Configuration Space Control using the Example of In-Vessel Components for Wendelstein 7-X

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Abstract **— Concurrent engineering with the design of increasingly complex components requires addition tools to avoid space conflicts. Configuration Space Control is a key technology necessary to achieve the required design efficiency and product development of a complex experiment. Easily accessible solutions available within CAD Frameworks, Product Data Management, and Configuration Management Systems currently only solve part of this task. Therefore, it has been vital to develop and control a set of procedures which handle the concurrent engineering issues and manage the compatibility of the various components being designed, manufactured and assembled. In addition a defined set of procedures are required to control the changes, additions and non-conformities to the design of components which occur in a developing experiment. To cope with these tasks, sophisticated tools and procedures have been adapted, developed and implemented. This paper covers the Configuration Space Control process for In-Vessel Components of Wendelstein 7-X, and demonstrates its application in the control of the as-assembled components.**

Keywords — Configuration space control; Configuration management; Reverse engineering; In-vessel components; Stellarator; Wendelstein 7-X

I. INTRODUCTION

The superconducting stellarator experiment Wendelstein 7-X (W7-X) is currently under construction in Greifswald, Germany, and is envisaged to start its first operational phase in 2015. The mission of this experiment is to demonstrate the reactor potential of the helical advanced stellarator type for steady-state operation [1], [2]. The machine features a helical magnetic axis characterized by a strong variation of the plasma cross-section from triangular shape to kidney shape and back, which is repeated with a five-fold rotational symmetry. Each of the five sectors is denoted as a torus module. W7-X is designed to operate in steady-state with 10 MW input power provided by the Electron Cyclotron Resonance Heating (ECRH) system with a pulse length of up to 30 minutes and peak power of up to 24 MW; the additional power provided by the Neutral Beam Injection (NBI) and the Ion Cyclotron Resonance Heating (ICRH) systems for 10 seconds. Diagnostics and heating systems are arranged around the machine, asymmetrically with regard to the torus modules.

During the design and construction phase, when the production of a variety of components had already started, an additional intermediate operational phase of the machine was introduced [3]. The technical requirements for the components used during this phase, which should last for about two years, are less challenging than the In-Vessel Components (IVCs) used for steady-state operation. In this intermediate stage, the machine will be operated at high power, with a reduced pulse length of 5-10 seconds. A temporary Test Divertor Unit (TDU) with inertially cooled target plates will be installed and is the main component designed specifically for this intermediate phase [4]. The other IVCs are the same but are mainly un-cooled during this phase. Consequently, the design and installation of the components inside the plasma vessel (PV) has been adapted to allow for the two different operational phases and to reduce as much as possible the efforts for the transition phase.

II. IN-VESSEL COMPONENTS

The plasma vessel of W7-X encloses a volume of ~80 m³ with an internal surface area of ~222 m². The installation space for the IVCs between vessel and plasma is very restricted and limited to a volume of ~22 m³ with a plasma-facing surface of ~205 m².

The IVCs (Fig. 1) consist of the actively water-cooled first wall protection, the divertor systems, the cryo-pumps and the control coils, as well as diagnostics and instrumentation, adding up to a total of ~700 000 components with a total weight (without coolant) of about 33 800 kg. The present design foresees 55 diagnostics and ~4 km of pipes assigned to 304 cooling circuits with 106 variants for 890 divertor targets, 300 stainless steel panels, 170 baffle modules and 162 heat shields to be installed [5], [6]. Each cooling circuit and wiring bundle enters the plasma vessel via feed-throughs inside of dedicated ports - the Plug-Ins, which ensure that the vacuum boundary between the plasma vessel and the torus hall atmosphere is maintained.

