The ITER Superconducting Magnets Program

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EFDA-CSU Garching

Outline

- Introduction
- Magnets system
- Model Coils
  - CSMC
  - TFMC
- Conductor Insert
  - Central Solenoid
  - Poloidal Field Coils
- Advanced strand procurement and qualification
- Design and interpretation codes validation
- Additional R&D
- Conclusions

Introduction

- NET 1983-1988
- ITER CDA 1988-1990

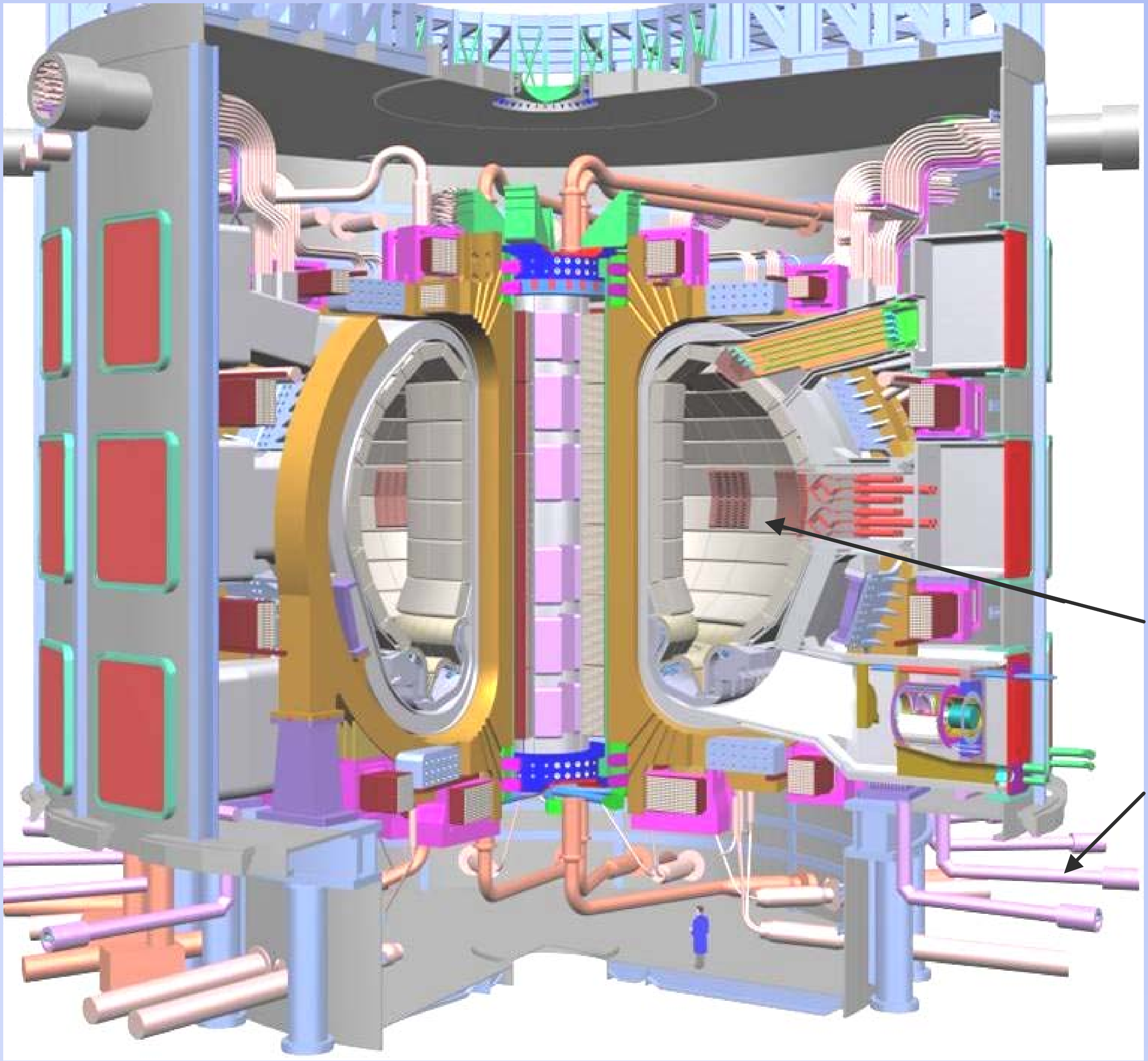
• Plasma Major Radius	6.0 m
• D.N. Vertical Elongation 95%	2
• Plasma Current	22 MA
• Magnetic Filed at 5.8m / max.	4.9T/10.4T

- 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

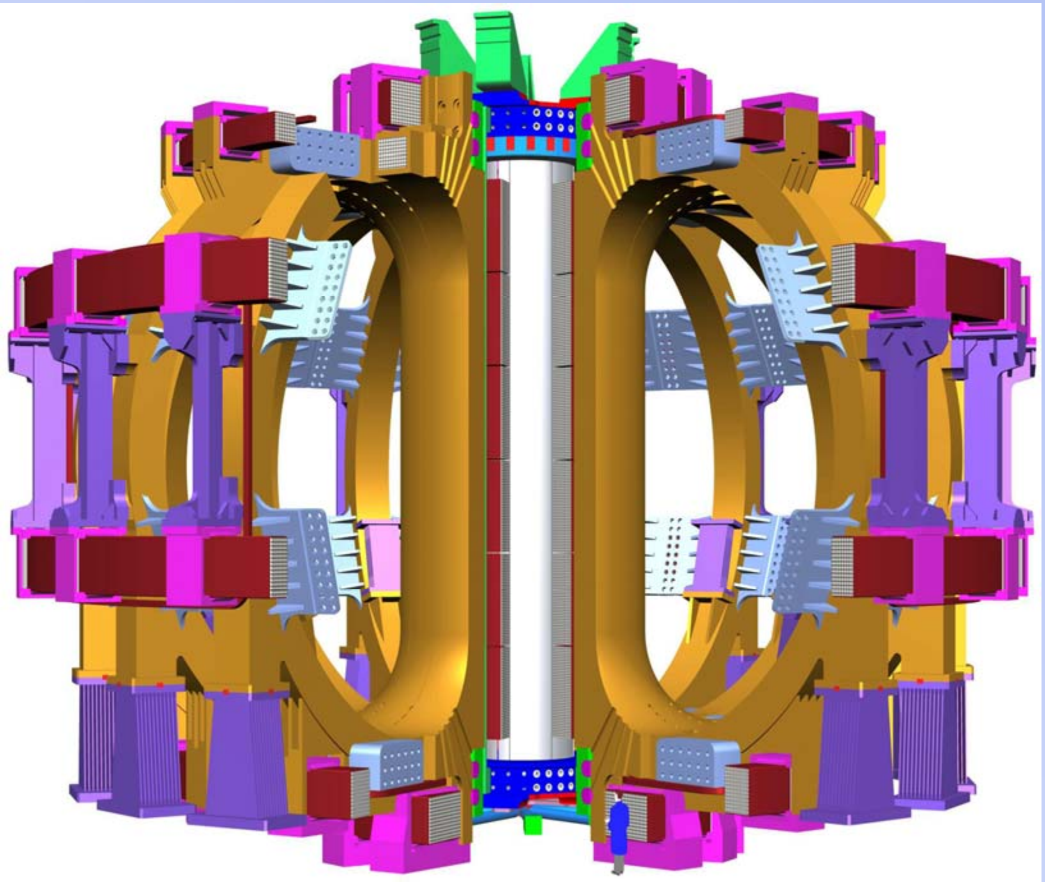
• Plasma Major Radius	6.2m
• S.N. Vertical Elongation 95 %	1.7
• Plasma Current	15/17 MA
• Toroidal Field at 6.2m/max	5.3T/11.8T



Sc. Magnet

Current feedthrough in horizontal position

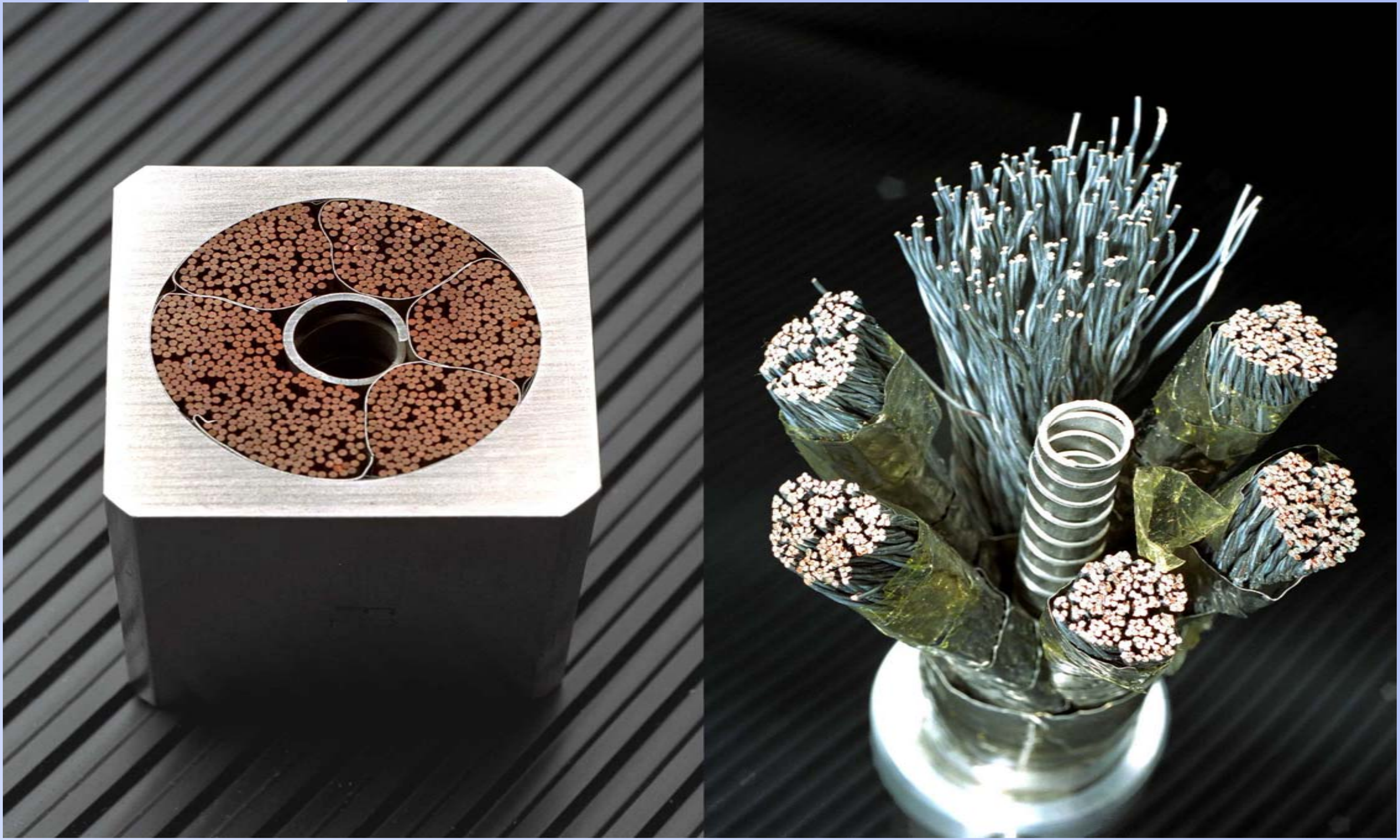
ITER - EFDA Magnets R&D Programme - Magnet System Components



	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

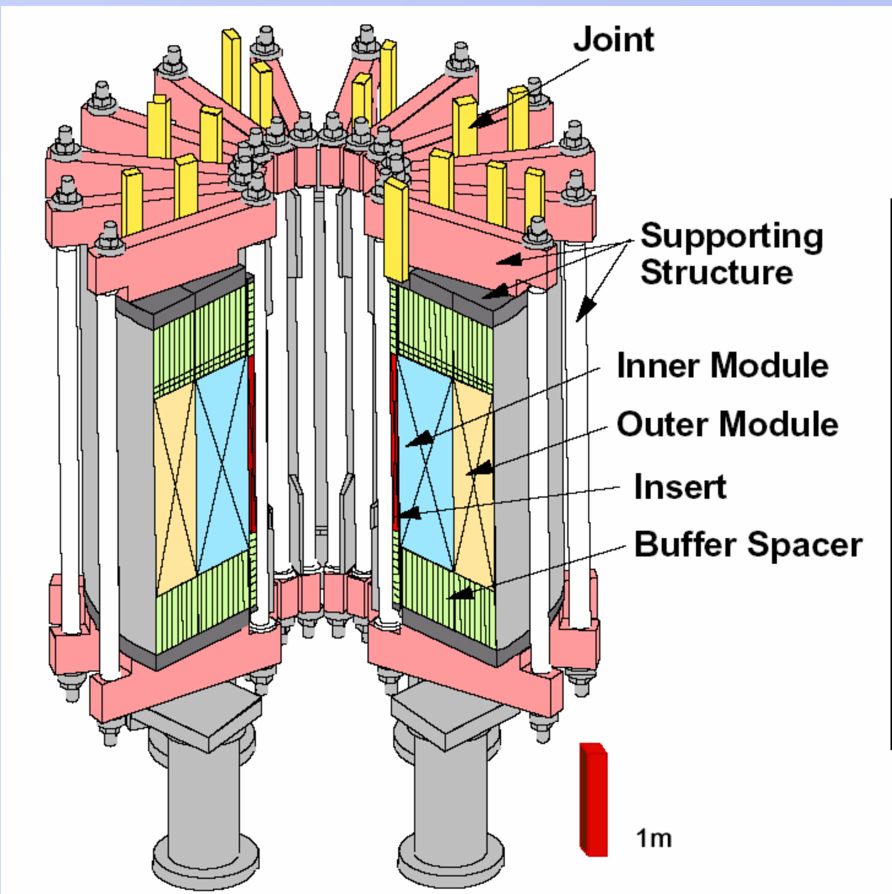
TABLE I: MAGNET SYSTEM PARAMETERS

Number of TF coils	18
Magnetic energy in TF coils (GJ)	~ 41
TF coil current (kA)	68
Maximum field in TF coils (T)	11.8
CS current, initial magnetization, [end-of-burn] (kA)	41.5, [45.2]
CS peak field, initial magnetization, [end-of-burn] (T)	13.5, [12.8]
PF coil current, normal operation, [backup mode] (kA)	45, [52]
Correction coil current (kA)	10
Weight of TF coils including structures (t)	5,621
Weight of CS including structures (t)	926
Weight of PF coils including clamps (t)	2,835
Weight of CCs including clamps (t)	80
Total weight of magnet system (t)	~ 10,135



Conductors of the two ITER model coils
left: CSMC conductor, right: exploded view of the TFMC conductor

ITER - EFDA Magnets R&D Programme - CS Model Coil (1/3)



Coil Design Parameters

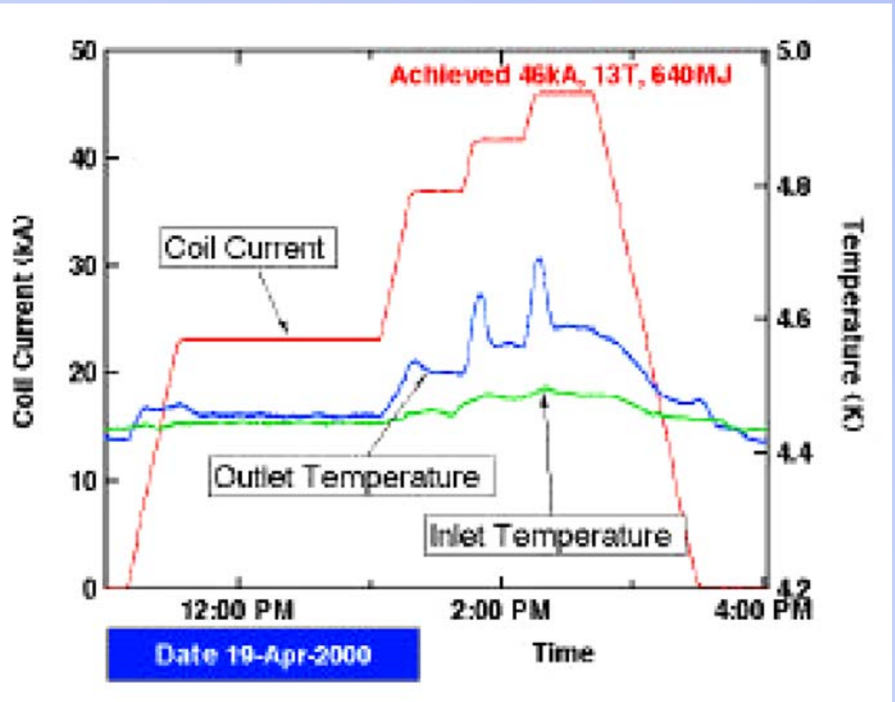
	CSI	CSMC IM	CSMC OM
Maximum Field	13 T	13 T	7.3 T
Operating Current	40 kA	46 kA	46 kA
Outer Diameter	1.57 m	2.71 m	3.62 m
Height	2.80 m	2.80 m	2.80 m
Weight	7.7 t	49.3 t	52 t
Stored Energy	11 MJ	640 MJ	

