Superconducting Magnets, part 3

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Superconducting Magnets

PART I

1. Basic introduction to superconductivity
2. Technical superconductors
3. Introduction to the superconducting magnet design

PART II

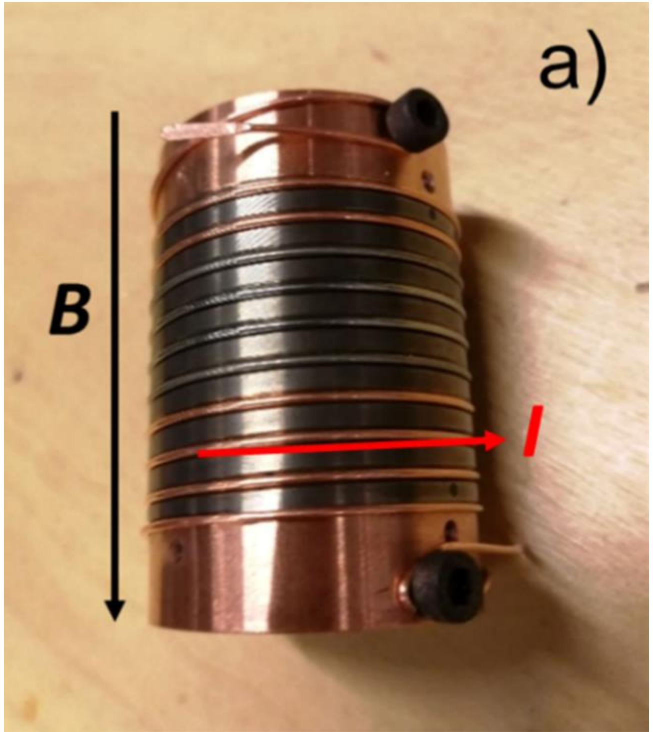
4. A stepped approach to superconducting magnet design
5. Lessons learned from fusion magnets from last century

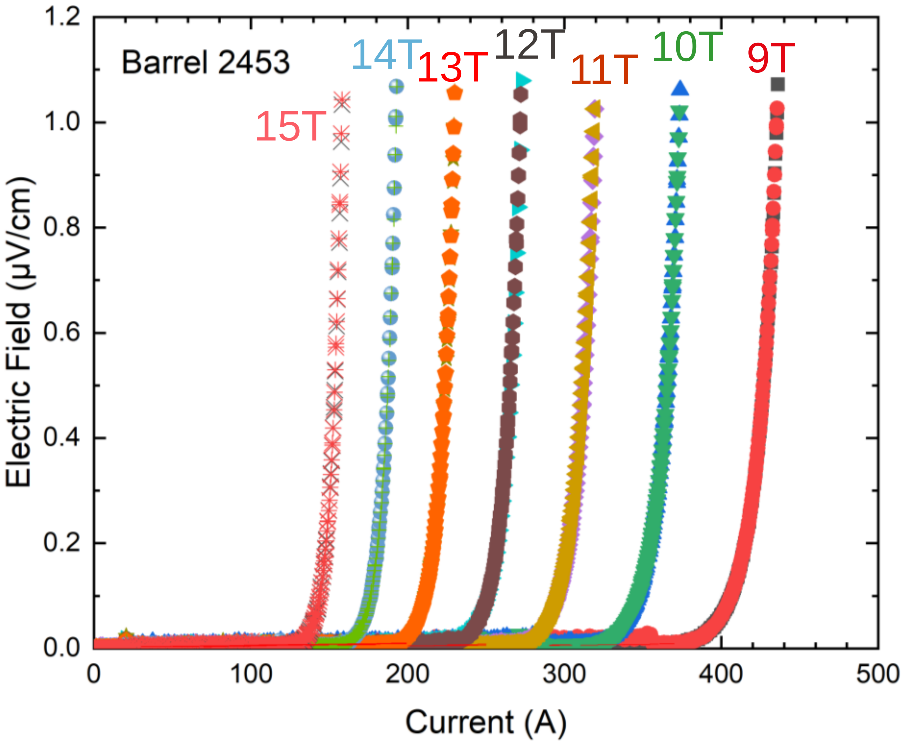
PART III

4. The challenges of ITER magnets
5. Toward DEMO
6. HTS for fusion?

I_c Measurement

- Superconducting strand is wound on a test cylinder (aka. “ITER barrel”).
- The barrel is cooled down, current is let into the strand and voltage over the strand is measured. Knowing the length of the strand, we calculate the electric field.





I_c Measurement

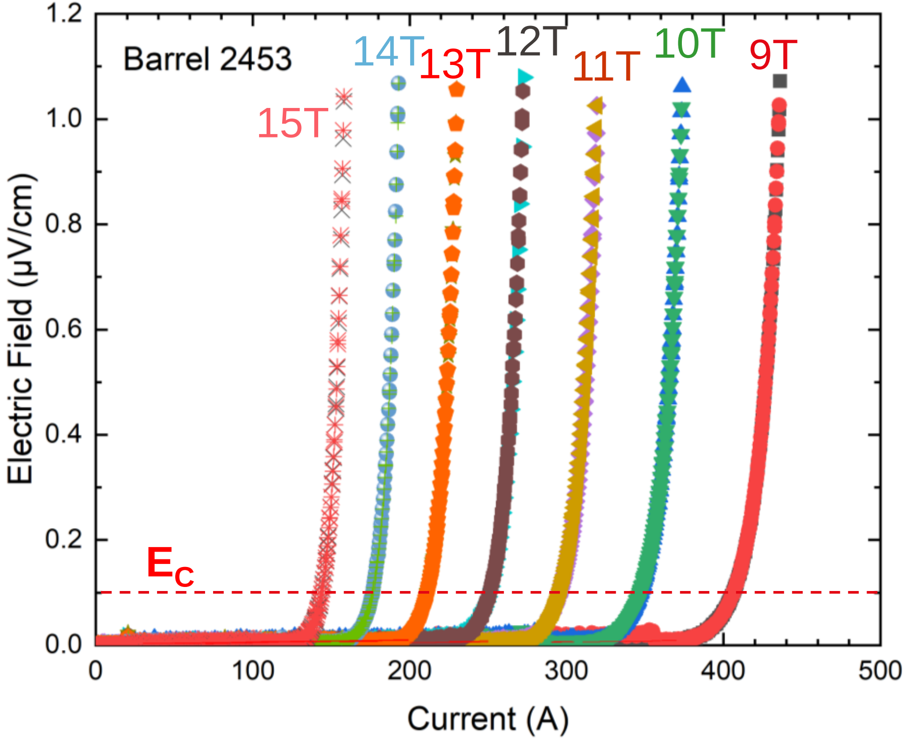
- Experimental definition of I_c:

$$\frac{E}{E_c} = \left(\frac{I}{I_c}\right)^n$$

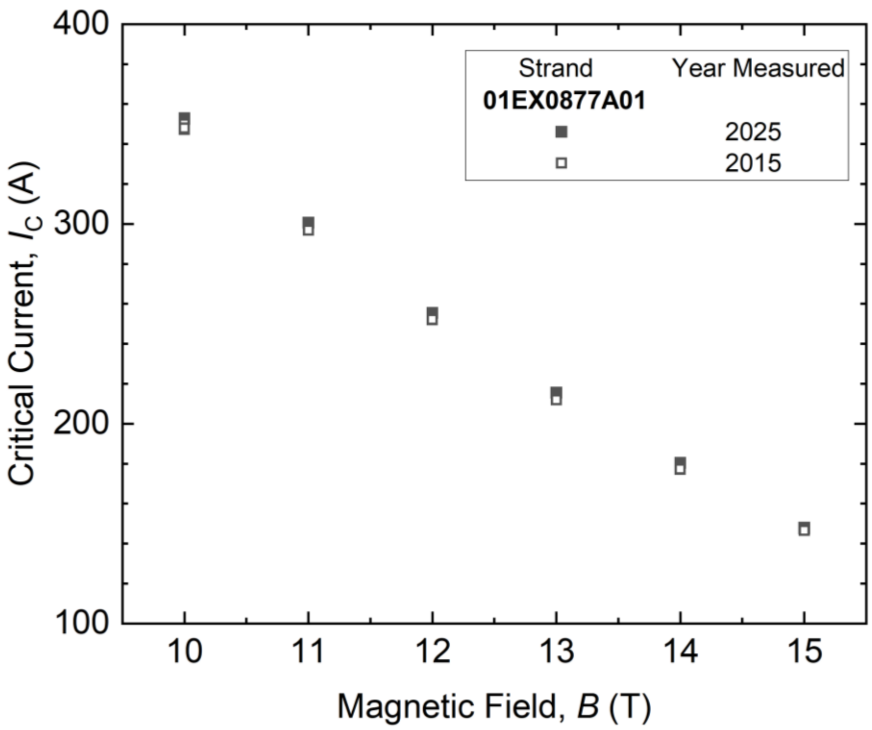
- E … Electric field (measured)
- E_C … Critical electric field, usually set to 0.1μV/cm in LTS and 1μV/cm in HTS.
- I … current (provided by power supply)
- I_C … critical current = current, at which $E=E_C$
- n-value … slope of the Electric field rise, when plotted as log-log graph

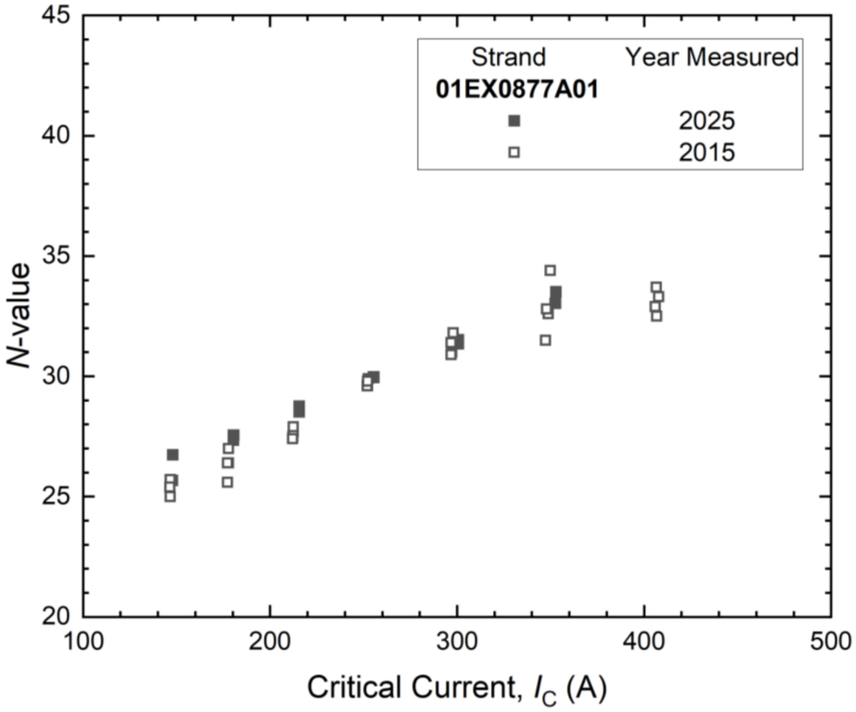
$$\ln E = n \cdot \ln\left[E_c\left(\frac{I}{I_c}\right)\right]$$

I_C measured on Nb_3Sn strand for ITER (sample EUTF13) at 4.2K. The $E-I$ data were fitted between 0.05 and 0.5 μV/cm to obtain n-value, and I_C was extracted at 0.1 μV/cm



I_c Measurement

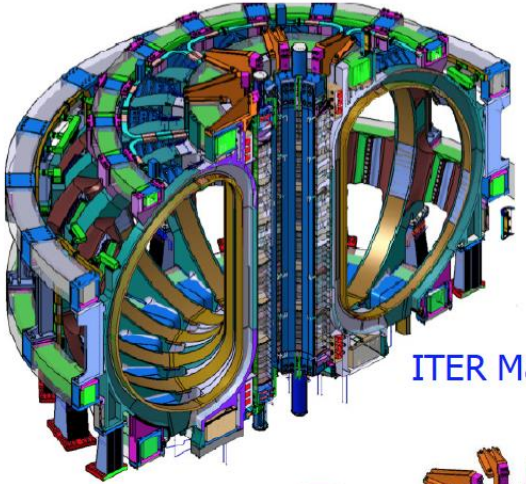




- High n-value (>30 for strands, >10 for cables) tells us that the strand is of a good quality.
- Low n-value (<20 for strands, <5 for cables) – sign of broken fillaments

ITER Magnet System

Key Data of ITER Magnet System



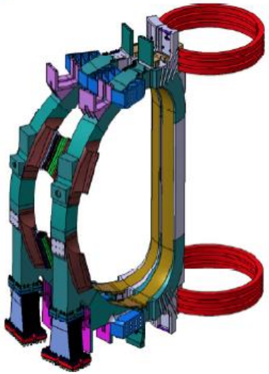
- The ITER magnet system is made up of
  - 18 Toroidal Field (TF) Coils,
  - a 6-module Central Solenoid (CS),
  - 6 Poloidal Field (PF) Coils,
  - 9 pairs of Correction Coils (CC's).