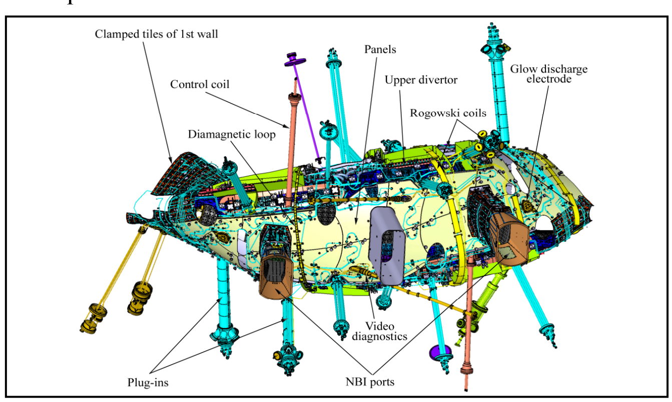


Fig. 1. In-Vessel Components using the example of torus module 2.

The main design and configuration management challenges are to fit the IVCs into the available complex 3D-space between the plasma vessel and the plasma, and to take into account the 245 ports for the various diagnostics, heating systems, coolant supply and instrumentation - all under simultaneous consideration of the different operational phases [7], [8].

III. Configuration Space Control

A. Requirements and background

Due to the extreme 3D-complexity of the W7-X geometry and the severely restricted space for its tightly packed close-tolerance components, it is necessary to cover the worst-case spatial claim for each individual component throughout its life cycle. To this end, the geometrical design data has been broken down into a minimum of 4 basically different conditions:

- As-designed: Nominal CAD geometry with manufacturing tolerances (tolerances might only be estimated at first, and refined in the advancing process of component production and assembly).

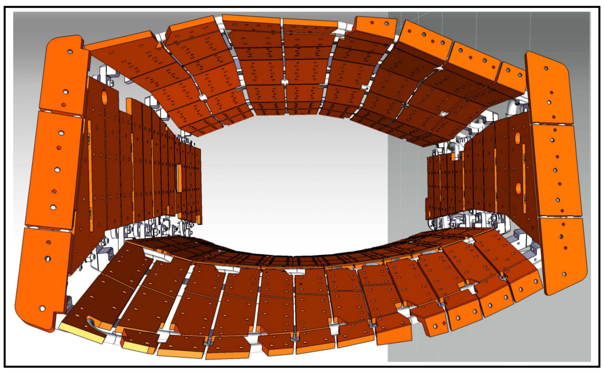


Fig. 2. As-designed geometry.

- As-built: Manufactured geometry of individual components, retracted to CAD by e.g. laser scanning and reverse engineering [9].

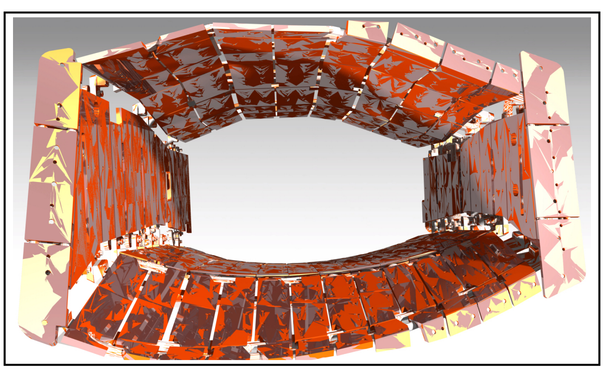


Fig. 3. As-built geometry (overlay: nominal and scanned geometry).

- As-assembled: Manufactured components, finally positioned and integrated in the facility. Geometry from e.g. laser tracker measurements and laser scanning reconverted to CAD by subsequent reverse engineering.

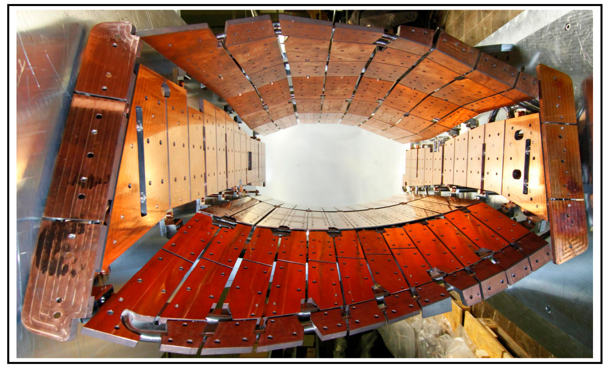


Fig. 4. As-assembled geometry.

