Which Superconducting Magnets for DEMO and Future Fusion Reactors?

Reinhard Heller

Inspired by Jean Luc Duchateau (CEA)
Outline

- Introduction - Status of activities on magnet for fusion reactors in Europe
- A few questions related to DEMO
- Circulating power in DEMO
- General considerations about DEMO TF magnet
  - From toroidal magnetic field $B_t$ to magnet dimensioning field $B_{t_{\text{max}}}$
  - The dominating role of structures
- A preliminary design of DEMO
- Challenges for superconducting materials in fusion
- Conclusions

General notes:

1 - Talk is based on presentation of J.L. Duchateau given at the EFDA-DEMO workshop on May 10th 2011 in Garching
2 - I concentrate mainly on TF magnets for DEMO
Introduction - Status of activities on magnet for fusion reactors in Europe

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Introduction - Status of activities on magnet for fusion reactors

- European laboratories were involved from the beginning in the development of superconducting magnets for fusion devices towards DEMO

- Next European Torus [1]
  NbTi at 1.8 K, Nb$_3$Sn at 4.2 K, react&wind or wind&react...

- ITER [2]
  Nb$_3$Sn CICC,
  TF coil with radial plates and casing,
  CS&PF with thick jackets and no casing


Introduction - Status of activities on magnet for fusion reactors

- Assessment of the use of HTS for DEMO in the frame of EFDA Task HTSMAG (Studies) and HTSPER (material database)
  - 3 options – high field, intermediate temperature and high temperature

**HTS for Fusion Magnets – Main Conceptual Options**

1) **High Field Option**
   - At present TF conductor fields < 15 T most probable
   - (higher neutron flux density problem)

2) **Intermediate Temperature Option**
   - Operating temperature at 20 - 30 K, ITER like fields.
   - HTS performance ok, increased efficiency but He still required.

3) **High Temperature Option**
   - Operating temperature at a level where no thermal shield and maybe no He is required (T > 65 K).
   - Simplification of reactor and significant increase of efficiency.
   - HTS performance to be confirmed.
   - Re-123 only option

A. Vostner, EFDA, May 2007, HTSMAG – HTSPER Meeting, Barcelona
Introduction - Status of activities on magnet for fusion reactors in Europe

A few questions related to DEMO

Circulating power in DEMO

General considerations about DEMO TF magnet
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A preliminary design of DEMO

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A few questions related to DEMO

1. Which kind of thermonuclear reactor to be envisaged: Steady state or pulsed?

2. How to select the couple \((R, B_t)\) for DEMO

3. Which superconducting conductor for DEMO? Should it be an extrapolation of the ITER solution (CICC)?

4. Which superconducting material for DEMO TF magnet system?

**Proposed approach**

The answer to these questions should not been brought independently from each other or “a priori” but consistently taking into account inter relationships.
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Circulating power in DEMO

- An important parameter is the circulating power in a fusion reactor
- Several components contribute (on different temperature levels)
  - Heating and current drive
  - Pumping in blanket
  - Superconducting magnets
  - Cryopumps

Courtesy of JLD
Circulating power in DEMO studies
$P_{eq} \sim 1.3 \text{ GW (from [3])}$

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Heating &amp; current drive</td>
<td>303</td>
<td>688</td>
<td>182</td>
<td>506</td>
<td>52</td>
</tr>
<tr>
<td>He pumping in blankets</td>
<td>282</td>
<td>641</td>
<td>256</td>
<td>395</td>
<td>40</td>
</tr>
<tr>
<td>SC magnets cryogenics</td>
<td>25</td>
<td>57</td>
<td>0</td>
<td>57</td>
<td>6</td>
</tr>
<tr>
<td>Cryopumps</td>
<td>7.5</td>
<td>17.1</td>
<td>0.0</td>
<td>17.1</td>
<td>2</td>
</tr>
</tbody>
</table>

Courtesy of JLD

Circulating power in DEMO

**Conclusion on circulating power from DEMO studies**

The circulating power of DEMO is very large

1. The magnet cryogenic power is contributing at a low level in the corresponding thermal power:

   57 MW over 970 MW (about 6%)

2. The possibilities of reducing the 970 MW have to be explored (pulsed reactor?)
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General considerations about DEMO TF magnet

- The DEMO magnet system is the cornerstone of the tokamak, the cost investment represents about 30% of the machine cost. The main orientations have to be discussed at the very early stage of the project.

- The factor of merit $\zeta = R^2 B_t^3$ is a key driver of the machine performances regarding the fusion power and the amplification factor $Q$ of energy. $R$ is the major radius of the Tokamak and $B_t$ is the magnetic field at the plasma centre.

- The selection of the couple $(R, B_t)$ has to be made in tight connection with: the questions of cost, of available technology and of accessibility to the plasma through the ports.

There is no guaranty that the highest magnetic field $B_t$ is the best solution.
General considerations about DEMO TF magnet

From toroidal magnetic field $B_t$ to magnet dimensioning field $B_{t_{\text{max}}}$

Starting from the plasma center, the project can be built up by successive layers towards the Tokamak axis.

Starting from $(R,B_t)$ and $\Delta_{\text{int}}$ it is not evident that a solution can be found.

