Analysis of the magnetic field perturbations during the assembly of W7-X

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Introduction

Magnetic configurations in Wendelstein 7-X are defined by currents in 50 modular non-planar coils and 20 auxiliary planar coils. The system has 5 periods and in the most part of the cases is characterized by ι=1 at the boundary. At different stages of the construction of the machine fabrication or assembly errors can occur, which will lead to the deviation of the filament position from the designed one, and to appearance of rather large resonant harmonics in the Fourier spectrum of the magnetic field. The sources of these errors are the difference between the designed and fabricated coil shapes at the manufacturing stage, deformations during to embedding process or misalignments of the coils at the assembly stages. As a consequence, new islands at any periodicity can be introduced, existing islands can be modified, stochastic region can be enhanced.

According to the Application for the Preferential Support, relative error fields in excess of $2\cdot10^{-4}$ are not permissible if they violate the stellarator symmetry of the magnetic field. For example, when every module is randomly declinated up to 0.1º, a perturbed magnetic field is slightly above the indicated limit. As a consequence, the separatrix has been modified, islands are combined in the groups, plasma in some parts is isolated and as a result the power load to the divertor plates is asymmetric.

In the real situation there will be a superposition of the fabrication errors, shift and declination of coils and modules, so the permissible limit can be easily achieved and violated. That's why the high precision of the assembly steps is a very important issuer and an assessment of sensitivity of the perturbed magnetic field to different kinds of errors becomes a first priority task.

Basis of numerical approach

To distinguish between different kinds of errors and indicate the most dangerous one, the numerical approach has been developed, which describes statistically the randomly distributed errors, taken within the given tolerances. As an input parameters for already existing coils the real measurements are used. Assumed errors for not fabricated yet coils consist of the systematic part, which is the same for all the coils of one coils shape type, and statistical errors, described within the repetition tolerances. This approach is based on the investigation of the shape deviations, measured for already manufactured coils.

Since any movement of a solid body can be represented by the shift of its centre of mass and rotation of the body around it, the assembly errors are split on shift and rotation of coils and modules around three axis in the space, going through the centre of mass of a coil. The calculations has been done for the pure shifts and declinations of coils and modules as well as for the combination of a manufacture errors with the assembly one for more than 600 cases.

Results of modeling

First result of the performed computations is that the rotation of the coils around different axis is characterized by different impact on the perturbed magnetic field. At fig.1 a magnetic field perturbation is represented for the coils with zero manufactured errors, when coils are rotated on different angles around vertical and binormal axis. The computation has been done for 10 different error distributions and red solid and dashed lines correspond to average and maximum B11 resonant components found between them. Blue solid and dashed lines indicate average and maximum B22 harmonics. Black dashed-dot line represents the permissible limit for the error fields of $2 \cdot 10^{-4}$. It is possible to conclude that the field perturbation goes linearly with the amplitude of the deviation. For the rotation around vertical axis (angle α) the largest permissible value of rotation angle is 0.1 grad, since at 0.2 grad the max B11 harmonic is already over the limit. Similar results were obtained also for the rotation around the horizontal axis. But for the rotation around toroidal axis (angle γ) even for the angle of 0.3 grad values of the resonant Fourier harmonics are under the limit. That means that the influence of the coils displacement is not identical for different directions with respect to perturbed magnetic field. Considered numerical approach can help to indicate the most sensitive to misalignments directions and therefore the tolerances given for the assembly procedure can be probably larger for not critical directions, but smaller for the dangerous one.

Fig.1 Magnetic field perturbation for the pure rotation of ideally manufactured coils.

