Accuracy Requirements for the Fabrication and Assembly of W7-X

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To achieve the scientific goal of the WENDELSTEIN 7-X stellarator (W7-X) requires a high geometrical precision during fabrication and assembly of the magnet system, the plasma vessel and the divertor. Statistical relative errors must be below $2 \cdot 10^{-4}$ for resonant Fourier components of the magnetic field. This limit would correspond, e. g., to a position error of 1 cm for one of the 50 non-planar coils of W7-X. For symmetric field errors which maintain the stellarator symmetry the requirement is less stringent.
During the design of W7-X, a first tolerance analysis of the coil fabrication and the magnet system assembly was performed. Using information from the first coils fabricated the analysis has been refined. Under worst-case conditions, the maximum position error of a single coil was determined. There from the maximum tilt of a coil and the maximum shift of a coil were estimated. Since shifts in vertical and radial directions have a similar impact and shifts in toroidal direction are less critical, this study is therefore limited to the analysis of radial shifts only.

Coil fabrication

The coil fabrication starts with the manufacture of the winding package (WP). Once a WP is ready, a survey of the shape of the WP is performed. The measured data are subject to a best-fit of the actual shape against the CAD-shape (Fig. 1). The co-ordinate system which is found during the best-fit minimises the sum of squares of the deviations between the actual WP and its design shape. The shape and position of each WP is marked by 8 reference pins (4 on each side of the coil). In the following analysis the position uncertainty and the misalignment of this co-ordinate system was analysed for each fabrication and assembly step.
An investigation of the measured data of the first coils shows that the initial uncertainty of position and orientation of the best-fit co-ordinate system (represented by the 8 reference points) is about 0.7 mm in shift and about 0.042° in orientation.
In the next fabrication step, the WP is embedded into a stainless steel case. During this operation the WP is precompressed which causes a shrinking of the WP. Calculations predict a change in the shape of the WP of 1 - 3 mm. As the actual measurements on the embedded WP do not show the behaviour expected from calculations, an additional uncertainty of the WP position must be assumed.
After embedding, machining of the coil case takes place. Starting from reference points on the WP, a set of new reference points are established on the steel case in this step. Transition from the WP reference system to the new steel case reference system in combination with machining errors causes additional uncertainties of 0.5 mm in shift and 0.029° in tilt.
Since the number of the machined reference points is not sufficient for all further assembly steps, auxiliary reference points have to be added to the coil case, which increases the position uncertainty of the original co-ordinate system of the WP by 0.3 mm in shift or 0.017° in tilt, respectively.

Assembly of the magnet system

The magnet system of W7-X consists of 70 coils which are arranged in 5 modules of 14 coils each. Each module consists of 2 flip-symmetric half modules [1].
Assembly of the magnet system starts with the adjustment of the 5 non-planar and 2 planar coils of a half module in their nominal position. This is done with a system of adjustable bars (Fig. 2). From practical experience, it is expected that all reference points of a coil (coil diameter approx. 3 m, coil weight approx. 6 t) can be placed within an error sphere with a radius of 1.5 mm wrt. its nominal position (Fig. 3). Hence it follows, that a maximum position error of 1.5 mm exists for a coil, exclusive of the measurement uncertainty of about 0.5 mm in worst case.
In the next assembly step the support structure (weight approx. 7 t) is fixed to the adjusted coils to complete a half module (Fig. 4). It is expected that this can be achieved with a similar adjustment accuracy as in the previous assembly step, i.e. the position error of each reference point of the support structure will be lower than 1.5 mm.
Once two half modules are assembled, they are jointed by bolts on a flange, which is machined precisely. In this way the additional position errors for a coil are comparably small and of the order of 0.5 mm in shift or 0.011° in tilt.
In the last assembly step, the 5 modules are adjusted on the machine foundation in the torus hall independently from each other in the global stellarator co-ordinate system. Only after all modules are in the right position they are jointed by shims. During this assembly a final adjustment of the modules within a range of 5 mm can be realised to balance errors during previous steps. Here, too, it is expected that the adjustment can be realised within maximum 1.5 mm at each reference point, which increases the position error of a coil by the same value.

Table 1 shows the summary of all potential adjustment errors and position uncertainties. In the worst case the overall errors and uncertainties for one coil will only slightly exceed the required geometrical accuracy mentioned above. The analysis helps to identify the most critical assembly steps, and procedures will be established to avoid intolerable displacements of the magnet system. In general the practically achievable adjustment error of about 1.5 mm can be considered as a reasonable number for the main assembly steps.
Since this simple analysis is not yet sufficient to give detailed information about the errors of the magnetic field, numerical field simulations are being performed.

