Superconducting Magnets - 1

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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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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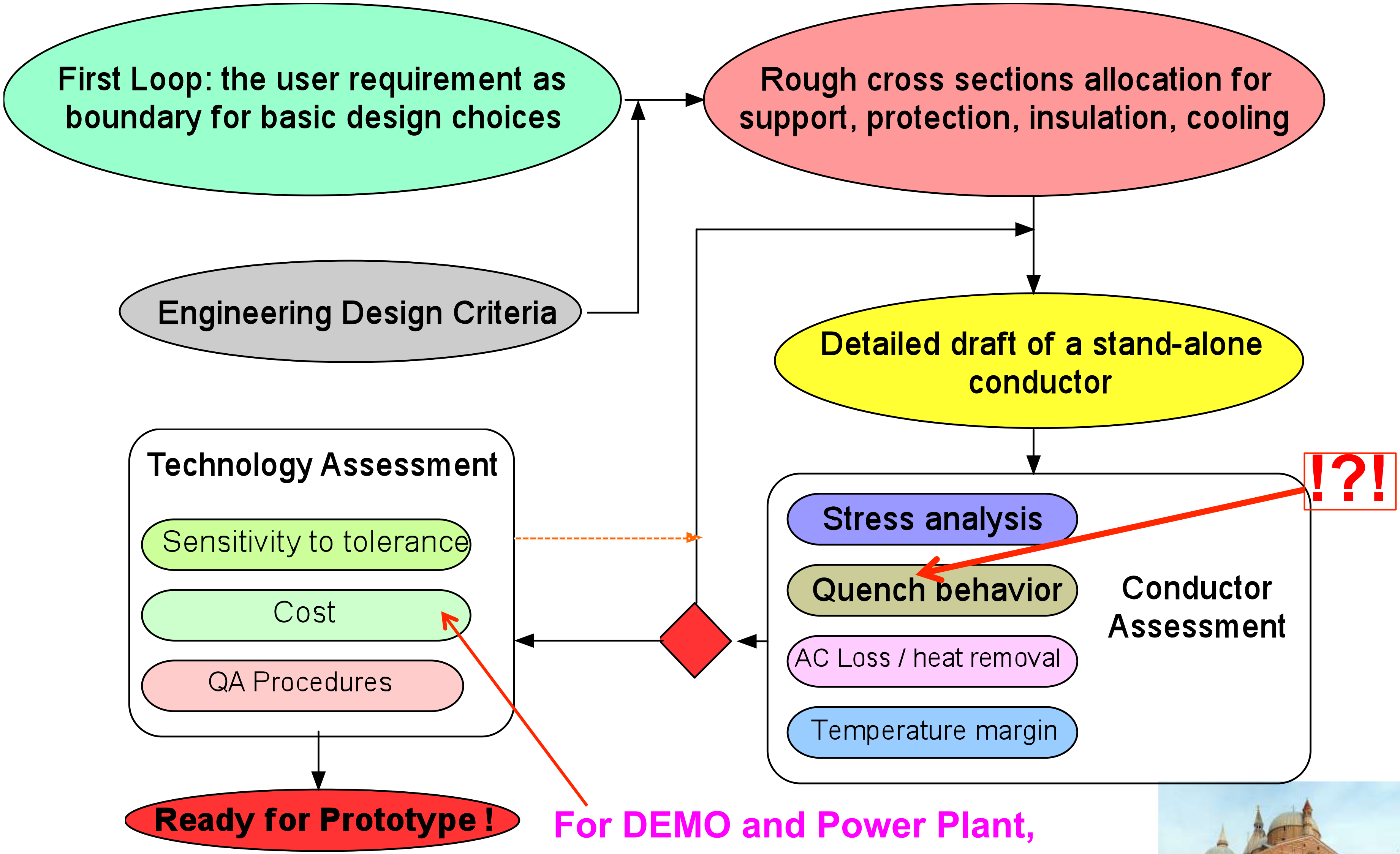
A stepped roadway for conductor/magnet design



For DEMO and Power Plant, the cost is a design driver

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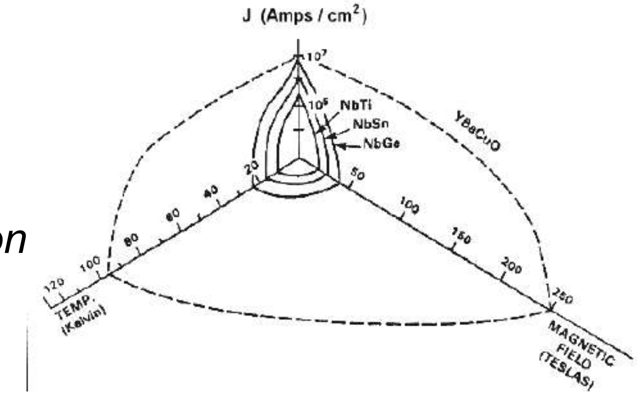
“Quench” ?

(do not look in the dictionary, it has nothing to do with forging and tempering)

In a superconducting coil a quench event is the
local, non-recovered loss of superconductivity:



The critical surface (B, T, I) is exceeded in a (short) section of the winding and the superconductor becomes resistive

The local ohmic power generation overcomes the heat removal capability

The temperature runaway may eventually lead to melting of the coil

A quench event is a serious safety issue for superconducting coils. Even if a quench event should never happen according to the design, countermeasures must be planned to face a quench event

Quench Detection, e.g. by accurate, fast voltage monitoring

Quench Protection, i.e. avoid temperature runaway / preserve the integrity of the coil

Quench Protection Strategy

*The interval between the start of the quench and the reliable detection with related action, is called "delay time", **t_d**, and can last up from few ms to few seconds, depending on the quench propagation rate, **v_q**. During t_d the power deposited at the quenched spot is in the range of few kW in large coils.*

The most common quench detection method is based on voltage monitoring of the winding sections. The voltage threshold for quench detection ranges from 10 mV to 1 V, depending on the achievable rejection rate of noise and inductive voltage.

The very first obvious action as soon as a quench is detected is to stop powering the quenched winding.

However, placing the power supply in "freewheeling" (basically a short circuit), is not effective to stop the current in the winding, which is sustained by the stored energy. Even if the power supply is short circuited, the current decays very slowly, as L/R_{quench}, depositing most of the stored energy at the quenched section of the winding, which expands moderately slowly.

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Quench Protection Strategy

Depending on the stored energy / mass of the winding, the amount of copper in the conductor, the heat diffusion in the winding, etc., various approaches can be taken to preserve the integrity of the coil in case of quench.

If all the stored energy is dissipated in the coil, the average final temperature, starting from ≈ 4 K, can be estimated comparing the conductor enthalpy with the density of the stored energy.

Example	Stored Energy	Conductor mass, kg	Energy density	Average, final temperature
15 T Lab Solenoid	250 kJ	50 kg	5 J/g	≈ 70 K
LHC Dipole	8 MJ	800 kg	10 J/g	≈ 100 K
CMS Solenoid	2.6 GJ	220 t	11 J/g	≈ 80 K (Al)
ITER TF coil	2.28 GJ	43 t	53 J/g	≈ 300 K

At large, the conductor enthalpy (mix of copper, superconductor, steel) is:
≈ 2 J/g up to 50 K
≈10 J/g up to 100 K
≈ 60 J/g up to 300 K

Energy Management

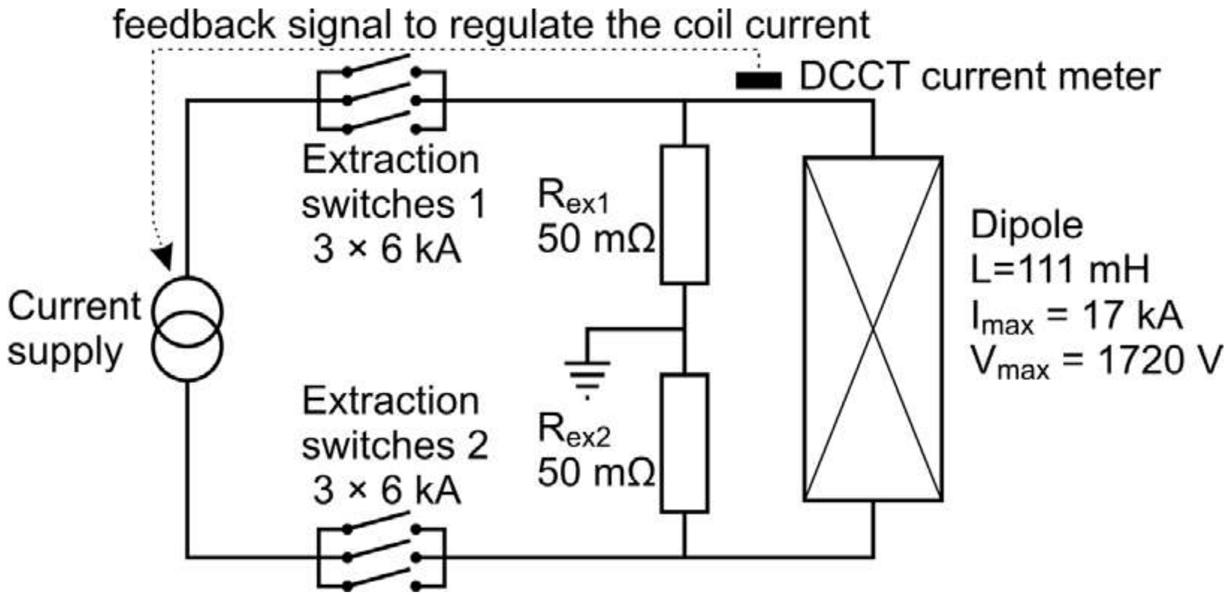
The energy is not dissipated homogeneously in the winding, with the largest fraction, and hence the largest temperature, at the spot where the quench initiated, also named "hot spot".

Large temperature gradients are dangerous because of thermal-mechanical induced stress, which can destroy the integrity of the winding. As a design criterion, the hot spot temperature is usually specified $T_{hot\ spot} \leq 150$ K in the rigid parts of the winding.

In superconducting magnets with stored energy density larger than few J/g, it is mandatory to extract the stored energy to limit the hot spot temperature.

Example	Measures in case of quench	
15 T Lab Solenoid	Passive: diodes and resistors in parallel with winding sections	
LHC Dipole	Active: fast heaters promote quench propagation + diodes	
CMS Solenoid	Active: current breakers and dump resistors in parallel	τ = 200 s, high λ, limited extraction
ITER TF coil	Active: current breakers and dump resistors in parallel	τ = 14 s, 90% energy extraction

Energy Extraction Scheme for Fusion Magnets



The key elements of a quench protection system are

- *The hot spot temperature in the coil, T_{max}*
- *The dump resistor outside the cryostat, R_{dump}*
- *The fast current breakers to open the circuit*
- *The maximum voltage at the terminal $V_{max}= I_{op}\cdot R_{dump}$*
- *The time constant of the current dump $\tau = L / R_{dump}$*
- *The quench detection time t_d*

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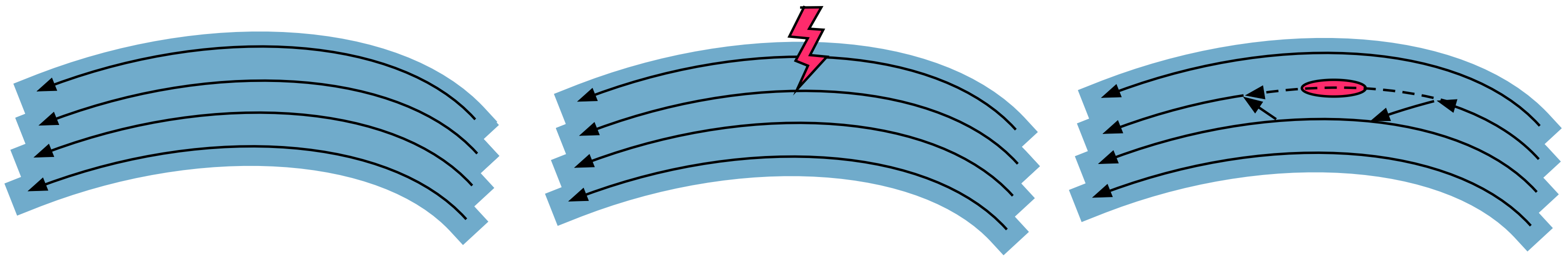
Non – Insulated Coils: the ultimate cure for quench?

- As soon as some voltage builds up at the quench location, the current starts to transfer to the adjacent turns.
- The whole stored energy is dissipated in the winding.
- You must just slowly run down the current at the power converter.



No temperature runaway, no high voltage, no breakers, no transient, no fast quench detection, no critical instrumentation

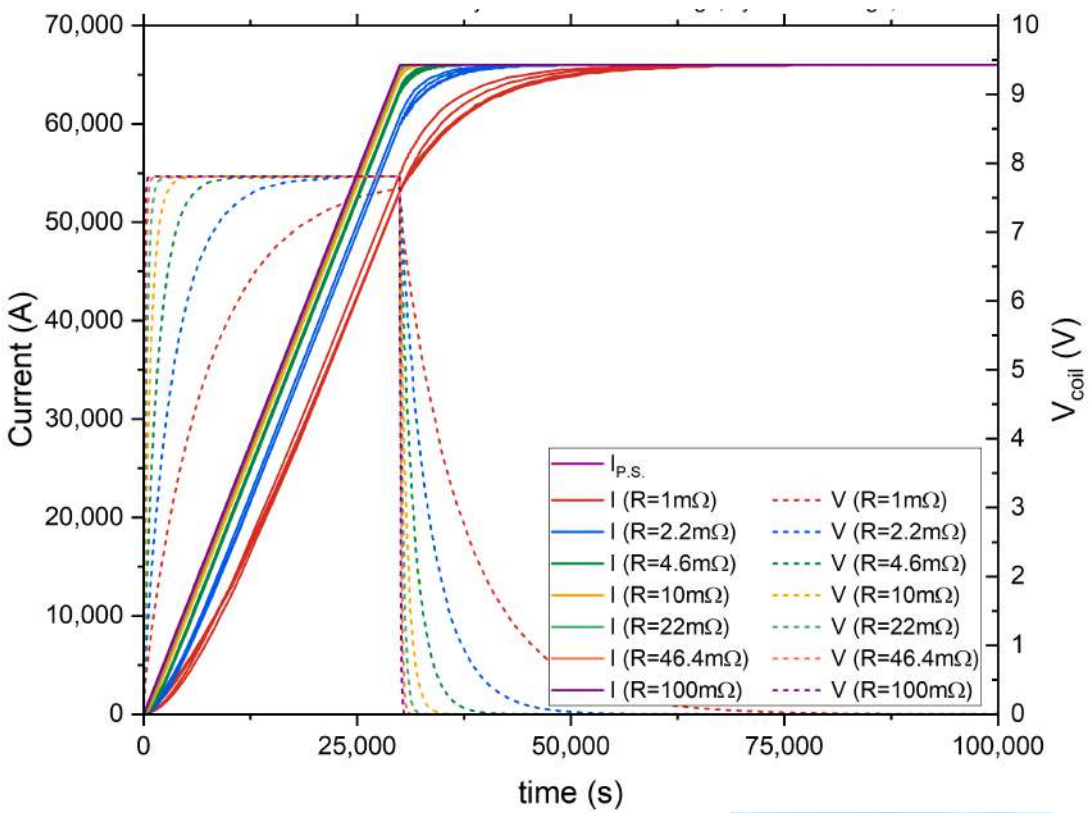
But…

The ability to control the coil current from the power converter is very poor. During the charge, the current in the superconducting turns is smaller than the output of the converter. The leakage current dies out slowly.

Only DC coil with long charge time can be "non-insulated".

Even in case of emergency, no fast discharge is possible.

As all the stored energy is dissipated in the coil, the re-cooling is time consuming.



Example of non-insulated DEMO TF coil

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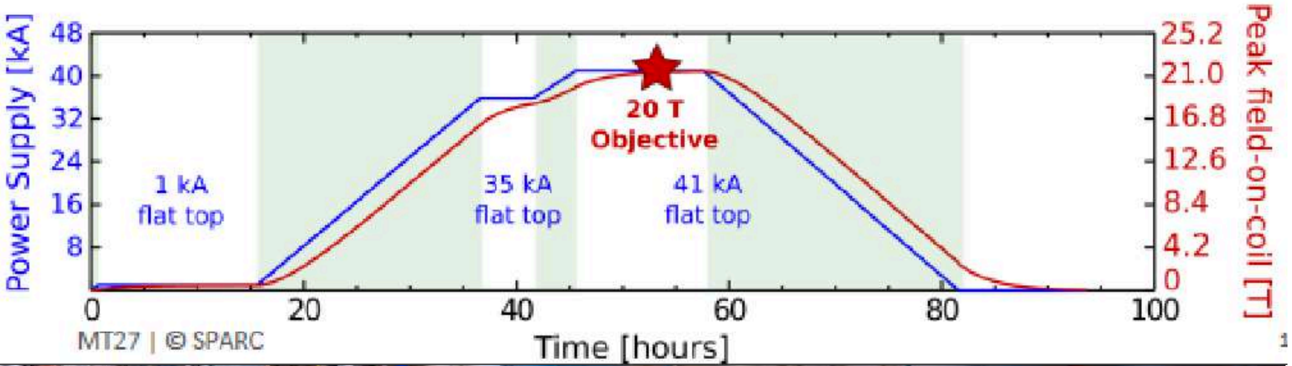
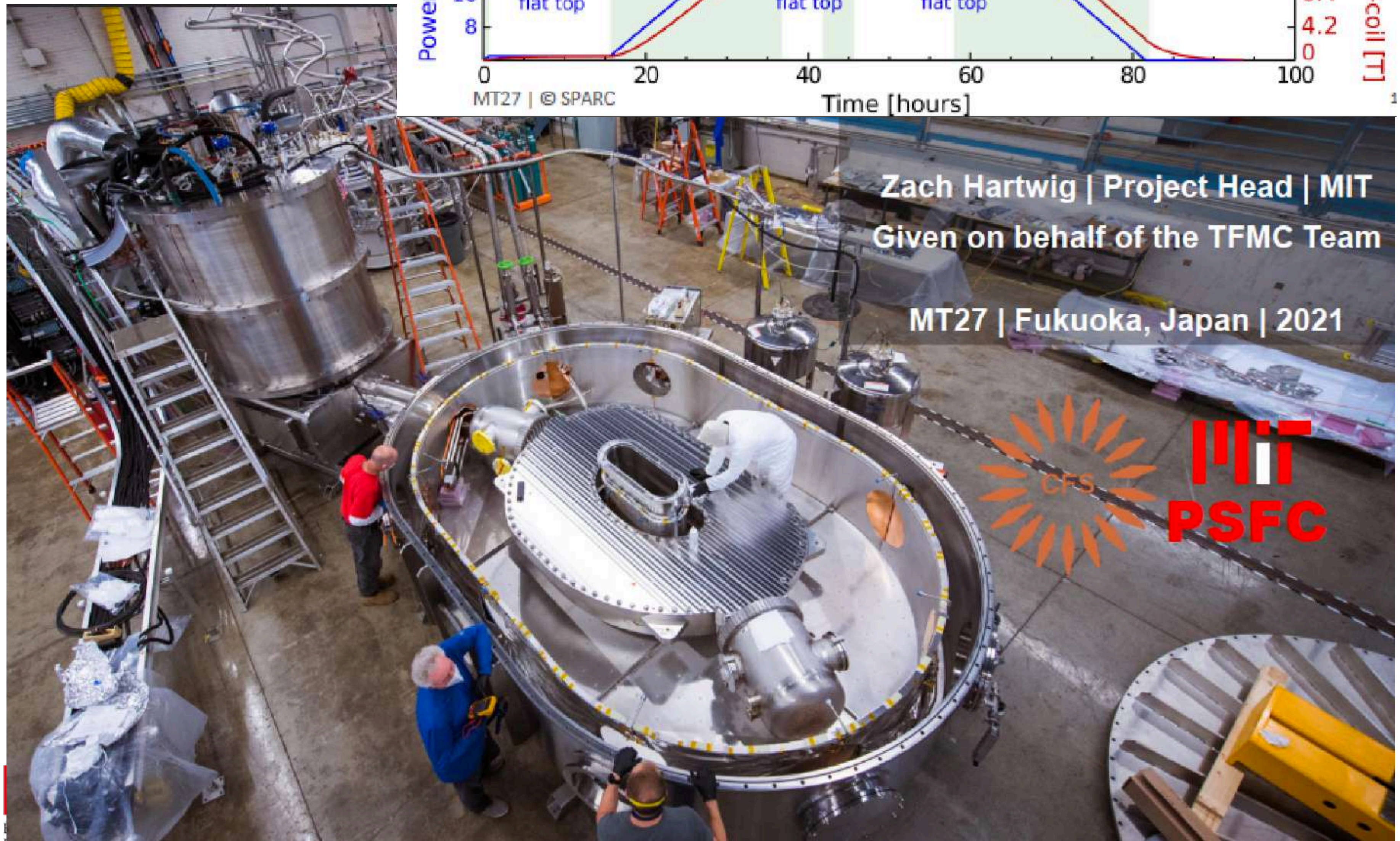
The SPARC TFMC





And…

- To avoid hot spots in the winding, the heat must diffuse "fast" through the turns, in axial and transverse direction. If the heat diffusion time is longer than the current decay time, large temperature gradients occur.

