Mangets Design and Technology

E. Salpietro
Outline

- Introduction
- Electromagnetics and mechanical aspects of Tokamak devices
- Toroidal Magnetic Field system design
- Central Solenoid and outer coils design
- Superconducting cables R&D status
- Structural and insulation materials R&D status
- Conclusions
Introduction

- **NET 1983-1988**
- **ITER CDA 1988-1990**
  - Plasma Major Radius 6.0 m
  - D.N. Vertical Elongation 95% 2
  - Plasma Current 22 MA
  - Magnetic Filed at 5.8m / max. 4.9T/10.4T
- **ITER EDA 1992-1998**
  - Plasma Major Radius 8.1m
  - S.N. Vertical Elongation 95% 1.6
  - Plasma Current 21 MA
  - Magnetic Field at 8.1m/max 5.7T/12.5T
- **ITER FEAT 1999-today**
  - Plasma Major Radius 6.2m
  - S.N. Vertical Elongation 95% 1.7
  - Plasma Current 15/17 MA
  - Toroidal Field at 6.2m/max 5.3T/11.8T
The Tokamak: A Transformer Device
Sc. Magnet

Current feedthrough in horizontal position
ITER - EFDA Magnets R&D Programme - Magnet System Components

<table>
<thead>
<tr>
<th>Component</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 – 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>≤ 68</td>
</tr>
<tr>
<td>Current lead</td>
<td>&lt; 30 mT</td>
<td>≤ 68</td>
</tr>
<tr>
<td>External current feeder</td>
<td>~ mT</td>
<td>≤ 68</td>
</tr>
</tbody>
</table>
Superconducting strands

• **High field > 5 T**
  - Nb$_3$Sn
  - $E = Ec(J/Jc \{B,T,E\})^n \{B,T\}$
  - Heat treatment (650 °C, ~ 200 h)
  - Cromium coating (~ 2µm)

• **Low Field < 5 T**
  - NbTi
  - $E = Ec(J/Jc \{B,T\})^n$
  - No heat treatment required during coil manufacturing
  - Coating Ni (~ 2 µm)
Typical measurement with new FBI setup

VAC Nb$_3$Sn strand 13T, $\varepsilon=0\%$

- measurement with 2cm U-taps
- Fit with $I_c=92\text{A}$, $n=12$
Engineering critical current density (and critical current) of the EM-LMI wire as a function of applied strain at a magnetic field of 12 T and at temperatures of 4.2 K and 0.5 K increments between 5 K and 10 K.

The symbols show the measured data, and the lines show the parameterization using the Interpolative Scaling Law.
Design criteria

- Forced flow cooling: nuclear heating, ohmic power removal and heat losses
- Stability: plasma disruptions, friction heat generation
- Quench protection
- AC losses
- $\text{Nb}_3\text{Sn}$ strain limit
- D shaped TF coils with SS casing
- SS jacket material
- Segmented central solenoid
- TFC winding pack with Radial Plates?
Superconducting cable

- Cables 5 stages (3x3x4x5x6)
- Last-but-one stage wraps
- Central cooling channel
- Jacket material SS
- Cooling He supercritical
Developed ITER Conductors - TF Model Coil

- Current: 80 kA (4.5 K, 9.7 T)
- 316LN stainless steel jacket (Ø 40.7 mm) wound in radial plates
- Cable diameter: 37.5 mm
- 720 Nb$_3$Sn strands (1080 strands total)

Strand Layout
Joints

- Between pancakes
- Between coil and normal conductor
- Low resistance and uniform distribution
Technical realisation of the joints

Cables are compacted in twin-material boxes of stainless steel and copper. The boxes are then soldered.
TFMC - Joints
Technical realisation of the joints

Shaking hand joint: inner joint of double pancake 1
Winding pack manufacturing

- Bending by multiple rollers
- Glass-kapton tape wrapping between turns
- Epoxy resin vacuum impregnation
- Glass-kapton tape vacuum impregnate for ground insulation
Conductor bending
Laser welding
TFMC
Winding Pack after Impregnation
ITER - EFDA Magnets R&D Programme - TF Model Coil
TFMC Operating Diagram
ITER - EFDA Magnets R&D Programme - TF Model Coil

TFMC (80 kA) + LCT (16 kA)  
TFMC (80 kA)

TFMC exceeded design values  
No performance degradation
ITER - EFDA Magnets R&D Programme - CS Model Coil

Coil Design Parameters

<table>
<thead>
<tr>
<th>Parameter</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>
Developed ITER Conductors - CS Model Coil