- In-operation: Deformation vectors derived from FEM calculations mapped to the CAD as-designed and/or as-built geometry by the method of shape morphing.

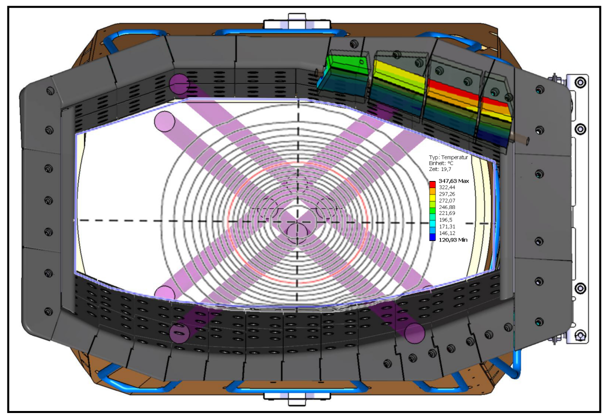


Fig. 5. In-operation geometry with NBI power density profile and local FEM temperature distribution.

For reasons of time and effort, not all 4 data types can be made available for each single component, but definitely for the critical ones.

All 4 types of data are prerequisites for sustainable compatibility checks of components and therefore the basis for Configuration Space Control which minimizes the risk of delaying the assembly process and/or operation of W7-X.

Back in the year 2004, the subdivision “Design and Configuration” of W7-X - as a pioneer in this field - initiated the required actions to procure the adequate personnel, tools and methods to provide this indispensable data. As a consequence, the methods of laser scanning, shape morphing and systematic compatibility checks were introduced to W7-X in the following three years. As a result, and due to the fact that the necessary functionality was not available in the former CAD-system CADDS5® for compatibility checks, such as: processing of point clouds from laser scanning, shape morphing and in general the handling of large assemblies with a multitude of components, it was necessary for the project to migrate to the CAD-system CATIA® V5, even whilst being in the on-going process of component production. Likewise, the existing Product Lifecycle Management (PLM) system had to be adapted to handle the CAD data of a different CAD system.

In the course of this migration, automatic CAD data conversion tools, based on the neutral exchange format STEP, were developed and implemented, and the migration was successfully completed in 2009. The first component design based on CATIA® V5 was the TDU [4].

B. Tools and procedures

For enabling systematic compatibility checks, a variety of auxiliary tools are also required:

- For the automatic synchronization of the full PLM CAD database between the two locations of W7-X development, Greifswald as the device site and Garching for IVCs and NBI heating systems.
- For the automatic generation and update of IVC specific sub-assemblies based on the PLM CAD database, comprising released and work-in-progress data.
- For procedures and forms which check requests by responsible officers for completed and released designs interfacing with IVCs (e.g. diagnostics).
- For programs and procedures for the automatic conversion and data reduction of laser scan point clouds to CAD surface data.
- For the localization of surroundings and automatic distances check report generation directly out of the CAD system.
- For the extraction, as well as templates and XSL stylesheets for the conversion, of CAD check reports from HTML to the PLM compatible DOC format.
- For the data management of generated documents covering all boundary conditions, parameters and CAD models.

All of these were developed and implemented allowing a strong coupling between the database systems and the CAD tools. Further detailed information can be found in [9]-[14]. With regard to the assembly sequence of W7-X, all support tools had been initially developed for the components in the cryo vacuum, i.e. the magnet system and its support and supply systems, and were subsequently adapted and extended for the specific requirements of the IVCs.

IV. Configuration Space Control - Sample Application for IVCs

A. The NBI port and port liner

NBI, in addition to ECRH, is foreseen as one of the main heating systems at W7-X. In a final stage 20 MW of NBI heating power will be installed, generated by two NBI boxes for balanced injection both exclusively located in one of the five modules. Each NBI box has 2 tangential and 2 radial source positions. For the experimental start-up phase each NBI box will be equipped with only 2 ion sources, one tangential and one radial source per box. The peak power-load to the port liner is 6.3 MW/m² for a pulse length of up to 10 s [15].

