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Title

Configuration Space Control for Wendelstein 7-X

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Abstract

The Wendelstein 7-X stellarator (W7-X) is a superconducting fusion experiment, presently under construction at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik. W7-X is a device with high geometrical complexity due to the close packing of the components in the cryostat and their complex 3-d shape e.g. of the superconducting coils. The tasks of Configuration Space Control are to ensure that all these components do not collide with each other under a set of defined configurations, i.e. at the time of assembly, at 4K or for various coil currents. To fulfill these tasks sophisticated tools and procedures were developed and implemented within the realm of a newly founded division that focuses on design, configuration control and configuration management.

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Main text

1 Geometrical Complexity of the device

The Wendelstein 7-X stellarator (W7-X) is a superconducting fusion experiment, presently under construction at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik. The complex 3-d shape of the superconducting coils and the tight packing of all components in the cryostat render a complex fusion experiment, that poses big challenges to ensure that the interdependencies of all components are properly managed. Recently a new division has been established within the project structure of W7-X that combines the hitherto distributed responsibilities to ensure proper design, configuration control and configuration management [2] of the device. In particular, it has to be ensured that all components in the cryostat are designed, fabricated and installed in such a way that they do not collide with each other in any of the many modes of operation of W7-X.

What makes W7X unique is the complexity of the geometries combined with close packing of the component in the cryostat.

The superconducting magnet system of W7-X is modular with five-fold symmetry and consists of 50 non planar coils and 20 planar coils of 7 different types (Fig 1). The currents of each type of coil can be set independently. The *complex 3d free shape* of the non-planar coils was designed such that when operated at the same current they generate a magnetic field optimized for good particle confinement, good plasma stability etc. The coils and all electrical connections, the magnet support structure and all the cryogenic helium supply lines are enclosed in a cryostat between the plasma vessel and the outer vessel (Fig. 1).

During operation some of the components in the cryostat are subjected to forces that lead to *large deformations*. For example, the coils experience J x B forces when they are operated and deform by up to 20 mm. Also the magnetic support structure deforms as a result of these forces.

There are many components in the cryostat and they are tightly packed due to the following reasons: superconducting bus lines electrically connect in series the coils of each type, each coil requires two cryo supply lines for the superconducting cable and for the coil housing, the magnetic support structure requires cryogenic helium cooling as well as the cryostat insulation of the plasma vessel, the outer vessel and the 245 ports that are located between the plasma vessel to the outer vessel. Since the bus bar lines (as well as the coil superconducting lines) have an aluminium casing they need to be supported on average every 20 cm to limit the internal stresses during operation to stay within the allowable values. Therefore the *number of conflicts* (see section 2.1.2*) is large*

The tightness of the available space in the cryostat precludes component design without constriction points to other components. In the present phase of assembly it is still necessary to design a number of components for the cryostat while the assembly of other components has already commenced. Thus configuration space control has to face the following challenges:

- identification and assessment of the conflicts to reduce the likelihood of intolerable collisions during any of the modes of operation,
- support of the design activities to limit the number of conflicts,

- assessment of the fabricated components as to whether fabrication deviations can be tolerated or need to be reduced (some *large deviations between as-built and as-design* have to been considered – see Fig. 3).

2 Principles of Configuration Space Control

2.1 Definitions

2.1.1 Tolerance chain

The volume of a component that has to be considered in collision studies consists of the properly placed CAD model and of the additional volume that the component might occupy to account for the following:

- tolerances (machining and assembly),
- adjustments possibilities (for example, the required high precision of the position of the coils might require a final adjustment of the modules relative to each other to statistically minimize the accumulated fabrication and assembly deviations),
- movement/deformation of the components during the various modes of operation,
- safety margin (minimal remaining distance).

This additional volume is termed “tolerance chain”, which is somewhat improper since it includes more than machining and assembly tolerance. The precise shape of this additional volume depends on

- the location of the constriction area
- and the relative position of the components.