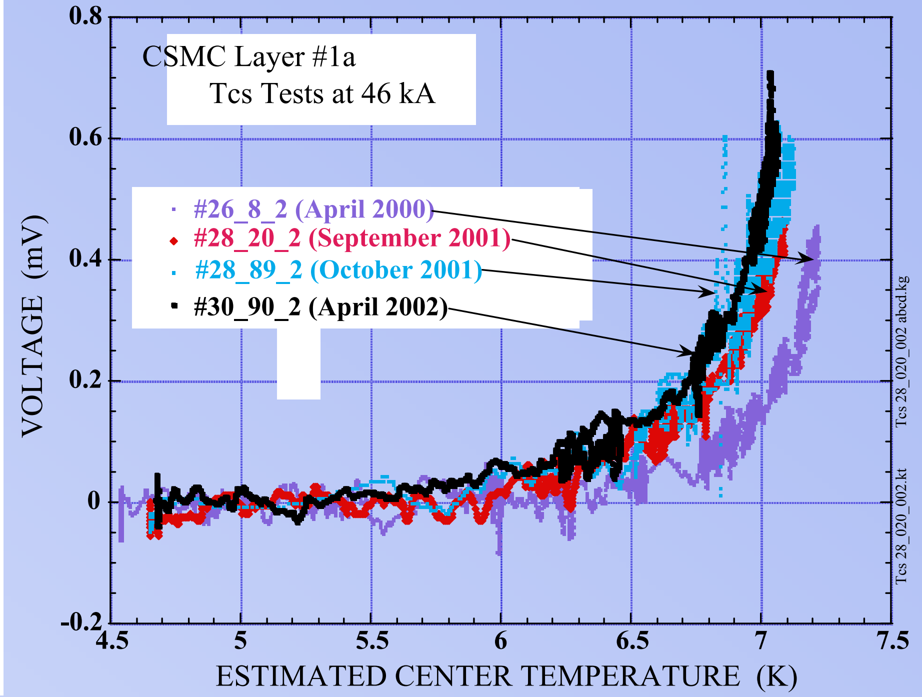
ITER - EFDA Magnets R&D Programme - CS Model Coil (2/3)

CSMC: Inner module

CSMC: Outer module

ITER - EFDA Magnets R&D Programme - CS Model Coil (3/3)

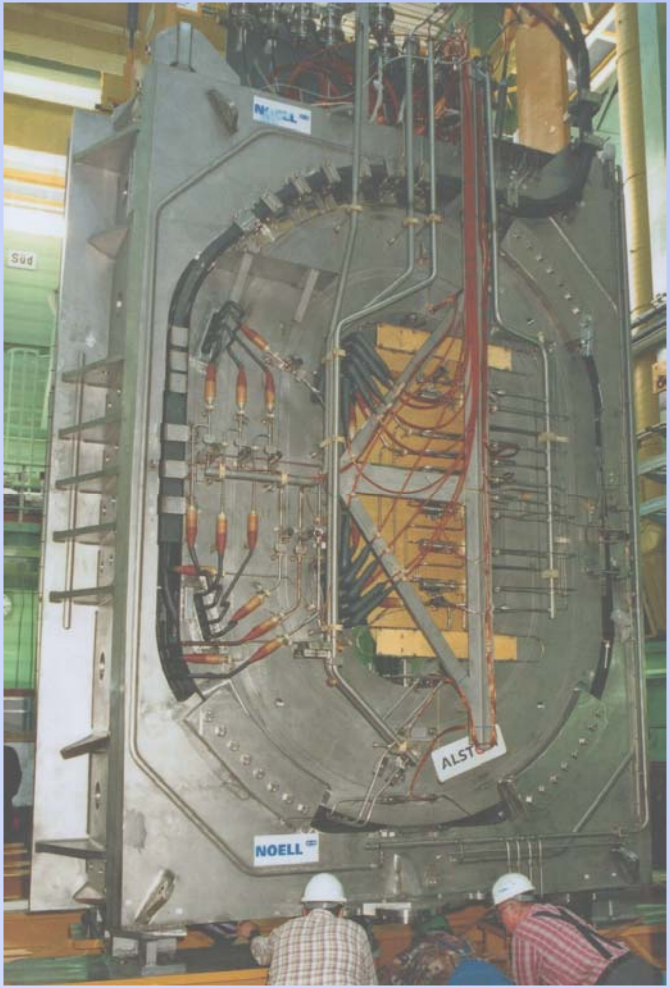




CSMC successfully achieved design values

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

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



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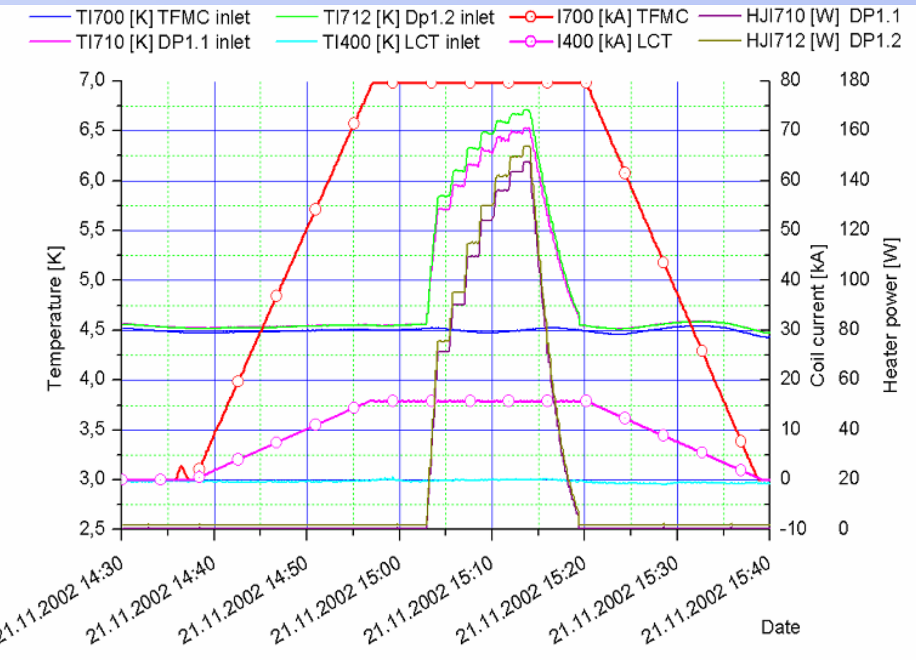
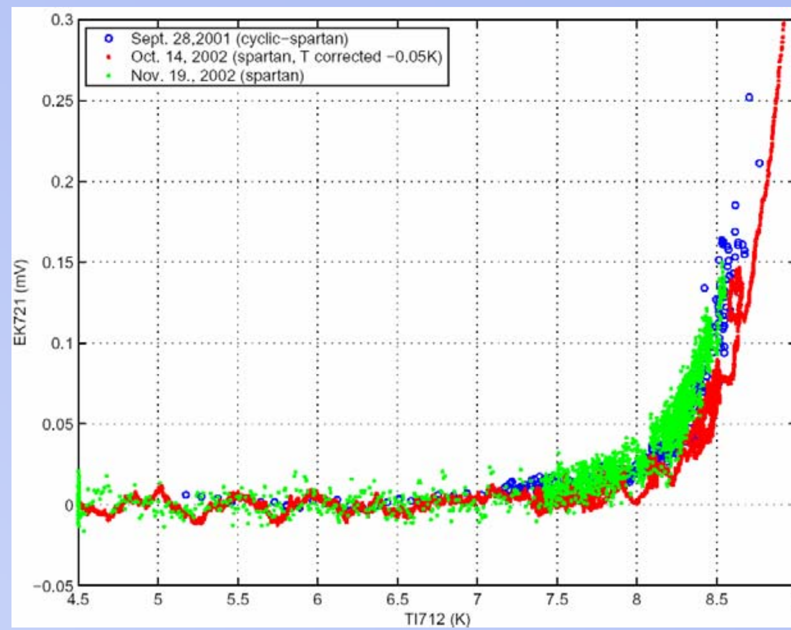
ITER - EFDA Magnets R&D Programme - TF Model Coil

TFMC (80 kA) + LCT (16 kA)



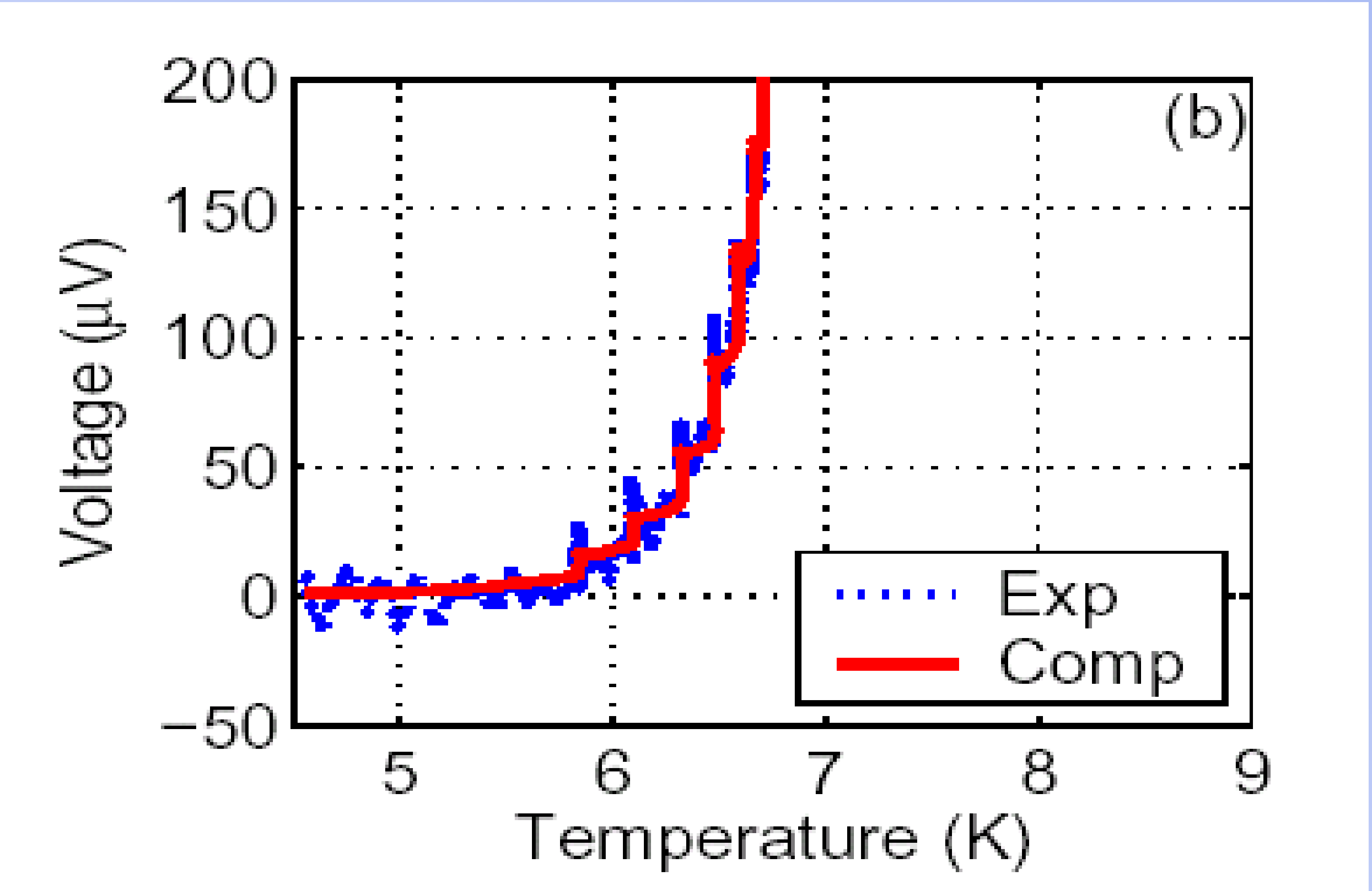
TFMC exceeded design values

TFMC (80 kA)



