Materials issues in fusion reactors

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Abstract: The world scientific community is presently engaged in one of the toughest technological tasks of the current century, namely, exploitation of nuclear fusion in a controlled manner for the benefit of mankind. Scientific feasibility of controlled fusion of the light elements in plasma under magnetic confinement has already been proven. International efforts in a coordinated and co-operative manner are presently being made to build ITER – the International Thermonuclear Experimental Reactor – to test, in this first step, the concept of 'Tokamak' for net fusion energy production. To exploit this new developing option of making energy available through the route of fusion, India too embarked on a robust fusion programme under which we now have a working tokamak - the Aditya and a steady state tokamak (SST-1), which is on the verge of functioning. The programme envisages further development in terms of making SST-2 followed by a DEMO and finally the fusion power reactor. Further, with the participation of India in the ITER program in 2005, and recent allocation of half – a – port in ITER for placing our Lead – Lithium Ceramic Breeder (LLCB) based Test Blanket Module (TBM), meant basically for breeding tritium and extracting high grade heat, the need to understand and address issues related to materials for these complex systems has become all the more necessary. Also, it is obvious that with increasing power from the SST stages to DEMO and further to PROTOTYPE, the increasing demands on performance of materials would necessitate discovery and development of new materials.

Because of the 14.1 MeV neutrons that are generated in the D+T reaction exploited in a tokamak, the materials, especially those employed for the construction of the first wall, the diverter and the blanket segments, suffer crippling damage due to the high He/dpa ratios that result due to the high energy of the neutrons. To meet this challenge, the materials that need to be developed for the tokamaks are steels for the first wall and other structural materials, copper alloys for the heat sink, and beryllium for facing the plasma. For the TBMs, the materials that need to be developed include beryllium and/or beryllium-titanium alloys for neutron multiplication, lithium-bearing compounds for tritium generation, and the liquid metal coolants like lead-lithium eutectic in which lead acts as a neutron multiplier and lithium as a tritium breeder. The other materials that need attention of the materials scientists include superconductors made of NbTi, Nb3Sn and Nb3Al for the tokamaks, coatings or ceramic inserts to offset the effect of corrosion and the MHD in liquid metal cooled TBMs, and a host of other materials like nano-structured materials, special adhesives and numerous other alloys and compounds. Apart from this, the construction of the tokamaks would necessitate development of methodologies of joining the selected materials.
This presentation would deal with the issues related to the development, characterization and qualification of both the structural as well as the functional materials required to carry forward the challenging task of harnessing fusion energy for use of mankind in engineered systems.

1. Introduction
The requirement of energy is ever increasing and more so in developing economies like India. Out of the various options available at our disposal today, we are able to harness only a small fraction of our requirement because of the constraints on desired quality and quantity of fuel and materials. Making energy available through the route of fusion of light elements is a new developing option. Fusion of light elements like deuterium and tritium, the hydrogen isotopes, can be achieved by using ‘Tokamak’, a device based on the concept of magnetic confinement of plasma. Moreover, fusion energy is virtually inexhaustible as well as potentially safer as compared to fission energy. Recognizing these, India has launched [1] a fusion research programme by establishing the Institute of Plasma Research at Gandhinagar, Ahmedabad, a constituent unit of the Department of Atomic Energy. Under this programme, India has already a working tokamak, Aditya, a machine for ‘Plasma Physics’ research. The programme has further progressed and a steady-state Tokamak-1 (SST-1) is on the verge of functioning. The programme envisages further development in terms of making a SST-2 by 2022, followed by a DEMO by 2037, and finally a fusion power reactor by 2050. Further, in the recent past, India joined as an equal partner in the International Thermonuclear Experimental Reactor (ITER) programme at Cadrache, France, in which the commitment of the country lies in delivering a large inventory of sophisticated components. India has also succeeded [2] in obtaining half – a – port for placing our Lead – Lithium Ceramic Breeder (LLCB) based Test Blanket Module (TBM) in ITER, the primary objectives of placing this TBM in ITER being to test its capability to (i) breed tritium with Tritium Breeding Ratio (TBR) >1, and to (ii) extract the high grade heat from the tokamak with acceptable thermal efficiency.

