Nb_3Sn and NbTi for high field applications

With emphasis to fusion magnets

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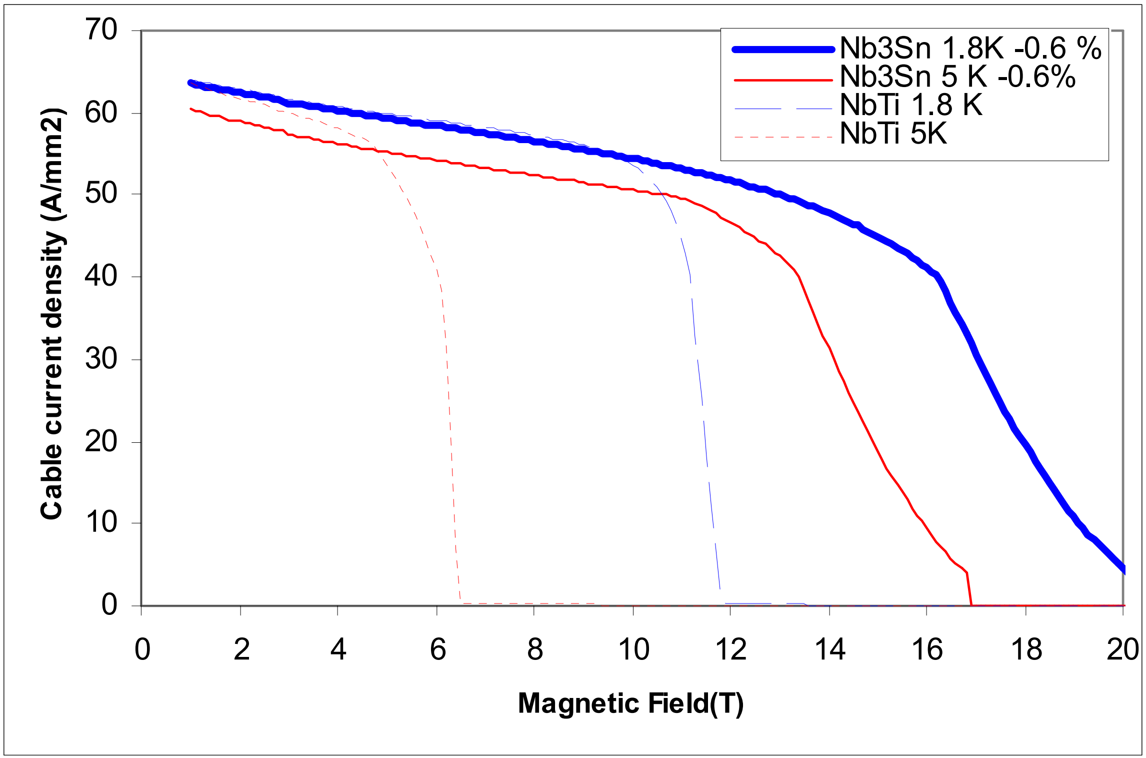
Outline

- Range of applications of NbTi and Nb_3Sn for fusion magnets
- Description of the TF model Coil (TFMC) and of its Nb_3Sn conductor
- Bending strain in Cable in Conduit Nb_3Sn conductors
- Upgrade Nb_3Sn strands for ITER
- Pushing NbTi at its limits in Particle Physics

Introduction



Range of application of NbTi and Nb_3Sn as a function of field and temperature
For a typical Cable in Conduit for fusion (15 s fast discharge)