- Current: 46 kA (4.5 K, 13 T)
- Incoloy 908 jacket (51 × 51 mm²)
- Cable diameter: 38 mm
- 1152 Nb₃Sn strands

Strand Layouts
ITER - EFDA Magnets R&D Programme - CS Model Coil

CSMC: Inner module

CSMC: Outer module
ITER - EFDA Magnets R&D Programme - CS Model Coil

CSMC successfully achieved design values

Small degradation (0.1 to 0.2 K) saturated after few cycles
**ITER - EFDA Magnets R&D Programme - PF Insert Coil**

**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>Height</td>
<td>1.40 m</td>
</tr>
<tr>
<td>Weight</td>
<td>6 t</td>
</tr>
</tbody>
</table>
Developed ITER Conductors - PF Insert Coil

- Current: 50 kA (4.5 K, 6.3 T)
- 316LN stainless steel jacket (51 × 51 mm²)
- Cable Ø: 38.7 mm
- 1440 NbTi strands

Strand Parameters

- $J_c > 2700$ A/mm² (5 T, 4.2 K)
- Strand Ø: 0.73 mm
- Cu:non-Cu ratio: 1.4
- Filament Ø: 9.8 µm
- Number of filaments: 2346
Reduction of PF Insert Superconductor
Evidence of stability limit from PFCI-FSS

\[ y = -29.508x^2 + 340.84x - 934.22 \]
\[ R^2 = 0.9802 \]

\[ y = -50.512x^2 + 573.14x - 1584.2 \]
\[ R^2 = 0.9747 \]

\[ y = -14.267x^2 + 151.8x - 335 \]
\[ R^2 = 0.9805 \]
ITER - EFDA Current Lead R&D Programme -
Design of the 70 kA HTS CL

PART 1: Clamp contact with three Nb$_3$Sn inserts
PART 2: HTS module with Ag/Au sheated Bi-2223 tapes
PART 3: Conventional heat exchanger with Cu discs
The current lead is designed with respect to the requirements given in the ITER-magnet design document:

- **Location**: The current lead needs to be installed horizontally in coil-terminal-boxes CTB.
- **Safety requirement**: The current lead has to withstand a loss of helium mass flow for 3 minutes at nominal current. To reach this goal the heat capacity of the HTS part has to be large.

Current leads needed for ITER (total current of 2.5 MA):

<table>
<thead>
<tr>
<th>Coils</th>
<th>No. of pairs</th>
<th>$I_{\text{max}}$</th>
<th>Type</th>
<th>$V_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF Coil</td>
<td>9</td>
<td>68 kA</td>
<td>F</td>
<td>10 kV</td>
</tr>
<tr>
<td>PF Coil</td>
<td>6</td>
<td>45 kA</td>
<td>V</td>
<td>14 kV</td>
</tr>
<tr>
<td>Correction Coil</td>
<td>9</td>
<td>8 kA</td>
<td>V</td>
<td>3 kV</td>
</tr>
<tr>
<td>CS Coil</td>
<td>6</td>
<td>45 kA</td>
<td>V</td>
<td>10 kV</td>
</tr>
</tbody>
</table>
Installation in TOSKA

Conventional (LTS) 80 kA CL and Aluminium bus bar installed in TOSKA

70 kA HTS CL installed in TOSKA
ITER - EFDA 70 kA HTS Current Lead

- 68 kA steady state up to a warm end temperature of 80 K ($T_{HTS} = 80$ K)
- Quench temperature at 68 kA: 92 K
- 80 kA steady state ($T_{HTS} = 55$ K)
- Heat load into 4.5 K: 13.5 W
- Cold end contact: 1.9 nΩ
- LOFA (68 kA, $T_{HTS} = 65$ K): > 6 min before quench (ITER requirement: > 3 min)
- Poor screw contact between HTS module and heat exchanger at warm end ($\approx 100$ nΩ)
Issues for Nb3Sn cables

- Residual thermal strain
- Actual strain distribution in the cable during operation
- Effect of bending strain on performance
- Effect of current and magnetic distribution on performance
- Validation of design codes taking into account coupled fields (thermo hydraulic, mechanical and electromagnetic)
First trials to demonstrate the feasibility of the jacketing of single strands successfully performed in 2003:

- Strand diameter: 0.81 mm
- SS tube drawn 3.15 → 2.04 mm
- Change of jacket thickness due to drawing process negligible
- It will be tested: straight and at different diameters of curvature
Strand jacketed in stainless steel tube 0.1-0.2 mm thickness

Comparison of measurement with MITSUBISHI (Kubo et al. 2004) results

Normalized $J_c$

Intrinsic Strain [%]