2. Materials for Tokamak
For the construction of the ‘Tokamak’ and its ‘Blanket’, which, presently, is in the form of TBMs’, a number of materials – both structural and functional – are required to be developed. As the materials have to face the high-energy 14.1 MeV neutrons generated due to the fusion of deuterium and tritium in the Tokamak, structural materials have to have the radiation resistance apart from other properties and the functional materials the required level of integrity. Finalizing the specifications for materials, their development, characterization, production and suitable fabrication into components is a major challenge. With increasing power and expected effective life of the tokamaks from the experimental stage to the demonstration stage and then further to the prototype stage, this challenge would obviously become increasingly formidable and would call for development of superior materials and processes.

Before listing the demands that these devices - the tokamaks and their blankets - would impose on materials for their safe and reliable operation, it may be worthwhile to look at the ‘Tokamak’, the D + T reaction that is exploited in it to get the ‘net’ energy and the subject of radiation damage of materials due to the 14.1 MeV neutrons. As has already been stated,
Tokamak is a device that is based on the concept of magnetic confinement of plasma wherein the following reaction occurs

\[ \text{D+T} = ^4\text{He} (3.5 \text{ MeV}) + \text{n} (14.1 \text{ MeV}) \]

Figure 1 is an artist’s view of ITER, an example of a Tokamak. A schematic view of the materials layout around the plasma is appears in Figure 2.

![Figure 1](image1.png)

**Figure 1** An artist’s view of ITER- a ‘Tokamak’.

The plasma is confined by the torodial and polodial magnetic fields in the form of a ring in a vacuum vessel that has the shape of a toroid and the heat from the fusion in the plasma is extracted by an appropriate coolant, the He gas and/or a eutectic alloy liquid flowing in the blanket modules in the vacuum vessel close to plasma. The heat is transported to the coolant through the walls of the TBMs by both radiation from plasma and the electrically neutral 14.1 MeV neutrons that escape from the plasma into their walls and the functional materials.
Also, since the blanket consists of Li\(^6\) either in the form of a ceramic compound or liquid metal (pure lithium or lead-lithium eutectic alloy), it transmutes to tritium by \((n,\alpha)\) reaction giving rise to additional heat to the coolant. Further, when the 14.1 MeV neutron escaping from the plasma enter the walls of the TBM, complications arise \([2,3]\) both due to the radiation damage (displacements and transmutations) of lattice atoms caused by them. Because of the high cross section of these high energy neutrons to cause the \((n,\alpha)\) and the \((n,p)\) reactions with almost all elements, atoms constituting the walls of the TBMs undergo these reactions leading to the formation of both helium and hydrogen in them at high rates causing serious damage to the structural material.

![Figure 2](image)

**Figure 2** A schematic view of the arrangement of materials in a tokamak.

The material behaviour at the high He/dpa ratios (dpa, displacements per atom is the unit in which the displacement damage of the lattice is expressed) likely to be encountered by the materials of the first wall of the tokamak as well as the materials in the TBMs is yet not completely understood. The challenge to put appropriate structural and functional materials in a tokamak as well as in a blanket module in a configuration to serve the purpose desired from these devices for the intended time is, indeed a challenge for the materials scientists. When the design and construction of the TBMs for even the experimental ITER is considered, the relevance of the points put forward until now becomes further evident.

The first wall of the Tokamak is the wall that is nearest to the plasma and, therefore, experiences, the high He/dpa ratios due to the damage due to the high energy neutrons apart from the high heat flux. The diverter and the limiter also fall in the same category. If material sputters into the plasma, it may get quenched. To avoid this from happening, an element that
either does not sputter due to the neutrons (and, occasionally, electrons and other ions from the plasma) hitting it or, else, it does not quench the plasma despite the fact that it sputters is selected. High Z (atomic number) elements fall in the first category in that they sputter less and the low Z elements, even though they may sputter into the plasma, they are not strong enough to quench it. The selection of the plasma facing element is based on this. Once selected, this element has to be an integral part of the first wall. Next to it in the first wall, especially in the diverter, has to be a material that can act as a heat sink and carrier of heat away from the first wall to avoid its excessive heating. This generally is OFHC (oxygen free high conductivity copper) alloyed with a little bit of Cr (<1 wt%) to give the Cu the required tensile strength) and even a lesser content of Zr (<0.1 wt%) to impart the required fatigue strength. Alternatives available are also listed in table 1. Next to the listed plasma facing material or directly bonded to it, is the structural material, generally a steel. This is the one that actually takes the entire load. Initially, austenitic stainless steel 316 was selected for use as the first wall structural and continues to be material of construction for the first wall of ITER in the form of low activation 316 LN (IG), IG meaning the ITER grade. However, because of its tendency to swell more under irradiation as compared to the ferritic steels and unacceptable fatigue life above 600 °C, especially with He (generated due to (n,α) reactions) in it, the material of choice for the first wall now for the DEMO reactors is the low activation Ferritic/Martensitic (F/M) steel (FMS), F82H, or, its equivalents.