2.1.2 Conflict

A “conflict” between two separate components exists if the distance between them in any configuration is less than 50mm. If the tolerance chains of both components at the position of the conflict overlap, the conflict has to been investigated in detail. In some cases, the conflict can be considered tolerable if the effect on the performance or lifetime of the experiment in the case of an actual collision is considered benign.

2.2 Mitigating principles

The procedure to insure collision free operation is classically based on several actions during the phases of the construction.

2.2.1 During design

Configuration Control tasks for W7X during design depends on component's location.

Outside the cryostat, where sufficient space is available, "space reservation models" are defined. Configuration Control defines the position and routing, allocates space and position and releases the space reservation models. These reservations incorporate the interface specification and all tolerances, and as long as the detailed design remains in the space reservation no additional configuration control is needed.

Inside the cryostat, due to the close packing of component, "generous" space reservations cannot be made. There is a high interaction between the design and the space available. Designers take into consideration with a great care available space. At the end of the design, a configuration control is performed which aims at checking that volumes needed for components don't overlap/collide each other (Fig. 2 – green volumes and section description of the procedure).

2.2.2 During manufacturing and assembly process

During the manufacturing process, one checks whether the actual component is fabricated according to its agreed upon tolerances.

There are several measurement and assessment methods that can be used to evaluate measurements of the components. In general, a "best fit method" (norm ISO) is used to to compare specified with the actual geometries. This method works quite well for simple regular geometries (for example, cylinder, plane, etc.). For complex 3D geometries, a Reverse Engineering processes was implemented that is described in detail in [3]. Depending on the density of the available point measurement so of the shape of a component, as-built CAD models of various degrees of accuracy are generated. These models are then compared with the original CAD models to determine whether some modifications are necessary on the component or on neighbouring components. These models can also be used instead of the original CAD models in configuration control.

2.3 Determination of the overall tolerance chain

The determination of the proper "tolerance chain" is critical for optimal configuration control. Since often insufficient information and experience is available, best guesses have to be taken for the individual elements of the tolerance chain. For example, in the beginning one can used the specified machining and assembly tolerances but only later information of the effective tolerance will become available. Also it is difficult to determine, how to add the different elements of the tolerance chain. For W7-X, two methods are being used: the WCS (Worst Case Scenario) and "statistical RSS" (Root Sum Squares), depending on the parameters interdependencies and on a quick risk analysis.

3 Main characteristic of W7X approach

3.1 Necessity of new approach

A good balance has to be found between high tolerance values with lower risk and lower tolerance value with higher risks (Fig. 5). The choice of pertinent values is critical: too pessimistic values (i.e. high values of the overall tolerance chain) lead to stringent (or even impossible) design requirements and extended configuration control, whereas too optimistic values (i.e. low values of the overall tolerance chain) might lead to collisions during assembly or failure of the machine operation.

Figure 6 represents a good situation where a “compromise” can be found between risks and design feasibility. Due to close packing in W7X, it happens quite often that the first reasonable value of the tolerance chain is larger than the maximal available space! In this case, there is no simple design solution. One is then forced to

1. accept a higher risk , or[1]
2. reduce some tolerances (amelioration of machining accuracy, improvement of assemblies procedures, etc.), or
3. lower the number of uncertainties (e.g. by using actual measurements of the components and therefore eliminating the fabrication or assembly tolerance in the tolerance chain.; see Fig. 5: from the blue curve to the green curve).

The first and second approaches are implemented if possible, but for important components like the coils, they are hardly feasible. Since a collision between coils and other components is a non-acceptable risk and the coils are already fabricated, one is forced to measure the coil casing exactly and thus reduce the fabrication and assembly uncertainty in the tolerance chain..

3.2 Systematic and extensive use of as-built and in-operations models

Inside Configuration Control for W7X, a group has been installed with the mission to create and manage as-built and in-operation models, and to develop tools for effective configuration control with the help of a CAD program.

As-built models are created with the help of 3D measurements [3].

