Evaluation of Wendelstein 7-X magnetic field perturbations during optimized module positioning

T. Andreeva[1], T. Bräuer[1], M. Endler[1], J. Kißlinger[2]
[1]*Max-Planck-Institut für Plasmaphysik, EURATOM-Association, Greifswald, Germany*
[2] *Max-Planck-Institut für Plasmaphysik, EURATOM-Association, Garching, Germany*

The majority of the planned operational plasma scenarios of Wendelstein 7-X is characterized by a rotational transform $\iota/2\pi=1$ at the boundary. Such configurations are very sensitive to symmetry breaking perturbations which are unavoidable because of tolerances in coil manufacture and magnet system assembly. The most critical consequences of non-symmetrical deviations from the designed coil shapes and positions are changes of the island topology, which result in asymmetric power loads on the divertor plates. In order to compensate for the impact of these errors, the position of each of the five machine modules was optimized individually, based on the up-to-date set of geometric survey data of coil and module alignments. In this paper the evolution of the magnetic field perturbations is documented for the whole sequential assembly of the Wendelstein 7-X magnet system. The residual magnetic field perturbation is shown for all reference magnetic field configurations.

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

Introduction

The most critical perturbation for the Wendelstein 7-X (W7-X) magnetic field is a break of the toroidal periodicity resonant with a rotational transform $\iota/2\pi=1$ at the boundary, since this is expected to redistribute the power flux to the divertor modules. The magnetic field errors can be represented by the most relevant low-order components $B_{m,n}$ of a poloidal-toroidal Fourier decomposition of the radial component of the magnetic field perturbation on a flux surface at the plasma edge. The principle of field error optimisation is that small perturbations have an almost linear behavior and the compensation is possible by a superposition of Fourier components with the same amplitude but with an opposite phase angle [1]. Focusing on a limited number of low-order error field Fourier components, although they may be generated by the joint manufacturing errors of the individual coils, they can be compensated by appropriate shifting and rotating of the five magnet modules forming the W7-X magnet system.

For this optimisation process a target function T was chosen as a sum of a magnetic "quality function" Q (where a low value of Q represents a high "quality" of the magnetic field) and a function G which is respresenting the engineering restrictions: $T = G + Q$, where $G=g\sum_j\left(\exp\left(\frac{|\Delta j|^2}{0.9t}\right)-1\right)$, $\Delta j \equiv (r_{target,\ new} - r_{target,\ old})$ and $Q = Q_0 + q_1 Q_1$, $Q_0=\sum_{k=1}^{4} g_{kk}^2/k$,

$Q_1 = \frac{1}{2} B_{23}^2 + \frac{1}{3} B_{34}^2 + \frac{1}{4} B_{43}^2$ [2]. The “magnetic” part Q of the target function focuses mainly on m = n components and monitors several additional low-m components of the resonant magnetic field, taken with the weight factor q_1 to be chosen such that the primary goal of the minimization of Q_0 is granted while still achieving a certain reduction of Q_1. The “geometrical” part G reflects the fact, that arbitrary positioning of the modules is not permitted due to the necessity to place a surrounding structure as designed. The boundary conditions for any repositioning of the modules were that the new target coordinates may not deviate by more than 5 mm from their values as measured at the moment when coils were aligned within a module and the true relative lateral shift of neighboring modules may not exceed 10 mm at the central support structure, including measurement inaccuracies. For each assembly step, the target function T was minimized by variation of those module positions, which had not yet been placed on the machine base, while the coil shapes and positions within these modules were unchanged.

Input and Output data for the optimisation procedure

The input for these calculations were the real coil shapes after completion of their manufacture and the geometrical surveys of the coil positions after fixing the coils within their module on the mounting stand II (MST II) and after placing of the module on the machine base (MST IV). To ensure the reliability of the coil position description on the machine base, a rigid transformation of the entire module from MST II onto the machine base was performed based on these surveys.

As an output the optimized individual coordinates for the positioning of each of the five modules on the machine base were generated. This calculation was provided before the positioning of each module on the machine base. After the completion of the module adjustment and the corresponding survey the evaluation of the magnetic field perturbations was updated.

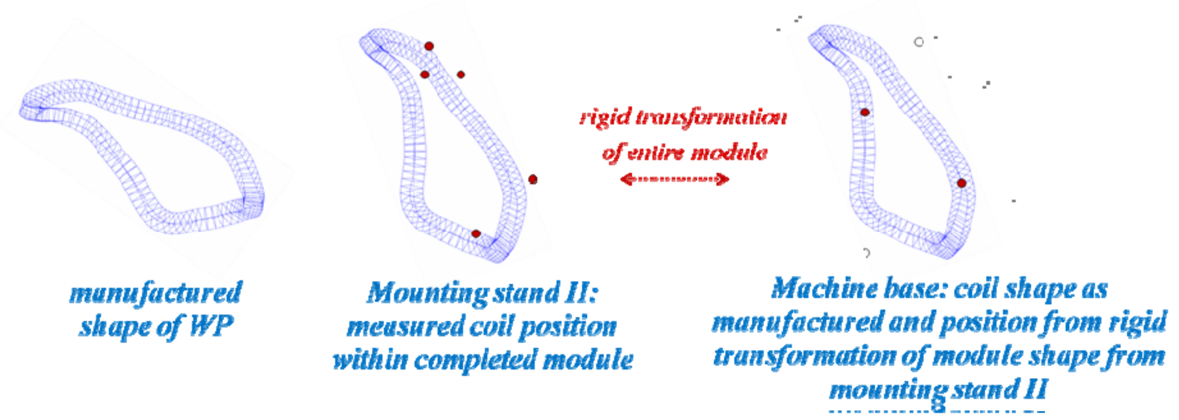

Fig.1 Scheme of the measurements used for the optimisation procedure. Red dots represent reference marks measured on one coil, white dots – reference marks measured on other coils of a modules used for the rigid transformation.

