Study on supporting structures of magnets and blankets for a heliotron-type fusion reactors

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1. Introduction

Advantages of Helical Fusion Reactor:
(1) no current-disruptions,   (2) no current-drive
(3) constant coil-currents       (owing to inherently current-less plasma)

Disadvantages:
(1) necessarily large major radius
to realize the self-ignition condition
to produce sufficient space for blankets.
(2) difficulty of replacement of HCs
(3) difficulty of maintenance of blankets

→ SC magnets, especially the helical coils (HCs), must be simplified
for high reliability of them, good maintainability of blankets, and reasonable construction cost.
Objectives

(1) To survey the major parameters of the reactor with the blanket space > 1.1 m

(2) To optimize the position of poloidal coils

(3) To discuss the simplified supporting structure for SC magnets

(4) To estimate the mechanical feasibility by Finite Element Method.
Coordinate of Helical Coil

Pitch parameter: \( \gamma = \frac{m}{l} \frac{a_c}{R_0} \), Coil current: \( I = \frac{2\pi R_0 B_0}{\mu_0 m} \)

Coil current density: \( j = \frac{I}{W \cdot H} \propto \frac{B_0}{R_0} \) (when the shape is similar)

Minimum gap for blanket \( D_b = \text{Min}(a_c - a_p) - H/2 - 0.1 \text{ [m]} \)

(0.1 m is a space for thermal shield.)
Scale-up Effects for SC Magnets

In the case of similar shape ($W$ and $H \propto R_0$),

(1) Stress is proportional to $B_0^2$ (not dependant on $R_0$).

- Hoop force: $V \propto f R_0 = (B_0 R_0)^2$
- Area of structures: $A \propto R_0^2$
- Stress: $P_m = V/A \propto B_0^2$

(2) Maximum field $B_{max}$ is proportional to $B_0$.

- Coil current: $I \propto B_0 R_0$
- Coil current density: $j \propto B_0/R_0$
- Maximum field: $B_{max} \propto (I j)^{0.5} \propto B_0$

In the case that $j$ is constant, $B_{max}$ is proportional to $(B_0 R_0)^{0.5}$
Plasma Parameter

<Scaling law of energy confinement time>

ISS95: \( \tau_{E}^{ISS95} = 0.079a^{2.21}R^{0.65}P^{-0.59}n_{e}^{0.51}B_{t}^{0.83}\tau_{2/3}^{0.4} \)

\( P \): Plasma heating power per unit volume
\( n_{e} \): Average electron density
\( B_{t} \): Central toroidal magnetic field
\( \tau \): Rotational transform

Under the condition that \( \tau_{E}, P, n_{e}, \) and \( \tau \) are constant,

\( \tau_{E}^{ISS95} \propto a^{1.03}R^{0.06}B_{0}^{0.83} \)

In the case of similar shape,

\( B_{0} \propto R^{-1.31} \) for constant \( \tau_{E} \)

H factor to ISS95 < 2
Minimum space for blanket;

\[ D_b = (a_c - a_p)_{\text{min}} - \frac{H}{2} - 0.1 \]

0.1 m is distance for thermal shields
(1) The normalized forces become lower with the smaller $\gamma$.

(2) The ‘force free’ is attained at $\gamma = 0.6 - 0.85$.

(3) The curves are shifted in the positive y-axis with the higher current density or the lower aspect ratio. It depends on mainly the ratio of area occupied by the coils in the torus surface.
(1) $B_{\text{max}}$ becomes higher at the lower $R_0/a_c$, owing to the increase of the current for the same $B_0$.

(2) $B_{\text{max}}$ becomes gradually higher at the smaller $\gamma$, owing to the increase of the current.

(3) The maximum transverse field $B_{\text{max}}$ in the helical coil is almost proportional to $j^2$. 

\[
y = 0.4819 + 0.4185x + 0.006685x^2
\]
Necessary Major Radius

For sufficient space for the blanket: $D_b > 1.1 \text{ m}$

1. High current density of the HC
   
   $j < 35 \text{ MA/m}^2$ due to cryogenic stability and mechanical support inside
   
   $B_{max} < 13 \text{ T}$ as a conservative value for A15 superconductors

2. Low $\gamma$; $\gamma = 1.15 - 1.25$
   
   Plasma confinement is comparable in 1.15 to 1.25. Low $\gamma$ also reduces the electromagnetic force.

3. Outward shift of plasma
   
   Unfortunately, plasma confinement is not good in LHD. It should be improved.

4. High ratio of $W/H$; $W/H = 2$ as a moderate value
   
   At higher ratio of $W/H$, $D_b$ is enlarged and $B_{max}$ is reduced. Nevertheless, it will bring problems for maintenance ports.

