Mangets Design and Technology

E. Salpietro

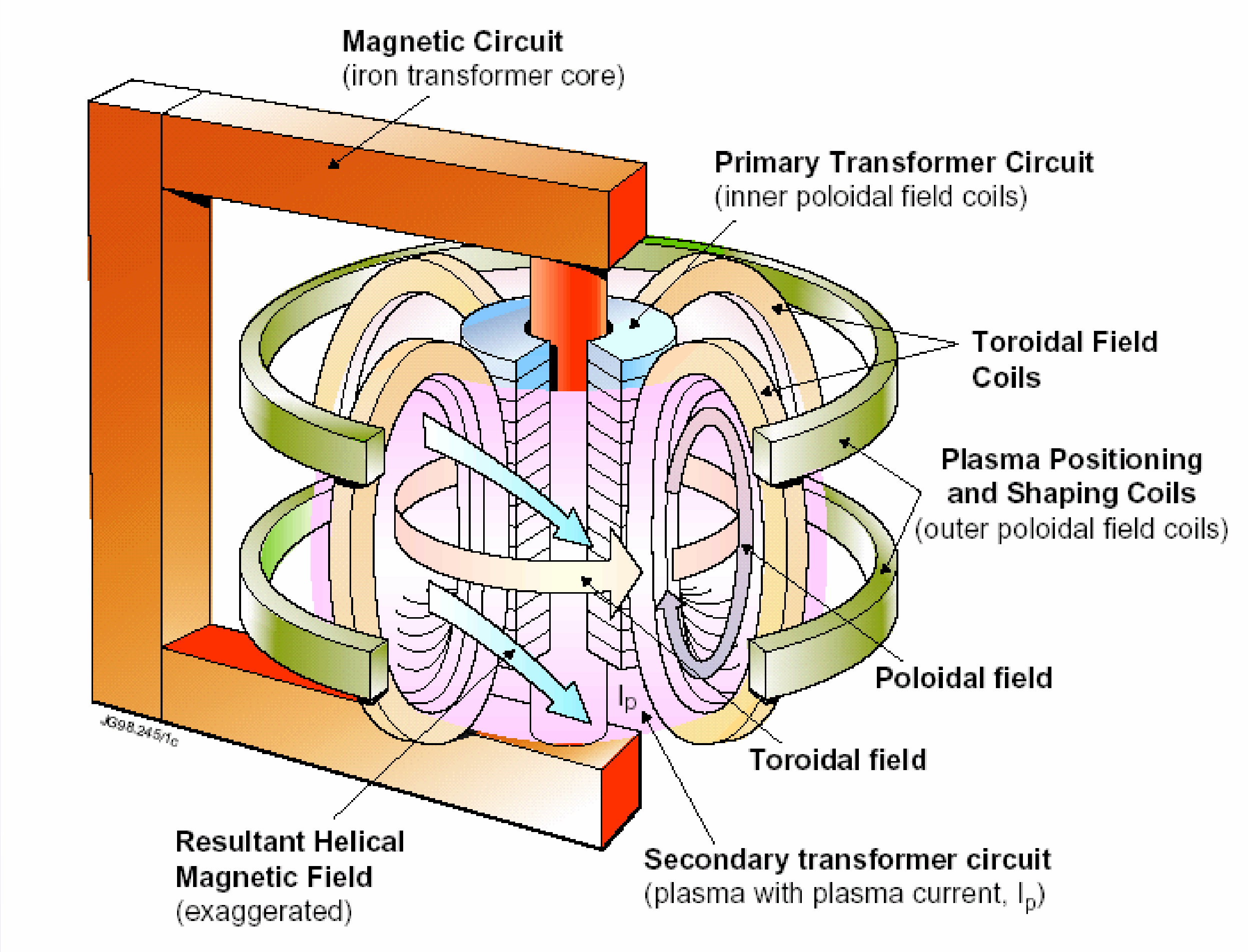
Outline

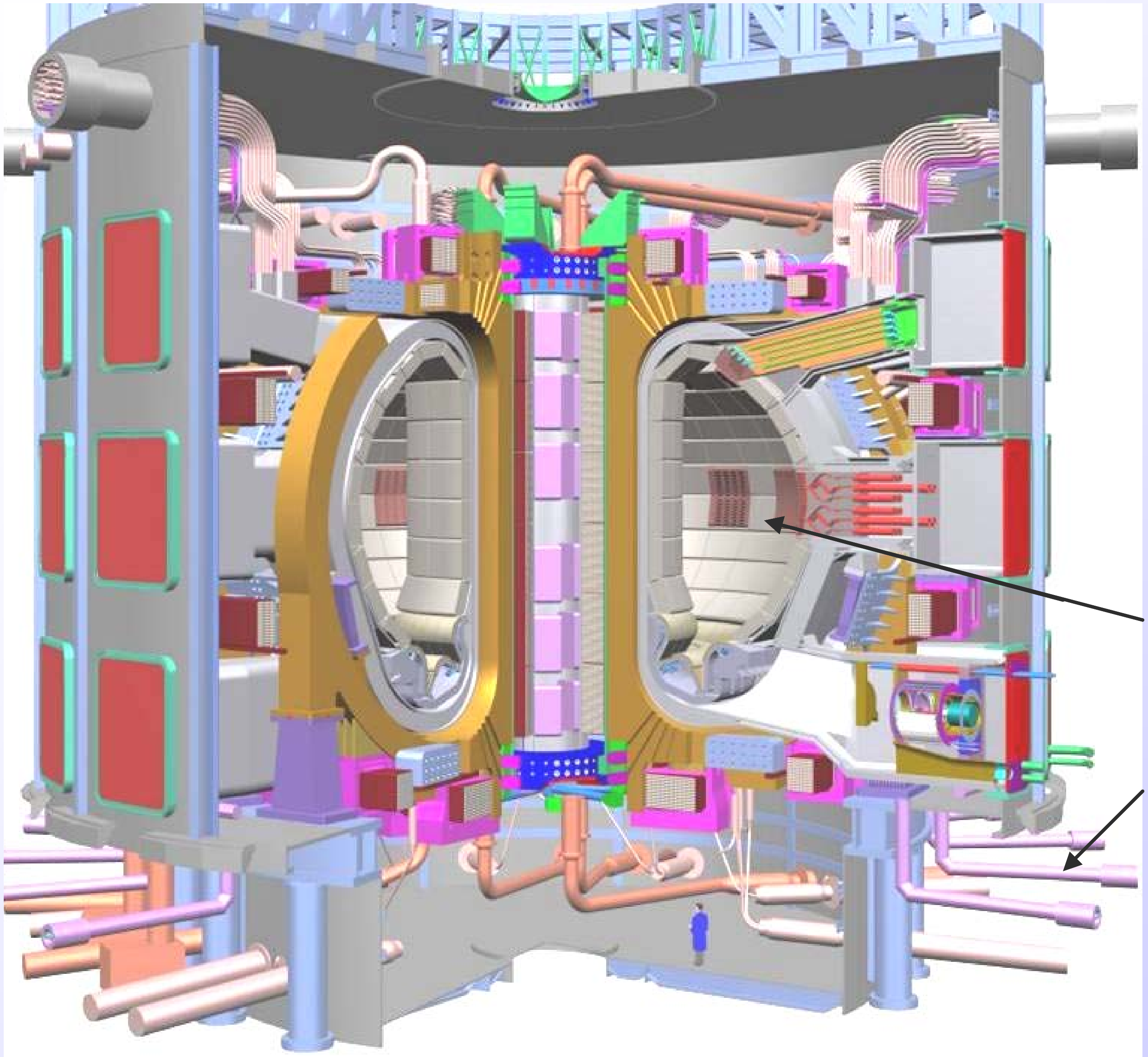
- Introduction
- Electromagnetics and mechanical aspects of Tokamak devices
- Toroidal Magnetic Field system design
- Central Solenoid and outer coils design
- Superconducting cables R&D status
- Structural and insulation materials R&D status
- Conclusions

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

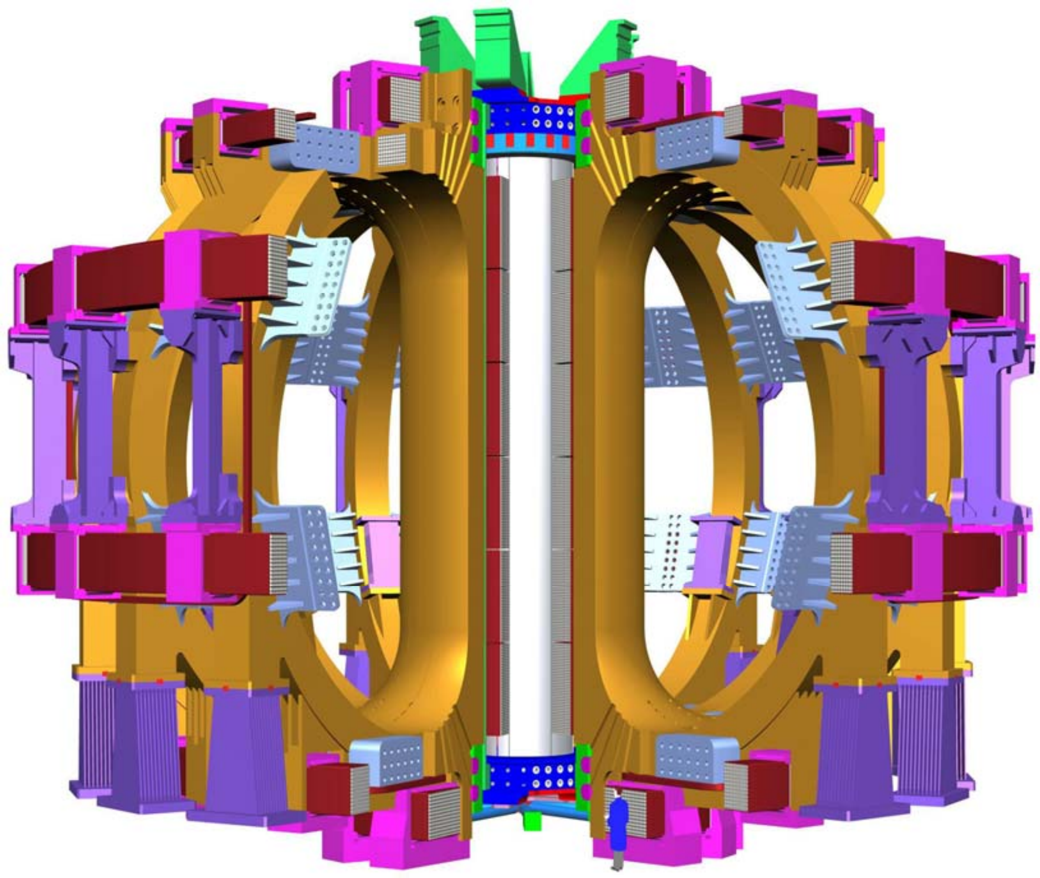




Sc. Magnet

Current feedthrough in horizontal position

ITER - EFDA Magnets R&D Programme - Magnet System Components

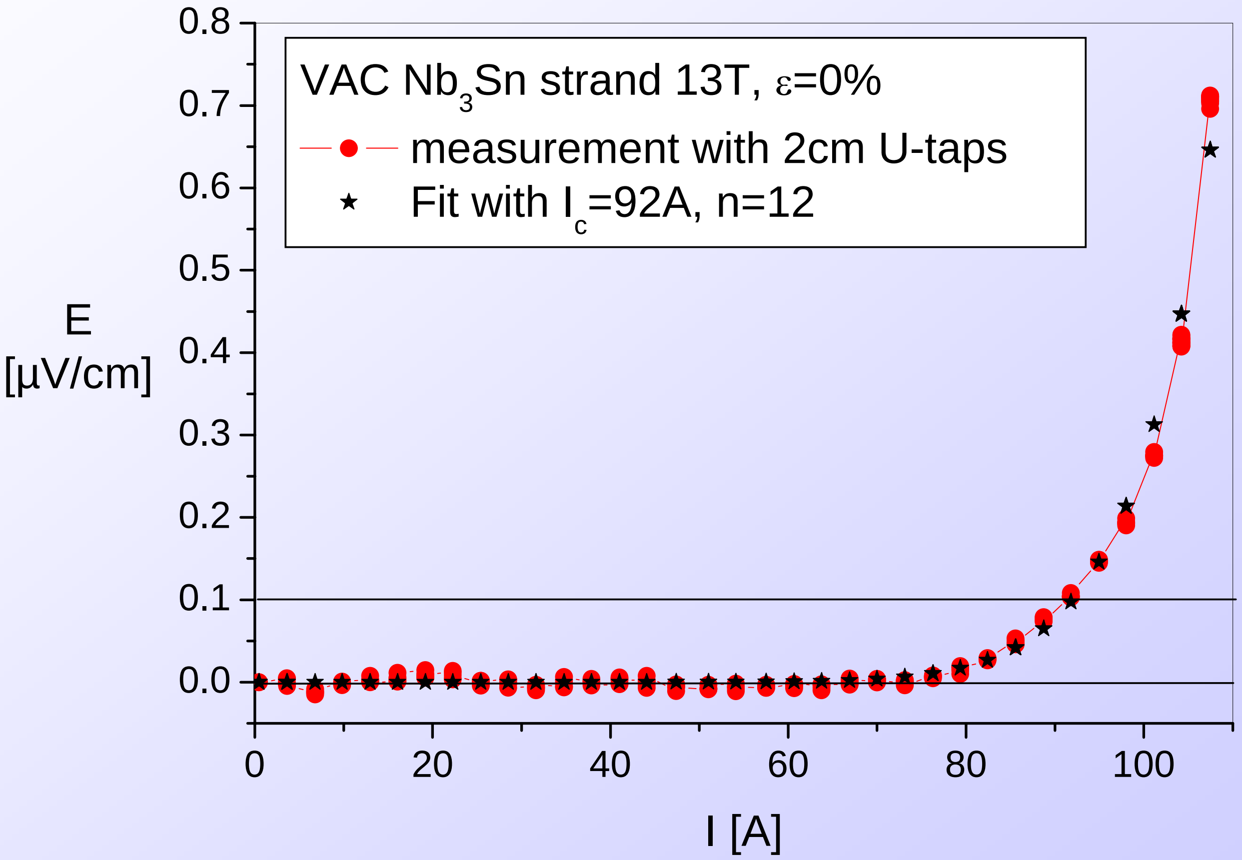


	Field (T)	***Current (kA)***
CS coil	13.5	42
TF coil	11.8	68
PF coil	4 – 6	45
Correction coil	< 6	10
Cryostat feedthrough	< 4	≤ 68
Current lead	< 30 mT	≤ 68
External current feeder	~ mT	≤ 68

