Superconducting Magnets - 3

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Outline

1. Stepped Approach for the Design of large Conductors and Magnets

2. Examples of Superconducting Fusion Magnets from last Century

3. The ITER Conductors and Coils

4. Toward DEMO - HTS

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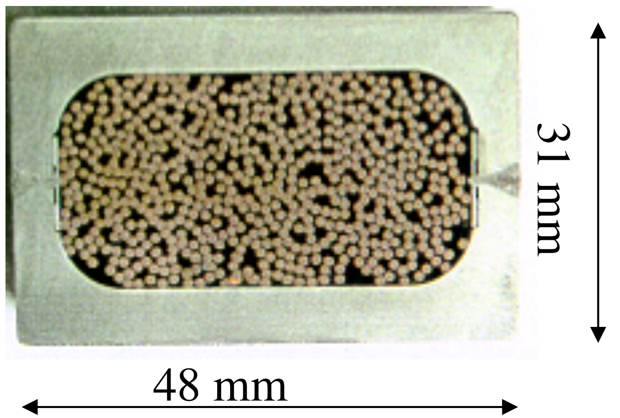
History of the ITER Conductor
The NET-ABB flat conductors

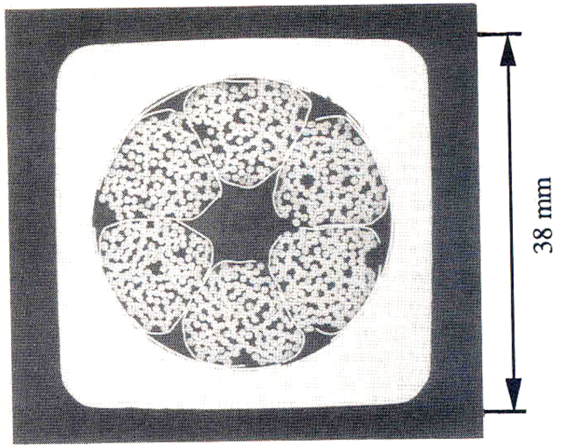
- The precursors of the present ITER conductors are the NET conductors, the first large Nb_3Sn cable-in-conduit developed in Europe in 1988-1990
- The design was based on
  - *A rectangular steel jacket either extruded or longitudinal welded.*
  - *The cable is a strand bundle with large void fraction, 40%-45%.*
  - *No pressure release channel*



- The prototype was first tested in 1991 and achieved 40 kA at 12 T. An in depth comparison of performance assessment vs. test results was not carried out

History - the NET/ CEA conductors

- A modified design of the NET conductor was proposed by CEA in 1992
- The CEA design was based on
  - *An extruded, oversize "circle-in-square" steel profile.*
  - *The round cable with wrapped substages*
  - *Pre-shaping of the substage cable to form a vault and a central channel.*



- The prototype was first tested in 1992 and achieved 50 kA at 11 T.

History - the early ITER conductors

- With the start of the Engineering Design Activity (EDA 1992-2000) the design of the NET-CEA became the reference
  - *Replacing the steel tubing by Incoloy tubing (US)*
  - *Introducing a steel spiral to define the space of the central channel.*
- Other modifications were enforced in 2004, including

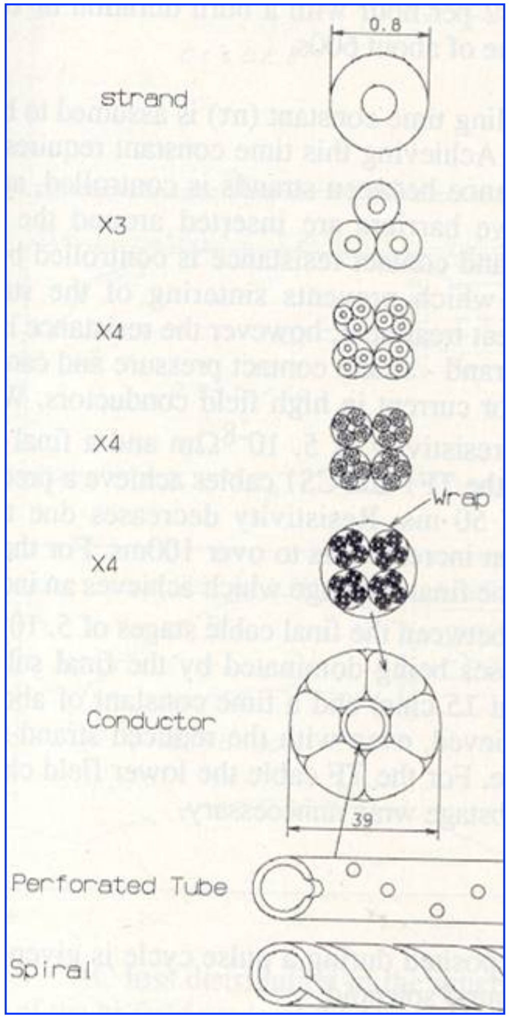
  Back to steel jacket

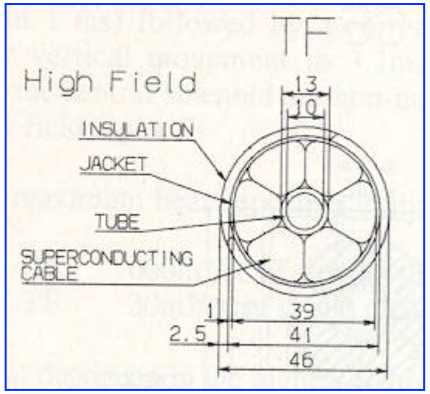
  Segregated copper for quench protection