The very large Lorentz forces are driving the solutions, imposing a very low overall current density in the TF and CS systems.
General considerations about DEMO TF magnet

About $\Delta_{\text{int}}$: the distance between plasma edge and the superconducting winding

\[ \Delta_{\text{int}} = e_{so} + e_{sh} + e_{\text{vac}} \]

- $e_{so}$: scrape off layer
- $e_{sh}$: first wall + blankets + vacuum vessel + neutron shielding
- $e_{\text{vac}}$: coil vacuum

$\Delta_{\text{int}}$ plays a major role in the amplification of magnetic field from $B_t$ to $B_{\text{max}}$
### General considerations about DEMO TF magnet

#### General considerations about DEMO TF magnet studies

**The dominating role of structures**

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Relative occupation (indicative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>79%</td>
</tr>
<tr>
<td>Helium</td>
<td>6.9 %</td>
</tr>
<tr>
<td>Total copper ((\tau' = 11) s)</td>
<td>8.8 %</td>
</tr>
<tr>
<td>Non copper</td>
<td>4.2 %</td>
</tr>
<tr>
<td>Wrappings</td>
<td>1.1 %</td>
</tr>
<tr>
<td>Total</td>
<td>100 %</td>
</tr>
</tbody>
</table>

- \(J_{TF} = 11\) A/mm\(^2\)
- \(J_{cable} = 52\) A/mm\(^2\)
- \(J_{noncopper} = 290\) A/mm\(^2\)
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## A preliminary design of DEMO

### Comment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER</th>
<th>DEMO (2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Plasma radius R(m)</td>
<td>6.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Minor plasma Radius (m)</td>
<td>2.</td>
<td>2.46</td>
</tr>
<tr>
<td>Plasma current Ip (MA)</td>
<td>15.</td>
<td>19.4</td>
</tr>
<tr>
<td>Toroidal Magnetic Field B_t(T)</td>
<td>5.3</td>
<td>5.86</td>
</tr>
<tr>
<td>Overall current density in TF inner leg J_{cond} (A/mm(^2))</td>
<td>11.</td>
<td>15.</td>
</tr>
<tr>
<td>Maximum field on TF conductor B_{max} (T)</td>
<td>11.8</td>
<td>14.4</td>
</tr>
<tr>
<td>Fusion Power P_{fus} (MW)</td>
<td>500</td>
<td>2401</td>
</tr>
<tr>
<td>Electrical Power P_{en} (MW)</td>
<td>0.</td>
<td>1000</td>
</tr>
</tbody>
</table>

Tentative set of parameters currently under investigation for DEMO

Probably too high value

\[ J_E > B_t \rightarrow F_L > A_{structure} \rightarrow J_E \]
A preliminary design of DEMO

Are CICC necessary for DEMO?
Most of existing superconducting magnets are indirectly cooled

- CICC have been selected for ITER because of pulsed operation (500 s) and because of the possible occurrence of disruption.
- DEMO conditions are different → Steady state operation, no disruption?
  → total shielding of nuclear heating is necessary
  But then fluence may be similar to ITER
- Other solutions are possible for the DEMO conductors such as conduction cooled conditions
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Indirect cooling solutions at NIFS

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$B^* =$ Magnetic field where critical current goes to zero

<table>
<thead>
<tr>
<th>Material</th>
<th>$B^*$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb$_3$Sn</td>
<td>20</td>
</tr>
<tr>
<td>Bi2223</td>
<td>15</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>10</td>
</tr>
<tr>
<td>YBCO</td>
<td>5</td>
</tr>
</tbody>
</table>

Temperature [K]

- LHe: 0
- LH$_2$: 20
- LHe: 40
- LN$_2$: 60
- LN$_2$: 80
- LN$_2$: 100

Coils for Fusion Reactors
Challenges for superconducting materials in fusion

- **T = 4.5 K: LTS (HTS) solution**
  - improve existing LTS materials like Nb$_3$Sn and/or
  - consider an appropriate winding technology.
  - Increase temperature margin (ITER: $\Delta T = 0.7$ K)

- Alternatives to CICC: Other solutions are possible for the DEMO conductors because of steady state conditions
  - Decrease of friction losses (pumping power)
  - Nb$_3$Sn with high filling factor in Rutherford type cable → higher critical properties
  - Possible use of HTS materials → high $\Delta T$ available
  - Direct cooling or conduction cooling
  - MgB$_2$ alternative solution for NbTi in PF coils if cheaper and reached mature technology

ITER: sensitivity to Lorentz cycling
Challenges for superconducting materials in fusion

- **T ~ 20 – 30 K: HTS-I option**
  - Material options
    - Bi-2212 round wire
    - REBCO tape
  - He cooling first option but cooling for example with liquid neon feasible
  - Decrease of cryogenic power but small gain in circulating power
  - Conduction cooling robust solutions possible
  - Large temperature margin in operation (compare: only 0.7 K in ITER!)

- **T > 50 K: HTS-II option - The dream of superconductivity (LN₂?)**
  - REBCO tape the only material option
  - Today possible only in self field (e.g. power cables) or for magnets in the range of ~1 T). At present not available for fusion (~13 T), a lot R&D needed
  - Gain in circulating power small compared to 20 K.
  - Simplifies design because no additional radiation shield may be necessary
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- For TF systems of future fusion reactors, the average current density is in the range of 10 A/mm² and is driven by the large amount of structures necessary to resist the Lorentz forces.
- Thereby it is possible to accept superconducting strands with low non-copper current density down to 150 A/mm², without substantially affecting the TF radial extension of the system.
- The ITER solution for the TF magnet system cannot be extrapolated straightforward because DEMO is with low AC losses (steady state?) without disruption(?)
  → other solutions have to be developed and tested
  HTS at intermediate temperatures?
- A solution with HTS materials at nitrogen temperature is very challenging
  → discriminate which solution (HTS or LTS) is the more economical