Superconducting strands

- **High field > 5 T**
  - Nb_3Sn
  - $E = Ec(J/Jc\{B,T,E\})^{n\ \{B,T\}}$
  - Heat treatment (650 °C, ~ 200 h)
  - Cromium coating (~ 2μm)
- **Low Field < 5 T**
  - NbTi
  - $E = Ec(J/Jc\ \{B,T\})^n$
  - No heath treatment required during coil manufacturing
  - Coating Ni (~ 2 μm)

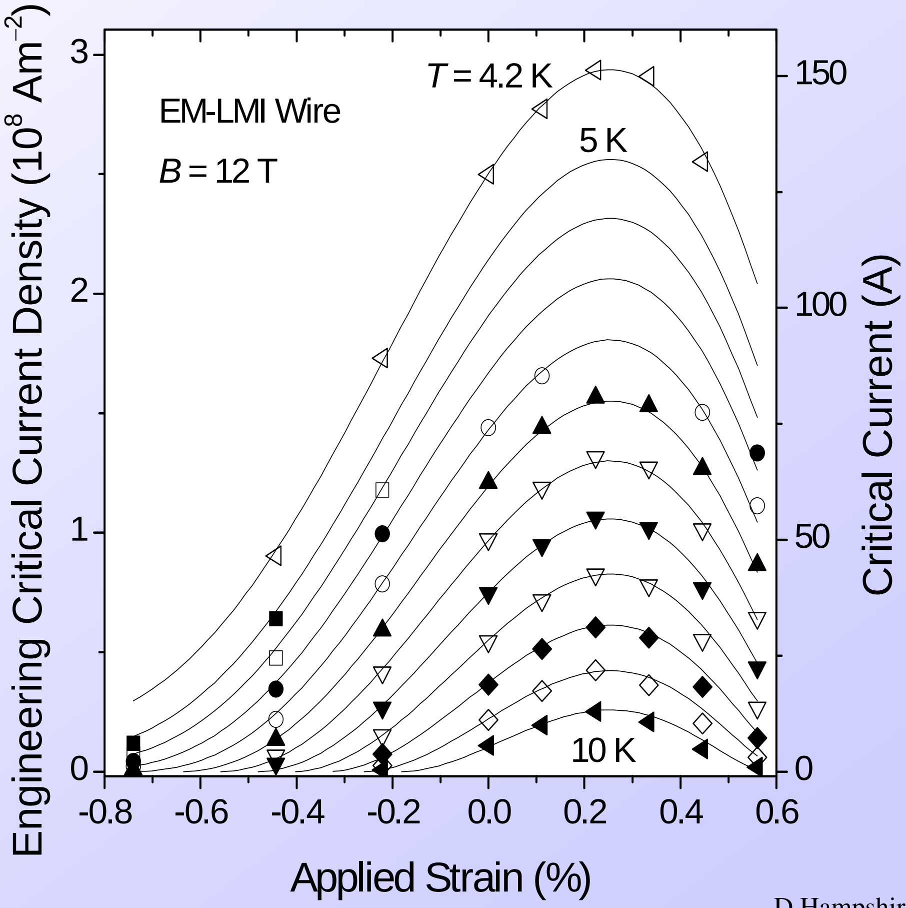
Typical measurement with new FBI setup



$J_C(B,T,\varepsilon)$ data

- 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.



D.Hampshire

Design criteria

- Forced flow cooling: nuclear heating, ohmic power removal and heat losses
- Stability: plasma disruptions, friction heat generation
- Quench protection
- AC losses
- Nb_3Sn strain limit
- D shaped TF coils with SS casing
- SS jacket material
- Segmented central solenoid
- TFC winding pack with Radial Plates?

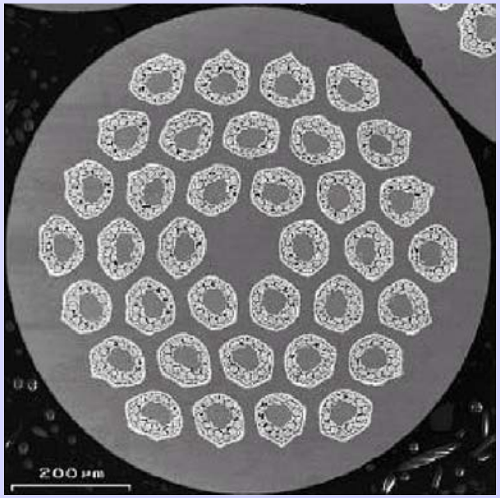
Superconducting cable

- Cables 5 stages (3x3x4x5x6)
- Last-but-one stage wrapes
- 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_3Sn** strands (1080 strands total)

Strand Layout



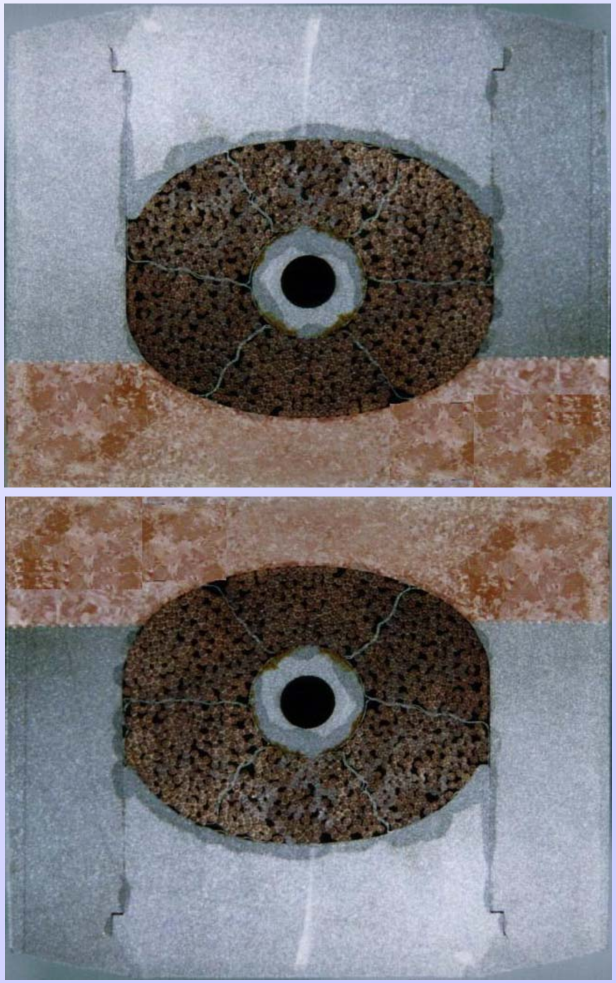
Joints

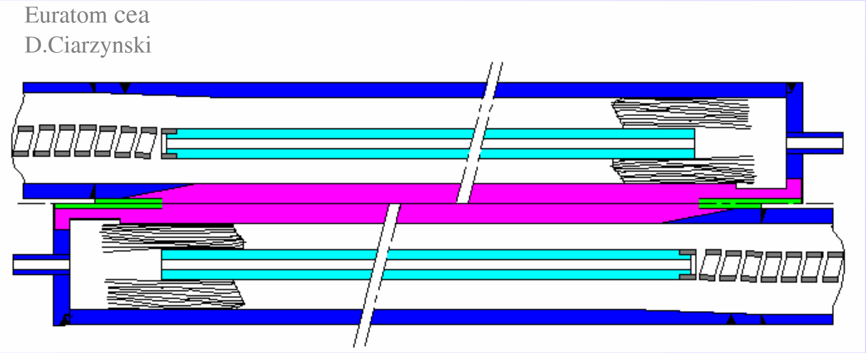
- Between pancakes
- Between coil and normal conductor
- Low resistance and uniform distribution

TFMC – Joints

Technical realisation of the joints

Cables are compacted in twin-material boxes of stainless steel and copper. The boxes are then soldered





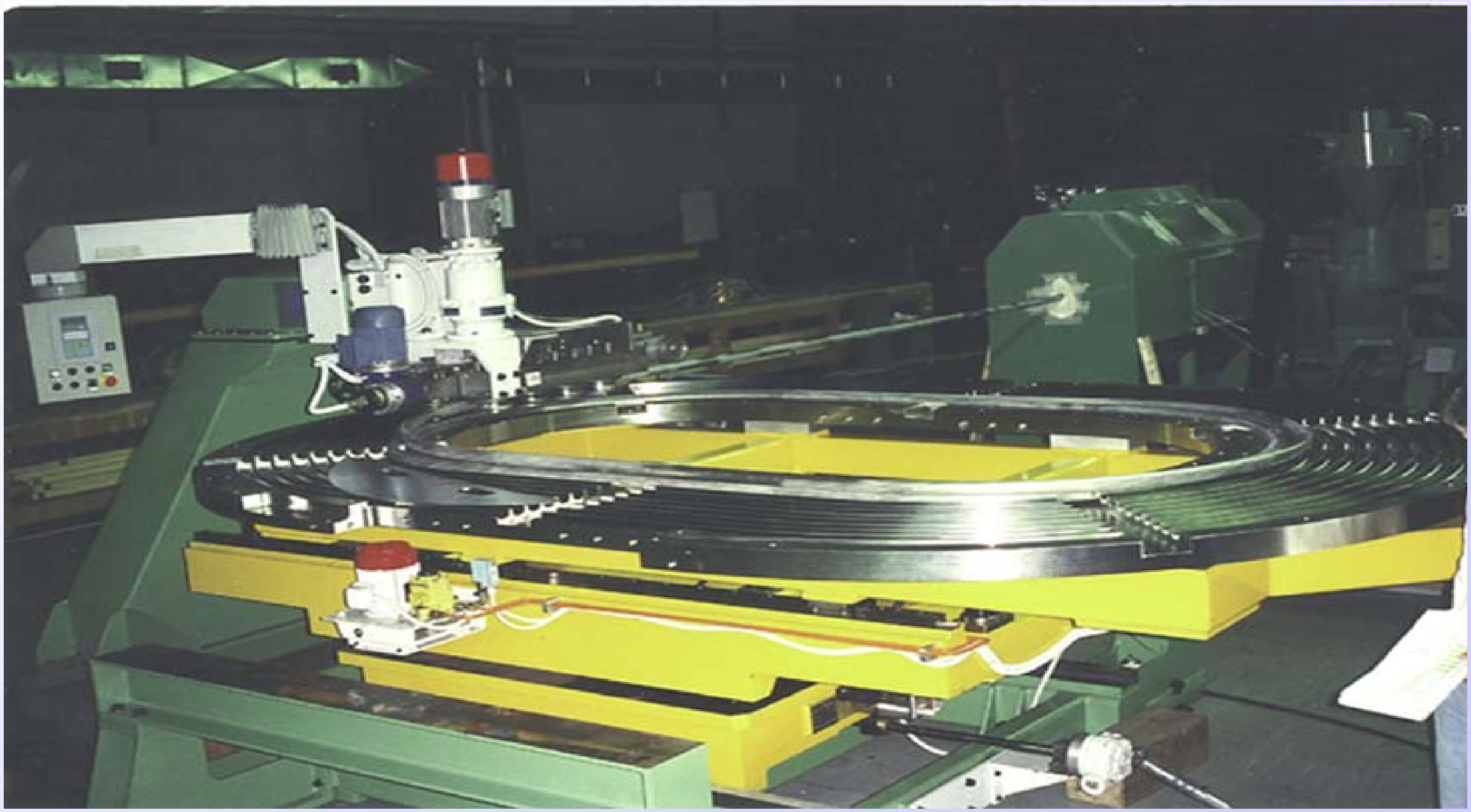
TFMC - Joints
Technical realisation of the joints