  More superconductor to offset the degradation

  Higher J_c for strand

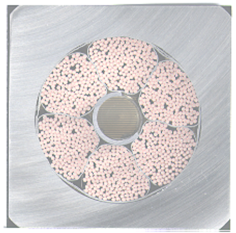
  Reduced void fraction



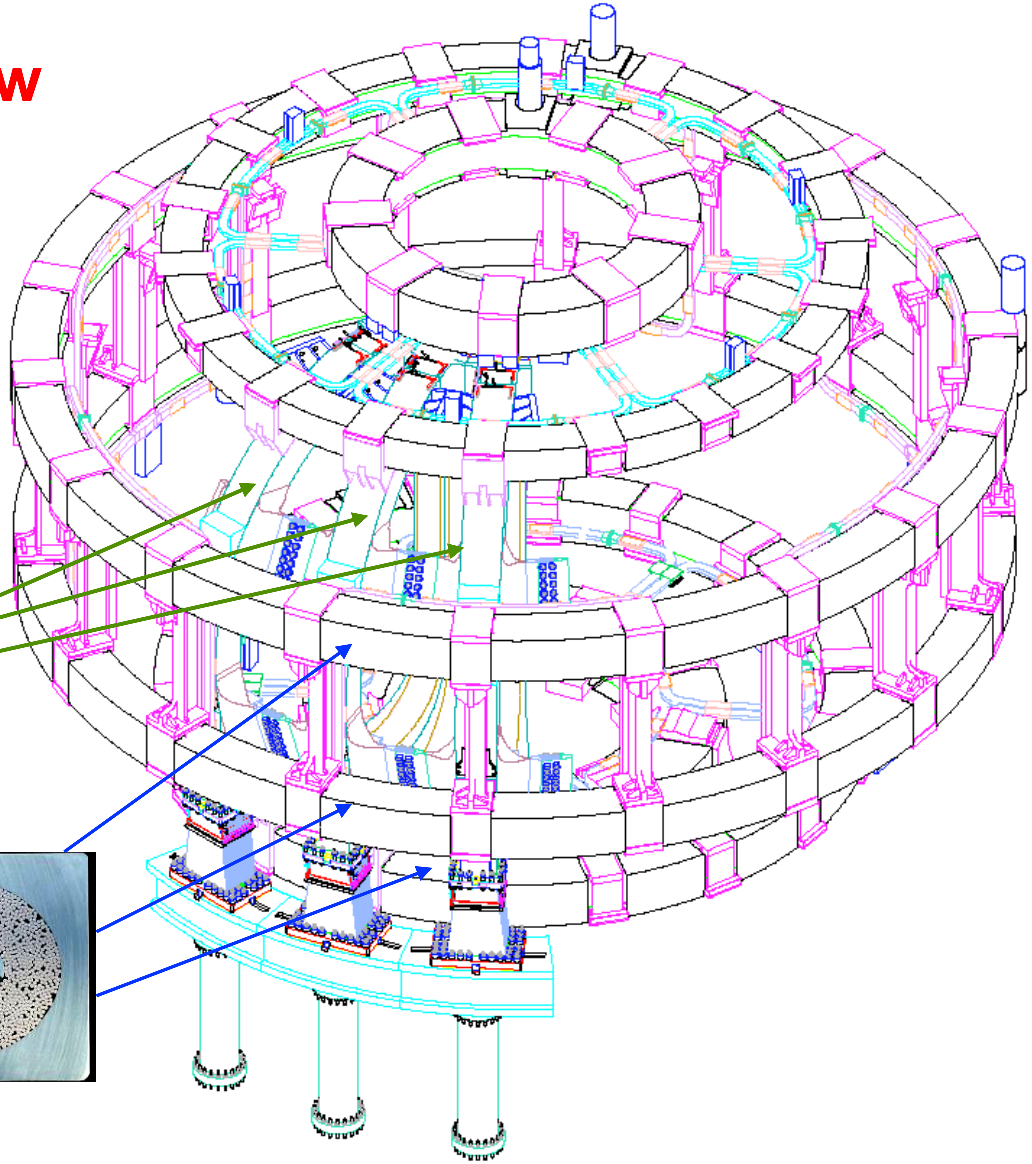


ITER conductors now

CS Conductor,
Nb_3Sn



TF Conductor,
Nb_3Sn



PF Conductor,
NbTi

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Summary of main conductor design criteria

- For non-Cu cross section, temperature margin ΔT at B_{eff}

$$\Delta T = T_{cs} - T_{op}$$

Nb_3Sn (TF, CS)	0.7 K
NbTi (PF, CC)	1.5 K

- For Cu cross section, hot spot temperature ≤ 150 K

- For pressure drop, 1 bar at nominal mass flow rate

Specification / Procurement Strategy

- The ITER TF conductors are procured to the same specification in six out of the seven ITER parties (EU, RF, JA, US, KO, PRC). The procurement is completed in Summer 2016.

- For the strand (both Nb_3Sn and NbTi) only the performance is specified (the layout is left to the supplier) -> **Functional Specification.** For the cable-in-conduit conductor, the detailed layout is specified by the ITER team and must be followed by the procuring parties -> **Blue Print Specification**

- A conflict arises in the **responsibility for the conductor performance** between the with ITER team and the Domestic Agencies who sign the Procurement Arrangements

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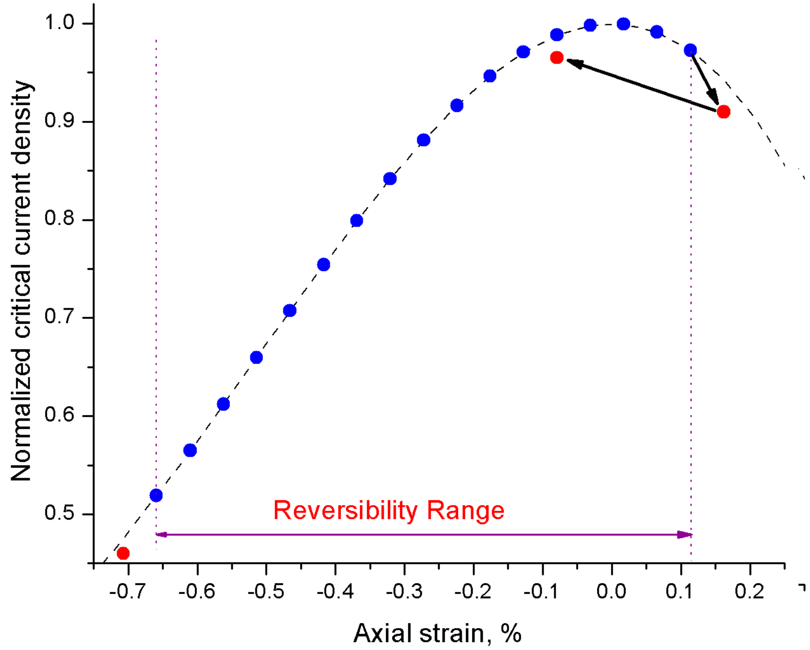
Nb_3Sn: strain sensitive ***and*** brittle

The strain sensitivity of Nb_3Sn strand has been the object of extensive investigations since decades. Now we have empirical, interpolative scaling laws able to predict $J_c(B, T, \varepsilon)$ starting from an experimental database.



The catch of the scaling laws is that they are valid only within the reversible range of strain, implicitly suggesting that only intact strands should be used.

High current density strands tend to have very limited reversibility in tension, i.e. they are prone to filament breakage by bending.

*The range of reversibility depends on the applied criterion (**threshold of electric field**). The stricter the criterion, the smaller the reversibility range.*

