THE ITER SUPERCONDUCTING MAGNET PROGRAMME

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Abstract
This note summarises the main objectives, development lines, evolution and results of the European Fusion programme during the last twenty years, from the Next European Torus (NET) till the present effort in the scope of the International Thermonuclear Experimental Reactor (ITER).

1. INTRODUCTION
The European fusion programme has evolved in the past twenty years, adapting to the changes in scope and boundary conditions. In 1983 the Next European Torus (NET) Team was created to design the fusion device to follow the Joint European Torus (JET). [1]

The NET magnet system was all superconducting, designed with Nb3Sn and NbTi superconducting strands, supercritical helium forced flow cooled and high current in the cables, in excess of 40 kA.

Following the agreement between United States and Russian Federation in 1987 the International Thermonuclear Fusion Reactor (ITER) Conceptual Design Activity started (CDA), it lasted three years, and in 1990, it was completed. [2]

The second phase of ITER started in 1992, named Engineering Design Activity (EDA). It lasted six years from 1992 to 1998. The partners for these two phases were Russia, United States, Europe and Japan. [3]

After completion of the EDA, the United States abandoned the project, ITER-FEAT started in 1999 and is going on to now. In table I are reported the major parameters of the ITER machines as designed in the different phases. [4]

<table>
<thead>
<tr>
<th>Table 1. ITER parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ITER CDA 1988-1990</strong></td>
</tr>
<tr>
<td>Plasma Major Radius</td>
</tr>
<tr>
<td>D.N. Vertical Elongation 95%</td>
</tr>
<tr>
<td>Plasma Current</td>
</tr>
<tr>
<td>Magnetic Field at 5.8m/max.</td>
</tr>
<tr>
<td><strong>ITER EDA 1992-1998</strong></td>
</tr>
<tr>
<td>Plasma Major Radius</td>
</tr>
<tr>
<td>S.N. Vertical Elongation 95%</td>
</tr>
<tr>
<td>Plasma Current</td>
</tr>
<tr>
<td>Magnetic Field at 8.1m/max</td>
</tr>
<tr>
<td><strong>ITER FEAT 1999-today</strong></td>
</tr>
<tr>
<td>Plasma Major Radius</td>
</tr>
<tr>
<td>S.N. Vertical Elongation 95 %</td>
</tr>
<tr>
<td>Plasma Current</td>
</tr>
<tr>
<td>Toroidal Field at 6.2m/max</td>
</tr>
</tbody>
</table>
2. THE BASIC CONSTRAINTS FOR THE LAYOUT OF THE ITER CONDUCTOR

The ITER device (Fig. 1) mainly consists of the cryostat, the magnet system, the vacuum vessel, the blanket and the divertor. The ITER-FEAT magnet system (Fig. 2) consists of 18 toroidal field (TF) coils, a central solenoid (CS), six poloidal field (PF) coils and correction coils (CCs).

![Figure 1. ITER device.](image)

<table>
<thead>
<tr>
<th></th>
<th>Field (T)</th>
<th>Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS coil</td>
<td>13.5</td>
<td>42</td>
</tr>
<tr>
<td>TF coil</td>
<td>11.8</td>
<td>68</td>
</tr>
<tr>
<td>PF coil</td>
<td>4 $\leq$ 6</td>
<td>45</td>
</tr>
<tr>
<td>Correction coil</td>
<td>$&lt; 6$</td>
<td>10</td>
</tr>
<tr>
<td>Cryostat feedthrough</td>
<td>$&lt; 4$</td>
<td>$\leq 68$</td>
</tr>
<tr>
<td>Current lead</td>
<td>$&lt; 30$ mT</td>
<td>$\leq 68$</td>
</tr>
<tr>
<td>External current feeder</td>
<td>$\sim$ mT</td>
<td>$\leq 68$</td>
</tr>
</tbody>
</table>

![Figure 2. Magnet System Components.](image)

The TF coil case, which encloses the winding pack, is the main structural component of the magnet system. The TF coil inboard legs are wedged all along their side walls. In the inner regions, the coils are connected by inner intercoil structures (IIS). At the outboard leg, the out-of-plane support...
is provided by outer intercoil structures (OIS) integrated with the TF coil cases. These are welded structures acting as shear panels, which are connected to each other to form four toroidal belts. There is electrical insulation between TF coils at the inboard leg wedged region and at the IIS and OIS.

The CS assembly consists of a stack of six independent modules and is hung from the top of the TF coils through its pre-load structure. This structure, which consists of a set of tie-plates located outside and inside the coil stack, provides axial pressure on the stack. The number of CS modules is chosen to suit the plasma equilibrium requirements.