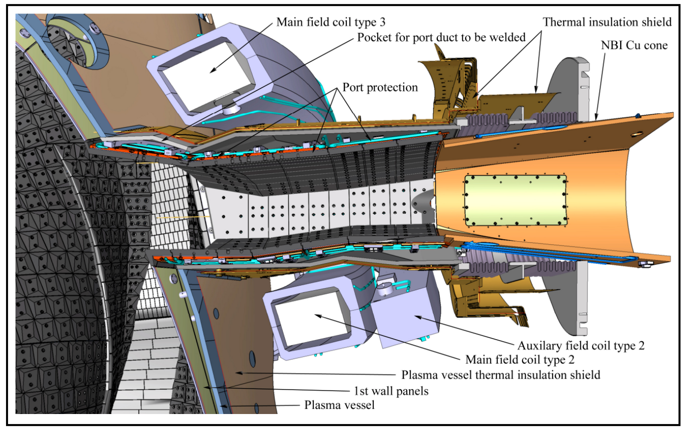


Fig. 6. Cross section of the NBI port and adjacent components.

The available space of each NBI port is restricted by the adjacent superconducting main field coils of type 2 and 3, the superconducting auxiliary field coil of type 2, the thermal insulation of the port and the port liner inside the port duct (Fig 6). A best-fit positioning of the liner with respect to the duct is not wanted, since the NBI direction vectors refer to the absolute coordinate system of the magnetic field. Considering the power-load, any further decrease of the available cross-section could lead to an overload of the port liner. Therefore, it was decided to design the port liner with the maximum cross-section based on the worst-case as-assembled geometry of both port ducts.

B. Assembly and as-built geometry of the NBI port duct

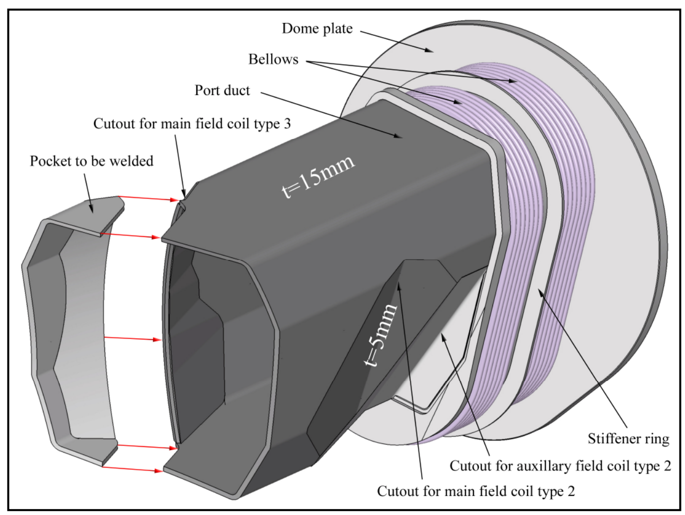


Fig. 7. NBI port components to be assembled and welded in situ.

Due to the restricted space, the port duct could not be inserted from the outside into the device and is therefore assembled and welded in situ in between the coils and the port insulation from 2 single parts with an individual thickness varying from 5 mm to 15 mm (Fig. 7). As a consequence the weld shrinkage, the nominal dimensions and the orientation of the port can be ensured with only limited accuracy. The same situation arises for the geometry of the plasma vessel and the position of the port openings, so that laser scanning has to be used to deliver the as-built and as-assembled geometries and positions of these components.