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

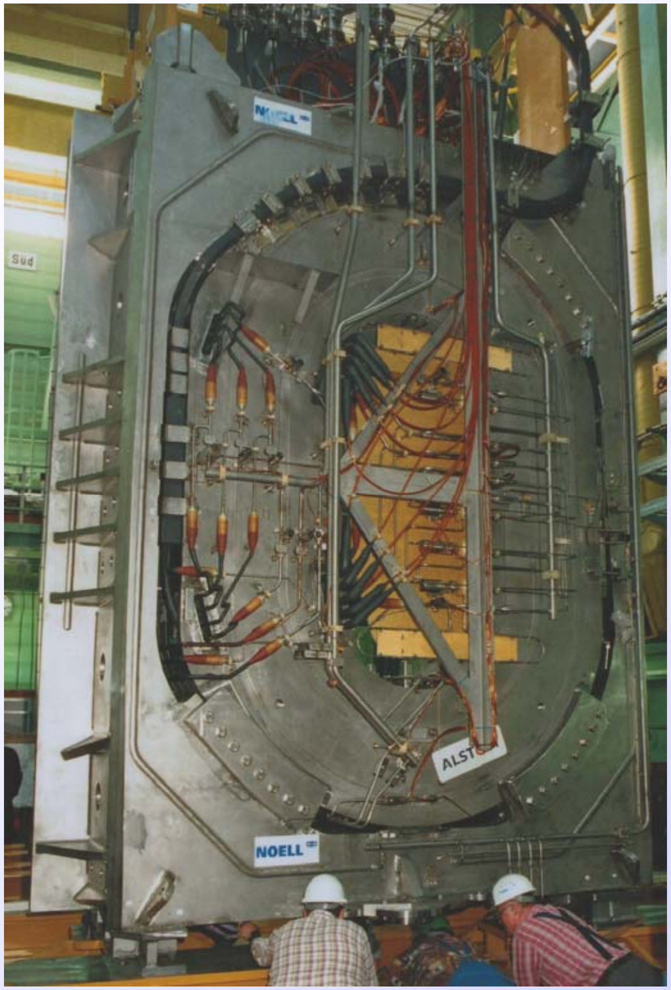
Conductor bending



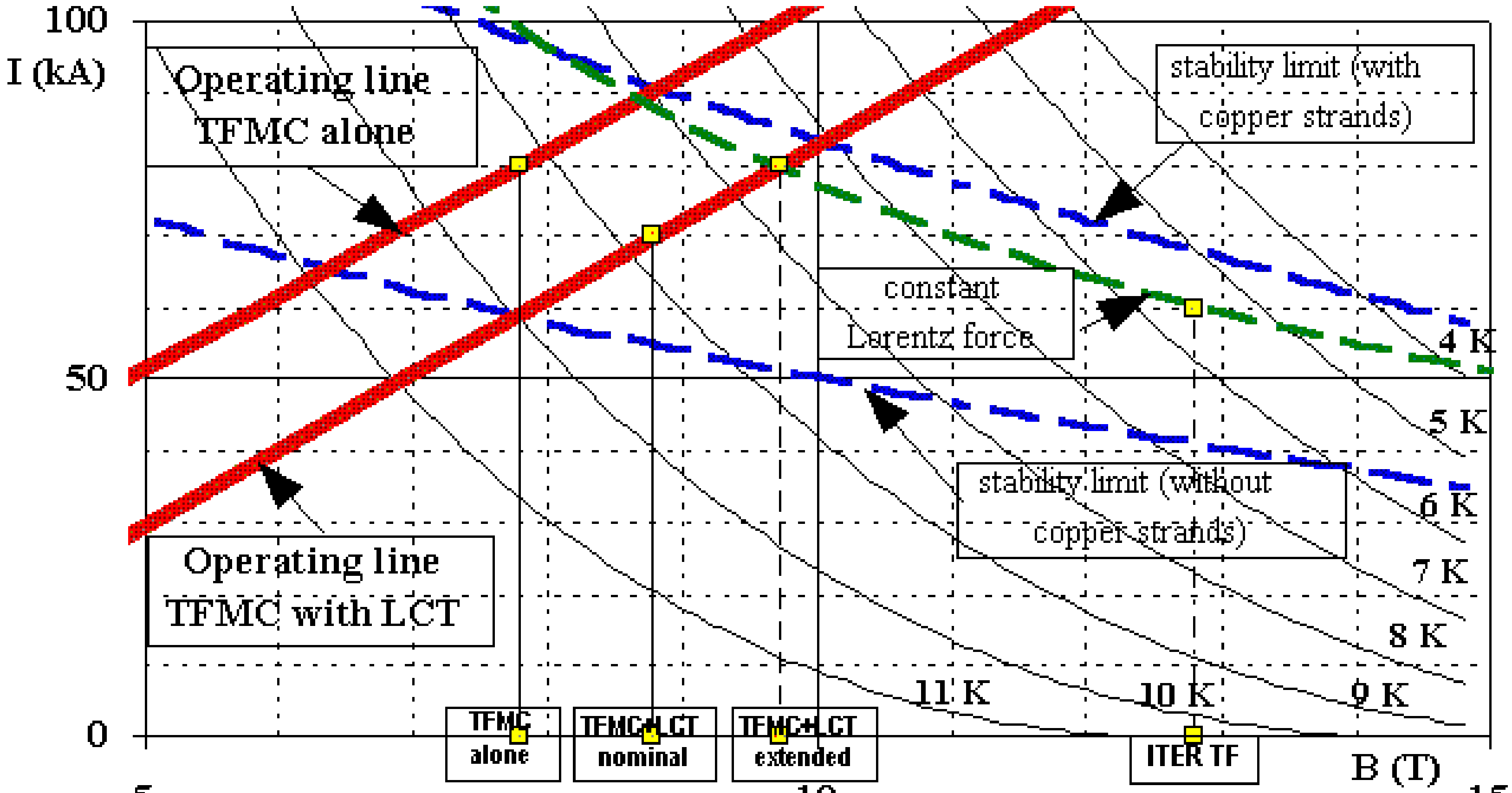
Laser welding

TFMC Winding Pack after Impregnation

ITER - EFDA Magnets R&D Programme - TF Model Coil

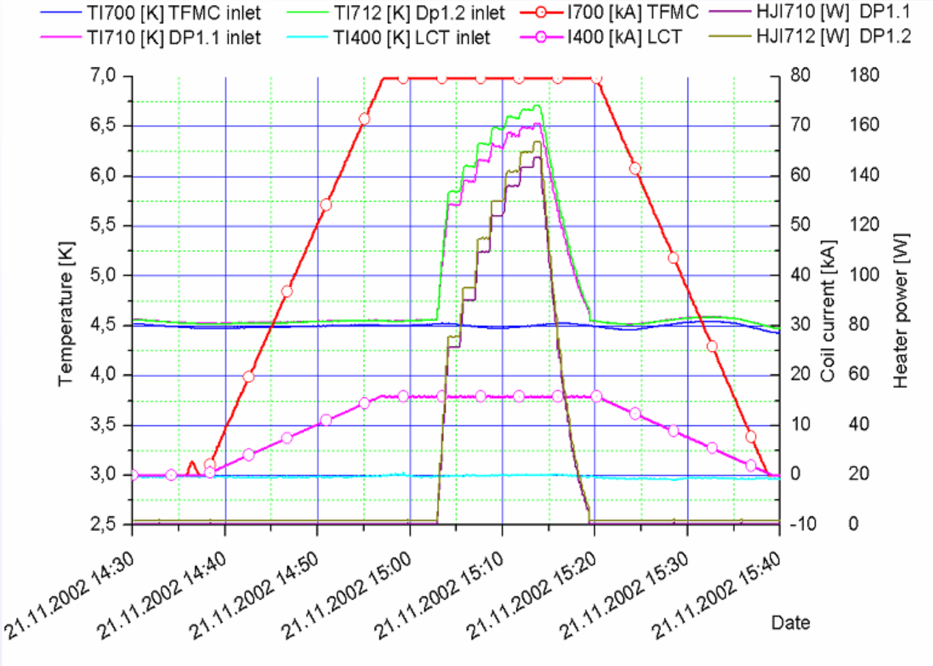


TFMC Operating Diagram

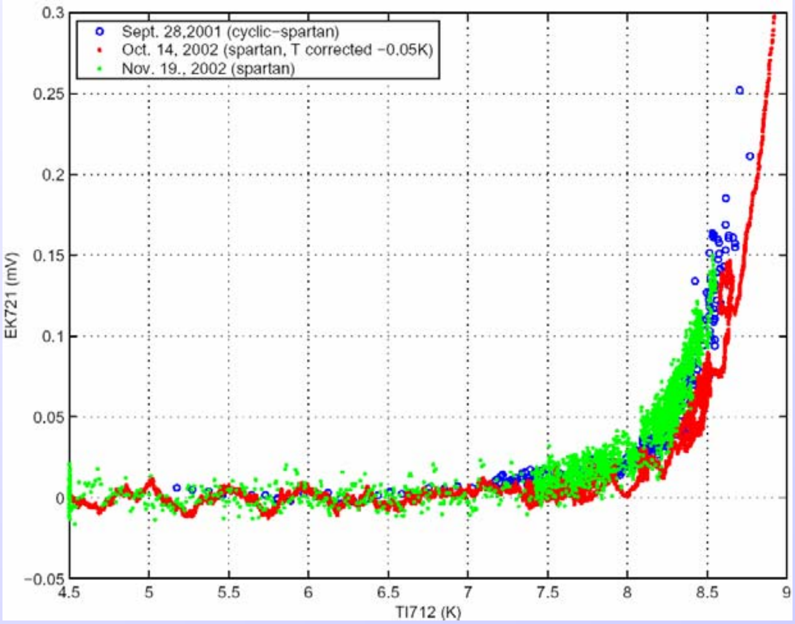


ITER - EFDA Magnets R&D Programme - TF Model Coil

TFMC (80 kA) + LCT (16 kA)



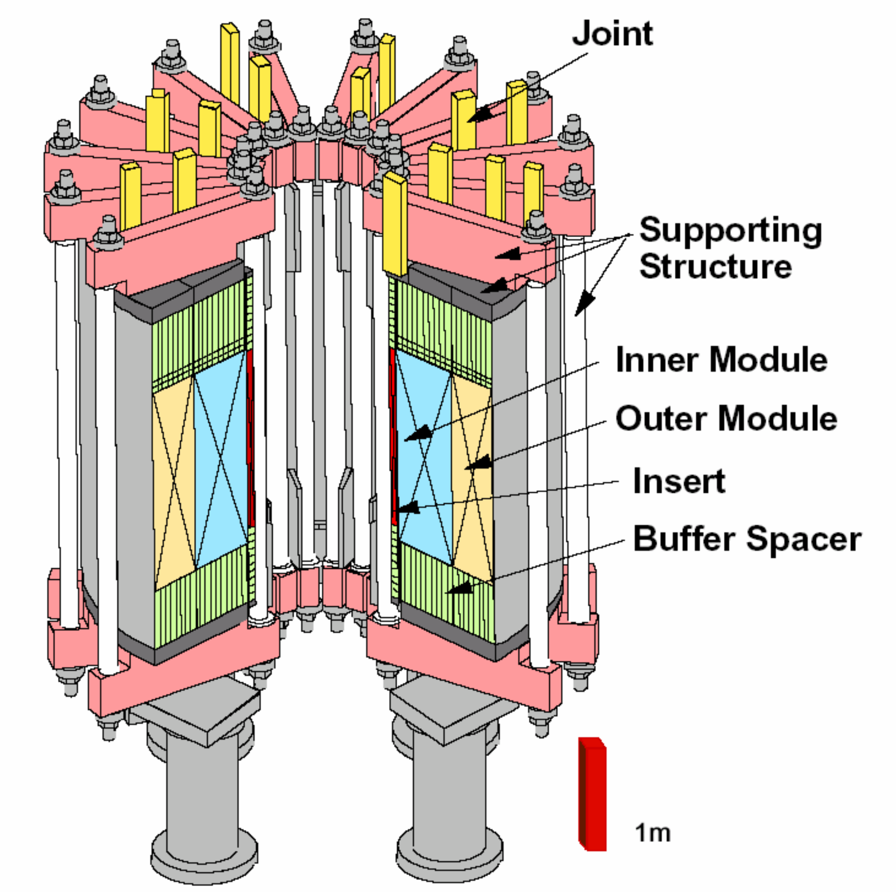
TFMC (80 kA)



TFMC exceeded design values

No performance degradation

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



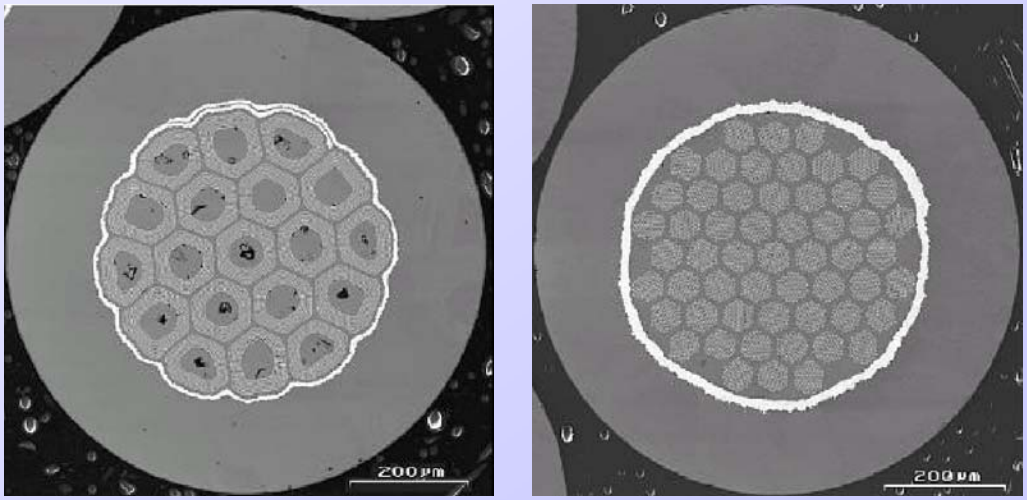
Coil Design Parameters

	CSI	CSMC IM	CSMC OM
Maximum Field	13 T	13 T	7.3 T
Operating Current	40 kA	46 kA	46 kA
Outer Diameter	1.57 m	2.71 m	3.62 m
Height	2.80 m	2.80 m	2.80 m
Weight	7.7 t	49.3 t	52 t
Stored Energy	11 MJ	640 MJ	

Developed ITER Conductors - CS Model Coil

- Current: **46 kA** (4.5 K, 13 T)
- **Incoloy 908 jacket** (51 × 51 mm^2)
- Cable diameter: 38 mm
- 1152 **Nb$_3$Sn** strands

Strand Layouts

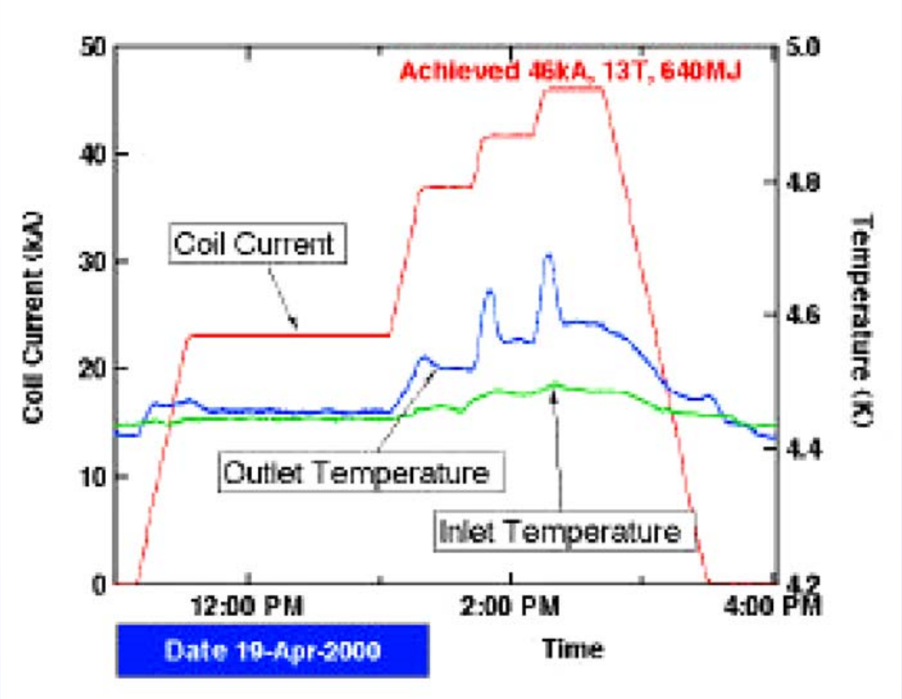


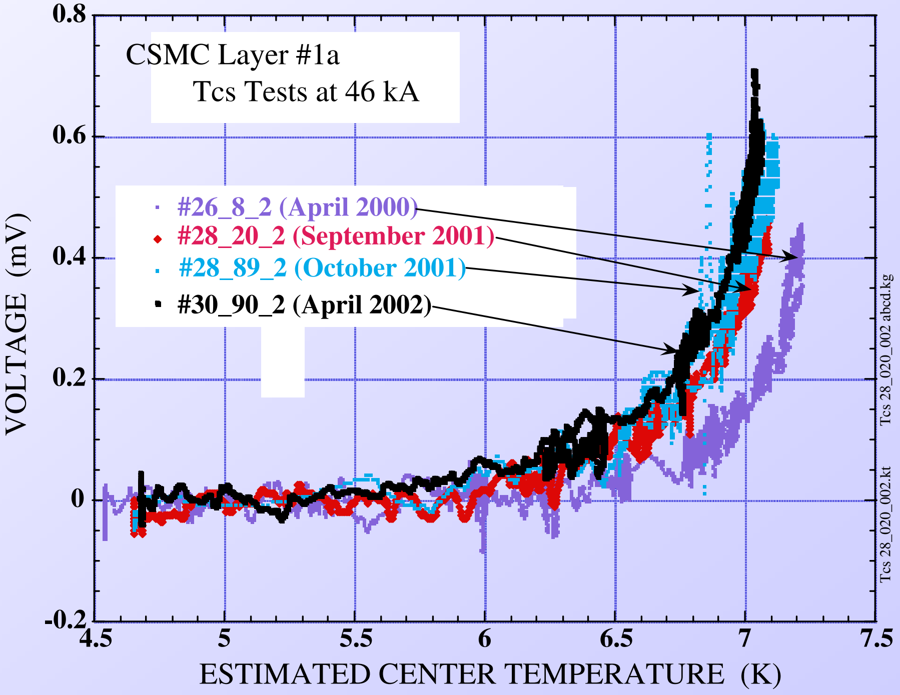
ITER - EFDA Magnets R&D Programme - CS Model Coil