The six PF coils (PF1 to PF6) are attached to the cases through flexible plates to allow radial expansion. The position and size of these coils are chosen to suit the plasma equilibrium and control requirements.

Both CS and TF coils operate at high field and use Nb3Sn-type superconductor. The PF and CC coils use NbTi superconductor. All coils are cooled at 4.5K. The whole magnet system is supported by flexible columns and pedestals, one under each TF coil. Each TF coil is electrically insulated from its support. The TF coil case also supports the vacuum vessel weight and operational loads.

Table 2 gives the ITER-FEAT main magnet parameters and Fig. 3 shows the ITER conductors layout.

Table 2. ITER-FEAT main magnet parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of TF coils</td>
<td>18</td>
</tr>
<tr>
<td>Magnetic energy in TF coils (GJ)</td>
<td>~ 41</td>
</tr>
<tr>
<td>TF coil current (kA)</td>
<td>68</td>
</tr>
<tr>
<td>Maximum field in TF coils (T)</td>
<td>11.8</td>
</tr>
<tr>
<td>CS current, initial magnetization, end-of-burn (kA)</td>
<td>41.5, [45.2]</td>
</tr>
<tr>
<td>CS peak field, initial magnetization, end-of-burn (T)</td>
<td>13.5, [12.8]</td>
</tr>
<tr>
<td>PF coil current, normal operation, backup mode (kA)</td>
<td>45, [52]</td>
</tr>
<tr>
<td>Correction coil current (kA)</td>
<td>10</td>
</tr>
<tr>
<td>Weight of TF coils including structures (t)</td>
<td>5.621</td>
</tr>
<tr>
<td>Weight of CS including structures (t)</td>
<td>926</td>
</tr>
<tr>
<td>Weight of PF coils including clamps (t)</td>
<td>2.835</td>
</tr>
<tr>
<td>Weight of CCs including clamps (t)</td>
<td>80</td>
</tr>
<tr>
<td>Total weight of magnet system (t)</td>
<td>~ 10.135</td>
</tr>
</tbody>
</table>

Figure 3. Conductors of the two ITER model coils: CSMC conductor, left, exploded TFMC conductor, right.
3. **ITER MAGNETS R&D**

In order to demonstrate the feasibility of the magnetic system, a comprehensive research and development programme has been launched in 1992. The main elements of the programme are the Central Solenoid Model Coil (CSMC) and the Toroidal Field Model Coil (TFMC). A third, complementary element is the Poloidal Field Coil Insert (PFCI).

The Central Solenoid Model Coil (CSMC) [5] has been built with the contribution of United States, Japan and Europe, and has been assembled and tested in the Naka site of JAERI, in Japan. The main CSMC parameters and test results are reported in Fig. 4 and Fig. 5.

![Coil Design Parameters](image)

<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>

Figure 4. CS Model Coil.

![Coil Design Parameters](image)

Figure 5. CS Model Coil test results. Left: CSMC successfully achieved design values, right: small degradation (0.1 to 0.2 K) saturated after few cycles.

It can be seen from the current waveform of Fig. 5 that the design parameters were achieved at first attempt (no training), some changes in the electric characteristic of the coil was detected in the following testing. This is probably due to a settlement of the cable inside the jacket. A lower coil
performance ($J_c,n$) compared to strand was measured: it is probably due to current redistribution inside
the cable and bending strain effects, which at present are not simulated in the interpretation codes.

The second element of the R&D programme is the Toroidal Field Model Coil (TFMC) [6]
(Fig.6), which has been built entirely in the European Union and has been tested in 2001 alone at FZK
Karlsruhe (Germany).

In 2002, the TFMC together with the LCT coil was tested to simulate the effect of the transversal
forces. The TFMC showed reduction of $n$ and AC losses, as the CSMC, but it did not change
performances with cycles, neither reduction of temperature current sharing from strand, after a proper
strand data set was used. (Figs. 7-8).

![TF Model Coil](image1)

**Figure 6. TF Model Coil.**

![TF Model Coil performance](image2)

**Figure 7. TF Model Coil performance.**
Figure 8. Simulation of the voltage–temperature characteristics in a run of the TFMC (top) and difference between the current sharing temperature Tcs as obtained from strand data and as measured in different runs (bottom) corresponding to a wide range of transverse Lorentz force.

It can be noted (Fig. 9) that the standard Summer’s low is not accurate enough when high compressive strain is present. The performance dependence on applied Lorentz forces, can be explained by the fact that the interpretation code doesn't take into account the bending strain effect.