- The heat diffusion time is also a function of the coil size: in the large TF coils of DEMO, the diffusion path is several ten meters…

- In the non-insulated TFMC of SPARC, the heat diffusion was slow and a region of the coil burnt upon a quench while the other regions remained cold.

In summary, the non-insulated coils are…

Good:

- Passive quench protection (safe and cheap)

- High current density (no need of large copper cross section)

Bad:

- No active control for field (only for certain DC coil)

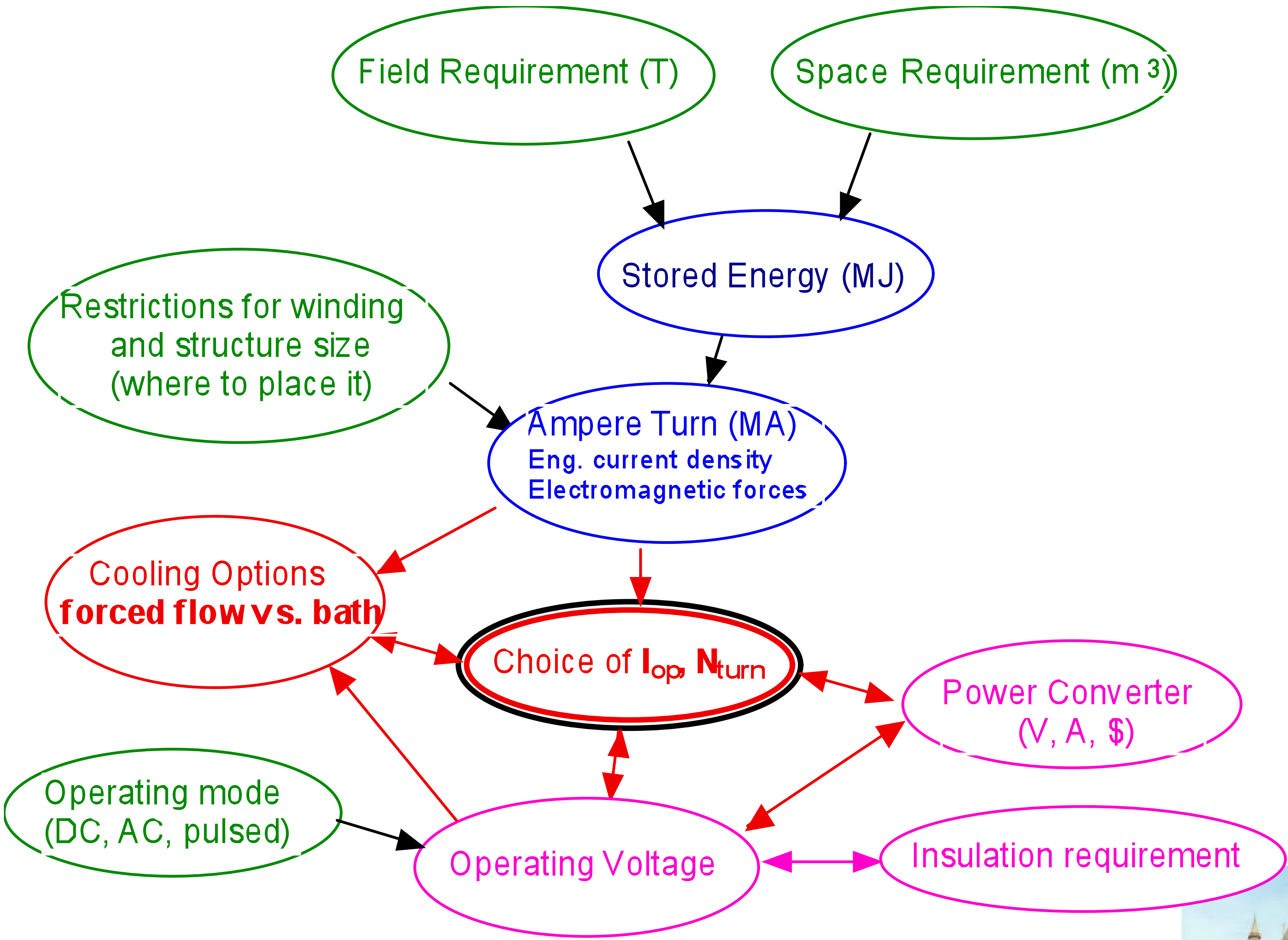
- Long re-cooling time after quench (100% of stored energy “in the coil”)

So far non-insulated coils are in use for small, high field insert solenoid.

The use in very large winding is problematic because of heat diffusion issues.

In case of coil systems, e.g. TF coils, it may be not acceptable that one coil is “hot” while the others remain cold.

The first loop



“Tools” for the first loop

Stored Energy
(Volume integral of magnetic field)

$$E = \frac{1}{2\mu_0}\int B^2\, dV \equiv \frac{1}{2} L I_{op}^2$$

Ampère law
(Field to current relation)

$$\oint B \cdot d\ell = \mu_0 I$$

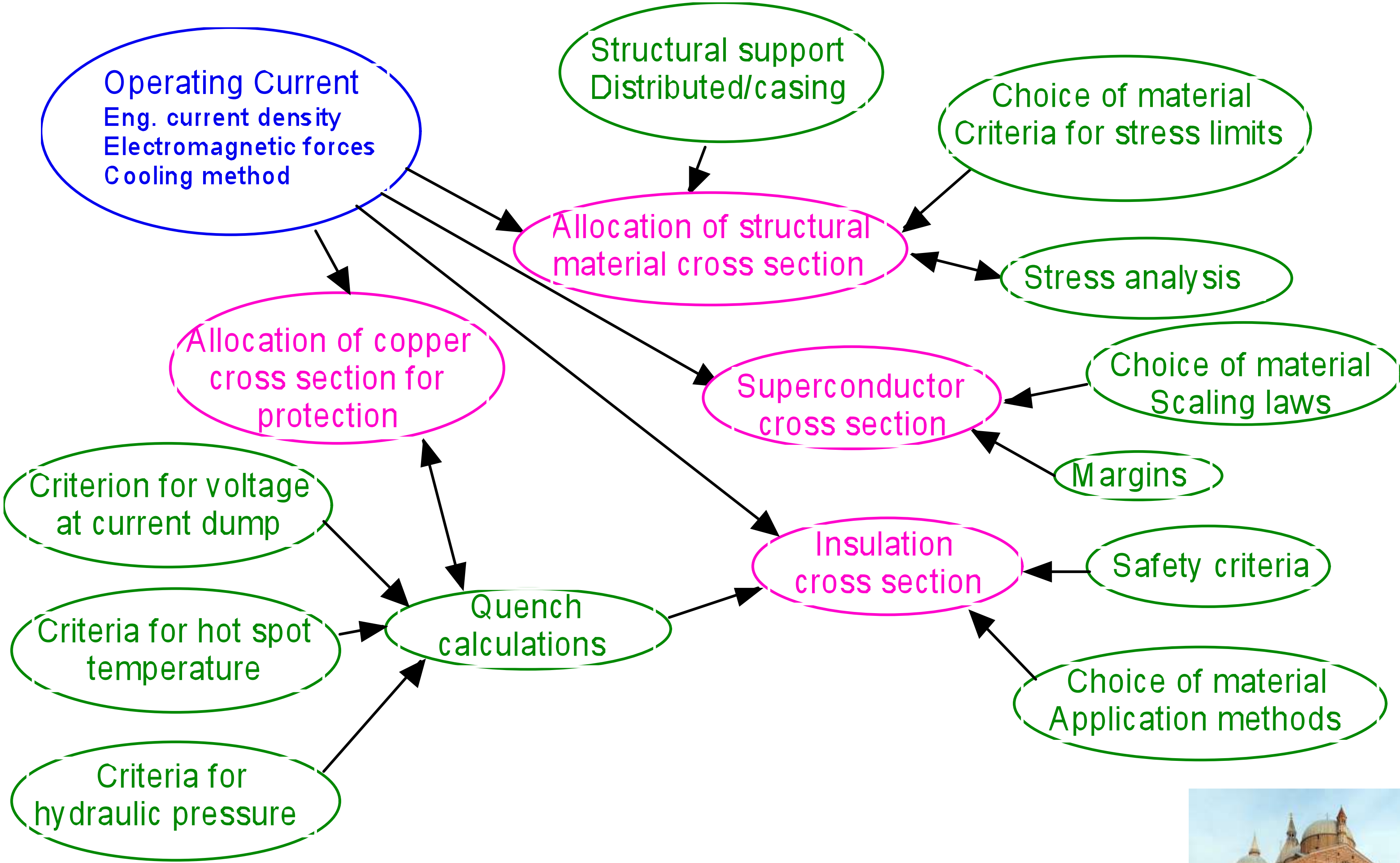
Lorentz force

$$F = \int j \times B\, dV = IB \int d\ell$$

Faraday-Henry law
(Inductive Voltage)

$$V = -L\,\frac{dI_{op}}{dt}$$

The second loop - Cross sections management



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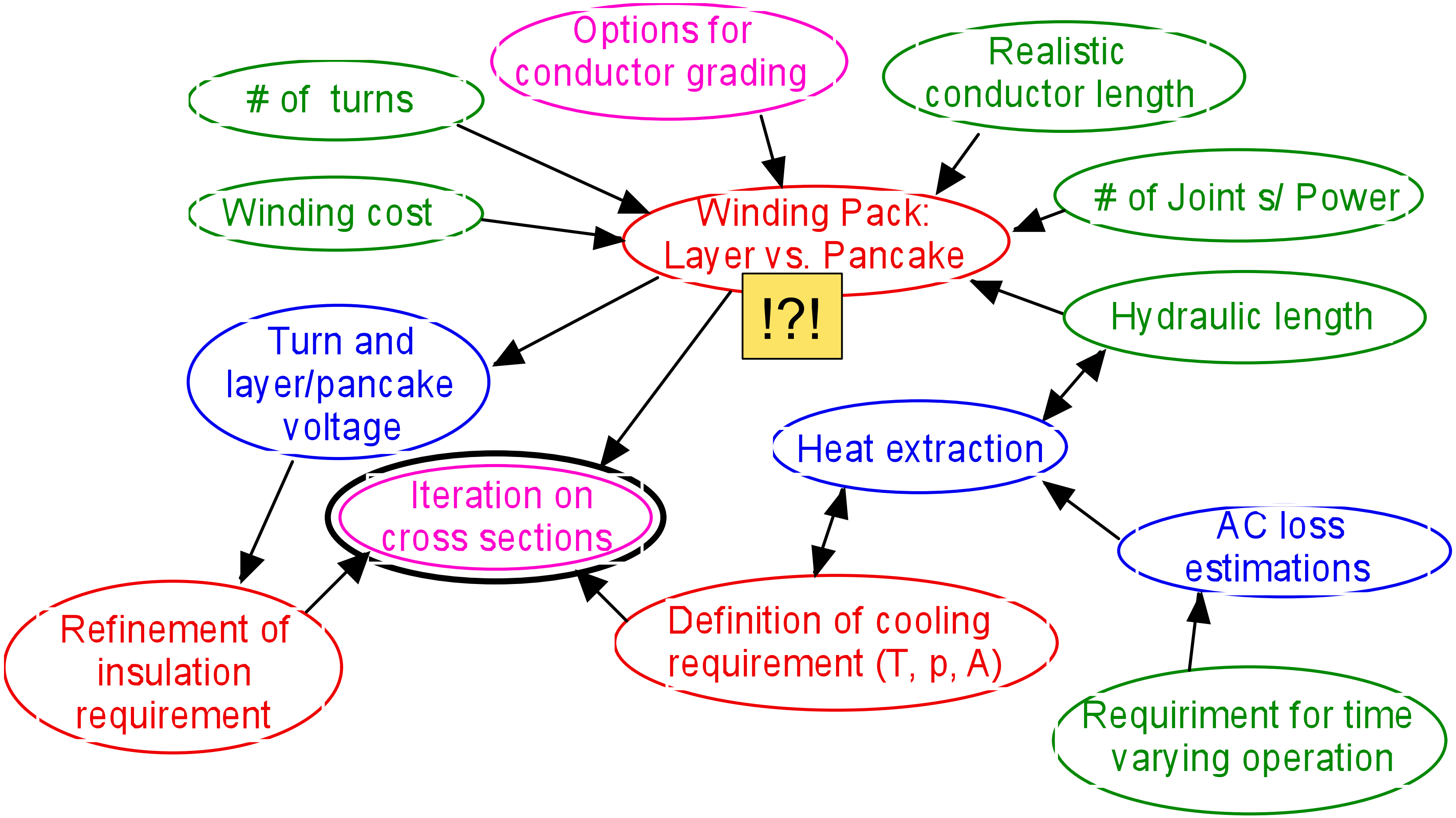
Cooling and Winding pack impact on cross sections



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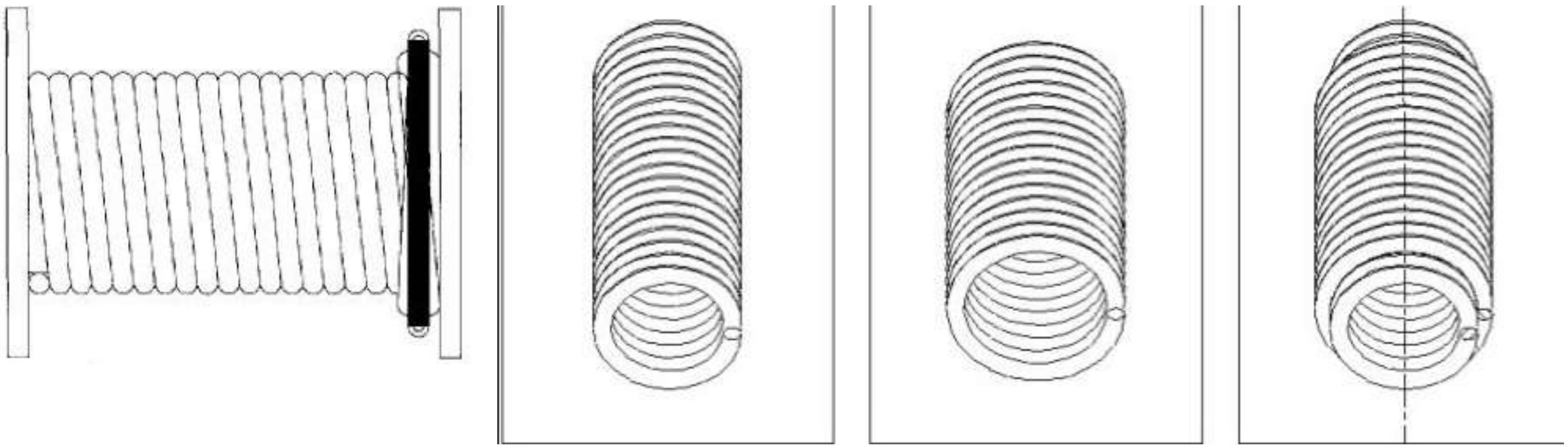
Layer Winding

A winding pack, e.g. a solenoid, can be wound as

Layers: *start winding at the inner radius,*
build the innermost layer by turns at the same radius
wind next layer on top of the former one
continuous winding, joints/terminations at top and bottom



Pancake Winding

A winding pack, e.g. a solenoid, can be wound as

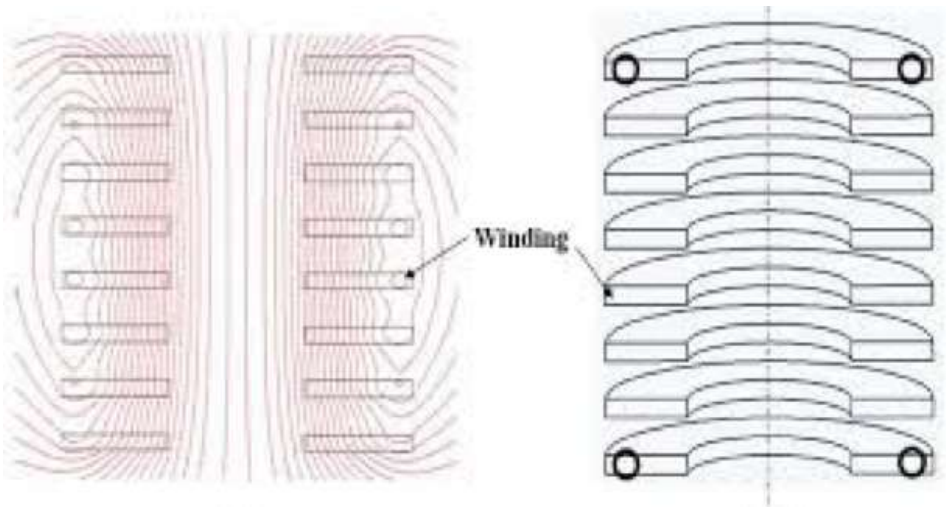
Pancakes: start at the inner radius

wind the turns at same high and increasing radius

separately wind next pancakes

stack all the pancakes on top of each other

joints at inner and outer radius



Pancake / Layer : Does it matter?

Layer

☺ *As each layer has a different peak field, the amount of superconductor can be adjusted in each layer, leading to cost and space saving (graded winding).*

☹ *In case of large and heavy winding, all the mass must be handed at the same time -> larger tools.*

☺ *Double layer windings and two-in-hand windings pose no problem.*

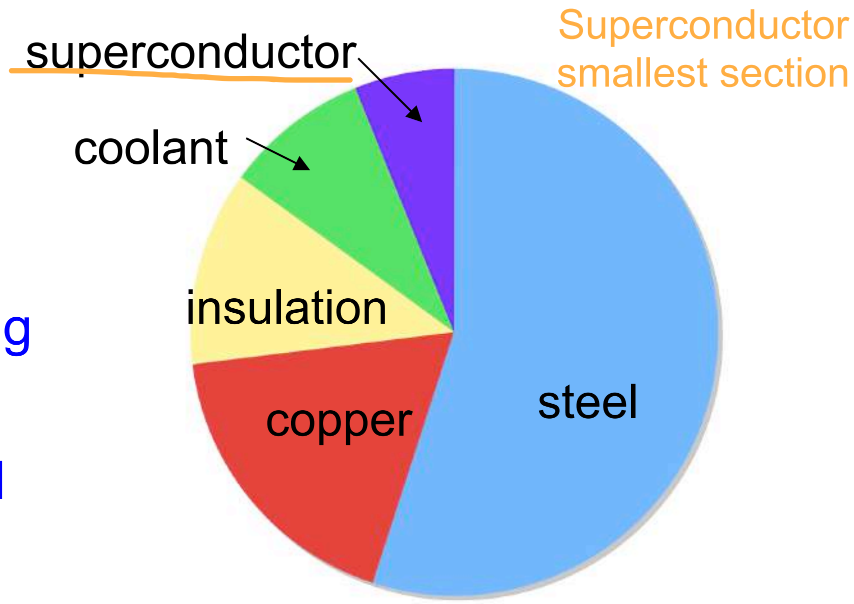
Pancake

☺ *The winding is fully modular, i.e. each pancake is wound separately and eventually stacked together -> lighter tooling for large coils.*

☹ *No grading is possible -> larger cost and space requirement.*

☹ *To avoid joints at the inner radius, double pancake is necessary, with complex handling.*

Conductor Layout



Once the cross sections and the operating requirement are roughly assessed,
the stand-alone conductor can be drafted accounting for:

!?!

Superconducting strands available on the market

Transposition / current distribution

Cable layout consistent with ac loss and mechanical constraints

Local heat removal / stability

Sensitivity to manufacturing tolerance

Applicable quality control procedures

Procurement time and cost

Strand…

(not a city district of London!)

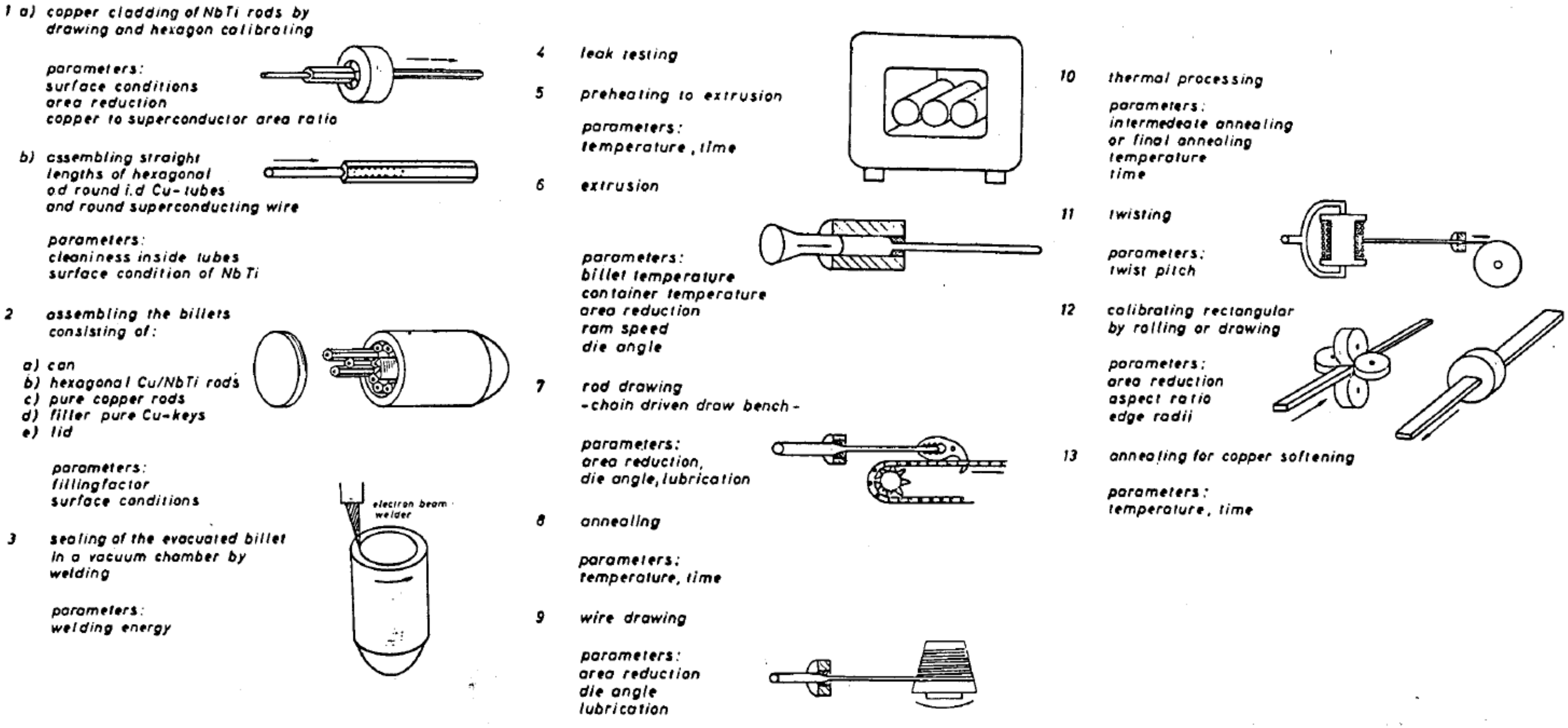
A “strand” is a multifilament composite wire, where the matrix is made of copper and/or copper alloys (for stability and quench protection) and the filaments are made of superconductor, typically NbTi or Nb_3Sn. A strand includes hundreds to thousands filaments. The need for thin filaments is driven by the flux jumps (sudden collapse of field profiles inside the filament).

