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Modelling of magnetic field perturbations and correction possibilities in WENDELSTEIN 7-X

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1. Introduction

WENDELSTEIN 7-X (W7-X) is a modular Advanced Stellarator realizing a 5-period Helias configuration. The device will be operated primarily with rotational transform $\iota/2\pi = 1$ at the boundary. In order to insure high quality of the magnetic field and to preserve the symmetry of the machine, the magnet system needs to be constructed and assembled with very high precision. The requirement of good plasma confinement and reliable divertor operation limits the ratio of error-field components (resonant Fourier harmonics, e.g. B_{11}, B_{22} and B_{33}) to a relative field strength of not larger than $2 \cdot 10^{-4}$ [1], which is a compromise between the technical possibilities and physical necessities.

2. Approach to assess the magnetic field perturbations

At different stages of the construction of the machine, fabrication or assembly errors can occur, which will lead to deviations of the filament positions from the designed one, and to the appearance of additional harmonics in the Fourier spectrum of the magnetic field, violating the stellarator symmetry. As a consequence, new islands at any periodicity can be introduced, existing islands can be modified and stochastic regions can be enhanced.

A numerical approach has been developed, which describes statistically the randomly distributed errors within the given tolerances and uses the measured geometrical shapes of already existing coils. This allows one to perform a sensitivity analysis of the perturbed magnetic field to different types of fabrication and assembly errors and to estimate their impact on the error fields based on a careful analysis of the tolerances. It will also help to make a final assessment of the magnetic configuration before the completion of each assembly step and indicate whether repositioning is necessary.

3. Main stages of W7-X assembly and assumptions about the positioning errors

The assembly procedure can be split into the following steps:

1) positioning of 5 coils in one half-module; measurement of the PIN (reference) points at the coils, which is the input for estimating the acceptability of the step performed;
2) connection of the support ring; welding of the lateral supports; connection of two half - modules into one module; measurement of the PIN points for half-modules at the support ring, which is the input for estimating the acceptability of step 2;
3) welding of the lateral supports between half-modules; mounting of the modules in pre-final positions; measurement of the PIN points for modules at the support ring, which can help to estimate the acceptability of step 3 and the necessity of a readjustment in order to reduce the error fields as much as possible; connection of the modules; welding of the lateral supports between modules.

It was assumed that the PIN points at each step are deviating randomly from their ideal positions in a sphere of 1.5 mm due to the positioning errors. Also there are the additional uncertainties of PIN determination, which are 0.5mm, 1mm and 0.8mm for the first, second and the third steps, respectively. Simulations were carried out for two different error distribution functions: even and cubic (i.e. the probability is a cubic function of the radius of a sphere). The average and maximum perturbation for each possible combination of errors was chosen from 20 different calculated distributions.

4. Results of modelling

The sensitivity analysis of the perturbed magnetic fields has shown that the impact of a rotation of coils and modules around a horizontal or vertical axis is significantly larger than the impact of shifts and manufacturing errors [2]. Also tilting of coils and modules around three different axes in space has an unequal influence on the main resonant Fourier harmonics.

The construction errors of the magnet system can be split into two stages. The first stage concerns the manufacturing errors, the second stage the assembly errors. For the manufacturing errors, not the absolute deviations from the ideal coil shape, but the statistical deviations from the average shape for each coil type cause symmetry-breaking error fields.

The determinative value for the perturbed magnetic field is mainly the average deviation of the central current filament. More than half of the winding packs of the non-planar coils are already manufactured. Their average deviations over 96 measured cross-sections are between 0.5 and 1.8 mm and have a mean value of 0.9mm, see Fig. 1. Expecting that the rest of the winding packs will have deviations in the same range, we estimate relative error field components of about $1\cdot10^{-4}$. That means that for the assembly of the magnet system the same value is available, allowing an additional average deviation of about 1mm. This is a small value compared with the diameter of the machine of about 15m.

Results of the perturbed magnetic field modelling are shown at Fig.2. Here blue columns correspond to the average value over 20 runs of the magnetic field perturbation $(10^{-4}\cdot\sqrt{(B_{11}^2+B_{22}^2+B_{33}^2)}/B_0)$ due to the positioning errors at each of three steps within the described tolerances; red columns show the maximum perturbation obtained in the course of 20 runs. Black horizontal lines indicate the summation of error-fields due to positioning and measurement uncertainties. Types of assembly errors considered: (1) and (2) – shift&rotation and rotation&shift respectively of coils, half-modules and modules with the even distribution function of statistical errors, (3) and (4) – shift&rotation and rotation&shift respectively with the cubic distribution function, (5) – current status of manufacturing errors.

