Compensation of Wendelstein 7-X construction errors by optimisation of module positions

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Wendelstein 7-X, currently under construction at the Max-Planck-Institut für Plasmaphysik in Greifswald, Germany, is a modular advanced stellarator, combining the modular coil concept with optimised properties of the plasma. Wendelstein 7-X magnetic configurations are rather sensitive to magnetic field perturbations caused by manufacturing deviations of the winding pack shapes from their designed values and by positioning errors during the machine assembly. In order to minimize the impact of these errors it was decided to optimize the position of each of the five machine magnet modules individually, based on up-to-date measurement data concerning the coil alignments available at the moment of calculation. This paper presents a choice of a corresponding quality function for the magnetic field evaluation. Results of the optimisation are shown for the sequential assembly of the first three machine modules. The influence of the step-by-step sag of the machine base on the magnetic configuration is also considered.

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

Introduction

The optimized magnetic field of Wendelstein 7-X (W7-X) is characterized by a rotational transform $\iota/2\pi=1$ at the boundary for the majority of operational cases. Non-symmetrical deviations from the designed coil shape and positions, due to fabrication and assembly tolerances, lead to a modification of the separatrix, affecting the island topology and the resulting power loads on the divertor plates [1]. Therefore, not only high precision of the coil assembly, but also subsequent evaluation and step-by-step optimisation of the magnetic field in order to compensate the accumulated perturbation is essential for the machine construction.

The principle of field error compensation is that small perturbations have an almost linear behavior. Hence, the compensation is possible by a superposition of Fourier components with the same amplitude but with an opposite phase angle [2]. The inputs for these calculations are the measurements of the coil shape and position deviations during fabrication and different assembly stages. As an output the optimized individual coordinates for the positioning of each of five modules on the machine base are received. This calculation is provided before the assembly of each module on the machine base and is followed by the evaluation of the updated level of the magnetic field perturbation after the completion of its adjustment and corresponding measurements.

Choice of the target function

To provide optimisation of module positions one should have a space for their variations. However, an arbitrary positioning of the modules is not permitted due to the necessity to place a surrounding structure as designed. Therefore, the overall target function T consists 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 responsible for the engineering restrictions: T = Q + G. The module positions are varied by shifts and rotations, while the coil shapes and positions within the modules are unchanged , until a minimum of the target function T is found. The boundary conditions for any repositioning of the modules of the magnet system to new target coordinates are the following: 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. Secondly, the true relative lateral shift (including measurement uncertainties and positioning error) of neighboring modules may not exceed 10 mm at the central support structure.

Target function T to be minimized should be continuous, whereas, from an engineering point of view, the geometric boundary conditions should be strictly obeyed. This conflict is solved by using functions of $\Delta \equiv (r_{target,\,new} - r_{target,\,old})$ which strongly grow for $|\Delta| > l$, where l is some appropriately chosen limit around 5 mm. The finally chosen function G is $G = g\sum_j (\exp(\frac{|\Delta j|^2}{0.9l}) - 1)$, where g is a properly chosen factor to adjust the relative weights of G and Q. The shifts due to the change of target coordinates of all reference marks on the magnet system as well as the relative shifts of several positions on neighbouring modules are checked additionally to insure the geometric boundary conditions.

The three-dimensional magnetic field on a flux surface can be Fourier transformed in toroidal and poloidal directions. The difference between the unperturbed (ideal) and the perturbed magnetic field is the error field. The most critical perturbation for the W7-X magnetic field is a break of the toroidal periodicity resonant with a rotational transform $\iota/2\pi=1$