The bending strain effect [7] was already investigated by Ekin in 1980 (Fig. 10) and this can explain the more pronounced degradation of performance (with bending strain) experienced by the CSMC (lower compressive strain due to Incoloy Jacket) than the TFMC (SS Jacket) as it is experimentally confirmed by the test results reported in Fig. 11.
Figure 9. Standard Summer’s Law is not accurate

Figure 10. Bending strain tests - Influence at high compression

Fig. 11, DC test results on voltage-current characteristics on two Nb3Sn cables.
The third element of the R&D is the Poloidal Field Conductor Insert (PFCI) [8], which is being built in Europe (Fig. 12) with a cable supplied by the Russian Federation, and will be tested in 2005 at Naka (J). All conductors used in the model coil have been tested in the SULTAN facility; Hall probes array has been used in order to determine the current distribution inside the cable and therefore improve the interpretation of the test results.

![Figure 12. PF Insert Coil](image)

### 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>Main Winding Envelope</td>
<td></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>Weight</td>
<td>6 t</td>
</tr>
</tbody>
</table>

4. **ITER CONDUCTOR OPTIMIZATION**

Following the test results of the model coil and inserts, as well as the progress in the strand fabrication, a conductor development programme has been launched in Europe to optimize the ITER conductor. [9] Six companies are presently producing strand in accordance to the specifications reported in Table 3.

The development programme outlined in Fig. 13 is designed to qualify the strand and cables at every stage of fabrication, and under applied tensile load up to the last but one stage.

The longitudinal strain dependence of the strand critical current is measured in the “small” FBI facility on a strand jacketed in a SS tube; the same test is curried out in the “big” FBI facility in subcables jacketed in SS tubes. The principle and details of the FBI facilities are shown in Figs. 14 and 15.
Table 3. Advanced Nb3Sn Strand specification, tender.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter of the strand</td>
<td>0.81 mm ±3 µm</td>
</tr>
<tr>
<td>Effective filament diameter</td>
<td>&lt; 50 µm (typical)</td>
</tr>
<tr>
<td>Strand pitch</td>
<td>&lt; 20 mm</td>
</tr>
<tr>
<td>Hard Cr -coating</td>
<td>2 µm +0.5 µm / ±0 µm</td>
</tr>
<tr>
<td>Non-Cu critical current density (at 12 T, 4.2 K, 0.1 µV/cm)</td>
<td>Min. guaranteed: 800 A/mm² Target value: 1100 A/mm²</td>
</tr>
<tr>
<td>Non-Cu hysteresis losses on a ±3T field cycle (Flux jumping not acceptable)</td>
<td>&lt; 1000 kJ/m³</td>
</tr>
<tr>
<td>n-value at 12 T and 4.2 K</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>n² time constant</td>
<td>&lt; 5 ms</td>
</tr>
<tr>
<td>RRR after reaction heat treatment</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Cu:non-Cu ratio</td>
<td>1.0 ± 0.05</td>
</tr>
<tr>
<td>Minimum acceptable length of strand</td>
<td>1.5 km or multiples (target value &gt; 3 km)</td>
</tr>
<tr>
<td>Heat treatment cycle</td>
<td>Unified cycle, as proposed by ITER IT</td>
</tr>
</tbody>
</table>

Procurement of Advanced Strand

- Single Strands
  - Jacketed Strands
    - Cross Checking and Extended Tests
  - Sub Size Samples
    - Bending Strain Tests
- Full Size Samples
  - Full Size Conductor Manufacture
  - Full Size Sample Test SULTAN

Figure 13. Conductor development programme – main stages
Small FBI
SC-strands: 20 cmØ 2 mm
split-coil magnet: 13.5 T
maximum force: 1 kN
maximum current: < 400 A
(with active cooling of current leads)
strain measured by Extensometers
all tests done in LHe

Figure 14. FBI Facility – Status and preliminary results

– subsize cable: 110 cm, Ø 2 cm
– split-coil magnet: 14 T
– maximum force: 100 kN
– maximum current: 10 kA

Facility should be ready for first measurements in April 2004.

