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Accuracy of the Magnet Configuration of WENDELSTEIN 7-X

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1. Introduction

WENDELSTEIN 7-X (W7-X) is in an advanced construction phase and assembly of the magnet system will start in autumn of 2004. The magnet system of W7-X is composed of 50 non-planar and 20 planar superconducting coils which are arranged in five equal modules. The coils are bolted to a central coil support structure and mutually supported by inter-coil supports /1/. In order to achieve the favourable magnetic confinement of W7-X the coils need to be constructed and assembled with high precision while obeying the symmetry of the machine. Small statistical deviations of the coils from their ideal shape or non-symmetric alignment cause field perturbations with a periodicity different from the five-fold periodicity of the device. Such perturbations may result in additional magnetic islands, ergodisation of existing islands, and uneven load of the divertor target plates or enhanced particle losses.

Fig. 1. Dimensional control of a non-planar winding package using a Faro arm

2. Outline of the design and assembly

Winding of the non-planar and planar coils requires forming of 108 resp. 36 turns of a cable-in-conduit superconductor into precisely machined winding forms. Conformance with the required shape is checked by careful control of some 800 positions along the four sides of the surface of the winding package (Fig. 1). A best fit of the measurement data defines the co-ordinates of eight precise reference pins mounted on the surface of the winding package. These pins carry the basic geometry information of the winding and are used as reference during all further manufacturing processes as well as during assembly. The winding packages are integrated and embedded in steel casings using glass fibre reinforced epoxy pads, glass balls, quartz sand and epoxy resin. The interfaces of the coil casing as well as the threads and holes which are used for fixation and adjustment are machined to an accuracy of a few tenths of a millimetre. During a final survey the positions of the coil fixtures and the contour of the surface of the casing are checked against the pin positions as well as against the CAD model.

Assembly of the magnet structure starts by stringing the coils across the plasma vessel (Fig. 2) and adjusting them in their nominal position. Half-modules of the magnet system are formed by joining five non-planar and two planar coils with a sector of the central coil support unit. Two half-modules are bolted to form magnet modules. After completing the five magnet modules with the outer vessel, the ports and the thermal insulation they are adjusted on the machine base and joined to a torus.

3. Accuracy requirements

As a general rule, non-symmetric disturbances of the magnetic field $\Delta B/B_0$, where B_0 is the toroidal field on the axis, must be small whereas symmetric disturbances e.g. systematic deviations of the shape and position of a coil are less critical. As a design criterion Fourier components ΔB_{mn} of the W7-X field must be smaller than $2x10^{-4}$ xB_0, where m denotes the toroidal and n the poloidal index of the Fourier component /2/. Most dangerous are the low order Fourier harmonics ΔB_{11} and ΔB_{22} which are resonant to the major rotational transform iota=1 and which break the symmetry of W7-X. As a consequence the manufacturing tolerance of the first non-planar winding package of each type is e.g. ±5 mm whereas the repetition tolerance of subsequent coils is +3 mm for the inner walls, ±3 mm for the side walls and ±5 mm along the outside of the winding packages.

4. Results of the metrology surveys

By the end of June 32 non-planar and 17 planar winding packages have been wound and impregnated and five non-planar coils and three planar coils have been completed. The shapes of the non-planar winding packages are surveyed by laser tracking and a Faro arm whereas the planar coils are surveyed by photogrammetry. These techniques ensure a measurement accuracy of better than 0.3 mm. From the measured co-ordinates of the surface of the winding package the geometry of the centre current filament of the coil is deduced. The geometry of the current filament is compared with its nominal geometry as well as with results of the surveys of already manufactured winding packages of the same type. As an example Fig. 3 shows the measured radial deviations of the centre current filament of six non-planar winding packages of the type 1 from the design geometry. The data show an average systematic deviation from the CAD model of <2.9 mm and an average statistical deviation from the average filament geometry of <1.1 mm. After embedding of the winding packages in the steel casings as well as after final machining of the interface areas the position of the reference pins are checked for any deformations.