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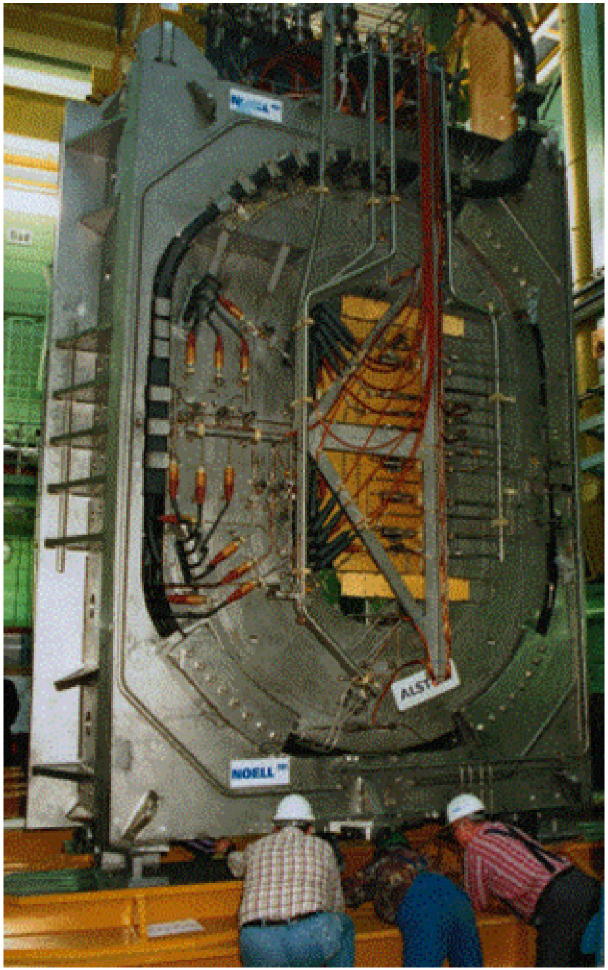
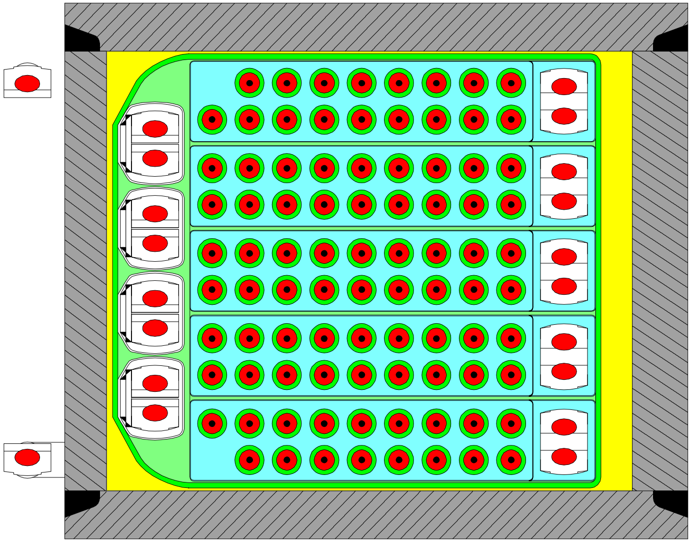
ITER TF model coil



The system of plates and casing is representative of ITER TF



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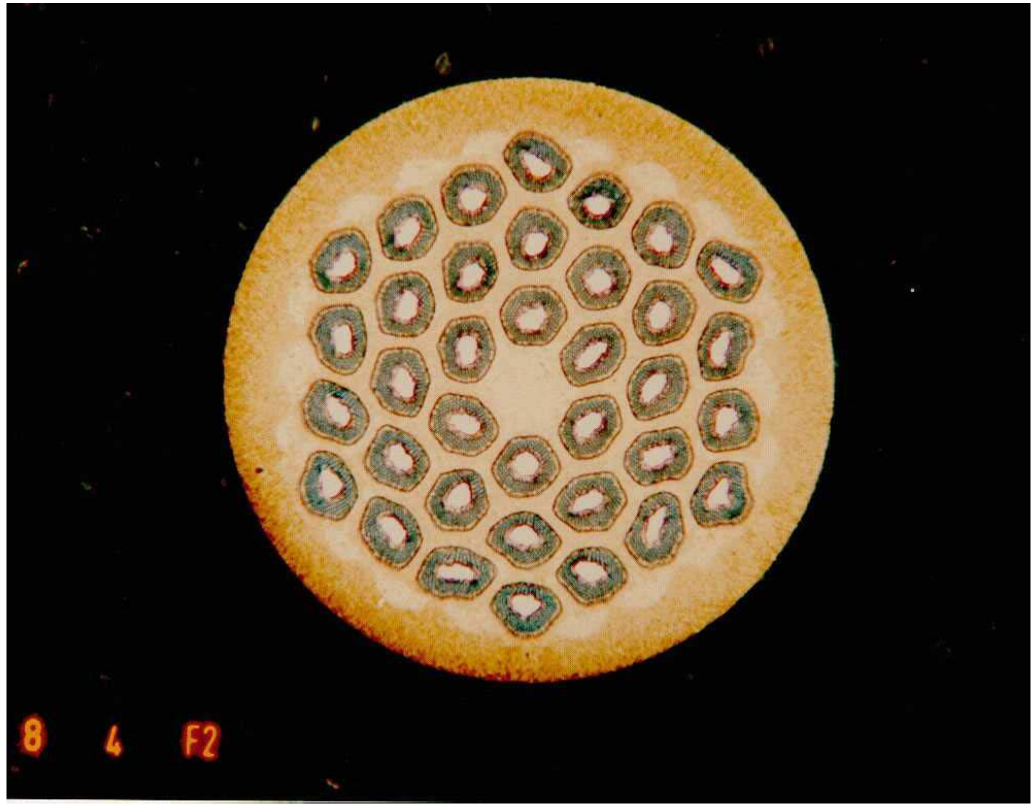
The conductors of the ITER model coils