}Nb3Sn (TF Coils and CS)

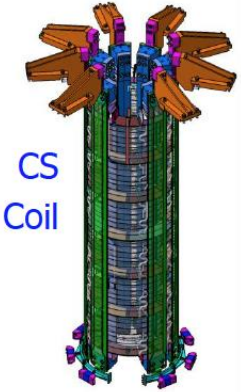
}NbTi (PF Coils and CC's)

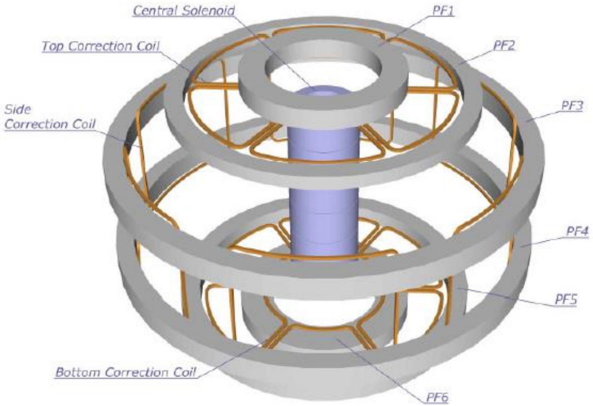
ITER Magnet System

Pair of TF Coils



CS Coil





PF Coils & CC's

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 - Conductors

- The ITER conductors have been procured to the same specification in six out of the seven ITER parties (EU, RF, JA, US, KO, China). The sharing of the procurement was fixed in 2006 in the ITER agreement.
- 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 ITER team and the Domestic Agencies who sign the Procurement Arrangements.
- Independent development of the tooling and methods for the same product (e.g. for the TF coil manufacture) at various companies; final tokamak performance limited by the weakest manufacturing solution.

Specification / Procurement Strategy - Magnets

- The TF magnets are procured at **Blue Print Specification** in JA (9 TF coils) and in EU (10 TF coils). The 18 TF coil cases are procured in Japan. The “casing” is done in EU and JA by the magnet suppliers.

- The seven modules of the Central Solenoid (one spare module) and the pre-compression structures are procured in US at **Functional Specification**

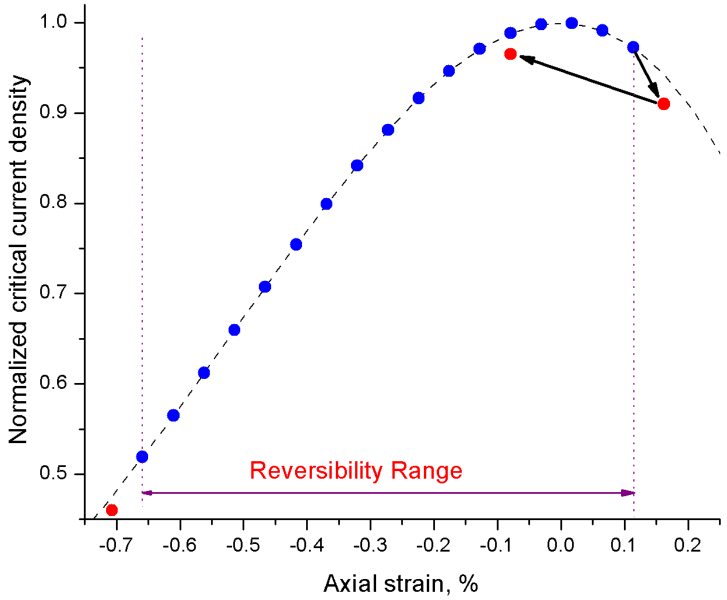
- The PF magnets are procured at **Blue Print Specification**
  - **PF1 is procured in RF and transported to Cadarache**
  - **PF2-PF3-PF4-PF5 and PF6 are procured in EU**
    - **PF6 is subcontracted from EU to CN and transported to Cadarache**
    - **PF2 – PF3 – PF4 and PF5 are manufactured on the ITER site**

Cyclic load degradation for Nb_3Sn Cable-in-Conduit

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.

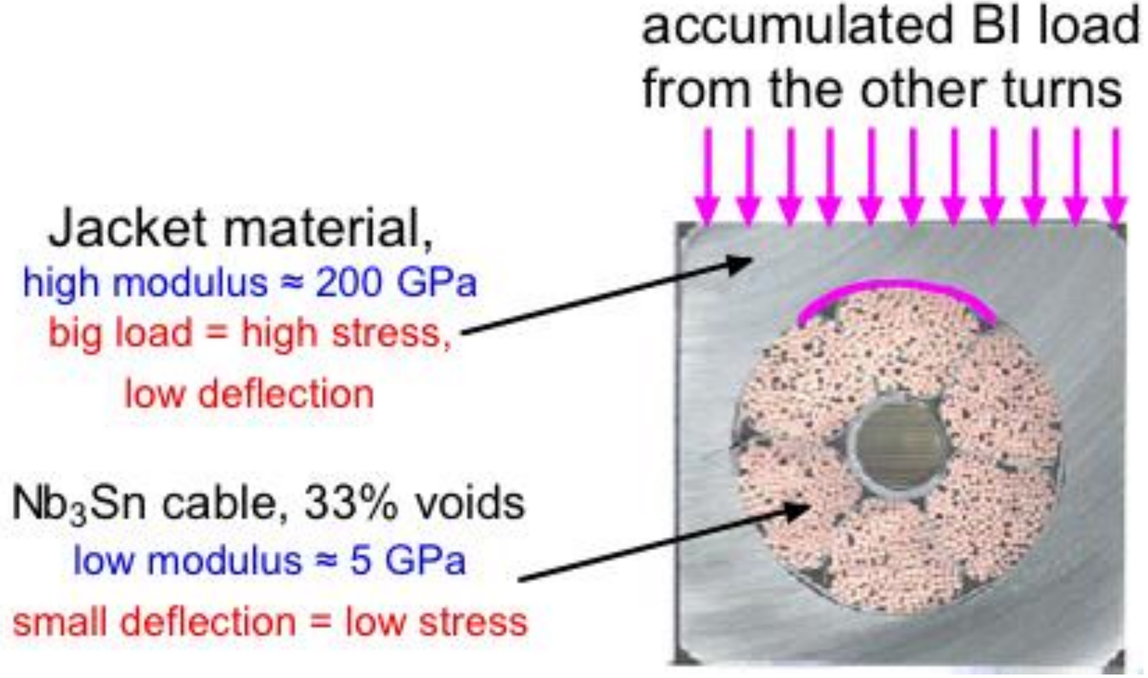
Nb_3Sn strands inside a CICC

- At first glance, the CICC design seems to prevent the detrimental effects of mechanical load on Nb_3Sn:
  - *The W&R method prevents high bending loads after heat treatment.*
  - *The jacket prevents the accumulation of the operating load in transverse direction.*
  - *The alloy "Incoloy" (originally envisaged for the ITER conductor jacket) matches the coefficient of expansion of Nb_3Sn and prevents thermally induced longitudinal compressive strain.*

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

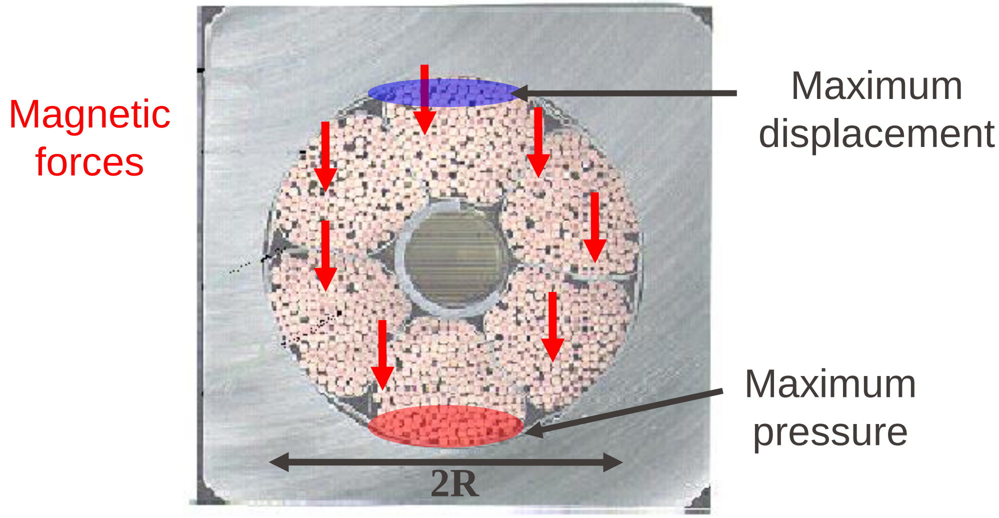
Nb_3Sn CICC and Transverse Load Accumulation

The transverse stress in the cable due to the accumulation of the operating load 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

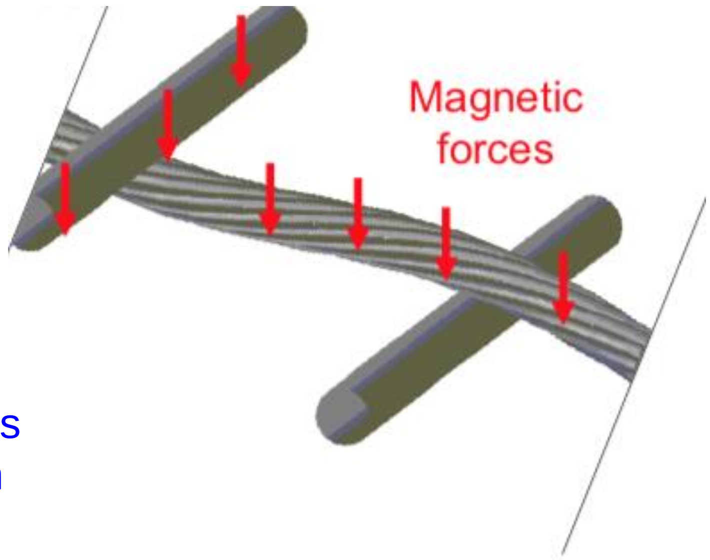
- Inside the CICC, the Lorenz force acts on the cable. The load is close-to-zero at one side and is maximum on the opposite side (body force).
- The load per unit length is ***BI_{op}*** (independent on geometric parameters), but the peak stress is ***$\propto BRJ_{cs}$*** where J_{cs} is the current 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 average 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

