ITER Superconducting Magnets

Carlo Sborchia

Magnet Project Team
ITER Department, Fusion for Energy Agency
Barcelona, Spain

Lecture on Fusion Reactor Engineering, Politecnico of Turin (I)
31 January 2011
Table of Content

Introduction
- Basic superconductivity concepts
- Why superconductivity for fusion?

1. Superconductor Applications for Fusion
- Superconductivity for fusion magnets
- Main types of superconductor materials

2. Magnetic Confinement Concepts
- Tokamaks: KSTAR, EAST, JT-60SA
- Stellarators: W7-X, LHD

3. ITER Magnet Design
- The ITER coils

4. ITER Magnet Procurement Sharing

5. Main Design Issues for ITER Magnets
- Large fields and mechanical forces
- Insulation design and high voltage

6. Superconductor Design
- Conductor concept
- ITER CICC conductor

7. ITER Magnet R&D
- Model coil programmes

8. Manufacturing of ITER conductors
- Internal tin and Bronze route
- Cabling & jacketing

9. Manufacturing of ITER magnets
- Large winding and impregnation
- Large structures and tight tolerances

10. Beyond ITER

11. Summary
1) Basic superconductivity concept
- Certain metals become **perfect conductors** of electricity when cooled down to cryogenic temperatures in the range of 4-80 K.
- The superconducting state appears quite abruptly below a critical temperature $T_c$ typical for each material.
- Not only the electrical resistance of the base material is very small, but below $T_c$ is absolutely zero.
- But each material has different current-carrying capability ($J_c =$ critical current density in A/mm$^2$) vs. applied magnetic field, stress and strain, etc.
- Adequate “**temperature margin**” shall be taken in the conductor design to control an abrupt phenomena called “**quench**”, where the superconductor state suddenly changes back into resistive, with a fast large release of energy and heating of the coolant and conductor (protection system required).

2) Why superconductivity for fusion magnets?
- It allows steady state and pulsed operation at high magnetic fields with very low consumption of energy (except for refrigeration costs).
- Main developments for use of superconducting devices for accelerators (HEP) and MRI/NMR medical magnets started in the 1970s.
Low Temperature Superconductors (LTS) - Main applications: fusion, high energy physics, MRI/NMR magnets (~70% of production), etc.
- NbTi, operation up to 6-7 T, no need for heat treatment
- Nb$_3$Sn, operation up to 14 T, heat treatment at 650 °C for 100-200 h required to become superconductor (before or after winding)
- Nb$_3$Al, operation up to 14 T, no need for heat treatment, base material & manufacturing process very expensive due to special technology

→ Nb3Sn wires: four competing technologies
- Bronze route
- Internal tin diffusion
- Powder in tube
- Sn-Ta route
* Even 50 years after the discovery of Nb3Sn, there is still potential to improve Jc

High Temperature Superconductors (HTS) - Main applications: small research or MRI magnets, high energy cables, switches, transformers, current leads, etc.
- Bi-2212: round wire (RW), operation up to 10-15 T at 20 K operating temperature
- YBCO: coated conductor, operation up to 16 T at 77 K operating temperature
- MgB2: operation still limited to a few T, 20-30 K operating temperature
- RE Iron Arsenides: fairly new material
The Discovery of Superconductivity 1911

The Nobel Prize in Physics 1913

"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium-

Heike Kamerlingh Onnes
the Netherlands
Leiden University
Leiden, the Netherlands
b. 1853
d. 1926

http://www.nobel.se/physics/laureates
Section 1.

Superconductor Applications for Fusion
The development of superconducting magnets for fusion has been started in the 1970s (i.e. T-7 and T-15 at Kurchatov Institute with forced flow and flat cables embedded in Cu)

In the quest to achieve higher magnetic fields and longer pulses

- Tore Supra and other superconducting devices with NbTi conductors have started operation in 1980s-1990s.
- Advanced multi-strand Nb$_3$Sn have been used to increase the operating magnetic fields.
- Cable-in-conduit conductors have been developed due to the large volume, energy and required stability for these magnets.
- The development of magnets for steady-state fusion devices has included, in between others, the 6 LCT coils in the 1980s, the POLO (EU) and DPC (JA-US) coils, and the ITER Model Coils in the 1990s.