Multifilamentary strands are manufactured by either single or multiple extrusion of billets and cold drawing with intermediate annealing steps.

Typical manufacturing batches (billet size) range from 50 kg to 200 kg

Typical diameter for strands in fusion magnets is 0.5 mm – 1.0 mm

Typical Manufacturing Route for NbTi Strand



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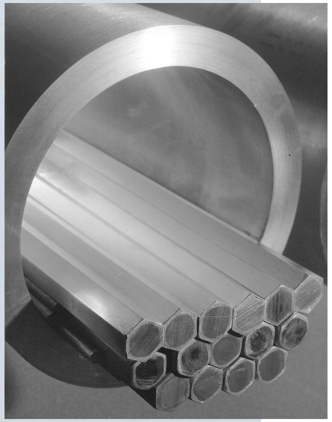
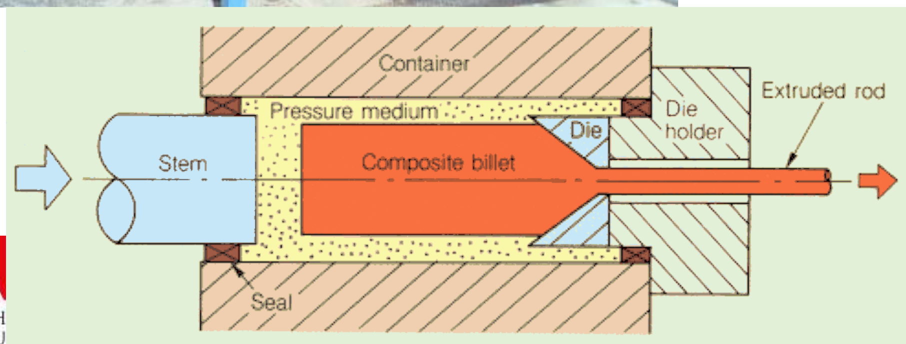
Hot extrusion



Cold drawing



Hidrostatic extrusion

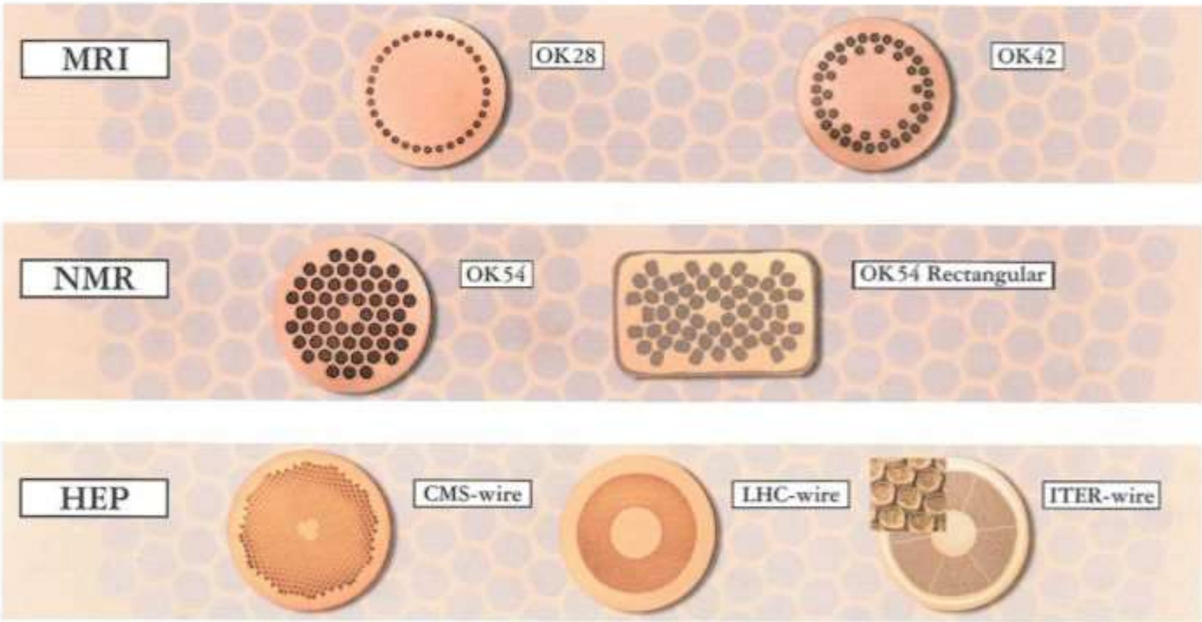
Technical superconductors today - NbTi

NbTi. NbTi is the best superconducting soluble alloy. T_c = 9.2 K, used in superconducting magnets up to 8T (4.2K) or 11T (2K).

Very ductile, co-drawn with copper down to submicron filaments, produced since 50 years in thousands of tons.

Today the main market is MRI, followed at distance by NMR, High Energy Physics, Fusion, laboratory magnets, etc.

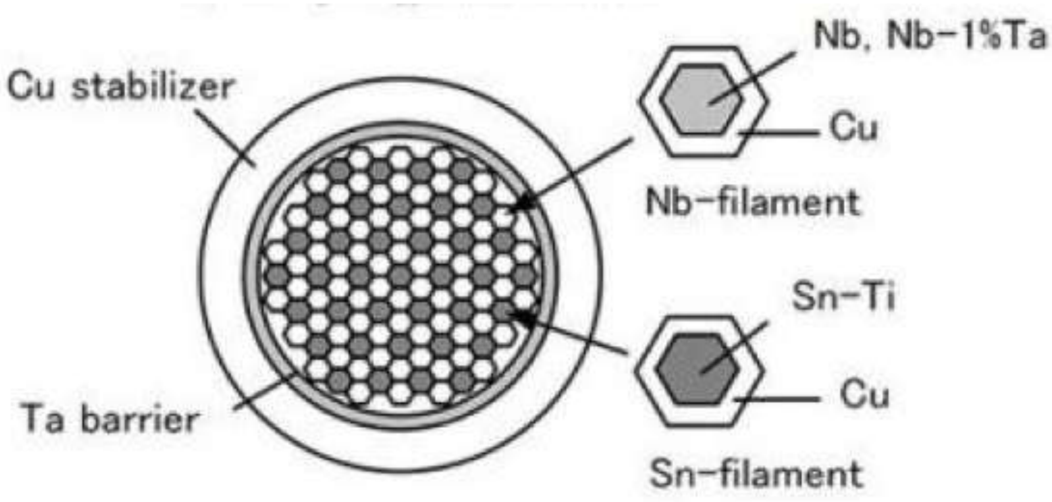
Price ≈ 150 €/kg
(≈30 times bulk copper)



Technical superconductors today – Nb_3Sn

Nb_3Sn is a *brittle* intermetallic A15 compound (fixed stochiometry). Since the 60' it is obtained by solid state diffusion of Sn into Nb (600-700C / 50-200 hrs). The multifilamentary composite is a precursor containing Nb filaments and Sn. The precursor is ductile and can be wound or cabled to the final form. Eventually it must be heat treated to build the Nb_3Sn. After heat treatment, it is very brittle and must be handed with care, controlling bending and loading.

It is produced by half dozen of companies worldwide by either "bronze" route or "internal Sn" method. Best customer today is ITER (500 t)



Price ≈ 650-1000 €/kg
More than bulk Ag

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Conductor-Coil Performance Assessment

Detailed conductor layout

Structural Assessment

In-plane load
Out of plane load
Stress in structural support
Shear stress / tension in insulation
Load on superconductor (Nb_3Sn)

Electrical Assessment

Local Field map
Peak operating conditions (B, T, ε)
Temperature margin (scaling law)
Estimate of ac loss

Thermal-Hydraulic Assessment

Stability (energy margin)
Steady state heat removal
Cool-down analysis
Cryogenic load

Safety Analysis

Quench (V, T, p)
Failure (insulation, q detection)

Assessment results vs. design criteria

Conductor Technology Assessment

When the magnet technology is well established, e.g. similar magnets have been already built, the assessment is done at industrial level, including

- Tolerance (minimum need, cost, impact of non-conformity)
- Tooling and methods (prefer low tech, affordable investment)
- Logistic and Interface (geographic and contractual split, transport)
- Quality control (where must it apply, recovery/repair measures)
- Acceptance and certification (what is the minimum to be covered)
- Warranty (strategy and cost for warranty, effectiveness of penalty)

In some cases, e.g. HTS coils, the technology is **not** well established. Crucial steps of R&D must be identified to bring to maturity the magnet technology before starting an actual project, e.g. “proof-of-principle”, “demonstrators”, “reduced scale models”, etc.

Non-mature technologies may be considered in the *conceptual phase* of a project. In the engineering phase, no doubts should remain about the **readiness** of the technology.

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Functional vs. blue-print Specification

In the functional specification, the supplier is thought to know better than the user about design, technology, layout, computations, etc.

-> The supplier guarantees for the performance

Lab Solenoid

In the blue print specification, the supplier makes anything the user says with his best manufacturing experience.

-> The supplier guarantees for the methods, the user takes responsibility for the overall performance

Fusion magnet

Depending on the maturity of the technology, it may be convenient the one or the other way.

Blue print is cheaper for exceptional items and non-existing products, e.g. an ITER TF coil, but can be inconvenient or even more expensive if you want to re-invent products which are already on the market, e.g. a vacuum pump.

Moving from ITER to DEMO and Fusion Power Plants, the design responsibility should drift to the suppliers, i.e. "functional specification"

Superconducting Magnets - 2

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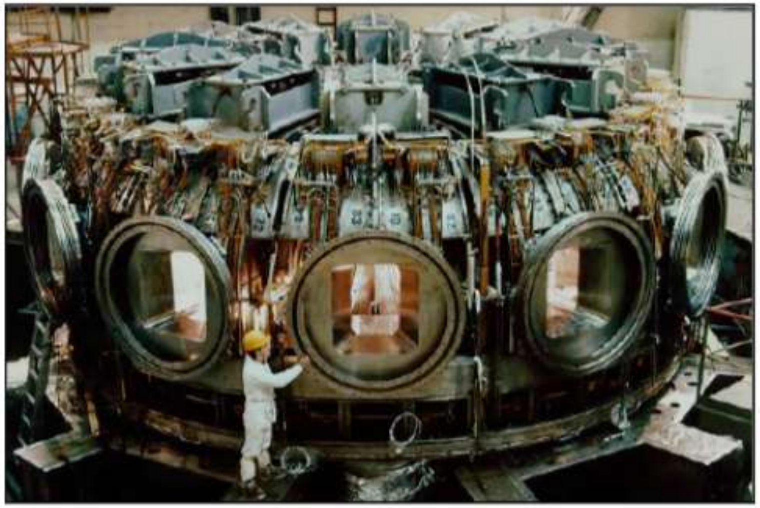
Tokamak T-15 ***Kurchatov Institute, Moscow***

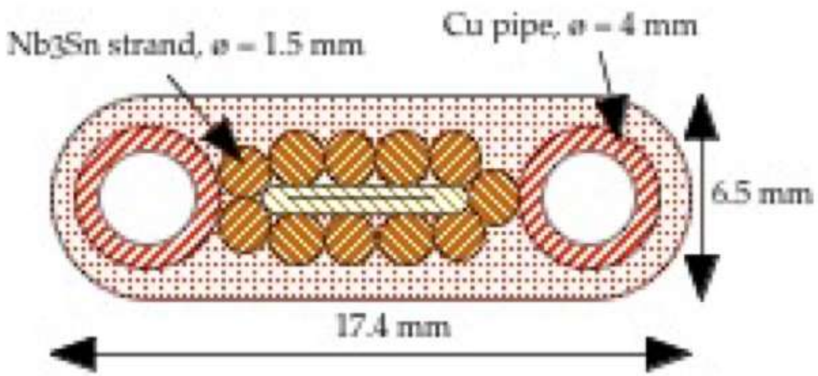
First, large Nb_3Sn based device (25 t strand)
Conductor manufacture ≈ 1980-1983



Stability is the design driver, with thick electro-plated cu used for conductor assembly.

One of the first large scale use of the **react and wind** technique.

???



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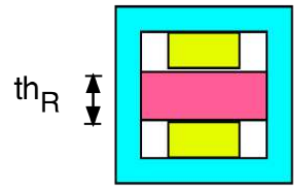
Coils made with Nb_3Sn strands

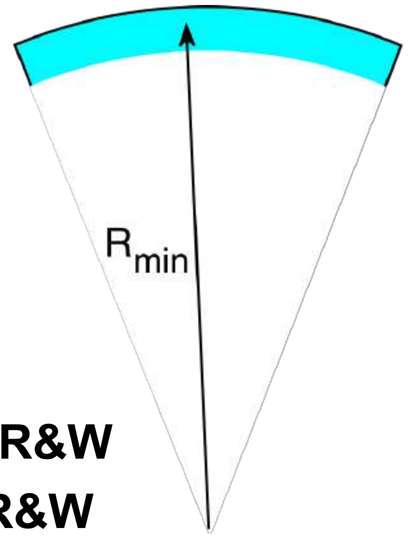
- As Nb_3Sn is very brittle, the strands cannot be bent/deformed after the heat treatment. **Cabling** must be done **before** the heat treatment.
- On the other hand, **Winding** can be done either *before* the heat treatment (Wind&React) or *after* the heat treatment (React&Wind), provided that the strain due to bending is kept low, say $\varepsilon_b < \pm 0.3\%$.



- For the feasibility of React&Wind, the key parameters are
  - *Conductor size in the radial direction, th_R*
  - *Maximum Bending Radius (usually ∞ at conductor straightening)*
  - *Minimum Bending Radius, R_{min} (e.g. in the final winding)*

  Assuming that the conductor is heat treated at $R_{ht} = 2R_{min}$,

  the largest bending strain is $\varepsilon_b = th_R / 2R_{ht} = th_R/4R_{min}$



Small solenoids: 1mm thick strand, 50 mm bore ➔ ε_b= 1% ➔ **no R&W**

ITER TF and CS: 40mm cable, ≈ 2 m Radius ➔ ε_b= 0.5% ➔ **no R&W**

10 mm flat cable for ITER: ➔ ε_b= 0.13% ➔ **R&W possible**

React & Wind vs. Wind & React

React & Wind	Wind & React
Conduit assembly after heat treatment -> lower thermal strain in operation -> less Nb_3Sn need -> **cost saving**	Straightforward conductor assembly, before heat treatment.
Conductor manufacture includes the heat treatment	Tough control of tolerance at winding, during the heat treatment, insulation and joint assembly.
No coil heat treatment -> much easier winding: loose tolerance on geometry, straightforward insulation and joint assembly -> **cost saving**	Higher thermal strain in operation (larger Nb_3Sn cross section).
More cross section for steel in the winding pack: high smeared modulus and lower stress	Less cross section for steel in the winding pack (also due to void fraction) -> lower smeared modulus, higher stress

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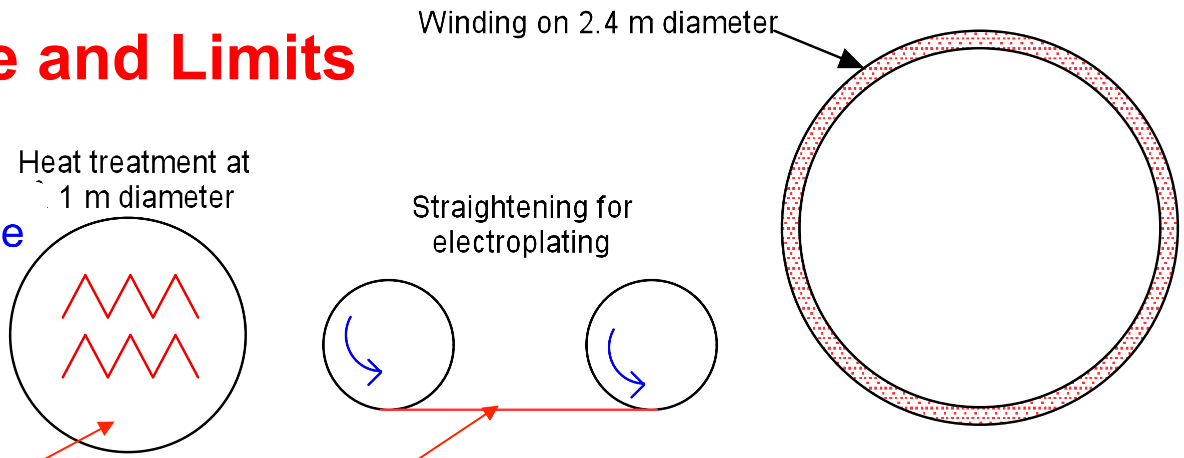
T-15: Performance and Limits

The coil method was R&W:

-Heat treat the 11-strand cable

-Unwind for electroplating

-Wind on final coil diameter



A voltage of 2.5 - 10 mV/coil was observed. The operation was restricted by the temperature rise due to the large power (up to 700 W) and limited heat removal capability by the cryo-plant.

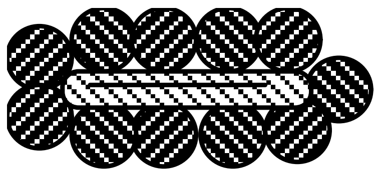
$R_{min} = 0.5$ m

$R_{max} = \infty$

$\varepsilon_b = th_R / 2R_{ht} = \pm 0.45\%$

The bending strain through the manufacturing process is up to ± 0.45%, i.e. itexceeds the irreversibility limit and causes performance degradation in terms of early voltage (low n index)

t = 4.5 mm



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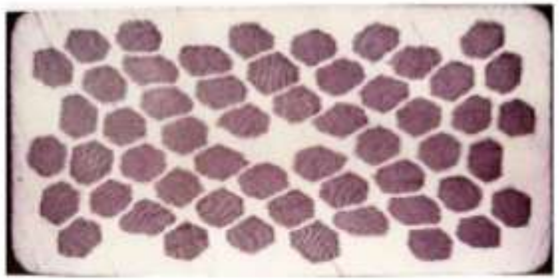
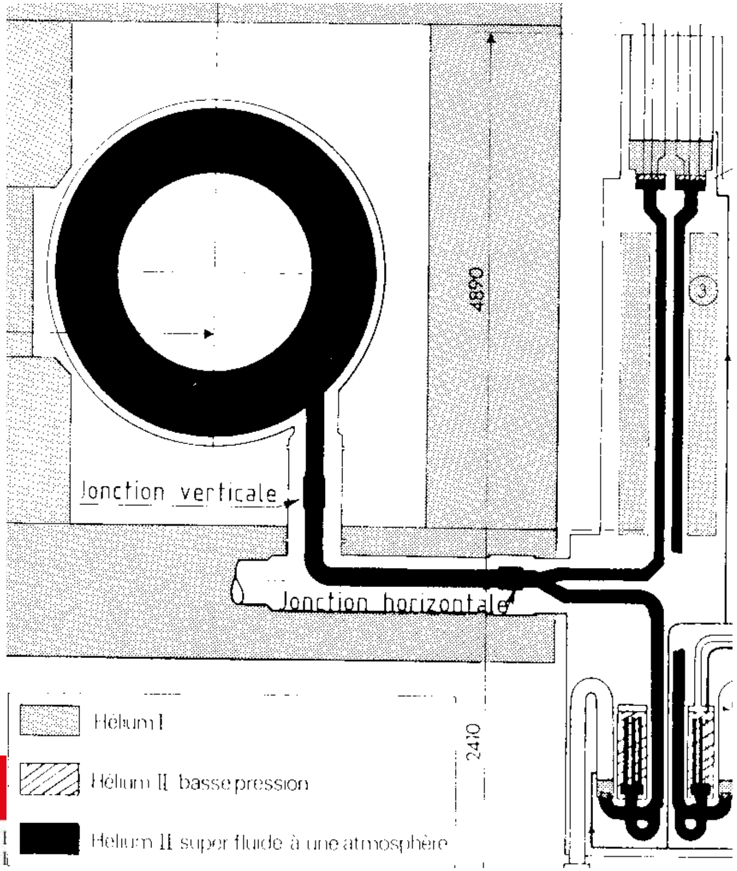
Tore Supra *Cadarache,* ***1987***

Conductor: 2.8x5.6mm NbTi mixed matrix composite

Cooling: atmospheric bath of super-fluid helium at 1.8 K (λ plate). Cryostat fed from the bottom.