CSMC
51 mmx 51 mmm
40 kA 13 T

TFMC
Φ 40,7mm, 80 kA, 9.7 T

The TFMC strand

C0=1.1 E10
Tc0m= 16.9 K
Bc20m=29.1 T
Simplified Summers model



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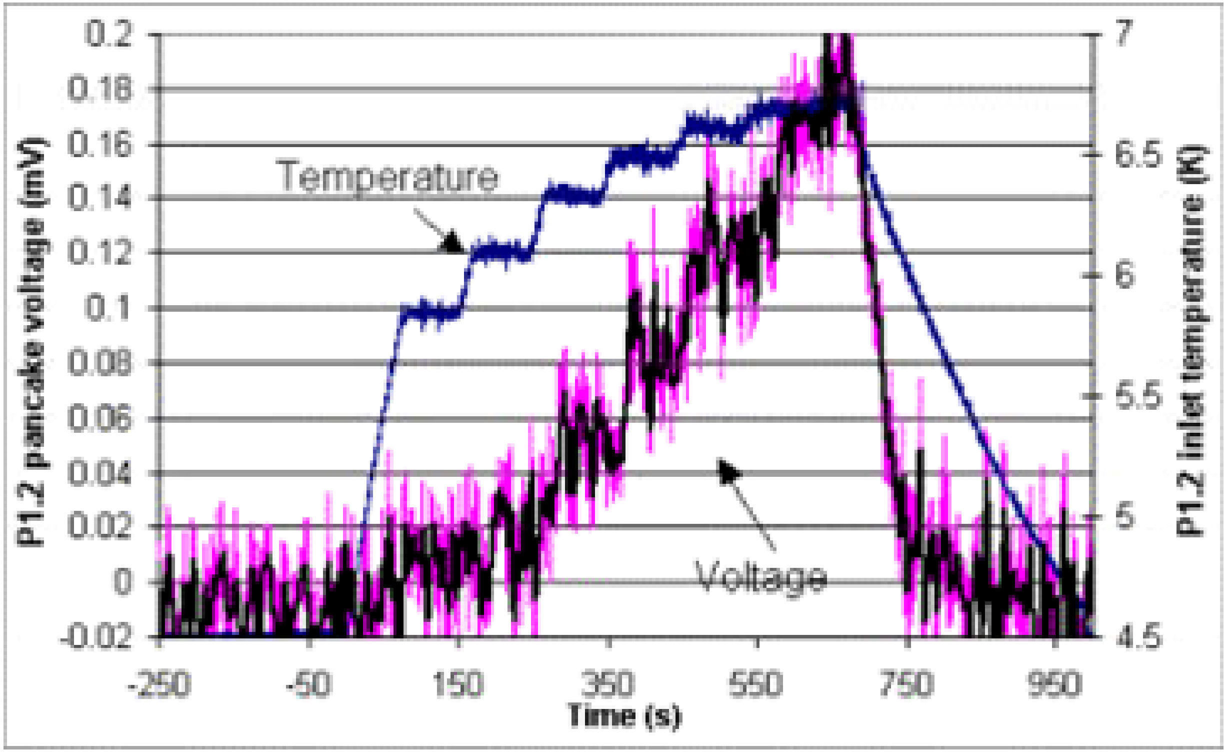
Φ=0.81 mm

Exploration of limits of the TFMC conductor by increasing the inlet temperature of DP1.2

At 80 kA and 9.7 T the conductor is so stable that it is possible to recover after a temperature excursion above the current 0.5 K above the current sharing temperature



Presentation concentrates on estimation of Tcs for the test (80 kA, 16kA)

Exploration of limits of the TFMC conductor
TFMC 80 kA LCT 16 kA

Sensitivity of Nb3Sn to compression in stainless steel conductors

If $B_{effective}$ and T are known
I the law J_{noncu} is known
The only unknown is then the filament strain ε

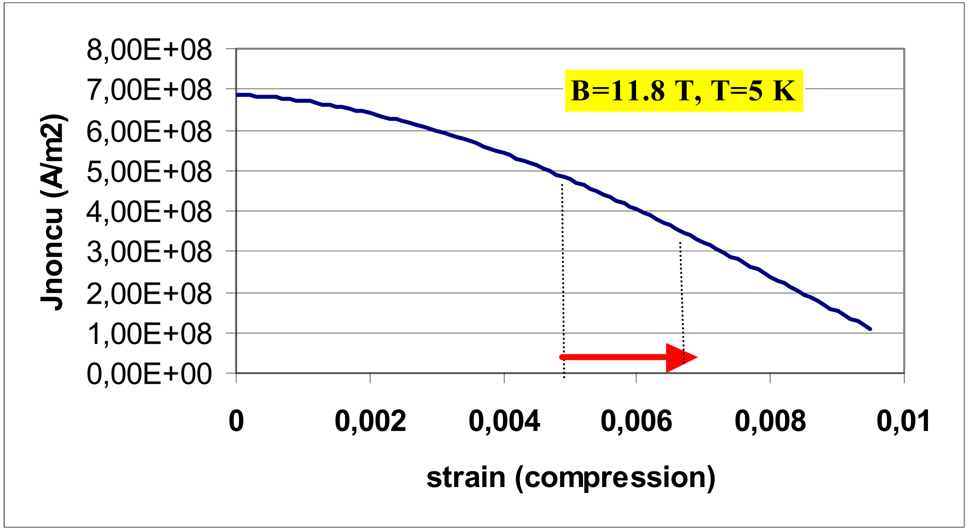
The sensitivity of Nb3Sn to compressive strain is well known. According to theory The effective strain ($\varepsilon_{effective}$ in a stainless steel conductor is the sum of two terms :