Evaluation of the magnetic field perturbation

The five modules were placed and positioned on the machine base sequentially. The assembly sequence for the module positioning was M05-M01-M04-M02-M03, where M0N means the internal numbering of the five machine modules. Before the positioning of each module, an optimization of the target coordinates was performed based on the latest available survey data (see Table 1). The optimzation procedure delivered new target coordinates for all modules still to be positioned, leaving those untouched which were already located on the machine base.

The optimization results are illustrated in Fig.2, representing the general evolution of the magnetic field perturbation during the assembly progress. A reduction of the magnetic field perturbations by a factor ~3 was achieved in comparison with the initial level, which would have resulted from a module positioning to as-designed coordinates.

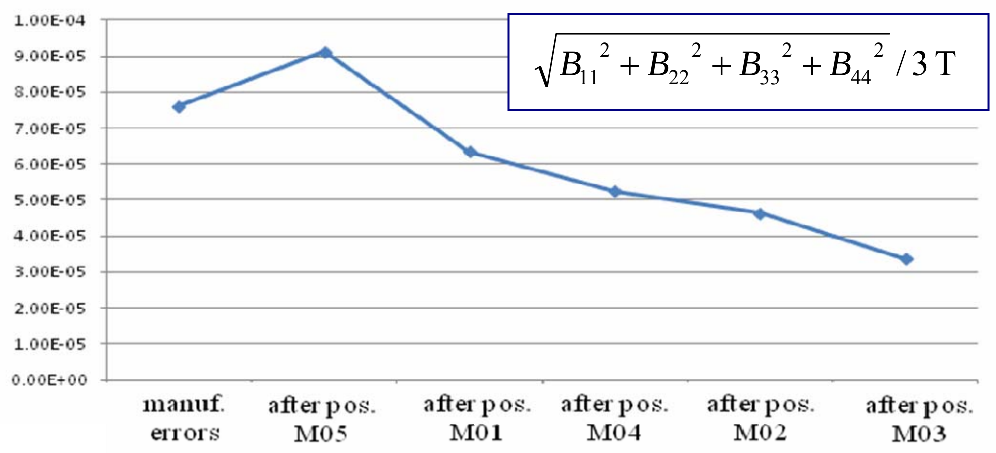

Fig.2 Evaluation of the magnetic field perturbation during the assembly progress. The assembly sequence for the module positioning was M05-M01-M04-M02-M03.

	M01	**M02**	**M03**	**M04**	**M05**
manuf.	manuf.	manuf.	manuf.	manuf.	manuf.
after pos. M05	MST II	MST II	manuf.	MST II	MST IV
after pos. M01	MST IV	MST II	MST II	MST II	MST IV
after pos. M04	MST IV	MST II	MST II	MST IV	MST IV
after pos. M02	MST IV	MST IV	MST II	MST IV	MST IV
after pos. M03	MST IV	MST IV	MST IV	MST IV	MST IV

Table1. Measurements served as input for the evaluation of the magnetic field perturbation during the assembly progress shown in Fig.2. Manuf – manufactured shape of WP, MST II – measured coil position within a completed module at the mounting stand II, MST IV – coil position within the module from MST II and position from rigid transformation of entire module into the mounting stand IV (machine base).

The magnetic field quality function Q used in the target function T is designed to minimise the field error for the standard magnetic configuration (equal current in all non-planar coils and zero current in planar coils).

The value of the magnetic field perturbation was checked also for all other Wendelstein 7-X reference operating cases on the basis of the optimized coordinates, evaluated for the positioning of the last magnet system module. Table 2 shows, that error fields are also optimized for other reference configurations and are of the same order of magnitude as for the standard case.

reference case	$\sqrt{B_{11}^2+B_{22}^2+B_{33}^2+B_{44}^2}/(3\cdot 10^{-4}\ \mathrm{T})$	
standard case	0.30	**$\iota_b/2\pi=1$**
low shear case	0.41	
inward shifted case	0.32	
outward shifted case	0.28	
low mirror case	0.29	
high mirror case	0.36	
limiter case	0.49	
low iota case	0.40	
high iota case	0.59	

Table2. Estimaties of the magnetic field perturbation for reference W7-X operating cases, based on optimized coordinates calculated for the last module.

Conclusions

The evaluation of the magnetic field accompanying the whole assembly procedure allowed to collect the data describing the influence of the main assembly steps and to make available as-built coil shapes and positions for further purposes. The optimisation of the module positions successively performed for each of the five Wendelstein 7-X magnet modules helped to avoid an error field accumulation during the assembly and to reduce magnetic field perturbations significantly. The relative magnetic field error after the positioning of the last module on the machine base is $\sqrt{B_{11}^2+B_{22}^2+B_{33}^2+B_{44}^2}\,/\,3\,\mathrm{T}\approx 0.3\cdot 10^{-4}$ for the standard operating case and is in the same order of magnitudes for all other reference magnetic configurations.

References

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