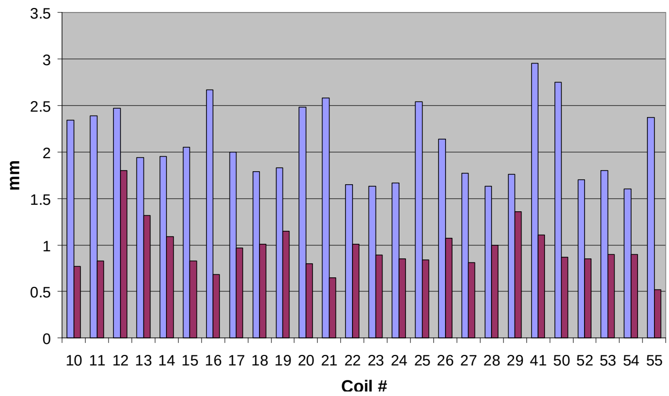
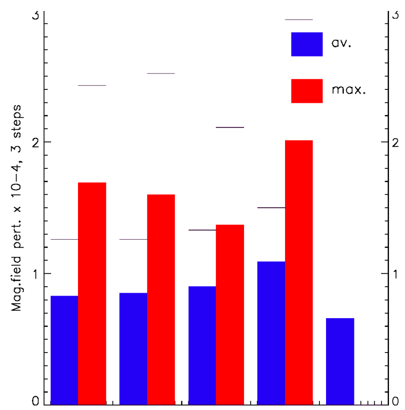


Fig. 1 Average deviations of already manufactured winding packs. In blue the absolute deviations from the ideal coil shapes and in red the statistical deviations from a mean value of coils of the same type.



(1) (2) (3) (4) (5)

Fig. 2 Perturbed magnetic fields due to the construction errors.

5. Correction possibilities

In order to stay under the limit for the error fields, correction possibilities are foreseen during the assembly. Fabrication and assembly of the machine components are continuously accompanied with a precise geometrical survey. The perturbing impact of measured deviations is then analysed by magnetic field calculations and becomes the basis for adjustments. It is foreseen during the last step of assembly, the connection of all modules, to reduce a few low-order Fourier harmonics by pre-calculated shifts and inclinations of modules. The gaps between the modules are then filled with shims.

In W7-X there are 10 control coils (2 per field period) installed in order to have a tool for plasma edge shaping and sweeping of the interaction zones on the target plates. These coils are also available for field error correction and are able to generate Fourier components as listed in Table I.

If larger correction fields are required the additional coils must be provided. One possibility which is considered, are coils on top of the outer vacuum vessel. Five normal conducting saddle shaped coils, one per field period, with dimensions of about 2m x 2m have a capability listed in Table I. Because of their large distance to the plasma of more than 2m only the lowest-order Fourier components have a significant amplitude. However in combination with the control coils, Fourier components up to B_{44} can be effectivly generated.

Table I.

Fourier component	$\mathbf{B_{11}}$	$\mathbf{B_{22}}$	$\mathbf{B_{33}}$	$\mathbf{B_{44}}$
Control coil [mT/kA]	*0.016*	*0.040*	*0.052*	*0.053*
Correction coil [mT/kA]	*0.036*	*0.014*	*0.003*	*0.003*

6. Conclusions

Final exact perturbed magnetic fields depend on the distribution of assembly errors realized. Expected error fields from the coil manufacturing are about $1 \cdot 10^{-4}$. At the assumption that each PIN-point deviates not more than 1.5 mm from its “ideal” value, the average simulated error field due to the assembly process is about $1.4 \cdot 10^{-4}$ for the even distribution function. Maximum perturbations found can exceed the permissible limit of $2 \cdot 10^{-4}$. Continuous accompanying of all assembly steps with the calculations of the magnetic configuration, usage of their feedback in maintenance of adjustment efforts and the investigations of correction coils foreseen will help to reach the planned goals.

7. References

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