Table 1. Materials for the First Wall of a Tokamak

| First Wall Plasma Facing [5-8] |
|--------------------------------|
| Low Z – Be, C-C composites – high sputtering but less quenching |
| High Z – W, Mo-based alloys – low sputtering but high quenching |

| First Wall Heat Sink [9-12] |
|------------------------------|
| Cu-Cr-Zr alloy |
| Copper alloys - dispersion strengthened by alumina |

| First Wall Structural |
|-----------------------|
| Steels [13-18] |
| Low activation austenitic steels [SS 316L(N) IG] for the first wall of ITER |
| Ferritic/martensitic steels (F82H, EUROFER) for the DEMO and the TBMs |
| Nanostructured ferritic/martensitic ODS steels or nanostructured high nitrogen carbide dispersion strengthened (CDS) F/M steels for the PROTOTYPE |
| Vanadium alloys [19,20] |
| SiC-fiber/SiC composites [21,22] |
3. First Wall Materials
Low activation is achieved by selection of appropriate alloying elements and control of
impurities, both substitutional and interstitial. Typical compositions of the alloy F82H and its
equivalents given in table 2, are actually derivatives of the commercially available modified
9Cr-1Mo steel. The changes in composition to arrive at F82H or, its equivalents, have been
made to ensure the desired low activation due to irradiation as well as to increase the high
temperature capability of this steel. The limits to which the various elements in this steel need
to be controlled to achieve the low activation are given in table 3.

Table 2. Typical compositions of the various F/M steels for the first wall of the tokamak

| Steel/Composition | Cr     | W      | Mn    | V     | Si | C    | Ta   | N     | Fe   |
|-------------------|--------|--------|-------|-------|----|------|------|-------|------|
| F82H              | 7.46   | 1.96   | 0.21  | 0.15  | 0.10| 0.09 | 0.023| 0.006 | balance|
| JLF-1             | 9.0    | 2.0    | 0.45  | 0.25  | 0.2 | 0.10 | 0.07 | 0.05  | balance|
| Eurofer 97        | 8.9    | 1.1    | 0.47  | 0.2   | ----| 0.11 | 0.14 | ----  | balance|
| CLAM              | 8.98   | 1.55   | 0.40  | 0.21  | ----| 0.11 | 0.15 | ----  | balance|

Table 3. Limits on the contents of impurities and interstitials in FMS for the desired low
activation

| Element | Wt ppm desired | Wt ppm achieved |
|---------|----------------|-----------------|
| N       | <300           | 600             |
| P       | <50            | 20              |
| S       | <50            | 20              |
| B       | <10            | 2               |
| O       | <100           | 100             |
| Nb      | <0.1           | 1               |
| Mo      | <1             | 30              |
| Ni      | <10            | 200             |
| Cu      | <10            | 100             |
| Al      | <1             | 30              |
| Ti      | <200           | 100             |
| Si      | <400           | 110             |
| Co      | <10            | 500             |

However, even F82H, or its equivalents, in their wrought form are not acceptable for the
prototype reactors because of the envisaged life of 30 years for these reactors and the
unacceptably large quantities of He that would accumulate in these steels in this period. The
alternative has been found in the form of a nano-structured F82H capable of distributing the
He into small bubbles by nucleating them on the surfaces of Ti-Y-O complexes introduced in
the steel in extremely large numbers through the route of attrition of powder of the steel with
nano yttria and hot extrusion or HIPing of the milled mixture. This steel is known as the 3rd
generation oxide dispersion strengthened (ODS) F/M steel [23,24]. Research continues [25] the world over for other easy-to-produce materials that might fit the requirements of the first wall of a commercial tokamak. The list of many such materials is table 1.

A comparison of the properties of the three types of first wall structural materials is made in table 4. At the moment, there is little choice but to go for FMS steels as the industrial experience of fabrication and joining of vanadium and its alloys is not as much developed and because of inherent brittleness, the bulk SiC and SiC-SiC composites still do not qualify for use. Further, because of poor compatibility of vanadium with the Pb-Li alloy, only pure Li can be used in combination with it necessitating the need of Be or beryllide as multiplier. Russia has designed [26] its liquid TBM that has vanadium alloy as its structural material.