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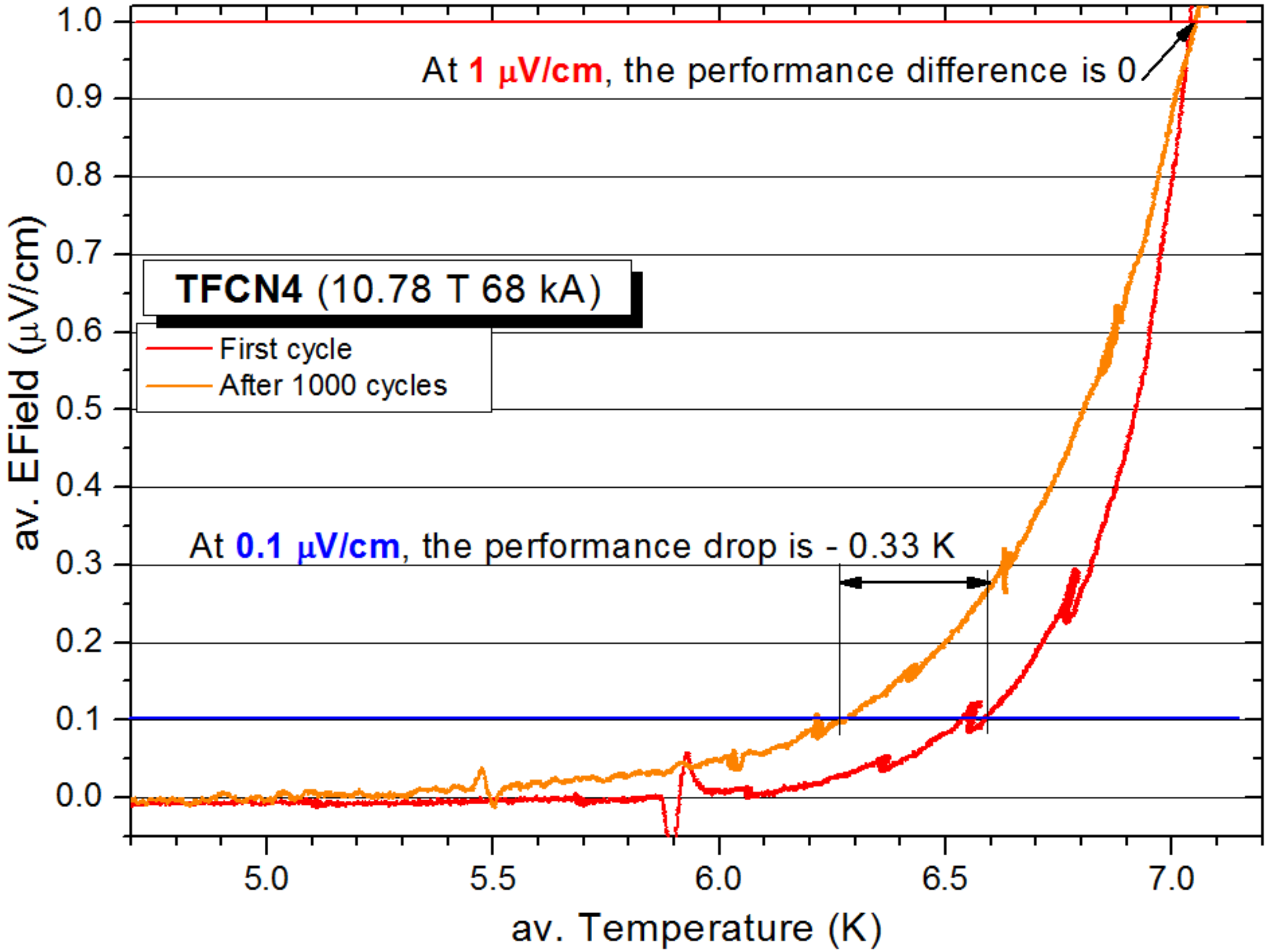
The electric field criterion for performance assessment matters…



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Nb_3Sn strands inside a CICC

- At first glance, the CICC design seems to prevent the detrimental effects of mechanical load on Nb_3Sn:
  - *The W&R method prevent high bending loads during manufacture*
  - *The jacket prevents the compressive load accumulation in transverse direction*
  - *The Incoloy jacket matches the coefficient of expansion of Nb_3Sn and prevents thermally induced longitudinal compressive strain*

- While the longitudinal strain issue came back in ITER with steel replacing Incoloy ≈ 2004, it was a common understanding that bending and transverse loads are not an issue for W&R CICC…

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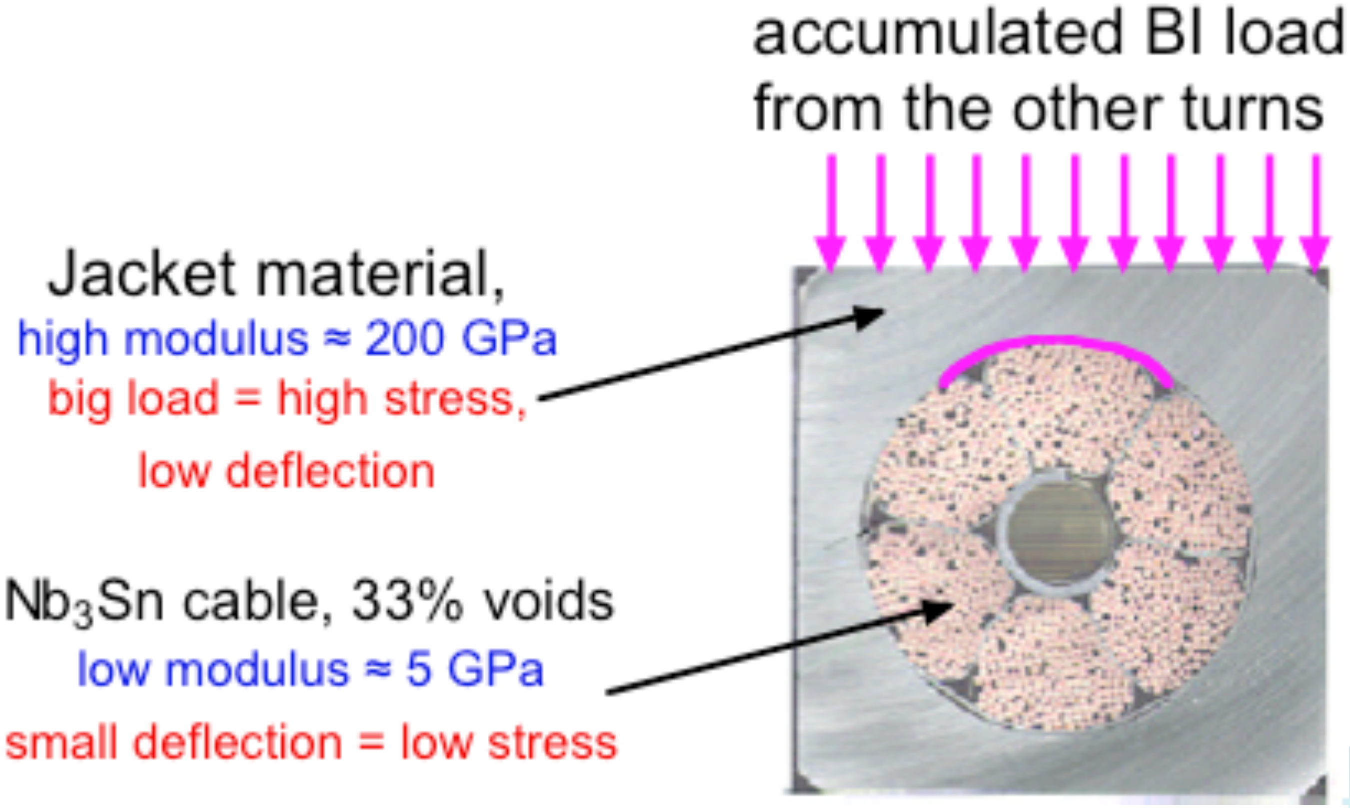
Nb_3Sn CICC and transverse load - load accumulation