Fig. 2. Stringing of a non-planar coil across the plasma vessel using the coil stringing unit

5. Analysis of the survey

A numerical code was established to assess the impact of the deviations during coil manufacture on the magnetic configuration of W7-X /3/. Evaluation of the centre current filaments of a total of 27 manufactured non-planar winding packages shows an average systematic error of <3 mm and statistical deviations below 1 mm. Assuming that all non-planar winding packages follow the average shape of those already manufactured, the dominant Fourier components $\Delta B_{11}/B_0$ and $\Delta B_{22}/B_0$ would account for $0.4\text{x}10^{-4}$ resp. $0.5\text{x}10^{-4}$ of the total field errors. The code allows also simulating misalignment during assembly and allows suggesting correction measures. The errors during assembly of the magnet system result from misalignment of the coils, distortions during welding of the lateral supports and from small errors during the adjustment of the half-modules and modules. Numerical analyses have shown that rotational misalignment of components has a greater impact on the field errors than radial or lateral shifts of the components. From assembly trials it is concluded that each reference point on coils, half-modules and modules can be positioned accurate to within a sphere with a radius of 1.5 mm. Statistical extrapolation of the inaccuracies occurring during all assembly steps while considering the accuracy of measurement result in an average error of the position of each coil of ±3.5 mm. A simulation of these errors during assembly shows Fourier components $\Delta B_{11}/B_0$ and $\Delta B_{22}/B_0$ equal to 2.8×10^{-4} and 1.4×10^{-4}. Comparing the figures it is evident that assembly errors contribute significantly more to the final field error than manufacturing errors of individual coils.

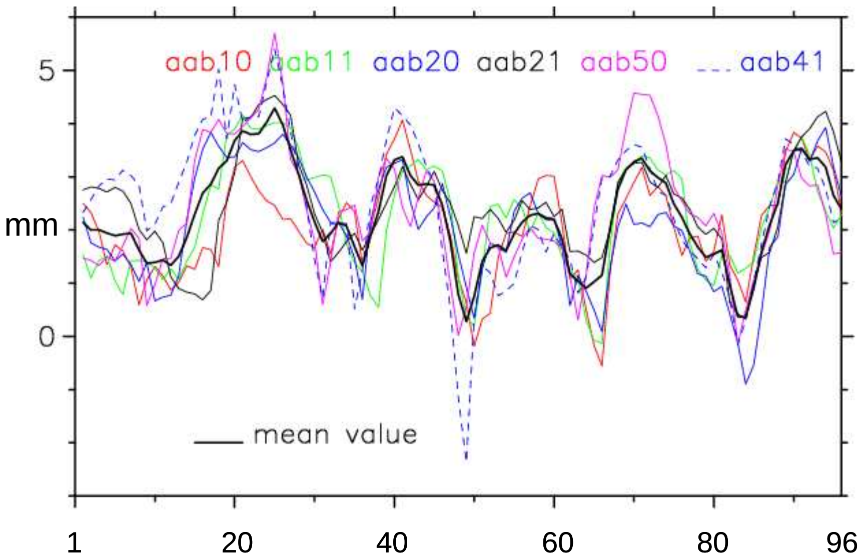

Fig. 3. Radial deviation of the central filaments of six coils along the circumference

6. Measures for corrections

Final assembly of the torus allows adjusting the position of each corner of the modules within a sphere with a radius of 5 mm by applying shims between the module sectors of the coil support structure. This correction measure could reduce the ΔB_{11} and ΔB_{22} components by approx. $2 \times 10^{-4} \times B_0$. During W7-X operation ten control coils behind the divertor can be used to compensate ΔB_{11} field components of up to $1.6 \times 10^{-4} \times B_0$. Additional compensation of field errors could be achieved by extra coils outside the outer vessel /2/.

7. References

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