-1,0 -0,8 -0,6 -0,4 -0,2 0,0 0,2 0,4 0,6 0,8 1,0 1,2 1,4

- 0,0 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1,0 1,1

- FBI SS-LMI_2 @ 13 T, 4.2 K
- Mitsubishi SUS_A @ 9 T, 4.2 K
- Mitsubishi SUS_B @ 9 T, 4.2 K

K.-P. Weiss FZK/ITP

May 2004

ISFRT, Erice, 26 July - 1 August, 2004
Mechanical Modeling of ITER Superconducting Cables

D. Bosio

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

ISFRT, Erice, 26 July - 1 August, 2004
Mechanical Modeling of ITER Superconducting Cables

Unit cell 3D mesh: 1998 elements
1979 nodes
7916 dof
Mechanical Modeling of ITER Superconducting Cables
VAC Strand Thermal Residual Strain at 4K

- Nb3Sn filaments: compression stress state
  final longitudinal strain: -0.271%

- Bronze: tensile stress state
  final longitudinal strain: 0.468%

- Copper: tensile stress state
  final longitudinal strain: 0.684%
Bending Strain Tests -
Influence at high Compression

- Contribution of transverse load effects on $I_c$ reduction maybe overrated ($I_c/I_{cm}$ almost independent on $\varepsilon_B$ at $\varepsilon_0 \approx -0.5 \%$)

- Strain sensitivity has to be checked for new advanced strand

[J. Ekin, 1980]

ITER operating point

Current transfer length $<<$cable twist peak
DC Test Results (Bending Strain Impact)

Ti jacketed Conductors: conductor A (residual strain about 0.3%) & solder-filled conductor B (residual strain about 0.4%)

**Conductor A**
- $I_c = 34.9 \, \text{kA}$
- $I_q = 48.8 \, \text{kA}$
- $n = 10$

**Conductor B, solder-filled**
- $I_c = 52 \, \text{kA}$
- $I_q = 56 \, \text{kA}$
- $n = 23$

Electric field (µV/cm)

Current (kA)

B = 11 T
$T_{op} = 6.85 \, \text{K}$
Bending Strain Tests - Current Transfer Length

- Measurement of the critical current at three different bending strains to check $I_c$ behaviour.
- Bending strain established by transferring reacted strands to different sample holder diameters.
- Bending strain value defined by the ratio of the barrel sample holder diameter.

[N. Mitchell 2003]

[Graph showing the relationship between bending strain and $I_c/I_{cm}$]
EM/TH coupling

Tstrand is used in the EM part to compute coefficients (material properties). In the EM step $t \rightarrow t + \Delta t$, the EM module uses $T_{st} @ t$ to compute the power sources. These are then used by the TH module to perform the TH step $t \rightarrow t + \Delta t$, and so on.

**Explicit EM/TH coupling**
Thelma joint model

- CICC short segments
- Resistive saddles between the CICCs
Geometrical model of CICC segments

Bundle cross-section

Strand/macrostrand axis

\[ \mathbf{OP}_{k-1} = \mathbf{OP}_k + r_k \cdot \cos(\omega_k s_k + \alpha_k) \cdot \mathbf{u}_{n_k} + r_k \cdot \sin(\omega_k s_k + \alpha_k) \cdot \mathbf{u}_{b_k} \]
Example

ITER-type CICC modelled with 17 strands + macrostrands
A current driven system is considered.

A cable-element can be either a single strand or a strand bundle.

The model is self consistent with given inlet and outlet currents or can be coupled with a termination/joint model.

The model is aimed to simulate real size coils
## Nb$_3$Sn Strand Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter of the strand</td>
<td>0.81 mm $\pm$ 3 $\mu$m</td>
</tr>
<tr>
<td>Strand pitch</td>
<td>&lt; 20 mm</td>
</tr>
<tr>
<td>Hard Cr-coating</td>
<td>2 $\mu$m $\pm$ 0.5 $\mu$m / –0 $\mu$m</td>
</tr>
<tr>
<td>Overall critical strand current</td>
<td>Min. guaranteed: 200 A$^a$ Target value: 280 A$^b$</td>
</tr>
<tr>
<td>Overall strand hysteresis losses</td>
<td>&lt; 500 kJ/m$^3$</td>
</tr>
<tr>
<td>n-value at 12 T and 4.2 K</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>RRR after reaction heat treatment</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Cu:non-Cu ratio</td>
<td>0.9 – 1.5</td>
</tr>
<tr>
<td>Minimum acceptable length of strand</td>
<td>&gt; 1.5 km</td>
</tr>
</tbody>
</table>