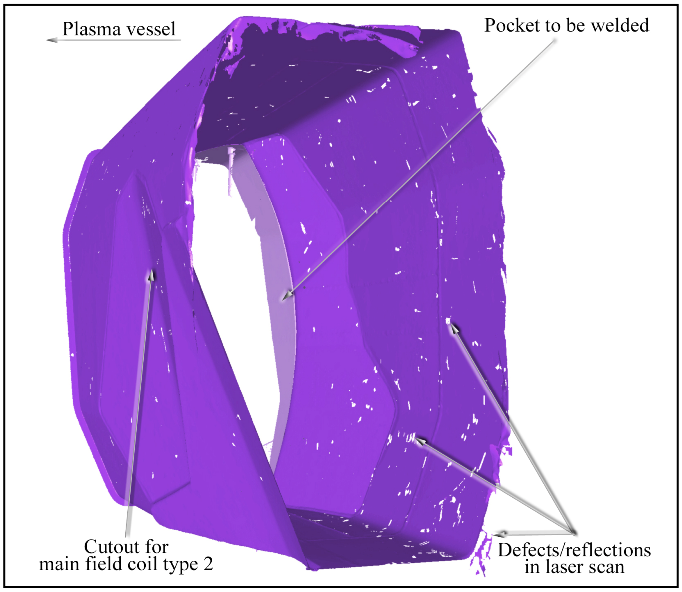


Fig. 8. Laser Scan of the as-built port duct components interior.

Derived from laser scanning, measurement data of the port is available as a point cloud, comprising ~300 000 points and meshed with ~550 000 triangles (Fig. 8). To enable fast compatibility checks the meshed point cloud was converted into a CAD surface (Fig. 9) - for handling reasons, a data reduction, down to 10% of the initial number of triangles, has been implemented in the automatic conversion tools. The reduction is based upon the variation of normal vectors between adjacent triangles, where areas of tight curvature are maintained and those were slight curvature occurs are greatly reduced. The accuracy of the resulting geometry still remains within a sufficient range of < 0.2 mm.

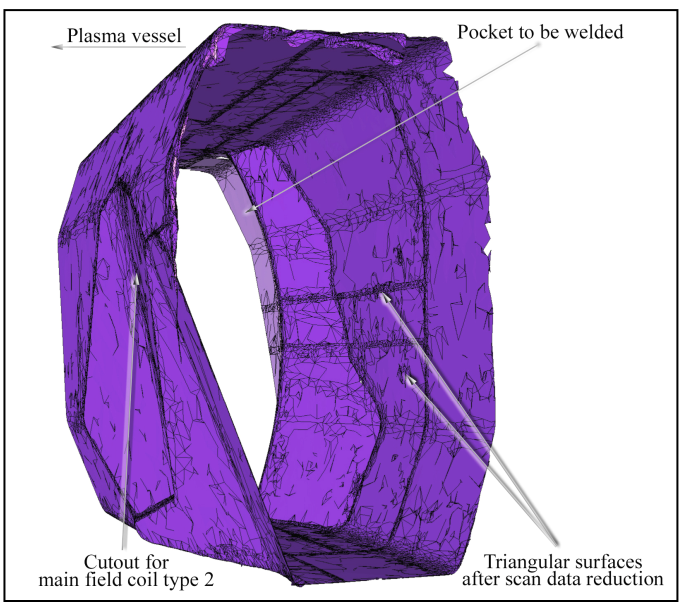


Fig. 9. Converted and data reduced as-built CAD surface of the port duct.

C. The NBI port liner

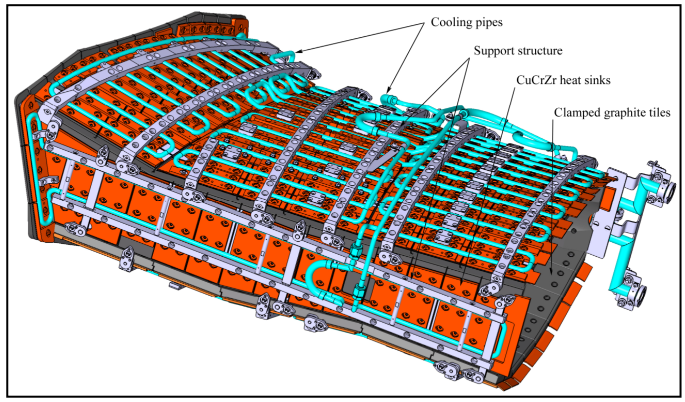


Fig. 10. Actively cooled NBI port liner.

The actively cooled port liner (Fig. 10) comprises fine grained graphite tiles, which are mechanically clamped using TiZrMo (TZM) molybdenum alloy screws via an intermediate Sigraflex® layer onto CuCrZr copper alloy heat sinks, which are brazed to stainless steel pipes. For assembly reasons, the liner is split up into 7 individual segments, so that it can be mounted in the port duct from the inside of the plasma vessel step-by-step. The total weight of one complete port liner is approx. 260 kg.