Table 4. Comparison between the properties of various structural materials short-listed for the FW

| Property/Material                                      | FMS       | V-4Cr-4Ti  | SiC/SiC   |
|--------------------------------------------------------|-----------|------------|-----------|
| Temperature Window, °C                                 | 300-600   | 400-700    | 700-1000  |
| Surface Heat Capability, kW/K.m                        | 4.32-2.74 | 4.61-4.63  | 1.05      |
| Thermal Expansion, 10⁻⁶/K                               | 11.1-12.3 | 10.3-11.4  | 2.5       |
| Thermal Conductivity, W/K.m                            | 33.4-32.3 | 31.3-33.8  | 12.5      |
| DBTT, °C                                               | <20       | 250-300    | Brittle   |
| RIS and He effects                                     | ✓         | ✓          | ✓         |

The critical issues related to the first wall materials include their transmutation and displacement damage due to the high-energy neutrons, manufacturing the large sized intricate shapes and their joining and codes for qualification of the materials for use in fusion environments. So far as the damage due to neutrons is concerned, all the effects that occur in the core of fast reactors occur in the fusion environment also, but more intensively. Helium produced because of the (n,α) reactions of the neutrons with the atoms constituting the first wall is an issue that is difficult to deal with. The rate of production of He in the material due to its irradiation particularly by the 14.1 MeV neutrons in a tokamak is very high (in the range of 200-600 appm/yr for steel) and, therefore, in its lifetime of 30 years, the material is likely to accumulate huge amounts of He. Since the solubility of He in any metallic matrix is known to be zero, the high temperature helium embrittlement is an issue of major concern. Furthermore, this He, under thermal fatigue likely to be experienced by the first wall of a tokamak, limits the life of the first wall austenitic steel severely. To overcome this challenge, the F/M steel has been substituted for the stainless steel 316 as this has a much better thermal conductivity. This is being further tackled by distributing He into nano-sized bubbles by developing ODS F/M steel of 3rd generation [23,24] in which yttria particles having sizes less than 3nm diameter are distributed in large numbers (10²³ particles/m³). Further, the nano-sized (18-20 nm dia) yttria gets refined to less than 3nm dia during attrition of its mixture with steel powder only in the presence of Ti and, therefore, this is to be added to the mixture before attrition. Ti-Y-O complexes form due to attrition. Interestingly, Ti is the only element that can effectively achieve this. The reason is yet to be established. Besides, the Ti-Y-O complexes act as sites for the nucleation of He bubbles [27,28].
The other issue relates to manufacturing of components, particularly joining of materials. Friction stir welding, electro-discharge welding, and diffusion bonding by HIP are the technologies that are currently being developed to advanced levels for meeting this challenge [29-34].

4. Materials for Other Components of TBM
Materials for the other components of a tokamak [35] are listed in table 5. Methods of manufacturing these materials and the components are well understood. The functional materials in the TBM are listed in table 6.

Table 5. Materials for the other components of the Tokamak

| Materials                  | Thermal Shield | Vacuum Vessel & Ports | VV Support | Blanket Support | Diverter |
|----------------------------|----------------|-----------------------|------------|-----------------|----------|
| SS 304 (plates)            |                |                       |            |                 |          |
| SS 304 L plates            | ✓              |                       |            |                 |          |
| Ti-6Al-4V (plates)         | ✓              |                       |            |                 |          |
| Steel 660 (bolts)          | ✓              | ✓                     | ✓          |                 | ✓        |
| Alloy 718 (bolts and plates)| ✓             | ✓                     | ✓          |                 |          |
| NiAl bronze (rod and plates)|              |                       | ✓          |                 | ✓        |
| Steel 430 Borated steel plates, SS 316 | |     |                      | ✓           |
| SS 316 L(N)-IG (plates & pipes) | ✓               |                       |            |                 |          |
| Cu-Ni-Be (collar)          |                |                       |            |                 | ✓        |