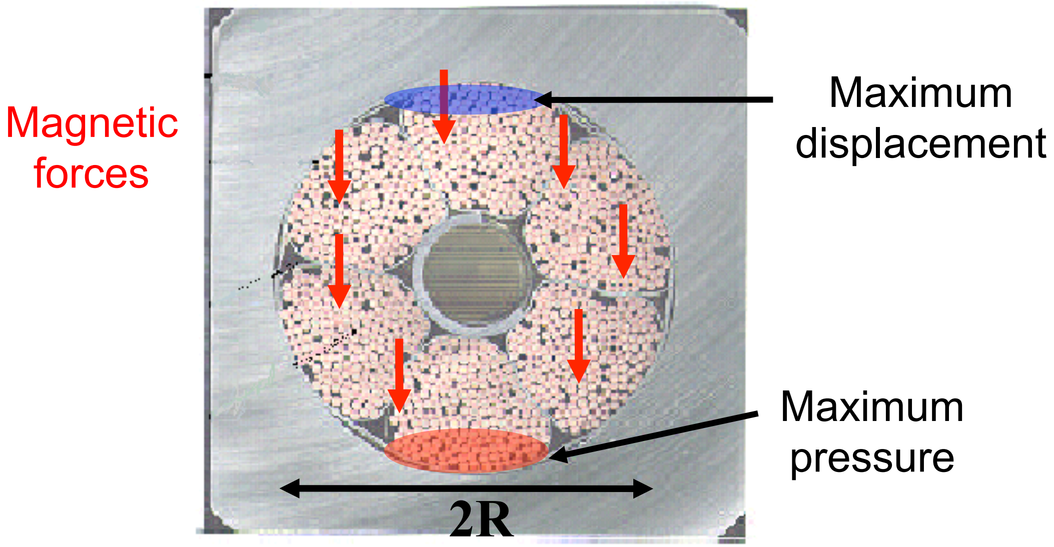
The transverse stress in the cable due to the load accumulation in the winding is negligibly low. The (thick) jacket of a CICC protects the Nb_3Sn cable from “**outer**” loads



Nb_3Sn CICC and internal load - the size matters

Inside the CICC, the Lorenz force acts on the cable. The load is zero at one side and is maximum on the opposite side (body force).

The force per unit length is $\boldsymbol{BI_{op}}$ (independent on geometric parameters), but the peak stress is $\boldsymbol{\propto BRJ_{cs}}$ where J_{cs} is the current density in the cable space. *For the same current density, the peak transverse stress increases with the cable size*

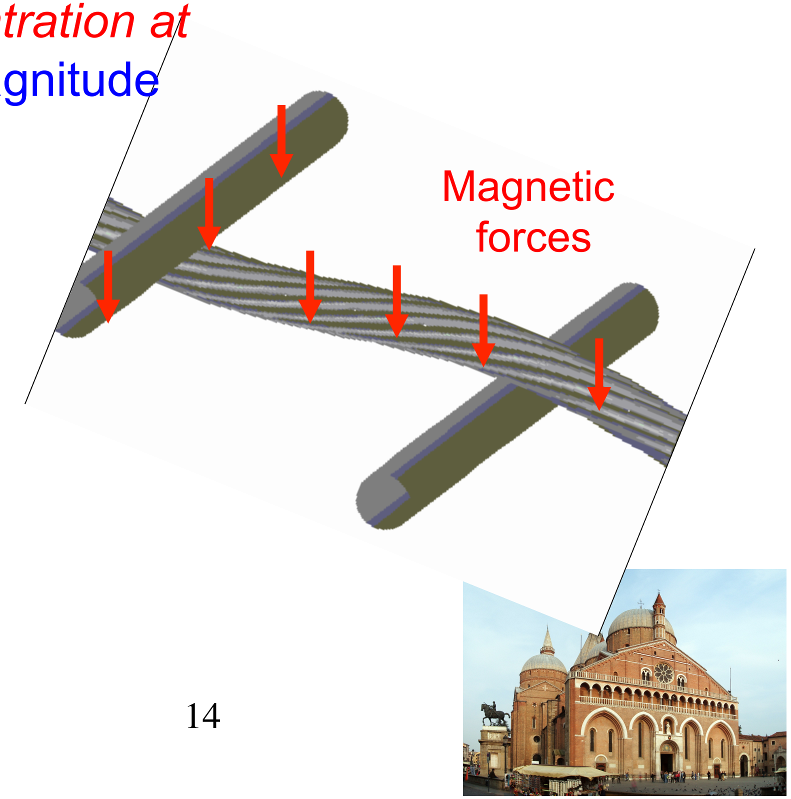


Nb_3Sn CICC and internal load - inside the cable

Even at large cable size, R = 20 mm, the peak stress (***BRJ_{cs}***) is "only" up to *15 MPa* for the ITER conductors, much smaller than the critical range of transverse stress for Nb_3Sn strands (*150 MPa*).

However, the cable is not a continuous medium. It consists of a bundle of strands with a network of "line" and "crossover" contacts. The *stress concentration at the strand crossover* can be one order of magnitude higher than the "average" BRJ_{cs}

The deflection under transverse load is the results of a large number of *strand micro-bending*, which reduce the void fraction and open a "gap" at the "zero-load" side of the cable



The strain state of Nb_3Sn in a CICC

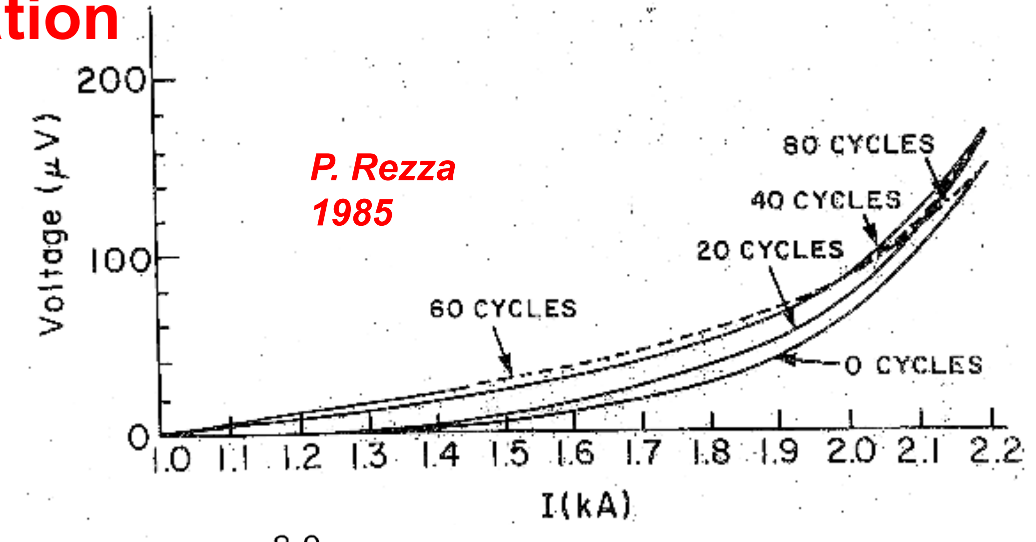
To make an effective use of the scaling laws in coil design, it is mandatory to know/predict the strain state of Nb_3Sn in the conductor. That's not easy…