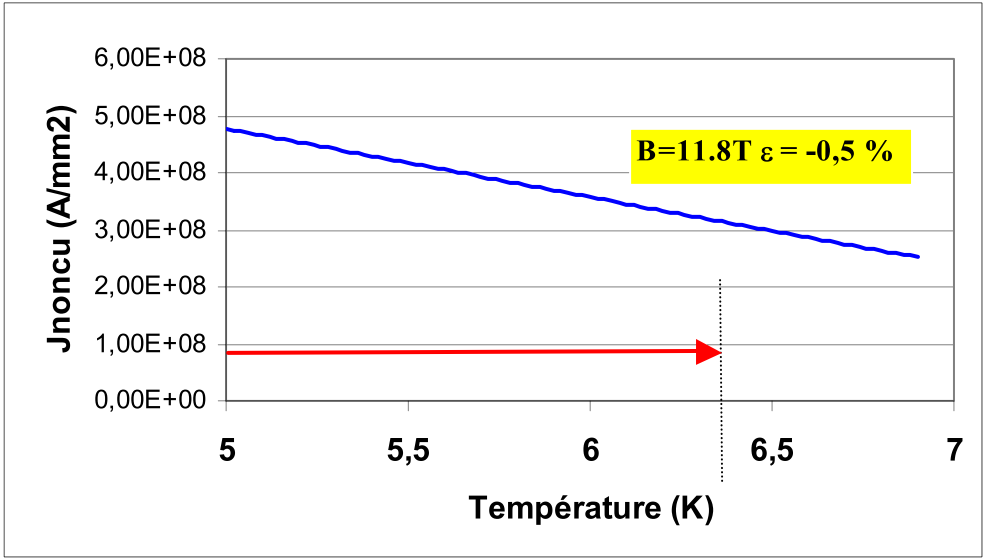
- The thermal compression ε_o due to thermal heat treatment
- The elongation ε_{op} which appears due to the electromagnetic forces in operation

$$\varepsilon_{effective} = \varepsilon_o + \varepsilon_{op}$$

According to theory the maximum value (in absolute) which can be awaited for ε_o is the differential thermal contraction from 923 K to 4 K between steel and Nb3Sn.
This parameter is not well characterized, moreover the cable void fraction can attenuate this effect due to imperfect bonding but this phenomenon is not well characterized too.

Influence of strain variation on Jnoncu (Europa Metalli strand) (according to Summers model)



