Influence of assembly and operation asymmetries on Wendelstein 7-X magnetic field perturbations

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Wendelstein 7-X is a modular advanced stellarator realizing a 5-period Helias configuration. An important part of the planned operational plasma scenarios is characterised by a rotational transform $\iota/2\pi=1$ at the plasma boundary. Such configurations are very sensitive to symmetry breaking perturbations, resonant with the value of the rotational transform at the boundary and violating the toroidal periodicity of the magnetic field. The most critical consequences of magnetic field perturbations are modifications of the island topology, which can result in uneven loads on the divertor targets and affect the plasma performance. In this paper the level of magnetic field perturbations due to possible symmetry distortions under electromagnetic loads is estimated and comparative analysis with previously investigated magnetic field errors is presented.

Keywords: magnetic field perturbation, Wendelstein 7-X, stellarator, optimisation

Introduction

The majority of the planned operational plasma scenarios of Wendelstein 7-X (W7-X) is characterized by a rotational transform $\iota/2\pi=1$ at the boundary. The most critical perturbation in W7-X is a breaking of the 5-fold symmetry of the machine, resonant with $\iota/2\pi=1$. The consequences of a magnetic field perturbation are modifications of the separatrix, changing the island topology. This leads to a decreased volume of the confined plasma as well as to a redistribution of the power flux to the divertor plates. An uneven power load distribution can result in overload of some divertor targets. These asymmetric divertor power loads correlate well with the amplitude of the resonant Fourier coefficients of the radial component of the error field close to the last closed magnetic surface [1].

Symmetry breaking perturbations arise either from non-symmetrical deviations in coil shapes during the coil manufacturing or from position displacements and coil deformations during the assembly process and machine operation. In order to compensate for the impact of the errors accumulated during coil system construction, the optimization of the module positions was successively performed for each of the five Wendelstein 7-X magnet modules. This allowed compensation of magnetic field perturbations to the level of $\sqrt{B_{11}{}^2 + B_{22}{}^2 + B_{33}{}^2 + B_{44}{}^2} / 3\,\mathrm{T} \approx 0.3 \cdot 10^{-4}$, where $B_{11},\ldots,B_{44}$ are the resonant Fourier coefficients of the radial component of the error field close to the last closed magnetic surface [2].

In order to keep the magnetic configuration of the machine as designed and to confirm compensation capabilities provided in W7-X (trim and control coils), the level of error fields needs to be quantified for all possible sources of perturbation.

Modeling of coil deformations during W7-X operation

Symmetry distortions during machine operation are caused by an asymmetry of the magnet system (MS) structure and its supports, resulting from variations of a coil case thickness, different gap sizes and friction factors at various sliding contact support elements, differences in bolt preload values, as well as due to a variation of material properties of the structure including the central support ring. In addition, the sequential torus connection procedure after the module positioning contributes to MS asymmetries.

The MS of W7-X comprising 70 superconducting coils and their support structure was intensively analysed with help of the finite element (FE) global model, created with the ANSYS code [3]. Results of such calculations were verified with the ABAQUS finite element model, and afterwards both models were improved [4]. FE simulations were performed with different parameter settings in order to predict the range of deformations under reasonable variations of the friction factor from 1% up to 20% at sliding pads, a variation of bolt preloads (50%, 80% and 100% of nominal), a variation of Young's modulus (80 % and 120% of design values), a change of narrow support element (NSE) gaps at different non-planar coils (in the range from -1.4 mm to 2.5 mm to mimic defined tolerances of installation) and a variant with 100% friction at bolted contacts to consider a case with so-called "cold friction". It was assumed that the symmetric boundary conditions do not influence the results significantly. More than 30 cases were run for each of nine W7-X reference operational scenarios at 3T [5]. These cases are also the basis for the determination of the design loads on the structural components.

For each run, the displacement along the perimeter of the winding pack (WP) was extracted at the centre of each of its 96 cross-sections, expressed in the local coordinate system, which rotates with the cross-section of the WP along the perimeter, i.e. in the radial, quasi-toroidal and electrical current direction. Calculated WP deviations were compared for all different structural asymmetry cases with each other. At each cross-section the minimum and maximum displacement for each coil type was obtained for nine W7-X operational scenarios. These differences served as an input parameter for corresponding error field estimation. Typical examples of a displacement distribution along the WP cross-section of a non-planar coil of type 1 are shown in Fig.1.