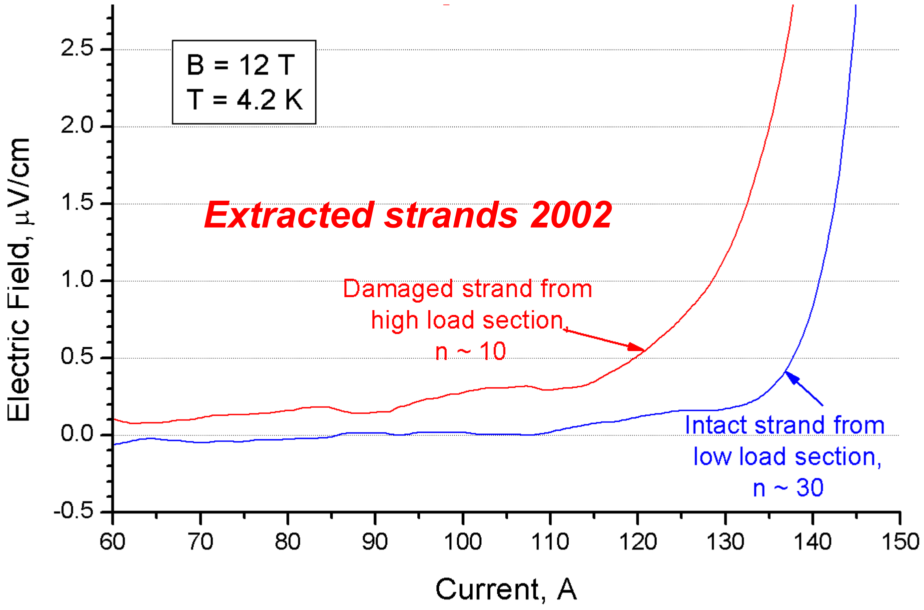
Thermal strain	**Operating strain**
Mismatch of coefficient of thermal expansion from heat treatment to 4K	Electromagnetic forces (B x I)
↓ Thermal-mechanical stress	↙ Hoop load on CICC ↘ Transverse load on cable
+ Friction of twisted strands in CICC	Hoop load on CICC ↓ Axial tension +Bending
↙ Axial compression ↘ Bending	Transverse load on cable ↓ Compression at strand crossover +Bending

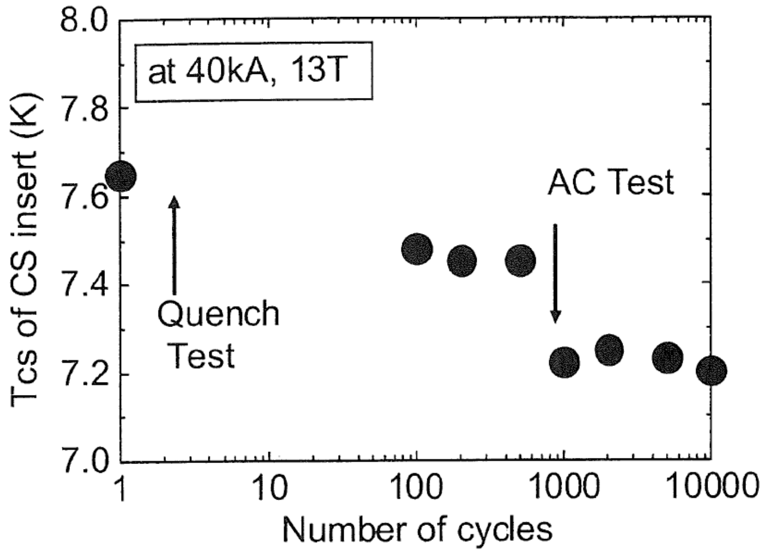
Do all the filaments stay in the reversible range after all these superposed loads?

Evidences of degradation

Performance degradation upon cyclic load was reported since 1985 with broadening of the transition



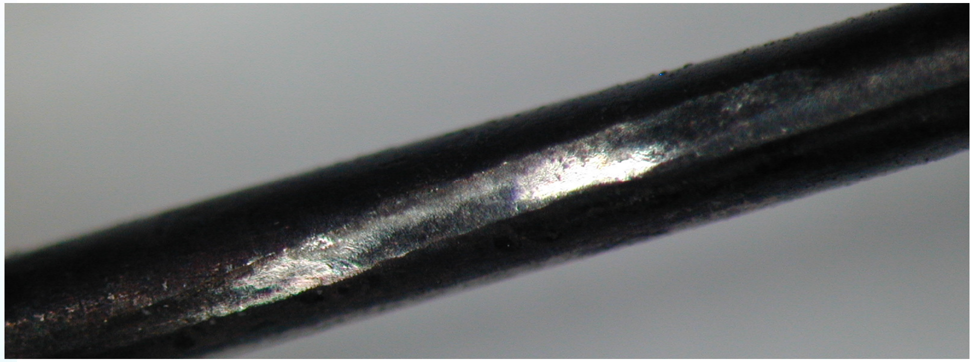




N. Mitchell, 2002

Experimental evidence - the extracted strands

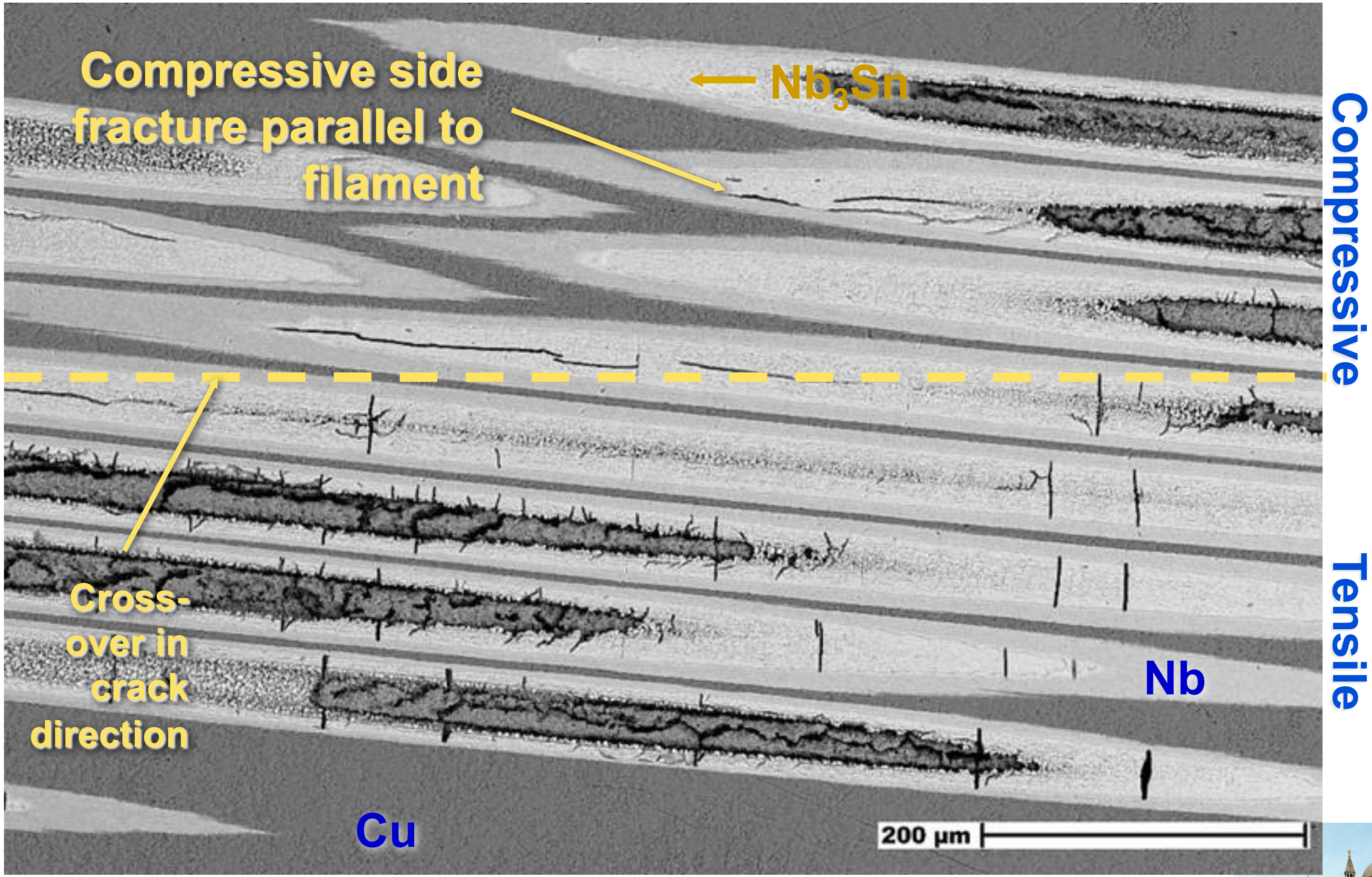
Spots with abraded Cr plating in strands extracted from the bundle of a CICC submitted to cyclic loading bring evidence of wearing at the strand crossover and indicate the typical distance for bending