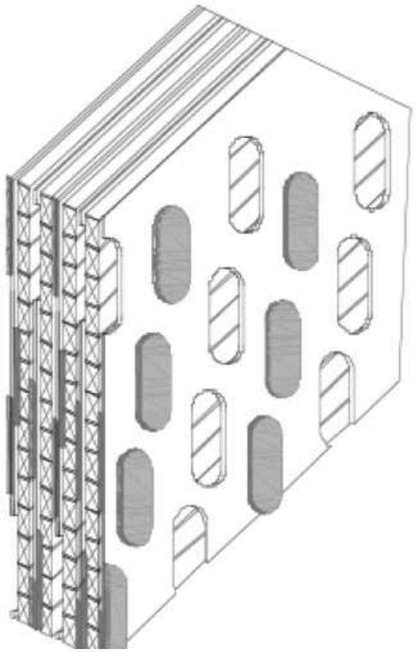
Quench Protection: Little copper is used in the cross section. In case of quench, the He pressure building at the top of the coil case expels all the liquid He through the bottom port: within 3 s the winding is dry and all the conductor is normal

Tore Supra: bath cooling insulation issue

The 18 circular toroidal coils are wound as double pancake. The conductor is fully supported and insulated by pre-preg tape in the radial direction. The coolant wets the conductor between pancakes, through a machined inter-pancake spacer.

The coolant is used as a dielectricum (pancake insulation 2mm). The nominal pancake voltage at a current dump was only 60V, i.e. below the Paschen minimum for Helium (160V).

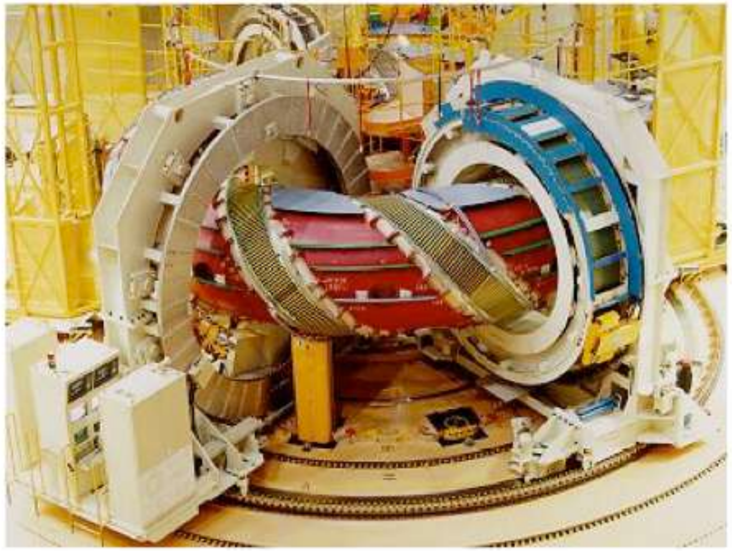
Nonetheless, a short occurred at a current dump and destroyed one coil, possibly due to some microscopic metallic chip, causing a high electric field peak



The design of Tore Supra was dominated by the initial decision for NbTi vs. Nb_3Sn, implying the

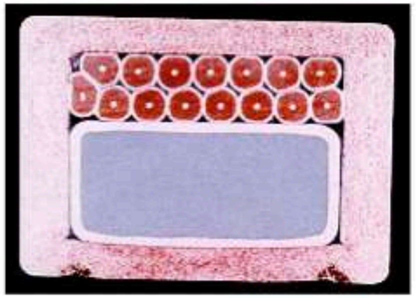
- most advanced cryogenic system to obtain 1.8 K
- improved I_c and stability due to superfluid helium
- high current density thank to low protection copper
- monolithic conductor with low ac loss

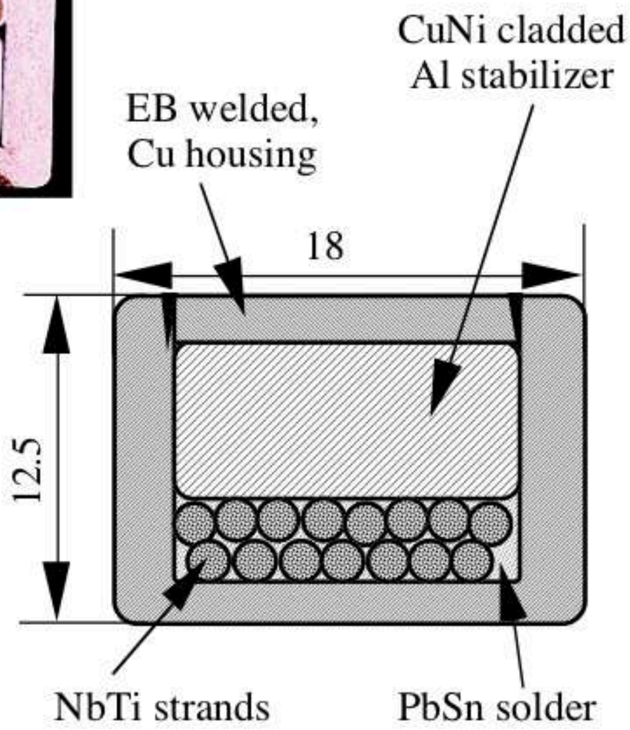
The design features are not scalable to higher energy devices. Only the "bad" lesson (pool cooling = short circuit) remains in the common memory



Helical Coils of LHD *NIFS, Toki, Japan*

Highly engineered conductor, **13 kA, 6.9 T**





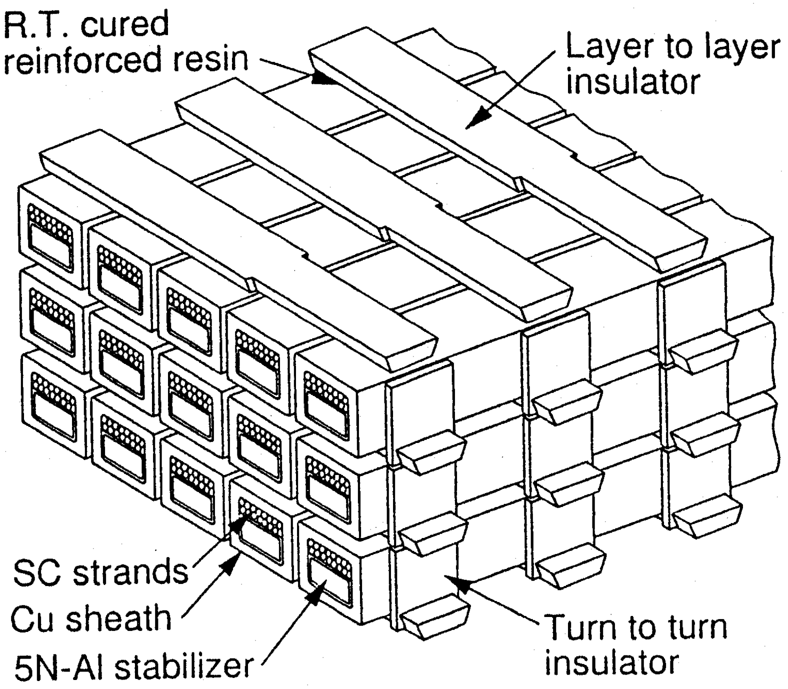
Cooling: helium bath @ 4.2K.

Supercondutor: flat cable of 15 NbTi strands, ø=1.74mm

Stabilizer: high RRR Al, sheathed by CuNi

Assembly: cable and stabilizer are solder filled into a Cu housing, sealed by two longitudinal EB welds

The design is driven by cryo-stability. The copper surface is treated (CuO) to improve the heat exchange to helium.



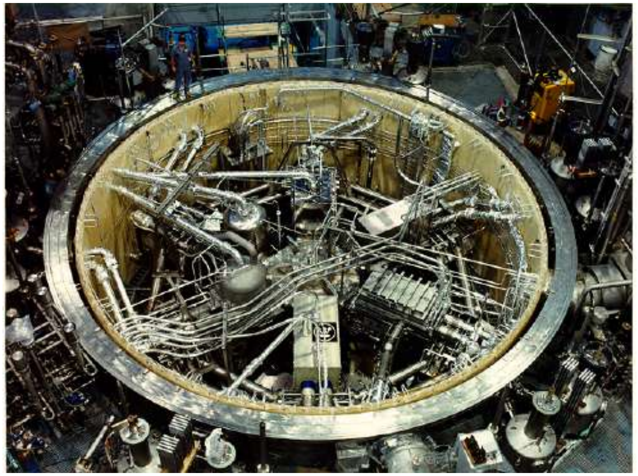
Helical Coil Winding

The design is a compromise between a solid support of the winding pack against the electromagnetic loads and the large wet surface for cryo-stability. The turn and layer insulation are obtained by spacers (2 and 3.5 mm), with coverage graded from 69 % (low field, high stress) to 42% (peak field, low stress).

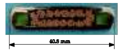
The expected cryo-stability was actually not achieved. The operating current had to be limited to 11.3 kA due to observed propagating normal zone.

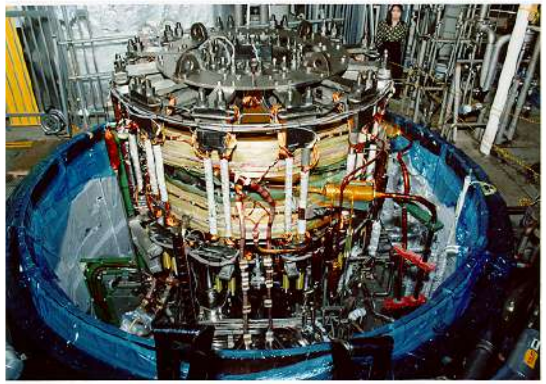
The lessons from Tore Supra (unreliable use of helium as dielectricum) and LHD (inadequate mechanical stiffness of a helium transparent winding) led to a serious prejudice against pool-cooled conductors for high energy windings, with high voltage at current dump (to extract as much as possible energy from the winding) and very high electromagnetic loads. On the other hand, the success of other pool-cooled systems should not be forgotten, as in the MTFT coils, TRIAM, Tespe and three out of six LCT coils.

Other Large Development Magnets in last Century



- Large Coil Task, Oak Ridge, 1981





- The DPC coils, Naka, 1988

- Polo, Karlsruhe, 1990

Technical Summary from last Century Devices

- Force flow cooling wins over bath cooling
  - *Mechanical stability, high quality insulation*
- From the very large composite to the cabled conductors
  - *Technical confidence, stability, ac loss, cost*
- In Nb_3Sn, react&wind is more frequent than wind&react
  - *Risk perception of the designer, furnace size, insulation issue*

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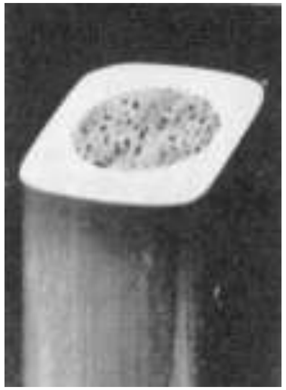
Fusion Devices in 21st Century

Completed: **EAST, KSTAR, SST-1, W7-X, JT60SA**

Under Construction: ***ITER, CFETR, BEST, SPARC***



Only Cable-in-conduit Conductors (except SPARC TF)

Only supercritical, force flow cooling

For Nb_3Sn, only wind-react-transfer method

Pancake windings dominate over graded, layer windings

Forced Flow vs. He Bath

The bath cooled conductors offer

*superior **stability** (cryostability option) and well defined **operating temperature***
***easy joining** technique (conductor grading possible even in pancake windings)*
easier conductor manufacture (no need of vacuum tightness)

The forced flow conductors offer

*superior **insulation**, allowing **high voltage** operation for pulse and dump*
*potted, stiff, monolithic winding pack, to withstand **high mechanical loads***
structural reinforcement easily added to the conductor cross section

High stored energy ⇒ forced flow option

Monolithic vs. Cable-in-conduit

At large current (> 30kA) the size of a soldered conductor was judged to be inadequate for heat removal and ac loss

The pressure drop issue for the cable-in-conduit conductor becomes less severe at very large conductor size and can be overcome by a pressure release channel

The low engineering current density, intrinsic for CICC design, is not a major problem for fusion conductor

For Nb_3Sn Round CICC, the W&R method is mandatory

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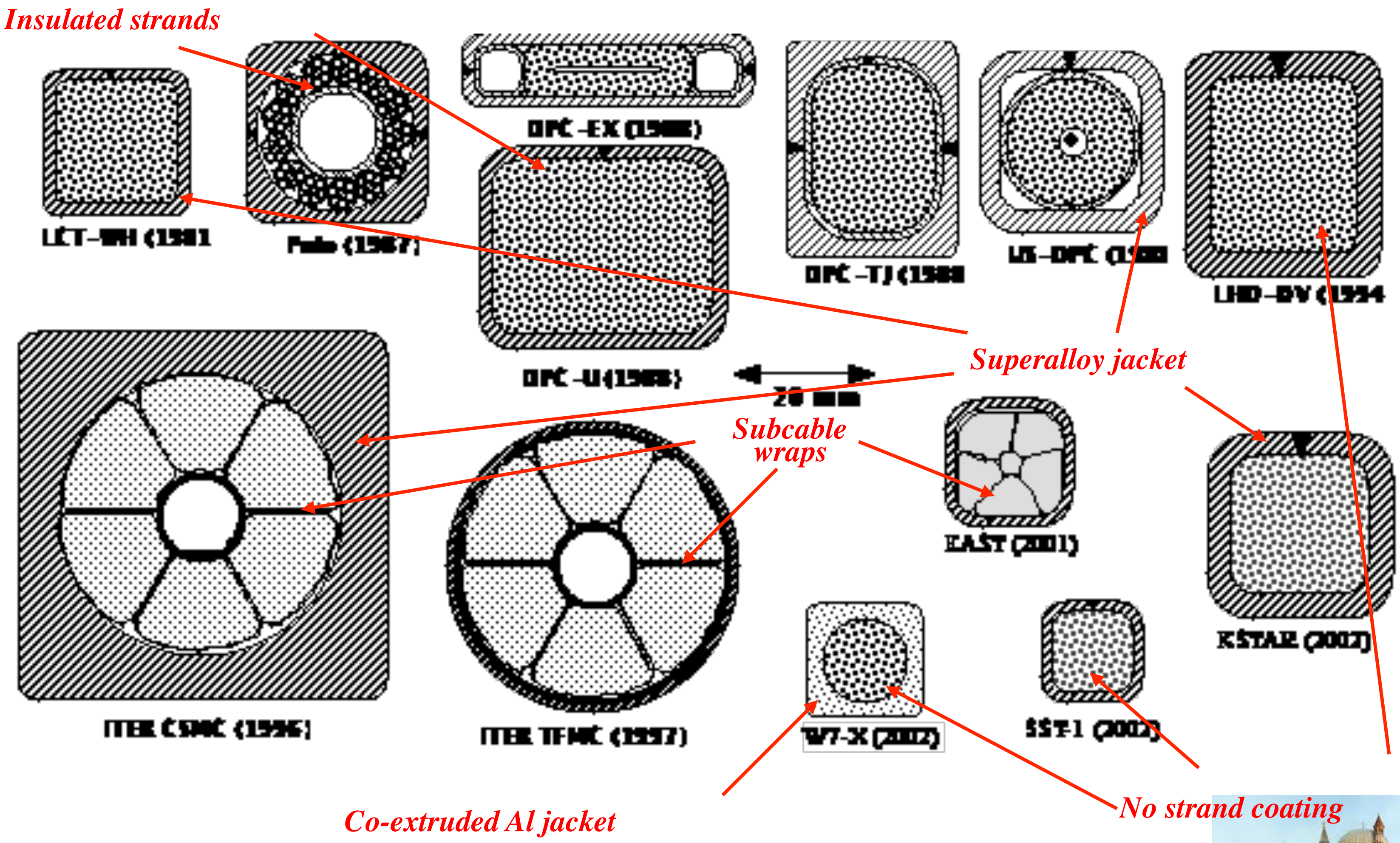
A Chart of most CICC's for Fusion



Insulated strands for CICC's ?

Aiming to 0 inter-strand coupling loss, Polo and DPC-U were made of insulated strands. Both CICC's achieved high pulsed current, but the DC properties were lower than predicted.

In Polo cable, the transposition of the current carrying elements is precisely controlled and the subcables are joined individually. Minor variations of the subcable joint resistance led likely to an overload of sub-cable current. Due to the inability to share current among subcables, the DC performance of the CICC was eventually ≈ 70% of the strands.

In the DPC-U, the current unbalance among the 486 varnish-coated strands was more severe, practically preventing DC operation.

Current unbalance is unavoidable in CICC due to both transposition errors in the strand bundle and non-homogeneous contact resistance of the strands at the splices. As long as the current can locally re-distribute among strands within the stability limits, current unbalance does not lead to performance degradation.

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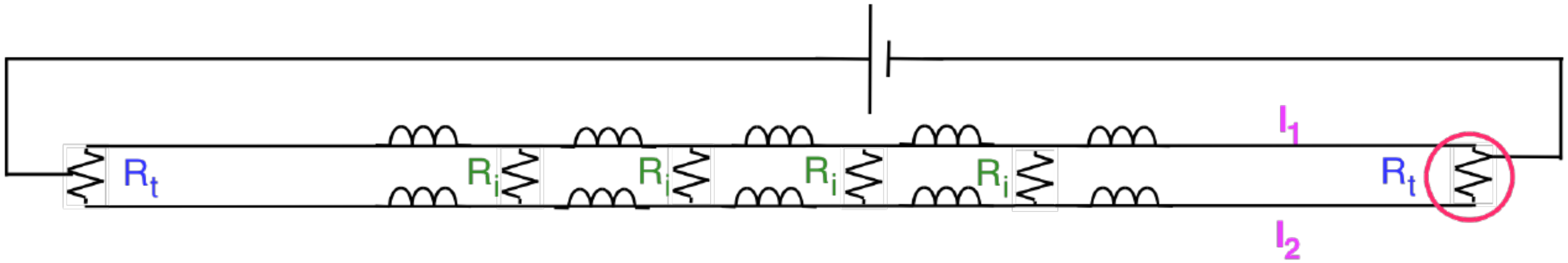
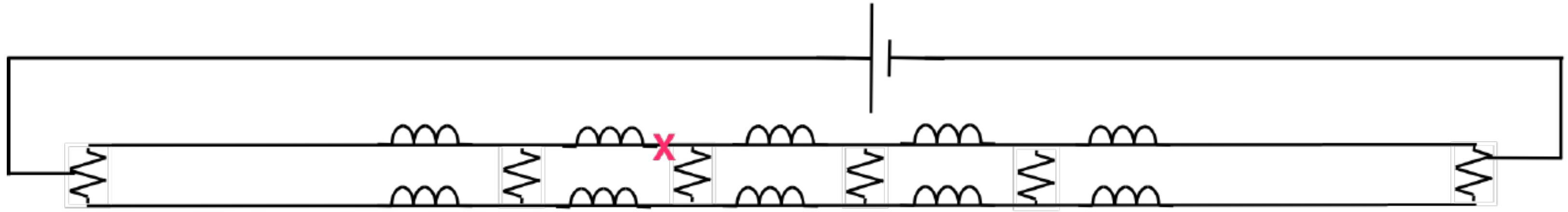
Current unbalance and Current re-distribution



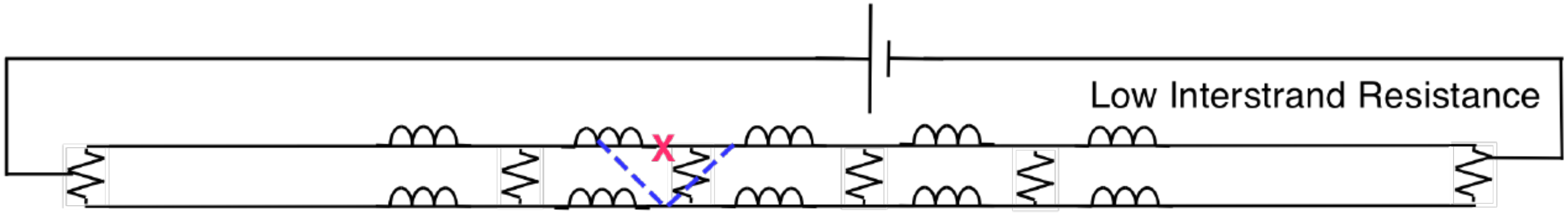
Unbalanced R_t -> Unbalanced DC Current, $I_1 > I_2$

Current unbalance and Current re-distribution



Unbalanced R_t -> Unbalanced DC Current, $I_1 > I_2$ -> Overloaded strand -> Quench in overloaded strand -> Voltage build up in overloaded strand

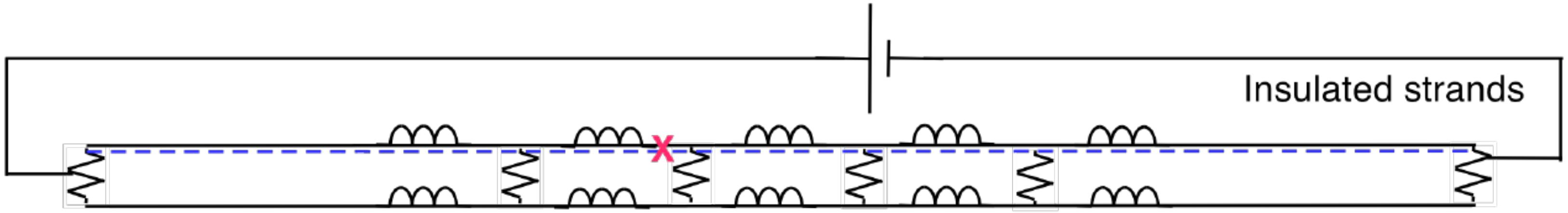
Current unbalance and Current re-distribution



Unbalanced R_t -> Unbalanced DC Current, $I_1 > I_2$ -> Overloaded strand -> Quench in overloaded strand -> Voltage build up in overloaded strand

For small R_i, very small voltage drives the local current re-distribution in the other strand -> the quench does not expand, the current is re-distributed and the quench recovers.