In-operation models are being created on the basis of FEM analysis [4].

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[1] See [2] for the procedure in this case.

For some components, especially coils, “as-built in-operation” models are created. These models are generated by applying in-operation deformation to real geometries. This aggregation of information is needed because of the very close packing of coils and the necessity to define precisely the reworking [5].

In parallel new methods and new tools have been implemented to perform systematic Configuration Control using these models.

Using all this it was possible to reduce the tolerance chain without increasing the risk (Fig. 6).

4 Procedures and tools

The main characteristics of our procedures and tools are:

- complex tolerance chain adapted to each conflict
- systematic book keeping with assessment of all conflicts (list of action items, status of conflict, etc.)[2]
- separation of configuration control and design (to avoid to be both judge and jury)
- systematic collision check using CATIA (reduce the probability to miss a problem, provided that the CAD database is up-to-date)
- auto conversion of models (in a context of migration from CADDS5 to CATIA)
- development and implementation of tools and database allowing deep coupling of database system with CAD tools (automatic generation of assemblies, automatic generation of collision report tools templates, etc.)[3]

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[2] Configuration Control procedures are of course linked with Configuration Management Procedure. Design changes due to non tolerable conflict are agreed and documented with CN [2]

- use of reverse engineering tools (Polywork) to analyse constriction areas and specify reworking of components

5 Conclusion

Sophisticated tools have been implemented and systematically applied to perform the configuration control needed to minimize the risk of operation of W7-X. The tools by themselves are standard to other complex devices, however, up to the knowledge of the authors this is the first time that (i) as-built and as-design models are systematically used for configuration control (ii) database and tools to cope with the amount of data and the complexity of the system have been comprehensively implemented for the whole device.

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[3] This is necessary. For one given component, in addition to the standard as-design model, we can have up to 5 other models (1 as-built model and 5 in-operation models). This multiplication of models has to be managed with appropriate tools.

Acknowledgement

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References

[1] F. Schauer, Status of Wendelstein 7-X construction, 24th SOFT Symposium on Fusion Technology, Warsaw, Sept. 2006

[2] R. Brakel, et al, Configuration Management for W7-X, 25th SOFT Symposium on Fusion Technology, Rostock, September 15–19, 2008, in press

[3] T. Rajna, F. Herold, C. Baylard, Reverse Engineering Process of Cryostat Components of Wendelstein 7-X, 25th SOFT Symposium on Fusion Technology, Rostock, September 15–19, 2008, in press

[4] V. Bykov, F. Schauer, et al, Structural analysis of W7-X: Overview, 25th SOFT Symposium on Fusion Technology, Rostock, September 15–19, 2008, in press

[5] G. Ehrke, et al, Transition of W7-X non planar coils from manufacturing to assembly, 25th SOFT Symposium on Fusion Technology, Rostock, September 15–19, 2008, in press

Figure captions

Figure 1. Overview of W7-X magnet system, main components: planar coils (light blue), non-planar coils (dark blue) and support ring structure (dark green)

Figure. 2. Example of constrictions areas (a) between non planar coils (b) between non planar coil and port isolation shield (c) between central ring and non planar coil

Figure. 3. Example of deviation in header region of the coils (Red) As-built model. (Green) CAD as-design

Figure 4. Concepts overview. In this simplified 2D picture, blue rectangles represent CAD design spaces. Green squares represent "volume that could be needed by the component". The tolerance chain is the "sum" of all additional spaces needed (tolerance, adjustment, etc.). In WCS (Worst Case Scenario: orange tolerance chain) we perform a simple arithmetic sum. With statistical addition (red tolerance chain in this picture), we consider that the probability for each tolerance to be fully "utilized" is low. In this example, with WCS assumption, we cannot accept the configuration: the distance between the 2 volumes is less than the safety margin. But if we accept some risks, we can tolerate this configuration (statistical tolerance chain).