at the plasma edge, since this is expected to redistribute the power flux to the divertor modules. This asymmetric power load correlates well with the amplitude of the resonant Fourier coefficients of the radial component of the error field close to the last closed magnetic surface . In terms of poloidal (m) and the toroidal (n) mode numbers the m = n components of the error field deserve particular consideration. Since the width of magnetic islands generated by the error field components scales ~1/m, the weight of the amplitudes of the individual components should be chosen accordingly in a quality function to be minimized. The (5, 5) component does not break the toroidal periodicity and is therefore not considered. The impact of higher-order components is neglected due to their decreasing weight. In addition the relative amplitude of high-m components decreases faster with increasing distance from the coils than that of lower-m components. It was also decided to monitor a number of additional error field Fourier components during the optimisation process and to minimize their increase. These are the (m, n) = (2, 3), (3, 4) and (4, 3) components. Finally, the quality function for the magnetic field Q is $Q = Q_0 + q_1 Q_1$, where $Q_0 = \sum_{k=1}^{4} B_{kk}^2/k$ and $Q_1 = \frac{1}{2}B_{23}^2 + \frac{1}{3}B_{34}^2 + \frac{1}{4}B_{43}^2$. The weight factor q_1 must be chosen such that the primary goal of the minimization of Q_0 is granted while still achieving a certain reduction of Q_1.

Optimisation results

Optimisation results are presented in the Table 1 for the first three modules of the machine, positioned on the machine base. Calculations were provided for the standard operational case (equal current in all non-planar coils and zero current in planar coils) with the average field strength of 3 T.

State	$\sqrt{Q_0}$ **[10^{-4} T]**
without optimisation of the target coordinates	1.85
theoretically attainable value before adjustment of the first module (module Nr. 5)	0.54
attained value after adjustment of the first module (Nr. 5)	0.61
attainable value before adjustment of the second module (Nr. 1)	0.49
attained value after adjustment of the second module (Nr. 1)	0.76
attainable value before adjustment of the third module (Nr. 4)	0.43
attained value after adjustment of the third module (Nr. 4)	0.52

Table 1: *Target function for the quality of the magnetic field during the positioning of the first three modules.*

One can see, that magnetic field errors were reduced due to the optimisation of the module positions by a factor of 4 in comparison to the pre-assembly state without optimisation and evaluated on the basis of the manufacture coordinates (where they were mainly caused by the deviations of the winding pack shapes of the coils of the same type from each other). The remaining deviations from the optimal module positions after the adjustment of the modules on the machine base increase the magnetic field errors by at most 50% compared with the theoretically reachable value of $\sqrt{Q_0}$.

Additional assessments were provided to clarify the issue, that the sequential machine assembly might introduce an additional deviation of the target module coordinates due to the step-by-step sag of the machine base. Due to such sag the real position of the modules already adjusted on the machine base would not correspond precisely to the measurement data, which serve as a basis for the calculation of the target coordinates for the next module. Two different scenarios for the sag of five modules were considered on the basis of the measurements of some reference points and FE assessments. Corresponding values of the sag and $\sqrt{Q_0}$ (last row) are presented in Table 2 and show, that the sag of the machine base due to the sequential assembly of the machine modules increases the magnetic field errors only moderately.

	Scenario 1 (optimistic)	**Scenario 2 (conservative)**
Sag of the first module [mm]	-0.4	-0.8
Sag of the second module [mm]	-0.2	-0.6
Sag of the third module [mm]	-0.2	-0.4
Sag of the fourth module [mm]	-0.1	-0.2
Sag of the last module [mm]	0	0
$\sqrt{Q_0}$ **[10^{-4} T]**	0.56	0.61

Table 2: *Change of the target function for the quality of the magnetic field, taken after adjustment of the third module, due to the sag of the machine base.*

Conclusions

Optimisation of module positions provided successively for the first three W7-X modules helped to reduce magnetic field errors significantly and to save assembly time planned for possible readjustment of these modules in order to improve the magnetic configuration. The impact of the sag of the machine base during the sequential assembly of the machine can be neglected. The further evaluation of the new optimized coordinates for the remaining two modules anticipates the risk to accumulate error fields during the assembly.

References

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