Average spacing between friction spots 6 mm

Metallographic examinations (US)

The power-in-tube strands offer a nice picture of what's happening

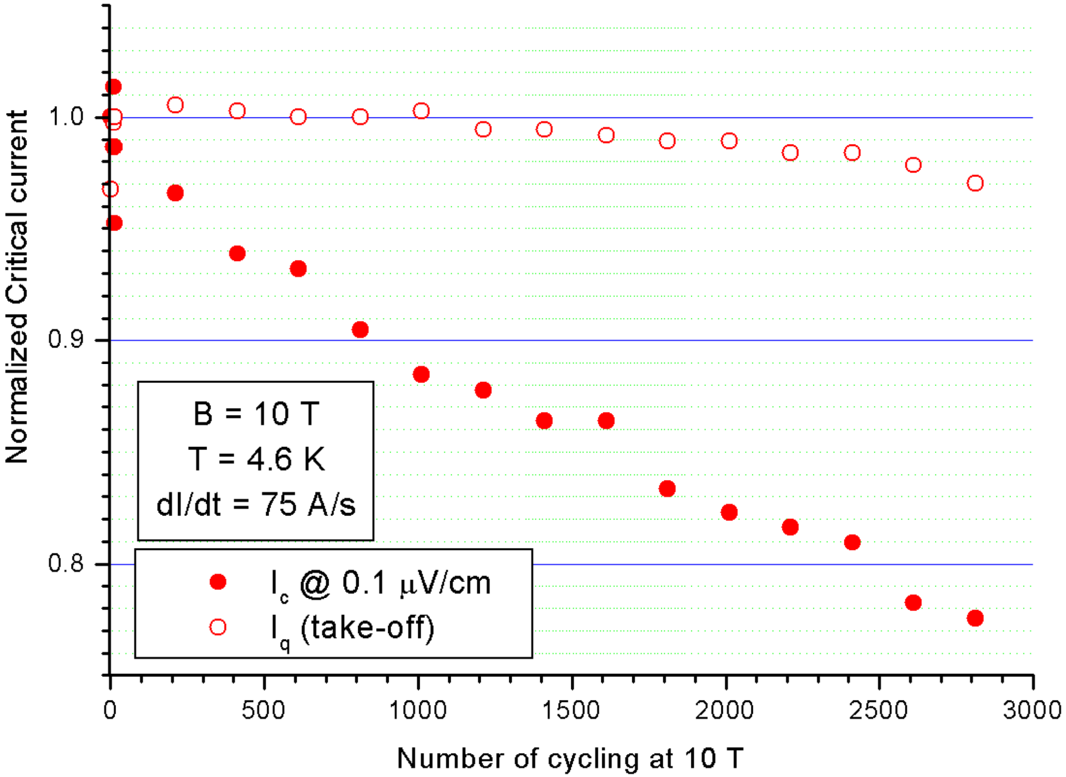


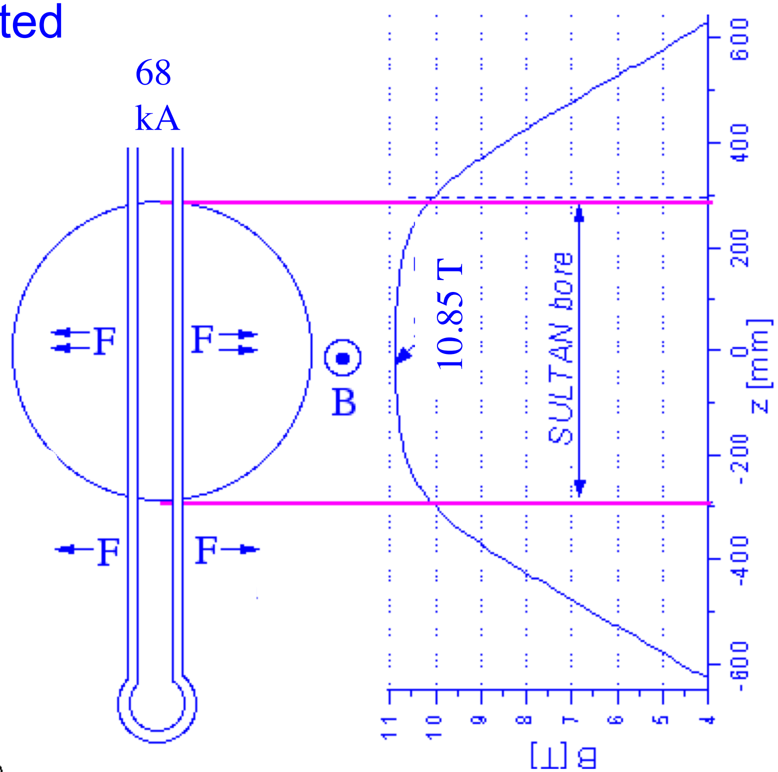
Degradation - cyclic load

As a function of the cyclic load, the CICC performance worsens. The rate of degradation strongly change from CICC to CICC.