**Jc Improvement**

![Graph showing magnetic properties of different superconductors](image)

- **YBCO B|| Tape Plane**
- **YBCO B⊥ Tape Plane**
- **Nb-Ti**
- **MgB\(_2\)**
- **RRP Nb\(_3\)Sn**
- **Bronze Nb\(_3\)Sn**

**Applied Field (T)**

- Maximal \(J_c\) for entire LHC Nb-Ti strand production (CERN T. Boutboul '07)
- 18+1 MgB\(_2\)/Nb/Cu/Monel Courtesy M. Tomsic, 2007
- SuperPower tape used in record breaking NHMFL insert coil 2007
- 427 filament strand with Ag alloy outer sheath tested at NHMFL

**Supernovae**

- **YBCO Insert Tape (B|| Tape Plane)**
- **YBCO Insert Tape (B⊥ Tape Plane)**
- **MgB\(_2\) 19Fil 24% Fill (HyperTech)**
- **2212 OI-ST 28% Ceramic Filaments**
- **4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT16-IEEE'04)**
- **Nb\(_3\)Sn RRP Internal Sn (OI-ST)**
- **Nb\(_3\)Sn High Sn Bronze Cu:Non-Cu 0.3**

**References**

- Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
- Complied from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
- 4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT16-IEEE'04)
- SuperPower tape used in record breaking NHMFL insert coil 2007
- 427 filament strand with Ag alloy outer sheath tested at NHMFL
**Nb$_3$Sn Conductors: $J_c$ Strain Sensitivity**

- **T = 4.2 K**
- $\mu_0H = 12$ T

---

**Intrinsic Strain (%)**

- **High J, Strand**
- **Advanced Strand**
- **Model Coil Strand**

---

**$I_c$ (A)**

- **OST 8056 (~1800 A/mm$^2$)**
- **OST I (1200 A/mm$^2$)**
- **OKSC (1100 A/mm$^2$)**
- **EM-LMI (740 A/mm$^2$)**
- **VAC (600 A/mm$^2$)**

---

*Courtesy of Durham Univ.*

Section 2.

Magnetic Confinement Concepts
Tokamak (ITER)

Transformer principle
Plasma current is induced
Discharges are pulsed

non-inductive current drive

Stellarator (W7-X) 3D

JET tokamak (resistive)

Steady-state configuration
No plasma current
Major Superconducting Tokamaks in the Worldwide Programme

- **Tore Supra**
  - (TF coils only)

- **SST-1**
  - (NbTi coils)

- **KSTAR**
  - (Nb$_3$Sn/NbTi coils)

- **EAST**
  - (NbTi coils)
Bilateral EU_JA Collaboration (Broader Approach)
ITER Satellite Tokamak, Naka (J)

JT-60SA Magnet System

<table>
<thead>
<tr>
<th></th>
<th>TF</th>
<th>CS</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>strand conductor</td>
<td>NbTi</td>
<td>Nb₃Sn</td>
<td>NbTi</td>
</tr>
<tr>
<td>cable-in-conduit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_{\text{max}}$ (T)</td>
<td>5.7</td>
<td>8.9</td>
<td>6.2</td>
</tr>
<tr>
<td>$T_{\text{op}}$ (K)</td>
<td>4.9</td>
<td>5.1</td>
<td>5.0</td>
</tr>
<tr>
<td>$I_{\text{op}}$ (kA)</td>
<td>25.7</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
Planar coils
Nom. current 16kA@4K@6T

Non-Planar Coils
Nom. current 18.2kA@4K@6.7T

Magnetic field on plasma axis 2.5 T (<3T)
Magnetic field at coils 6.7 T
Magnetic energy 920 MJ
NbTi superconductor >3.4 K
Strand quantity 34 tonnes
50 non-planar coils
5 types
20 planar coils
2 types

Under Assembly at IPP Greifswald (D), Operation in 2014

Courtesy of IPP

Major Stellarators in the Worldwide Programme

(Large helical coil in NbTi)

- LHD
- NCSX
- HSX
- QPS
- CHS-qa
Section 3.