Current unbalance and Current re-distribution



Unbalanced R_t -> Unbalanced DC Current, $I_1 > I_2$ -> Overloaded strand -> Quench in overloaded strand -> Voltage build up in overloaded strand

For insulated strand, the current re-distribution occurs at the termination.
A larger voltage, i.e. a quench propagation, is necessary to drive LdI/dt.
A thermal runaway occurs at the quench location before the current re-distribution at the termination is effective to reduce the generated power.

Superconducting Magnets - 3

Pierluigi Bruzzone

EPFL-Swiss Plasma Center, Villigen, Switzerland

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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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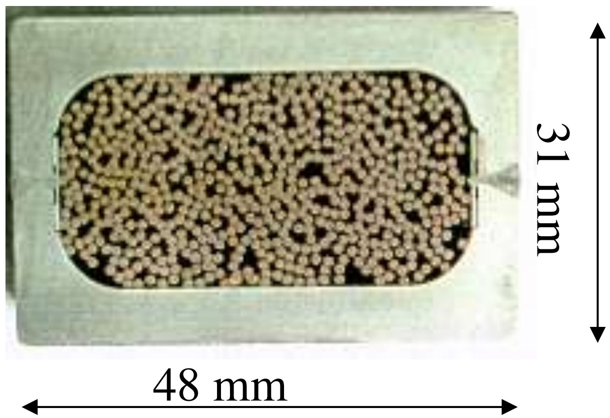
History of the ITER Conductor
The NET-ABB flat conductors

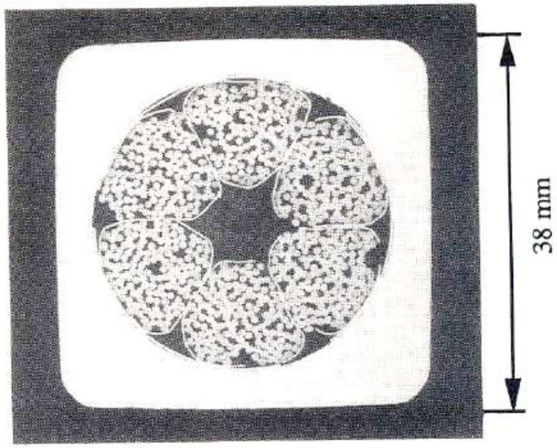
- The precursors of the present ITER conductors are the NET conductors, the first large Nb_3Sn cable-in-conduit developed in Europe in 1988-1990
- The design was based on
  - *A rectangular steel jacket either extruded or longitudinal welded.*
  - *The cable is a strand bundle with large void fraction, 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

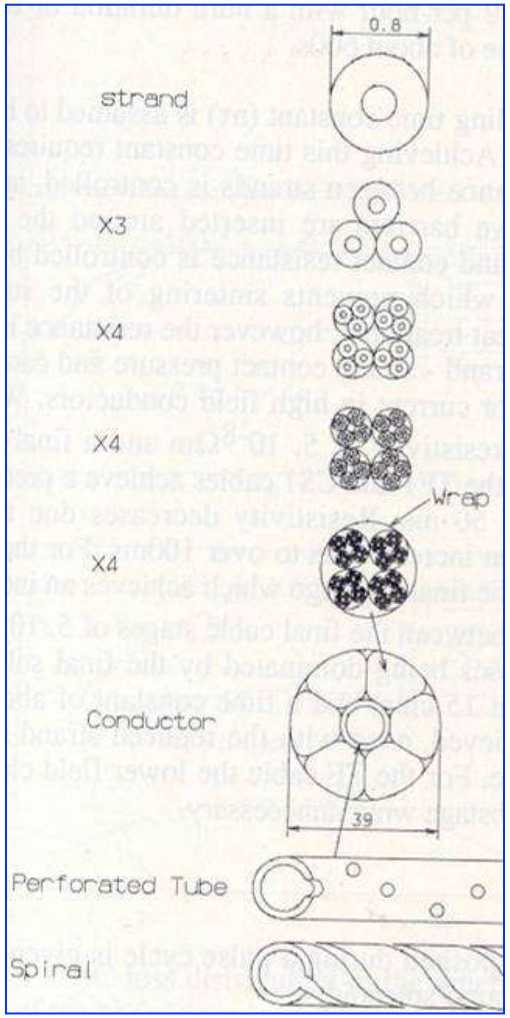
  Back to steel jacket

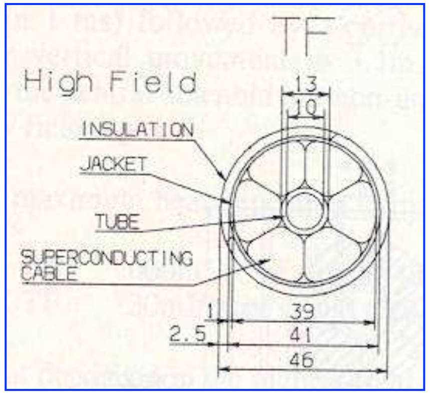
  Segregated copper for quench protection

  More superconductor to offset the degradation

  Higher J_c for strand

  Reduced void fraction





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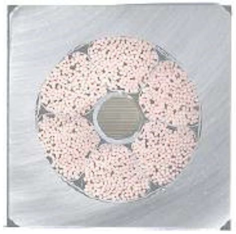
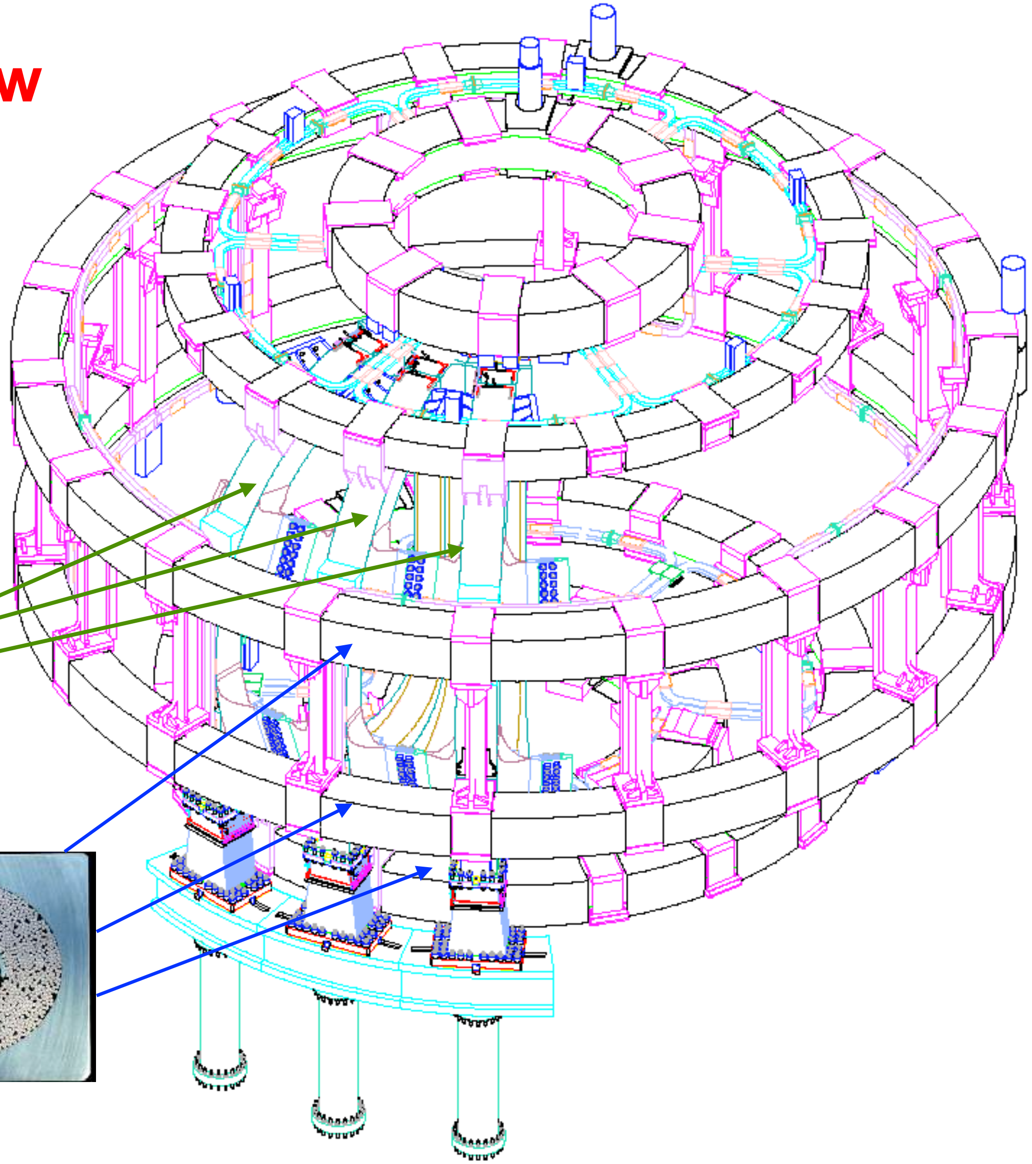
ITER conductors now

CS Conductor,
Nb_3Sn



TF Conductor,
Nb_3Sn

PF Conductor,
NbTi



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

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Specification / Procurement Strategy

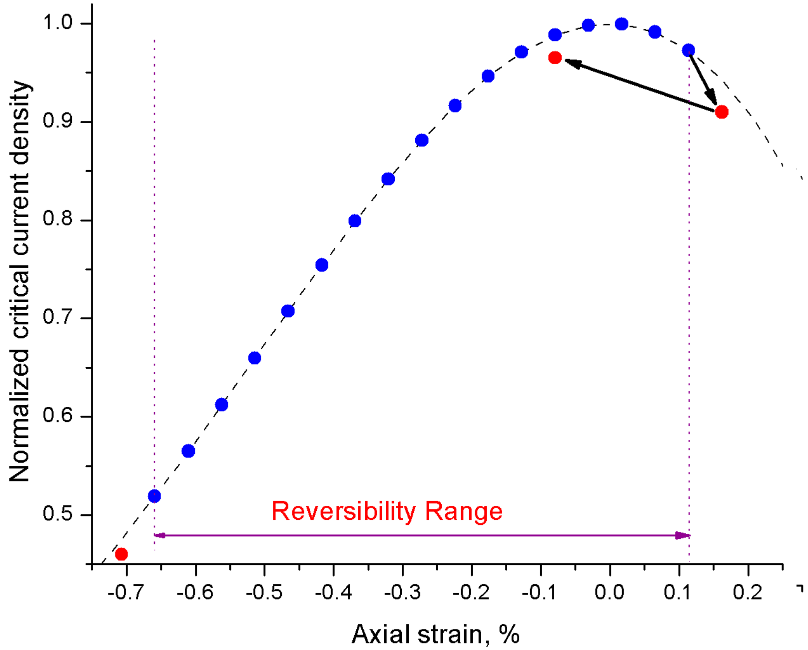
- The ITER TF conductors are procured to the same specification in six out of the seven ITER parties (EU, RF, JA, US, KO, PRC). The procurement is completed in Summer 2016.

- 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

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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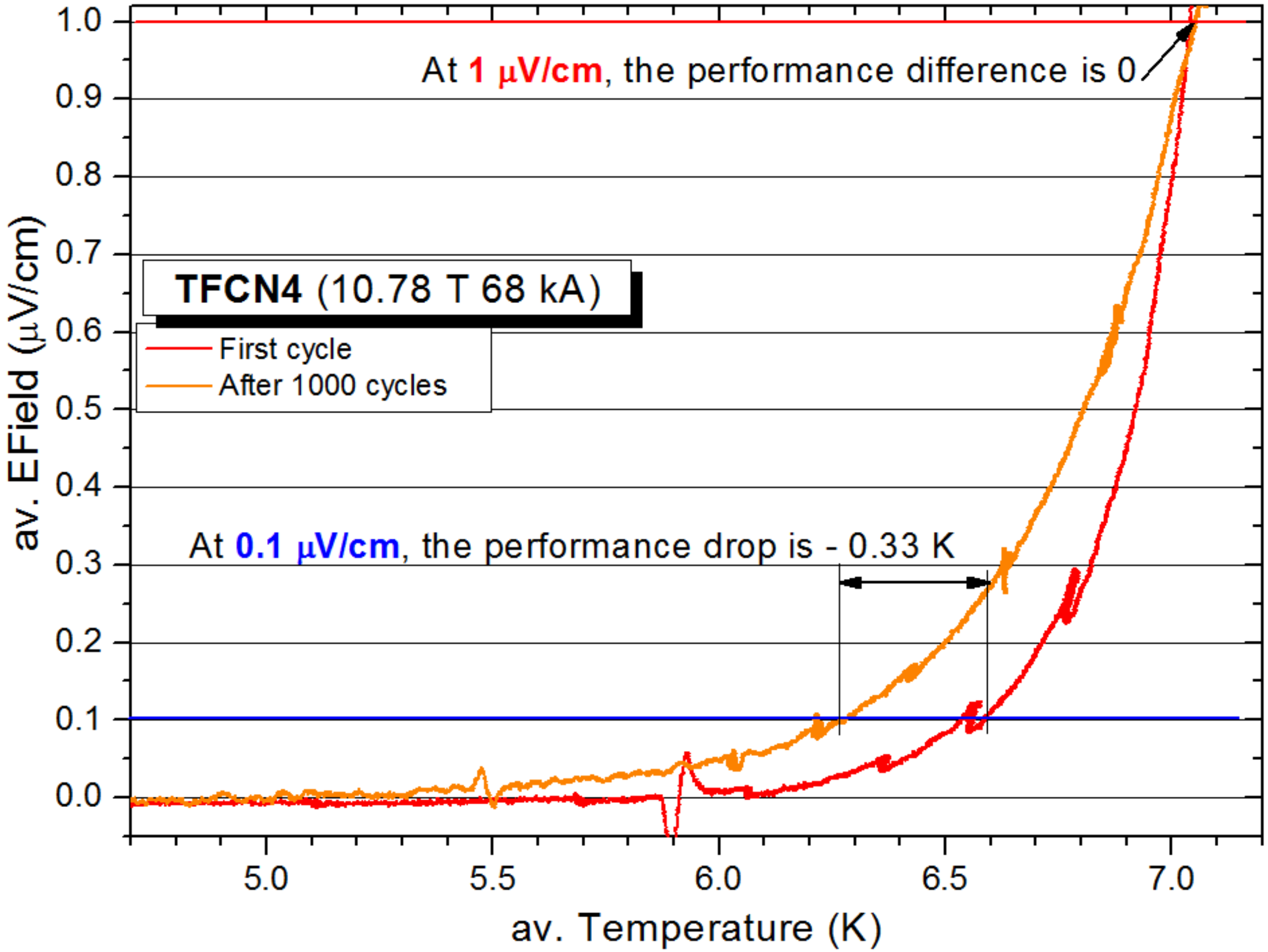
The electric field criterion for performance assessment matters…



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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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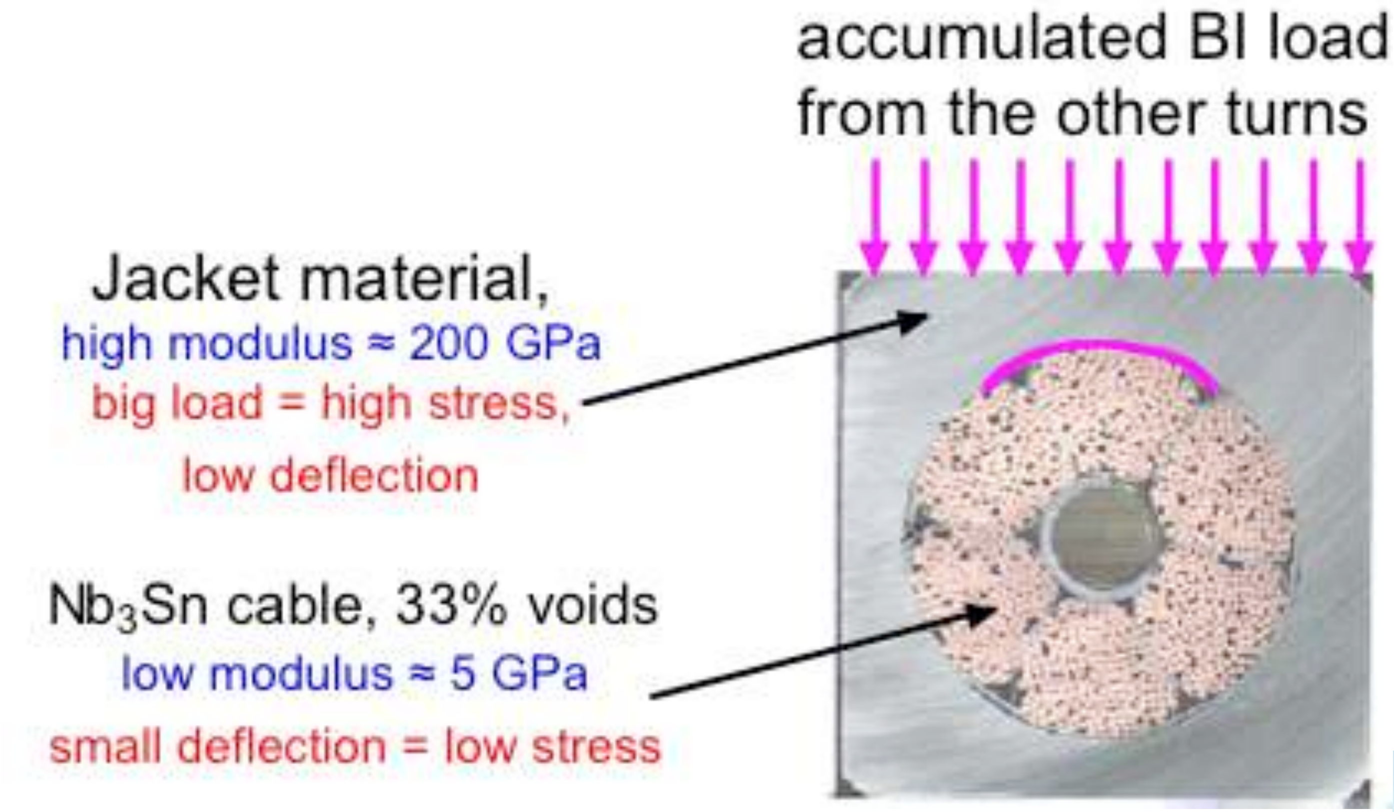
Nb_3Sn CICC and transverse load - load accumulation

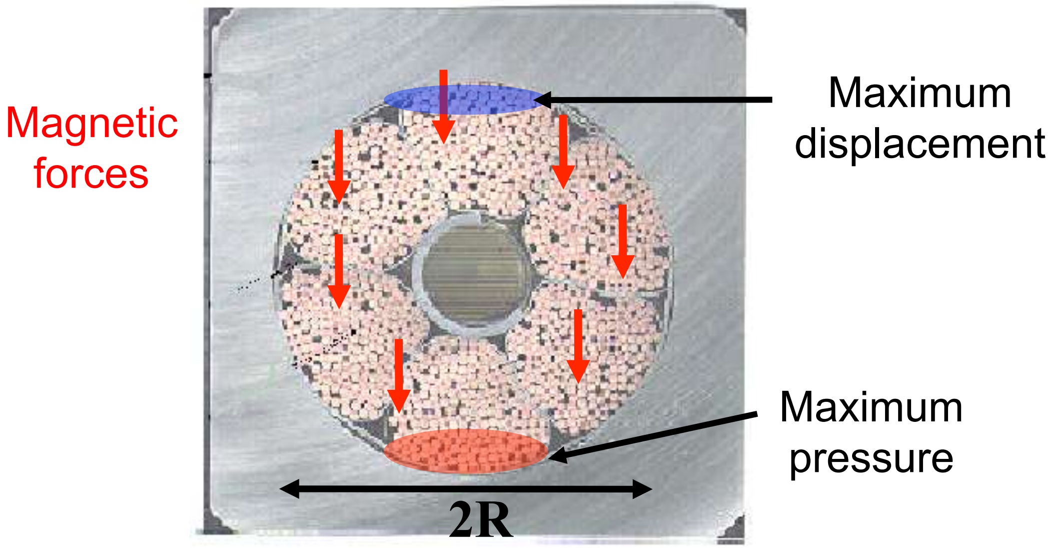
The transverse stress in the cable due to the load accumulation in the winding is negligibly low. The (thick) jacket of a CICC protects the Nb_3Sn cable from “**outer**” loads