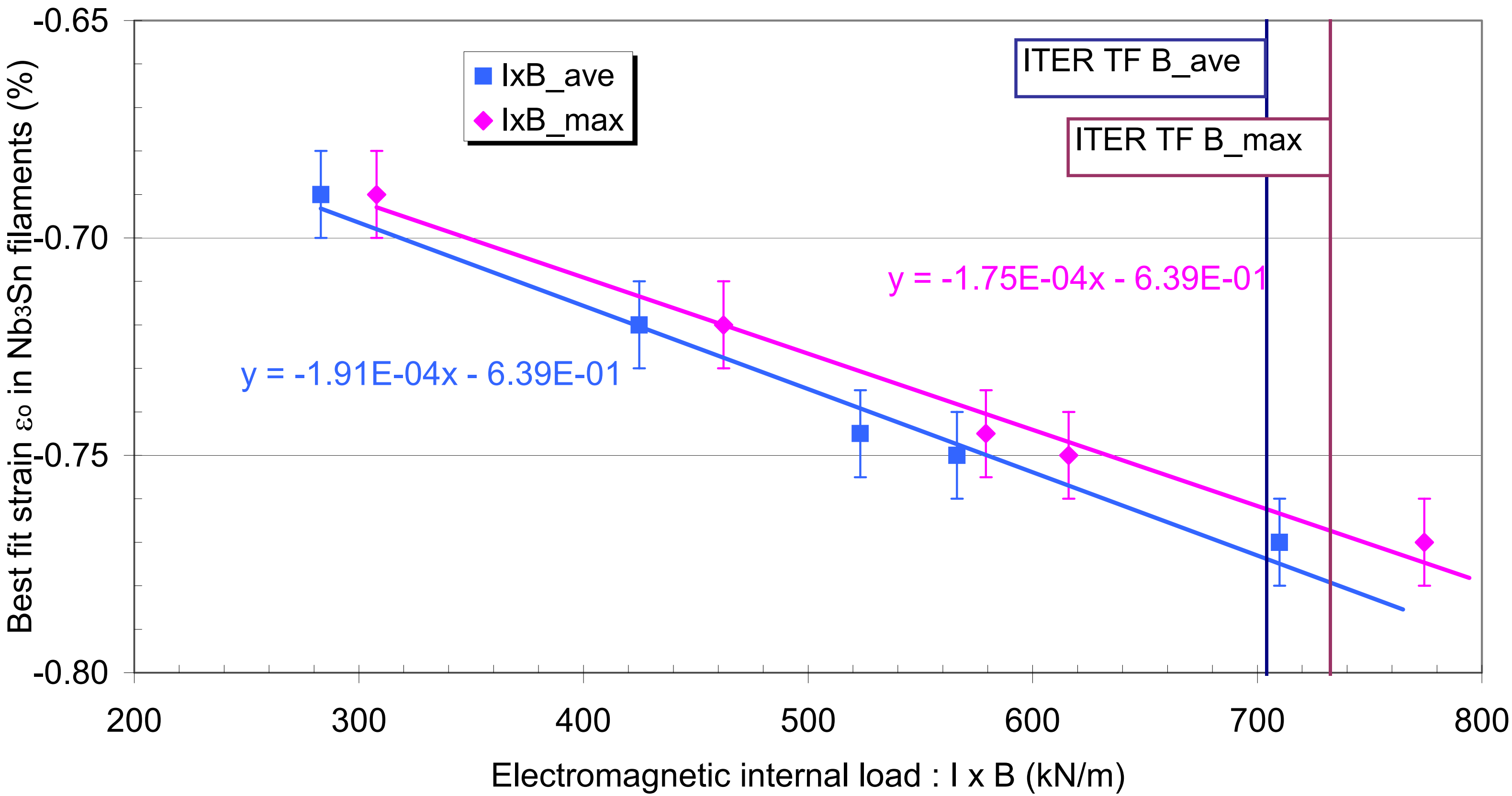


0.2 % in addition in compression is equivalent to 1.3 K temperature increase In ITER TF conditions

ε_0 is depending on the magnetic load in a way which is not completely understood

It was possible by the test at 80 kA in TFMC and 16 kA in LCT to push the TFMC in a magnetic load range relevant of ITER.

TFMC Phase II conductor performances from ENSIC simulations



Overall results brought by the TFMC experiment concerning the filament strain ε_0

1. In phase II experiment the TFMC was tested in a magnetic load range relevant to ITER.
2. The Nb_3Sn filament strain ε_0 is depending on the magnetic load which was not expected by a simple classical model
3. At ITER TF relevant magnetic load load the filament compression ε_0 is larger than expected: [0.75, 0.79] instead of 0.6 in ITER design
4. The 'n' value (around 10) is lower than expected (20)

Points 2-4 suggest that the simple model of compression during cool down from reaction and stretching during operation is too simple and not effective to account for the experiment.

Bending strain such as described by Ekin [1] in 1980 could be an explanation

[1] Ekin J W 1980 "Filamentary A15 superconductors" editors M. Suenaga and A. F. Clark Plenum Press

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Bending strain in Cable in Conduit Conductors

Bending strain in CICC is not originated like in Ekin publication by reacting Nb_3Sn strands and winding them on a mandrel

Bending strain in CICC according to Mitchell model [2]could be induced by the twist of the strands inside the jacket and can appear:

- during thermal compression induced by the cool down from reaction temperature before any loading

- during coil energization due to magnetic load

In this model the strain can vary across the filament section and along the strand with a wavelength of typically 5 to 10 mm

[2] Mitchell N "Mechanical and magnetic load effects in Nb_3Sn CICC" 2003 Cryogenics 255-270

Possible driving factors for bending strain in CICC

A finite element model has been developed by Mitchell but **no quantitative dependency can be given.**

Following parameters are supposed to play a role :

- Twist pitch of the strand can affect the current redistribution between filaments within a strand and average the effect of strain distribution across the strand section

- Geometry of the strand and associated effective resistivity of the matrix can also help to average the strain. This can be very different from one company to another.

- Cable void fraction can also play a role to minimize this effect

A R&D program will be launched in Europe on subsize conductors (36 strands) in the existing FBI test facility (FZK) to play on these different parameters and help the understanding.

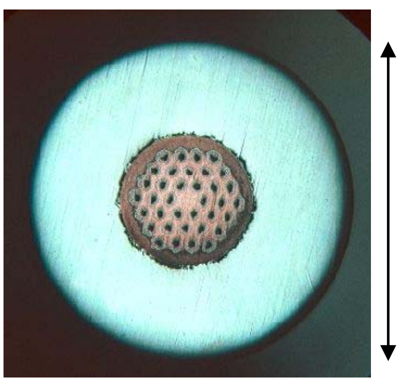
WHAT ARE STILL THE OPEN QUESTIONS ABOUT STRAIN IN NB3SN ?

Is the differential thermal contraction applied in the same way in a Cable in Conduit and in a wire soldered on a spring (tests made at Durham and Twente) ?

Is Applying an axial stress on the wire to strongly compress it, an exact simulation of the effect of the thermal contraction in a CICC.

Is the Summers model correctly accounting for behaviour of strands under high compressive strain which are related to stainless steel jackets

Mechanical properties of Nb3Sn are different according to the vendor : what is the simpler short sample representative of the mechanical properties of the material embedded in a conduit.