CSMC: Inner module

CSMC: Outer module

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

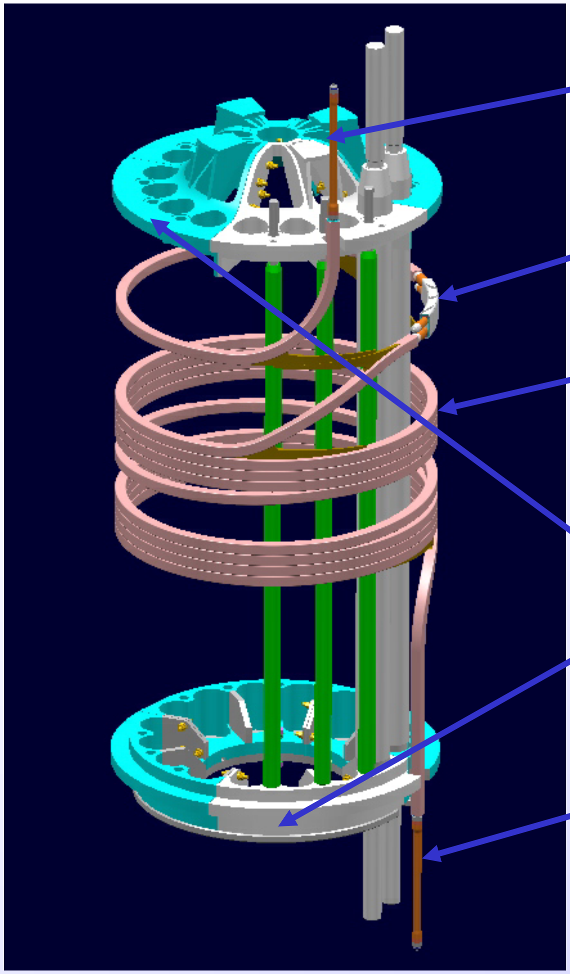




CSMC successfully achieved design values

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

ITER - EFDA Magnets R&D Programme - PF Insert Coil



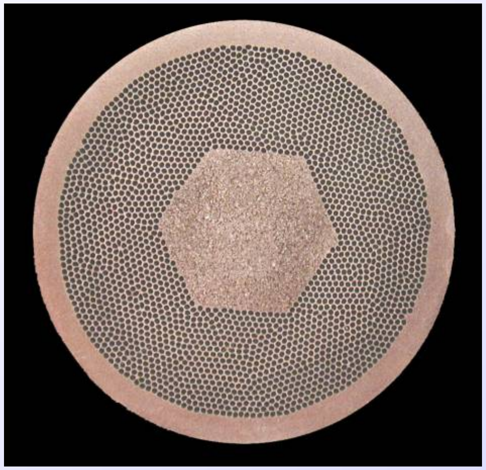
Coil Design Parameters

		PFI
Maximum Field		6.3 T
Maximum Operating Current		50 kA
Maximum Field Change		2 T/s
Conductor length		49.50 m
Main Winding Envelope	Outer Diameter	1.57 m
	Inner Diameter	1.39 m
	Height	1.40 m
Height		1.40 m
Weight		6 t

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

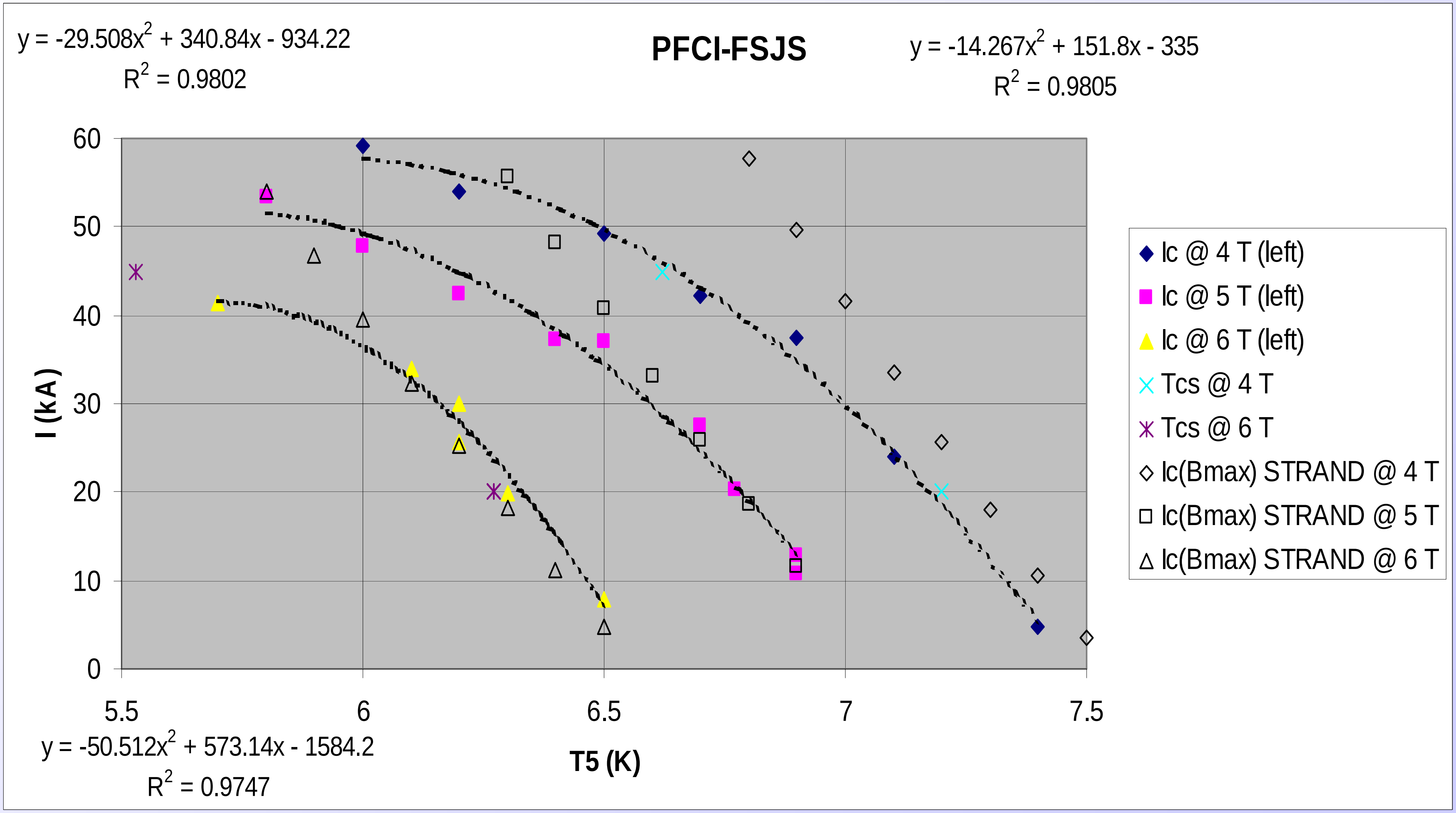
Strand Parameters



- $J_c > 2700$ 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

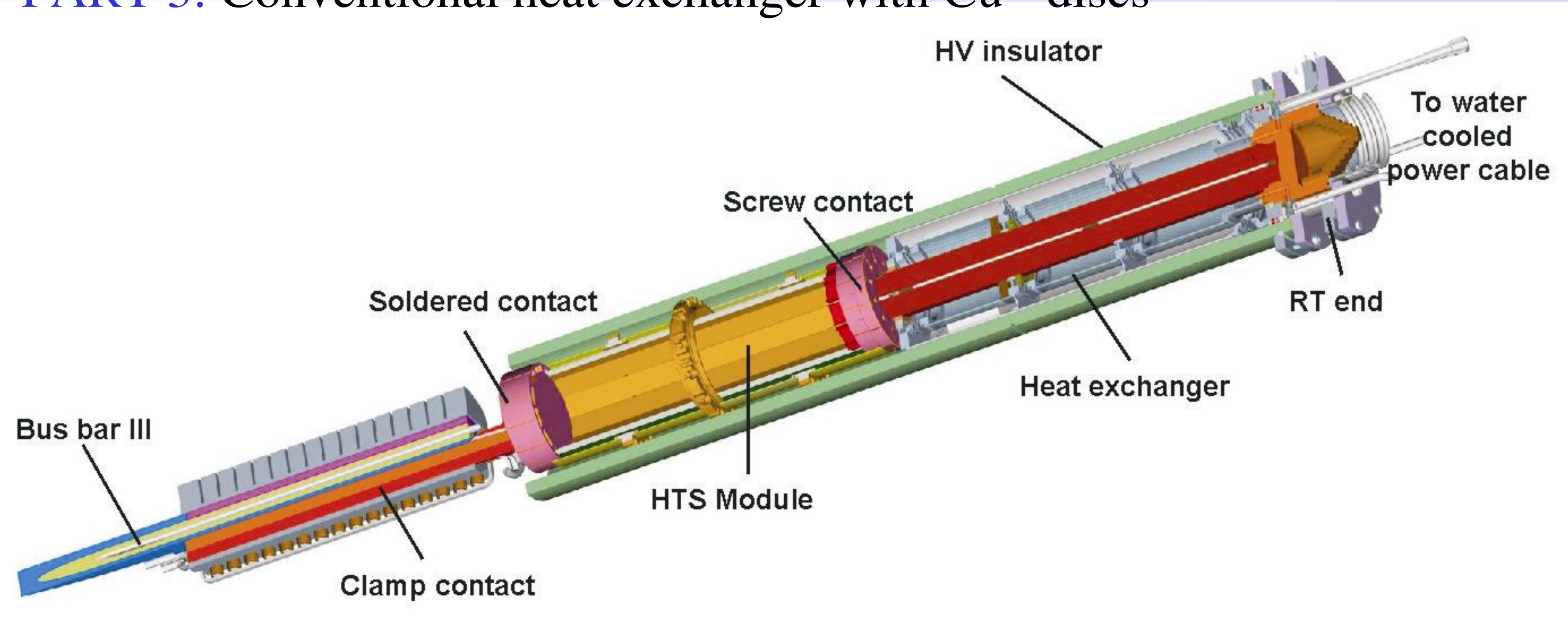


ITER - EFDA Current Lead R&D Programme - Design of the 70 kA HTS CL

PART 1: Clamp contact with three Nb_3Sn inserts

PART 2: HTS module with Ag/Au sheated Bi-2223 tapes

PART 3: Conventional heat exchanger with Cu - discs



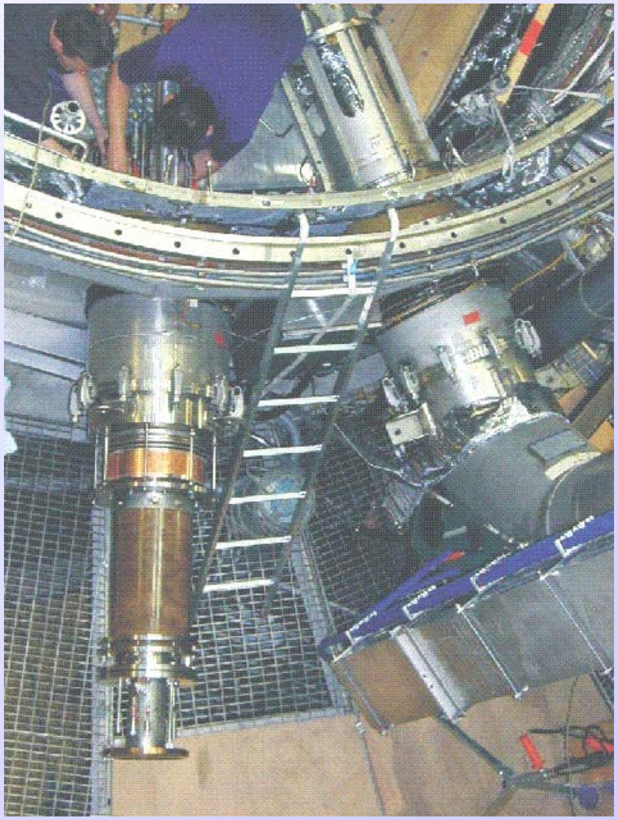
70 KA HTSC Current Lead

- 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):

Coils	No. of pairs	I_{max}	Type	V_{max}
TF Coil	9	68 kA	F	10 kV
PF Coil	6	45 kA	V	14 kV
Correction Coil	9	8 kA	V	3 kV
CS Coil	6	45 kA	V	10 kV

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

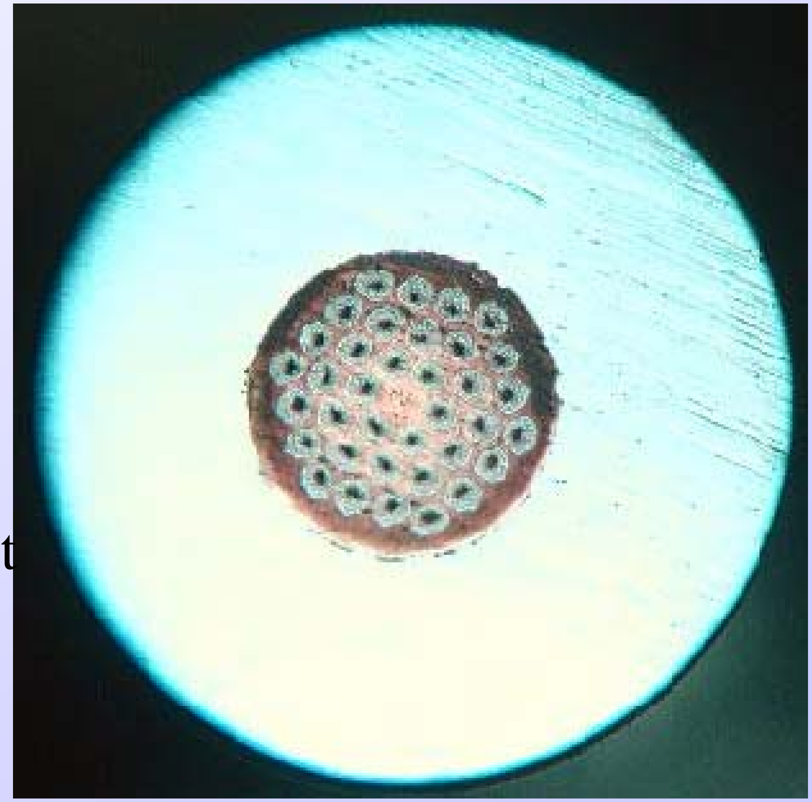
- 68 kA steady state up to a warm end temperature of 80 K (T_{HTS} = 80 K)
- Quench temperature at 68 kA: 92 K
- 80 kA steady state (T_{HTS} = 55 K)
- Heat load into 4.5 K : 13.5 W
- Cold end contact: 1.9 nΩ
- LOFA (68 kA, T_{HTS} = 65 K): > 6 min before quench (ITER requirement: > 3 min)
- Poor screw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