D. Compatibility check: NBI port liner vs. NBI port duct

The first quick step to start a compatibility check between two individual components is the band analysis (Fig. 11). The minimum admissible distance between liner and duct is 1 mm, so that the parameters for the band analysis were set to 1 mm and 2 mm to indicate the gradient of distances for the determination of additional margins.

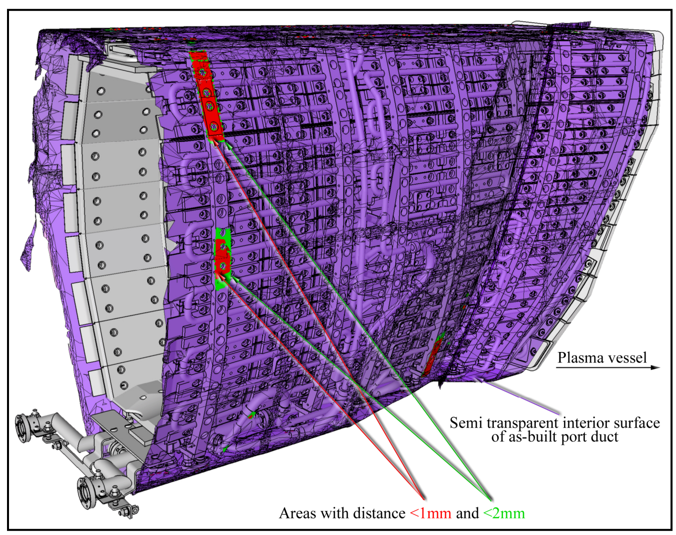
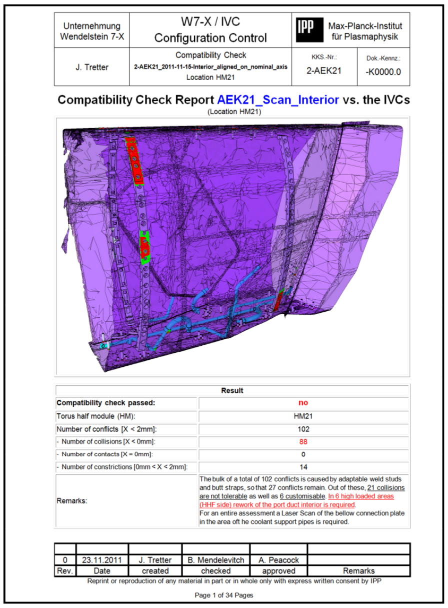


Fig. 11. Band analysis of minimal distances:1mm (red) and 2mm (green).

Subsequently, a dedicated compatibility check examining all of the endangered sub-components and their exact values of distances to the port, based on CATIA® V5's capability for fast clash analysis, was performed. The conversion of the CAD check report from HTML to the PLM compatible DOC format by XSL stylesheets (Fig. 12) and the collection of all information for the database system was triggered. The resulting report was revised, to evaluate each detected conflict, and to define the required actions.



Unternehmung Wendelstein 7-X	W7-X / IVC Configuration Control	IPP Max-Planck-Institut für Plasmaphysik	
J. Tretter	Compatibility Check 2-AEK21_2011-11-15-Interior_aligned_on_nominal_axis Location HM21	KKS.-Nr.: 2-AEK21	Dok.-Kennz.: -K0000.0

Compatibility Check Report AEK21_Scan_Interior vs. the IVCs
(Location HM21)

Result	
Compatibility check passed:	no
Torus half module (HM):	HM21
Number of conflicts [X < 2mm]:	102
- Number of collisions [X < 0mm]:	88
- Number of contacts [X = 0mm]:	0
- Number of constrictions [0mm < X < 2mm]:	14
Remarks:	The bulk of a total of 102 conflicts is caused by adaptable weld studs and butt straps, so that 27 conflicts remain. Out of these, 21 collisions are not tolerable as well as 6 customisable. In 6 high loaded areas (HHF side) rework of the port duct interior is required. For an entire assessment a Laser Scan of the bellow connection plate in the area oft he coolant support pipes is required.