Figure 5. Determination of the value of the tolerance chain. A balance has to be found between risk and design effort. The design effort and the number of potential conflicts increase with the value of the tolerance chain. The risk decreases with the value of the tolerance chain, but increases with the number of uncertainties/unknowns (blue curve, high uncertainties, green curve, low uncertainties).

Figure 6. Extract of one configuration control report. This example shows a conflict between one planar and one non planar coil. The tolerance chain with manufacturing tolerances is 11mm and 3mm without. Considering deformation during operation and

as-design geometries, we have a collision (-2,8mm). With the help of as-built in-operation models, we see that we can tolerate this conflict (minimal distance 16,3mm).

Figure 1

Click here to download high resolution image

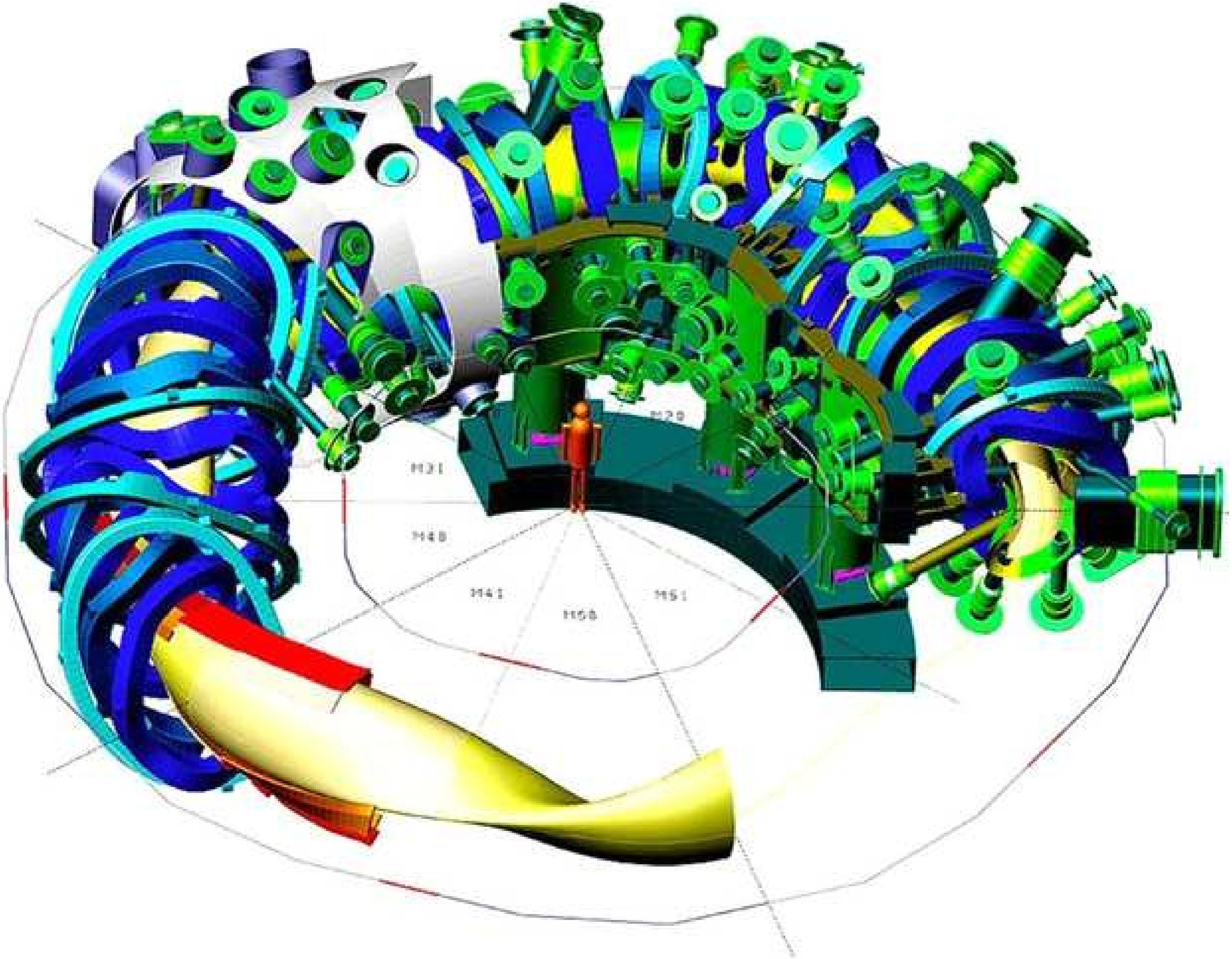


Figure 2

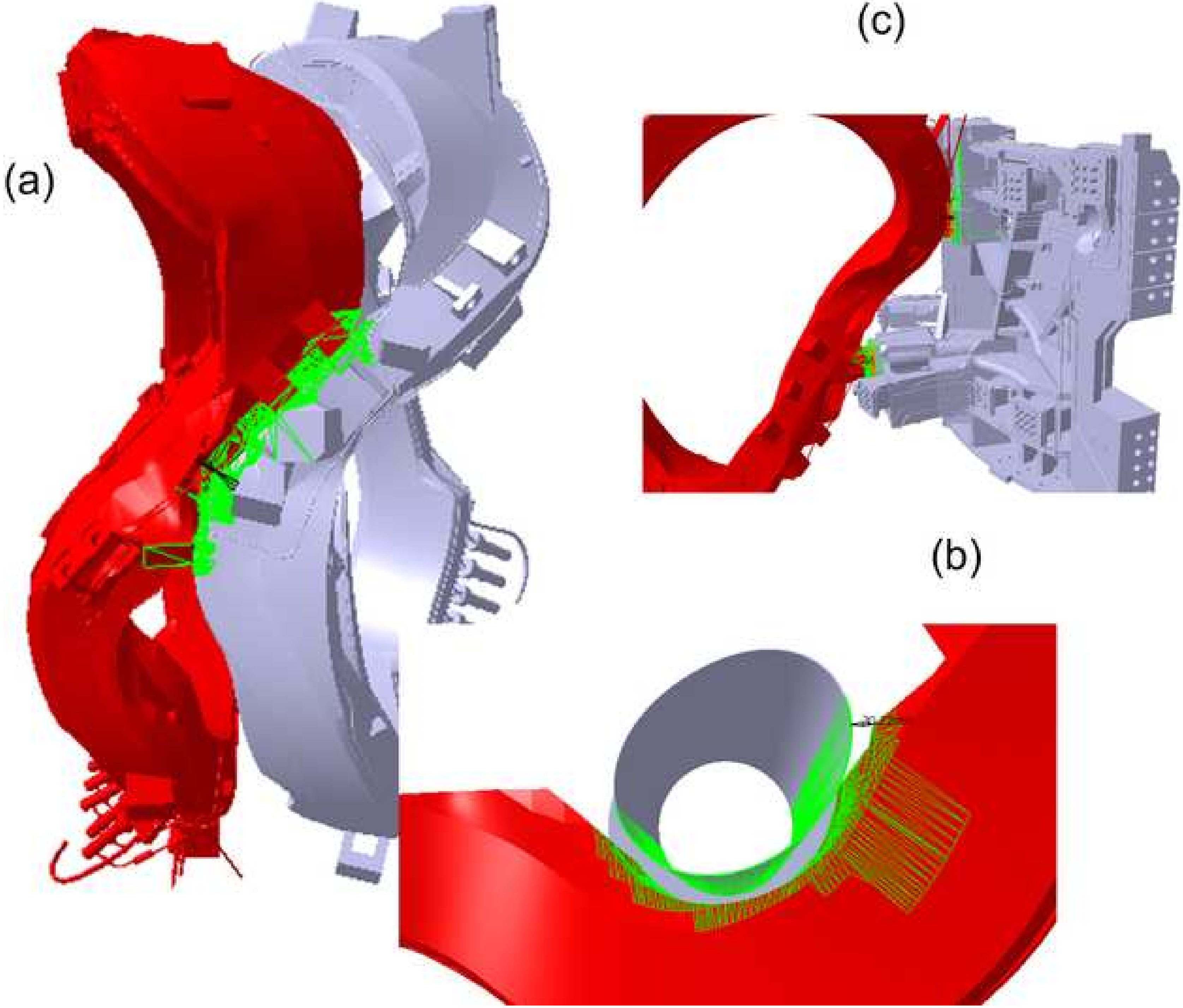


Figure 3
Click here to download high resolution image

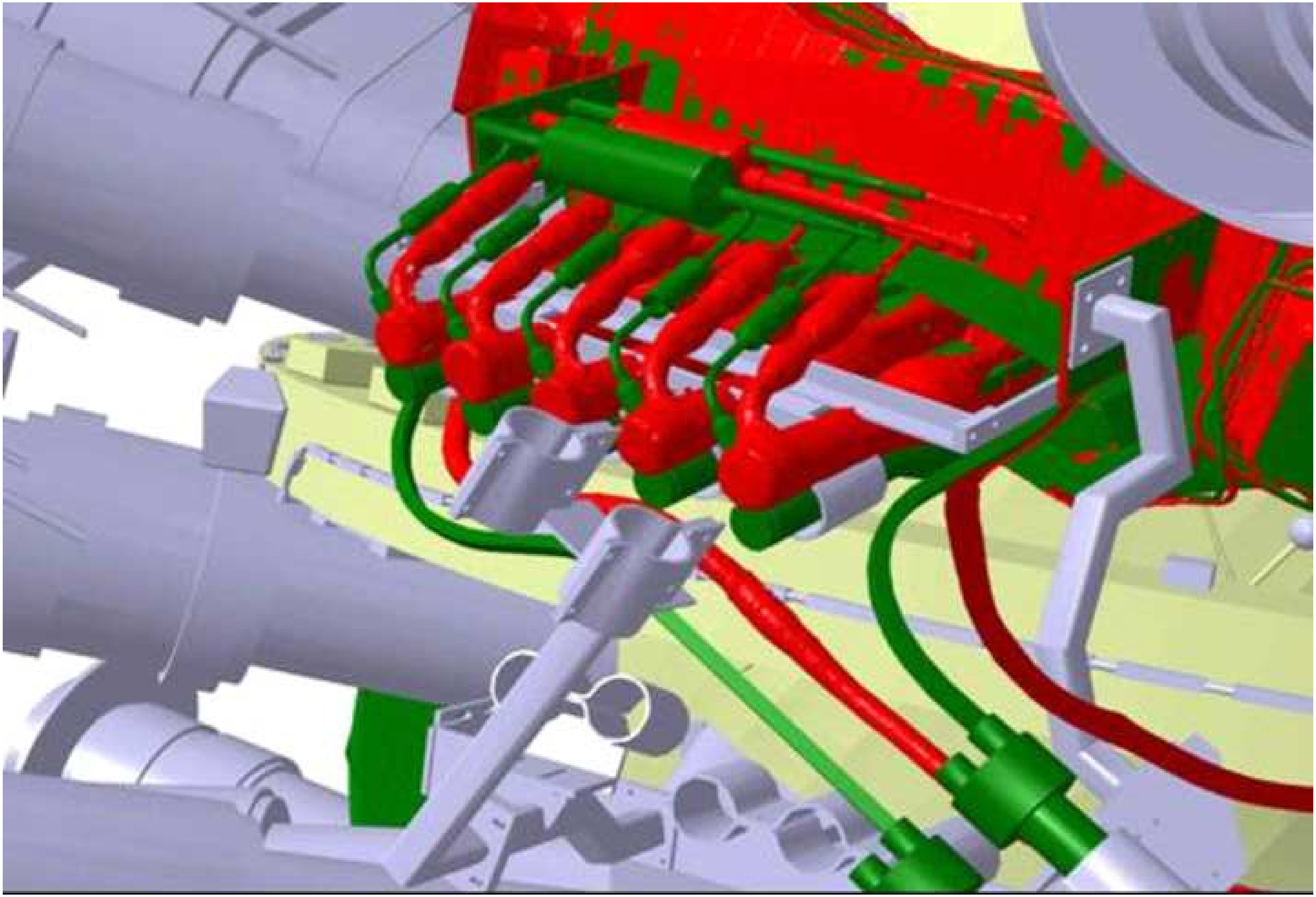


Figure 4

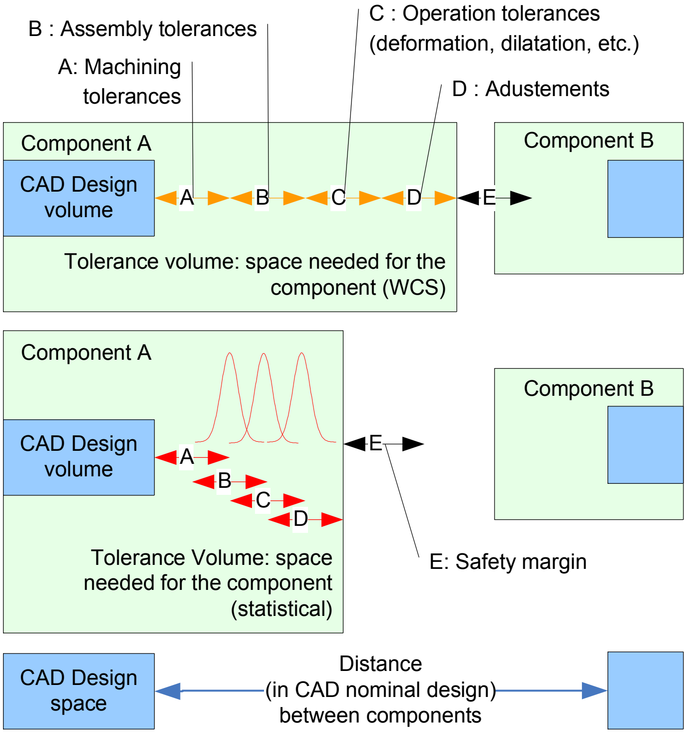
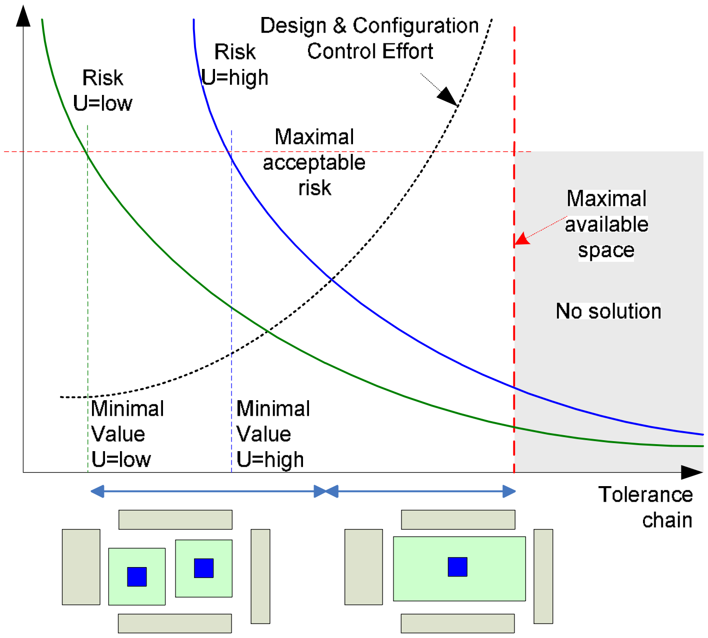

B : Assembly tolerances
A: Machining tolerances
C : Operation tolerances (deformation, dilatation, etc.)
D : Adustements
Component A
CAD Design volume
A
B
C
D
E
Component B
Tolerance volume: space needed for the component (WCS)
Component A
CAD Design volume
A
B
C
D
E
Component B
Tolerance Volume: space needed for the component (statistical)
E: Safety margin
CAD Design space
Distance (in CAD nominal design) between components