Bending Strain Tests - Jacketing of Single Strands

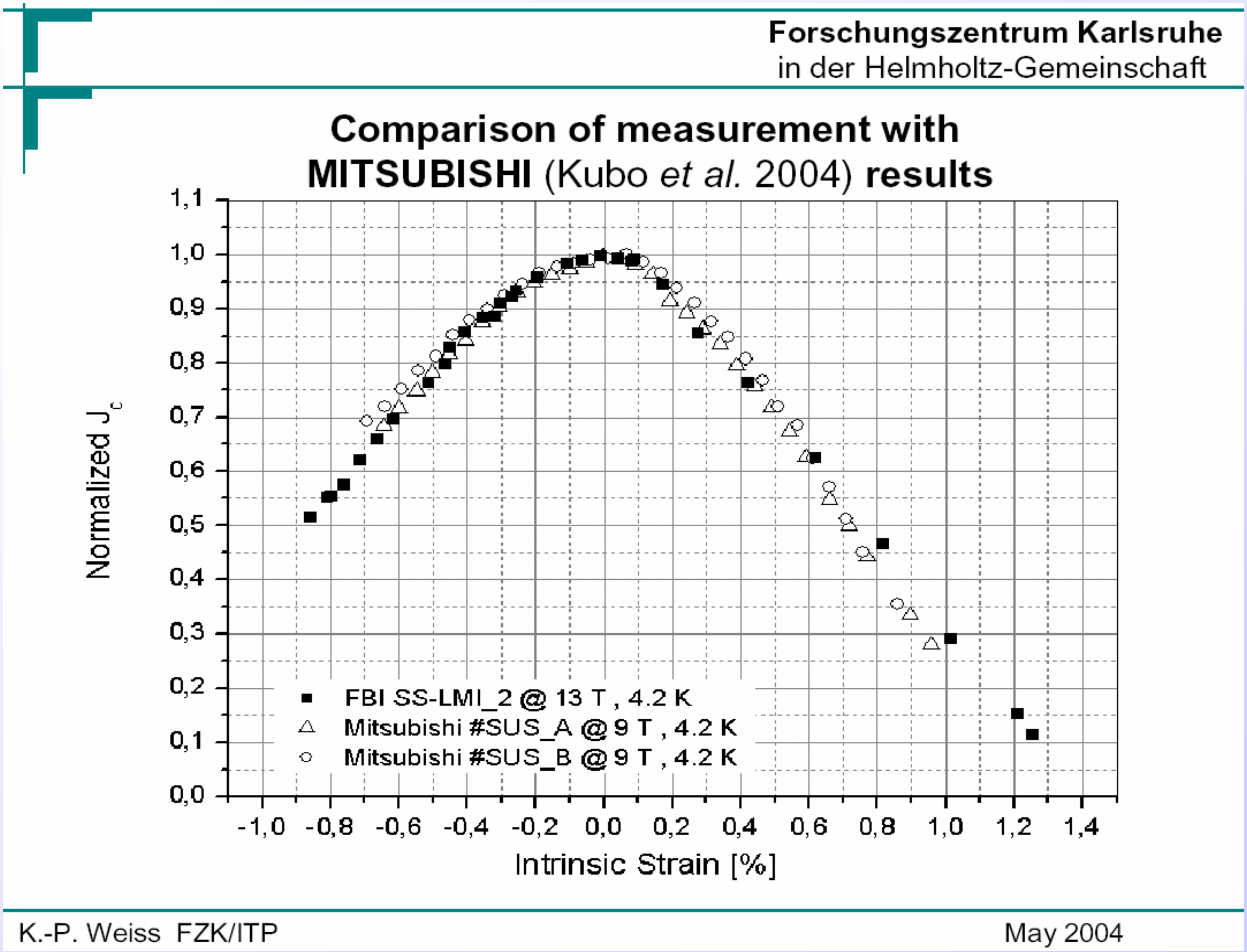
First trials to demonstrate the feasibility of the jacketing of single strands successfully performed in 2003:



- 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



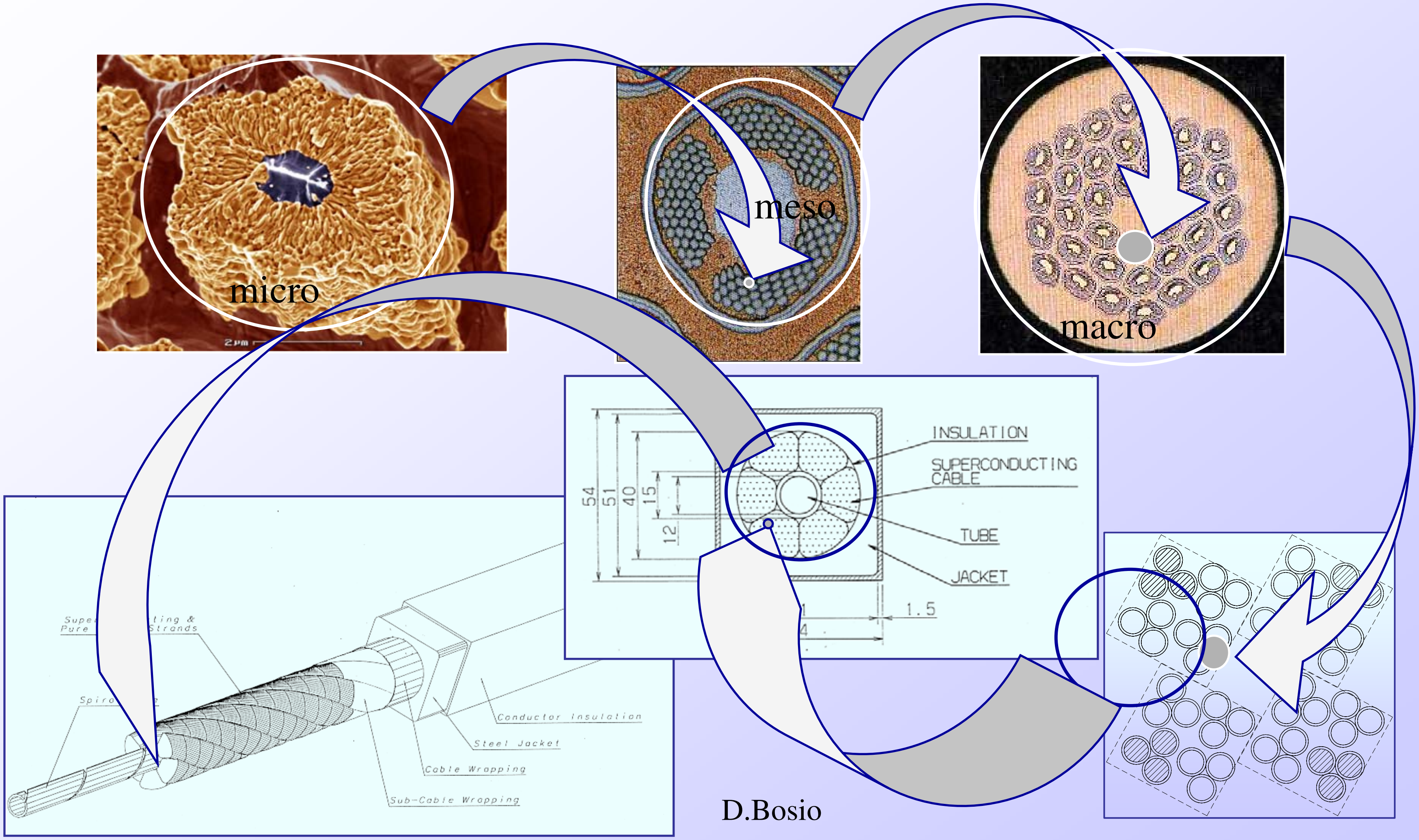
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

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

K.-P. Weiss FZK/ITP

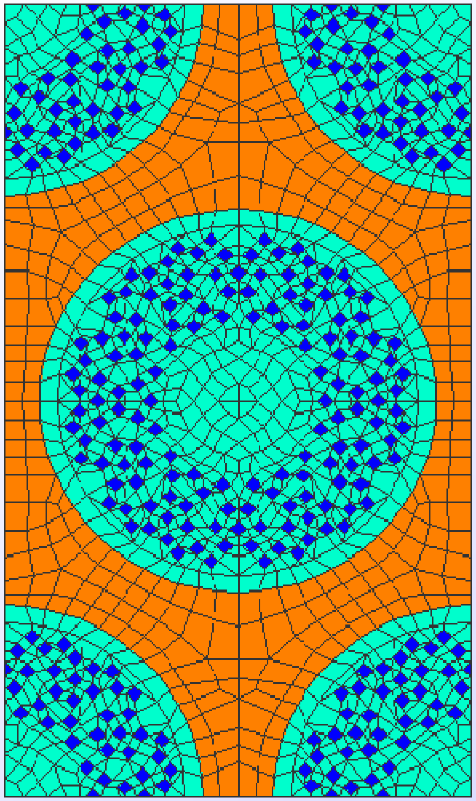
May 2004

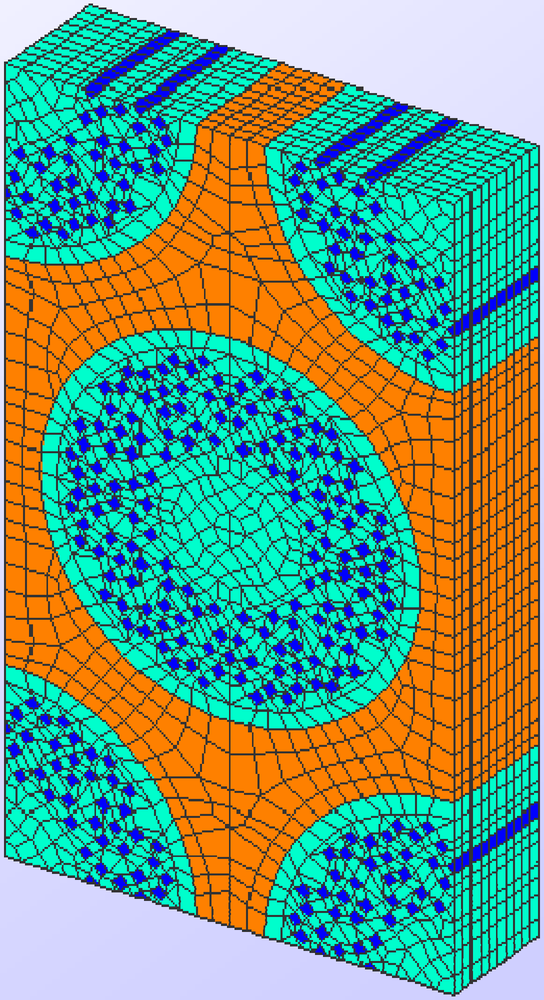
Mechanical Modeling of ITER Superconducting Cables



D.Bosio

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

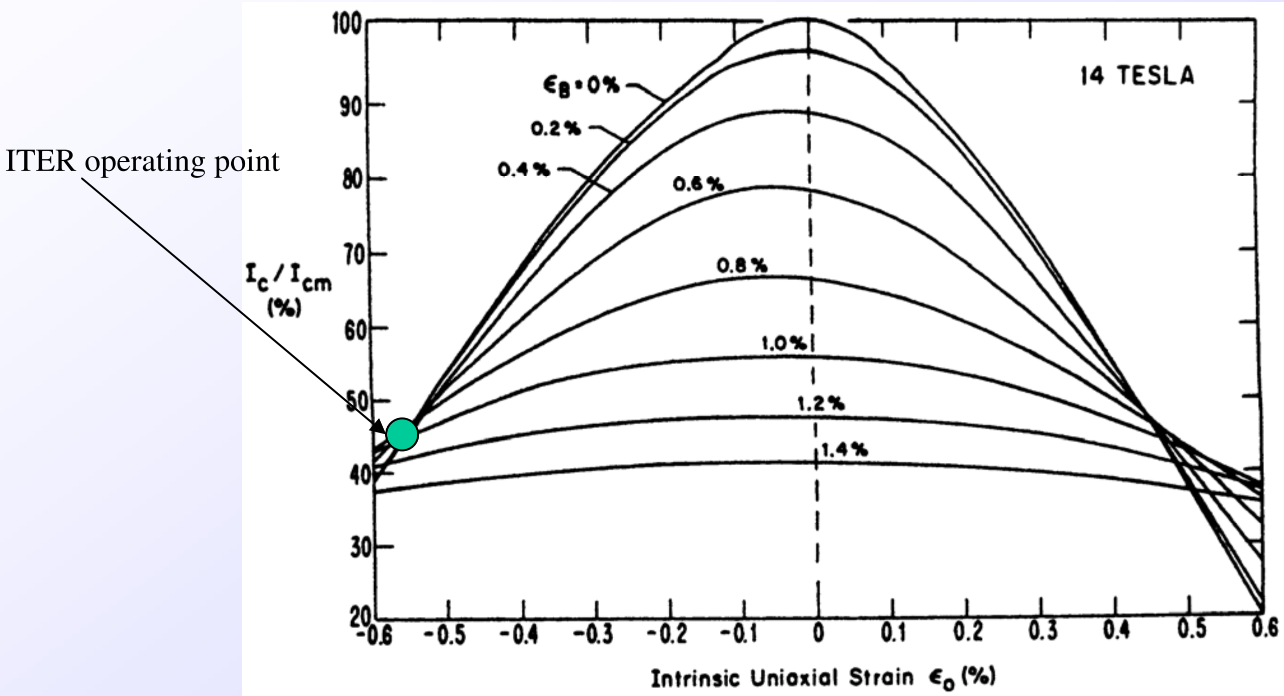
  final longitudinal strain: 0.468%

- 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 ε_B at $\varepsilon_0 \approx -0.5$ %)