The degradation is appreciated in terms of I_c (or T_{cs}) at 0.1 μV/cm

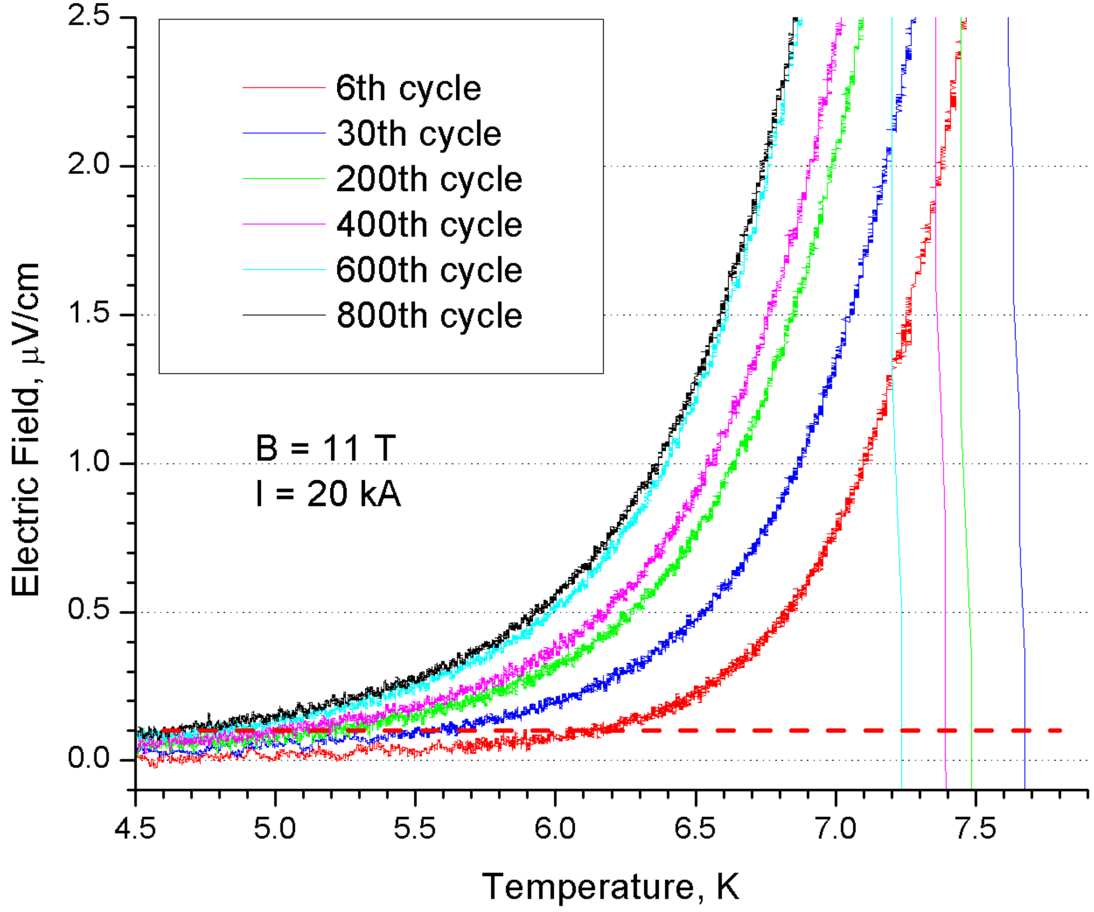
The take-off point (either I_q or T_q) is little affected





n Index - cyclic load

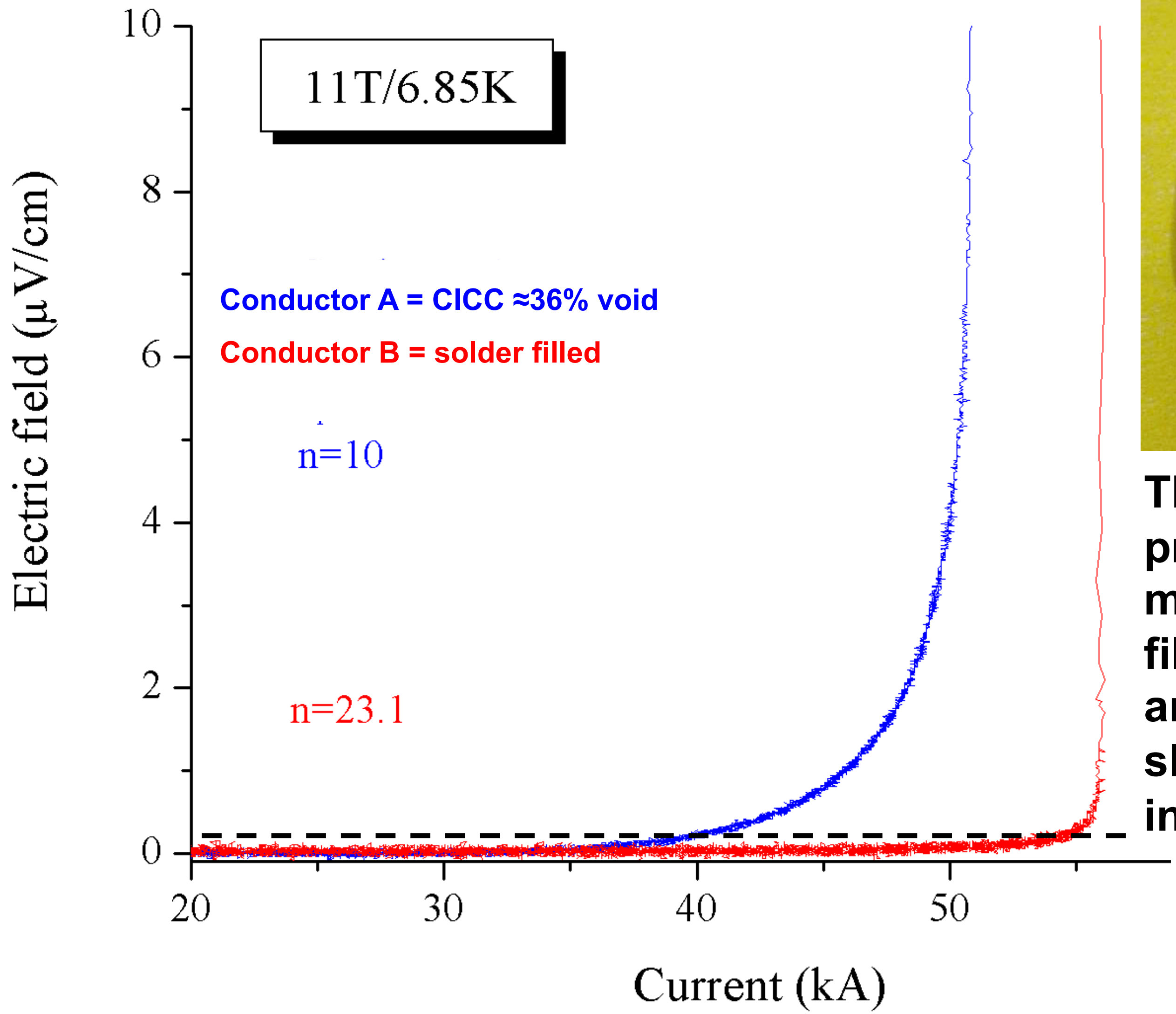
With increasing filament damage, the superconducting transition becomes broader and broader.