It is seen that the TBM has to perform two main functions [2]. It has to breed tritium (the naturally non existing fuel for the fusion reactor), with a TBR more than one and also extract the heat efficiently. Keeping these functions in view, a number of concepts have been proposed to design the TBMs, first for the ITER. Some of these are termed as solid test blanket modules and some as liquid test blanket modules, the difference being on the physical state in which the breeder material is in the TBM. If the breeder (basically, Li\textsuperscript{6}) is in the form of a solid ceramic compound, it is solid breeder TBM and, if the breeder is in liquid state (as pure Li liquid or eutectic Pb-Li alloy liquid), it is called a liquid breeder TBM. In the case of a solid TBM, the coolant, more often than not, is He. In one such concept proposed by Japan, it is water. To have enough neutrons for the breeding reaction, Be or beryllide is to be inserted in the solid TBM as a neutron multiplier. The solid TBM thus consists of the structural material (low activation F/M steel), the ceramic breeder (lithium titanate or lithium silicate), the neutron multiplier (Be or beryllide) and the coolant, He. The material of
Table 6. Functional Materials in the TBM

For neutron multiplication
- Beryllium, Be-8at%Ti (beryllide), BeO in solid form
- Liquid lead

For Tritium breeding
- Li\(^6\) enriched liquid lithium or eutectic Pb-17at%Li
- Li\(^6\) enriched ceramics like lithium titanate and lithium silicate

For Tritium extraction
- He (purge gas through the ceramic breeder)
- Liquid lead lithium eutectic

For self-healing coatings (required to reduce the MHD drag and prevent tritium permeation)
- Alumina on FMS
- AlN, CaO, Er\(_2\)O\(_3\) or Y\(_2\)O\(_3\)

The construction of TBM has been chosen to be F/M steel to gain experience with this material as this is a candidate for the first wall of a DEMO. When Pb-Li is used, Li works as the breeder and Pb as the neutron multiplier. The liquid itself sometimes is made to act as the coolant as well. As a coolant, it creates the extra issue of Magneto-Hydro-Dynamic (MHD) drag on its own flow in the TBM, which raises further requirements in terms of electrically insulating coatings on steel to reduce the drag, powerful pumps to push the liquid through the TBM and, of course, the integrity of the material under forced flow at high temperature of liquid metal. However, obviously, there is no need to insert Be or beryllide for neutron multiplication in this case. The concepts [36,37] of both the solid and liquid TBMs proposed by the various partners in ITER and that of a ‘hybrid’ concept proposed by India are listed in tables 7 and 8.

The hybrid concept proposed by India has been accepted by ITER for its implementation and is elaborately in the following paragraphs. Be it a solid, a liquid or a hybrid TBM, its design must ensure that (i) the net tritium breeding ratio >1 (to be met through neutron multiplier and enrichment of the breeder material in Li\(^6\)), (ii) efficient extraction of heat (from heterogeneous volumetric nuclear heat generated in the TBM) while maintaining the temperatures of the structural and the functionals within their allowed windows, (iii) liquid metal coolant circulates despite the MHD drag if it is the coolant, and (iv) safety of the TBM, the tokamak, the environment and people in and around the tokamak and, above all, (iv) the design of the TBM and the materials that go into it have to be compatible with the DEMO design. The design of our Lead-Lithium Ceramic Breeder (LLCB) TBM is also been done keeping these points in view. From an artist’s point of view, the location of a TBM, be it solid or liquid, in the tokamak [38] is shown in figure 3 and the schematic of Indian LLCB TBM is shown in figure 4.
Table 7. Concepts of solid TBMs proposed by various partners of ITER

| Design Parameters | China | Europe | Japan | Korea | Russia | USA | India |
|-------------------|-------|--------|-------|-------|--------|-----|-------|
| **Option**        | HCCB  | HCCB   | HCCB  | HCCB  | HCCB   | HCCB| HCCB  |
| **Breeder**       | Li$_4$SiO$_4$ (400-950 °C) | Li$_4$SiO$_4$ (450-900 °C) | Li$_2$TiO$_3$ (900 °C) | Li$_4$SiO$_4$ (400-900 °C) | Li$_4$SiO$_4$ (1000 °C) | Not decided | Li$_2$TiO$_3$ (850 °C) |
| **Neutron Multiplier** | Be (400-620 °C) | Be (450-600 °C) | Be/Be$_2$Ti (600 °C) | Be (450-600 °C) | Be (650 °C) | Be (500 °C) | Be/Be$_2$Ti (600 °C) |
| **Structure**     | Eurofer (550 °C) | Eurofer (550 °C) | F82H | Eurofer (550 °C) | F82H | FMS (550 °C) | Indian LAFMS |
| **Coolant**       | He (300-500 °C) | He (350-550 °C) | Water (150-250 bar) | He (350-500 °C) | He (300-500 °C) | He (300-500 °C) | He (300-550 °C) |
| **Purge Gas**     | He O.5 bar | He O.5 bar | He O.5 bar | He O.5 bar | He O.5 bar | He O.5 bar | He O.5 bar |