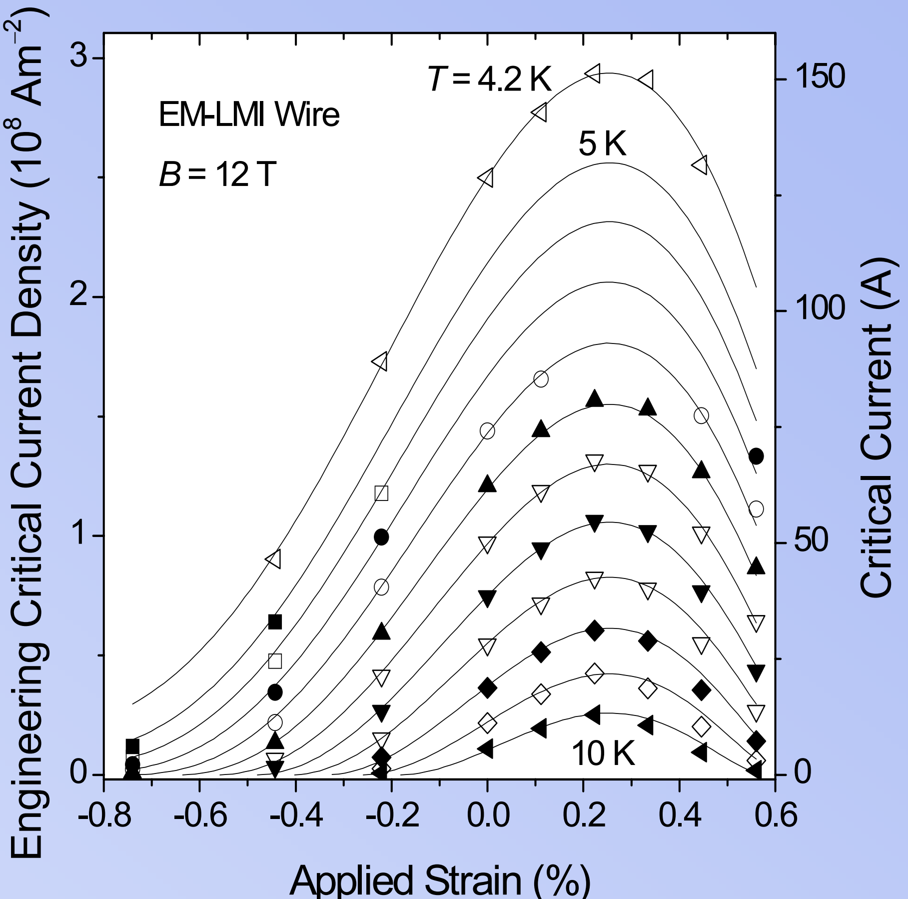
No performance degradation

TFMC Tcs at 80/16 KA

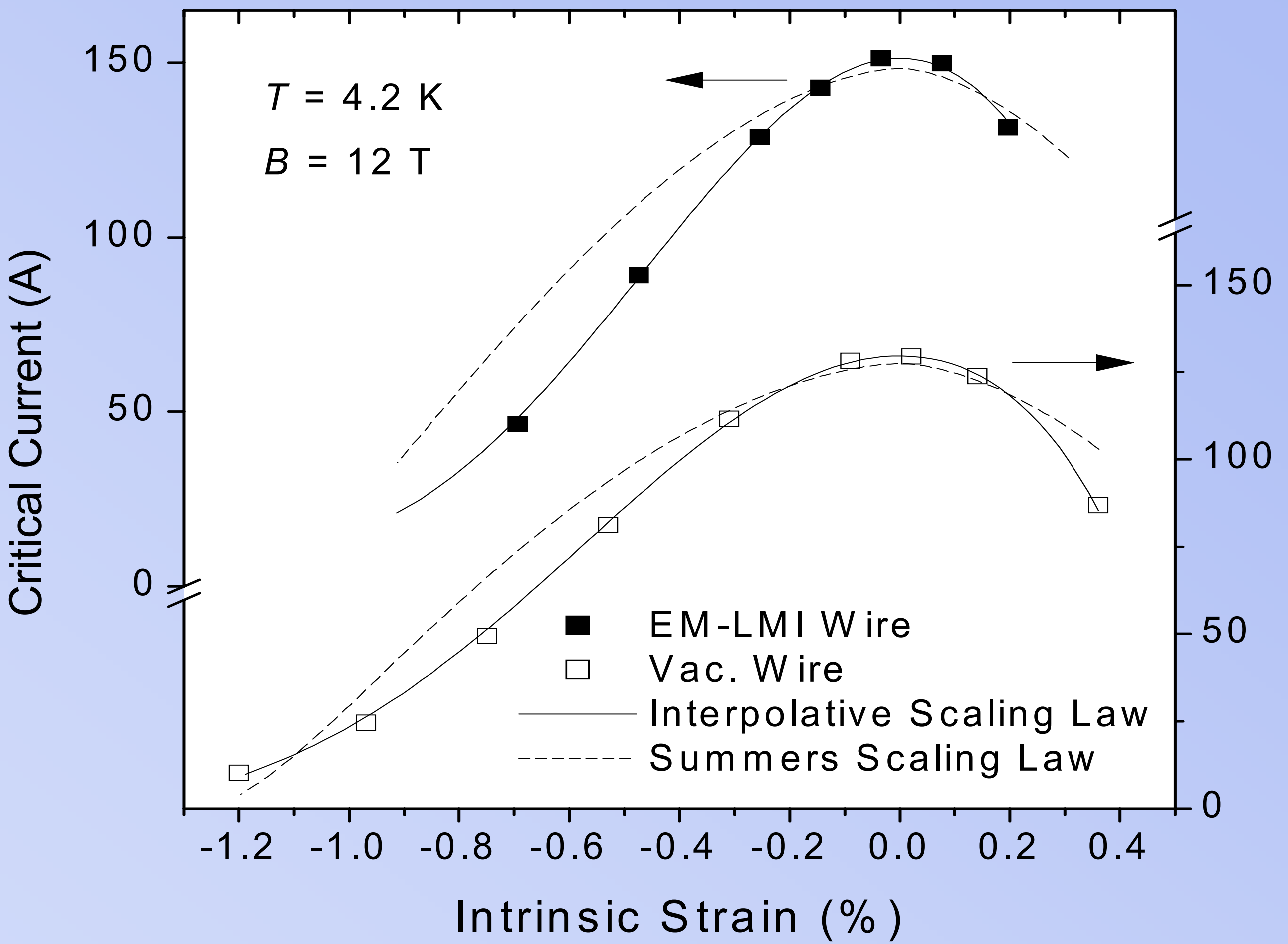


$J_C(B,T,\varepsilon)$ data

- **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.**



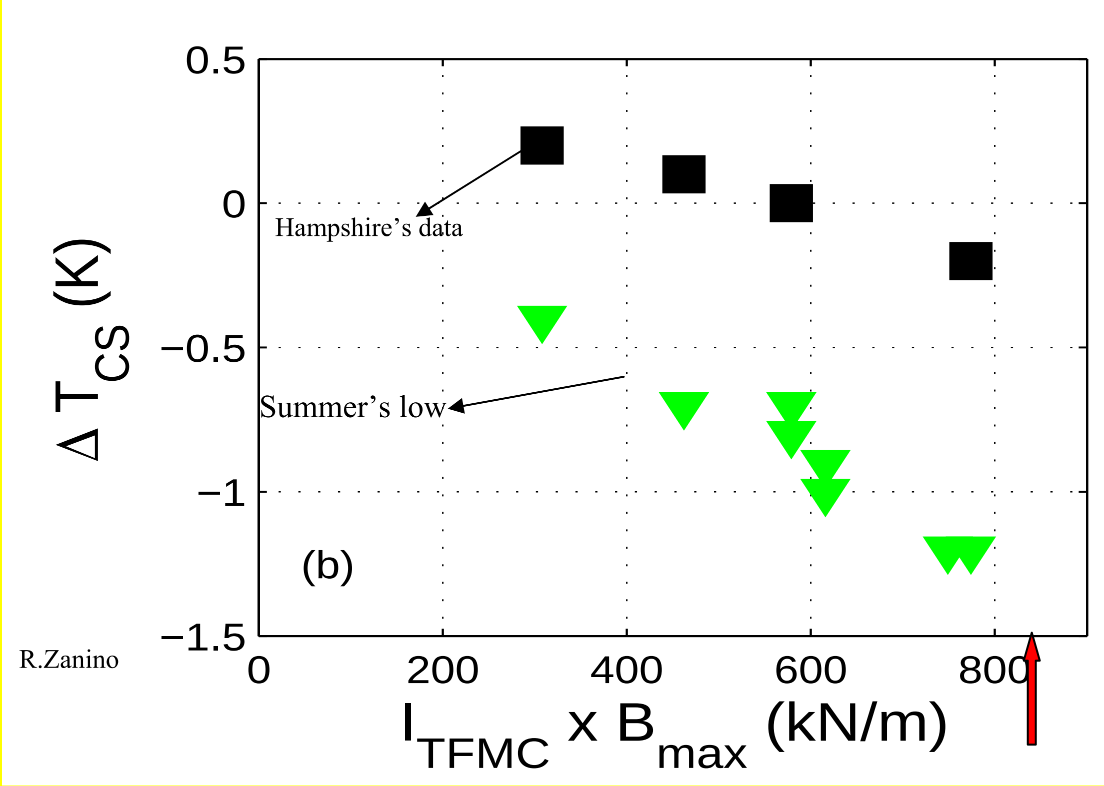
D.Hampshire



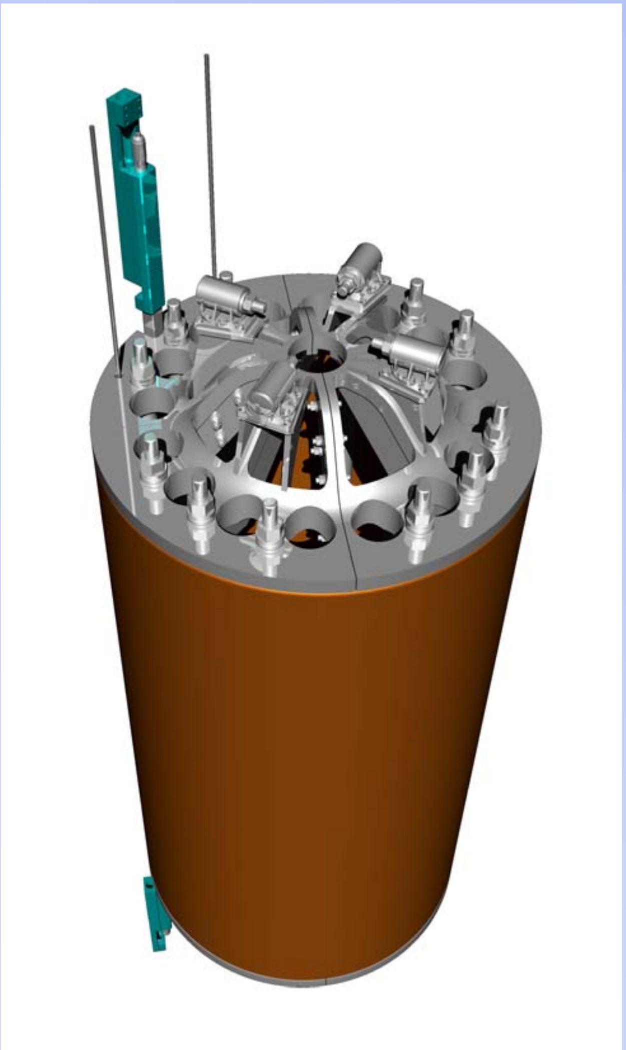
– **Standard "Summer's law " is not accurate**

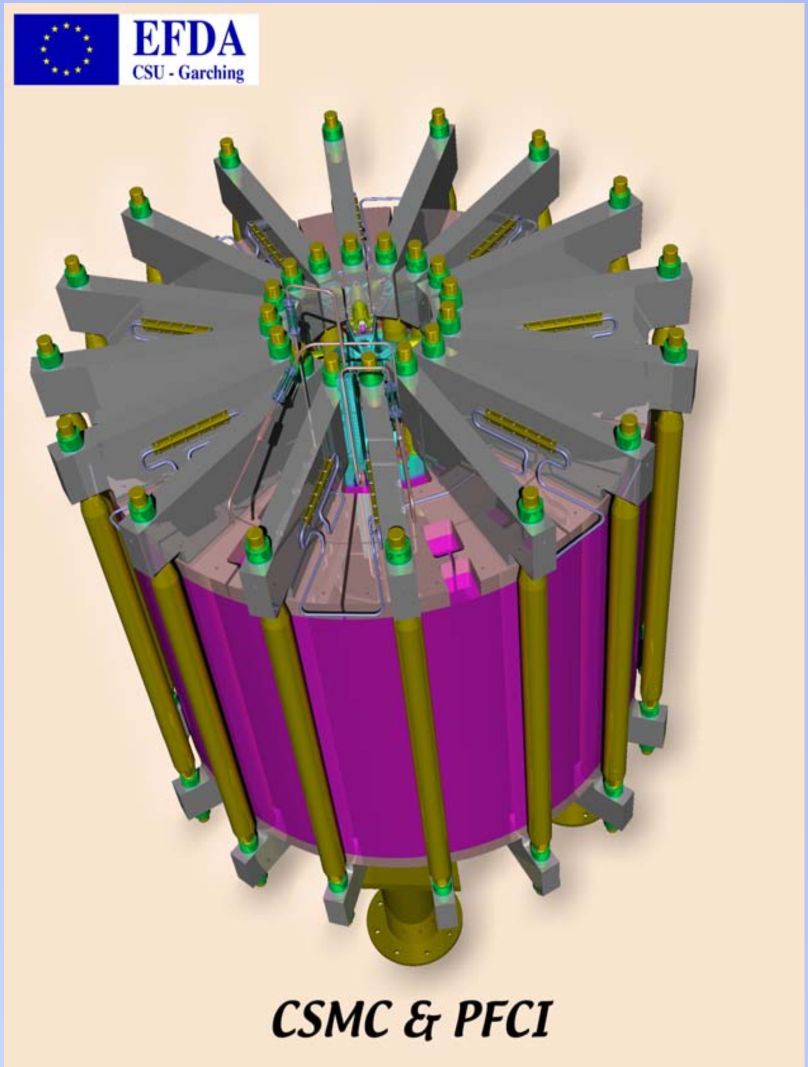
Coil vs. Strand Performance

– Conductor n ~ 6-9 << n_{strand} ~ 12-25 and increasing with I_C (confirms previous analysis)



I_{TFMC} (kA)	I_{LCT} (kA)	n
80	16	9
80	0	7
60.6	13.9	7
49.1	11.3	6

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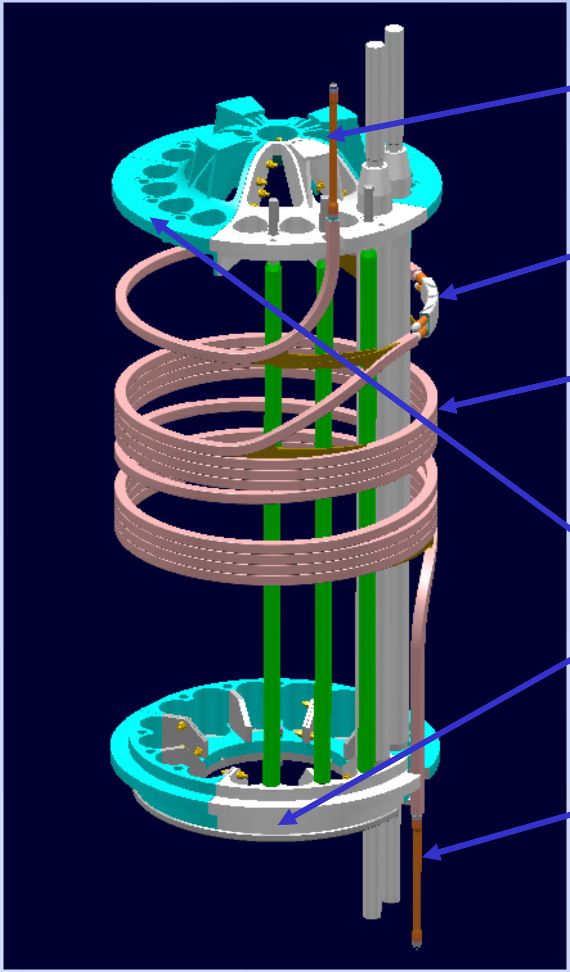
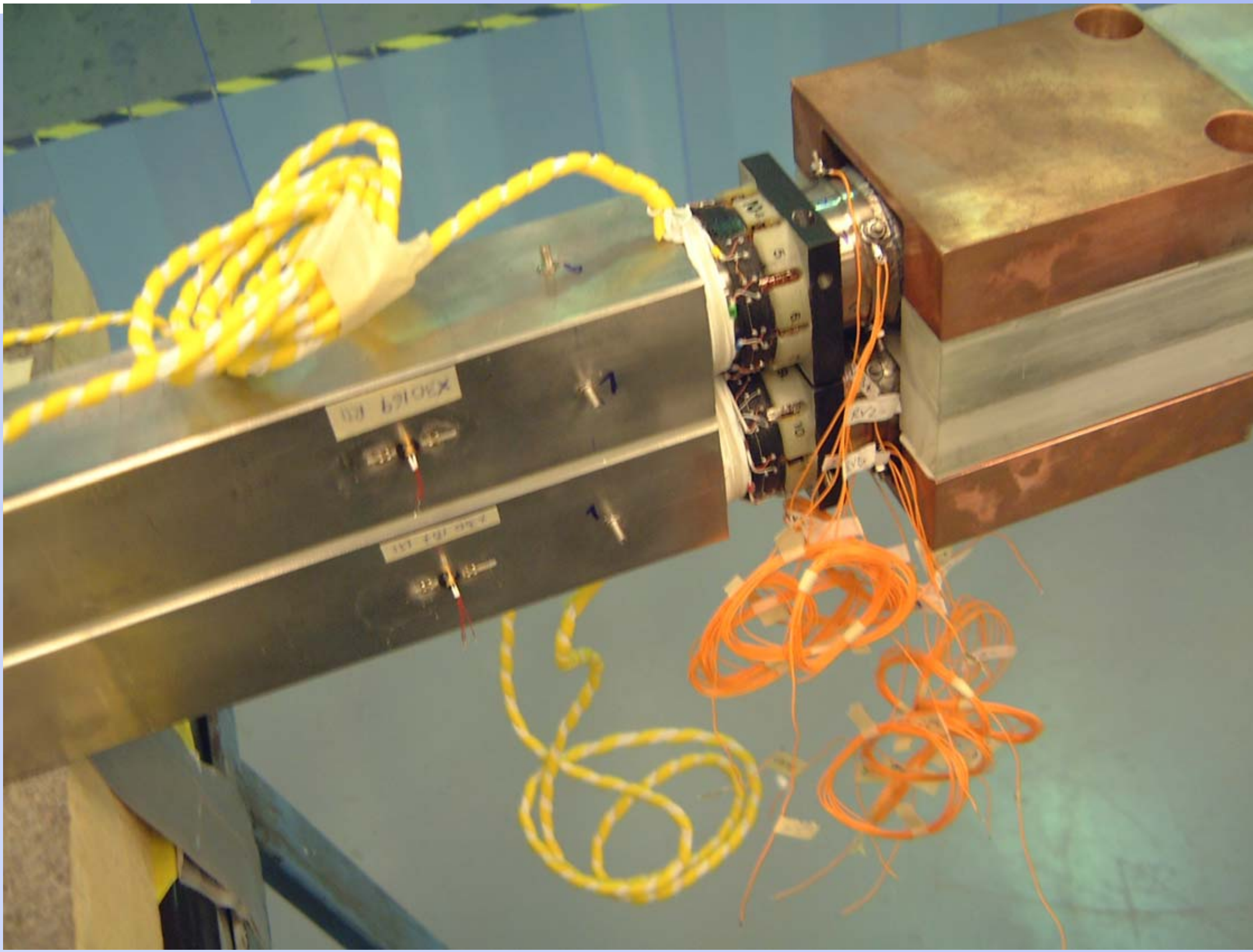
CSMC & PFCI