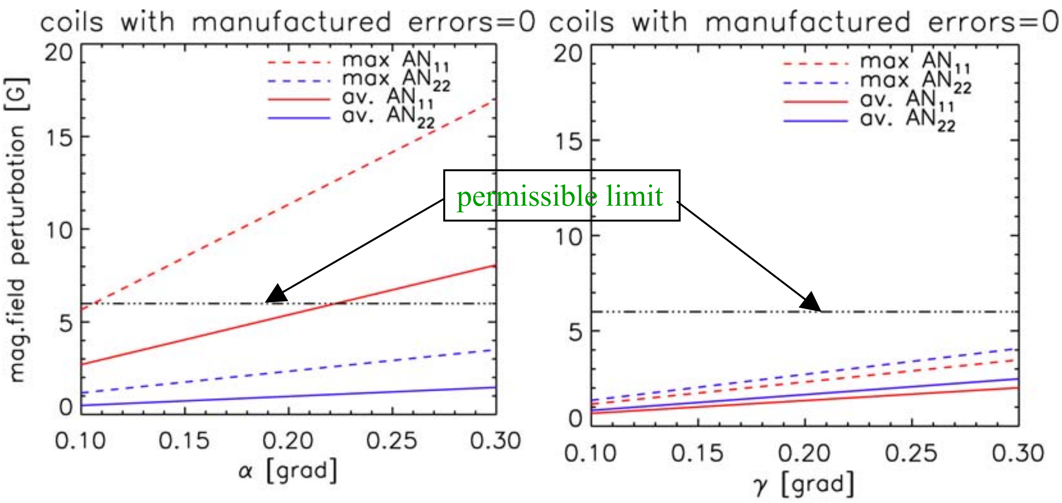


Fig.2-5 represent series of modeling results when the rotation of coils is accompanied by their shift. Left hand side pictures correspond to the case of ideally fabricated coils, right hand side - to the coils with manufacturing errors. Indications for the resonant error field components are the same as in Fig.1. Fig.2 illustrates that requirements for permissible perturbed magnetic field are not violated up to the value of coils shift of 0.45 cm when coils are randomly rotated up to the angle 0.05º. At the angle of rotation 0.1º (fig.3) maximum resonant B_{22} components are slightly above the limit in the case with not ideally manufactured coils for the values of the shift starting from 0.3 cm. Fig.4 shows that at the angle of rotation 0.2º maximum B_{11} and B_{22} both exceed value of $2 \cdot 10^{-4}$ independently on fabrication errors. Fig.5 corresponds to the case when coils are rotated up to 0.3º. Here already average B_{11} and B_{22} components are over the permissible limit.