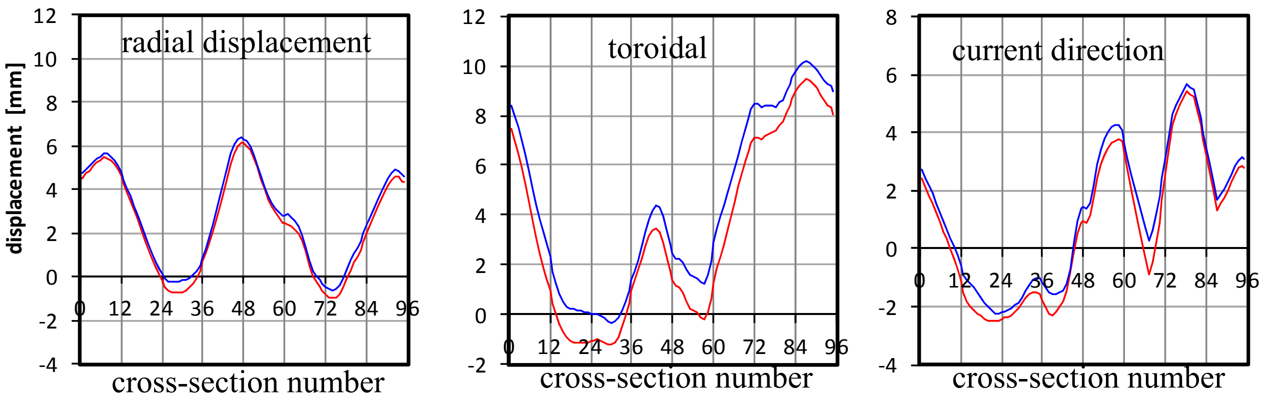

Fig.1 Minimum (red) and maximum (blue) WP deformation of a non-planar coil of type 1 along the coil perimeter under electromagnetic loads for the different parameter sets

For each coil type the parameter set which results in the maximum deviation was determined for each of the nine reference operating cases. For non-planar coils these are mainly uncertainties of NSE gaps and for planar coils a case with 100% friction at bolted contacts, variation of NSE gaps and a change of the friction factor at pads.

Assessment of a magnetic field perturbation resulting from structural asymmetries

Coil deformations resulting from different parameter sets were an input for the magnetic field analysis. For each parameter set these were coil displacements in one machine module, calculated for each of 96 WP cross-sections. Fig.1 shows that coil deformations under electromagnetic loads consist mainly of systematic displacements and depend to a smaller degree on specific parameter settings, however precisely this smaller portion is of interest for error field studies. Maximum winding pack displacement variation, contributing to the error fields, is less than 2 mm, and the error fields are of the same order of magnitude as those introduced by an asymmetrical assembly procedure. To simulate corresponding magnetic field perturbation due to parameter set variation each of five W7-X modules was represented by coils deformed accordingly to different structural FE results. More than 50 combinations were analysed for the standard operating case at 3T. Average relative magnetic field perturbation calculated for these runs is less than $0.2 \cdot 10^{-4}$, while a maximum value $\approx 0.32 \cdot 10^{4}$. In addition, 20 random variants of WP deformations were simulated for a case with x-, y- and z-coordinates of each cross-section centre being changed randomly within a ±1.8 mm. These simulations were performed for two different kinds of error distributions – using the equal-likelihood probability distribution and a Gaussian one with $3\sigma = 1.8$ mm. The average relative magnetic field perturbation for these 20 runs is $0.4 \cdot 10^{-4}$ and $0.23 \cdot 10^{-4}$, respectively.

Conclusions

Analysis of non-systematical coil deformations due to structural parameter variations under electromagnetic loads for all reference W7-X configurations showed, that maximum WP cross-section displacements found for each coil type are less than 2 mm in each direction. The corresponding average relative magnetic field perturbation $\sqrt{B_{11}{}^2 + B_{22}{}^2 + B_{33}{}^2 + B_{44}{}^2} / 3\,\mathrm{T}$ estimated for the standard operating case at 3T is of the same order of magnitude as a residual magnetic field error calculated after the positioning of the last W7-X module on the machine base. Even with a safety margin to cover calculation uncertainties and an inaccuracy of the structural global model, the level of the magnetic field perturbation is below the compensation capacities of the installed trim coils. Additional deviations caused by the sequential assembly procedure also do not exceed 2 mm.

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