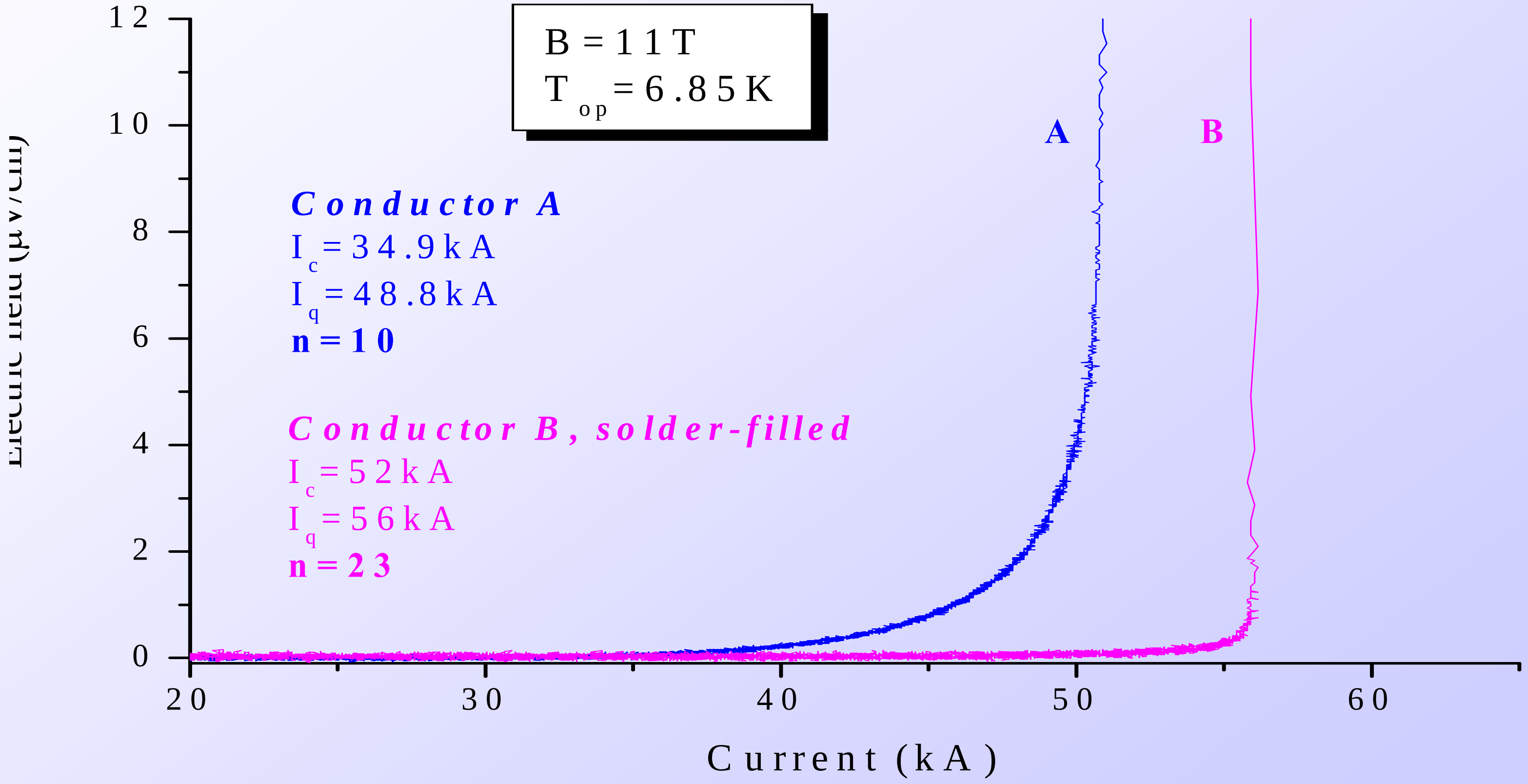
[J. Ekin, 1980]

Current transfer length <<cable twist peach

- Strain sensitivity has to be checked for new advanced strand

DC Test Results (Bending Strain Inpact)

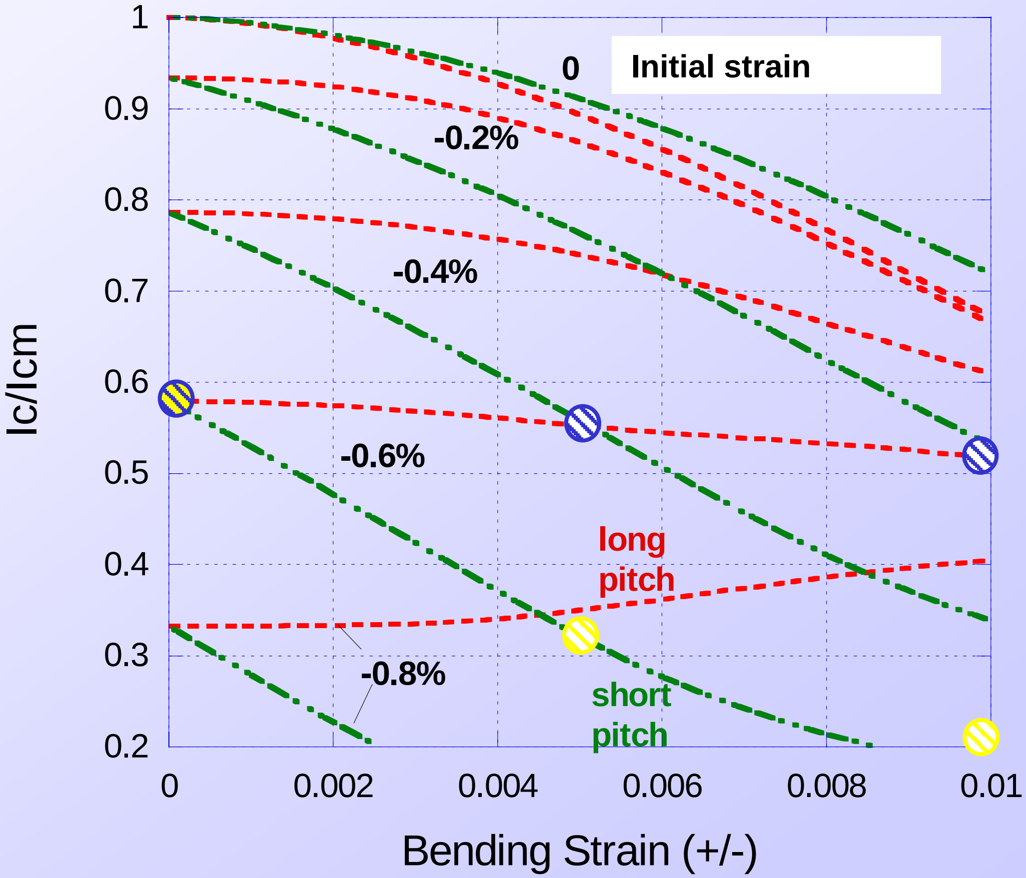
Ti jacketed Conductors :conductor A (residual strain about 0.3%)
solder-filled conductor B(residual strain about 0.4%)



P.L. Bruzzone

Bending Strain Tests - Current Transfer Length

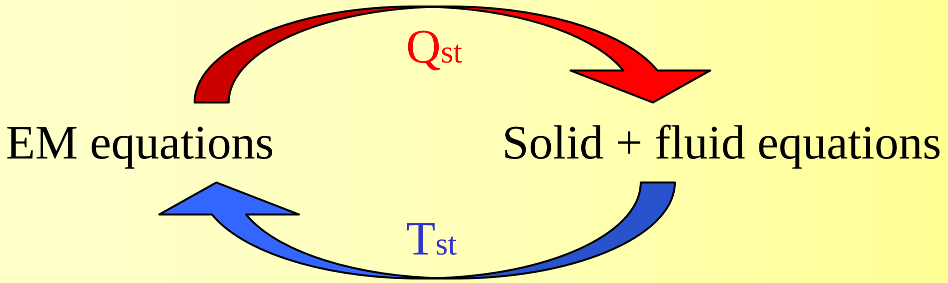
- Measurement of the critical current at three different bending strains to check I_c behaviour
- Bending strain established by transferring reacted strands to different sample holder diameters
- Bending strain value defined by the ratio of the barrel sample holder diameter



[N. Mitchell 2003]

EM/TH coupling

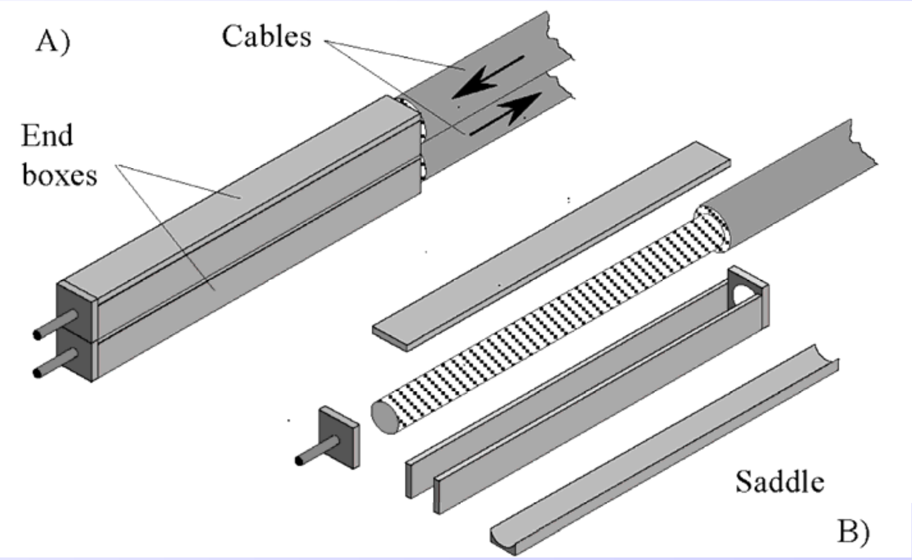
Tstrand is used in the EM part to compute coefficients (material properties). In the EM step $t \rightarrow t + \Delta t$, the EM module uses Tst @ t to compute the power sources. These are then used by the TH module to perform the TH step $t \rightarrow t + \Delta t$, and so on