ITER Magnet Design
ITER Magnet Design Features

- **TF & CS Coils** use Nb$_3$Sn “cable-in-conduit” superconductor due to large operating field (TF 11.8 T, CS 13.0 T)
- **TF Coils** wound in double pancakes, thin wall circular conductors embedded in radial plates
- **CS Coils** wound in hexa- or quadru-pancakes with thick wall square conductors
- **PF Coils** are manufactured in NbTi, since operating field is <6.5 T, wound in double pancakes with square conductors
- **Stainless Steel Jackets** are used in the superconducting coils and they are designed to operate at high operating fields and for a large number of cycles (60,000)
- **Stainless Steel TF Coil Cases** with their intercoil structures form the main support structure of the magnet system
- **Composite Pre-compression Rings** at the inner leg of the TF coils to reduce tensile stresses and fatigue in the structures
- **High Strength Insulated Shear Keys and Bolts** for the mechanical connection at the inner and outer intercoil structures
48 Superconducting Coils:
- 18 TF coils
- 6 CS modules
- 6 PF coils
- 9 pairs of CC
- Feeders

<table>
<thead>
<tr>
<th>System</th>
<th>Energy GJ</th>
<th>Peak Field T</th>
<th>Total MAT</th>
<th>Cond length km</th>
<th>Total weight t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal Field TF</td>
<td>41</td>
<td>11.8</td>
<td>164</td>
<td>82.2</td>
<td>6540</td>
</tr>
<tr>
<td>Central Solenoid</td>
<td>6.4</td>
<td>13.0</td>
<td>147</td>
<td>35.6</td>
<td>974</td>
</tr>
<tr>
<td>Poloidal Field PF</td>
<td>4</td>
<td>6.0</td>
<td>58.2</td>
<td>61.4</td>
<td>2163</td>
</tr>
<tr>
<td>Correction Coils CC</td>
<td>-</td>
<td>4.2</td>
<td>3.6</td>
<td>8.2</td>
<td>85</td>
</tr>
</tbody>
</table>

(i.e. 41 GJ vs. 10.5 GJ magnetic energy in the 27 km tunnel of the Large Hadron Collider at CERN)
### Toroidal Field Coils

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of coils</td>
<td>18</td>
</tr>
<tr>
<td>Total stored energy (GJ)</td>
<td>~41</td>
</tr>
<tr>
<td>Max. conductor field (T)</td>
<td>11.8</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>Operating current (kA)</td>
<td>68</td>
</tr>
<tr>
<td>Operating temperature (K)</td>
<td>5</td>
</tr>
<tr>
<td>Number of turns</td>
<td>134</td>
</tr>
<tr>
<td>Height (m)</td>
<td>12.6</td>
</tr>
<tr>
<td>Weight (t)</td>
<td>~310</td>
</tr>
<tr>
<td>Centering force per coil (MN)</td>
<td>~400</td>
</tr>
<tr>
<td>Discharge time constant (s)</td>
<td>11</td>
</tr>
<tr>
<td>Max. voltage (kV)</td>
<td>7</td>
</tr>
</tbody>
</table>

**Design confirmation by Model Coil project launched in 1996**

Construction of TF Winding Pack

DP insulation

Conductor

Holes for VPI

Cover Plate

Radial Plate
Central Solenoid Coils

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of modules</td>
<td>6</td>
</tr>
<tr>
<td>Total stored energy (GJ)</td>
<td>~6.4</td>
</tr>
<tr>
<td>Max. conductor field (T)</td>
<td>13</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>Operating current (kA)</td>
<td>45</td>
</tr>
<tr>
<td>Operating temperature (K)</td>
<td>5</td>
</tr>
<tr>
<td>Turns per module</td>
<td>535</td>
</tr>
<tr>
<td>Total weight of all modules (t)</td>
<td>~980</td>
</tr>
<tr>
<td>Max. voltage to ground (kV)</td>
<td>20</td>
</tr>
</tbody>
</table>

CS stack composed of 6 independently powered modules wound in hexa-pancakes

Detailed design phase in progress

*Design validation through CS Model Coil tested in 2000, but new CS Insert required to confirm conductor performances under tensile hoop load conditions*
6 PF coils independently powered, wound in double pancakes

- Confine and shape the plasma
- PF1 & PF6 control plasma vertical displacement
- Conductor field limited to 6.5 T → NbTi, three grades of conductors depending on max. field
- Coils are large (24 m diameter) but use of NbTi simplifies construction

Design validation through PF Insert Coil tested in 2008
Section 4.