Table 8. Concepts of liquid TBMs proposed by various partners of ITER

| Design Parameters | China | Europe | Korea | Russia | USA | India |
|-------------------|-------|--------|-------|--------|-----|-------|
| **Breeder and coolant** | Pb-Li (480 - 700 °C) He cooled (DFLL) | Pb-Li (530 °C) He cooled (HCLL) | Li (550 °C) He cooled | Li (350-550 °C) He cooled | Pb-Li (500 °C) He cooled (DCLL) | Li$_2$TiO$_3$ ceramic and Pb-Li eutectic (LLCB) |
| **Neutron Multiplier** | Be (550 °C) |
| **Structure**     | CLAM (550 °C) | Eurofer (550 °C) | Eurofer (550 °C) | V alloy | FMS | Indian LAFMS |
| **Electro-insulation** | SiC/Sic, Al$_2$O$_3$ | SiC | -------- | CaO, AlN, Er$_2$O$_3$, Yttria | SiC$_2$/SiC Flow Channel Inserts | Al$_2$O$_3$ |
| **Reflector**     | Graphite | WC / TiC (650 °C) | SS 316 | SS 316 L | |

5. Materials for Magnets
Similarly, the low temperature superconductors required for the tokamak, are at an advanced stage of development. The required operating conditions are listed in table 9, the two suitable materials and their characteristics in table 10. For the Nb$_3$Sn superconductors, internal tin strand fabrication process is adopted.
Summary

The issue of materials is the second most important issue (the first being ignition of the plasma and its sustenance) to be resolved for commercial exploitation of the fusion power through tokamaks. What needs to be done, to begin with, is to develop the above listed materials with characteristics and life that are desired for their application in the environment of tokamaks. Li needs to be enriched in $\text{Li}_6$ followed by manufacture of lithium ceramic pebbles with desired characteristics both as individual pebbles and collectively. The same applies to the beryllium and beryllide pebbles required for the helium cooled solid ceramic breeder modules. The desired low activation of the F/M steel needs to be achieved by further refining the steel. The issue of coatings that would reduce the MHD drag without getting corroded or eroded by the flow of high temperature liquid coolant needs to addressed. Apart from these, the unknown domain of behaviour of all these materials and their joints in the fusion environment of 14.1 MeV neutrons needs to be explored both theoretically as well as experimentally to the extent possible by using the current level of knowledge in this area and the available sources of irradiation till the International Fusion Materials Irradiation Facility (the IFMIF) is created [42]. New Materials Test Reactors (MTRs) and innovatively designed dual beam irradiation facilities need to be developed. The task to develop and qualify materials for this high-tech application is indeed mammoth but, as has often happened in the past, the collective will of people to master fusion will eventually succeed.
LLCB Parameters
- Ceramic Breeder: Lithium Titanate
- Coolant, Multiplier: Pb-Li
- FW coolant: Helium, 80 bar, 300-525 C
- Pb-Li Mass flow: 42 Kg/s
- Velocity (ref): 0.2 m/sec

Figure 4 The Indian Lead-Lithium Ceramic Breeder (LLCB)TBM and its schematic
Table 9. Operating conditions of the superconducting magnets for experimental tokamaks

- High field variations (dB/dt ~ 2T/s)
- Very high structural & operational loads (~1000 MPa)
- High vacuum (10^-6 mbar)
- High inductive loads (~ 100 H or more)
- High fields (12-14 T: central solenoid & TF, 6-8 T: PF)
- Very high stored energy (> 100 GJ)

Table 10. Characteristics of Superconducting Magnets

| NbTi                        | Nb₃Sn                                      |
|-----------------------------|--------------------------------------------|
| Solid solution              | Intermetallic compound                     |
| Tc of 9.8 K                 | Tc of 18 K                                 |
| Hc2 of 11 Tesla at 4.2 K    | Hc2 of 22.5 Tesla at 4.2 K                 |
| The alloy is produced by    | The alloy is produced by                   |
| multiple EB melting-        | multiple EB melting-                       |
| fabrication through         | fabrication through                        |
| a thermo-mechanical route   | a thermo-mechanical route                  |

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