$^a$ equivalent to a non-Cu $J_c$ of 800 A/mm$^2$, a Cu:non-Cu ratio of 1 and a strand diameter of 0.81 mm

$^b$ Equivalent to a non-Cu $J_c$ of 1100 A/mm$^2$, a Cu:non-Cu ratio of 1 and a strand diameter of 0.81 mm
„Big“ FBI facility

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

<table>
<thead>
<tr>
<th>ILSS\textsuperscript{SBS}</th>
<th>ALSTOM 0°</th>
<th>ALSTOM\textsubscript{Kapton} 0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unirr.</td>
<td>80 ± 4</td>
<td>81 ± 4</td>
</tr>
<tr>
<td>5×10\textsuperscript{21} m\textsuperscript{-2}</td>
<td>44 ± 3</td>
<td>50 ± 4</td>
</tr>
<tr>
<td>1×10\textsuperscript{22} m\textsuperscript{-2}</td>
<td>31 ± 4</td>
<td>35 ± 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ALSTOM 90°</th>
<th>ALSTOM\textsubscript{Kapton} 90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unirr.</td>
<td>77 ± 4</td>
<td>75 ± 4</td>
</tr>
<tr>
<td>5×10\textsuperscript{21} m\textsuperscript{-2}</td>
<td>37 ± 4</td>
<td>45 ± 6</td>
</tr>
<tr>
<td>1×10\textsuperscript{22} m\textsuperscript{-2}</td>
<td>24 ± 3</td>
<td>27 ± 4</td>
</tr>
</tbody>
</table>

\textit{No fatigue-values available due to the low ILSS!}
## System Overview

**TFMC 1**
- **Type**: DGEBA
- **Resin**: Araldite F
- **Hardener**: HY905
- **Additives**: DY040
- **Impregn. Temp.**: 75 +/- 5 °C
- **Impregn. Viscosity**: < 80 mPa s
- **Curing Temp.**: 100 - > 135°C
- **Supplier**: Huntsman
- **Filler Material**: R-Glass + Kapton H
- **Currently used**: Proposed by Huntsman at high price

**TFMC 2**
- **Type**: DGEBA
- **Resin**: MY745
- **Hardener**: HY905
- **Additives**: DY072, DY073
- **Impregn. Temp.**: 80 – 85 °C
- **Impregn. Viscosity**: < 80 mPa s
- **Curing Temp.**: 90 - > 105°C
- **Supplier**: Huntsman
- **Filler Material**: R-Glass + Kapton H
- **Currently used**: Currently used

**Test 1**
- **Type**: DGEBA
- **Resin**: AroCy-L10
- **Hardener**: HY905
- **Additives**: --
- **Impregn. Temp.**: 40°C
- **Impregn. Viscosity**: 100 mPa s @25°C
- **Curing Temp.**: 80°C gel/100-160°C
- **Supplier**: Huntsman
- **Filler Material**: R-Glass + Kapton H
- **Proposed by**: Proposed by Huntsman at 60% low price

**Test 2** (blended)
- **Type**: Cyanate Ester
- **Resin**: AroCy-L10
- **Hardener**: HY905
- **Additives**: --
- **Impregn. Temp.**: 70°C
- **Impregn. Viscosity**: 350 mPa s @25°C
- **Curing Temp.**: 80°C gel/100-160°C
- **Supplier**: Huntsman
- **Filler Material**: R-Glass + Kapton H
- **Proposed by**: Proposed by Huntsman at 40% high price

**Test 3**
- **Type**: DGEBA purified
- **Resin**: MY790-1
- **Hardener**: CW229
- **Additives**: --
- **Impregn. Temp.**: 50°C
- **Impregn. Viscosity**: 350 mPa s @25°C
- **Curing Temp.**: 80°C gel/110-140°C
- **Supplier**: Huntsman
- **Filler Material**: Ca-Glass fibres
- **Proposed by**: Proposed by Huntsman low price

**Test 4**
- **Type**: DGEBA
- **Resin**: MY790
- **Hardener**: HY1102
- **Additives**: HY5200
- **Impregn. Temp.**: 70°C
- **Impregn. Viscosity**: 2000 mPa s @60°C
- **Curing Temp.**: 100°C gel/110-140°C
- **Supplier**: Huntsman
- **Filler Material**: R-Glass + Kapton H
- **Proposed by**: Proposed by Huntsman