5. Large major radius
## Parameters of Heliotron-type Reactor

<table>
<thead>
<tr>
<th>Items</th>
<th>FFHR2m1</th>
<th>FFHR2m2</th>
<th>FFHR2</th>
<th>LHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarity / Field period</td>
<td>$l/m$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil pitch parameter</td>
<td></td>
<td></td>
<td>1.15</td>
<td>1.25</td>
</tr>
<tr>
<td>Coil major radius</td>
<td>$R_c$ m</td>
<td>14.0</td>
<td>17.3</td>
<td>10.0</td>
</tr>
<tr>
<td>Plasma major radius</td>
<td>$R_p$ m</td>
<td>14.0</td>
<td>16.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Plasma radius</td>
<td>$a_p$ m</td>
<td>1.73</td>
<td>2.80</td>
<td>1.20</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>$V_p$ m$^3$</td>
<td>831</td>
<td>2475</td>
<td>284</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$B_0$ T</td>
<td>6.18</td>
<td>4.43</td>
<td>10.0</td>
</tr>
<tr>
<td>Max. field on coils</td>
<td>T</td>
<td>13.3</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Magnetic energy</td>
<td>GJ</td>
<td>120</td>
<td>142</td>
<td>147</td>
</tr>
<tr>
<td>Coil current density</td>
<td>$j$ MA/m$^2$</td>
<td>26.6</td>
<td>32.8</td>
<td>25.0</td>
</tr>
<tr>
<td>Min. Blanket space</td>
<td>m</td>
<td>1.20</td>
<td>1.10</td>
<td>0.70</td>
</tr>
<tr>
<td>Electron density</td>
<td>$ne(0)$ $10^{19}$ m$^{-3}$</td>
<td>26.7</td>
<td>33.5</td>
<td>16.3</td>
</tr>
<tr>
<td>Temperature</td>
<td>$Ti(0)$ keV</td>
<td>15.6</td>
<td>15.6</td>
<td>18.7</td>
</tr>
<tr>
<td>H factor of ISS95</td>
<td></td>
<td>1.96</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Average beta</td>
<td>$&lt;\beta&gt;$</td>
<td>2.84</td>
<td>3.56</td>
<td>4.06</td>
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<tr>
<td>Fusion power (*1)</td>
<td>$P_F$ GW</td>
<td>1.90</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Neutron wall load</td>
<td>MW/m$^2$</td>
<td>1.50</td>
<td>2.37</td>
<td>1.31</td>
</tr>
</tbody>
</table>

(*1) A heating efficiency is 0.9, density fraction of He and O are 2% and 0.5%. Density profile and temperature profile are parabolic.
2. Layout of Magnets

One set of poloidal coils (PCs) is necessary to adjust the major radius of the plasma, the quadruple field, and the stray field.

<Conditions from Plasma>
1. $B_D = B_Z @ R_0 \ (R_p)$: fixed
2. $B_Q$ (plasma shape): fixed
3. Low stray field
4. Low field near the torus center
5. Less stored energy

<Conditions from Coil Supports>
1. Large ports are arranged at upper, lower, and outer side for maintenance of blankets.
2. Helical coil is supported from outside to enlarge the inner space.

$B_0 = 6.18 \ \text{T}, \ <a_p> = 1.73 \ \text{m}$
For $B_Z=0$ @ $R=50m$  
$R_{Ov}=18.49$ m, $Z_{Ov}=5.52$ m,  
$I_{Ov}=-24.8$ MA  
Wide outer space, but  
$W_B=152$ GJ, $B_Z(R=0)=2.4$ T
In the case of two pairs of PCs, the number of degrees of freedom is six. After minimizing the field near the center of the torus, two degrees are remained. The position of the coils can be optimized by considering the layout of the mechanical support.
Layout of Magnets of FFHR2m1

<table>
<thead>
<tr>
<th>Mode</th>
<th>BD 100%</th>
<th>BD 105%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>43.257</td>
<td>43.257</td>
</tr>
<tr>
<td>OV</td>
<td>-21.725</td>
<td>-22.518</td>
</tr>
<tr>
<td>IV</td>
<td>-22.100</td>
<td>-21.601</td>
</tr>
</tbody>
</table>

$B_0=6.18 \text{ T}$
1: HC winding \((W/H=1.8/0.9 \text{ m,} \ j=26.6 \text{ MA/m}^2)\)

2: HC support \((t=0.35\text{ m})\)

3: PC winding \((j\sim 25 \text{ MA/m}^2)\)

4: PC case \((t=0.1-0.2\text{ m})\)

5: Inner and Outer support \((t\sim 0.5 \text{ m})\)
3. Structural analysis of the magnets

Software : ANSYS
Analysis type: Static
Element type: 3-D solid, Elastic
Coupling : Periodic symmetry
Joint type : Rigid
Force : EM force on nodes

![Graph showing EM Force of HC and PC](image)

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EM Force of HC (MN/m)
Fast (minor-radius)
Fb (overturning)
FZ of OV
FR of OV
FZ of IV
FR of IV

EM Force of PC (MN/m)

Toroidal Angle, Phi (deg)

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Fa (minor-radius)
Fb (overturning)
FZ of OV
FR of OV
FZ of IV
FR of IV

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The modulus of support is partially reduced to relax the stress.

The modulus of the real winding area is not isotropic. It depends on the design of the conductors and inner supports.

→ Future work
1,000 MPa is allowable for strengthened stainless steel at low temperature.
Results of Structural Analysis (2/4)

Stress in HC winding < 600 MPa
Results of Structural Analysis (3/4)

Stress in PC winding & PC case < 600 MPa
Peak stress is induced at the joint area to HC support. It can be reduced by modification of the shape.
Summary

(1) Two sets of poloidal coils (PCs) make it possible to reduce the magnetic field near the center and stored energy.

(2) The position of PCs is not optimized yet. Slightly larger radius of OV coils will reduce the peak stress.

(3) The supporting structure with wide ports at upper, lower, and outer area was proposed. The feasibility of this concept was confirmed by structural analysis.

(4) Future works are new design of winding with high rigidity and strength, further optimization of supporting structure ($\sigma < 900$ MPa), and conceptual design of remote maintenance of blankets.