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

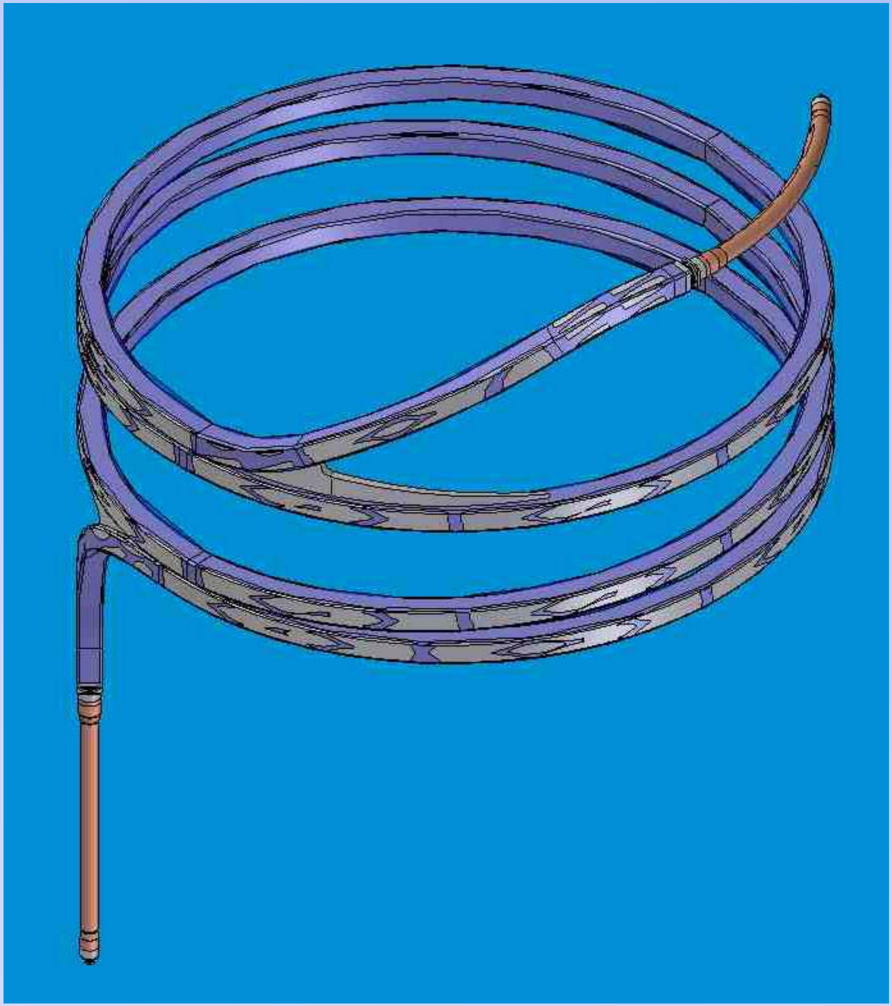


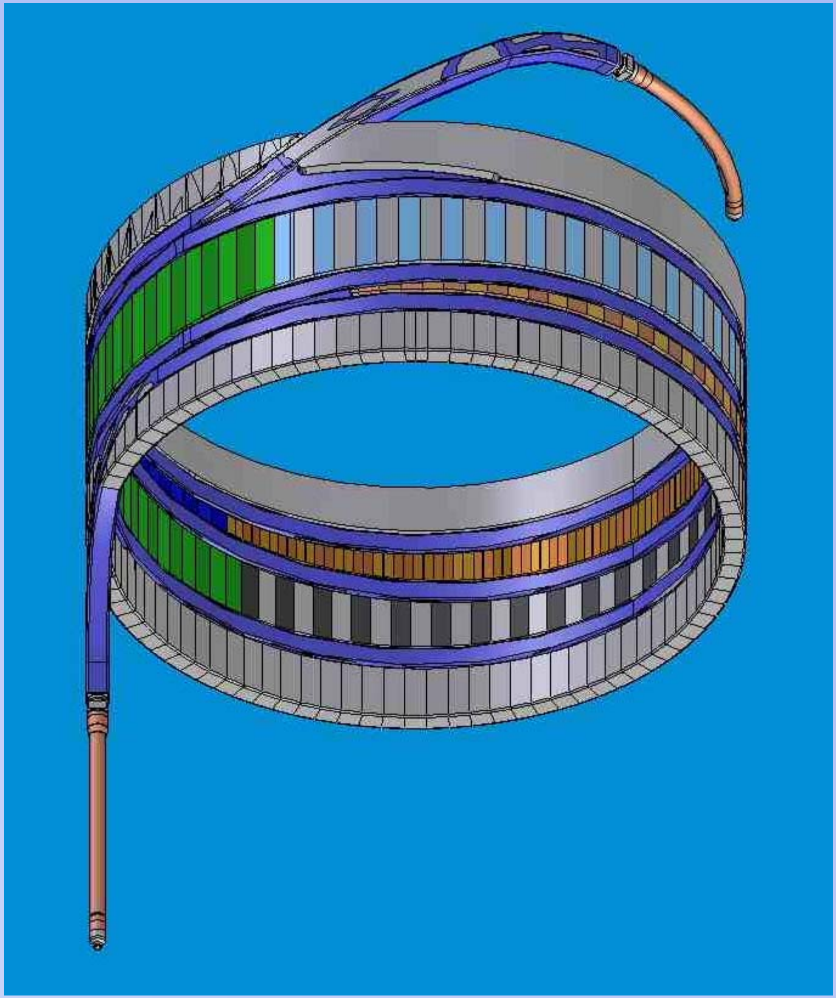
Coil Design Parameters

		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



Assembly of Hall Probes





Iso-views of Dummy Winding

Reduction of PF Insert Superconductor

Advanced Nb_3Sn Strand Specification

Tender

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

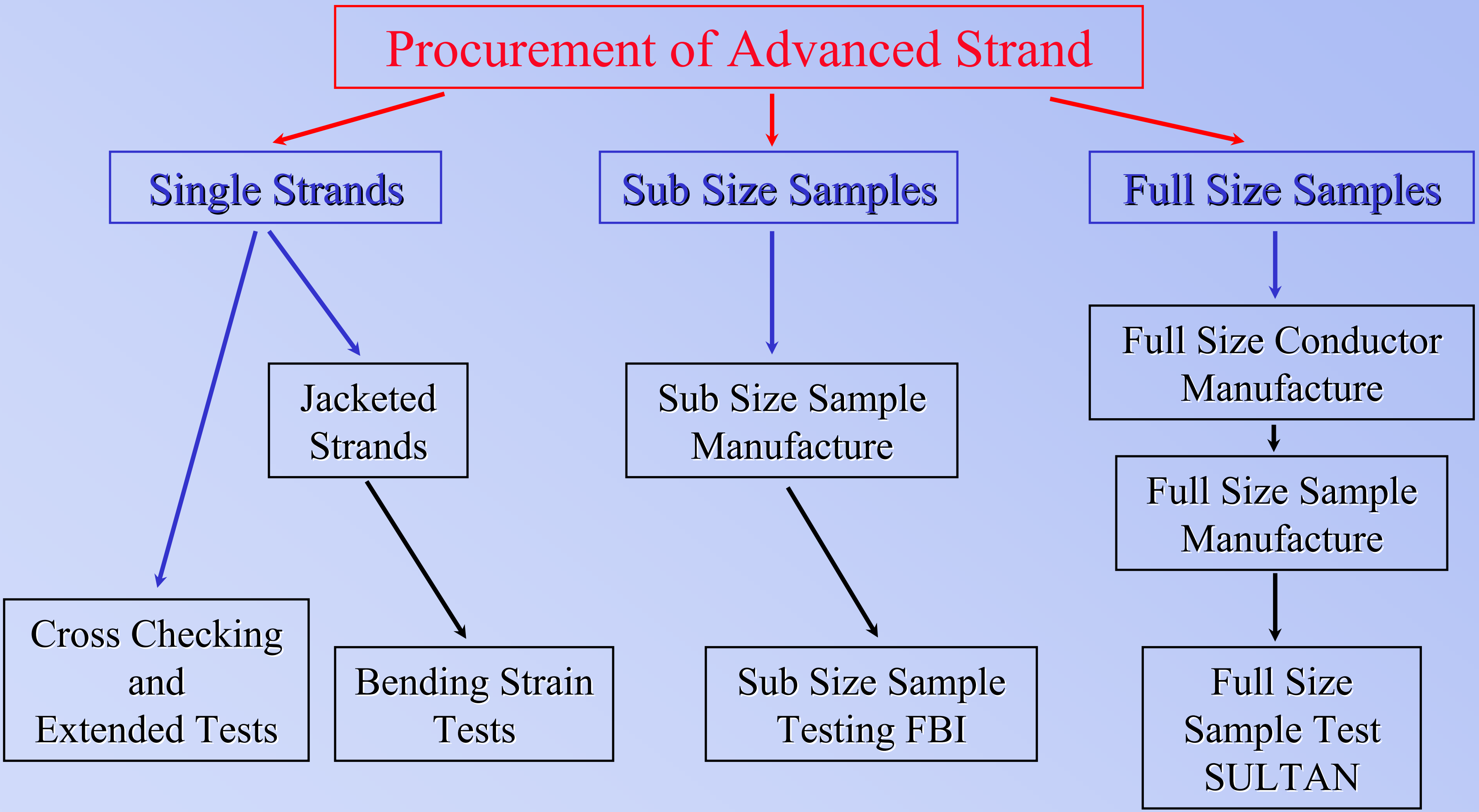
Contract

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/m³
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/mm², 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/mm², a Cu:non-Cu ratio of 1 and a strand diameter of 0.81 mm

Conductor Development Programme - Main Stages

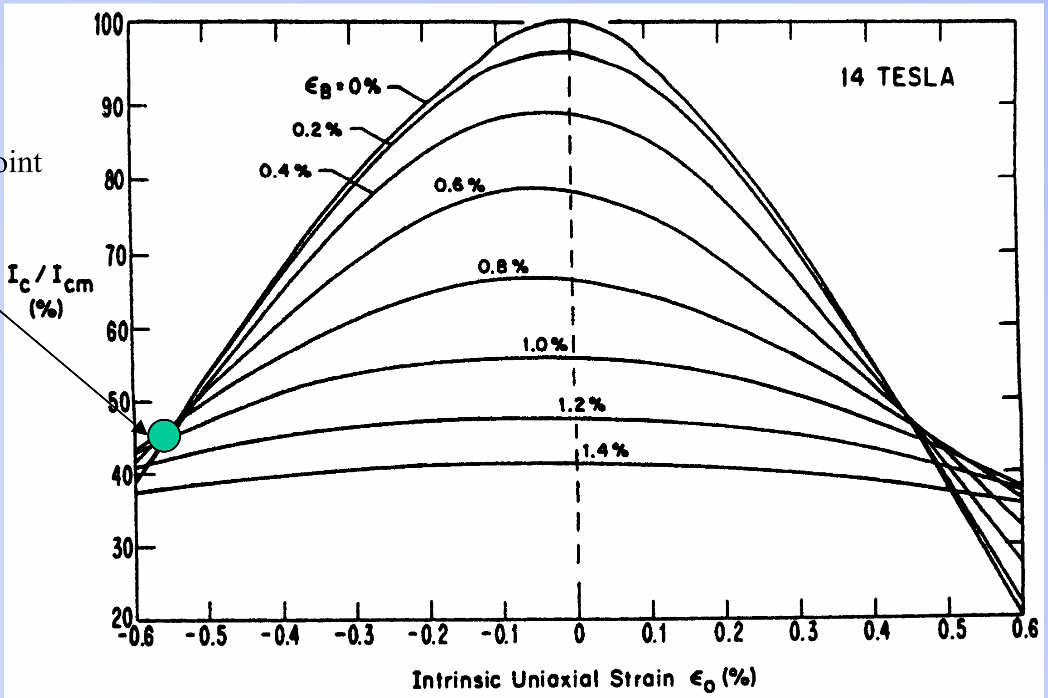


Bending Strain Tests - Influence at high Compression

– 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]

ITER operating point



– Strain sensitivity has to be checked for new advanced strand

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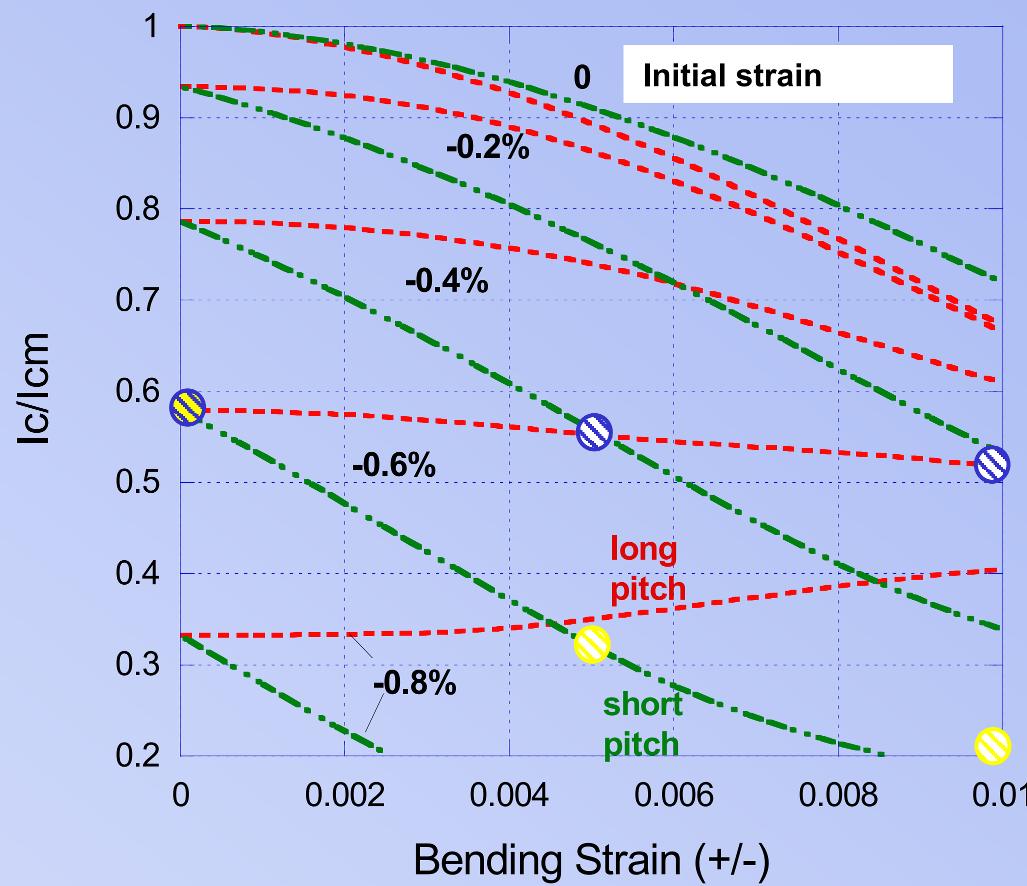
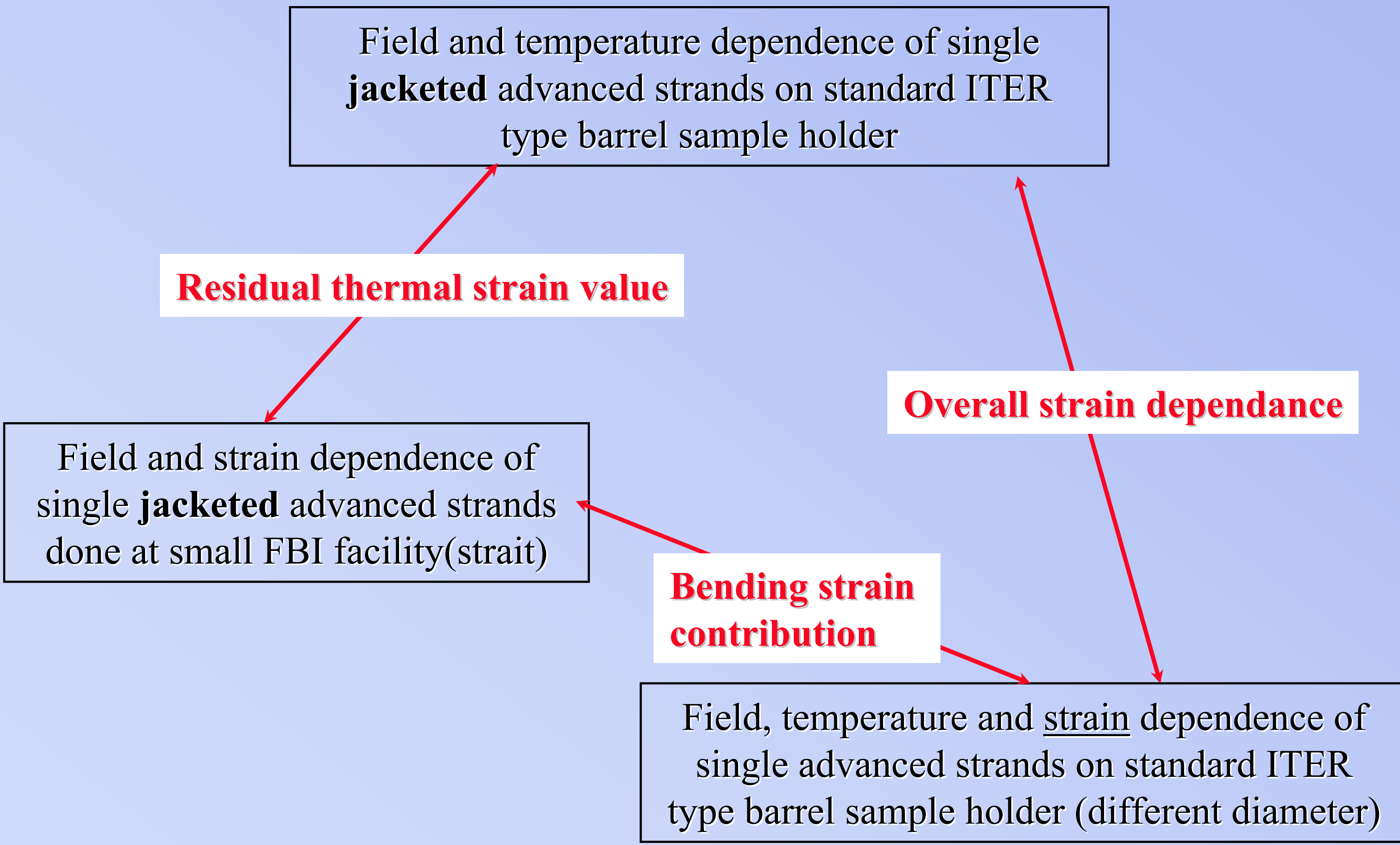
Bending Strain Tests - Current Transfer Length

