Which superconducting material for the toroidal field system of the fusion DEMO reactor?

J L DUCHATEAU, P HERTOUT
Association EURATOM-CEA F-13108 St Paul Lez Durance Cedex, France
E-mail: jean-luc.duchateau@cea.fr

Abstract. The reflexion about DEMO, a fusion demonstration reactor, has already been initiated in the framework of European tasks and the decision to build ITER at CEA Cadarache has even reinforced the interest for such studies. A key component of this fusion demonstration reactor is the superconducting magnetic system, which represents in ITER 30 % of the investment cost. Which superconducting materials are adequate for DEMO and are the emerging HTc superconducting material a necessary technology which cannot be avoided? This crucial question will be examined and discussed, taking into account key parameters of the project such as:
- the toroidal magnetic field $B_t$ which plays a determining role in the fusion power and the amplification factor, in association with the major radius $R$ of the machine which is a characteristics of the reactor size.
- the operating temperature of the magnet system which can affect the global efficiency of the reactor. As a matter of fact the electrical power associated with the cryogenic refrigeration of the magnet will be estimated and discussed. Two temperatures will be considered: 5 K and 20K.
The dimensions of the TF magnet system can be estimated, thanks to a simplified approach. These dimensions have an impact on the machine and enable to obtain a realistic integration of the superconducting magnet system with all aspects of the machine within a system approach.

1. Introduction

The decision to build ITER at Cadarache has simultaneously put on the agendas the question of the design of DEMO. DEMO is a thermonuclear demonstration reactor the construction of which is supposed to start 15-20 years hence [1]. Contrary to ITER, DEMO will be a thermonuclear reactor prototype, able to generate electricity in quasi steady state. To reach this goal, based on ITER guidelines, the major radius of DEMO and the toroidal magnetic field of DEMO will have to be larger than those of ITER. A key component of DEMO is the superconducting magnet system, which represents 30 % of ITER investment cost and will probably have the same relative importance in DEMO.

A preliminary design of DEMO is under development and a tentative set of parameters is under investigation (see table 1).

---

1 This work, supported by the European Communities under the contract of Association between EURATOM and CEA was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
Table 1. Tentative set of parameters currently under investigation for DEMO

| Parameter                                              | ITER  | DEMO  |
|--------------------------------------------------------|-------|-------|
| Major plasma radius R(m)                               | 6.2   | 7.5   |
| Minor plasma radius a (m)                              | 2.0   | 2.46  |
| Plasma current Ip (MA)                                 | 15    | 19.4  |
| Toroidal magnetic field B_t (T)                        | 5.3   | 5.86  |
| Overall current density in TF inner leg J_{cond} (A/mm^2) | 11    | 15.   |
| Maximum field on TF conductor B_{max} (T)              | 11.8  | 14.4  |
| Fusion power P_{fus} (MW)                              | 500.  | 2401. |
| Electrical Power P_{en} (MW)                           | 0.0   | ~1000.|

Due to the higher magnetic toroidal field B_t of DEMO in comparison with ITER, it is not too early to start to evaluate whether the DEMO magnet system will be a simple extrapolation of the ITER magnet system or whether it will need a complete technological revolution. The impact of the value of B_t at given plasma fusion performance factor, on the general design and cost investment of DEMO is large as already shown in a previous study [2].

2. DEMO inner radial build

A sketch of DEMO is presented in figure 1 with its main components: the blanket, the vessel-shield system and the TF system. The inner radial build of DEMO constitutes a real important technological stake. In this region the different components have to pile up such as to occupy the minimum space.

Any increase in the radial extension of this region has a direct impact on the reactor size and in particular on the major radius. This point is again highlighted in figure 2.

Δ_{int} is the distance between the internal plasma edge and the superconducting winding, including successively the plasma scrape off layer (e_{so}), the first wall and the blanket (e_{blan}), the blanket vacuum (e_{vac1}) the vacuum vessel-shield thickness (e_{sh}), the coil vacuum (e_{vac2}) and the TF backplate (e_{bp}) [2]. Previous studies have highlighted the crucial role of Δ_{int} and in particular the impact of the maximum magnetic field B_{max} on the TF conductor (see equation (1)). The coefficient k is an amplifying factor from the average field to take into account in particular the sides of the casing [2].

\[
B_{\text{max}} = \frac{k B_t}{1 - \frac{a}{R} - \frac{\Delta_{\text{int}}}{R}}
\]

With \(k\approx 1.03\)

\[
\Delta_{\text{int}} = e_{so} + e_{blan} + e_{vac1} + e_{sh} + e_{vac2} + e_{bp}
\]

(see table 2)
Figure 2. A focus on the DEMO inner radial build (in the equatorial plane) starting from the major plasma radius and showing the main DEMO components.