2 mm

A simple idea to explore strain on a single stainless steel jacketed strand manufacture at **ENEA** and to be stretched at **FZK** on FBI test Facility to investigate compression and effect on Ic

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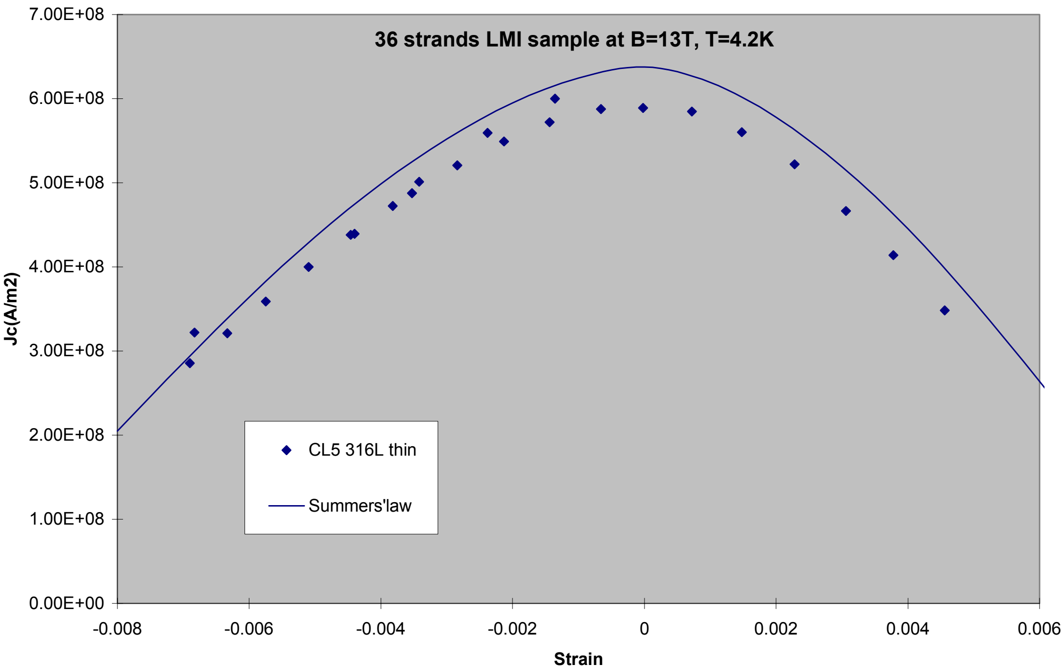
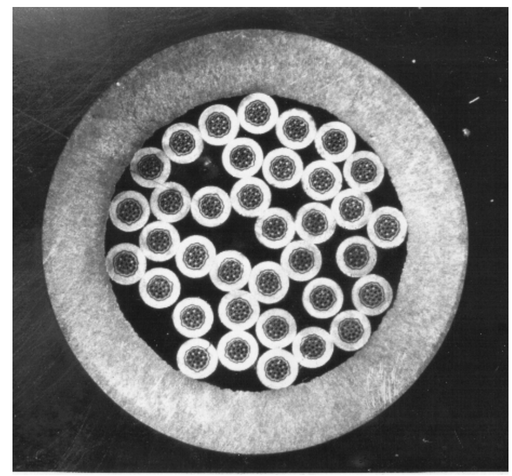
Stretching a subsize (36 strands) Nb_3Sn conductor in the FBI facility
EM strand 12 T 4.2 K (A316 jacket) 1997





8.5 mm

Stretching the sample showing good conformity with Summers's law

Test results on mechanical samples (36 strands) 12 T 4.2 K (1997)
At FBI test facility (FZK)
(only thin samples)

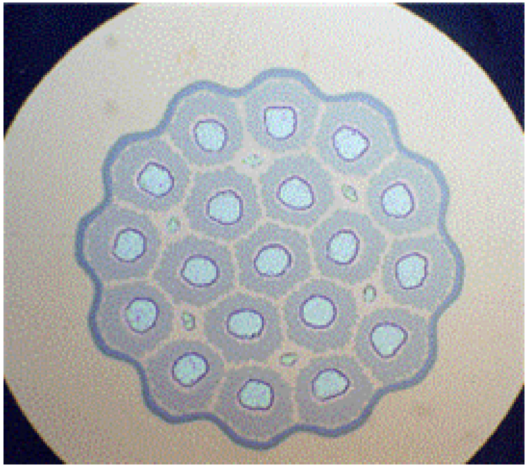
Sample Thin jacket	εexp	Icompressed /Imax (Observed)	Icompressed /Imax (Summers According to εexp)
CL5	-0.69 %	0.48	0.46
CL6	-0.66 %	0.51	0.5
CV3	-0.70 %	0.52	0.52
CV4	-0.70 %	0.55	0.52