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 ***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*



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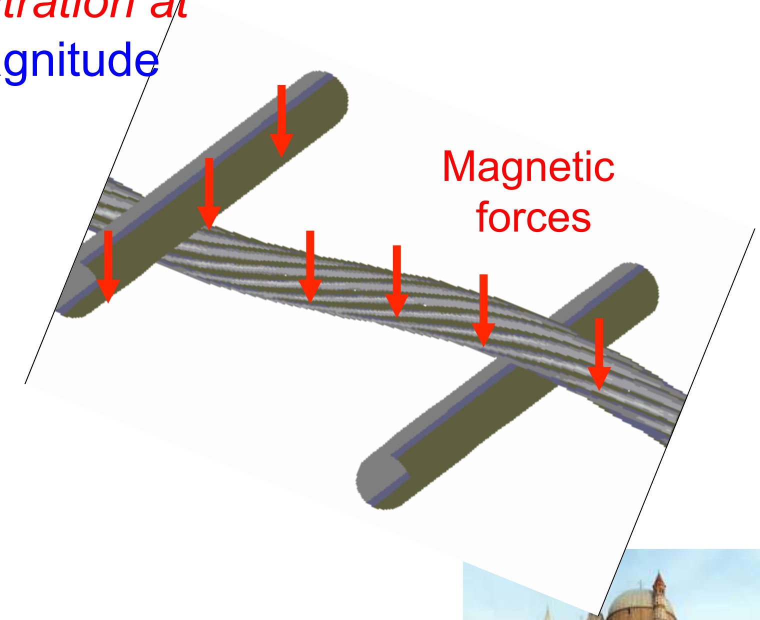
Nb_3Sn CICC and internal load - inside the cable

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

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

↓ Axial tension +Bending

↘ Transverse load on cable

↓ Compression at strand crossover +Bending

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

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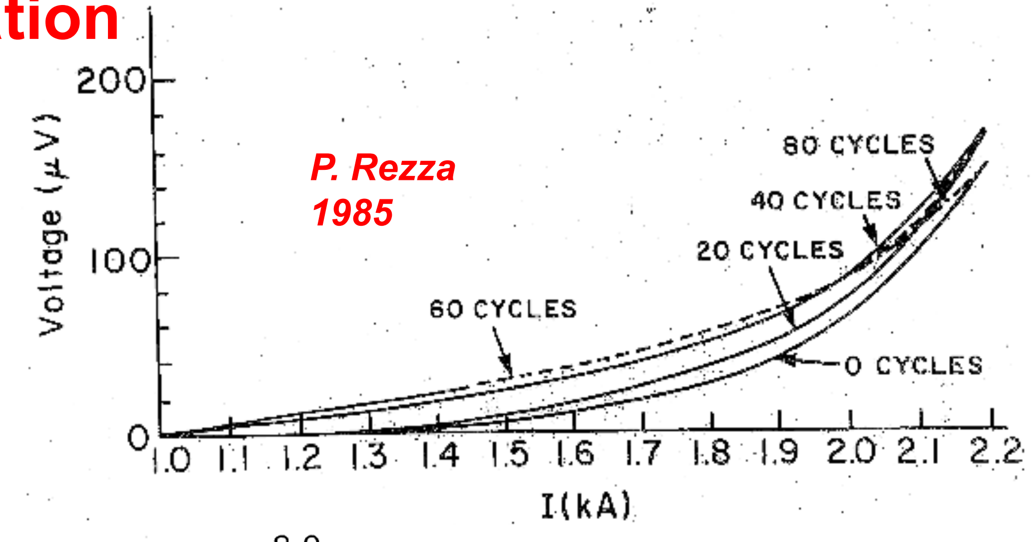
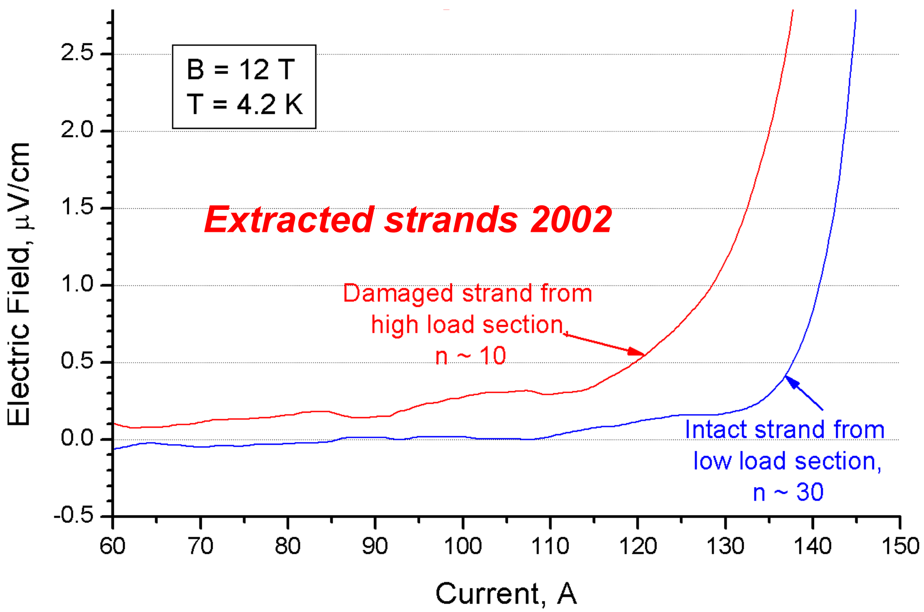
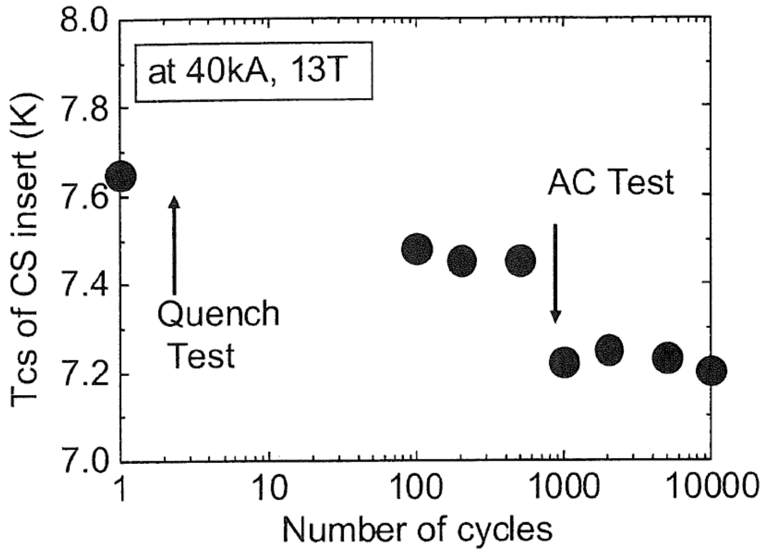
Evidences of degradation

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







N. Mitchell, 2002

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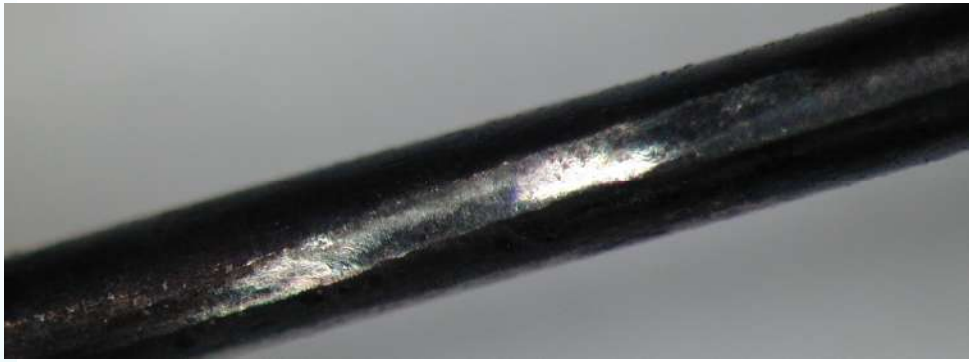
Experimental evidence - the extracted strands

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

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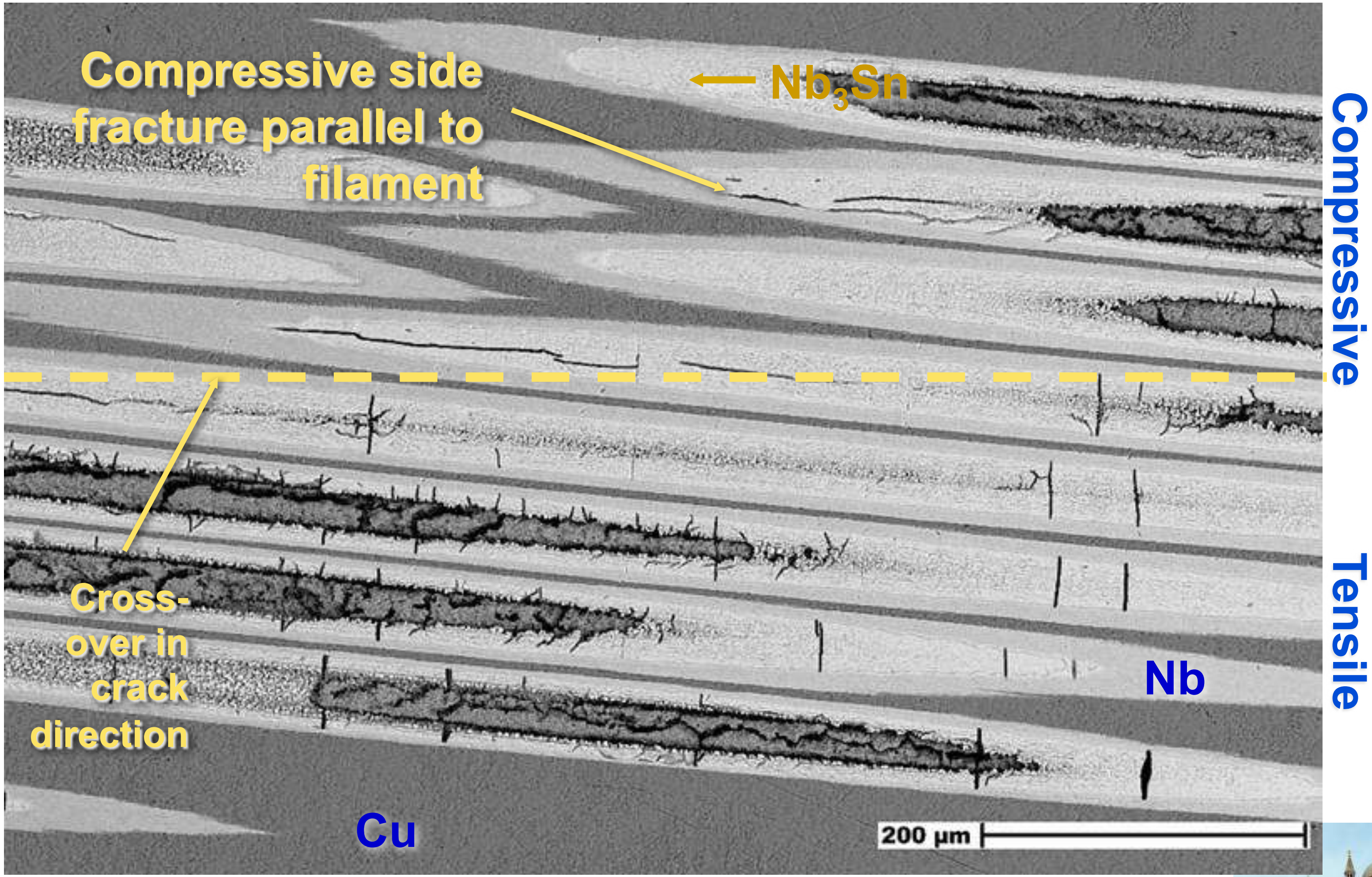
Metallographic examinations (US)

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



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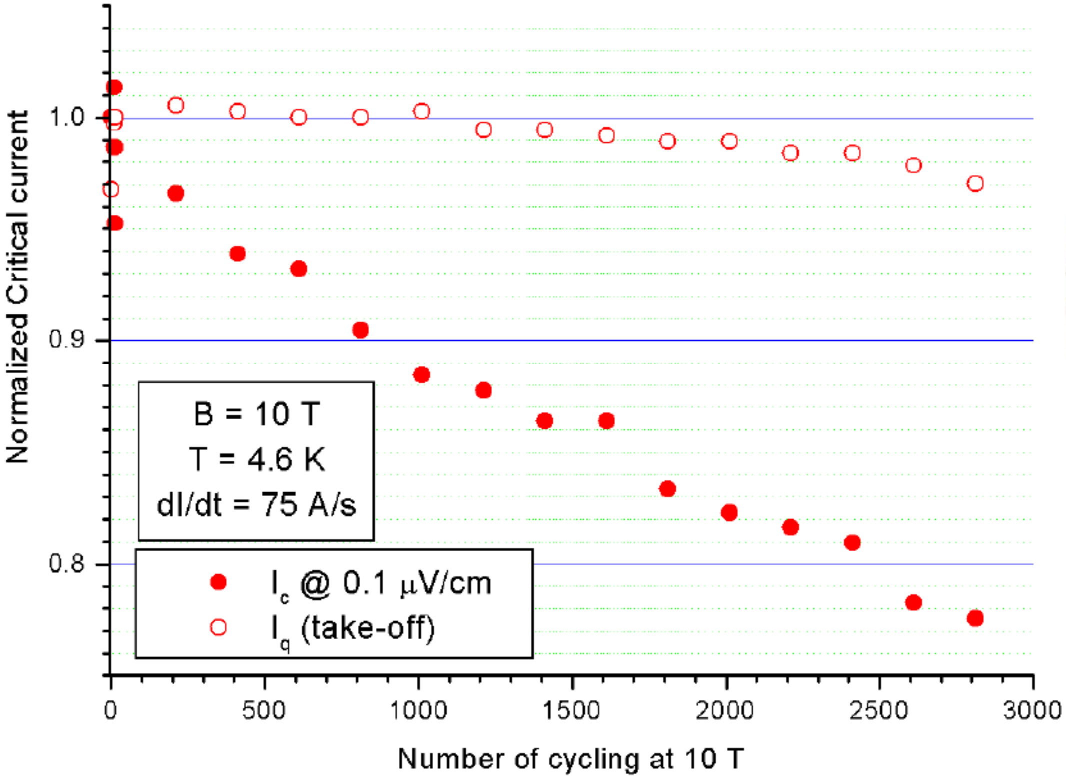
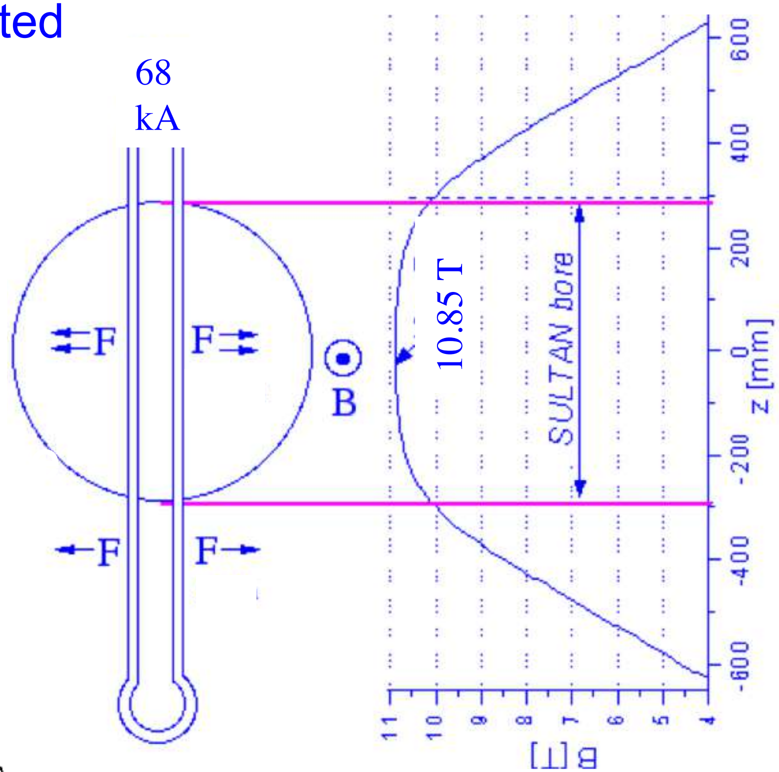
Degradation - cyclic load

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

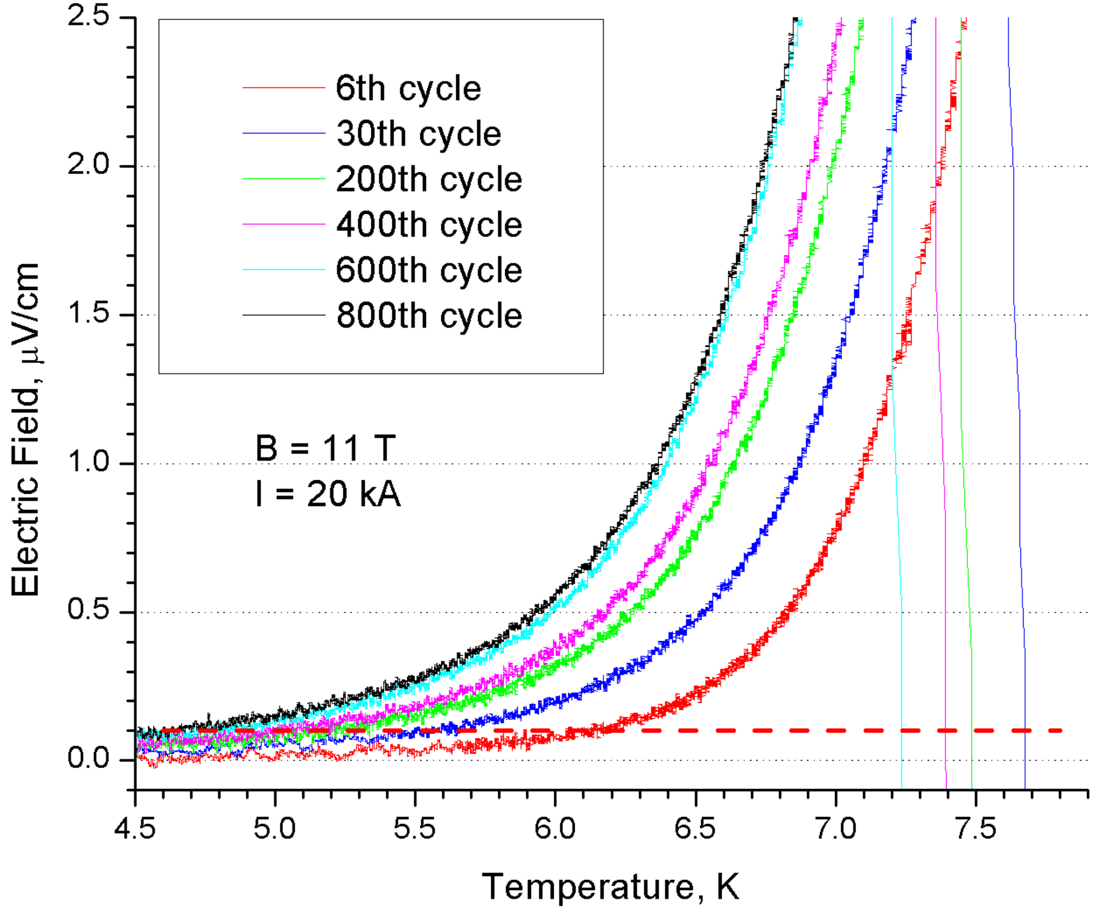
The take-off point (either I_q or T_q) is little affected





n Index - cyclic load

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



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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