Numerical simulations of field perturbations due to misalignments of coils

The fabrication or assembly errors introduced at different stages of the construction of the machine, which have been listed above, will lead to a deviation of the filament position from the design, and to the appearance of rather large harmonics in the Fourier spectrum of the magnetic field resonant to iota=1. As a consequence, new islands at any periodicity can be introduced, existing islands can be modified and stochastic regions can be enhanced.
To distinguish between different kinds of errors and indicate the most dangerous ones, a numerical approach has been developed, which describes statistically the randomly distributed errors, taken within the given tolerances. This approach should help to avoid the most critical types of errors during the assembly of the machine, and a further correction procedure, which is now under development, will allow to estimate the perturbed magnetic field at every assembly step and to correct it by proper positioning of modules in the final assembly step. The input parameters are the real measurements for already existing WP’s and an assumption that the manufacturing errors of not yet existing WP’s will consist of a systematic part, which

will be the same for all coils of one coil type, and statistical errors, described within the repetition tolerances.

First results of these computations show that the influence of the coil displacements is not identical for different directions with respect to the perturbed magnetic field. Statistically distributed assembly misalignments leading to an average deviation of a filament position of 1.5 to 2 mm may generate effective relative field perturbations in the range of $2 \cdot 10^{-4}$, which had been defined as a limit for the allowed error fields. It was possible to conclude that the magnetic field is most sensitive to rotation of the coils and modules. The impact of shift and manufacturing errors is in the same order.

This numerical approach is used to estimate the acceptability of the newly fabricated coils and will be a basis for assessment of the error fields at each assembly step described within the given tolerances. Further numerical procedures will help to estimate the optimum positioning of coils and modules during the construction, to indicate whether any repositioning is necessary and to make a final assessment of the magnetic configuration before the finish of each assembly step.

References

[1] L. Wegener, e.t., "Status of the Construction of the W7-X Magnet System", IEEE Trans. Appl. Superconduct., Vol. 12, No. 1, March 2002, p. 653-658

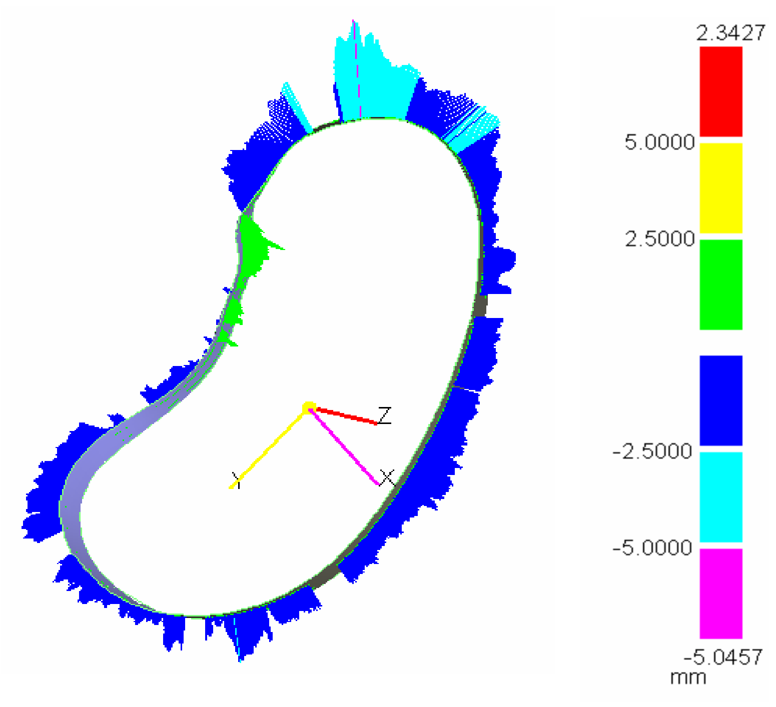

Fig. 1

Plot of the displacements of the manufactured winding package of a non planar coil relative to the design shape. The best-fit co-ordinate system is defined as the one minimising the deviations (sum of the squares) between the actual WP and its design shape.

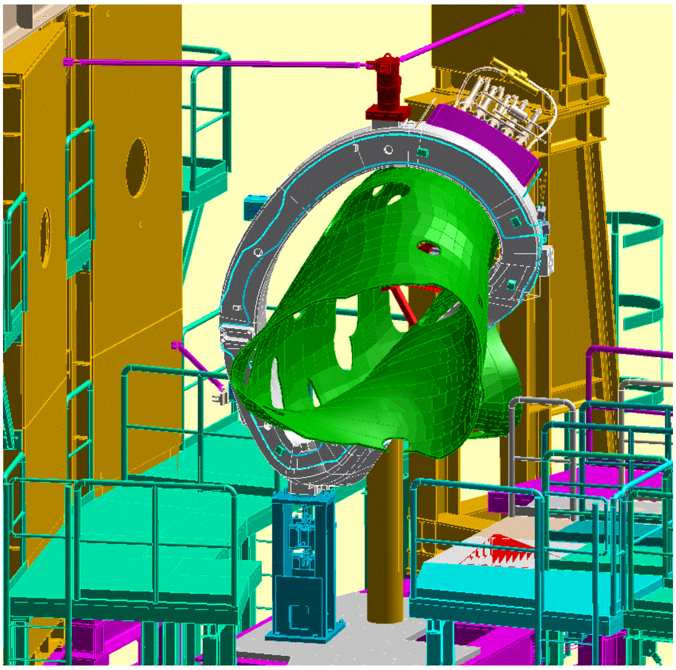

Fig. 2
Adjustment of a coil by use of assembly bars (violet). The expected adjustment accuracy is better than 1.5 mm

