Design of structural components and radial-build for FFHR-d1


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Introduction

- LHD-type helical DEMO reactor appropriately operates as a demonstration device for a fusion power plant.
- A blanket system and a divertor system will be installed in the device. These systems require maintenance and parts exchange.
- The components must be able to accommodate a maintenance scheme, for example equipment of the components with large access ports.
- An LHD-type configuration offers limited space in this region. Many components have to be installed at definite geometric positions.
- A radial build design concept and a structural design procedure for helical DEMO reactor FFHR-d1 are introduced.
The estimated radial-build space at the inboard of the torus ($\Delta c-p$) is 890 mm.

A 700-mm blanket space can be achieved, and a clearance of 30 mm is assigned between the plasma surface and the first wall.

Other components must fit in the remaining 160-mm space.
Radial build design

- To maintain the geometric position: part1; blanket side,
  - The blanket toroidal/poloidal cross section is divided into several sectors.
  - The support for the blanket system is set near its coil side to restrict the inward displacement of the blanket.
  - The vacuum vessel is composed of a thin steel plate and is attached to the surface of the blanket.
  - The thermal shield is connected to the outer surface of the vacuum vessel.
Radial build design

- To maintain the geometric position: part2; coil side,
- Both HC and coil support structure exhibit a continuous structure throughout their circumference.
- Although the extent of deformation depends on the design of the coil support, a displacement of ±10 mm at the bottom of the coil frame is permissible.
- The positions of the HC and the support structure should be set, considering thermal contraction and electromagnetic hoop deformation.
**Coil support system**

*Cross section of HC*

- Cross section of the helical coil: on the basis of a rectangle of aspect ratio 2.08, creating a step-like shape by maintaining the gross area.
- The aspect ratios of the poloidal coils were set, considering the geometries of the vacuum vessel and the coil support structure.

*These geometries will need to be modified on the basis of the conductor size, insulation, cooling scheme, etc.*

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Design parameters of the superconducting magnet in FFHR-d1.

<table>
<thead>
<tr>
<th></th>
<th>HC</th>
<th>IVC</th>
<th>OVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current density (A/mm²)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Magnetomotive force (MA)</td>
<td>36.66</td>
<td>18.5</td>
<td>-19.9</td>
</tr>
<tr>
<td>Major radius (m)</td>
<td>15.6</td>
<td>7.2</td>
<td>22.2</td>
</tr>
<tr>
<td>Minor radius (m)</td>
<td>3.9</td>
<td></td>
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</tbody>
</table>
• The coils and surrounding vacuum space were modeled as a vector potential element in an ANSYS program.

Magnetic field at toroidal angle 18 deg.
Coil support system
Electromagnetic force

- The EM force may be divided into two directions, corresponding to the hoop and overturning directions with respect to the coil winding direction.
- The maximum EM hoop force is 70 MN/m, while the maximum EM overturning force is ±10 MN/m

Overall EM forces on the HC at every cross section. Fa: direction of the minor radius of the HC. Fb: perpendicular to the coil winding and the minor radius direction.

EM forces on the IVC and the OVC. Because of dyad rotational symmetry, only the upper portions are shown. The positive value indicates an expansion or a repulsion force.
Coil support system

Support structure: *large apertures for maintenance ports are required*

- An analytical model of the coil support structure;
- made of stainless steel (SS) 316; 300 mm thick,
- a vacuum gap of 200 mm between the support and the outer surface of the vacuum vessel,
- IVC and OVC were surrounded by 200 mm–thick SS and were connected to the support.

### Material properties for FEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Young’ modulus</th>
<th>Poisson’s ratio</th>
</tr>
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<tbody>
<tr>
<td>Helical coil</td>
<td>80 GPa</td>
<td>0.3</td>
</tr>
<tr>
<td>Poloidal coil</td>
<td>110 GPa</td>
<td>0.3</td>
</tr>
<tr>
<td>Support</td>
<td>200 GPa</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Coil support system
FEM result: stress and deformation

- The maximum von Mises stress was at the corner area of the port region. The maximum stress of 600 MPa is the permissible limit for SS 316 at cryogenic temperature.
- As spatial stress distribution did not exceed 400 MPa, the soundness of the support structure can be consequently guaranteed.
- A maximum deformation of 32 mm appeared near the OVC.
Coil support system
Deformation near the radial build

- The displacement near the bottom region of the HC toward the plasma side was 7 mm. With a thermal contraction of 40 mm, there would be a 30-mm gap between the surface of the thermal shield and the bottom of the coil case during the construction/maintenance phase.
The poloidal coils work to set off the vertical magnetic field generated by the HC.

Poloidal coils act to reduce the overturning force on the HC.

If only HC is excited, the maximum stress will be 860 MPa, which exceeds the permissible limit for SS 316.

The maximum deformation of 25 mm will appear near the bottom coil frame in this case.

These results suggest that there may be contact among the radial build components. Therefore, the coil excitation mode should be carefully selected.

Overall EM forces on the HC at every cross section for HC only mode.
Fa: direction of the minor radius of the HC.
Fb: perpendicular to the coil winding and the minor radius direction.
Vacuum vessel ports

- Fundamental geometry of vacuum vessel is decided according to a particle orbit of plasma, radial build design, and surrounding magnet support structure.
- Large opening port sections in the vacuum vessel are ensured for divertor pump system and for remote maintenance.
Weight of the support structure

- The total weights of the blanket system and the magnet system are estimated to be 35000 tons and 22000 tons, respectively.
- Total weight of the coil support is proportional to the stored magnetic energy, and actual superconducting fusion devices have been in close agreement with this virial theorem.
- With a stored magnetic energy of 160 GJ, the total weight can be estimated to be between 10000 (theoretical) to 30000 tons (extrapolation from actual devices).
- The total weight of the magnet system is probably reduced to lower than 20000 tons by optimization.

Gravity support for cryogenic component

- The LHD-type support post with a “folded multi-plate” design was also suitable for the cryogenic post for FFHR-d1 from both mechanical and thermal viewpoints.

- By using the same design of cryogenic post for FFHR2m1; number of posts: 40 (625 ton / post) thermal contraction 67 mm (at OVC position).

Cryogenic post design for FFHR2m1.
(H. Tamura et al., Plasma Fusion Res. 3, S1051 (2008))
The position of the cryogenic post for one toroidal sector will be
1 at bottom of IVC,
1 at bottom of support structure,
2 at bottom of OVC.

Gravity support for superconducting magnet.
Gravity support for blanket system

- The blanket system should be divided into several sections and supported by using a rigid gravity support.

Example of gravity support for blanket system.
The structural design of a fusion reactor considering the space for a blanket system and a superconducting magnet system is critical.

The radial-build design, which ensures gaps between components are maintained during the operation phase and the construction/maintenance phase, was introduced.

The maximum stress in the coil support structure was within the permissible limit for SS, and the gap in the radial build was not compromised by the deformation of the coil support system.

The total weight of the coil support system can be reduced by optimizing the design for points of mechanical strength and applying the virial theorem.

Preliminary gravity support design was introduced. Detail will be conducted considering manufacture and maintenance.