Impact of TFMC results on ITER specifications
Typical ITER Specification for the Nb_3Sn strand of the ITER TF system
Source : EFDA

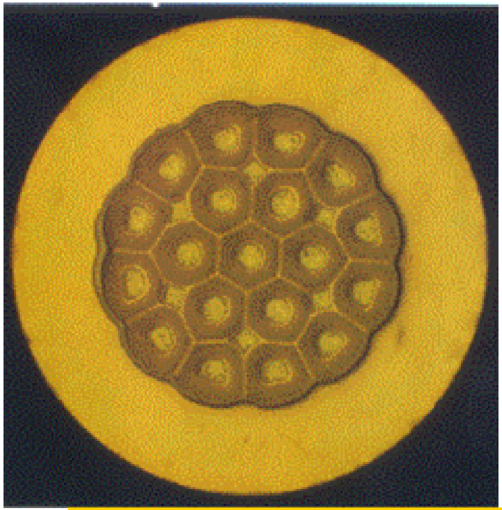
Min J_{noncu} @12t, 4.2 K, 10 µV/cm Without external deformation	minimum 800 A/mm^2 Target value 1100 A/mm^2
Max hysteresis losses per non Cu volume @ ± 3T cycle	1000 kJ/m^3
Cr coating thickness	2 µm -0 µm +0.5 µm
RRR(273 K/20 K)	>100
Unit length	1.5 km or multiples
Strand diameter	0.81 mm ± 3 µm
Cu/non Cu	1
Strand Twist pitch	<20 mm
Index "n" @12 T, 4.2 K	>20

A procurement task has been launched in Europe by EFDA for this advanced strand

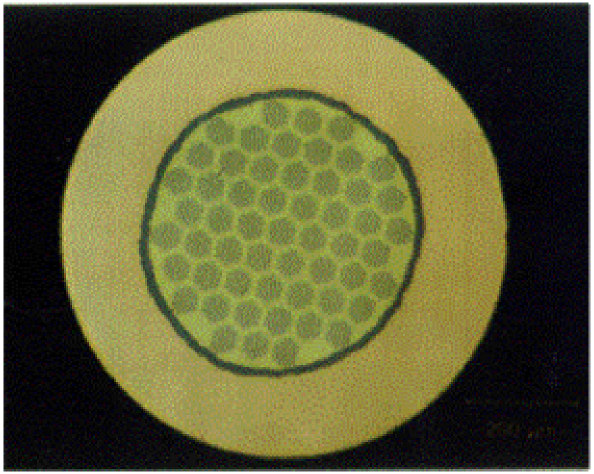
Prototype Nb_3Sn strands produced by european companies in the framework of ITER



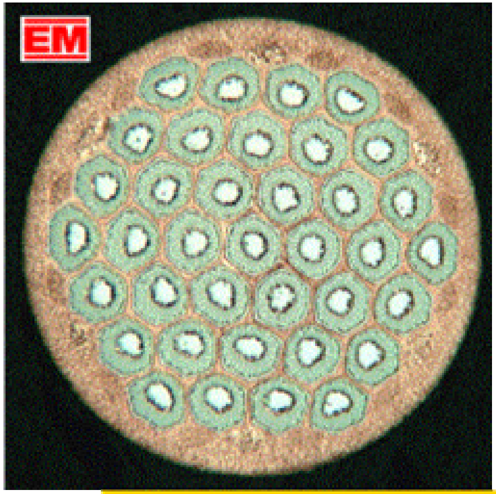
Alstom MSA



Outokumpu -IGC



Vacuumschmelze



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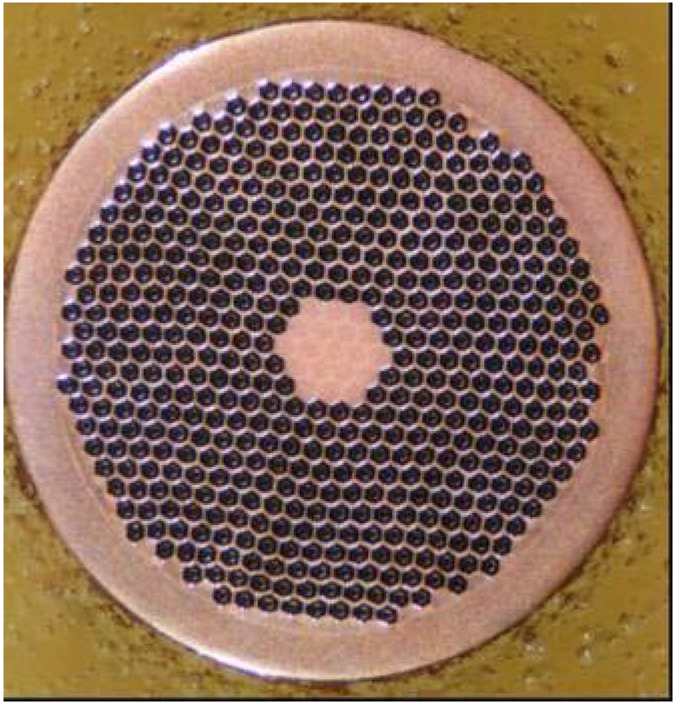
SMI is participating to this procurement task



Pushing NbTi at its limits in Particle Physics
Can Tantalum addition help ?