ITER Magnet Procurement Sharing
### Magnet Procurement Sharing

<table>
<thead>
<tr>
<th>Component</th>
<th>IO</th>
<th>CN</th>
<th>EU</th>
<th>KO</th>
<th>JA</th>
<th>RF</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF Conductors</td>
<td>7%</td>
<td>20%</td>
<td>20%</td>
<td>25%</td>
<td>20%</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>TF Windings + Insertion</td>
<td></td>
<td>10 coils</td>
<td></td>
<td>9 coils</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TF Case Sections</td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-compression Rings</td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TF Gravity Supports</td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS Conductors</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS Coils + Structure</td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF Conductors</td>
<td>65%</td>
<td>21%</td>
<td></td>
<td>14%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF Coils</td>
<td></td>
<td>5 coils</td>
<td></td>
<td>1 (PF1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF Supports</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC Conductors</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC + Supports</td>
<td>18 coils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet Feeders</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instrumentation</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

19 Procurement Arrangements between ITER Organization (IO) and Domestic Agencies signed up to now, last one to be signed in Feb. 2011
TF Coil Sharing
(A Project Management Challenge...)

TF Coil
Japan
Europe

TF coil cases
Japan

Conductor
China
South Korea
Japan
Russia
United States
Europe

Another Big Challenge: the ITER Schedule

- 2 years qualification programme with the manufacture of mock-ups and dummy windings
- Delivery of the first conductors in 2010
- Start of installation of the first PF and TF coils in 2015
- Completion of the deliveries with the last PF coil and CS coils in 2017

=> A true managerial and technological challenge ...
Section 5.

Main Design Issues for Fusion Magnets
Main Design Issues for Fusion Magnets

- **Very high magnetic fields** (up to 13 T) with large operating currents (40-70 kA) → impact on superconductor design and amount

- **Large forces:**
  → Robust structural components
  → **Large steel fabrication** (welding, forging, etc.) with **tight tolerances**

- **Large nuclear heating** on conductor → impact on cooling requirements

- **Neutron irradiation** → impact on insulation selection

- **Large stored energy** → impact on conductor and design voltages

- **High electric voltage** (in vacuum) → impact on insulation selection and quality control procedures
Very large electromagnetic forces on all magnets, i.e. for TF coils:

- **In-plane forces:**
  - 403 MN centripetal force
  - Wedged inner legs, outward forces in the outboard leg which induce an outward movement

- **Out-of-plane forces:**
  - Overturning moments

- TF radial expansion is mainly determined by the structure
- Mostly steel cross section
- Critical current density of superconductor at operating conditions has minor impact on the structure size
• In a toroidal system the field varies inversely to $R \rightarrow$ large bending stresses

• Since the field is equal to $B(R) = \frac{B_0 R_0}{R}$, where $R$ is the distance from the center of the torus, a way to maintain a constant tension along the coil is to shape it with the local radius of curvature $\rho$ inversely proportional to $B$

• This reduces the bending effect to zero, plus allows to develop the tokamak TF coils into a D-shape and give more space to elongated plasmas

• Pure tension can be achieved on filaments, but on real coils with a finite thickness the approximation has to be refined to minimize the bending stresses

$\rho = \left\{ 1 + \left( \frac{dR}{dz} \right)^2 \right\}^{3/2} \frac{d^2 R}{dz^2} = \frac{TR}{B_0 R_0 I} = KR$

*Inner Legs can be Wedged or Bucked against Central Coil to react net centripetal loads developed in the toroid*
Radial Lorentz Force is reacted by wedging. \( F_{\text{tor}} = 52.322 \times \frac{18}{2\pi} = 149.89 \text{ MN/m} \)

Lorentz Force in toroidal direction is 5.72 MN/m.

Lorentz Force in radial direction is 52.32 MN/m.

Radial Lorentz Force is reacted by wedging. \( F_{\text{tor}} \times \cos(10) = 147.62 \text{ MN/m} \)

\( F_{\text{tor}} \times \sin(10) = 26.03 \text{ MN/m} \)

Reaction loads:
- 92.65 MN/m
- 49.79 MN/m
- 10.90 MN/m

Courtesy of ITER

Out-of-plane displacements along the perimeter of the coil casing for all load cases of the Reference Scenario

Points along perimeter of coil

Courtesty of ITER

The cyclic principal stress range is required for the crack growth analysis (LEFM) and for the assessment according SN data. Due to the cyclic loading the direction of the principal stresses is not constant. Therefore two procedures are used to calculate the cyclic stresses, i.e. constant direction and rotating direction. The difference becomes significant when shear is involved.