Fig. 2 Effect of shift and rotation on δB *(α=β=γ=0.05 degree)*

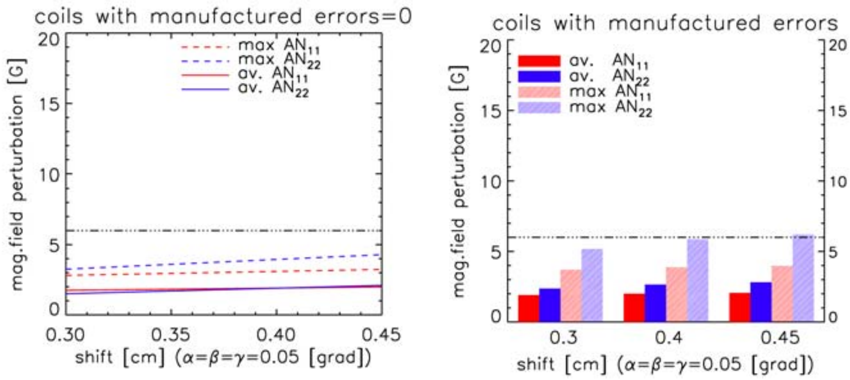


Fig. 3 Effect of shift and rotation on δB *(α=β=γ=0.1 degree)*

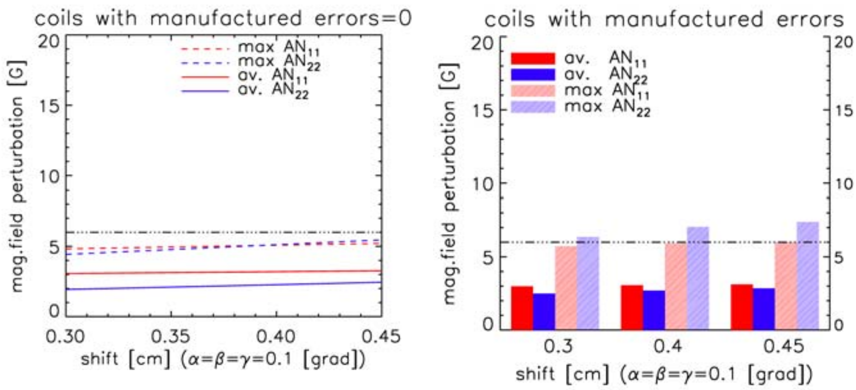


Fig. 4 Effect of shift and rotation on δB *(α=β=γ=0.2 degree)*

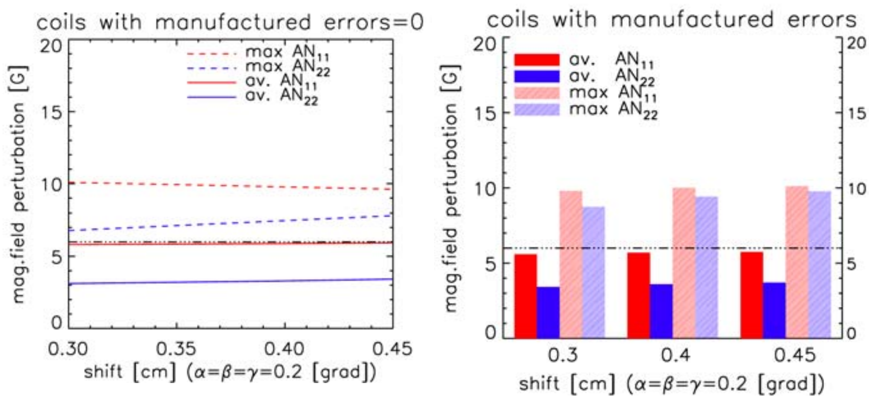
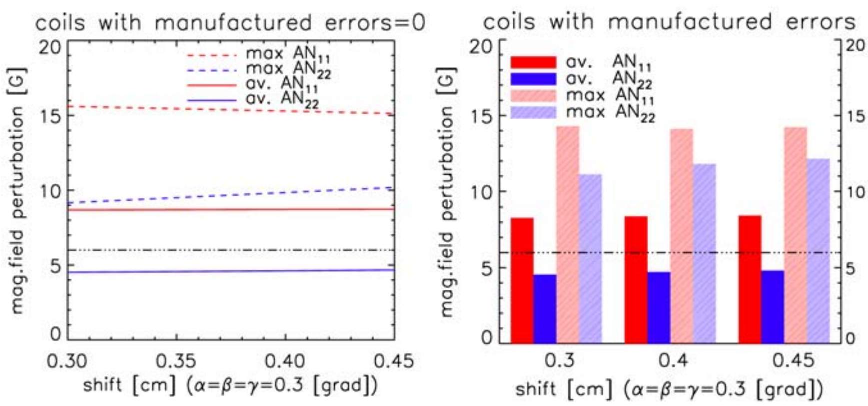


Fig. 5 Effect of shift and rotation on δB *(α=β=γ=0.3 degree)*



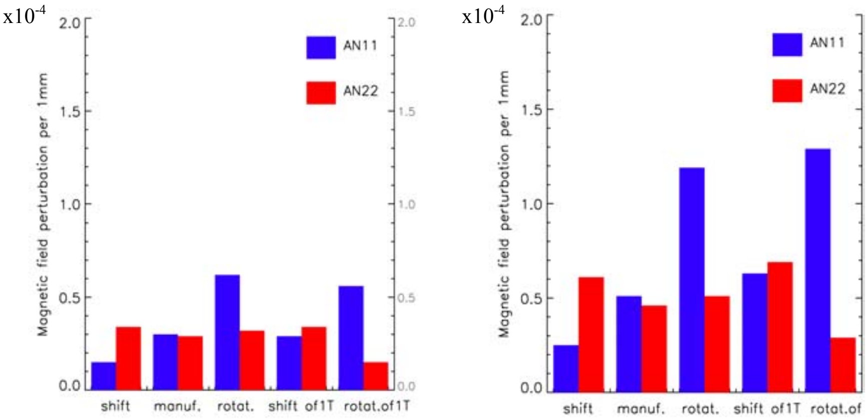


Fig. 6 δB for an average deviation of 1 mm

Analysis of the error field sensitivity to the different sources of perturbation is shown at Fig. 6. To compare the impact of fabrication errors, shift of coils and modules, and rotation of coils and modules, a relevant quantity which is the same in all considered sources of perturbation had to be chosen. As such a magnitude an average deviation of the filament position from the designed one has been taken into account. That is a sum of deviations in all 96 cross-sections in all 50 coils divided by product 96·50. At Fig.6 there are the values of B_{11} and B_{22} resonant components, produced by each kind of the magnetic field perturbation and giving an average deviation of the filament position equal to 1mm. It is possible to conclude that perturbed magnetic field is mostly sensitive to the rotation of coils and modules. The impact of manufacturing errors and a shift is in the same range. Rotation and fabrication errors affect more AN11 than AN22 harmonic, but the influence of the shift is just the opposite. Maximum values of the magnetic field perturbation, shown at the left histogram, indicate that deviations of the filament position with an average value of 1.5 to 2mm may generate effective field perturbations in the range of $2 \cdot 10^{-4}$.

Conclusions and further plans

Numerical approach has been developed, which allows to assess the sensitivity of the magnetic field to the different types of errors and to identify the most dangerous one. The simulation has shown that the influence of the coils and modules rotation is much larger than the impact of the shift and manufacturing errors.

Since the magnetic configuration of W7X is very sensitive to symmetry breaking perturbations, a high geometrical precision during the manufacturing and positioning of the coils is required. Considered numerical approach now has being used to estimate the acceptability of the newly fabricated coils and it will be a basis for the assessment of the error fields at each assembly step described within the given tolerances.

The numerical procedure will be developed further in order to estimate the optimum positioning of coils and modules during the construction. It will help to make a final assessment of the magnetic configuration before the completion of each real assembly step and indication whether any repositioning is necessary.

When the whole machine is assembled, a careful analysis of remaining errors is necessary for their compensation by additional tools.