Figure 15. “Big” FBI Facility

To assess the effect of bending strain on critical current the SS jacketed strand is reacted in the standard ITER sample older and tested, then transferred to other cylinder radius and measured again. The FBI, now, has been improved and it is possible to measure the critical current with the 10 microVolt/m criteria.
Mechanical modeling (Fig. 16) of the superconducting cables is being developed: the aim is to compute the strain in the filaments after heat treatment and during operation. [10] The algorithm scheme being developed for cables homogenisation is the following:

1. Compute effective coefficients at micro level
2. Compute effective coefficients at macro level
3. Apply increment of forces and/or temperature at the macro level, solve global homogeneous problem
4. Compute global strain [$E_{11}$, $E_{22}$, $E_{12}$]
5. Apply [$E_{11}$, $E_{22}$, $E_{12}$] to meso level cell by equivalent kinematical loading (displacement on the border)
6. Solve the kinematical problem, compute stress (unsmearing for meso level) and strain
7. Apply [$E_{11}$, $E_{22}$, $E_{12}$] from meso to micro level cell by equivalent kinematical loading (displacement on the border)
8. Solve the kinematical problem, compute stress (unsmearing for micro level) and strain
9. Verify yielding of the material at the physically true situation at the micro level. If yes change mechanical parameter of the material and repeat the procedure.

The final intention is to perform an analysis of the mechanical state of a complete cable. This analysis will start from the model of a last-but-one stage, or a petal as it is called in the present jargon, through homogenisation, finally to a model of the complete cable.

The analysis model for the $3 \times 3 \times 4$ petal is composed of two types of Finite Elements: rod elements schematising the strands and specially formulated contact elements along the sub-cable to schematise strand-to-strand interactions. The rod type elements are characterized by the mechanical and thermal properties derived numerically from the first level of this analysis.
The identification of mechanical parameters for the homogenised petal model will be based on three kinds of theoretical analyses:

- Homogenisation based on the results of previous investigations and taking into account the specific spatial organisation of the sub-elements of the petal;
- Identification of the homogeneous model of the petal using various techniques of parametric identification;
- Non symbolic constitutive model using Artificial Neural Networks

The final level of this complex study consists of a Finite Element analysis of the six petals cable, each petal considered as homogeneous with the characteristics derived from the tree previous parameter identification methods.

The effects of the compaction due to the jacket as well as the effects due to the thermal treatment from 923°K to 4°K can be analysed. Once the global behaviour of the cable is studied the “unsmearing” analyses will provide the strain state of the individual stand.

At present the model has reached the following objectives

- A homogenized constitutive macro model for the complex geometry and non-linear, temperature dependent material properties is developed;
- Identification of the micro cell (averaged geometrical characteristics) and micro level homogenisation (Nb3Sn – bronze cell);
- Identification of the meso cell (averaged geometrical characteristics) and meso level homogenisation (homomicro – bronze cell);
- Mechanical and thermal characteristics for the micro and meso homogenised model: orthotropic material.

An application of the code has been made to compute the residual strain in a Nb3Sn strand produced by VAC, going from reaction heat treatment to 4 K. The results of 0.271% residual strain that has been computed is very close to the experimental value.

Other on-going modelling efforts are:

- A predictive code (Thermo-Hydraulic Electro-Magnetic Analysis – THELMA) has been developed in 2001-2002 by University of Bologna, University of Udine and Polytechnic of Turin under the co-ordination of ENEA and EFDA for the analysis of superconductive magnets in transient conditions [11]
- A reconstruction tool (CUrrent Numerical DETermination – CUNDET) is under development since 2001 by C.R.E.A.T.E. for the current distribution estimation from experimental measurements. [12]

It is now necessary to test extensively the predictive code against a set of experimental data and apply it to the prediction of results of new campaigns, and to validate the reconstruction code against experimental results and the predictive code.

5. **RADIATION EFFECTS**

The insulation system of the toroidal field model coil has been tested under radiation. The test results are such that the insulation system is at the limit. Therefore a new insulation system is being developed. Figure 17 shows the resin composition and fig. 18 the results on the various insulation systems.
A resin system made of epoxy and Cyanide has been chosen for qualification. Also, the effect of the radiation on superconducting strand is being assessed. [13]

It seems that the radiation effect on superconductors characteristic is negligible at the fluence level expected for operation of ITER.
6. CONCLUSIONS

The feasibility of the ITER coils with Nb3Sn strand is demonstrated by the extensive research and development programme carried out worldwide.

The feasibility demonstration of the niobium titanium coils awaits the testing of the poloidal field conductor insert to be curried out in 2005.

An extensive development programme has been launched in Europe, to qualify the advanced performance strand to improve the ITER conductors.

Design codes are being developed to compute the current distribution and strain distribution in the cables in order to better assess the performance of the coils.

An advanced insulation system is being qualified also after irradiation.

REFERENCES

[8] C. Sborchia et al.; PFCI design and fabrication