Mismatch of coefficient of thermal expansion from heat treatment to 4K

Thermal-mechanical stress

+

Friction of twisted strands in CICC

Axial compression

Bending

Operating strain

Electromagnetic forces (B x I)

Hoop load on CICC

Transverse load on cable

Axial tension

+Bending

Compression at strand crossover

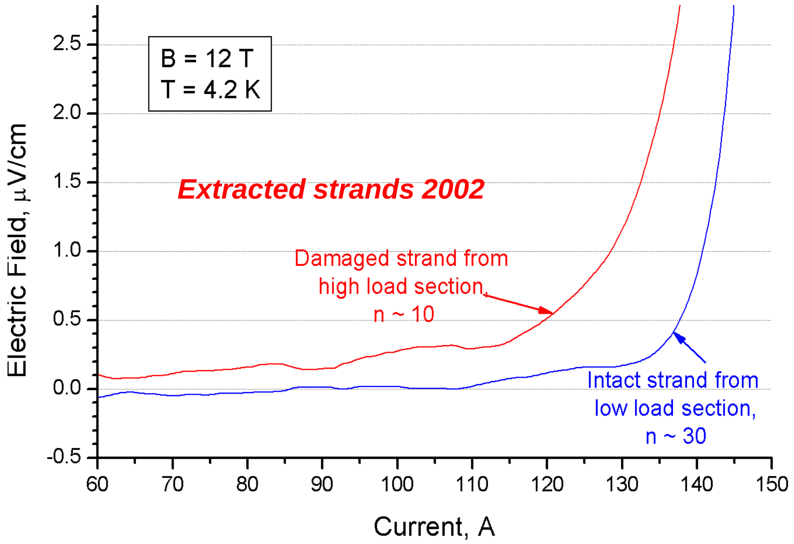
+Bending

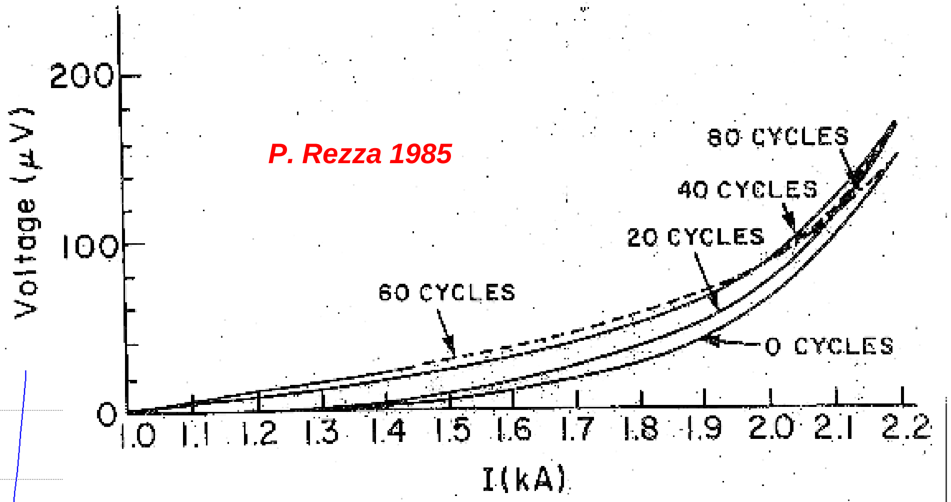
Do all the filaments stay in the reversible range after all these superposed loads?

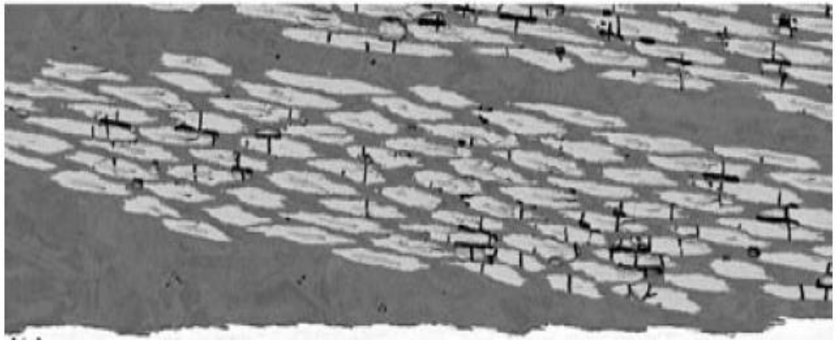
Do all the filaments have the same strain?

Evidences of Nb_3Sn strand damage

Performance degradation upon cyclic load has been reported since 1985 with broadening of the transition.



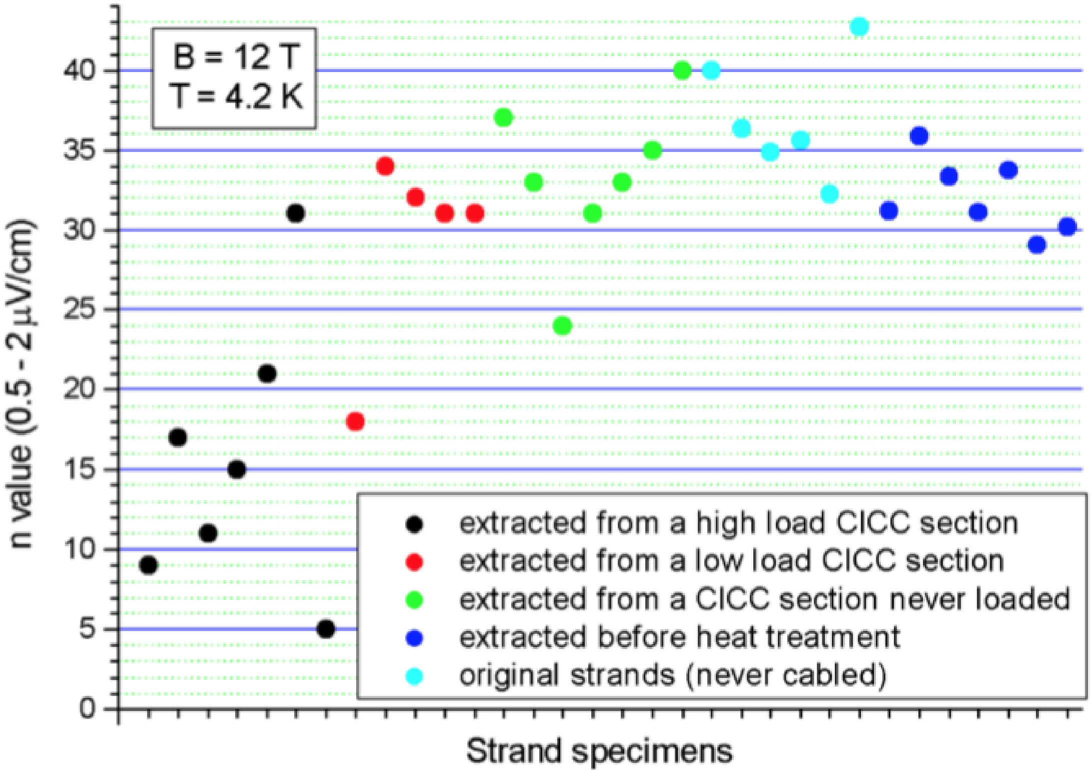




Filament cracks at bending, Jewell 2003

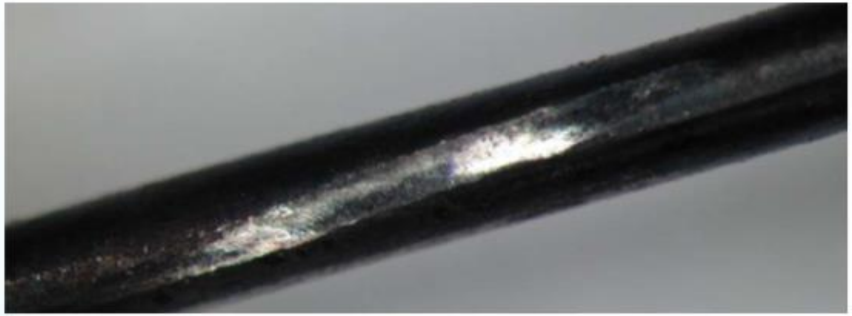
Experimental Evidence - the n-Value

The experiment on extracted strands also proved that the low n-value observed in the CICC is not a feature of current re-distribution effect, but reflects the low n-value of the degraded strands.



Experimental evidence - the extracted strands

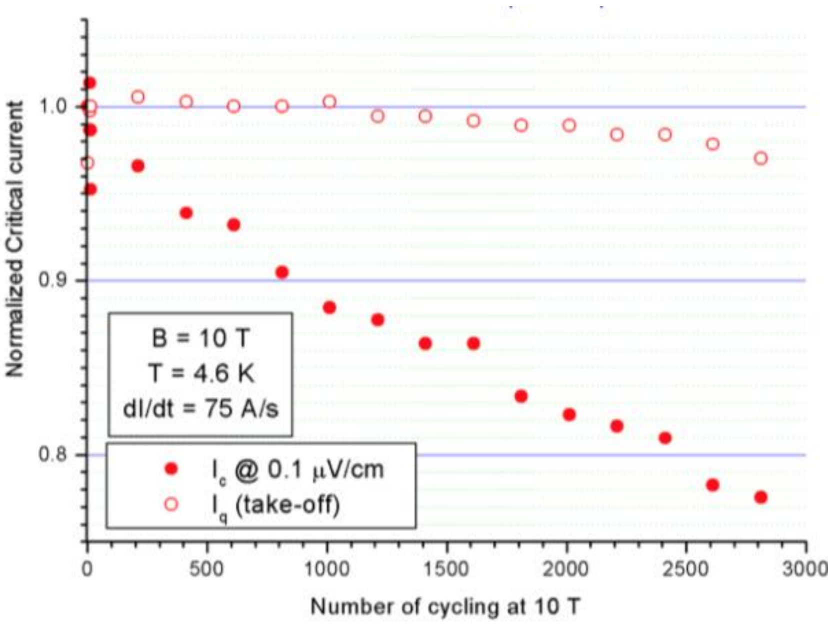
Spots with abraded Cr plating in strands extracted from the bundle of a CICC submitted to cyclic loading bring evidence of wearing at the strand crossover and indicate the typical distance for bending

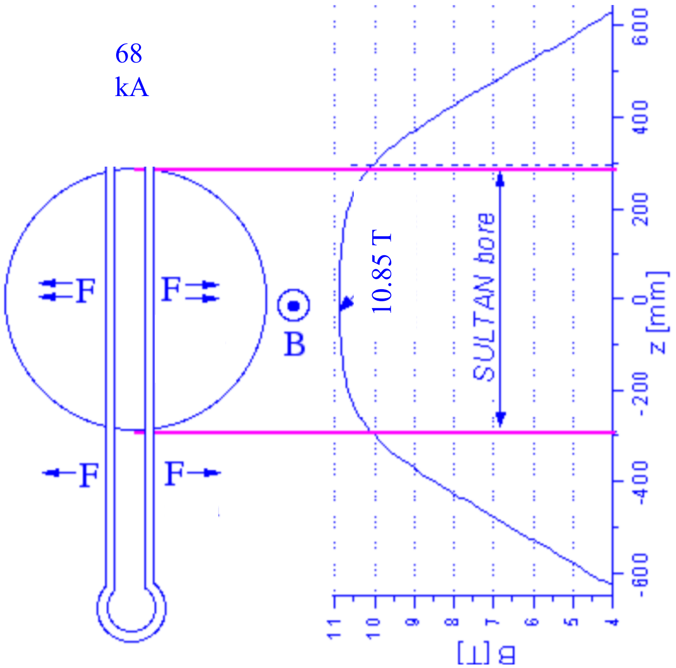


Average spacing between friction spots 6 mm

Degradation - cyclic load

- As a function of the cyclic load (current on and off), 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.