Courtesy of ITER

Electrical Insulation

• Four simultaneous constrains:
  – High radiation
  – Large stress on insulation
  – Presence of high voltages (tens of KVs)
  – Magnets are operated in vacuum

• Preferred design solution:
  – Glass-polyimide tapes
  – Vacuum pressure impregnation with resin
The impact of high voltage... selection of insulation type

Voltage during TF coil operation

<table>
<thead>
<tr>
<th></th>
<th>Normal Operation (fast discharge) $V_n$ (kV)</th>
<th>Fault scenario $V_f$ (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn to RP</td>
<td>0.6 (1.2 for a few ms)</td>
<td>1.2</td>
</tr>
<tr>
<td>DP to DP</td>
<td>1.2 (2.4 for a few ms)</td>
<td>2.4</td>
</tr>
<tr>
<td>WP to ground</td>
<td>3.5 (7 for a few ms)</td>
<td>18</td>
</tr>
<tr>
<td>Co-wound QD tape to conductor</td>
<td>0.01</td>
<td>0.1</td>
</tr>
</tbody>
</table>

...has driven decision to use polyimide barrier ....

For Nb$_3$Sn coils (TF and CS) the insulation must be applied after the heat treatment.

Joints and hydraulic connections region in the ITER TF coil

- Electric joints
- HV breakers
- Helium inlets/outlets: high voltage
- High voltage and sensors wiring

Very stuffed region, insulation must be applied by hand, typically resin wet glass/polyimide & pre-made G10 sleeves… high risk area… intermediate Paschen tests (or equivalent) needed to check quality of insulation between assembly steps
Section 6.

Superconductor Design
Conductor Concept

Requirements

- High amperage conductor (large ampere turns and acceptable voltages)
- Large heat removal capability (nuclear heat, AC loss, ...)
- High stability (local disturbances and peak loads)
- High mechanical strength (hoop and out-of-plane forces)
- Quench protection (hot spot limitation)

Solution

- Large number of parallel superconducting strands to enable high currents
- Cabling with ~1/3 void between strands for coolant (supercritical He)
- Outer jacket of high strength material to withstand large cyclic loads
- Flexible design: variable currents by scaling the amount of strands

→ Cable-in-Conduit Conductor (CICC)
CICC is the most used option in fusion magnets.

A Chart of most CICC’s for Fusion

- Insulated strands
- Superalloy jacket
- Subcable wraps
- Co-extruded Al jacket
- No strand coating

Example diagrams:
- LCT-WH (1981)
- Polo (1987)
- DPC-EX (1988)
- DPC-TJ (1988)
- LHD-OV (1994)
- DPC-U (1988)
- EAST (2001)
- KSTAR (2002)
- ITER CSMC (1996)
- ITER TFMC (1997)
- W7-X (2002)
- SST-1 (2002)
All four magnet systems (TF, CS, PF and CC) are using the same concept:
- Strand type (NbTi or Nb$_3$Sn) defined by max. field
- Number of strands defined by nominal current
- Outer conduit material and shape (steel, round) defined by magnet design
- Production started in 2008 by six ITER Members (strand, cabling & jacketing)
Typical Strand Design (Bronze Route)

- 0.81 mm quaternary strand
- 8035 NbTa filaments
- CuSnTi bronze (~15wt% Sn)
- $J_c \sim 790 \text{ A/mm}^2$
- Non-Cu losses 200 kJ/m$^3$
- Unit length > 20 km

[A. Szulczyk, EAS 2005]
Section 7.