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Fig. 12. Header of automatically generated check report.

E. *Defining counter measures*

Due to the fact that the port liner was already manufactured, modifications of its endangered components were no longer possible. Therefore it was decided to remove material from the port duct interior in 3 areas (Fig 13). The actual material thickness in these areas was 15 mm, and after a positive feedback from an accompanying FEM analysis, the necessity to remove 4 mm of material was approved by the Configuration Control Board of W7-X. An additional margin of 5 mm around the identified areas allowing for the detected gradient of distances was added to ensure a smooth transition from the bottom of the excavations to the interior of the duct. The definition of the areas was based on the intersection set geometries generated by the compatibility check routines.

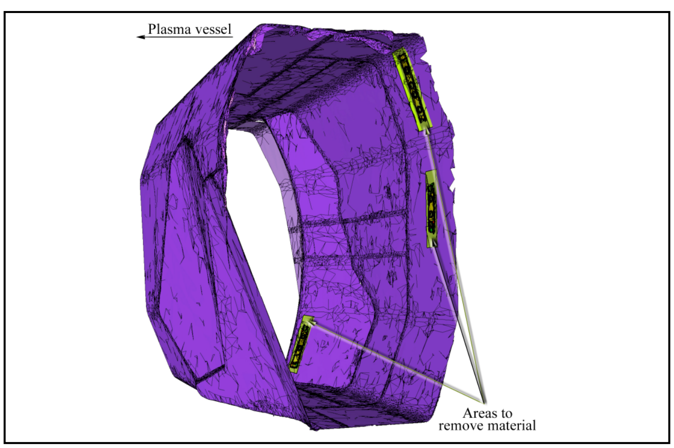

Fig. 13. Three endangered areas to remove material.

The marking of the areas, with the help of cardboard templates (Fig 14), and the removal of material was carried out by manual field work. This approach comes from the compromise between the just-in-time detection of non conformities provided by the as-assembled geometry and the tight assembly schedule.

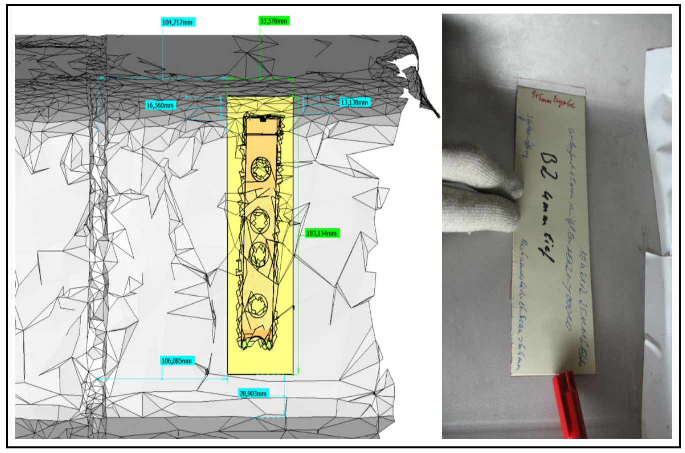

Fig. 14. Transfer of one area of rework from CAD to reality.

F. *Checking the results*

Due to the extremely limited clearance between the port liner and the duct, i.e. only 1 mm, a verification scan of the final geometry of the port duct interior and another compatibility check was performed to ensure the success of the conducted modifications. The scan highlights the desired smooth transition from the bottom of the excavations to the interior of the duct (Fig 15).