- 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]

Bending Strain Tests -Characterisation



FBI Facility
Status and preliminary results

„Small“ FBI

SC-strands : 20 cm, Ø 2 mm

split-coil magnet : 13.5 T

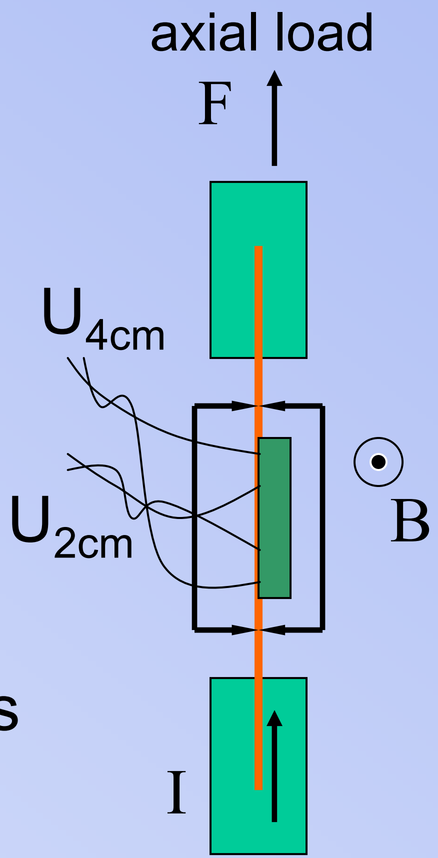
maximum force : 1 kN

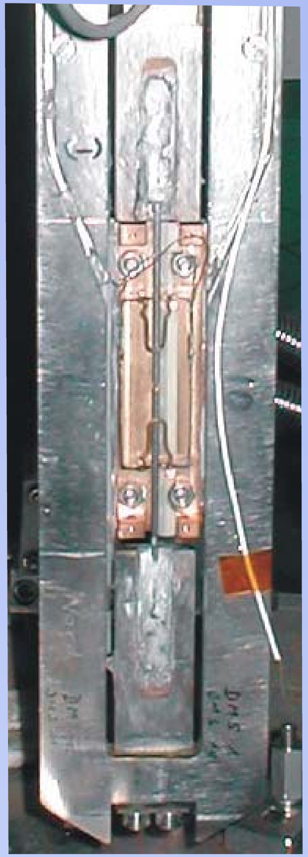
maximum current : < 400 A

(with active cooling of current leads)

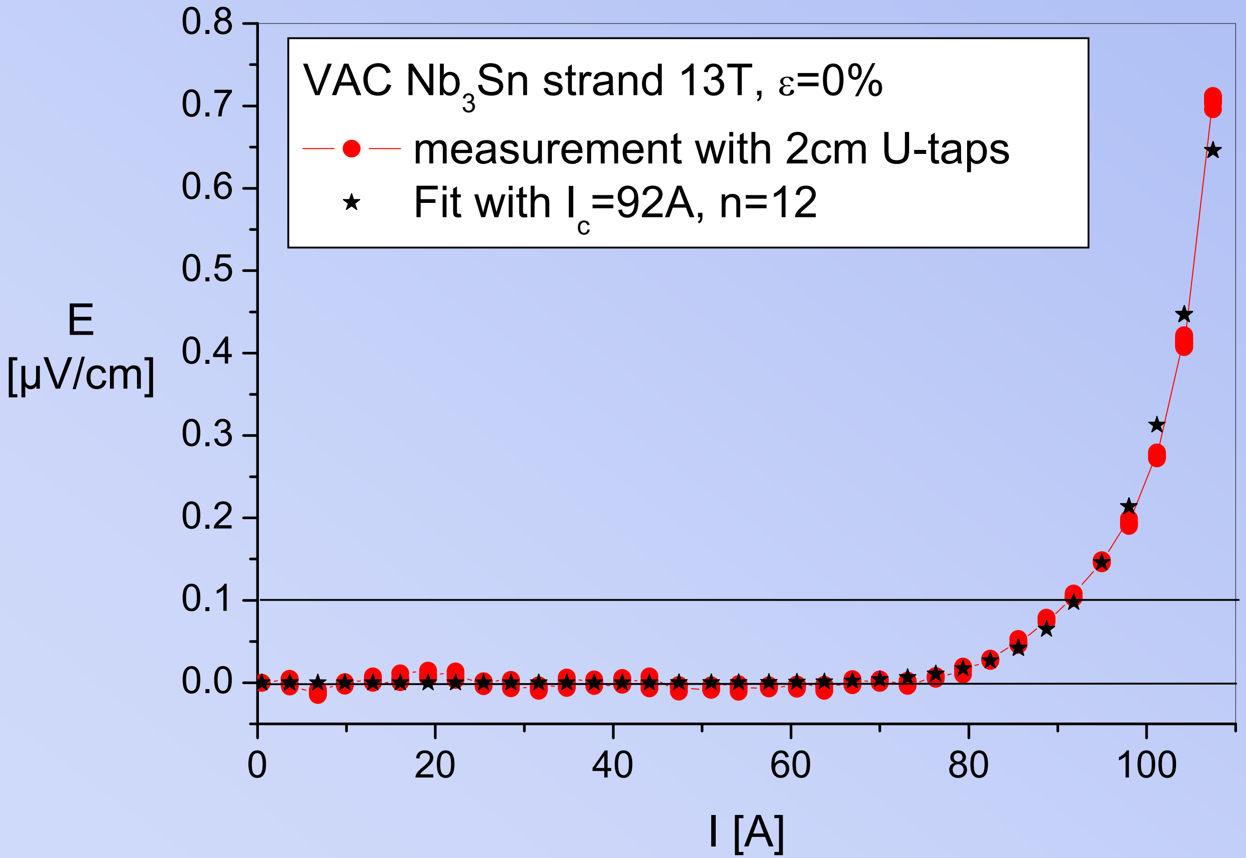
strain measured by Extensometers

all tests done in LHe

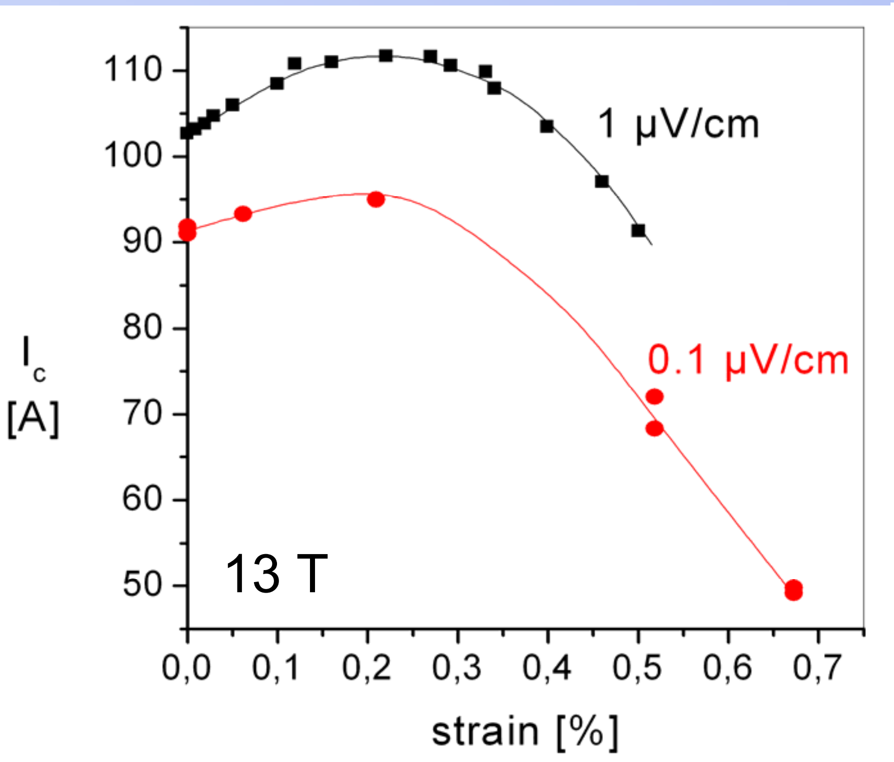


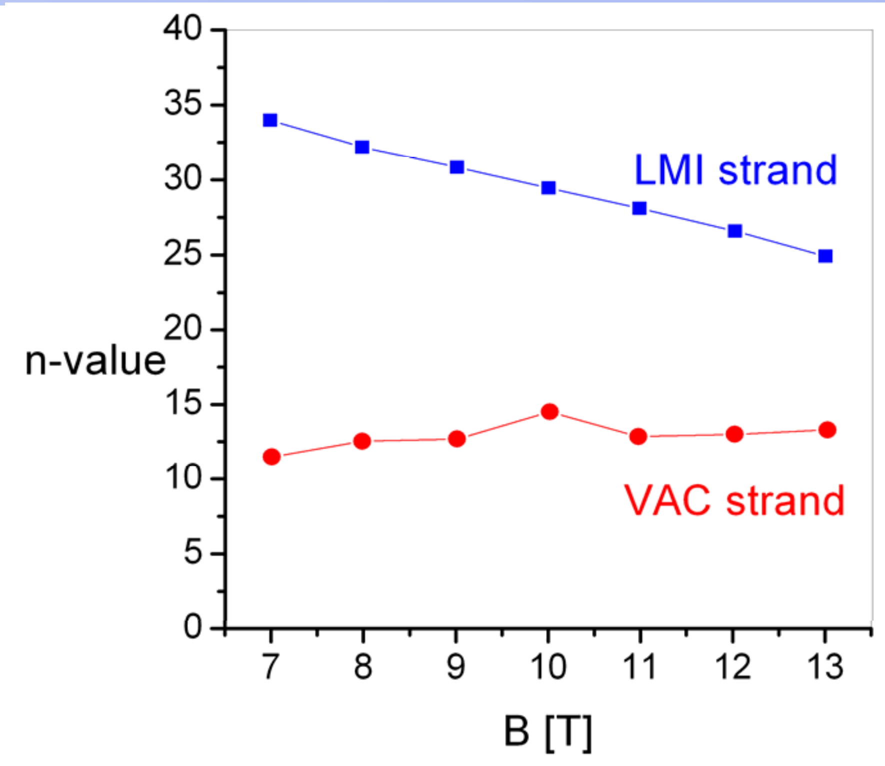


Typical measurement with new setup



I_c vs. strain and n-value of VAC strand





EFDA Report October 1997 GB5-M27
W.Specking et al.

H.G. Knoopers *et al.*
Applied Supercond. 158, 1271 (1997)

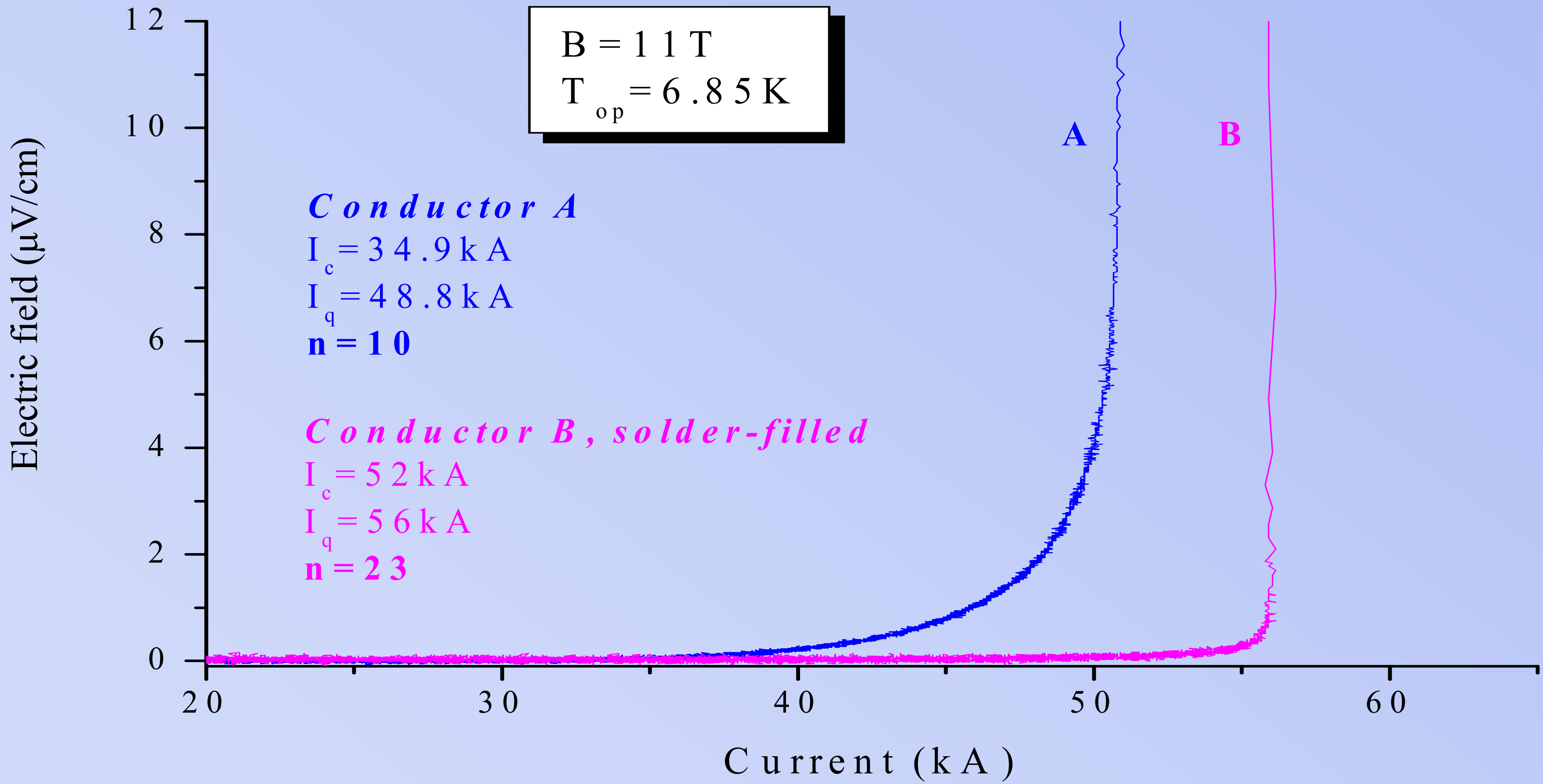
„Big“ FBI facility

- 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.