R&D Carried out to Support the Design and Manufacture of the ITER Magnets
TF Model Coil

TFMC inserted into TOSKA facility (FzK) for Phase II testing
### TFMC Results

<table>
<thead>
<tr>
<th></th>
<th>ITER TF</th>
<th>TFMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak field (T)</td>
<td>11.8</td>
<td>9.9</td>
</tr>
<tr>
<td>Conductor current (kA)</td>
<td>68</td>
<td>80</td>
</tr>
<tr>
<td>Number of turns</td>
<td>134</td>
<td>98</td>
</tr>
<tr>
<td>No. of double pancakes</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Stored magnetic energy (MJ)</td>
<td>41,000</td>
<td>337</td>
</tr>
<tr>
<td>Coil height (m)</td>
<td>12.6</td>
<td>4.6</td>
</tr>
<tr>
<td>Total coil weight</td>
<td>310</td>
<td>40</td>
</tr>
</tbody>
</table>

- **TFMC exceeded design values**
- **No degradation with cycling**
- **Conductor performance in coil lower than expected from short sample tests**

→ **conductor upgraded to recover margin**

[A. Ulbricht et al., Fus. Eng. Des. 73, 189-327 (2005)]
**Coil Design Parameters**

<table>
<thead>
<tr>
<th></th>
<th>CSI</th>
<th>CSMC IM</th>
<th>CSMC OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Field</td>
<td>13 T</td>
<td>13 T</td>
<td>7.3 T</td>
</tr>
<tr>
<td>Operating Current</td>
<td>40 kA</td>
<td>46 kA</td>
<td>46 kA</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>1.57 m</td>
<td>2.71 m</td>
<td>3.62 m</td>
</tr>
<tr>
<td>Height</td>
<td>2.80 m</td>
<td>2.80 m</td>
<td>2.80 m</td>
</tr>
<tr>
<td>Weight</td>
<td>7.7 t</td>
<td>49.3 t</td>
<td>52 t</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>11 MJ</td>
<td>640 MJ</td>
<td></td>
</tr>
</tbody>
</table>

Coil installed and tested in Naka, Japan

CSMC Results

CSMC successfully achieved design values

- Small degradation (0.1 to 0.2 K) saturated after few cycles

- Differences to present design
  - Pancake winding (not layer winding)
  - Jacket material: high Mn steel or SS (not Incoloy)

[Tsuji et al., ]
PF Insert Coil

Test carried out in June-Aug. 2008

Coil Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Field</td>
<td>6.3 T</td>
</tr>
<tr>
<td>Maximum Operating Current</td>
<td>50 kA</td>
</tr>
<tr>
<td>Maximum Field Change</td>
<td>2 T/s</td>
</tr>
<tr>
<td>Conductor length</td>
<td>49.50 m</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>1.57 m</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>1.39 m</td>
</tr>
<tr>
<td>Height</td>
<td>1.40 m</td>
</tr>
<tr>
<td>Height</td>
<td>1.40 m</td>
</tr>
<tr>
<td>Weight</td>
<td>6 t</td>
</tr>
</tbody>
</table>


PF Insert Coil Result

Excellent DC performance according to strand

Application of HTS current leads saves ~ 25% of the total cryogenic power needed (18 kW at 4.5 K)

- Large R&D program initiated in EU to develop a 70 kA HTS current lead
- Program successfully completed in 2005 by test of a 1:1 prototype in the TOSKA facility (Karlsruhe)

Section 8.

Manufacturing of ITER Conductors
Internal Tin Strand

- Most commonly employed technique with largest potential
- No limitation of Sn content (additional tin rods)
- Strands properties achieved by several suppliers:
  - $J_c$: 1000 – 1200 A/mm\(^2\) (4.2 K, 12 T)
  - non-Cu losses: 400 – 1000 kJ/m\(^3\)
  - unit lengths (0.81 mm): 3.5 – 13 km
- Ta and/or Ti added to improve $J_c$ field and strain dependence
- After Sn insertion, extrusion is not possible, only cold drawing
- Final billet sizes:
  - 40 kg standard (20 kg for TFMC)
  - 100 kg billet successfully drawn to final diameter

→ In the past, production of Nb\(_3\)Sn has been limited to a few tons/year worldwide, ITER has required a scale-up to industrial scale production of ~100 tons/year
1.) Deep hole drilling for Nb rods
2.) Insertion of Nb rods into holes
3.) HIPing
4.) Extrusion (80 mm)
5.) Straightening
6.) Deep hole drilling for Sn rod
7.) Insertion of Sn rod into central hole
8.) Draw subelement rod shapes
9.) Form barrier (Ta) into tube
10.) Assembly of restack, barrier, stabilizer
11.) Drawing and twisting (no extrusion!)