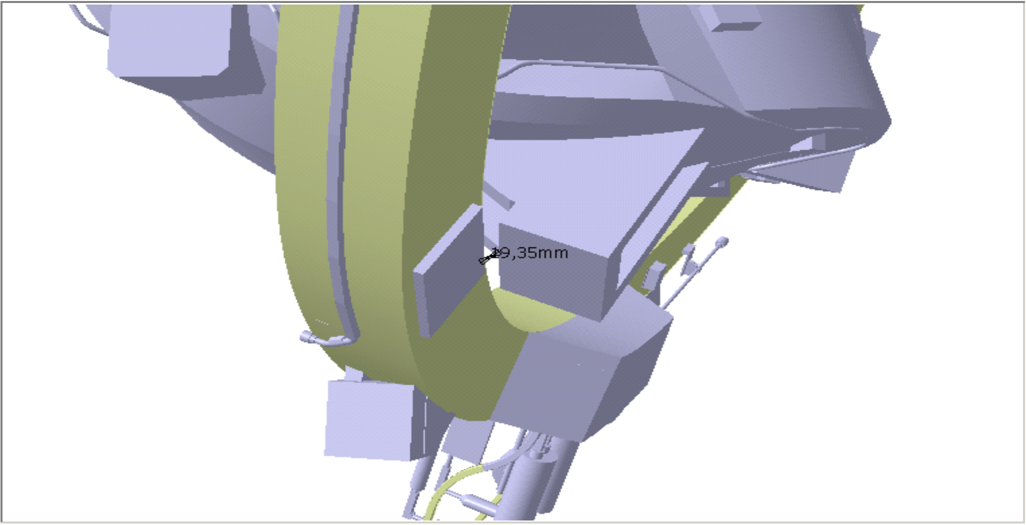
Figure 5



For low values of tolerance chain, we have a lot of design freedom, but the risk is high

For high values of tolerance chain, we have only one design solution, the risk is low

Figure 6

lfd. Nummer	2
Komp. 1	ID: aac41 Referenz Model: 1-aac01--g (Version: 1, Änderungsdatum: 05.11.2007, Status: 230) Positionspfad: 1-w--a.1 --++-- 1-amd4--a_1 --++-- 1-aac4--a_1 --++-- 1-aac44--g_1
Komp. 2	ID: aab57 Referenz Model: 1-aab14--g (Version: 4, Änderungsdatum: 19.11.2007, Status: 230) Positionspfad: 1-w--a.1 --++-- 1-amd4--a_1 --++-- 1-aab4--a_1 --++-- 1-aab14--g_1
Bild	
Kommentar	**Bewertung:** Tolerieren - Restabstand in allen as-built Konfigurationen >5mm unter Beachtung u. g. Toleranzen und Justageräume.

Komp.	Fertigungstoleranz	Positionstoleranz	Montagetoleranz	Justageraum
1	Spulengehäuse innen: ±3		Einzelspule: ±1.5	Magnetsystem: ±5
2	Anschweißblock: ±5		Einzelspule: ±1.5	Magnetsystem: ±5
Summe der oberen Toleranzgrenzen (zur Bestimmung des Worst Case Szenarios WCS)			as-designed:	11
			as-built:	3

	Konfiguration→ ↓Wert	RT	4K	HI	LI	LS	ST	H1	H2
Ergebnisse (in mm)	as-designed-Geometrie	19.3	22.1	10.6	8.2	8.8	9.2	-	-
	as-built-Geometrie	23.1	23.1	19.5	19.3	19.8	20.4	-	-
	Wert im as-designed-WCS	8.3	11.1	-0.4	-2.8	-2.2	-1.8	-	-
	Wert im as-built-WCS	20.1	20.1	16.5	16.3	16.8	17.4	-	-