Explicit EM/TH coupling

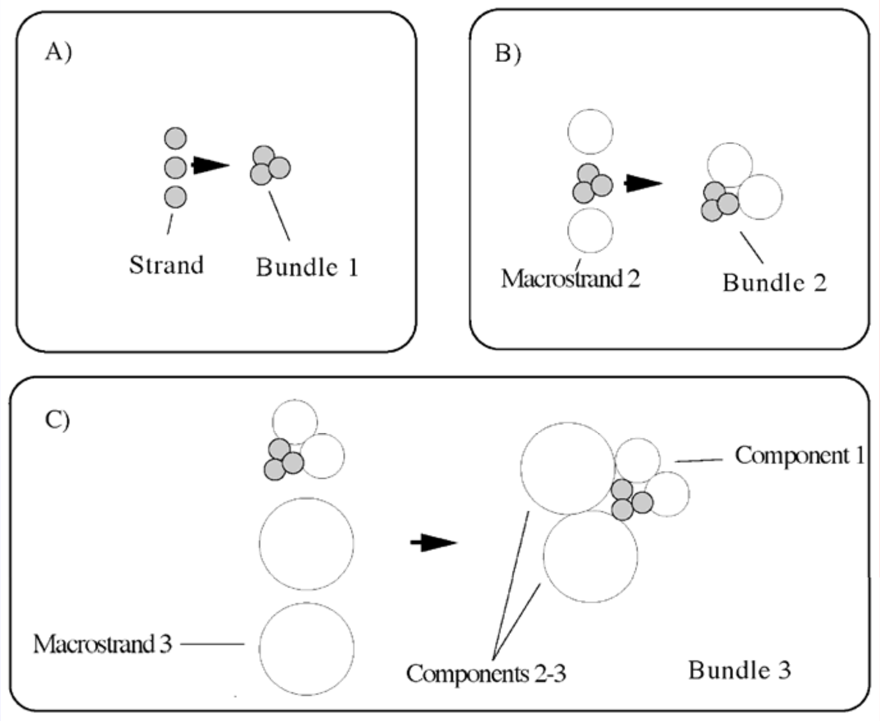
Thelma joint model

- CICC short segments
- Resistive saddles between the CICCs

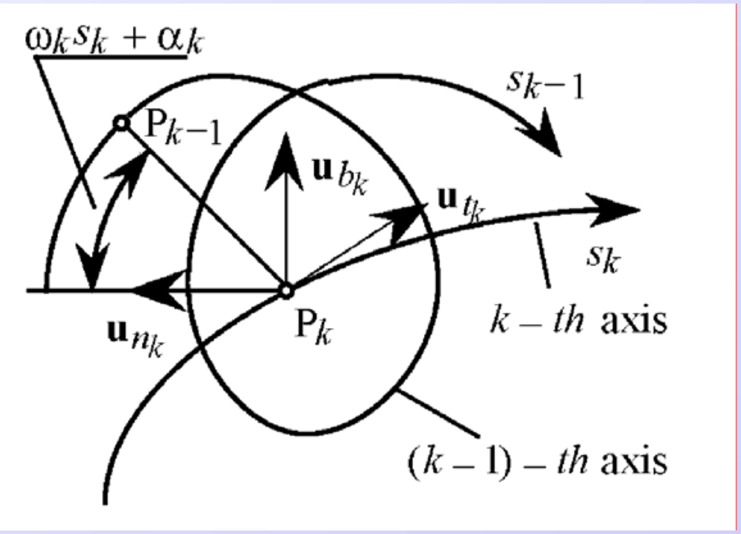


Geometrical model of CICC segments

Bundle cross-section



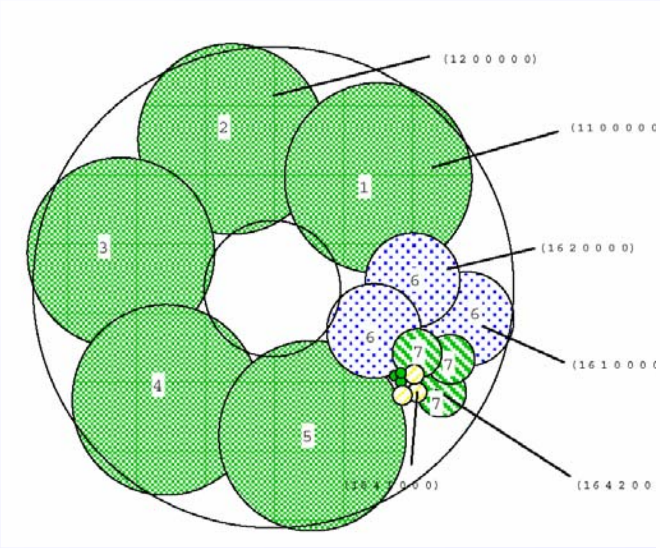
Strand/macrostrand axis

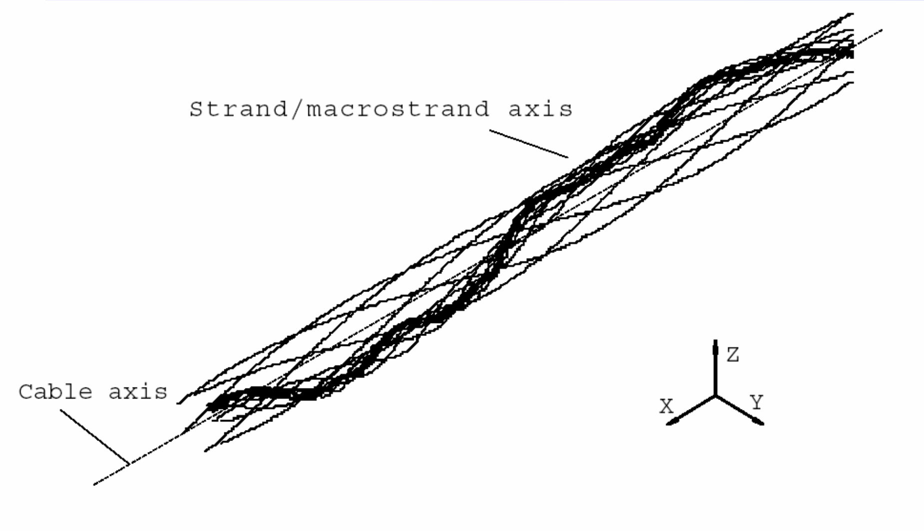


$$\mathbf{OP}_{k-1} = \mathbf{OP}_k + r_k \cdot \cos(\omega_k s_k + \alpha_k) \cdot \mathbf{u}_{n_k} + r_k \cdot \sin(\omega_k s_k + \alpha_k) \cdot \mathbf{u}_{b_k}$$

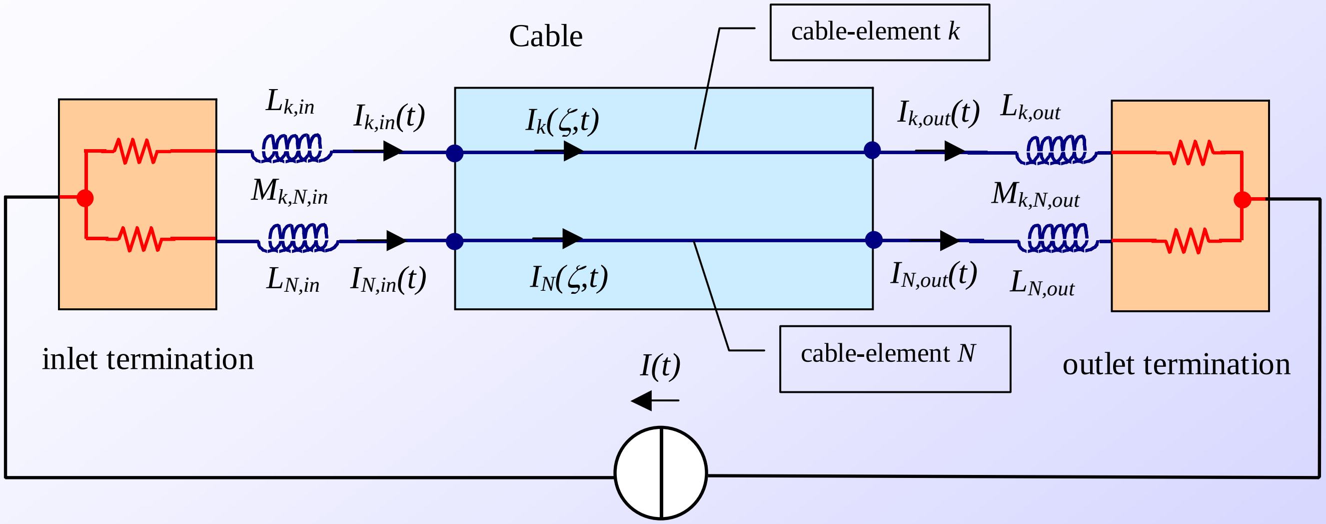
Example

ITER-type CICC modelled with 17 strands + macrostrands





THELMA CABLE MODEL



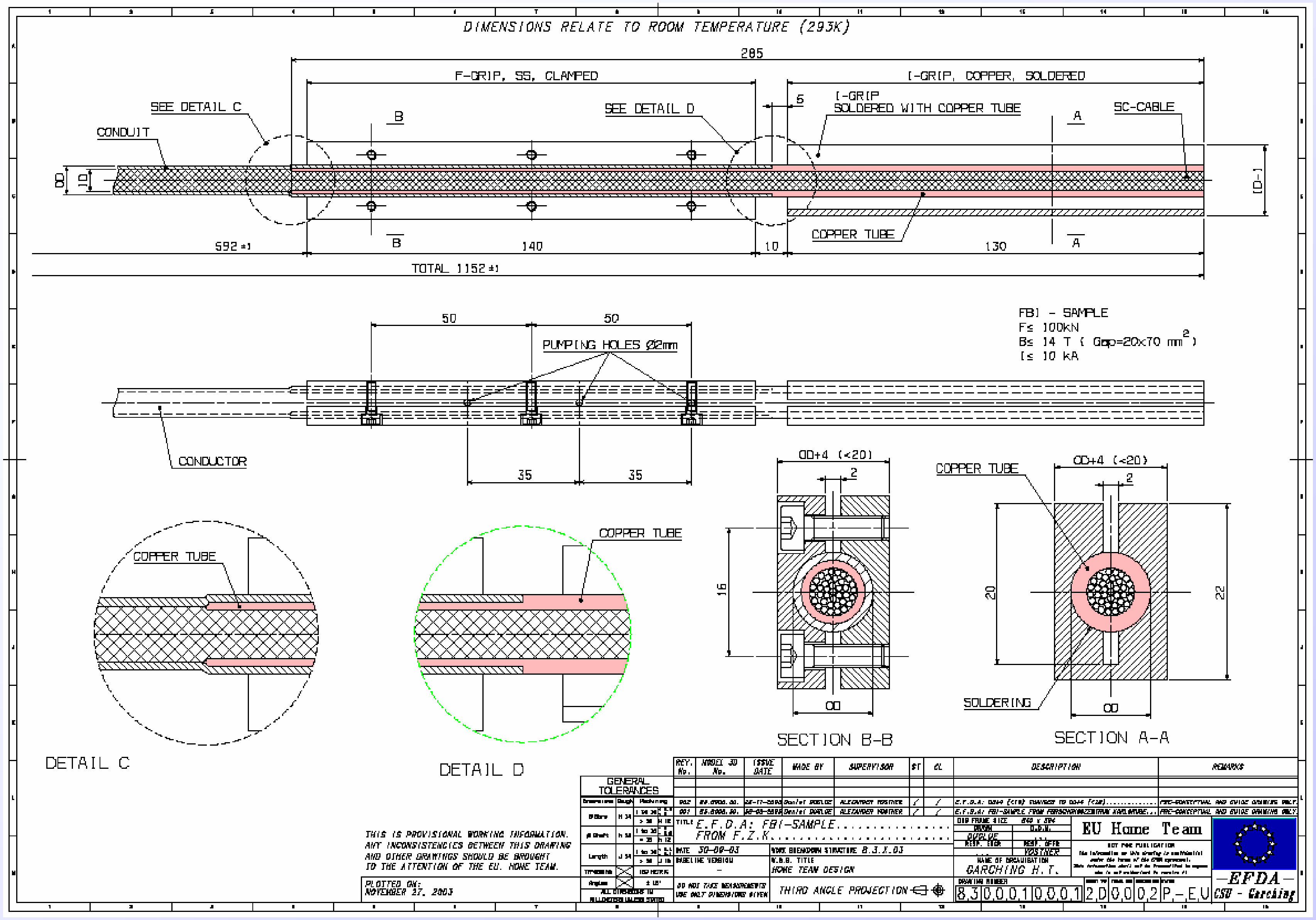
- ♦ A current driven system is considered.
- ♦ A cable-element can be either a single strand or a strand bundle.
- ♦ The model is self consistent with given inlet and outlet currents or can be coupled with a termination/joint model.
- ♦ **The model is aimed to simulate real size coils**

Nb_3Sn Strand Specification

Outer diameter of the strand	0.81 mm ±3 μm
Strand pitch	< 20 mm
Hard Cr-coating	2 μm +0.5 μm / –0 μm
Overall critical strand current (at 12 T, 4.2 K, 0.1 μV/cm)	Min. guaranteed: **200 A**[a] Target value: **280 A**[b]
Overall strand hysteresis losses (on a ±3T field cycle)	< 500 kJ/m^3
n-value at 12 T and 4.2 K	> 20
RRR after reaction heat treatment	> 100
Cu:non-Cu ratio	**0.9 – 1.5**
Minimum acceptable length of strand	> 1.5 km

[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] Eequivalent 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


DIMENSIONS RELATE TO ROOM TEMPERATURE (293K)
285
F-GRIP, SS, CLAMPED
I-GRIP, COPPER, SOLDERED
SEE DETAIL C
CONDUIT
B
SEE DETAIL D
5
I-GRIP
SOLDERED WITH COPPER TUBE
A
SC-CABLE
OD
ID
[D-]
COPPER TUBE
592 ±1
140
10
130
TOTAL 1152 ±1
FBI - SAMPLE
F≤ 100kN
B≤ 14 T (Gap=20x70 mm2)
I≤ 10 kA
50
50
PUMPING HOLES Ø2mm
CONDUCTOR
35
35
OD+4 (<20)
2
16
OD
SECTION B-B
COPPER TUBE
OD+4 (<20)
2
20
22
SOLDERING
OD
SECTION A-A
COPPER TUBE
DETAIL C
COPPER TUBE
DETAIL D
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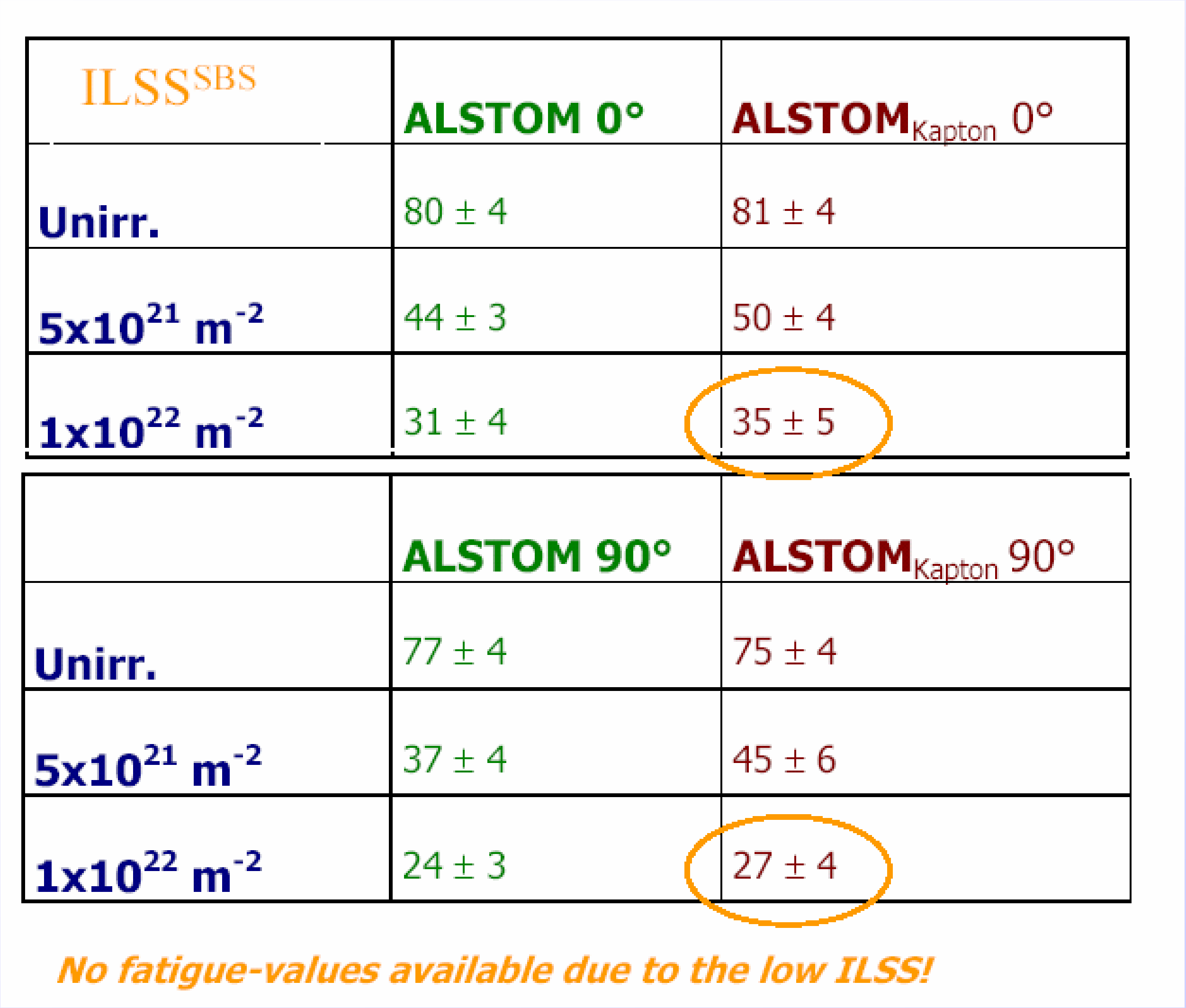
W.B.S. TITLE
HOME TEAM DESIGN
DO NOT TAKE MEASUREMENTS
USE ONLY DIMENSIONS GIVEN
THIRD ANGLE PROJECTION
NAME OF ORGANISATION
GARCHING H.T.
EU Home Team
NOT FOR PUBLICATION
DRAWING NUMBER
8.3 0.0.0.1 0.0.0.1 2.D 0.0 0.2 P.-.E.U
-EFDA-
CSU - Garching

„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



$ILSS^{SBS}$	**ALSTOM 0°**	**$ALSTOM_{Kapton}$ 0°**
Unirr.	80 ± 4	81 ± 4
$5x10^{21}$ m^{-2}	44 ± 3	50 ± 4
$1x10^{22}$ m^{-2}	31 ± 4	35 ± 5

	ALSTOM 90°	**$ALSTOM_{Kapton}$ 90°**
Unirr.	77 ± 4	75 ± 4
$5x10^{21}$ m^{-2}	37 ± 4	45 ± 6
$1x10^{22}$ m^{-2}	24 ± 3	27 ± 4

No fatigue-values available due to the low ILSS!