**Test 5**
- **Type**: DGEBA compatible
- **Resin**: LY1025/CH
- **Hardener**: HY906
- **Additives**: Orlitherm 44
- **Impregn. Temp.**: 80°C
- **Impregn. Viscosity**: ∼500 mPa s @40°C
- **Curing Temp.**: 100°C gel/120-160°C/+180°C Nh
- **Supplier**: Huntsman
- **Filler Material**: R-Glass + Kapton H
- **Proposed by**: If available without filler (Huntsman)

**Test 6**
- **Type**: DGEBA
- **Resin**: MY790-1
- **Hardener**: HY906
- **Additives**: HY1102
- **Impregn. Temp.**: 70°C
- **Impregn. Viscosity**: 70 mPa s @80°C
- **Curing Temp.**: 100°C gel/130°C
- **Supplier**: ABB
- **Filler Material**: R-Glass + Kapton H
- **Proposed by**: Currently used

**Test 7**
- **Type**: DGEBA purified
- **Resin**: MY790-1
- **Hardener**: HY906
- **Additives**: HY1102
- **Impregn. Temp.**: 80°C
- **Impregn. Viscosity**: 350 mPa s @25°C
- **Curing Temp.**: 70°C gel/120°C
- **Supplier**: Huntsman
- **Filler Material**: R-Glass + Kapton H
- **Proposed by**: Proposed by Huntsman low price

*) Huntsman is a follow-up company of Vantico which was a follow-up company of former CIBA-Geigy
**) contains less than 0.1% of boron (100% is the full volume of impregnated material)
*****) highly purified, no metal compounds in resin and hardener.
*******) same resin system as Test 3, but reduced curing temperature
******) highly chlorine purified resin

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Search for Systems with higher radiation resistance
Critical currents of both wires are enhanced after irradiation to $5 \times 10^{21} \text{ m}^{-2}$ ($E>0.1$). $\Rightarrow$ Next step: $1 \times 10^{22} \text{ m}^{-2}$ ($E>0.1 \text{ MeV}$).
ITER - EFDA Magnet Structures R&D Programme TF Coil Case

Model 1 Forged

Model 1: 316 LN forged and welded
Model 2: new high-Mn SS cast
Model 3: new high-Mn SS forged
### Mechanical data for forged 316LN steel

**Table 28.** Tensile and fracture toughness test results of the samples provided from the tube forging of Type 316LN material at 4.2 K and at 7 K.

<table>
<thead>
<tr>
<th>Material designation test codes and sample orientation in ( )</th>
<th>Young’s Modulus GPa</th>
<th>Yield Strength MPa</th>
<th>Ultimate tensile strength MPa</th>
<th>Uniform Elongation %</th>
<th>KIc JETT MPa√m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forg. T601 (trans.)</td>
<td>209/209</td>
<td>1185/1165</td>
<td>1625/1635</td>
<td>46.5/40.5</td>
<td>238/163</td>
</tr>
<tr>
<td>Forg. L600 (long)</td>
<td>204/207</td>
<td>1113/1062</td>
<td>1620/1624</td>
<td>47/61</td>
<td>206/192</td>
</tr>
<tr>
<td>Forg. R602 (radial)</td>
<td>207/207</td>
<td>1140/1168</td>
<td>1457/1418</td>
<td>13/7</td>
<td>218/210</td>
</tr>
<tr>
<td>Forg. R602 (radial)A</td>
<td>199</td>
<td>1155</td>
<td>1467</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Forg. T604 (trans.)</td>
<td>210</td>
<td>1010</td>
<td>1523</td>
<td>44</td>
<td>-</td>
</tr>
<tr>
<td>Forg. L603 (long)</td>
<td>201</td>
<td>1083</td>
<td>1525</td>
<td>45</td>
<td>-</td>
</tr>
<tr>
<td>Forg. R605 (radial)</td>
<td>209</td>
<td>934</td>
<td>1473</td>
<td>48</td>
<td>-</td>
</tr>
</tbody>
</table>

*This specimen has a 12 mm Ø and the test was conducted in LHe, whilst all others are 4 mm Ø standard ones and tested at 7 K under gaseous helium environment.*
Fatigue crack growth rate of aged Type 316LN and Incoloy 908 jacket materials at 7 K and at different load ratios. The newly developed cast steel’s FCGR represent the measurements at 7 K in all three spatial orientation.
Conclusions

- The feasibility of the reactor coils with Nb3Sn strands has been demonstrated.
- The feasibility demonstration of NbTi coils awaits the testing of the PFCI.
- Advanced Nb3Sn strands allow an improved conductor performance.
- Better understanding of current and strain distribution in the cable will allow reduction of design safety factors.
- An advanced insulation system is being qualified for reactor fluence.