Degraded Conductors

- Degraded conductors are not easy to deal in the design (although they may work to some extent in the practice)
- As strand and CICC have different n-index, the comparison strand vs CICC, and hence *the quantification of the degradation, depends on the retained electric field criterion* (the lowest the criterion, the higher the performance loss)
- Filament *cracks do not obey the strand scaling law*, which are drawn for intact filaments. Scaling the CICC behavior over a broad operating range is a nightmare
- Acceptance tests on degraded conductors are highly questionable, but have to be somehow defined

A Crucial Comparison



The mechanical support provided by the solder matrix prevents the filament micro-bending and preserves the sharp transition (high n-index)

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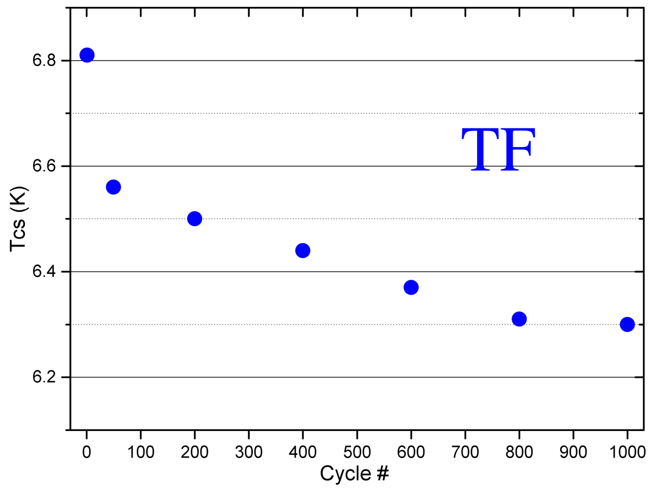
Results of the ITER Nb_3Sn Conductors

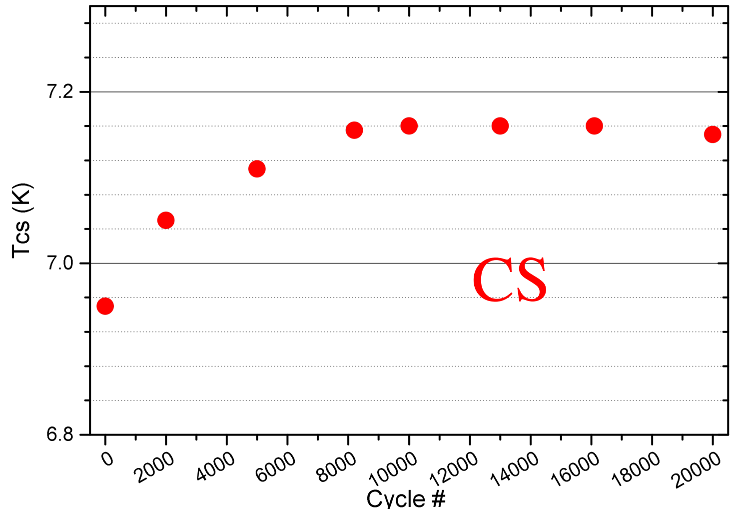
Two features affect the performance evolution for Nb_3Sn based CICC:

☺ the thermal strain relaxation due to the settling in the strand bundle in operation.

☹ the filament breakage due to local bending of the strands upon transverse load.

In the TF conductors with "long" cable pitch sequence, the filament breakage dominates over the strain relaxation and the net performance change is a degradation of the T_{cs}.





In the CS conductors, the rigid structure of the tightly twisted first triplet of strands, withstands the transverse loads without significant bending. The strain relaxation dominates over the filament breakage and the net performance change is an improvement of the T_{cs}.

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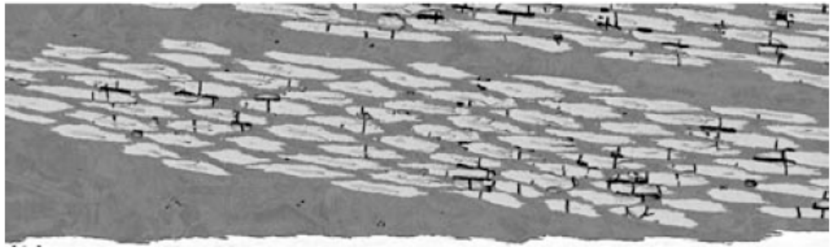
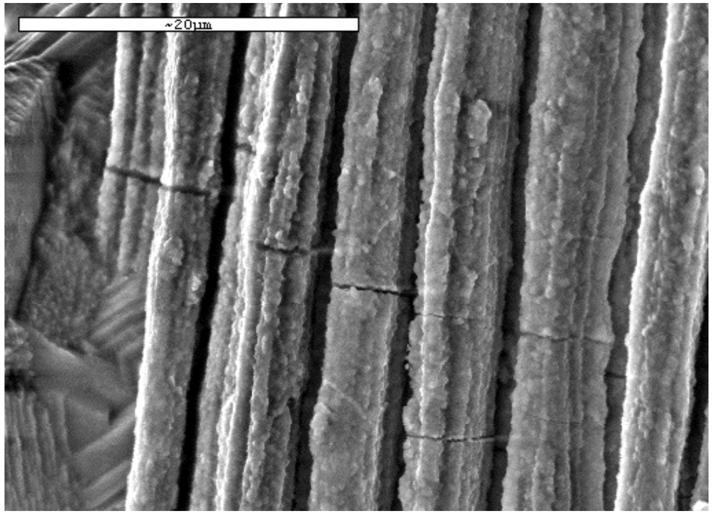
Summary on Performance of ITER Nb_3Sn CICC

The reason of the cyclic load degradation is due "*filament breakage (ratcheting) upon transverse load*". Very short triplet pitch drastically mitigates the effect.

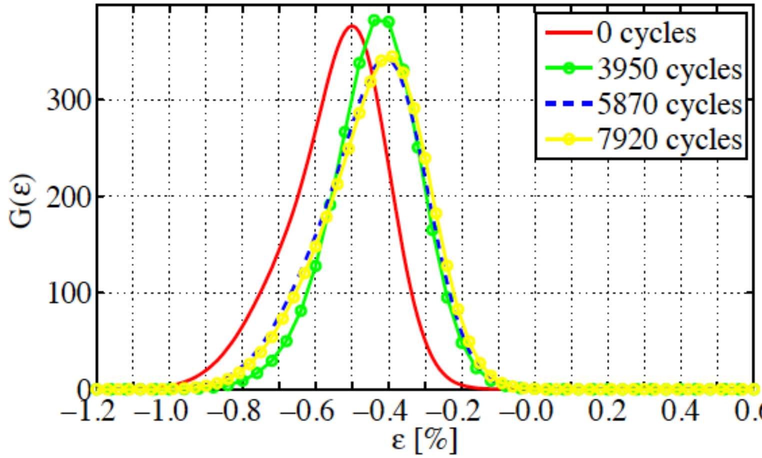


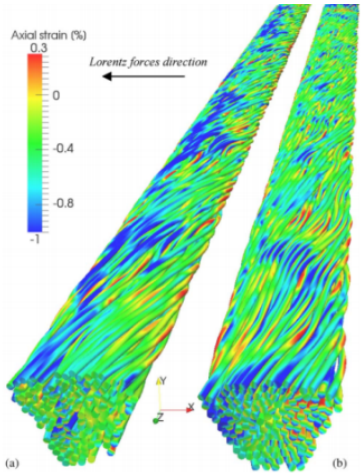
Cracks at bending, Jewell 2003

Bochvar 2002



The reason for missing the expected performance is largely due to "strain distribution": the compressive "tail" of the distribution dictates the performance.





Calzolaio 2012

Bajas 2011

So what?

- ITER uses Nb_3Sn CICC from all the suppliers with various degree of performance degradation. A large over-design is retained to balance the degradation over the lifetime.

- For the CS conductor, with very large number of load cycles, the “short twist pitch” layout is an effective mitigation of CICC degradation.

- In future fusion machines, DEMO, a more effective use of Nb_3Sn is mandatory to reduce the cost and improve the reliability of the design.