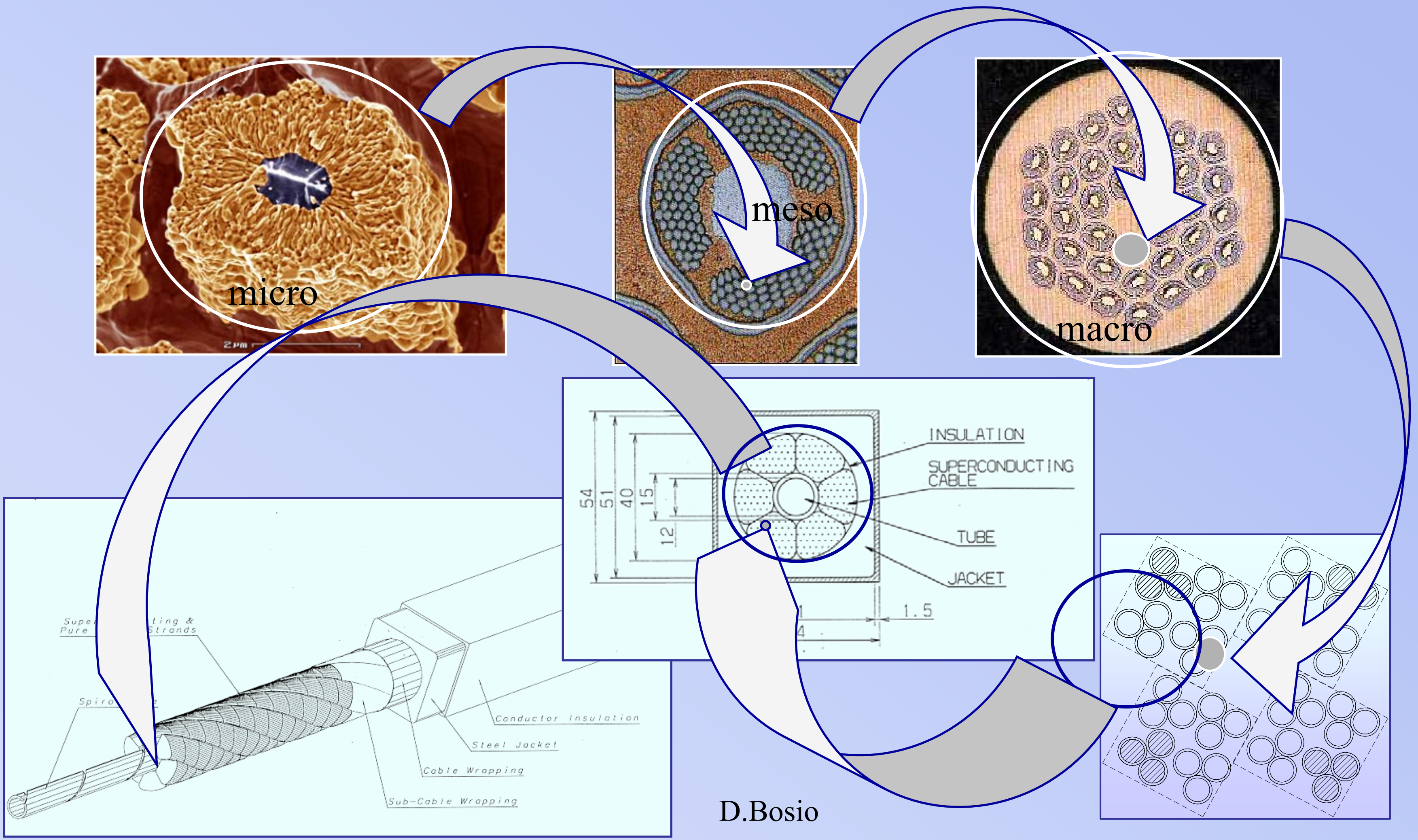
DC Test Results (Bending Strain Inpact)

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



P.L. Bruzzone

Mechanical Modeling of ITER Superconducting Cables



D.Bosio

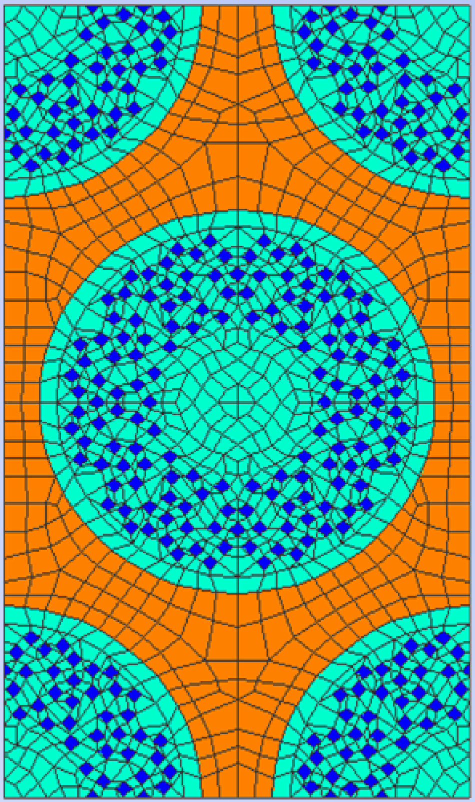
Mechanical Modeling of ITER Superconducting Cables Homogenisation: Algorithm Scheme

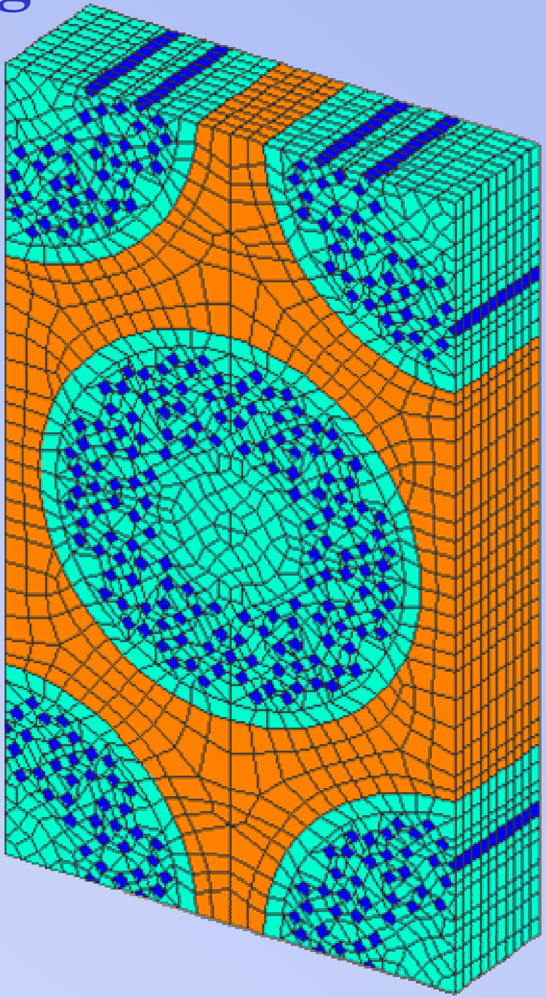
1. Compute effective coefficients at micro level
2. Compute effective coefficients at micro level
3. Apply increment of forces and/or temperature at the macro level, solve global homogeneous problem
4. Compute global strain [E11, E22, E12]
5. Apply [E11, E22, E12] to meso level cell by equivalent kinematical loading (displacement on the border)
6. Solve the kinematical problem, compute stress (unsmearing for meso level) and strain
7. Apply [E11, E22, E12] from meso to micro level cell by equivalent kinematical loading (displacements 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.
10. Go to 1.

Modeling Status

– 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 characteristic for the micro and meso homogenised model: orthotropic material

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%

– Analysis of a 3x3x4 sub-cable stage.

It will be basically composed of two types of Finite Element: rod elements schematising the strands and specially formulated contact elements along the sub-cable to schematise strand-to-strand interactions. The rod type element are characterized by the mechanical and thermal properties derived numerically from the first level of this analysis

– Identification of mechanical parameters for the homogenised petal model.

At this level three kinds of theoretical analyses will be performed:

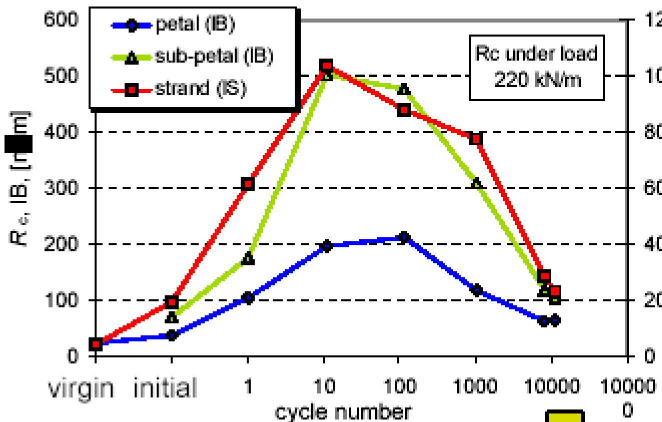
1. Homogenisation based on the results of previous investigations and taking into account the specific spatial organisation of the sub-elements of the petal;
2. Identification of the homogeneous model of the petal using various techniques of parametric identification, non symbolic constitutive model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

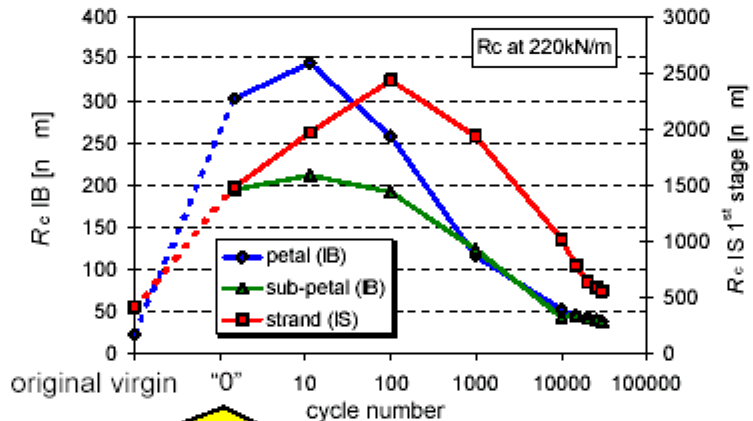
Mechanical Modeling of ITER Superconducting Cables Future Developments

– Analysis of the whole cable .

The final level of this complex study consists of a Finite Element analysis of the six petals, considered as homogeneous with the characteristics derived from the three previous steps. 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 will be analysed. Once the global behaviour of the cable is studied the "unsmearing" analyses will provide the strain state of the individual strand

R_c from CRPP sample without petal wraps after “interruption”





Press defect (bearings) after 11,381 cycles

Sample stored at RT/air with *F*=zero for few weeks.

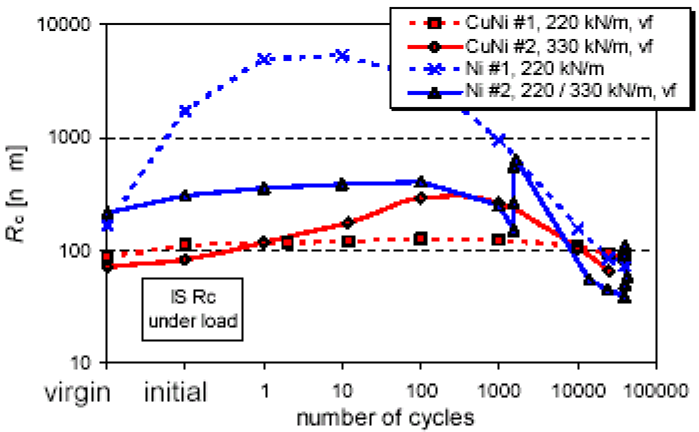
R_c 1st triplet (IS): from 420 to 10,400 to 560 nΩm.

R_c sub-petal (IB): from <70 to 500 to 40 nΩm.

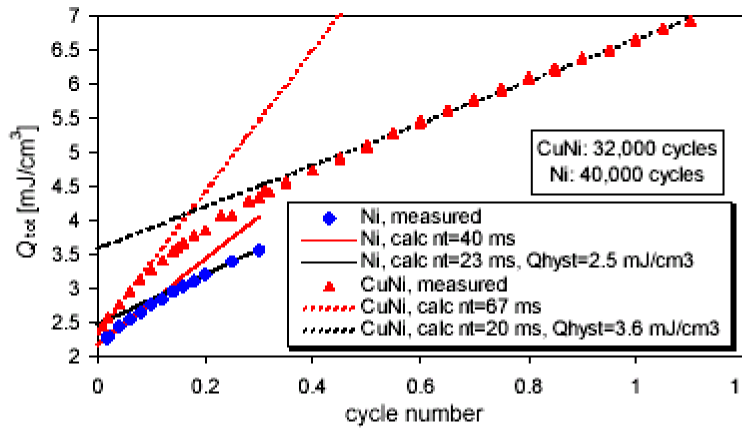
R_c inter-petal (IB): from 24 to 210 to 40 nΩm.

R_c peaks again at 10-100 loading cycles: almost saturation after 40,000 cycles

Summary EM Ni & Alstom CuNi PF samples



IS R_c versus cycling



AC loss after cycling

- AC loss in virgin state and after several cycles corresponds to FSJS in SULTAN.
- R_c Alstom CuNi PF < R_c EM-Ni PF along cycling, Ni plating more sensitive to cycling.
- Alstom CuNi more stable than EM-Ni (Zani, Gislon et al.), suggesting an impact of R_c on stability (joint ?). Higher *I* and *E* for CRPP NbTi #2 (solder) and #3 (Ni) after cycling 1400 times compared to directly after virgin (presentation Yuri Ilyin).

- **Combination of void fraction and force determines development of R_c and $n\tau$, suggesting that for NbTi PF CICC's a lower *vf* would be favourable.**

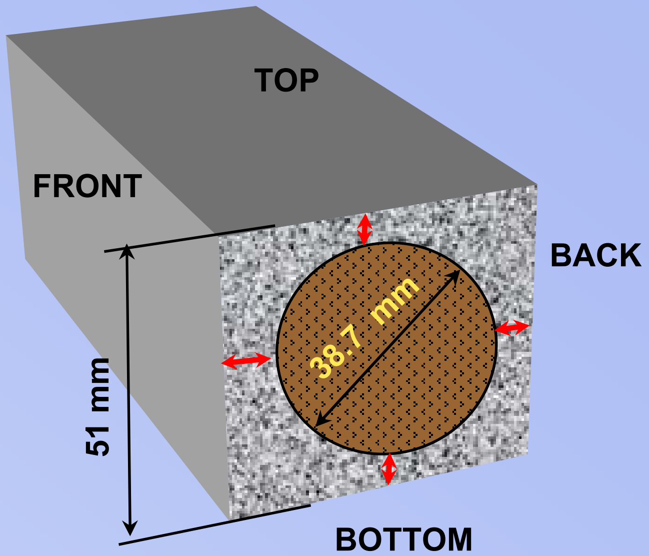
A predictive code (Thermo-Hydraulic Electro-Magnetic Analysis – THELMA) has been developed in 2001-2002 by University of Bologna, University of Udine and Polytechnic of Turin under the co-ordination of ENEA and EFDA for the analysis of superconductive magnets in transient conditions.

A reconstruction tool (CUrrent Numerical DETermination – CUNDET) is under developed since 2001 by C.R.E.A.T.E. for the current distribution estimation from experimental measurements.