Search for Systems with higher radiation resistance

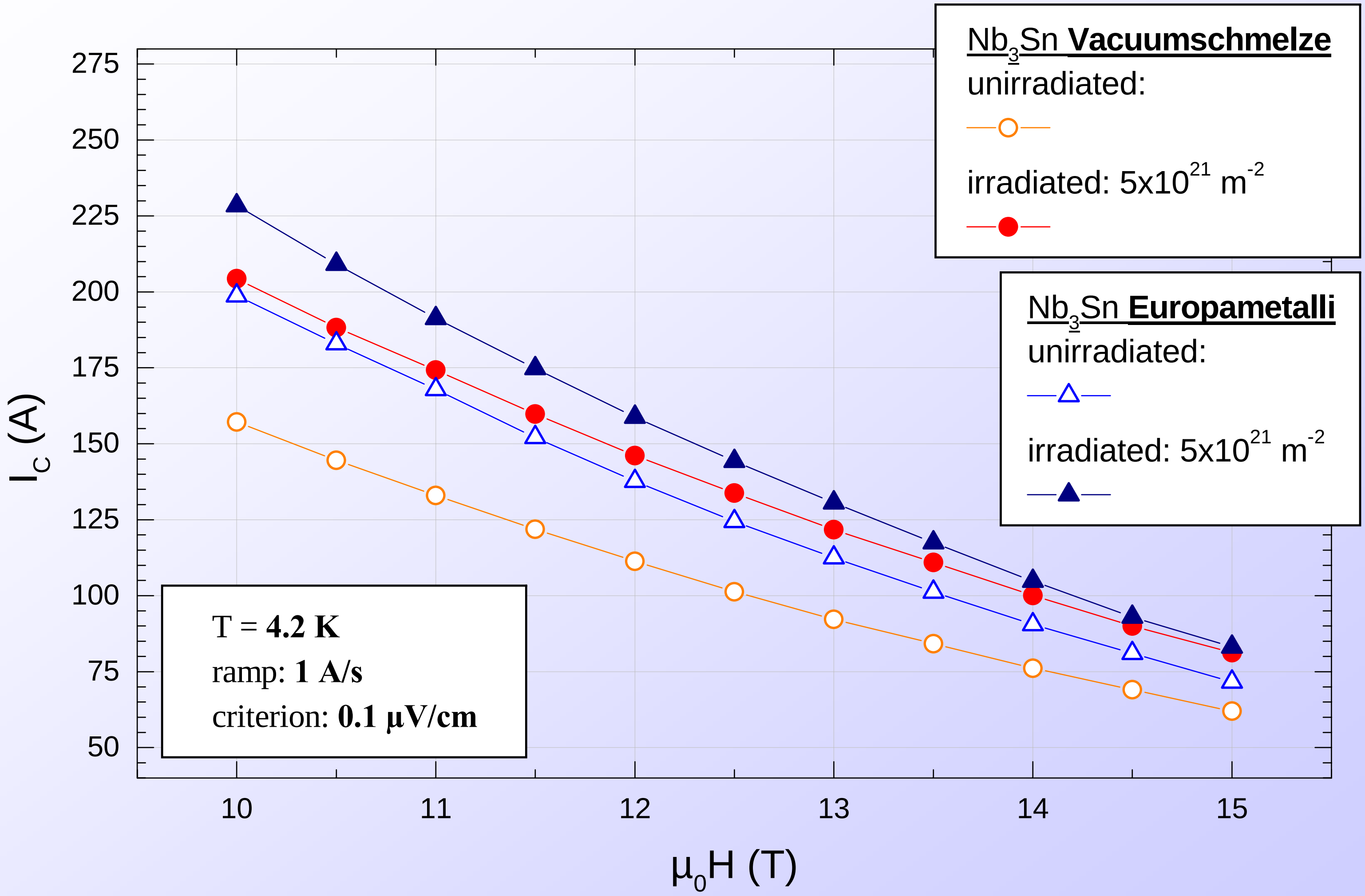
System Overview

August 2003

	TFMC 1	TFMC 2	Test 1	Test 2 (blended)		Test 3	Test 4	Test 5	Test 6	Test 7
Type	DGEBA	DGEBA	Cyanate Ester	DGEBA about 60%	Cyanate Ester about 40%	DGEBA purified	DGEBA	DGEBA compatible	DGEBA	DGEBA purified
Resin	Araldite F	MY745	AroCy-L10	PY306	AroCy-L10	MY790-1	CW229	MY790	LY1025/CH *****)	MY790-1
Hardener	HY905	HY905	----	--	--	HY1102	HW229	HY5200	HY906	HY1102
Additives	DY040	DY072 DY073	Mn Acetyl-acetonat in Nonyl-phenol		Mn Acetyl-acetonat in Nonyl-phenol	***)	(filled)**)	***)	Orlitherm 44	
Impregn. Temp.	75 +/- 5 °C	80 – 85 °C	40°C	70°C		50°C	70°C	70°C	80°C	75°C
Impregn. Viscosity	< 80 mPa s	< 80 mPa s	100 mPa s @25°C	350 mPa s	@25°C	350 mPa s @25°C	2000 mPa s @60°C	~500 mPa s @40°C	70 mPa s @80°C	350 mPa s @25°C
Curing Temp.	100 - > 135°C	90 - > 105°C	80°C gel/ 140°C	80°C 100-160°C	gel 5 hours	80°C gel/ 120-140°C	80°C gel/ 110-140°C	100°C gel 120-160°C/ +180°C Nh	100°C gel/ 130°C	70°C gel/ 120°C ****)
Supplier	Huntsman	Huntsman	Huntsman	Huntsman	Huntsman	Huntsman	Huntsman	Huntsman	ABB	Huntsman
Filler Material	R-Glass + Kapton H	R-Glass + Kapton H	R-Glass + Kapton H	R-Glass +	Kapton H	R-Glass + Kapton H	Ca-Glass fibres	R-Glass + Kapton H	R-Glass + Kapton H	R-Glass + Kapton H
	Currently used	Currently used	Proposed by Huntsman *) high price	Proposed 60% low price	by Huntsman + 40% high	Proposed by Huntsman low price	Proposed by Huntsman	If available without filler (Huntsman)	Currently used	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

Sc irradiation



Critical currents of both wires are enhanced after irradiation to $5x10^{21}$ m^{-2} (E>0.1). ⇒ Next step: $1x10^{22}$ m^{-2} (E>0.1 MeV).

ITER - EFDA Magnet Structures R&D Programme TF Coil Case

Model 1 Forged

Model 2 Cast

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

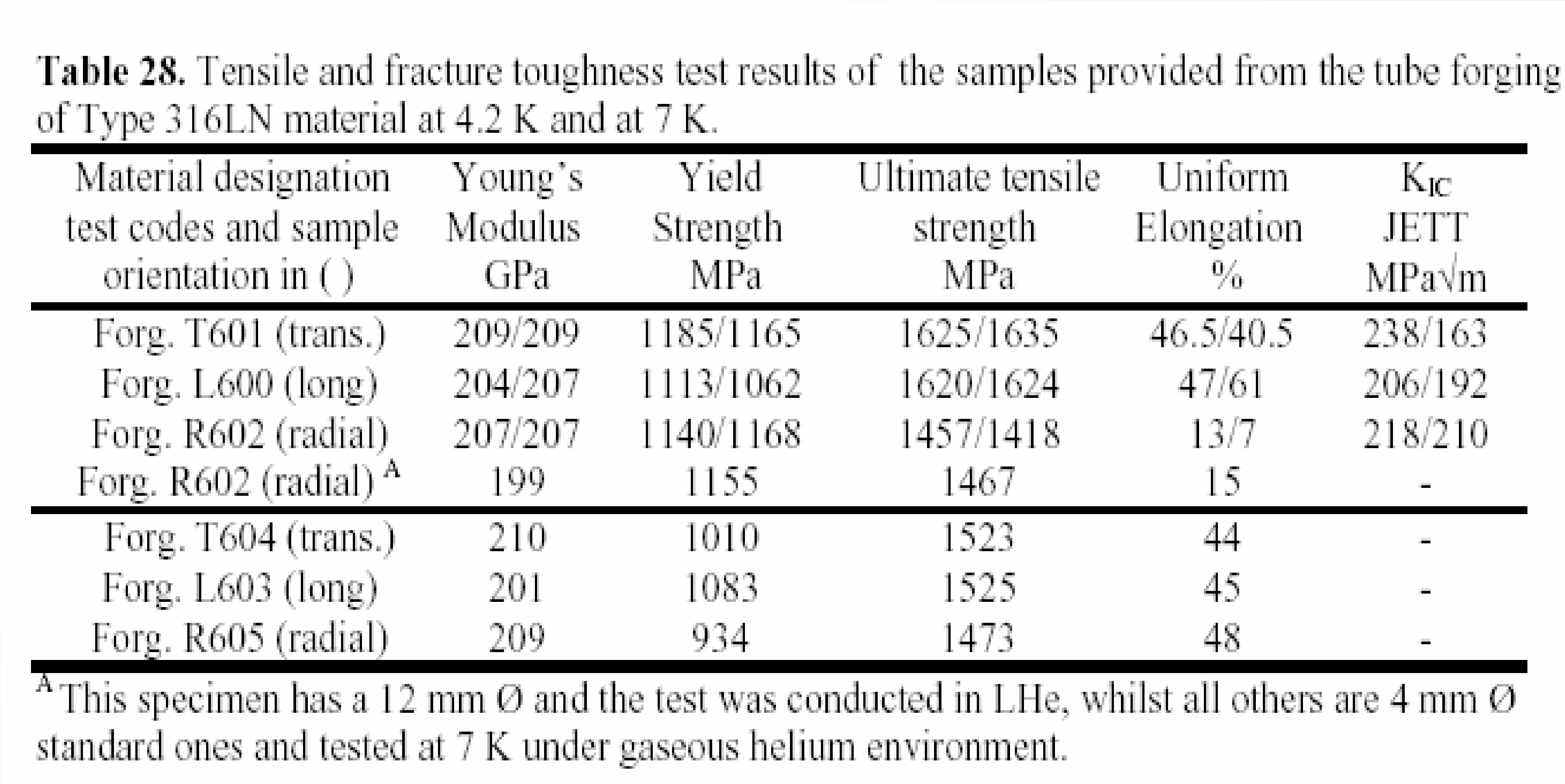
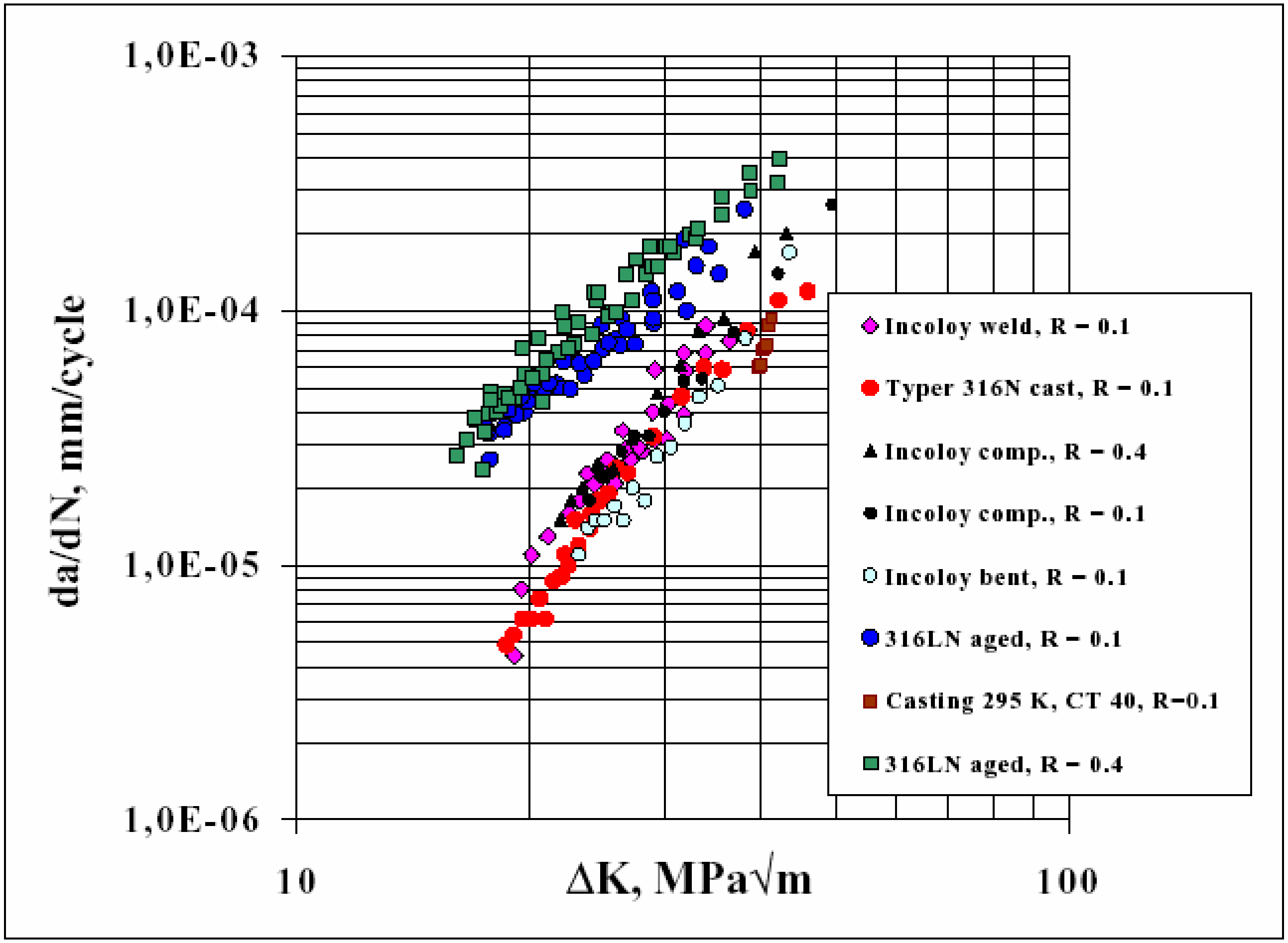


Table 28. Tensile and fracture toughness test results of the samples provided from the tube forging of Type 316LN material at 4.2 K and at 7 K.

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

[A] 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