Table 2. Illustration on DEMO of the different components of $\Delta_{int}$

| $\Delta_{int}$ | $e_{so}$ | $e_{shin}$ | $e_{vac1}$ | $e_{sh}$ | $e_{vac2}$ | $e_{bp}$ | $e_{r}$ | $r_{e-TF}$ |
|----------------|----------|------------|------------|----------|------------|----------|--------|-----------|
| 1.902 m        | 0.13 m   | 0.802 m    | 0.1 m      | 0.65 m   | 0.1 m      | 0.12 m   | 3.138 m| 3.258 m   |

$r_{e-TF}$ TF case vault outer radius  $r_{i-TF}$ TF case vault inner radius  $r_{e-TF} = R_{a} - \Delta_{int} + e_{bp}$

$\mu_0 J_{cond} \pi (r_{e-TF}^2 - r_i^2) = 2 \pi R B$

An exact estimation of $J_{cond}$, the overall current density in the TF inner leg, is crucial to estimate the radial extension of the TF inner leg (blue part in figures 1 and 2).

3. Analysis of the TF inner leg

3.1. Non copper section

The non copper current density $J_{noncu}$ is a decreasing function of the magnetic field. The estimation presented in the following figure 3, is based on the recent developments regarding Nb$_3$Sn strands for ITER TF system [3, 4, 5]. The performance of five types of strands fitting to the ITER specifications ($J_{noncu} = 800 \text{ A/mm}^2$ @ 12 T, 4.2 K and -0.1 %) are presented in a representative condition of strain [6]. The performances are presented as a function of the magnetic field for a temperature of 5.7 K which includes a margin for stability and operation of 0.7 K and a typical strain of -0.77 %, such as presently considered for ITER.

$J_{noncu}$ for ITER is in the range of 270 A/mm$^2$, but due to the increased magnetic field in DEMO TF system, $J_{noncu}$ for DEMO is presently estimated under 150 A/mm$^2$. The magnetic field value to consider, is the effective field value [2] (around 13.5 T) lower than $B_{max}$.
Figure 3: Performance from different European Nb$_3$Sn strands as a function of magnetic field [3, 4, 5].

For the present study a value of 150 A/mm$^2$ for $J_{\text{noncu}}$ will be taken into account for the TF DEMO system based on possible improvement of Nb$_3$Sn strands.

3.2. Copper section

The copper section in the CICC plays a leading part in case of quench detection and associated fast safety discharge. The copper section can be calculated using the so-called hot spot criterion [7]. The amount of copper has to be such as to maintain the temperature at the end of the fast safety discharge less than 250 K (hot spot criterion). The time constant of the discharge $\tau$ is linked to the acceptable maximum voltage to the ground $V_{\text{maxg}}$ at the beginning of the discharge. This voltage is a function of the magnetic stored energy $W_{\text{mag}}$ of the system, of the number of groups of coils $N_c$ of the TF system and of the conductor current $I_{\text{op}}$. Each group is in series between two banks of discharge resistors. $N_c$ cannot be larger than the number of coils in the TF system. The following formula (2) can be given, if the discharge acceleration linked to the case is neglected in a first approach, $L$ being the inductance of the TF system. The real time constant taking into account the case is $\tau'$.

$$W_{\text{mag}} = 0.5 L I_{\text{op}}^2$$
$$V_{\text{maxg}} = L I_{\text{op}}/(2 N_c \tau)$$
$$\tau = W_{\text{mag}}/(L_{\text{op}} N_c V_{\text{maxg}})$$

In table 3, both situations in DEMO and in ITER are compared. The copper section is calculated such as not to exceed the allowable voltage of 4 kV and locally adiabatically the maximum temperature. Due to the larger stored energy in DEMO than in ITER, even by increasing the number of groups of coils (in comparison with ITER) and increasing slightly the voltage to the ground, $\tau$ is nearly two times the time constant of ITER which means that the copper section has to be large.

Table 3. Fast discharge parameters in ITER and DEMO

|        | ITER     | DEMO     |
|--------|----------|----------|
| $W_{\text{mag}}$ | 40 GJ    | 120 GJ   |
| $I_{\text{op}}$ | 68 kA    | 57.3 kA  |
| $N_c$  | 9        | 16       |
| $V_{\text{maxg}}$ | 3.5 kV   | 4 kV     |
| $\tau$ | 18.7 s   | 32.2 s   |
| $\tau'$ | 11 s     | 20 s     |
The different components of the DEMO TF CICC are presented in Table 4. The resulting CICC current density is lower than in the ITER CICC (42.1 vs 52.3 A/mm$^2$). Note that in Table 1, the cable current density is equal to 100 A/mm$^2$. At this stage the aim is not to deliver a very precise estimation of the TF CICC cable current density but to give useful guidelines for the calculation of the DEMO TF radial build.

### Table 4. The different components of the DEMO CICC according to cable design criteria

| Component                  | Section (mm$^2$) | Relative occupation |
|----------------------------|------------------|---------------------|
| Helium                     | 408              | 30 %                |
| Total Copper ($\tau'=20$ s) | 500              | 37 %                |
| Non copper wrapping        | 382 ($J_{noncu}=150$ A/mm$^2$) | 28 %                |
| total                      | 70               | 5 %                 |
| $J_{cable}$ (I=57.3 kA)    | 1360             | 100 %               |
| $J_{cond}$                 | 42.1 A/mm$^2$    |                     |

3.3. Influence of the cable current density on the DEMO TF radial build

Using the results of the previous section and the analytical structural analysis presented in [2] it is possible to calculate the TF inner leg radial build as a function of the cable current density. The main results of this analysis are presented in figure 4, giving the overall current density $J_{cond}$ and the current density in the winding pack $J_{JE-WP}$. Taking into account $J_{cable}$ from Table 4 it can be seen that a realistic value of $J_{cond}$ is around 10 A/mm$^2$ and not 15 A/mm$^2$ as taken in Table 1.