**Diffusion barrier (non Cu inside)**

**Sn cores**

**High RRR Cu**

**Nb filaments**
Bronze Route Manufacture

Complex and laborious manufacture ...

Step 1a
Subelement assembly
(Nb rods (~50) + bronze matrix)

Step 1b
Stabilizer assembly
(Cu rod + barrier + Cu tube)

Step 2a
HIPing, extrusion and drawing

Step 2b
HIPing and extrusion

Step 3a
Hexagonal shaping
(~10 mm)

Step 3b
Deep hole drilling

Step 4
Final billet assembly
(OD ~200 mm)

Step 5
Extrusion and drawing

Strand Production: Status 2010

- More than **1,600 billets** (100 tons, all TF) produced by the end of 2010
  - about 50 t produced in 2 years, step up of one order of magnitude from previous \( \text{Nb}_3\text{Sn} \) worldwide production rate
- Most material from JA, followed by KO, RF, EU and US:
Conductor Manufacture

1st Stage
- Strand
- Cu Wire

2nd Stage
- Cu Core Cable
- Cu Sub-Cable

3rd Stage
- Sub-Wrap

4th Stage
- Conductor

Central Spiral

Wrap

Cable

Jacket Assy

Conductor

Jacket
Cabling & Jacketing

- Final cable covered by steel wrap
- After final wrap, cable ready for insertion and compaction into jacket

Final stage (5th) cabling around central spiral

Welding and inspection of circular and square extruded tubes

Thousands of tubes to be produced and welds to be made and inspected to find/repair defects...

TF and CS Jacketing in JA

First full length dummy conductor completed in 2010 by JA
TF Jacketing in RF
EU and US jacketing facilities being prepared, KO to get support from another Party
Section 9. Manufacturing of ITER Magnets
• The TF coils are made using W,R&T technique. The complex manufacturing technique, together with the large dimensions, make the **TF coil a huge technological challenge**.

  ➔ **Major issue is the permanent deformation of the superconductor winding during heat treatment which makes difficult transfer into radial plates**

  **Note:** up to 10 conductor supplies with different behaviour.

• EU has chosen a multiple split procurement between radial plates, coil windings and insertion in the cases ➔ **Contract for winding manufacture awarded to Iberdrola/ASG/Elytt.**

• JA to use one prime contractor, Toshiba, at least for the first two years of preparation phase, with the manufacture of prototypes of coil winding, radial plates and cases

---

1-3 scale winding table for TF coil prototype (JA)
WP1: Radial Plates

WP2: Winding Pack

WP3: Coil insertion

Winding Pack’s main components

- High accuracy required to reduce error fields
- Reduce machining of huge components
- Fitting gaps carry stress penalty

Coil Case from JA DA

Conductor from IO

Conductor

Radial Plate
Two options for machining of the radial plates

- Machining Method (M)
  - Use of conventional machine.
  - Use of welding technique to minimize deformation after welding between segments
  - Use of manufacturing technique to minimize deformation and machining time

- Laser Welded Method (LW)
  - LBW

Radial Plate
Cover Plate
Holes for VPI
Conductor
Holes for VPI
DP insulation

Manufacture of Radial Plate Prototypes (EU)

Forging of radial plate segment (CNIM)

Machined side radial plate segment (CNIM)

Radial plate segment produced by powder HIPping (SIMIC)

Assembly of radial plate with MAG welding (in progress at SIMIC)

Local vacuum Electro Beam welding machine (CNIM)
The experience on heat treatment gained on TFMC is quite relevant to the full size TF coils.
A big challenge: the conductor change in length during HT

In the TFMC the measured change in length was +0.05%

Extrapolating to the full size TF coils = Elongation of 7 mm!
On paper we have a solution for the transfer process...

- Radial plate (under the support)
- Open TF coil double pancake
- Umbrella structure
- Heat treatment support
- Support platform

...this is relatively straightforward operation...