n-Value and m-Value - cyclic load

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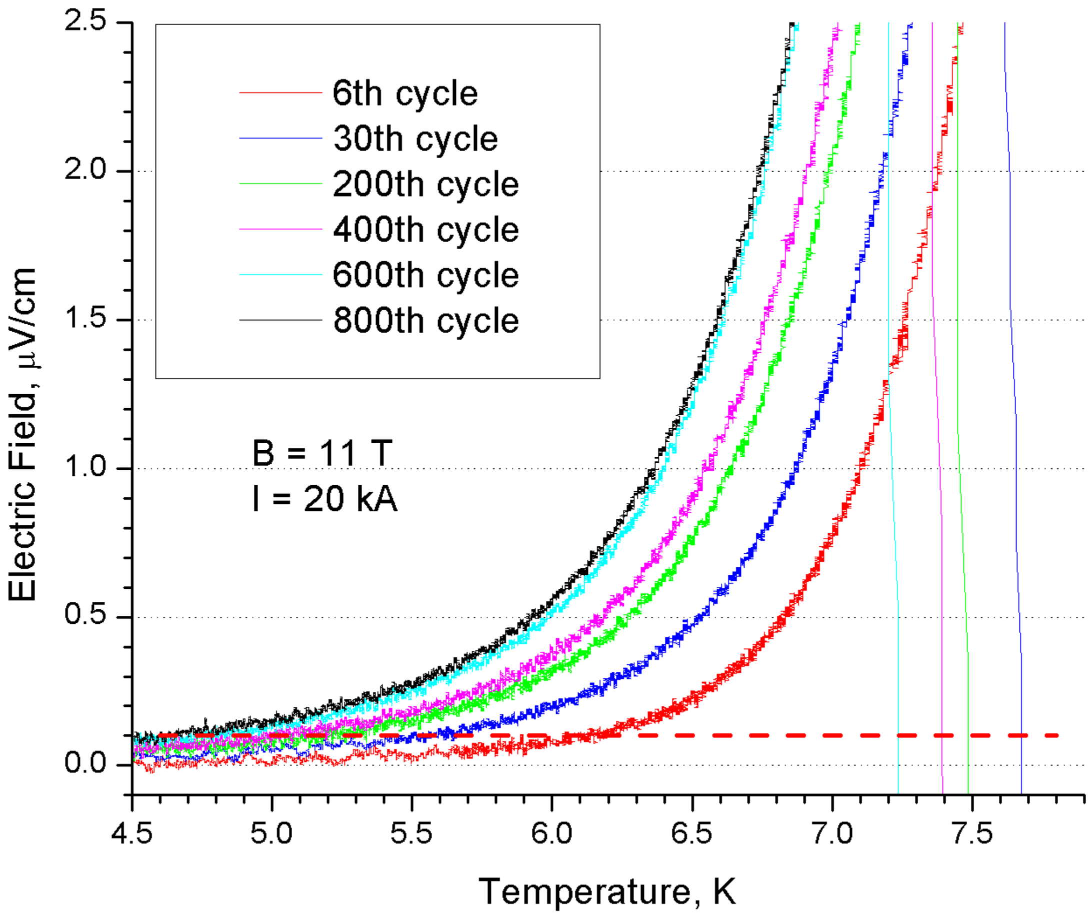
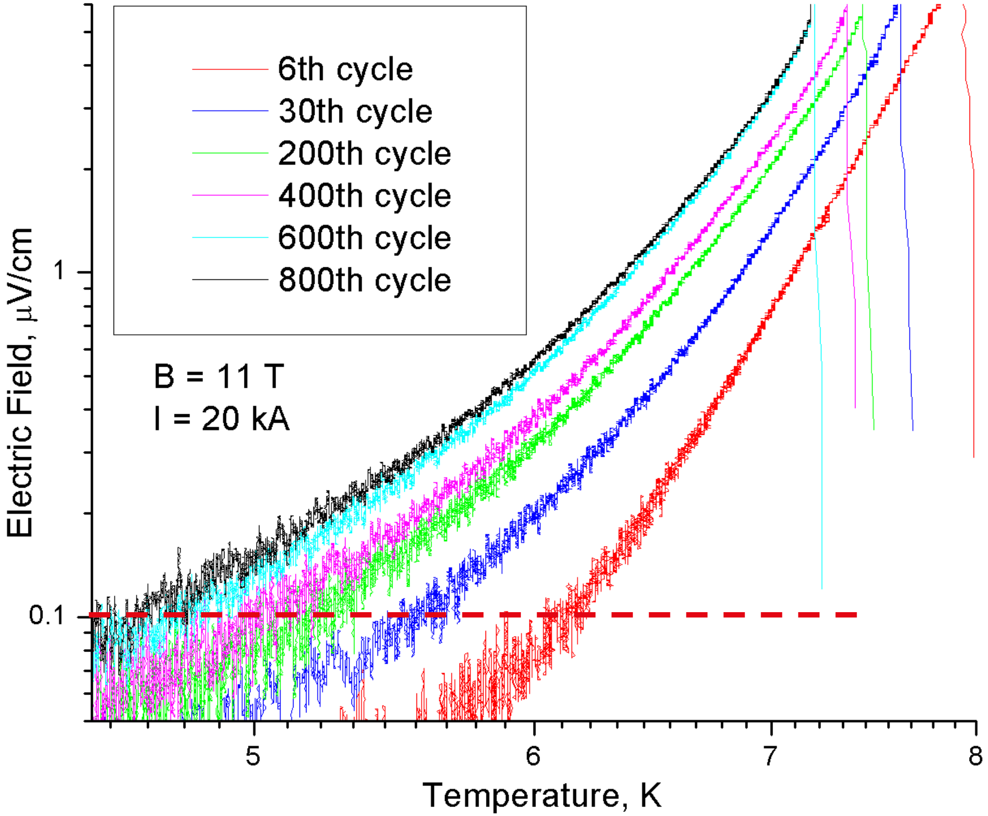


- With increasing filament damage, the superconducting transition becomes broader and broader.
- On the plot, electric field (EF) is plotted as a function of temperature, not as a function of current, but the principle of EF broadening is the same.

$$E = E_c \left(\frac{I}{I_c}\right)^n$$

$$E = E_c \left(\frac{T}{T_{cs}}\right)^m$$

n-Value and m-Value – Degraded Cable



- Log-log plot:

$$\ln E = m \cdot \ln\left[E_c\left(\frac{T}{T_{cs}}\right)\right]$$

Degraded Conductors

- Degraded conductors are not easy to deal with in the design (although they may work to some extent in practice).
- As strand and CICC have different n-value, the comparison strand vs. CICC, and hence *the quantification of the degradation, depends on the retained criterion on the critical electric field* (the lower the criterion, the higher the performance loss).
- Irreversible damage can be caused by filament cracks and/or plastic deformation of the strand matrix material. *Irreversibly damaged strands do not obey the strand scaling law*, which was drawn for intact filaments.
- Acceptance tests on degraded conductors are highly questionable, but have to be somehow defined for imperfect (real-world) conductors.

The TF Conductor Performance and Degradation

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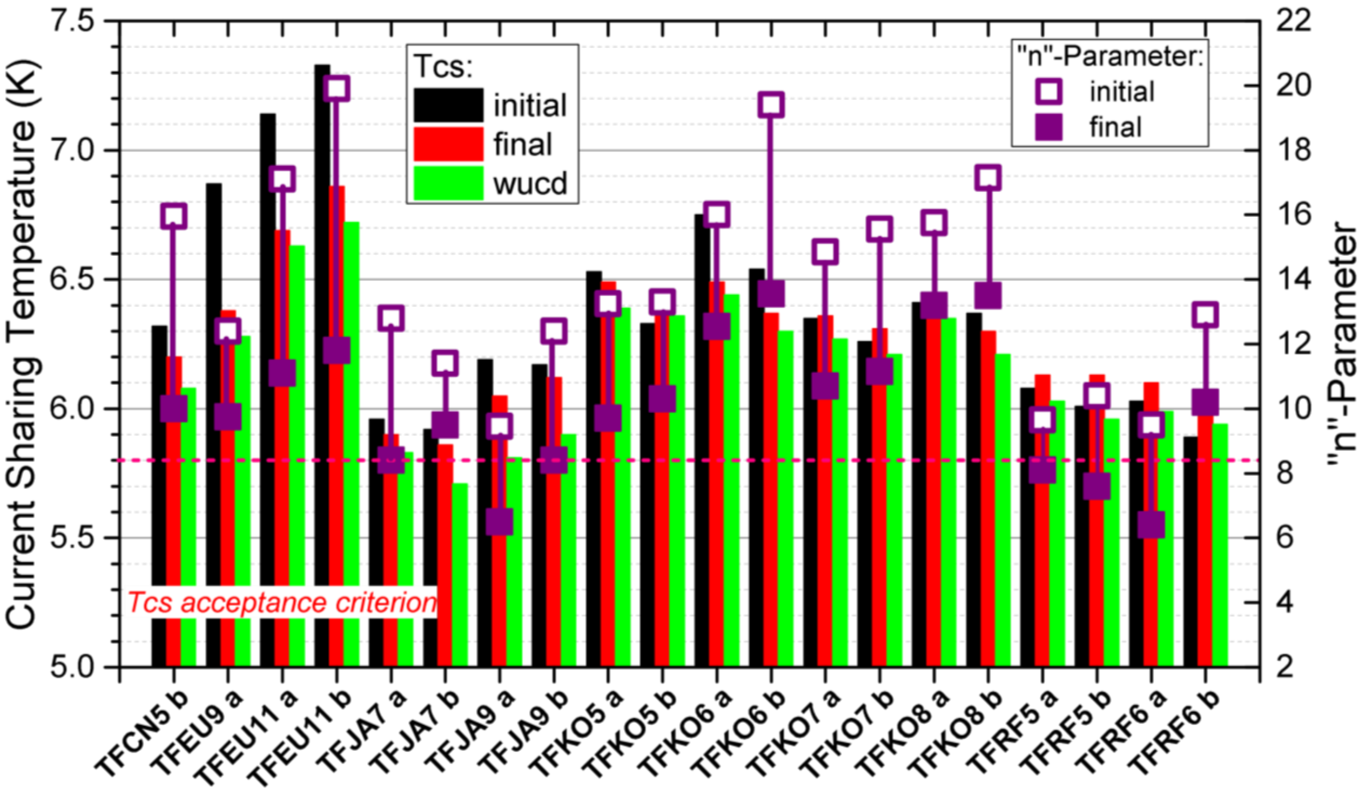
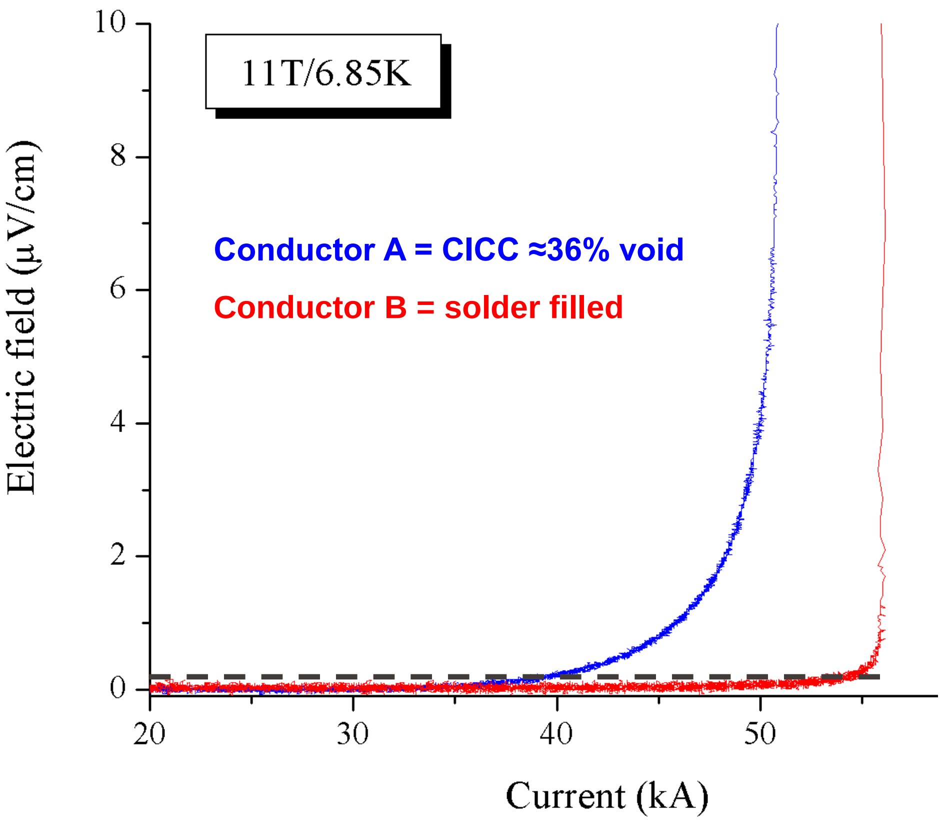
The large performance drop is offset by overdesign, with actual strand J_c up to 30% larger than specified.