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;
- validate the reconstruction code against test experiment and predictive code.

Thickness Survey



The thickness of the jacket of BB III was measured on 3 July 2003 making use of an ultrasonic probe (EFDA, july 2003)**.**
Two sections of the busbar were subjected to the measurement.
The minimum jacket thickness on the four sides of the busbar was determined at intervals of 50 mm along BB III.

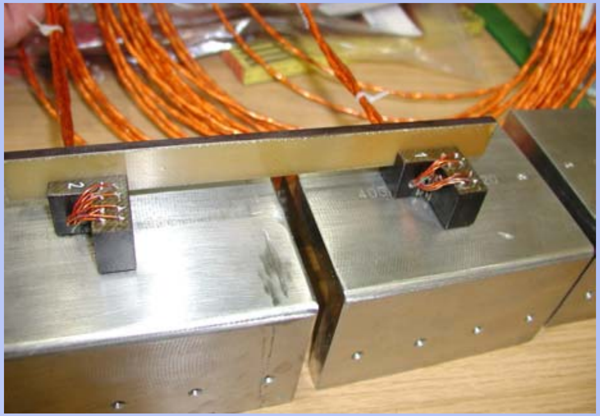
The obtained measurements are:

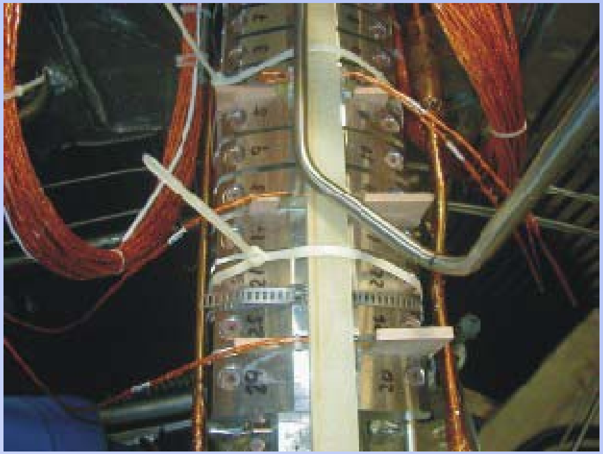
Section 1 (area of HP heads):	**Average**	=	**6.144 mm**
	STD	=	**0.392 mm**
Section 2:	**Average**	=	**6.055 mm**
	STD	=	**0.156 mm**

The nominal value is 6.15 mm
Variation is always within the manufacturing tolerance of +/- 1 mm.
(Section 2 seems to be more uniform than Section 1).

The CDM experiment

– Hall probes (IEE Bratislava)





Installation of Hall sensors on BB III and on joints

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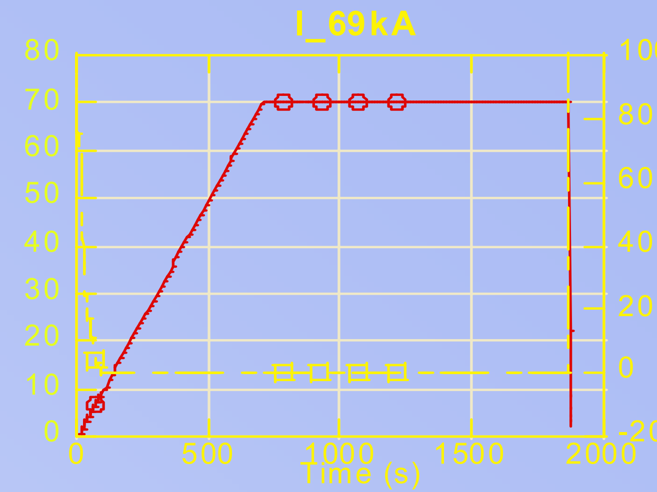
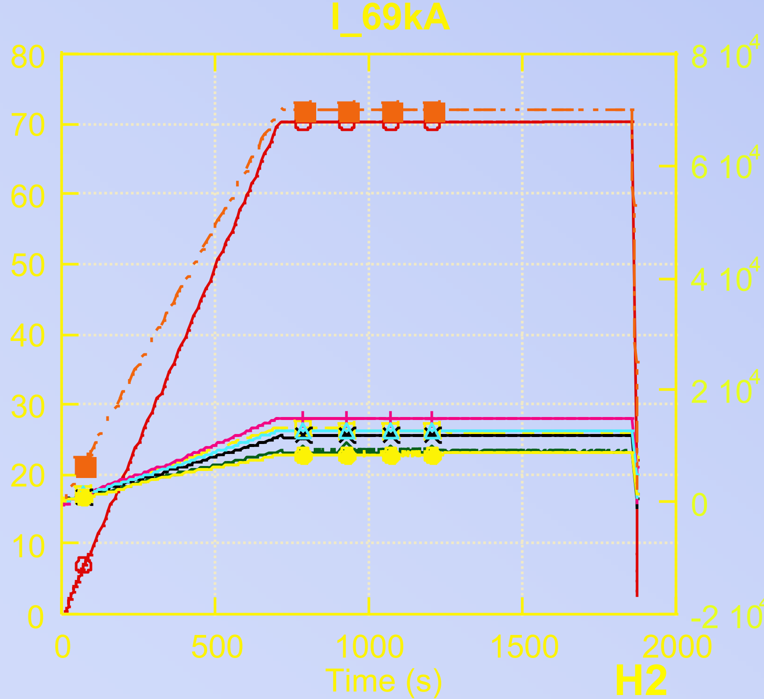
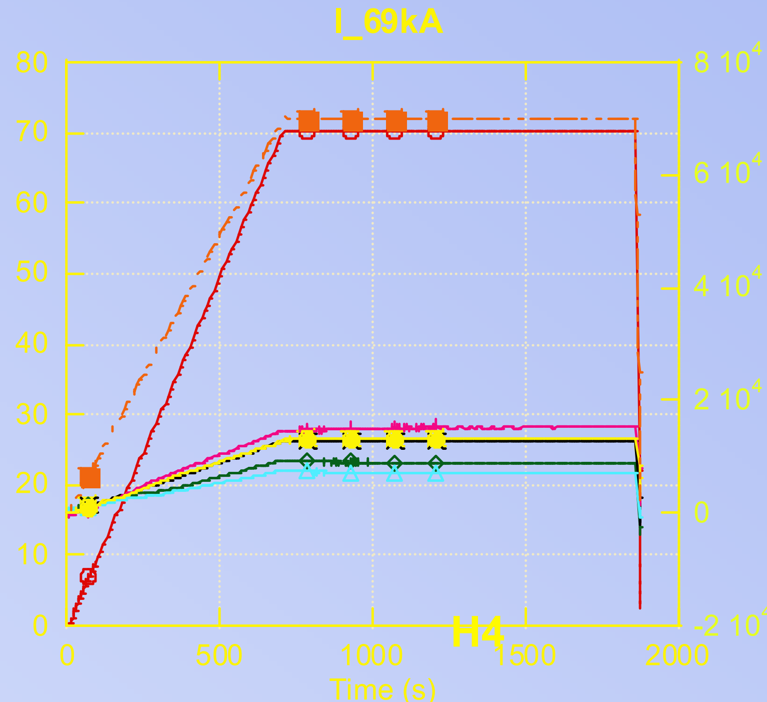
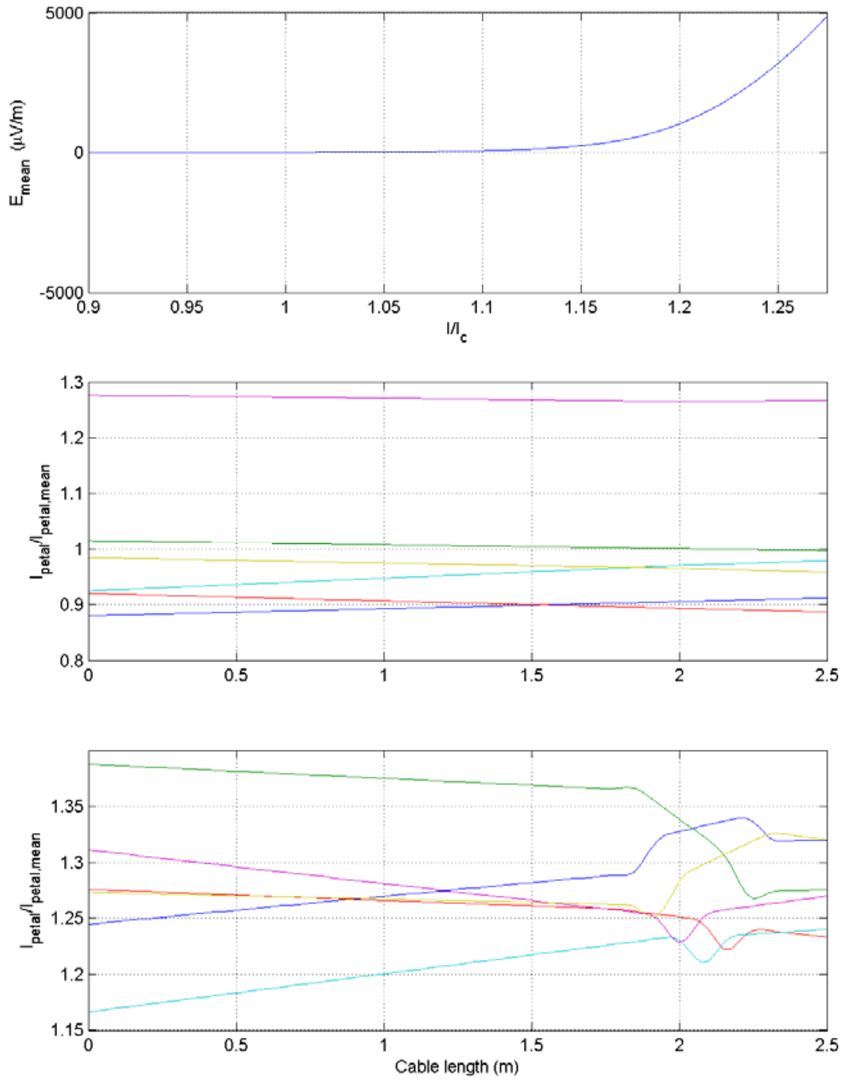
A sample current reconstruction in TFMC: a case with I_{tfmc}=69kA, I_{lct}=0, in superconducting state (CDM_021023_1403_0kA_69,3kA)







PFCI-SULTAN Sample



ITER - EFDA Current Lead R&D Programme - Results of the 20 kA HTS CL

- 20 kA steady state ($T_{int} \approx 70$ K)
- 40 kA short time ($T_{int} \approx 60$ K)
- Quench current: 30 kA ($T_{int} \approx 85$ K)
- Heat load into 4.5 K at 20 kA: 3.6 W
- Clamp resistance: 6.6 nΩ
- LOFA (20 kA, T_{int} = 70 K): 15 minutes before quench

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):

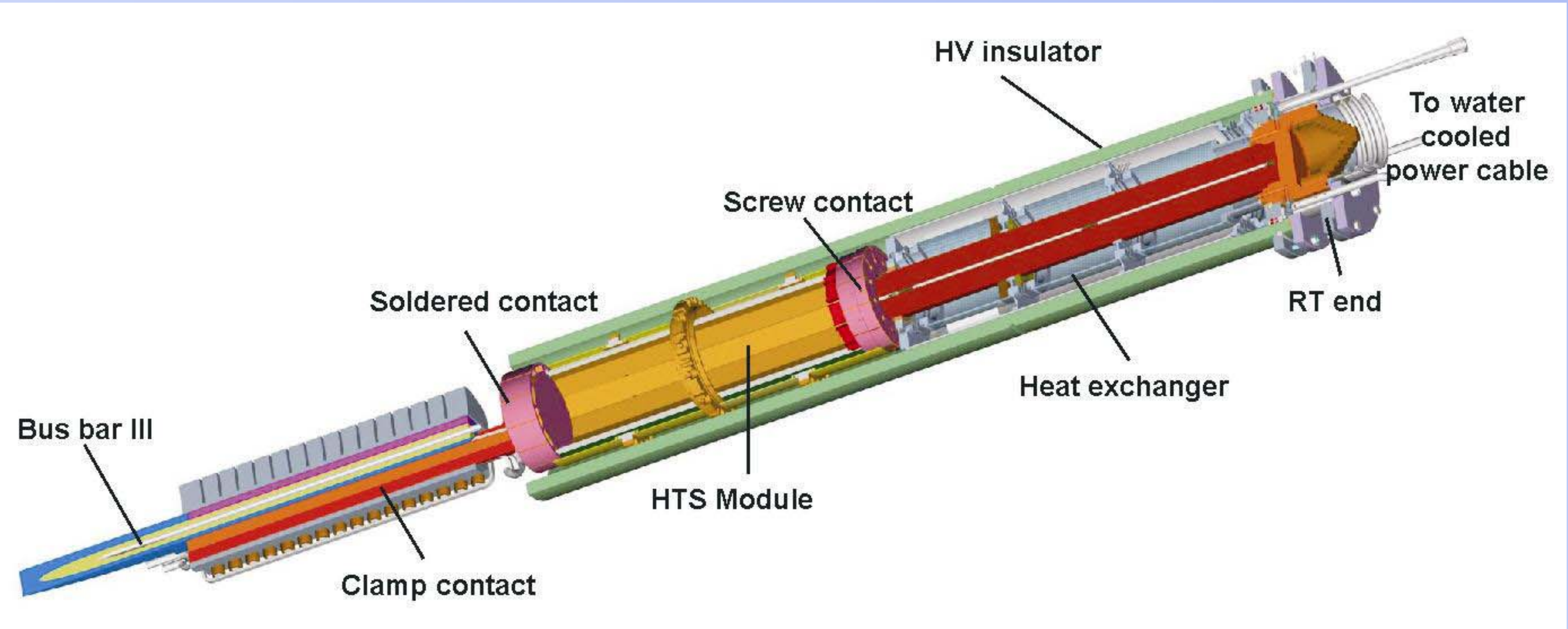
Coils	No. of pairs	I_{max}	Type	V_{max}
TF Coil	9	68 kA	F	10 kV
PF Coil	6	45 kA	V	14 kV
Correction Coil	9	8 kA	V	3 kV
CS Coil	6	45 kA	V	10 kV

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

PART 1: Clamp contact with three Nb_3Sn inserts

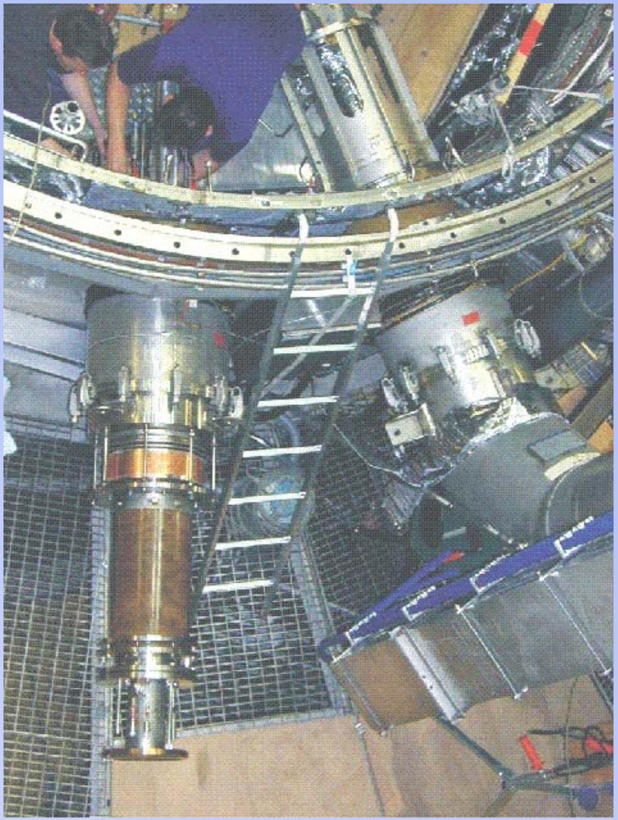
PART 2: HTS module with Ag/Au sheated Bi-2223 tapes

PART 3: Conventional heat exchanger with Cu - discs



Status of the installation in TOSKA

Conventional 80 kA CL and Aluminium bus bar installed in TOSKA



70 kA HTS CL installed in TOSKA

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!