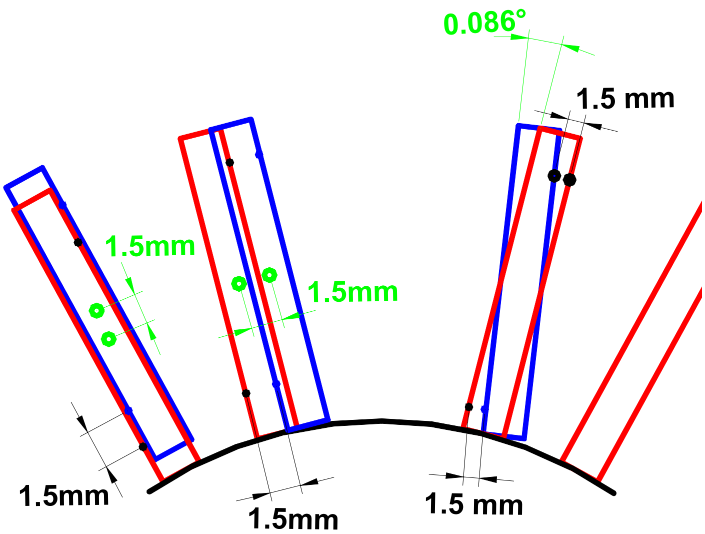

Fig. 3
Schematic presentation of the adjustment residuals (black) and the resulting position displacements (green) during coil adjustment

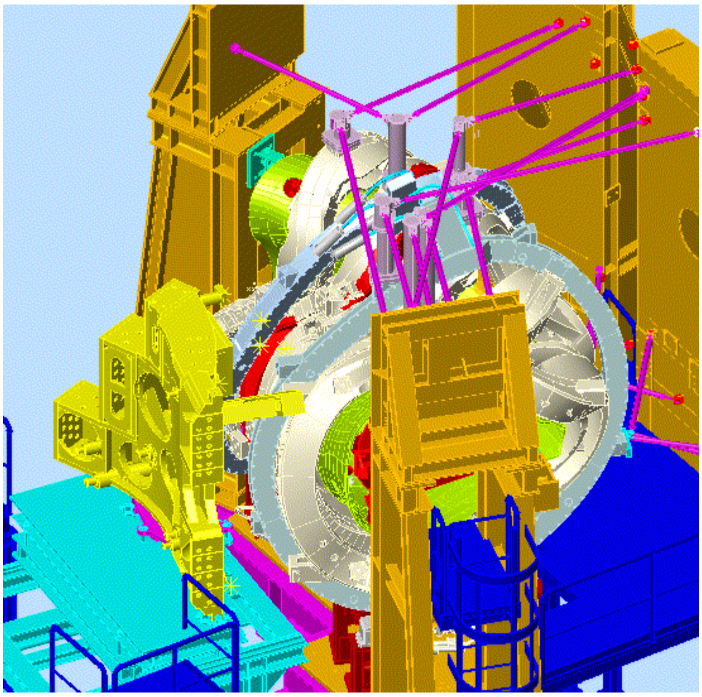

Fig. 4
Assembly of support structure (yellow). After adjustment the support structure is joined to the coils by screws.

Table 1: Summary of the adjustment inaccuracies and uncertainties during W7-X assembly

	type of deviation	angle error [°]	radial error [mm]
1	**fabrication of coil**		
1a	uncertainty in survey of winding pack (position of BF-Cosy, position of PIN)	0.042	0.7
1b	uncertainty of PIN-Systems due to shrinking of WP during embedding (PIN movement about 1mm, for uncertainty 25%)	0.014	0.25
1c	fabrication and survey uncertainty during machining	0.029	0.5
1d	preparing of new reference points	0.017	0.3
2	**assembly of coils to half module**		
2a	sum of measurement uncertainties	0.021	0.5
2b	adjustment residual	0.086	1.5
3	**assembly of support structure to coil pack**		
3a	sum of measurement uncertainties	0.02	0.5
3b	adjustment residual	0.082	1.5
3c	welding error (during attachment of coils)	0.086	1.5
4	**assembly of 2 half modules to module**		
4a	residual gap at flange	0.011	0.001
4b	radial adjustment residual between both half modules	0	0.5
5	**assembly of 5 modules to torus**		
5a	sum of measurement uncertainties	0.014	0.8
5b	adjustment residual	0.047	1.5
	Σ	**0.47**	**10.05**