It is now assessed that the nominal operating conditions of the LHC dipole conductor are far from the critical properties of the conductor

Typically at 8.33 T and 11850 A at constant field:

ΔTmargin=2K   I/Ic=0.5

A general question is, how it is possible to increase the field ?
What is limiting the operation ?
Can tantalum help by increasing the margin in temperature?

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Pushing NbTi at its limits in Particle Physics
Can Tantalum addition help ?

Temperature margin in LHC dipole (analytical presentation)

J=1259 A/mm2 current density in NbTi at 8.33 T and 11850 A in the cable

Jc(1.9 K,8.33 T)= 2482 A/mm^2

Simple description of critical current density as a function of field and temperature:

$J_c(T,B) = -\alpha[B+B_{c20}((T/T_{c0})^{1.7}-1)]$ B_{c20}=13.87 T T_{c0}=9.2 K α=625

Determination of Tcs at LHC dipole operation point

$J= -\alpha[B+B_{c20}((T_{cs} /T_{c0})^{1.7}-1)]$

Analytical expression of Tcs at LHC dipole operation point

$T_{cs}=T_{c0}[1-J/(\alpha\, B_{c20})-(B/ B_{c20})]^{1/1.7}=4.12$ K

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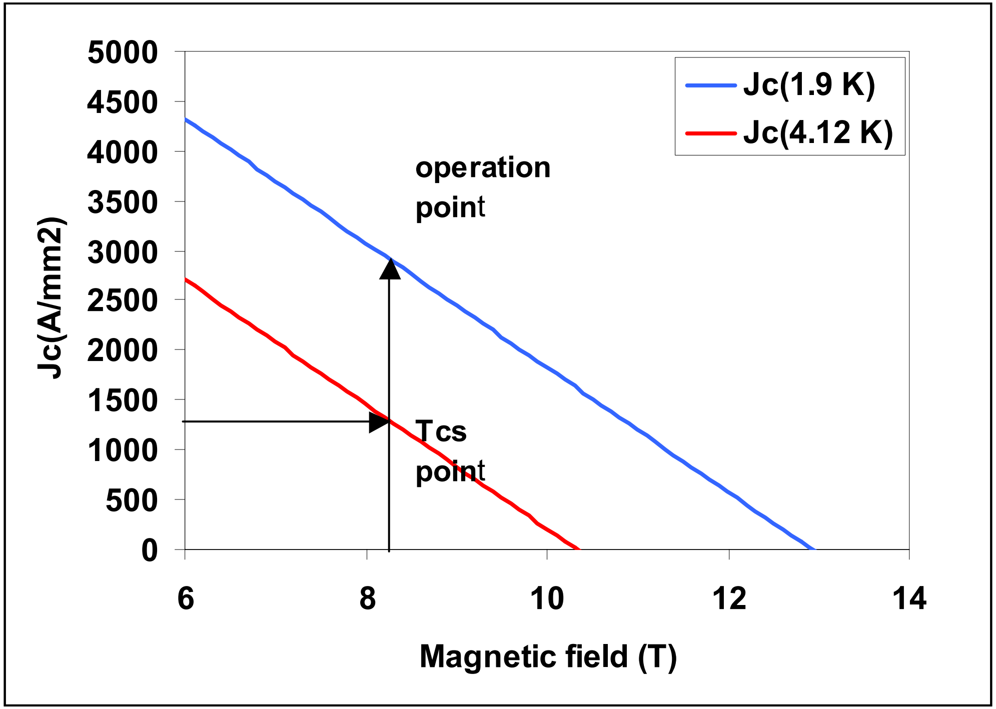
Temperature margin in LHC dipole (graphical representation)
The margins at given field in current and in temperature are represented



Pushing NbTi at its limits in Particle Physics
Can Tantalum addition help ?

The two preceding slides demonstrate that temperature margin in LHC, for a given operating temperature is driven only by the critical properties of the alloy at the considered field around Tcs and not around Top.

Supposed that the aim is to design a dipole at 10.5 T

- the binary material is better than any Ta Ternary at 10.5 T
- The margin is driven by the properties around 3 – 3.5 K a range where the advantage of the ternary vanishes in comparison with the binary which is even better.

Conclusion Tantalum can bring no help to increase the dipole field as the increased properties are in a range which is playing no role for the margin.

Pushing NbTi at its limits in Particle Physics (Conclusion)

The tantalum way is probably not the solution for dipoles at field higher than 8.3 T

The temperature margin (around 2 K) which is large at present in LHC dipole is probably not driving the stability limits.

This stability limit is more probably driven by the copper amount in the conductor, than the NbTi section so the copper section has to be increased.

The economic impact of the copper section increase and associated decrease of the current density has to be evaluated