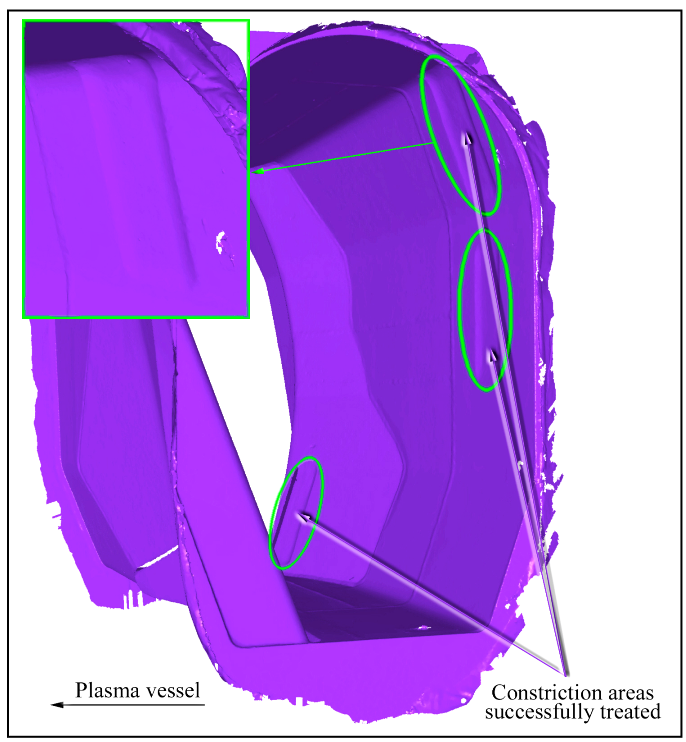

Fig. 15. Scan of adapted port duct interior.

The final compatibility check - after the exclusion of all material required for mounting (weld studs, fasteners, etc.) - showed an adequate general clearance ≥ 1.0 mm between all adjacent components (Fig. 16).

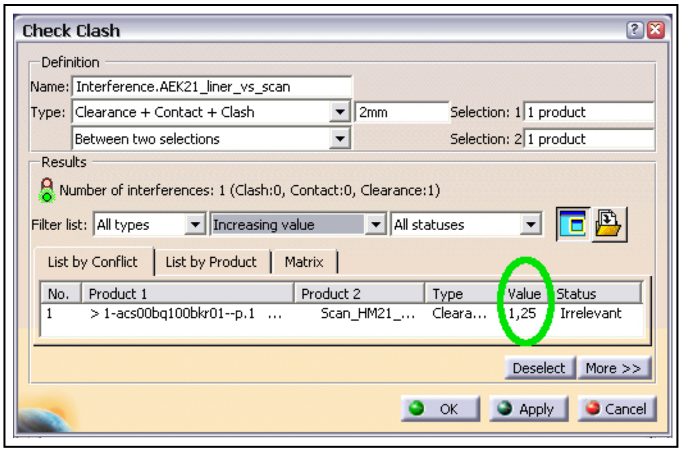

Fig. 16. Numerical confirmation of compatibility.

G. Summary

The Configuration Space Control of the NBI port liner versus the non-conform port duct was successfully accomplished within a period of four weeks over a distance of 900 km starting with the detection of incompatible components and concluding with the completion and verification of results. In parallel, all of the information generated and used was traced and documented, ensuring the consistency of the W7-X system documentation. The port has already been welded to the plasma and the outer vessel, and the installation of the first port liner is scheduled in the next few weeks.

V. Conclusion

Specially customized soft- and hardware tools as well as approved procedures are necessary to ensure an instant just-in-time response to the technological challenges occurring the designing, manufacturing and assembling of a complex experiment. With the background of a skilled and responsible staff, a tight assembly schedule and ongoing concurrent engineering of components, these tools and procedures are the prerequisites to:

- Detect and evaluate non-conformities.
- Determine and realize counter measures.
- Verify and ensure the desired results.
- Avoid delays in the assembly process.
- Reduce the risk of endangering experimental operation.

This basic example of the application of the Configuration Space Control of IVCs for Wendelstein 7-X involved the compatibility check between only two structural components, but the tools and procedures shown demonstrated their essential benefits. The tools and procedures developed continue to be used under more complex circumstances with components interfacing with a multitude of adjacent IVCs.

Acknowledgment

The authors gratefully acknowledge the support for the provided tools and procedures by the subdivision “Design and Configuration” of W7-X, especially C. Baylard, D. Hartmann, F. Herold and A. Holtz as well as by the subdivision “In-Vessel Components” of W7-X, especially G. Ehrke and A. Vorköper and certainly project head T. Klinger and chief engineer M. Gasparotto.

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