![Figure 4](image_url)

**Figure 4:** Influence of the cable current density on the winding pack current density and on the overall current density in the DEMO TF inner leg

4. Influence of the TF temperature for a reactor like DEMO

There is some interest to increase the operating temperature of DEMO coils to decrease the recirculating power of the reactor and improve its global efficiency. From the study reported in [8], the electrical power of the DEMO magnet cryogenic plant is in the range of 20 MW, if the magnets are operating at 5 K like for ITER. This electrical power is in any case a small part of the total estimated recirculating power, which is 558 MW. The expected benefit to increase the operating temperature of the magnets therefore cannot be very large. Moreover increasing the operating temperature will affect only a part of the electrical power of the cryogenic plant, the part regarding the magnets winding pack $P_{c1}$, namely half of 20 MW.
4.1. Which temperature for the magnet system of DEMO
From estimated losses at 5 K $P_{5K}$, it is possible to derive $P_{c1}$ using the following formula:

$$P_{c1} = P_{5K} f \frac{T_2}{(T_1 - T_2)} \quad \text{with} \quad f \sim 0.25$$

(3)

$f$ being the refrigerator efficiency, $T_2$ the magnet temperature and $T_1$ the room temperature. From formula (3), to decrease $P_{c1}$ there is little interest to increase the temperature $T_2$ above 20 K.

4.2. Potentiality of Bi2212 HTc superconducting materials
The main interest for the use of HTc materials is probably not an increase of the reactor efficiency as explained in the previous section. A solution with classical A15 materials as in ITER cannot therefore be eliminated. An increase in the temperature margin and an associated simplification of the magnet cryogenics in comparison with ITER can be however an interesting target. This simplification could bring a better reliability for the magnet system of DEMO.

The data base regarding the behaviour of Bi2212 strands around 20 K as a function of field is not very large and should deserve to be improved. The Bi2212 conductors are still in development, aiming at producing in several companies (Oxford, Nexans, Showa) (see figure 5) round strands sufficiently mechanically resisting. This kind of strands is very similar to classical multifilamentary composites and could be cabled to constitute large CICC.

Figure 5. Round Bi2212 strand developed by Nexans

From recent measurements of $J_{\text{noncu}}$ performed at CEA Saclay on Bi2212 tapes at variable temperature and from measurements at 4.2 K on round wires, it can be deduced that a realistic value for a round wire at 20 K and 13 T is around 800 A/mm$^2$. A preliminary design of a DEMO CICC made with Bi2212 round strands and operating at 20 K and 13 T leads to a value of $J_{\text{cable}}$ not very different from a Nb$_3$Sn CICC cable in the range of 54 A/mm$^2$, in spite of the higher $J_{\text{noncu}}$ because of the constraint linked to the protection of the coil (see section 3.2).

5. Conclusion
The solution for superconducting materials in the TF system of DEMO has to be selected in tight relation with the cryogenic refrigeration concept of the magnet. Whatever the solution, it is observed that the overall current density in the tentative set of parameters for DEMO is too large. The reason for this is linked to the selection of a too high value of the cable current density around 100 A/mm$^2$ while a more realistic value is around 50 A/mm$^2$ in relation with the amount of copper in the cable to protect the machine in case of a quench. To relax the overall current density it is suggested to increase the major plasma radius of the DEMO system in the range of 8.5 m while decreasing the toroidal magnetic field around 5.5 T, such as to keep constant the thermonuclear fusion power [2].
References
[1] Maisonnier D et al. 2006 Fusion Engineering and Design 81 1123
[2] Duchateau J L, Hertout P, and Johner J 2007 IEEE Trans. Appl. Supercond 17 1342
[3] EFDA Internal note 2007 Qualification of industrial suppliers of Nb₃Sn strands with increased values of Jc, N11 TD 91 FE ITA 11-02-EU
[4] Taylor D M J and Hampshire D P 2005 Supercond. Sci. Technol. 18 241
[5] Ilyin Y, Nijhuis A and Krooshoop E 2007 Supercond. Sci. Technol. 20 186
[6] Ulbricht A, Ciazynski D, Duchateau J L, Fietz W, Fillunger H, Fink S, Heller R, Maix R, Raff S, Ricci M, Salpietro E, Zahn G, Zanino R et al. 2005 Fusion Engineering and design 73 189
[7] ITER Design Description Document 2004 DDD11, Magnets, Section 1, Engineering Description, ITER project documentation, N11DDD178 04-06-04 R0.4
[8] Duchateau J L, Journeaux J Y and Millet F Nucl. Fusion 46 94