet in the HAZ of the weld had to be reduced with processes of a less heat up effect. Therefore the LASER hybrid technique could be a method to be observed for this low thermal energy effect. The flexible separated control of an arc weld method may bring gap bridging > 1mm. For this method follow also Fig. 16. The effect of low thermal HAZ with arc / beam joining methods may also allow less welding process time because of reduced plies structures.

6. Conclusions and further R&D

The replacement of HCPB blanket with the submitting of in-bore tools is realistic to be foreseen as a method of maintenance and reliability.
For path detection the task had to be foreseen to allow further precision development. The segmentation with compensation systems is not avoidable and could be done. Further material R&D for fatigue resistance is necessary to calculate load alternations higher than 20.000. Welding torches smaller than 1.2m are necessary to allow the passing of the present in-bore tool radius of $r \geq 1.5 \times D_{internal}$. The LASER Hybrid technique seems to be a possible further joining method for in-bore welding torches.

References

[1] HERMSMEYER, S., et al., "Revision of the EU helium cooled pebble bed blanket for DEMO", (Proc. 20th IEEE/NPSS Symp. on Fusion Engineering), San Diego (2003).

[2] NAGY, D., et al., "**Remote Handling Concept for the Modular HCPB Blanket integrated in a TOKAMAK Fusion Reactor DEMO**", (KTJ 10.-12.05.05), Nürnberg, Germany (2005).

[3] HERMSMEYER, S, et al., "**Development and Reactor Integration of Helium Cooled In-Vessel Components for DEMO**", (20^{th} Fusion Energy Conference IAEA-FT/P7-11, 01.-06.11.2004), Vilamoura, Portugal (2004).

[4] WITZENMANN, et al., "**Compensators – The Manual for Compensatortech-nique**", Witzenmann GmbH, Pforzheim, Germany (2004).

[5] FRAMATOME ANP, et al., "**Products for Component Replacement & Repair; Sevice Equipment for Pipe Cutting, Machining & Inspection**" Flyer Paper, Framatome ANP GmbH, Offenbach/Erlangen, Germany (08/2004).

[6] FRAMATOME ANP, et al., "**Manipulators for the Performance of In-Pipe Operations; Remote-Controlled Pipe Inspection, Examination Machining, Welding and Suction Extraction**" (Flyer Paper), Framatome ANP GmbH, Offenbach/Erlangen, Germany (08/2004).

[7] INSPECTORSYSTEMS, et al., "**New developments in nuclear technology with state of the art multifunction robots**" Flyer Paper, Inspectorsystems GmbH, Rödermark, Germany (03/2005).

[8] INSPECTORSYSTEMS, et al., "**Pipe roboters for inspection, examination and maintenance of pipe loop systems**" Flyer Paper, Inspectorsystems GmbH, Rödermark, Germany (03/2005).