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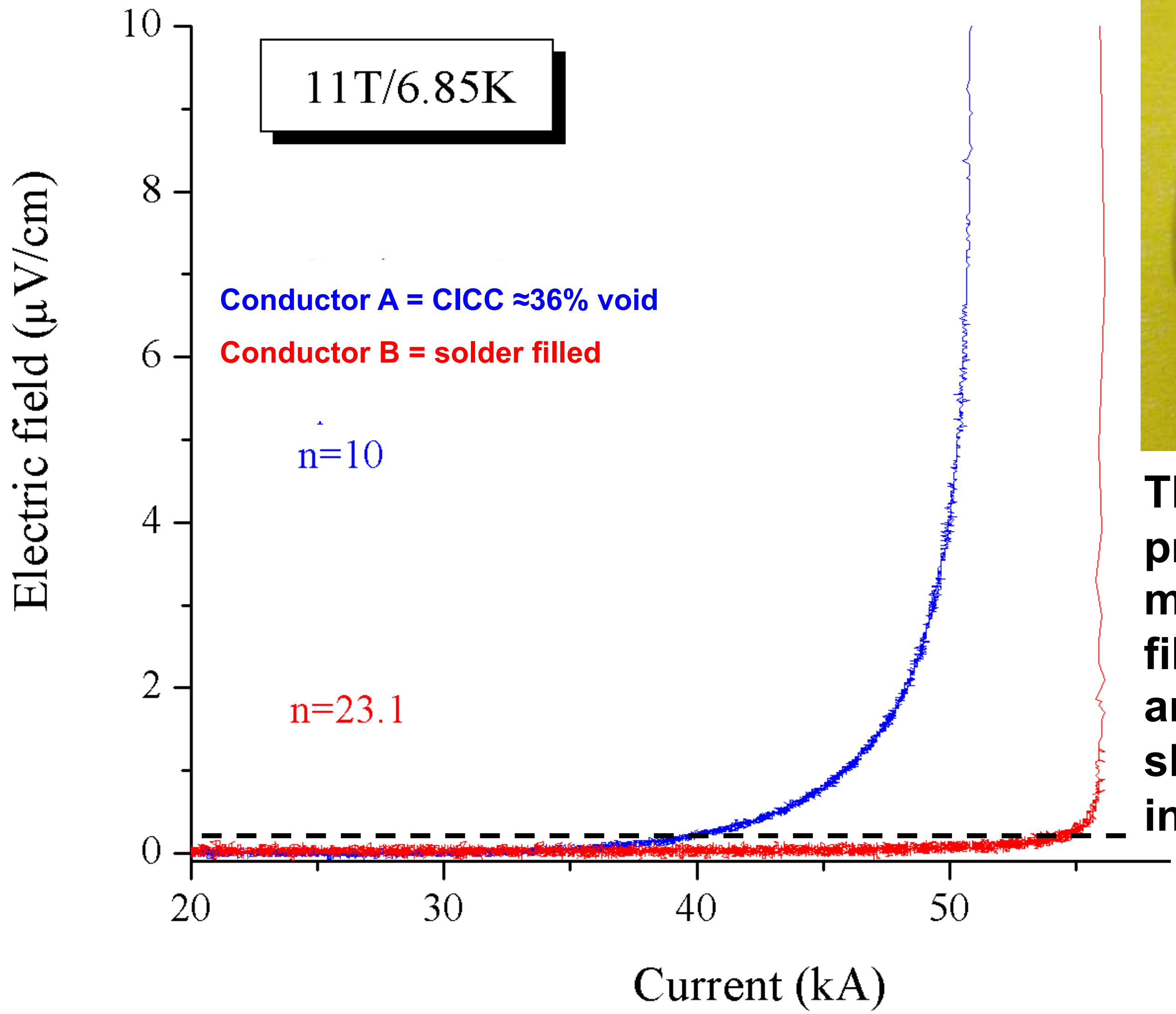
A Crucial Comparison



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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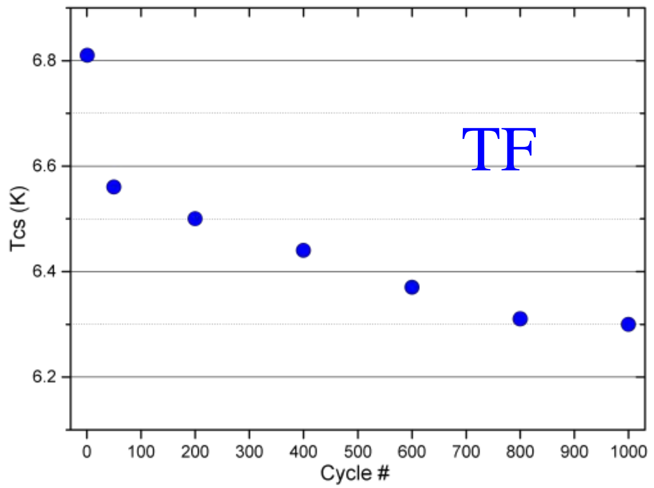
Results of the ITER Nb_3Sn Conductors

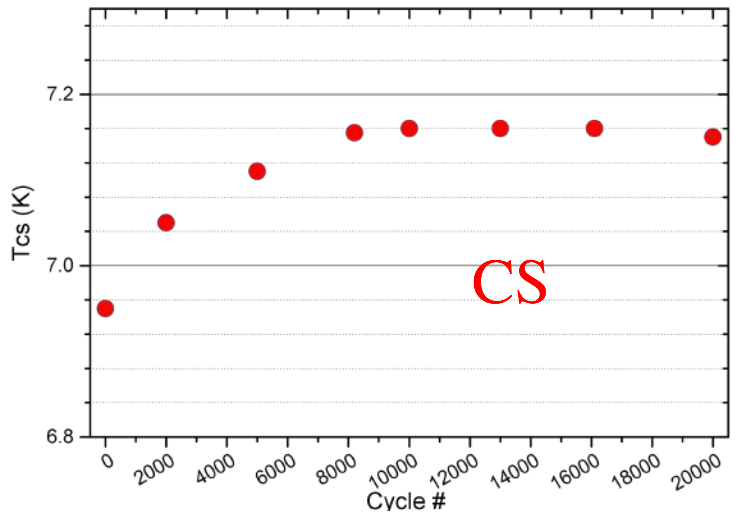
Two features affect the performance evolution for Nb_3Sn based CICC:

☺ 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}.

EPFL
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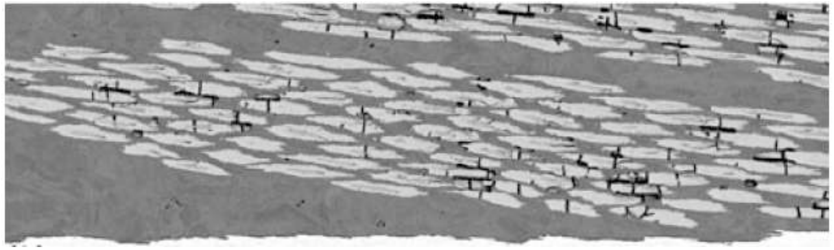
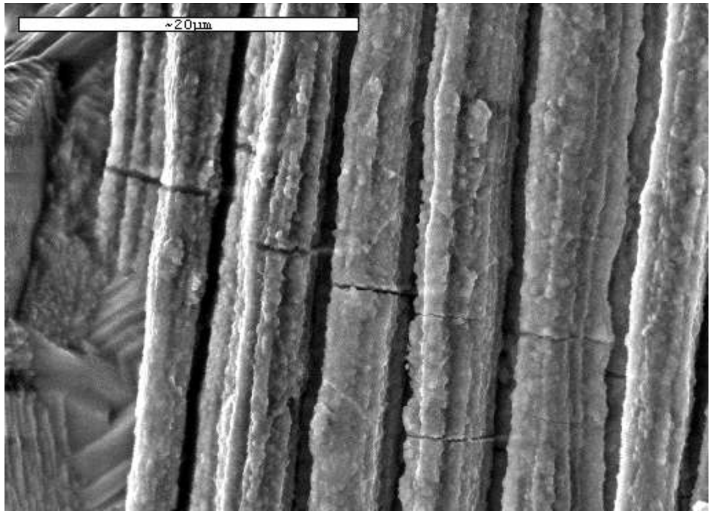
Summary on Performance of ITER Nb_3Sn CICC

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

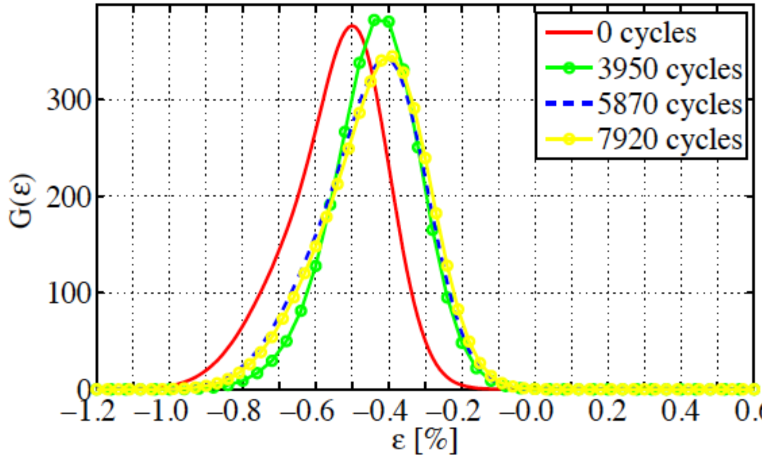


↑ *Cracks at bending, Jewell 2003*

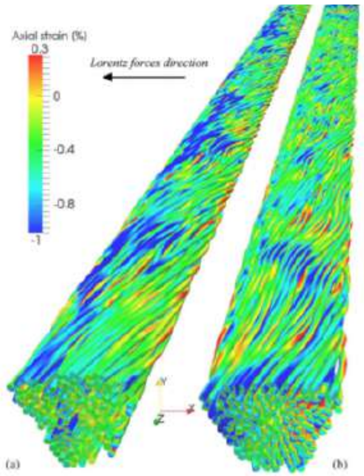
↓ *Bochvar 2002*



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.

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Superconducting Magnets - 4

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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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Fusion today in Europe and beyond

- According to the roadmap 2014, *“DEMO” is the step between ITER and the commercial power plant*. The design of DEMO is finalized after crucial knowledge is gained from early operation of ITER.
- The *sliding delay of ITER* plasma forces the EUROfusion DEMO in a never ending phase of Pre-Conceptual Studies and technology R&D.
- In China, two large Tokamaks, *CFETR and BEST* are in advanced manufacturing. Korea is also willing to launch a DEMO Tokamak, without waiting for ITER results.
- In US, the Commonwealth Fusion Science (CFS, a spin-off of MIT) launched 10 years ago the *SPARC – a smaller size, very high field Tokamak* to demonstrate the HTS technology for Fusion.
- The European roadmap to Fusion needs an update…

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Trends for Fusion Magnets

Despite the variety of design, materials, shape and performance, some clear trends can be identified in the fusion magnets:

- Forced flow cooling – Bonded (potted) coils
- Large stored energy, e.g. 10GJ in one DEMO TF 2018 $$E = L\frac{I_{op}^2}{2}$$
- For TF magnets, long dump time constant, τ = 35 s in TF DEMO 2018, must be used to limit the electromagnetic loads on the vacuum vessel

$$V_d = L\frac{I_{op}}{\tau}$$

- The dump voltage and operating current are linked by the stored energy and dump time constant

$$V_d \cdot I_{op} = \frac{2E}{\tau} \approx 570\,kW$$

-> e.g. for V_d= 10 kV, I_{op}= 57 kA

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High Voltage Operation

In W7-X, JT60 and ITER failures are detected for the ground insulation during the acceptance test. In 2021, two major accidents occurred in JT60 PF coil and ITER CS#3.

The pressure on the designers increases for magnets operating at low voltage, <5 kV maximum terminal voltage.

For the steady state TF coils, the highest voltage occurs at the safety discharge. For CS and PF, the highest voltage is at plasma breakdown and plasma control actions.

Low Voltage DEMO Coils

The key parameter to reduce the operating voltage is the self-inductance, ***L***, which is proportional to the square of the number of turns, N_t^2. For a magnet with a given Ampère Turns ($N_t \cdot I_{op}$), the number of turns can be reduced by increasing the operating current.

In EUROfusion DEMO, in TF, CS and PF coils, the terminal voltage can be reduced well below 5kV increasing the operating current to the range of 100-105 kA.

A R&D is started to develop superconducting cables with high operating current. China also goes for 100 kA conductors for BEST. The major challenges are self-field instability (NbTi), internal electro-magnetic loads (Nb_3Sn and HTS), current distribution, AC loss…

Tokamaks: pulsed or steady state?

With the exception of the spherical DEMO Tokamak (US Princeton), all other Tokamaks are pulsed, with burn time of the range of few hours. A critical parameter for the design of a pulsed tokamak power plant is the number of operating plasma burn cycles. For a lifetime of 40 years the **number of cycles** is in the range of 1-2 10^5. Is it a problem?

YES, a big one.

- Applying fatigue-crack growth criteria to *the conduit of the CS* (hoop load), the allowable stress drastically decreases. The steel cross section increases by a factor of 2-3 and the available flux decreases…
- The *vacuum vessel and in-vessel components* are exposed to a prohibitive number of thermal cycles.

In the long term, the tokamaks must become quasi steady state devices. However, the DEMO of next generation are still pulsed tokamaks, with an intrinsic conflict of requirement between DEMO and Power Plant.

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Alternative conductor designs

In standard CICCs, the jacket provides:

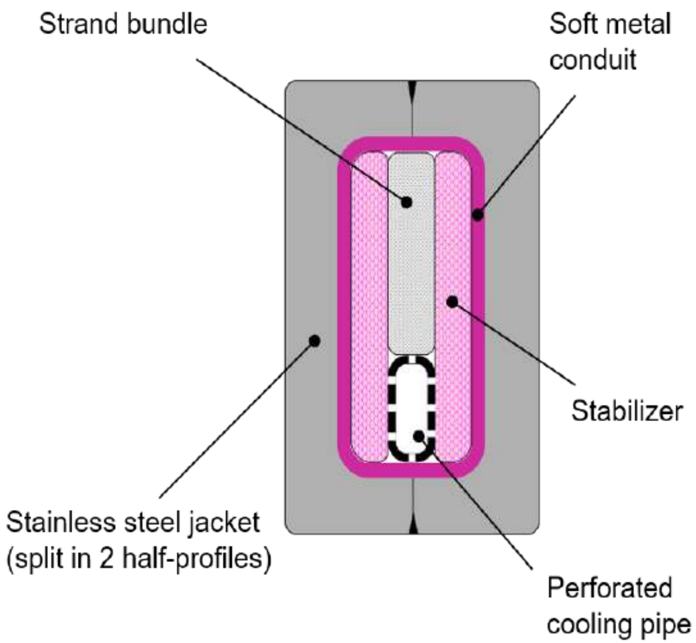
__Structural support__ for the operating loads

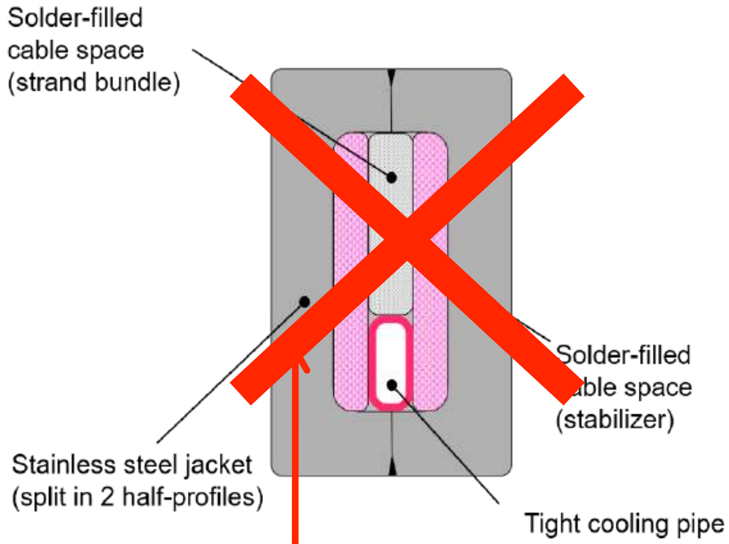
__Helium containment__ function (which imposes stringent constraints in the mechanical design, since no local crack can be tolerated through the jacket wall thickness).

Decoupling the two main functions of a CICC jacket can be very attractive.

If the presence of a local crack is acceptable from the structural point of view, the **required** jacket **cross section** might be **closer to** the **static** load case.

Two alternatives are considered:





Prohibitive AC loss
Poor transient stability

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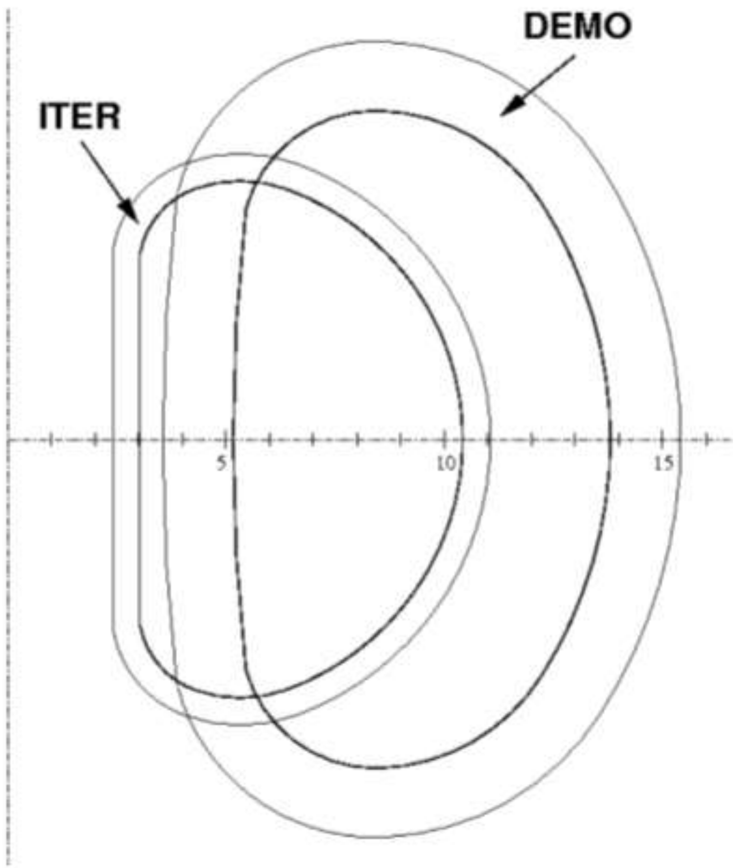
DEMO vs. ITER: the giant and the ant



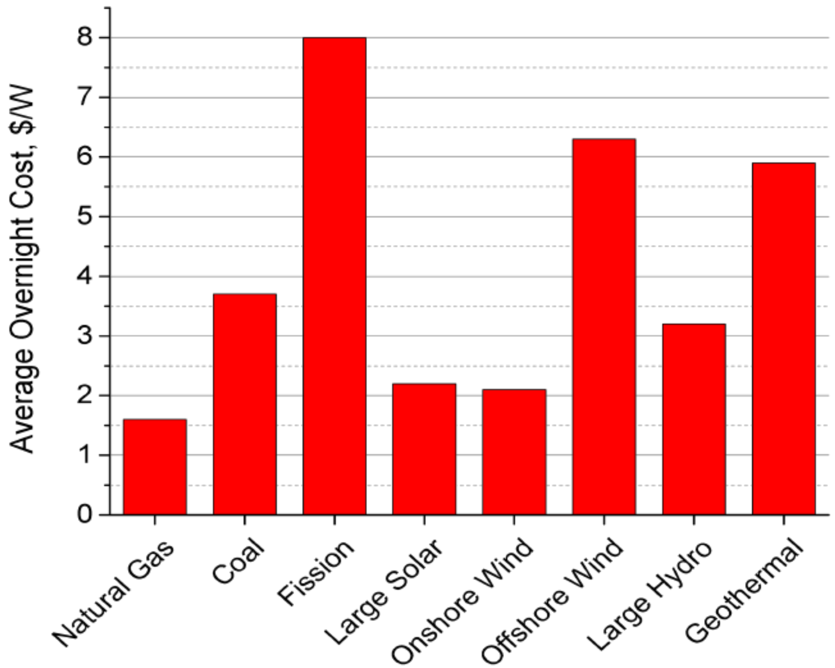
	ITER	DEMO 2018
Number of TF coils	18	16
Peak Field on TF coils	11.8 T	12 T
Current in one TF coil	9.1MA	14.9 MA
Stored Energy/TF coil	2.28 GJ	10.0 GJ
Dump time constant	11 s	35 s
TF case thickness	286 mm	520 mm
One TF coil assembly	340 t	>1000 t

The increase of the major radius from **6m to 9m** is a challenge in terms of engineering, logistics and price. The ITER technology experience will be of little help for DEMO.

A crude Estimate

- Take a 1.2 GW fusion power plant with Q = 20 and burn/dwell time = 2
- The averaged electric power is, say, (1200•0.4)·2/3 = 320 MW.
- For heating, the power recirculation is 110 MW and for cryogenics 30 MW
- Disregarding shut down for maintenance, we sell 320 – 110 – 30 = 180 MW.
- At an energy price of 6-8 ¢/kWh, we earn 110 M/year before taxes.
- The operation cost (maintenance, consumable, salaries) makes > 30 M/year.
- In a very optimistic view, ***80 M/year*** are left to mortgage the investment.
- To keep the mortgaging period within 30 years, the construction cost must be 2.4 B

A capital investment of 2.4 B for 180 MW gives an **overnight cost** of 13.3, even higher than a nuclear power plant.



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Pro and Cons for HTS in Fusion

A new technology/material can successful establish if:

- The newcomer is cheaper than the old one for the same performance
- The new technology enables a new/broader range of applications

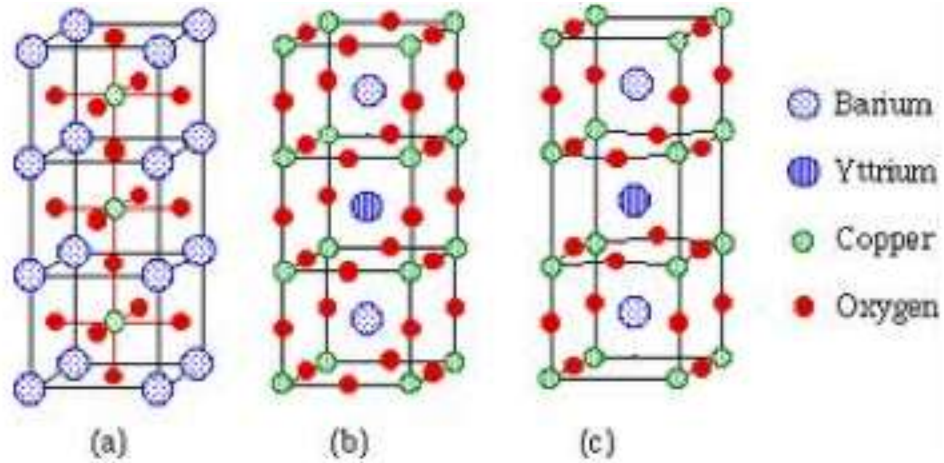
E.g.	**NbTi**	replaces	Copper	($B > 1$ T, $J_{op} > 20$ A/mm^2)
	Nb_3Sn	replaces	NbTi	(magnets with $B > 9$ T)
	HTS	replaces	Nb_3Sn	(either $T > 20$ K or $B > 18$ T)

A successful example of use of HTS in Fusion are the Current Leads (only self field, T up to 70K), where the advantage in terms of cryogenic power saving overcomes the material cost.