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

Search for Systems with higher radiation resistance

System Overview

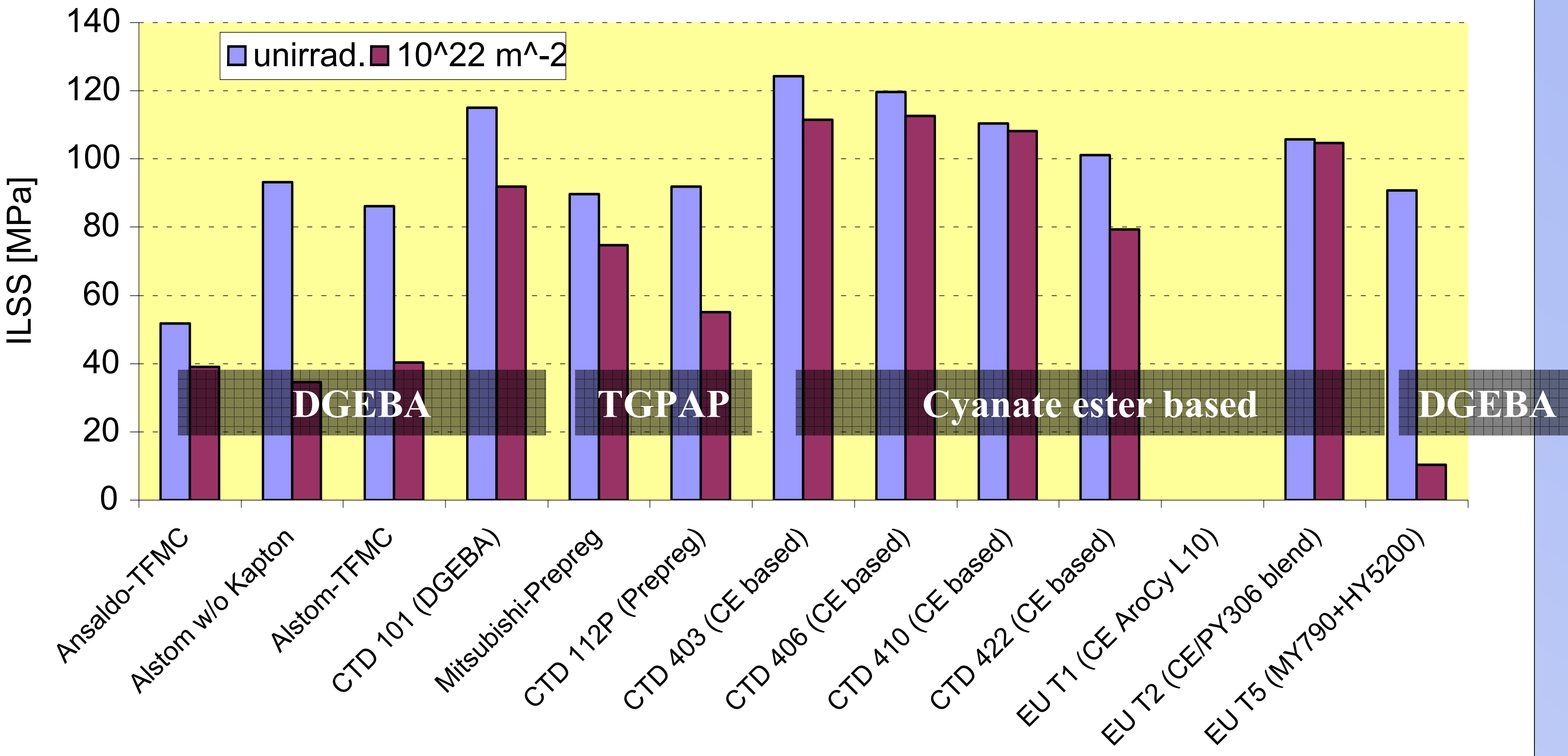
August 2003

	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

Results of SBS screening tests on vario insulation materials

All values FE corrected



T2 (cyanate-ester/epoxy blend)

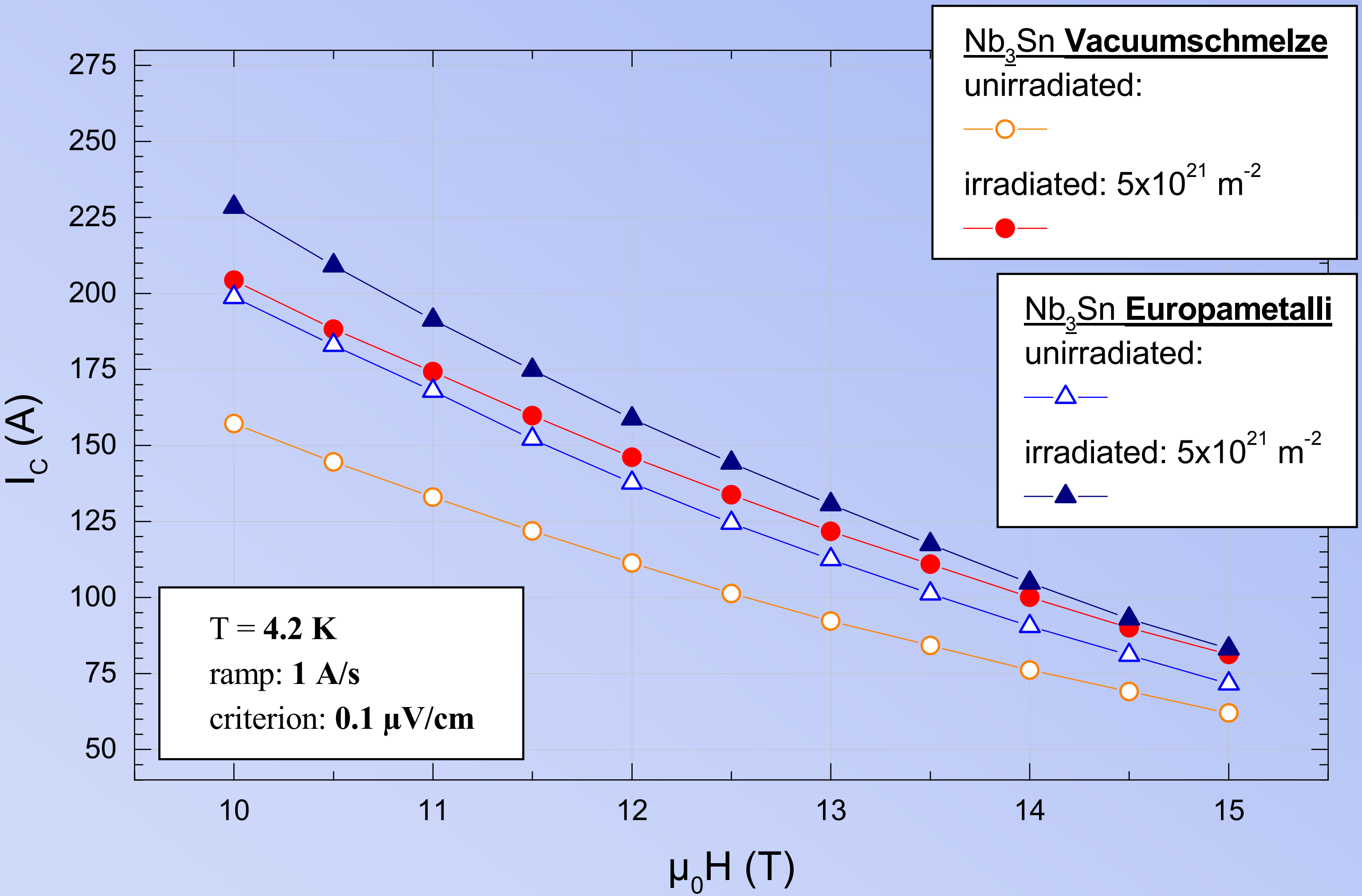
	T2 0°	T2 90°
UTS unirradiated	1027 ± 20 MPa	414 ± 20
UTS 1x10^{22} m^{-2}	945 ± 18 MPa	397 ± 21

	T2 0°	T2 90°
Fatigue unirradiated	308 MPa=30%	166 MPa=4(
Fatigue 1x10^{22} m^{-2}	284 MPa=30%	159 MPa=4(

	T2 0°	T2 90°
ILSS^{SBS} unirradiated	92 ± 3 MPa	83 ± 4 MPa
ILSS^{SBS} 1x10^{22} m^{-2}	91 ± 3 MPa	81 ± 4 MPa

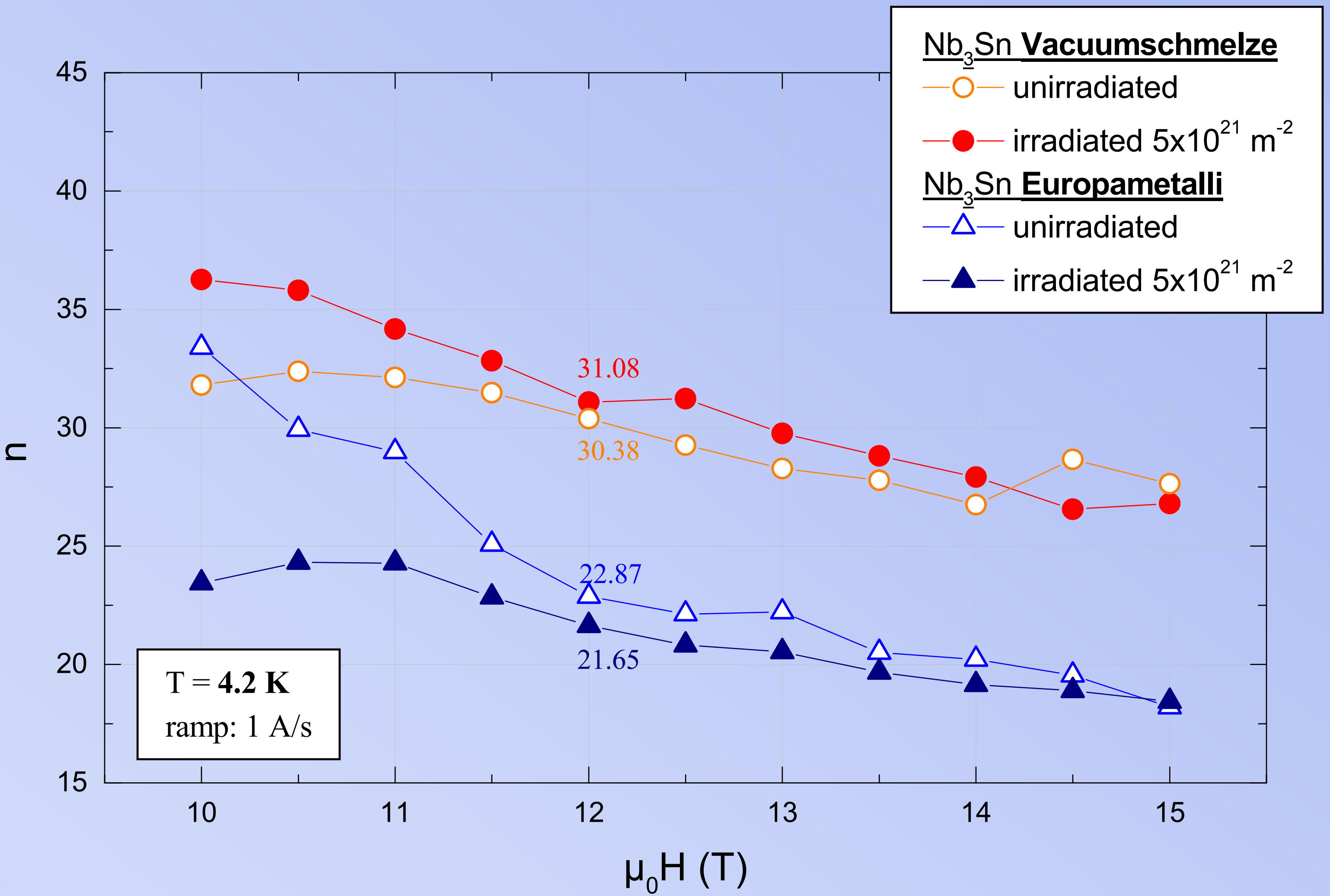
- *Improvement of radiation resistance !*

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).**

Sc irradiation



n-value is quite low for the EM-wire.

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 16LN 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.

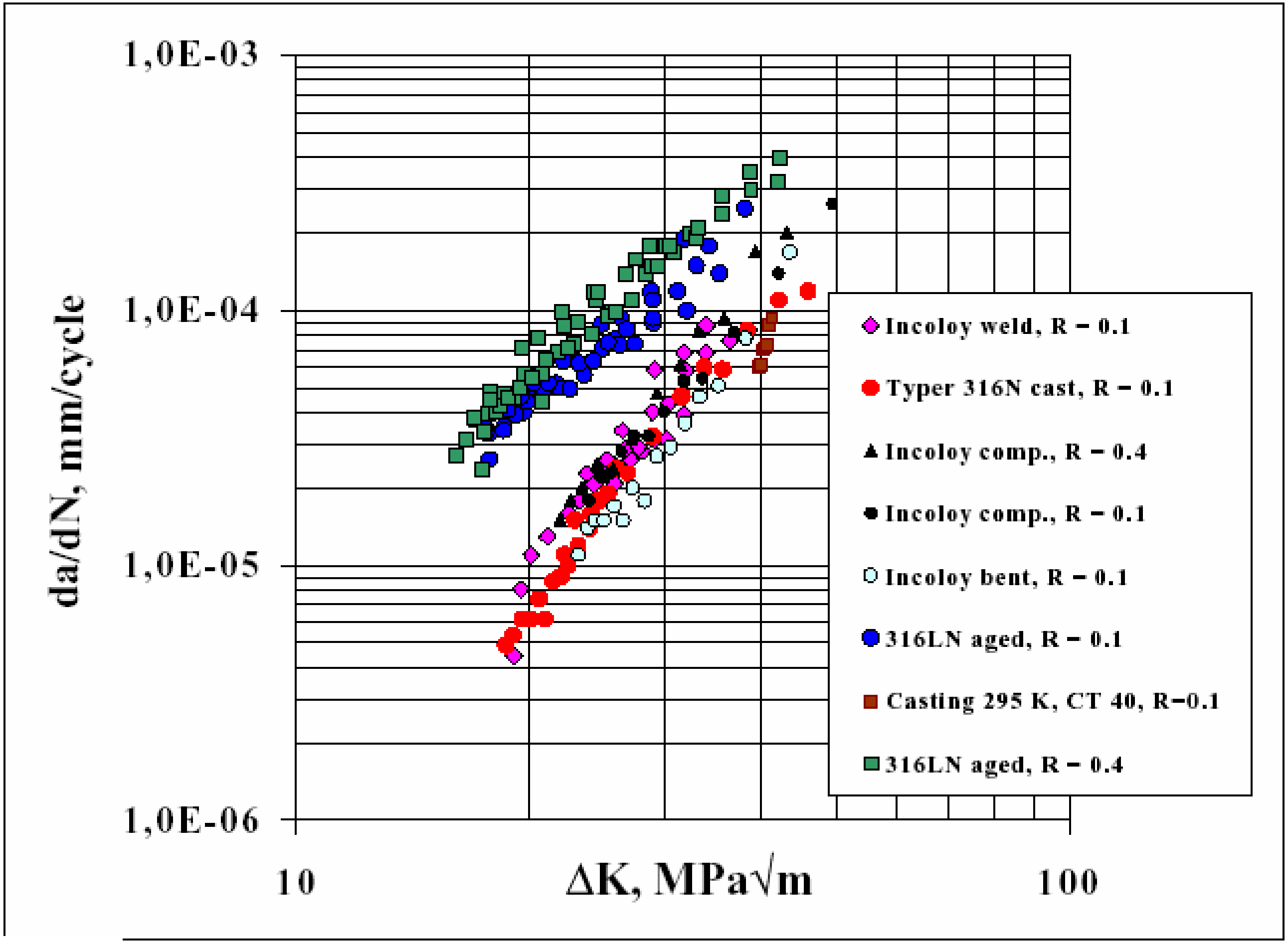


Figure 55. Fatigue crack growth rate of aged Type 316LN and Incoloy 908 jacket materials at 7 K and at different load ratios. The newly developed cast steel's FCGR represent the measurements at 7 K in all three spatial orientation.

Conclusions

– The feasibility of the ITER 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 ITER conductor
– Better understanding of current and strain distribution in the cable will allow reduction of design safety margins
– An advanced insulation system is being qualified