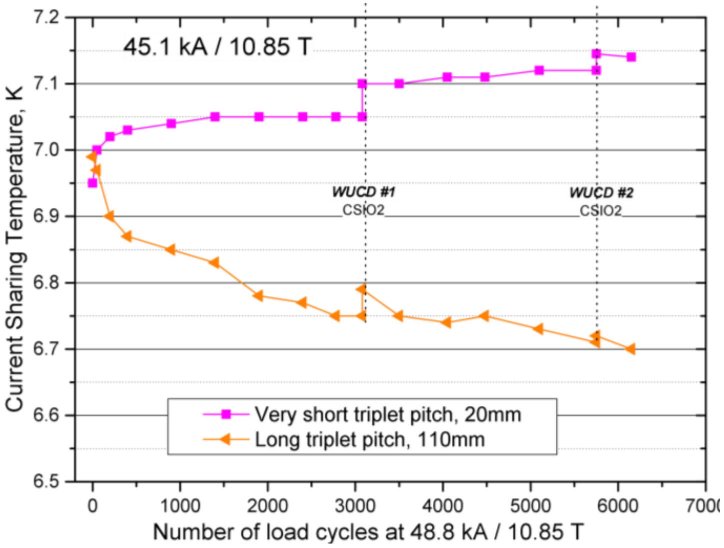
A Crucial Comparison (2003)

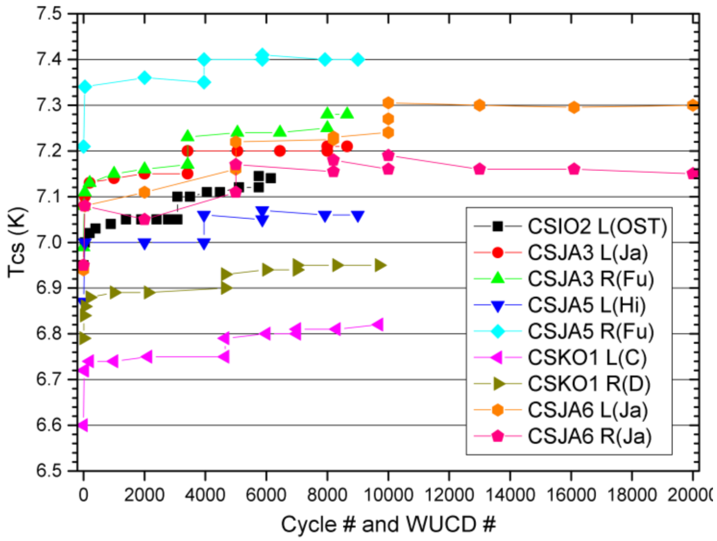


The mechanical support provided by the solder matrix prevents the filament micro-bending and preserves the sharp transition (high n-index)

The Breakthrough of CS Conductor in April 2012

- In the CSIO2 sample, one conductor has "short", 20/45/78/155/423 mm, and the other "pseudo-long", 110/117/125/139/352 mm sequence of pitches, with quasi parallel strands. The direct comparison leads to the dramatic conclusion, verified on nine strands, bronze and internal-Sn, that *the "very short" pitch (in the triplet) prevents strand bending and filament breakage upon transverse load*.

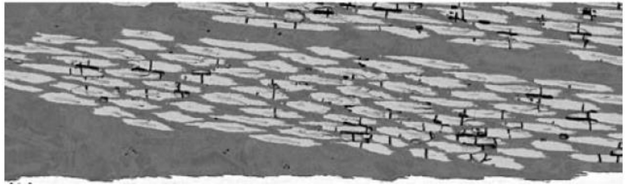




The "very short" pitch is retained in the CS conductor spec, but it was considered "too late" to apply the "very short" pitch to the TF conductor.

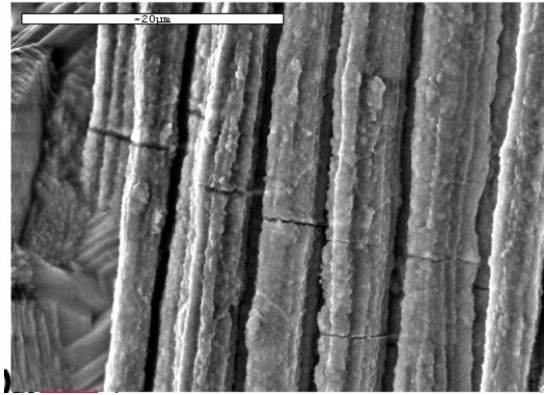
Summary on Performance of ITER Nb_3Sn CICC

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

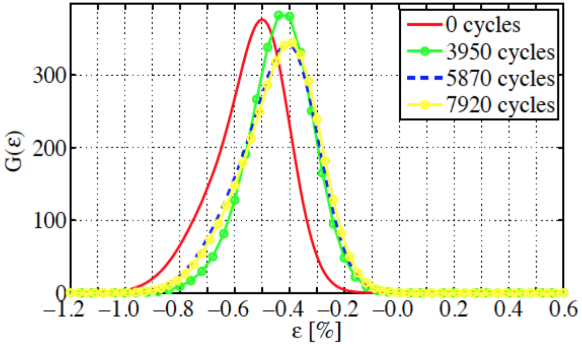


↑ *Cracks at bending, Jewell 2003*

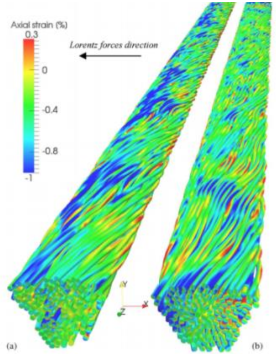
↓ *Bochvar*



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*

Lessons from ITER

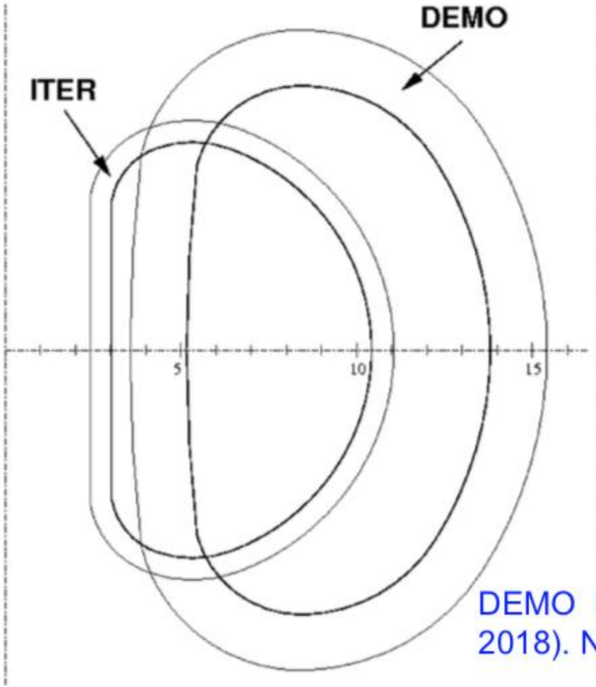
- ITER uses Nb_3Sn CICC from all the suppliers with various degrees of performance degradation. A large over-design is retained to balance the degradation.
- The TF conductor degradation does not stabilize, but continues over electro-magnetic and thermal cycles. The ITER TF magnets have limited lifetime, hopefully sufficient for the lifetime of the ITER.
- For the CS conductor with very large number of load cycles, the “short twist pitch” layout is the most promising option.
- In future fusion machines, DEMO, a more effective use of Nb_3Sn shall reduce the cost and improve the reliability of the design.

DEMO Magnet System

DEMO Activity in Europe

- While ITER was a world-wide project, the next fusion machine “DEMO” will likely be built in various countries/regions independently – KO, JA, EU, US, China (DEMOs with very different designs).
- In Europe, a number of coordinated design studies about DEMO have been carried out since 2011 by EFDA and the European Associations (from 2014 EUROfusion).
- The actual input for the layout of DEMO was supposed to come from the fusion results of ITER. Due to the series of delays in ITER construction, this “waiting strategy” is questionable.
- The “pre-conceptual design studies” are aimed at investigating technology issues for post-ITER tokamaks. They will be followed by the “conceptual design” and later by the “engineering design”.

DEMO vs. ITER



	DEMO	ITER
Number of TF coils	16	18
Peak field at the TF conductor, B_p, T	13.45	11.8
Total current in one TF coil, I_{TF}, MA	19.8	9.11
Operating current, I_{op}, kA	85.3	68
Number of turns/coil, N_t	232	134
Stored energy per coil, E_c, GJ	11.56	2.28
Decay time constant for current dump, s	23	11
Inductance per coil, L, Hy	3.2	0.98
Peak voltage at current dump, V_d, kV	11.78	6.05
Mean circumference of the TF coil, P_{av}, m	44.2	34.1
Total conductor length in one TF coil, Le_c, km	10.25	4.57
One TFC inboard cross section, with case, A_c, m^2	2.72	≈ 0.8
Volume of one winding pack, $V_{wp} = P_{av} \cdot A_{wp}$, m^3	57	16.4
Weight of one TF coil assembly, t	>1000	340

pitches

DEMO has a TF peak field very close to ITER (baseline 2018). Nb_3Sn remains the choice for DEMO TF coils.

The increase of 50% of the major radius compared to ITER (9 m in DEMO) drives a number of “upgrades” in terms of engineering and logistics, which make DEMO very expensive and challenging from the logistic point of view and construction time. The manufacturing technology experience of ITER is not directly transferable to DEMO.

