Wendelstein 7-X (W7-X), currently under commissioning at the Max-Planck-Institut für Plasmaphysik in Greifswald, Germany, is a continuation of the helical advanced stellarator line, with the final goal to demonstrate the reactor capability of modular stellarators.

Most of the envisaged magnetic configurations of the machine are very sensitive to symmetry breaking perturbations which are the consequence of unavoidable construction displacements and manufacturing tolerances. In order to keep the magnetic configuration of the machine as designed and to confirm compensation capabilities provided in W7-X, the level of error fields needs to be quantified for all possible sources of perturbation. One of such sources is the sequential torus assembly procedure after the placement of magnet system modules on the machine base.

This presentation shows results of the evaluation of the influence of the asymmetrical torus assembly as well as a comparative analysis for different sources of W7-X error fields.

**Consequences of the magnetic field perturbation**

First contact with target

**Target overload factor**

<table>
<thead>
<tr>
<th>Standard case</th>
<th>Standard case: no perturbation</th>
<th>Perturbation $B_0/\mu T$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Finite element calculations on deformations of W7-X magnet system and resulting magnetic error field

- sequential torus assembly after module positioning
- deviations are partly systematic, max variation in non-symmetrical part: $2.0 \, \text{mm}$
- causes of possible magnetic system deformation: the sequential loading of the magnetic field base, the connection of adjacent modules to each other and the removal of temporary supports. Deformations are calculated with $3D$ ABAQUS FE Model, including W7-X machine base.
- simulation of error field: deformed filaments of 70 coils derived from FE analysis served as an input. Corresponding magnetic field perturbation $S_	ext{M}$ varies from $1.17$ to $1.25 \times 10^{-4}$, its maximum value is found in low iota case, dominating component $B_0$.

**TYPICAL RESULTS OF FE ANALYSIS**

Displacements along WP of NPC1 in half-module HSM1, where $x = 1, \ldots, 5$

**RESULTS OF ERROR FIELD MODELLING:**

<table>
<thead>
<tr>
<th>Reference case</th>
<th>$B_0/\mu T$</th>
<th>$B_0/\mu T$</th>
<th>$B_0/\mu T$</th>
<th>$B_0/\mu T$</th>
<th>$S_	ext{M}$/10$^{-4}$</th>
<th>$S_	ext{M}$/10$^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core shear case</td>
<td>1.19</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>External disturbed case</td>
<td>1.19</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>External disturbed case</td>
<td>1.19</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>Core torus case</td>
<td>1.22</td>
<td>0.11</td>
<td>0.10</td>
<td>0.02</td>
<td>1.26</td>
<td></td>
</tr>
<tr>
<td>High internal case</td>
<td>1.18</td>
<td>0.11</td>
<td>0.10</td>
<td>0.02</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>External case</td>
<td>1.21</td>
<td>0.11</td>
<td>0.10</td>
<td>0.02</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>Core torus case</td>
<td>1.24</td>
<td>0.11</td>
<td>0.10</td>
<td>0.02</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>High internal case</td>
<td>1.16</td>
<td>0.14</td>
<td>0.11</td>
<td>0.02</td>
<td>1.17</td>
<td></td>
</tr>
</tbody>
</table>

- uncertainties of parameters of the magnet system
- deviations are partly systematic, max variation in non-symmetrical part: $2.0 \, \text{mm}$
- system performance: variations of coil case thickness, gap sizes and fiction factors at various sliding contact support elements, differences in bolt preload and structure material properties in the five modules. Deformations are calculated with $3D$ ANSYS Global FE Model.
- simulation of error field: 90 random sets derived from FE analysis of 5 modules were compiled and served as an input. The average value of the magnetic field perturbation $S_	ext{M}$ is $0.2 - 10^{-4}$, the maximum value $0.32 - 10^{-4}$, dominating component $B_0$.

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**Conclusions**

- Non-systematical coil deformations due to the sequential torus assembly: maximum WP cross-section displacements $< 2 \, \text{mm}$ in each direction.
- Corresponding magnetic field perturbation varies from $1.17 \times 10^{-4}$ to $1.25 \times 10^{-4}$ (dependently on reference operation case), and its maximum value corresponds to the low iota case.
- A comparison of the analyzed sources of magnetic field perturbation showed that, even with a safety margin to cover calculation uncertainties and small inaccuracies of the FE models, the corresponding cumulative estimation is $S_	ext{M} < 2 \times 10^{-4}$. This level of the magnetic field perturbation is below the compensation capacities of the installed trim coils and leaves enough potential to eliminate the impacts of possible additional magnetic field perturbations. Hence, the compromise between physical needs and engineering challenges can be successfully met.

**Comparison of different sources of magnetic field perturbation for standard operation case**

- Manufacturing tolerances
- Magnetic field perturbation with $50-60$ non-planar winding packs (NP WPs), real W7-X coil allocation and CAD coil positioning: $S_	ext{M} < 0.75 \times 10^{-4}$ (mostly compensated by optimized module positioning).

**End of module positioning**

Magnetic field perturbation with $50-60$ NP WPs, real W7-X coil allocation and real W7-X coil positioning: $S_	ext{M} < 0.34 \times 10^{-4}$ (will be compensated by trim coils).

**Evolution of magnetic field perturbation during optimized module positioning**

Sequential torus assembly after module positioning (mainly removal of temporary supports)

For $50$ initially ideal NP WPs with CAD positioning derived from FE analysis deformations contribute to magnetic field perturbation as following: $S_	ext{M} < 1.21 \times 10^{-4}$ (will be compensated by trim coils).

**Uncertainties of parameters of the magnet system (variation of structural characteristics)**

For $50$ initially ideal NP WPs with CAD positioning derived from FE analysis deformations contribute to magnetic field perturbation as following: $S_	ext{M} < (0.2-0.3) \times 10^{-4}$ (will be compensated by trim coils).

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**Motivation**

Wendelstein 7-X (W7-X), currently under commissioning at the Max-Planck-Institut für Plasmaphysik in Greifswald, Germany, is a continuation of the helical advanced stellarator line, with the final goal to demonstrate the reactor capability of modular stellarators.

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