- Main challenge is to impregnate the turns inside the radial plates after laser welding of the covers

A section of the TFMC Dummy DP

- The resin penetrates through holes in the covers. The distance between holes is determined with preliminary R&D

A fully impregnated TFMC DP
Electrical Joints

Very critical manufacture, joint resistance may have a severe impact on cooling requirements.
- High accuracy required to reduce error fields
- Reduce machining of huge components
- Fitting gaps carry stress penalty
Prototype of side plate for TF coil case under forging process (above) and finished shape (below)
PF Coil Fabrication

Proposed winding scheme by EU DA: call-for-tender for manufacture of PF2-PF5 is in progress, supply contract to be placed in early 2011

Winding tooling prepared by RF DA for PF1 double pancakes: insulating and impregnation equipment & devices have been designed and procurement is in progress

The DPs stacking

Aligning columns
PF Coil On-site Manufacturing Building

(Full occupation of building not realistic)
Extensive quality control and quality assurance are foreseen throughout the manufacture of conductors and coils.

Extensive databases for strand and cable properties, winding geometry and all quality control test protocols.

Staged procurement and production-proof samples of the manufactured conductors are required.

A series of leak tests on conductors and coils during different stages of jacketing and winding.

High voltage tests throughout the coil manufacture, also in Paschen-minimum conditions.

Tight control of non-conformities.

Cold testing of all magnets is proposed down to 77 K to check leak and high voltage integrity and measure joint resistance with moderate current (TF windings before insertion and finished CS/PF coils).
Section 10.

Beyond ITER
Long Term Fusion Magnet R&D

ITER ➔ Demo / Proto ➔ Commercial Fusion Power Plant

≈ 2018 ➔ ≈ 2030 ➔ ≈ 2045

Need for Efficiency
**Scope of DEMO & DEMO Studies**

**Requirements for DEMO**
- core dimension, comparable to ITER
- steady state (year-long)
- certain level of economic viability

**Two conceptual DEMO designs proposed by JAEA and CRIEPI**

**SlimCS**

- compact low-A DEMO with reduced-size central solenoid
- potentially economic & low-A merit in design margins

**JAEA**

- \( R_p = 5.6 \text{ m} \)
- \( a = 2.1 \text{ m} \)
- \( P_{fus} = 2.95 \text{ GW} \)

**Demo-CREST**

- in-life upgrade strategy to bridge the gap between ITER and economic CREST

**CRIEPI**

- \( R_p = 7.25 \text{ m} \)
- \( a = 2.1 \text{ m} \)
- \( P_{fus} = 2.97 \text{ GW} \)

*Source: AEC report, 2005*
Three possible operating scenarios for fusion reactors beyond ITER

1) **High Field Option**
   Operating temperature at 5 K, but toroidal field at 13 - 17 T

2) **Intermediate Temperature Option**
   Operating temperature at 20 - 30 K, ITER like fields
   HTS basic material performance ok, increased efficiency but vacuum and 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, significant increase of efficiency and reliability.
   HTS performance to be confirmed
   → YBCO only viable option
HTS show enhanced superconducting and irreversible properties compared to the established LTS (NbTi, Nb₃Sn):

- Much higher superconducting transition temperatures up to 135 K
- Very high upper critical fields of the order of 100 T
- High irreversible (operating) fields at higher temperatures
- Excellent critical current densities up to high temperatures and magnetic fields

**Research projects already started to manufacture samples and prototype coils**

**Suitable HTS compounds:** Bi-2212, Bi-2223, Y-123 and for PF- MgB₂
Section 11.

Summary
Main drivers for fusion magnets design are:

- Large forces & stresses
- Radiation on windings
- Large stored energy
- Operation in vacuum
- Large heating in the conductor

The magnets being manufactured for ITER present many challenges.

The Model Coil programs have addressed many issues, but because of the size scaling some major manufacturing issues of full scale coils still need to be addressed.

The magnet program is very aggressive because it does not foresee construction and testing of full scale prototypes of the coils.

Technical solutions have to be developed directly on the real coils.

Therefore, a preliminary 2 year qualification phase is foreseen to tackle some of the manufacturing issues (i.e. dummy double pancake construction).
The ITER project sets new limits for conductor and coil dimensions, quality assurance and project management:

- Currents up to 68 kA
- Coils up to 13 m (Nb$_3$Sn) and 24 m (NbTi) in diameter
- More than 530 t of Nb$_3$Sn strands for TF and CS coils
- About 300 t of NbTi strands are required for PF and CC
- Complex coils with a total weight of up to 350 tons

HTS current leads using Bi-2223 tapes up to 68 kA

The ITER magnet system will be a challenge for industry, worldwide...
Thank you for your attention