The Key Upscaled Parameters of DEMO

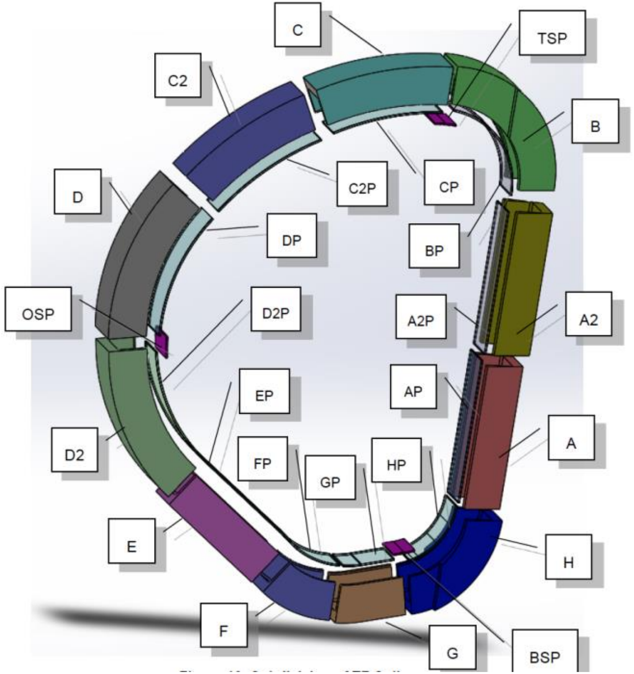
- The major radius (6m -> 9m) is the main driver of the scale-up:
  - The stored energy jumps by a factor of 5 up to 11 GJ/TFcoil
  - A long current discharge time of TF coils, τ > 35 s, is dictated by the loads on the vacuum vessel.

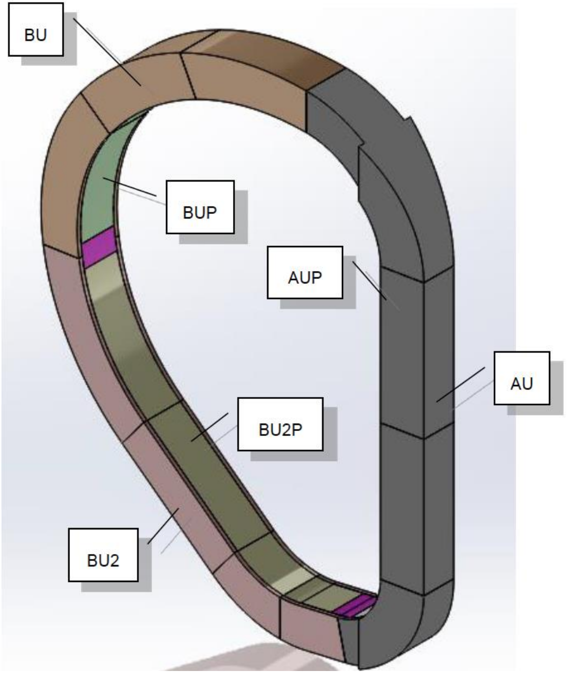
$$\boxed{V_d = L\frac{I_{op}}{\tau}} \quad \boxed{E = L\frac{I_{op}^2}{2}} \quad \boxed{V_d \cdot I_{op} = \frac{2E}{\tau} \approx 1GW}$$

High operating current (large conductor) is mandatory to keep operating voltages at current dump in the same range of ITER, i.e. around 5 kV. (Significant increase of discharge high voltage would increase the risk of the coil damage during operation.)

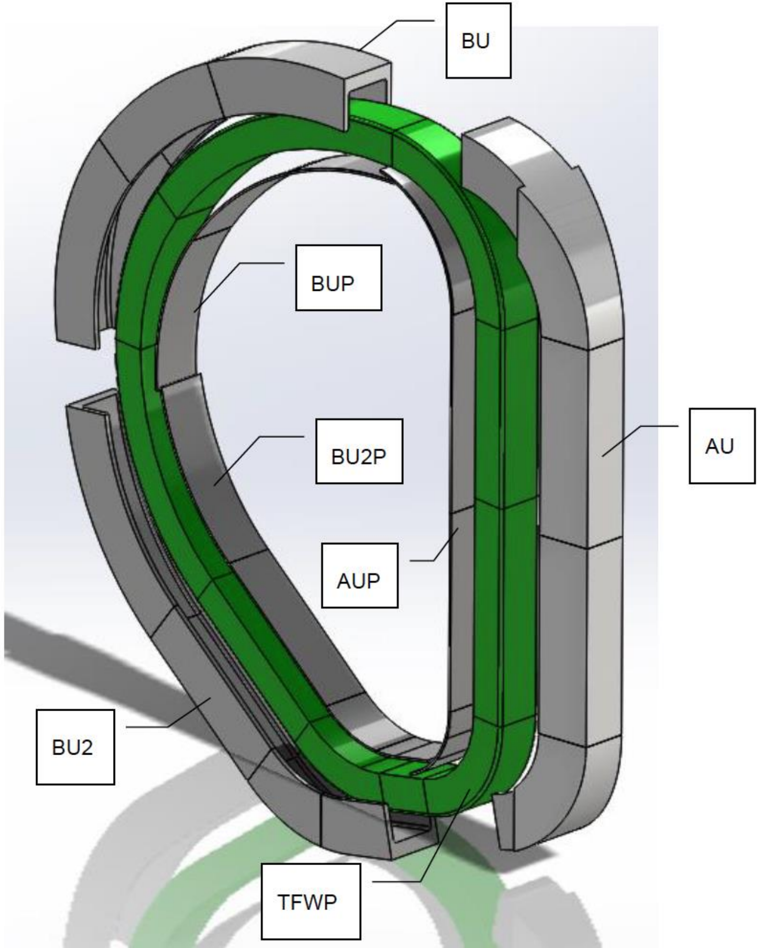
The Weight-Size Challenge – TF case

- The DEMO TF case is divided into 25 sections to limit the weight of the individual forged parts < 50 t. After machining, they are welded into 6 macro-sections.
- At the inboard side, the TF case of DEMO is thicker than 500 mm. The “closure weld” of the case after insertion of the TF winding cannot be done by standard welding.

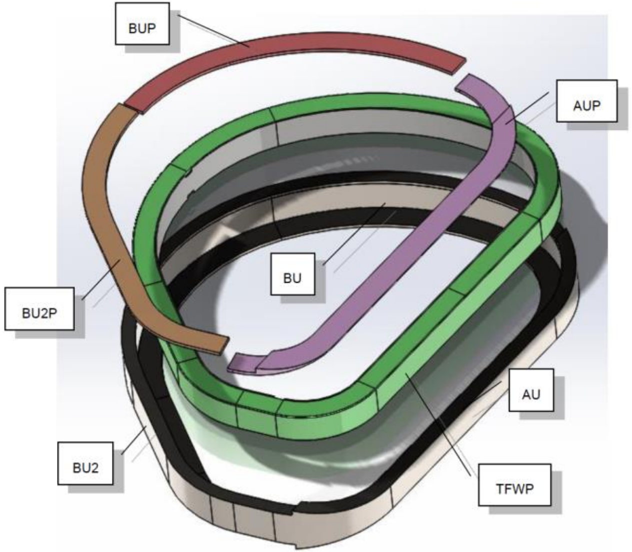




The Closure Weld of the TF Case



The 6 macro-sections are assembled with the TF winding pack. Opposite to the weld joining the initial 25 sections, the three “closure welds” can be performed only from the outside: the weld thickness, now 556 mm, is too large for narrow TIG welding …
Alternative assemblies are being considered.



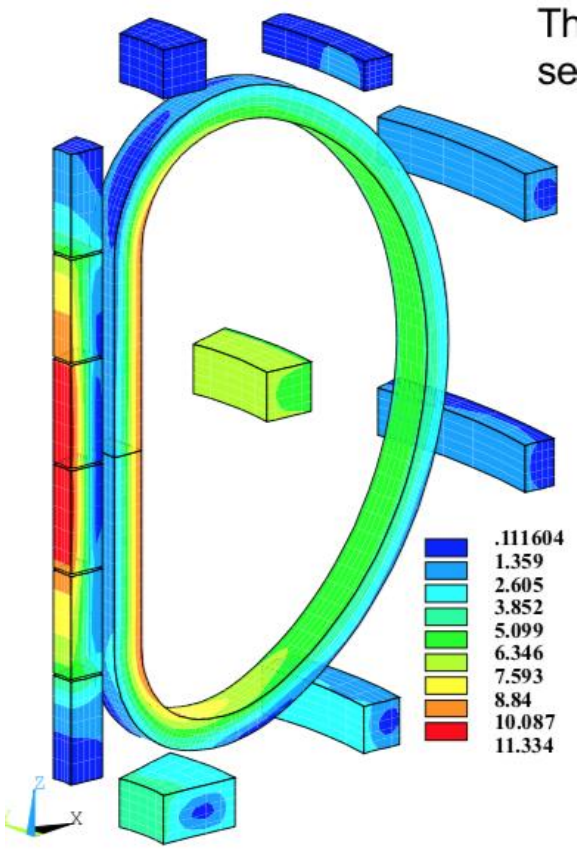
The logistic Challenge

- A DEMO TF coil assembled in its case exceeds **1400 t**, compared to **360 t** in ITER.
- The DEMO tokamak building should be over **100 m** in width, compared to **70 m** in ITER.
- The crane for the DEMO tokamak building will be one of the world largest, comparable to the shipyard cranes…

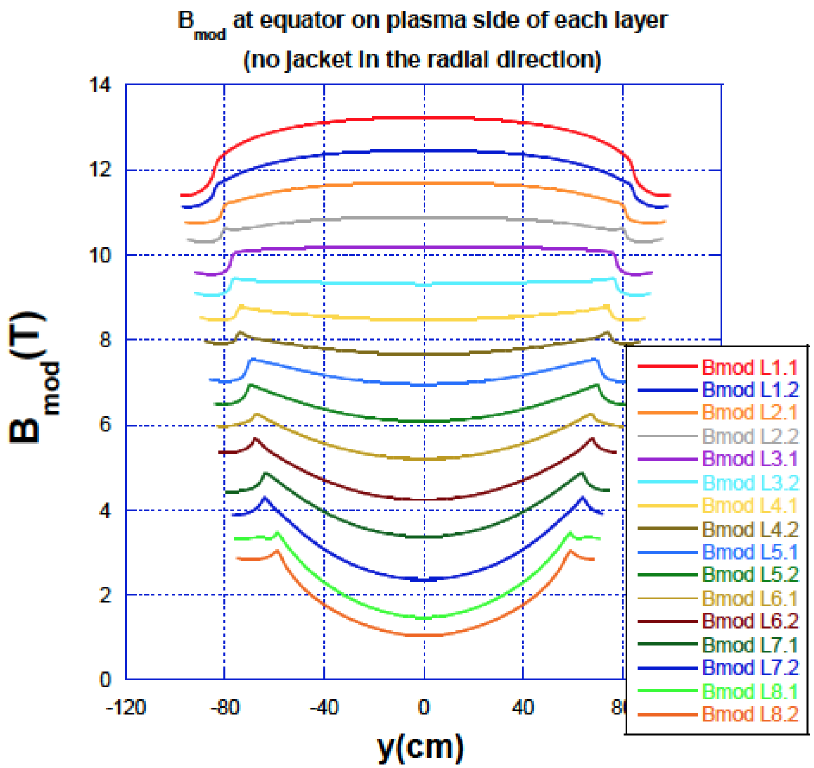
Taisun, Yantai, 2009
Lifting capacity 20 000 t
Width 120 m
Height 80 m

Kockums, Malmö 1974
Lifting capacity 1500 t
Width 175 m
Height 138 m

Field Distribution – Layers vs. Pancakes



The peak field is at the inner radius of the in-board section and decreases rapidly at larger radii.



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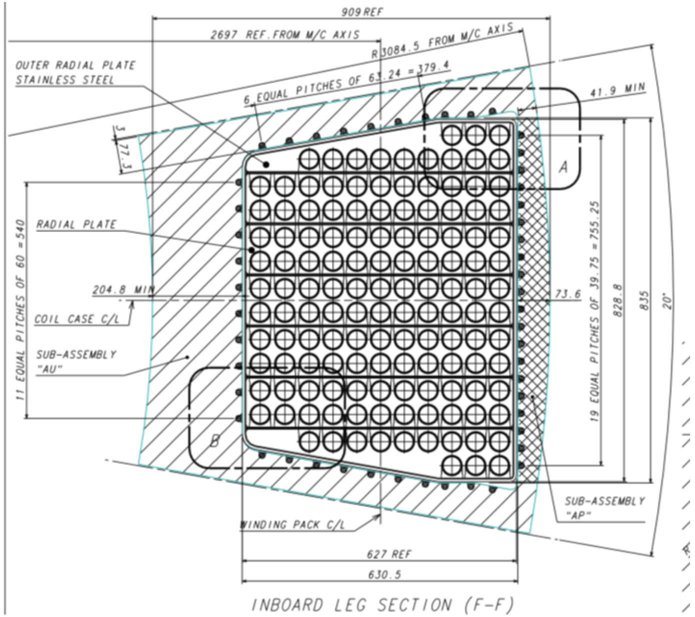
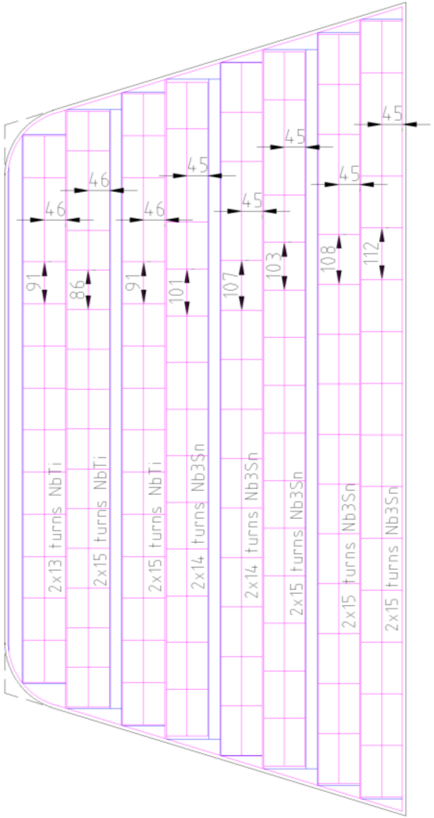
ITER- Pancakes



DEMO - Layers



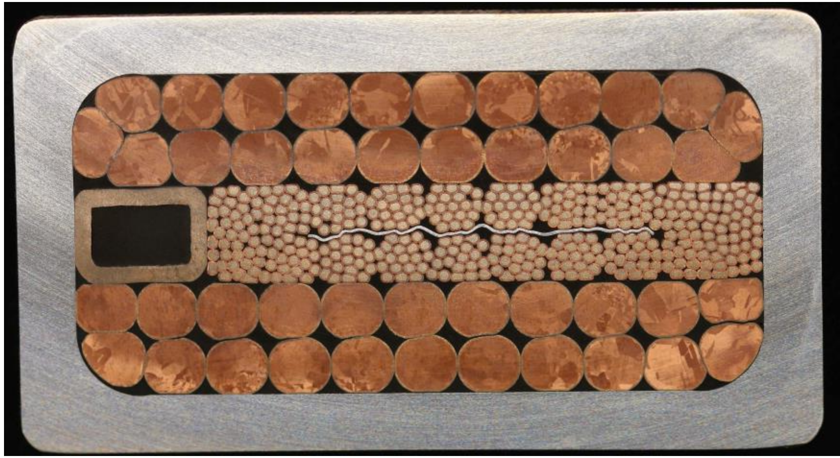
- In pancake wound ITER, all conductor sections must be designed for the peak field, no grading is possible.
- In layer wound DEMO, the conductors of each layer are designed for their peak field ➔ grading.

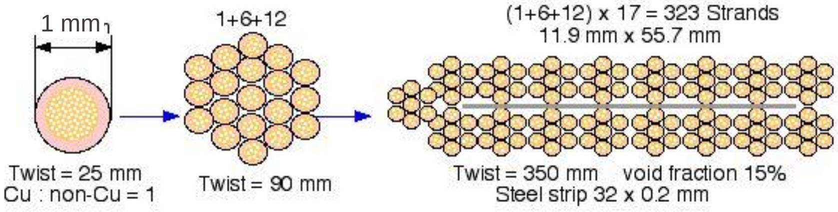
React & Wind Conductor

- If the steel conduit is assembled after the heat treatment (R&W), the thermal strain on the Nb_3Sn is marginal and the performance is up to twice better compared to the W&R method.

- To prevent displacement and local bending under transverse load, the void fraction is very small. The Nb_3Sn cable is flat to allow winding loads at minimum bending strain and distribution of the transverse forces at minimum compressive loads.

- The very large copper cross section for quench protection (very large decay time constant) is segregated from the Nb_3Sn cable.





What DEMO should learn from ITER

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Outstanding advantages can be obtained from ITER to DEMO by:

pancake winding -> layer winding	Conductor grading
Wind-and-react -> React-and-Wind	Much lower thermal strain (less Nb_3Sn needed)
CICC -> Compact rectangular cable	No transverse load degradation

Other fields for learning lessons from ITER to DEMO:

contract awarding:	Stimulate competition
specification:	More functional spec
manufacturing:	Most on-site manufacturing
team organization:	Clear responsibility

Is the Cost a Challenge?

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- In ITER, the cost is a challenge because it exceeds the agreed budget.
- In DEMO, the cost will scale up by one order of magnitude compared to ITER. Even with smart technology solutions (React&Wind, Graded Winding, etc.), the cost of the DEMO magnets is dominated by the "size" and the related infrastructures. As each Fusion Plant will require its own infrastructure (on site factory), there is little room for benefitting from future "economy of scale".
- The cost challenge for DEMO magnets will be much tougher than ITER. The issue will be not "stay in the budget", but convince the utilities that the investment can be paid back.

Intermediate Conclusions

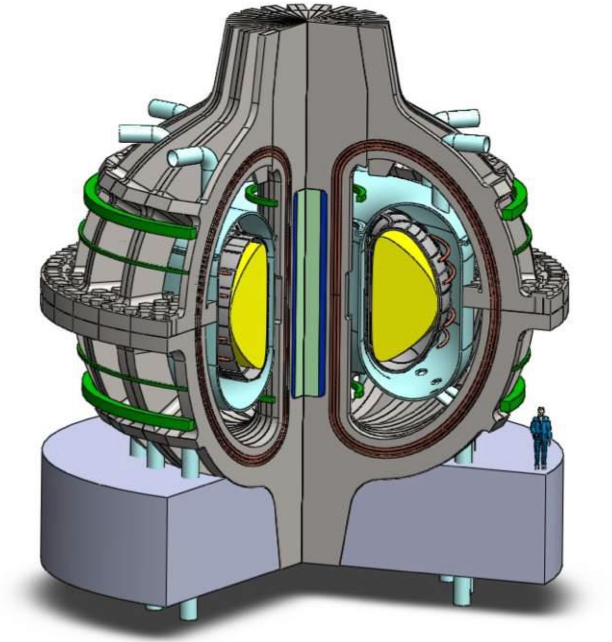
- The technical challenges for fusion magnets evolved during the last decades. Viable solutions have been found for all the issues. We learned the most critical lessons. The quest for improvements and simplification remains a constant challenge.
- The major technology challenges, today for ITER and tomorrow for DEMO, are related to the increasing size of the fusion magnets and the difficulty to carry out relevant, full size R&D. The opportunities to learn and improve are less and less frequent.
- The cost requirement for future power plants is the major challenge for DEMO (magnets). It is unlikely that such challenge can be solved maintaining the very big size envisaged today for the future power plants.

HTS for Fusion

HTS For Fusion

- Operation at "high" temperature (liquid nitrogen) would be great – saving a lot of energy on cooling:
  - Price of cooling gas (Nitrogen vs. Helium)
  - Cooling efficiency (worse than Carnot cycle)
- T_c well above 80 K, however at temperatures of liquid Nitrogen and high magnetic field, the critical current density is very low – not realistic for fusion magnets (however OK for electric grid application).
- T_{op} at 20 K or below is much more practical – one can reach field > 20 T in the winding pack, approx. double the field of LTS magnets (Nb_3Sn).
- 2 times higher field → 16 times higher fusion power.
- In Fusion Applications, HTS should be called High Magnetic Field Superconductors rather than High Temperature Superconductors.

ARC tokamak designed by MIT (now developed under Commonwealth Fusion Systems, CFS): 23 T peak field, based on HTS. Much more compact than ITER.



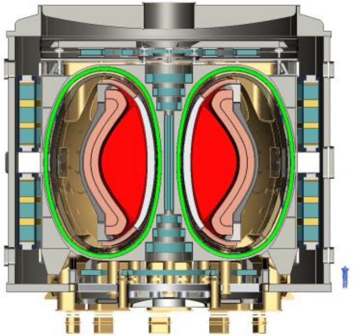
HTS For Fusion

- Until approx. 2010, and HTS fusion magnet looked unrealistic:
  - High price of the HTS tapes, about 10 times higher compared to LTS (which is also quite expensive).
  - Limited production length of HTS tapes (a few tens of meters).
  - Limited production capacity – enough for small coils, but not for a fusion-size magnet.
- In 2024:
  - Price of HTS dropped significantly – still higher than LTS, but not dramatically.
  - Production lengths and capacity orders of magnitude higher. Three large (almost fusion-size) coils manufactured and tested: 2 by CFS, 1 in China.
  - Remaining key challenges:
    - Degradation of the coil due to very high mechanical loads.
    - Quench protection; high AC losses

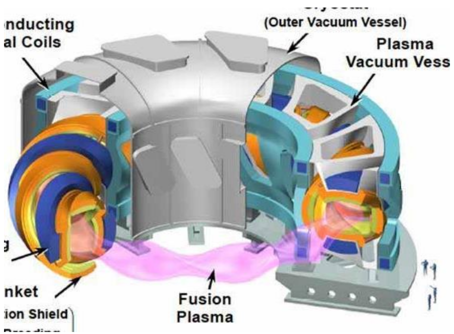
HTS Fusion Devices

- Several fusion projects world-wide consider the use of HTS for magnets.

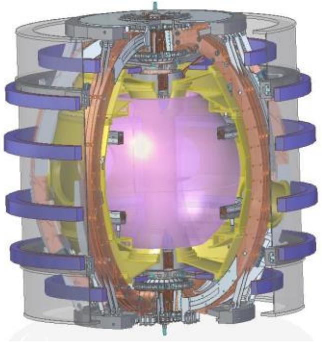
Princeton



Stellarator, Japan



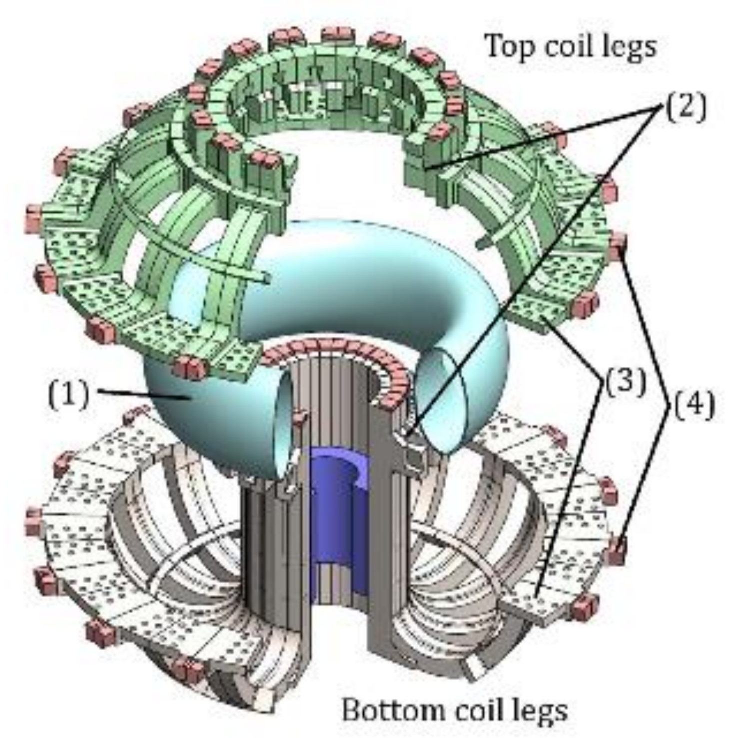
Tokamak Energy



- BTW, ALL projects have HTS **current leads**. Here a trend started to move from the BSCCO to the CC technology.

SPARC manufactured by CFS

Peak Field 23 T
Cooling by LH_2



- High magnetic field → small size (for the same fusion power); easier and faster manufacture → failure during the R&D phase allowed.
- Demountable coils made of HTS conductors are proposed with plug-in joints for each turn, allowing easy access and even removal of the vacuum vessel. (Not clear whether demountable joints are still considered.)

HTS Challenge 1 – Quench Protection

- In LTS superconductors, a quench propagates quickly along the conductor length, and can be detected early and reliably by measuring the voltage at the coil terminations.
- HTS operate with large temperature margin and at higher temperature → the quench propagation along the conductor is very slow (order of magnitude slower compared to LTS), making the quench detection by voltage challenging.
- Alternative quench detection methods must be developed, e.g. by the detecting local temperature increase by
  - optical fibers
  - co-wound, electrically insulated superconducting wire with a low Tc
  - a thermocouple array
- Alternatively, a possibility to make the HTS coil with electrically non-insulated turns is being investigated.
  - In steady-state operation, all currents flows through superconducting turns
  - During quench, current can bypass around the quenched area

HTS Challenge 2 – Mechanical Stability

- The issue of degradation of the conductor performance with the electromagnetic and thermal cycles occasionally observed for LTS superconductors is much more severe for the HTS superconductors. Until 2025, only one conductor (Viper of SPARC, CFS) had not degraded (at least not significantly). Other HTS prototypes tested in the SULTAN test facility showed signs of degradation. In many cases, the test campaign had to be interrupted prematurely due to the severe degradation.

- Likely sources of degradation:
  - Sheer stress leading to the HTS tape delamination
  - Insufficient mechanical support of the HTS tapes (e.g. voids in the tapes soldering)

HTS Challenge 3 – High AC Losses

- The hysteretic loss depends on the filament size. While the filament size in LTS strands is of the order of ~10µm, in case of HTS tapes it corresponds to the tape width, which can be up to several mm.
- Due to high hysteretic loss, AC coils do not look very suitable for the coils operating in pulse mode (CS and PF coils). It should not pose a big problem for the DC coils (TF coil).
- Ongoing R&D: make tape striation by laser-cutting the HTS layer in the tape into submillimeter wide strips.
- Thanks to the fact that HTS can operate at 20K instead of at 4.5K for LTS, and also due to higher temperature margin, larger heat load can be tolerated and removed compared to the LTS conductors.

HTS Challenge 4 – Field Orientation of the J_c

- The superconducting properties depend on the field orientation with respect to the tape:
  - At very low temperatures, when B is perpendicular to the HTS tape surface, J_C is several times lower compared to the case when B is parallel to the HTS tape.
- Conductor design needs to take this effect into account.

HTS Challenge 5 – Degradation Due to Irradiation

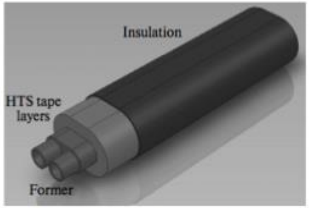
- The superconducting properties degrade when the HTS tapes are exposed to very high irradiation levels, e.g. due to neutrons passing into the TF coils trough all the shielding.

- Studying of the irradiation with a relevant neutron spectra and fluxes is not easy (nuclear reactors have different neutron spectrum compared to the fusion tokamaks). It also seems that the effect of temperature irradiation can be temperature dependent. On a positive side – part of the degradation can be recovered by warming up the magnet to room temperature (or slightly above room temperature).

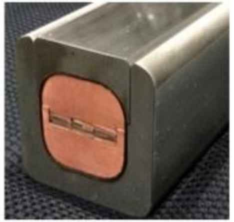
- Thicker shielding can reduce the neutron flux to the coil winding pack.

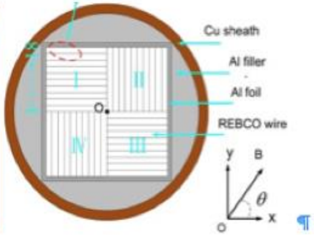
HTS in Fusion – Conductors

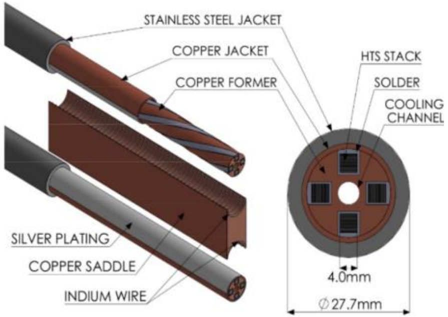
- *“Wrapped” tapes*

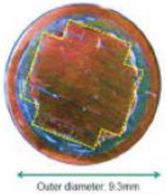


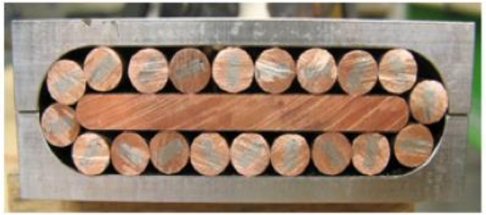
- *Stacks of tapes*

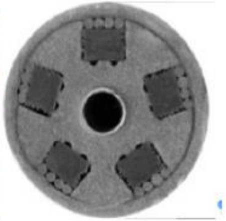




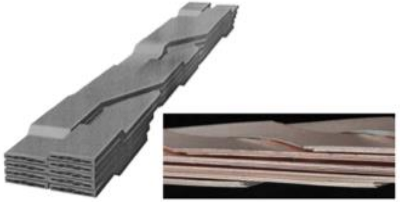






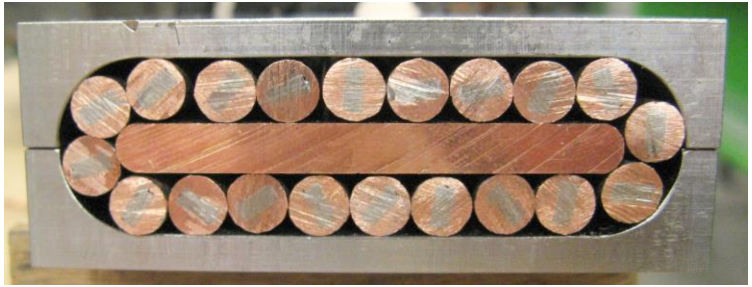


- *“Braided” tapes (Röbel)*



HTS in Fusion – Conductors Developed by SPC

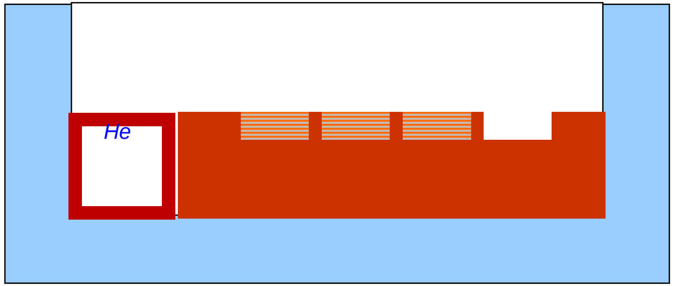
SPC: 60 kA, $B_{\perp}$ 12.5 T, 7.8 K, 2016



The SPC conductor is transposed, scalable to 50-100 kA, designed for $B_{\perp} > 12$ T, AC tolerant, force flow.

(Nikolay Bykovskiy)

NTNT – Non-Twisted Non-Transposed conductor, 2024



(Davide Uglietti)

ASTRA prototype construction & testing

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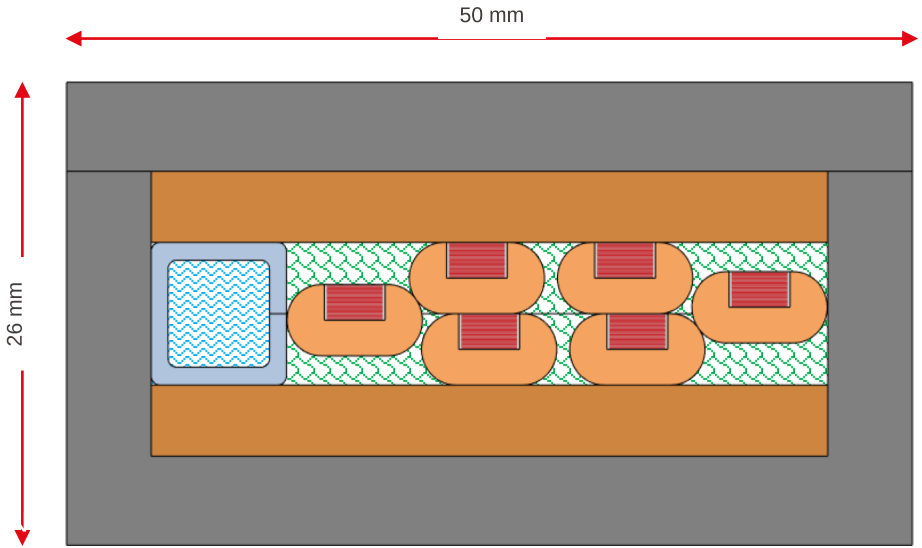
3.3 mm tapes
21 tapes in a stack
8 x 4 mm copper profile



Nikolay Bykovskiy, SPC, 2023.

Conceptual Designs of HTS Fusion Magnets

- EUROfusion. Use HTS REBCO in the high grade of CS. Allow a peak field up to 18T to increase the flux (burn time) for the same coil size.
- CFETR (China). Plan to use CICC made by BI 2212 wires in CS high grade.
- BEST (China). Plan to use BiSCO tapes for the CS coil.
- SPARC (MIT). Up to 23 T, compact tokamak, (quick replacement of the vacuum vessel by demountable TF coils).
- FFHR (NIFS). Large size Helical coils assembled in segments. Medium Field. HTS is chosen for cryogenic economy.
- FNSF (PPPL). Spherical tokamak, field up to 16 T, HTS is proposed for the high current density.
- ST60 (Tokamak Energy,UK). Compact spherical tokamak. HTS is proposed to allow a thin nuclear shield, with large heat removal at 30 K.
- Various Startups: Proxima Fusion, Gauss Fusion, …, mainly stellarators.

The End

Very complex windings FFHR (Japan)

- To overcome topological difficulties with traditional winding methods, a coil can be built by a large number of pre-bent, short sections of HTS superconductor (segmented fabrication, 16 m segments).

- The challenge is a very large number of permanent joints and the related heat removal, the continuity of structural support and the electrical insulation.