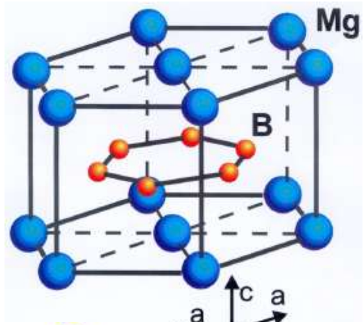
For the large DEMO Tokamaks (EUROfusion, China and Korea), the peak field in TF is < 16T, no HTS is required in TF, but the use of HTS is considered in CS to enhance the flux generation.

The use of HTS in TF coils would allow drastically increasing the field on Torus and the power ($P \alpha B^4$), hence reducing the major radius. Besides the feasibility of large HTS coils (SPARC), a broad criticism is raised about the exhaust of very large power density and the high radiation load.

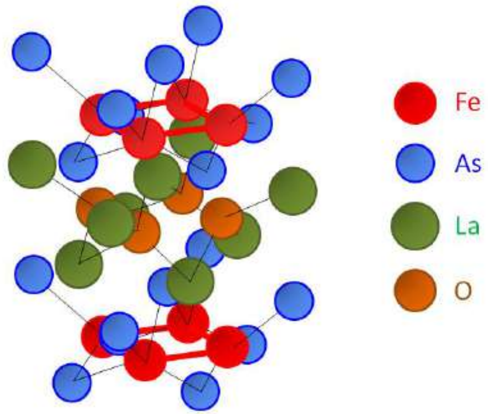
HTS – Materials



1986. The main family of HTS superconductors belongs to the perovskite, a kind of cuprates, with T_c up 120 K and B_{c0} up 50 T.



2001. Another popular new material is MgB_2 a binary compound with T_c 39 K and B_{c0} < 10 T.



2008. The youngest family of HTS materials is iron based pnictides, with T_c in the range of 50 K.

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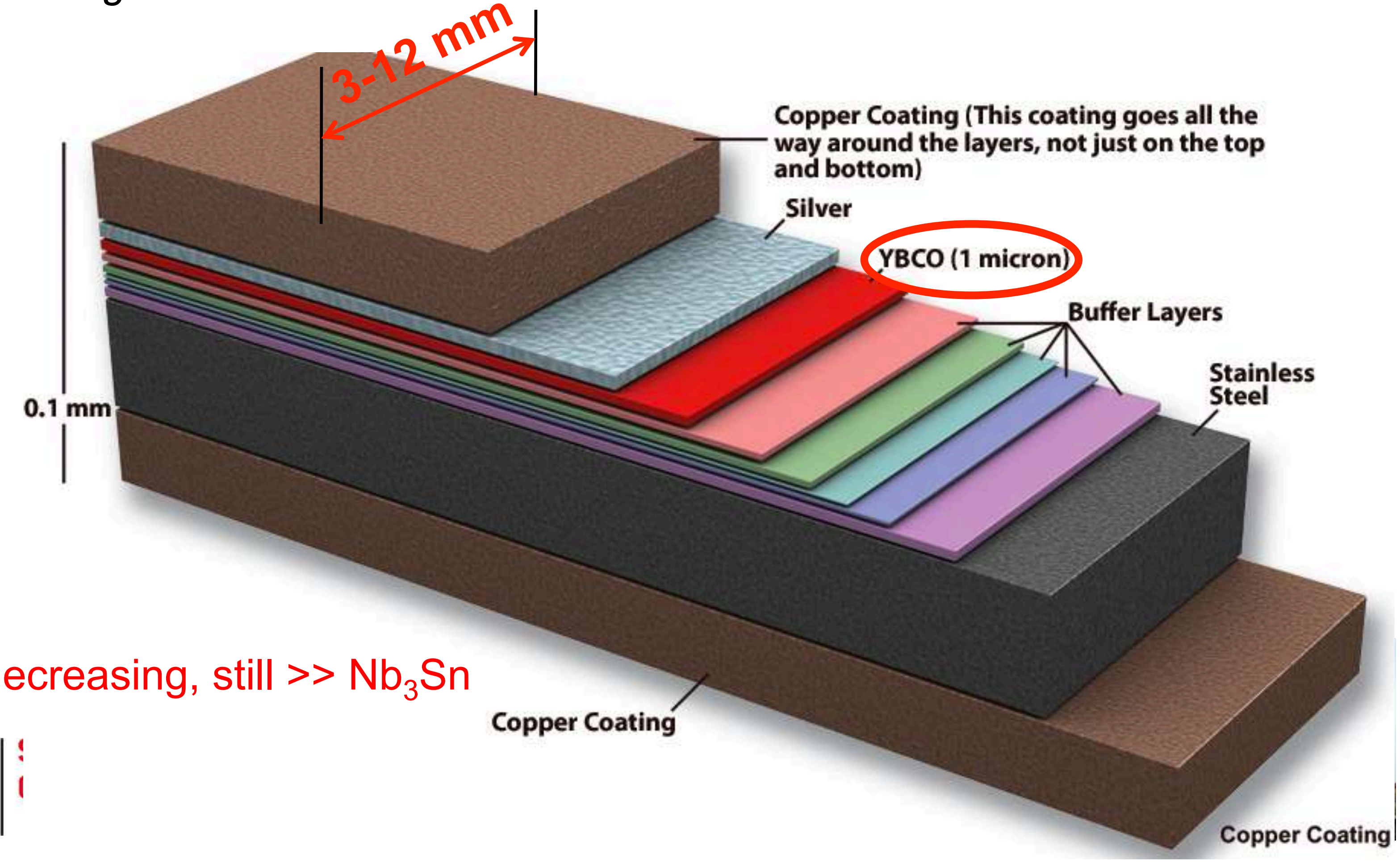
HTS superconductors today – Rare Earth perovskite

Two perovskite superconductors are produced commercially on small scale:

REBCO *based cuprates ("coated conductors"), Y(or Ga)$Ba_2Cu_3O_{7-x}$ are available as thin tapes prepared by CVD or laser assisted PVD. Best candidate for high field coils.*



Price/kg decreasing, still >> Nb_3Sn

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HTS superconductors today – Bi perovskite (highest T_c)

Two perovskite superconductors are produced commercially on small scale:

Bi - Sr *based cuprates, $Bi_2Sr_2Ca_{n-1}CuO_{2n+4+x}$, available as*

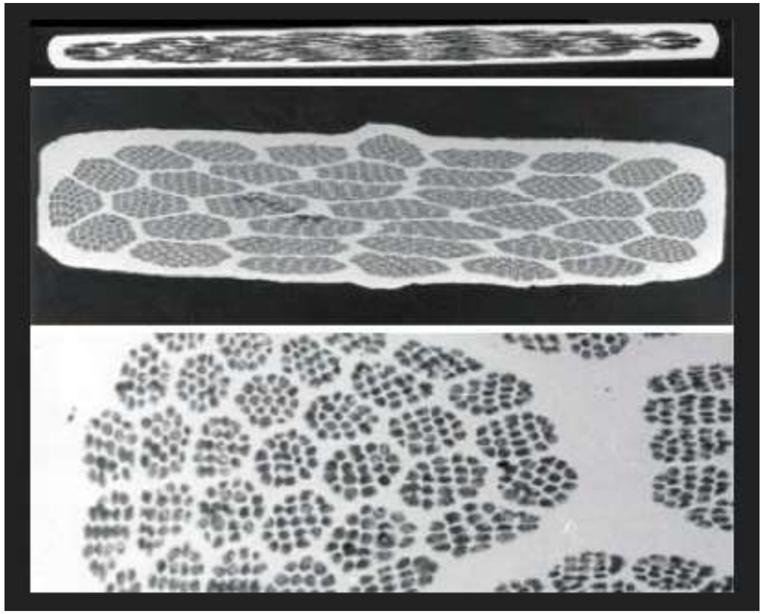
wire Bi2212 (precursor)

tape Bi2223 (heat treated)

The matrix of both multifilament composites is Ag (transparent to Oxygen) The Bi2223 tape, with high anisotropy, is in use mostly for HTS hybrid current leads. The Bi2212 wire is a candidate for high field winding, but with serious problems at the heat treatment.

Price/kg stationary >> Nb_3Sn

For Bi2223 tape, no commercial production after 2024, For Bi2212, very limited production by only one supplier



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IF the price would not be an issue….

Which technical advantages would HTS bring in a fusion magnet?

Operating temperature

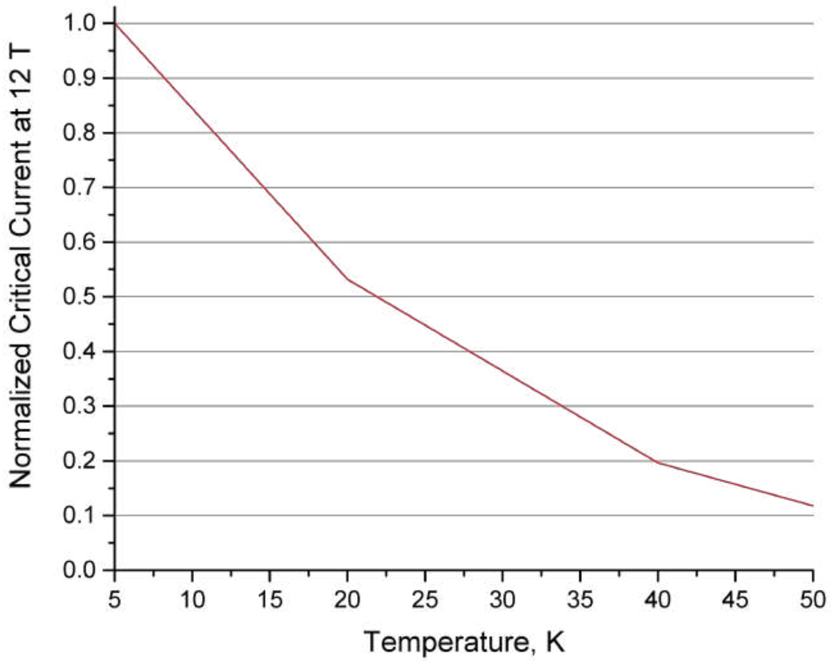
At B > 12 T, HTS require low operating temperature, say T < 25 K.

The available cryogenic fluids are He, H and Ne:

He density is very low at 25K

Ne is a poor dielectricum

Liquid H could be ok (if accepted)



The low dJ_c/dT compared to NbTi and Nb3Sn allows operating close to I_c with large T margin

Operating Field

Field > 20 T would be accessible, but

large magnets > 20 T are mechanically challenging

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IF the price would not be an issue….

Which technical **drawbacks** would HTS bring in a fusion magnet?

Protection

When operating with large temperature margin and at higher temperature, the quench propagation is very slow, making the quench detection challenging -> NI magnets?

AC Loss

Hysteresis loss is large for REBCO tapes (tape width). It matters for CS and PF coils.

Anisotropy

The performance sensitivity to field orientation limits the exploitation of the high J_c.

Technology

HTS are made of ceramic.

As a Wind&React (Bi2212) HTS has similar issues as Nb_3Sn

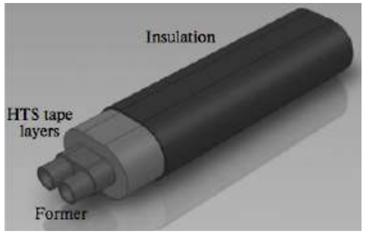
As React&Wind tape (ReBCO) HTS has limited bending and poor shear strength

IF the price would not be an issue….

HTS Conductor could compete with Nb_3Sn for high field fusion magnets

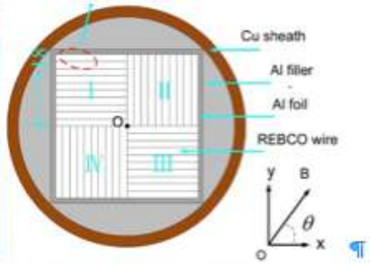
For REBCO tapes, three cable architectures

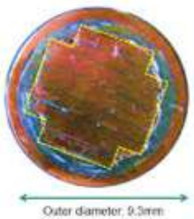
- *“Wrapped” tapes (CORC)*

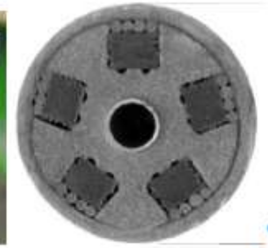



- *Stacks of tapes*

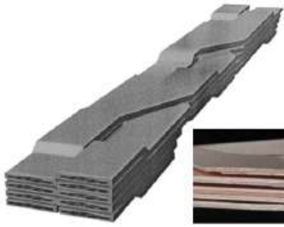






- *Transposed tapes (Röbel)*



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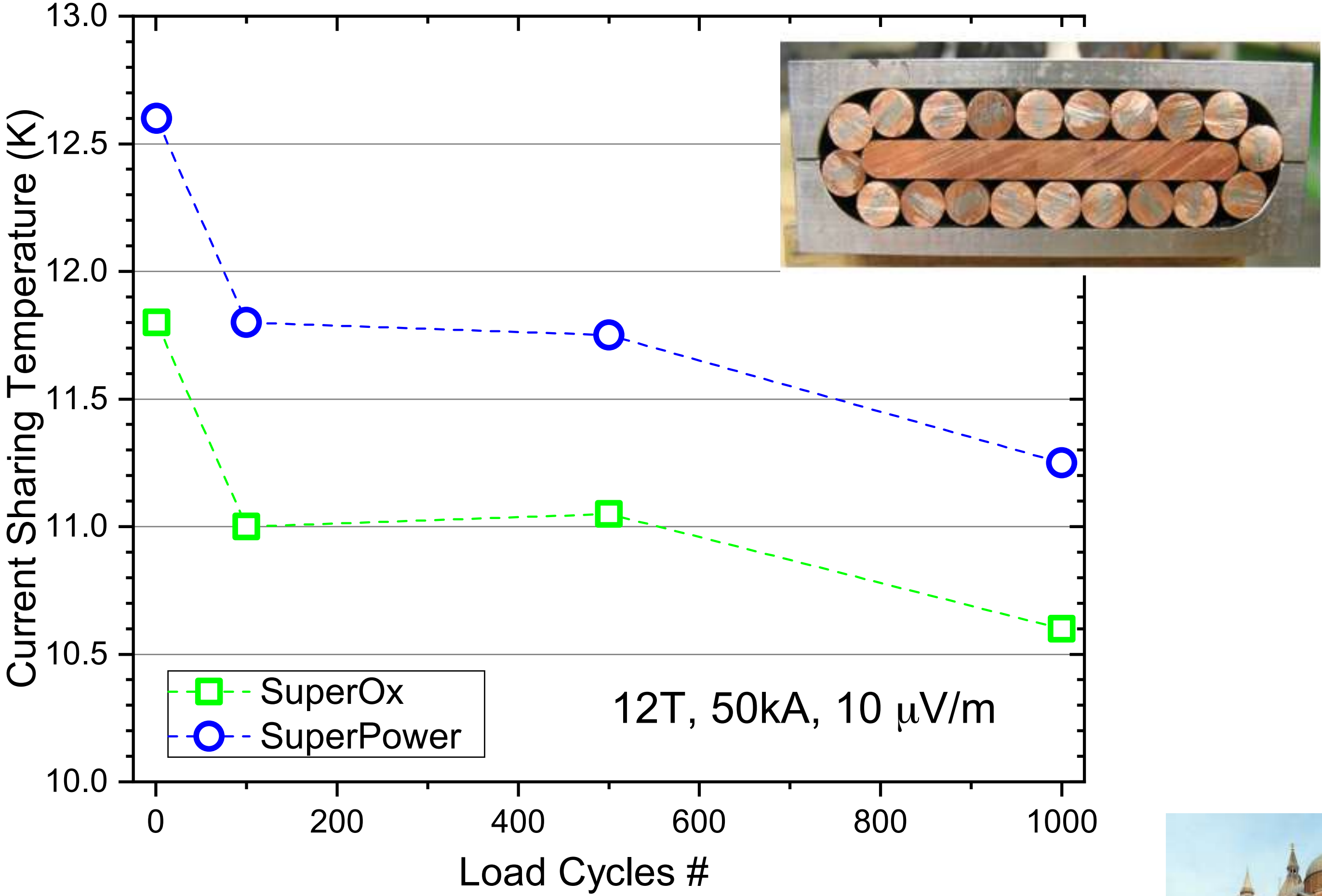
2015
Good initial results (zero resistance).
Substantial performance loss upon cyclic loading.



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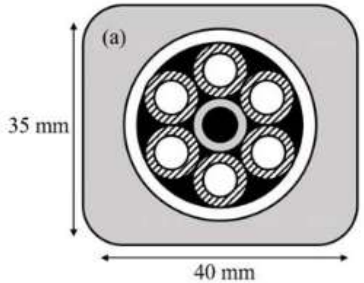
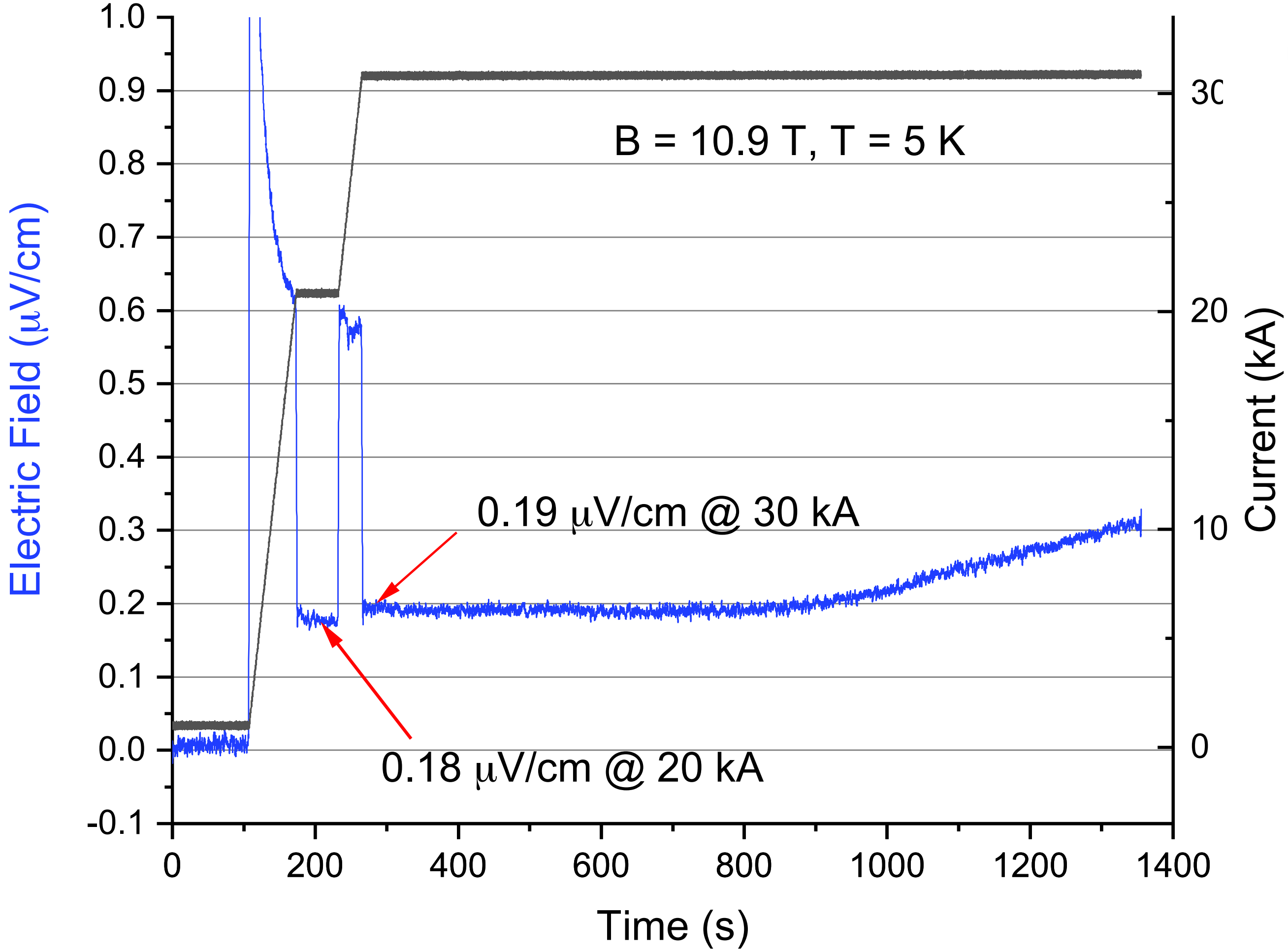
2017 - 2024
Voltage (resistance) > criterion even at low current.





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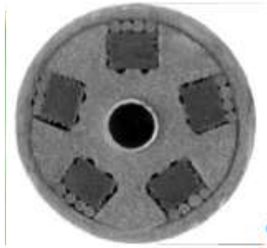
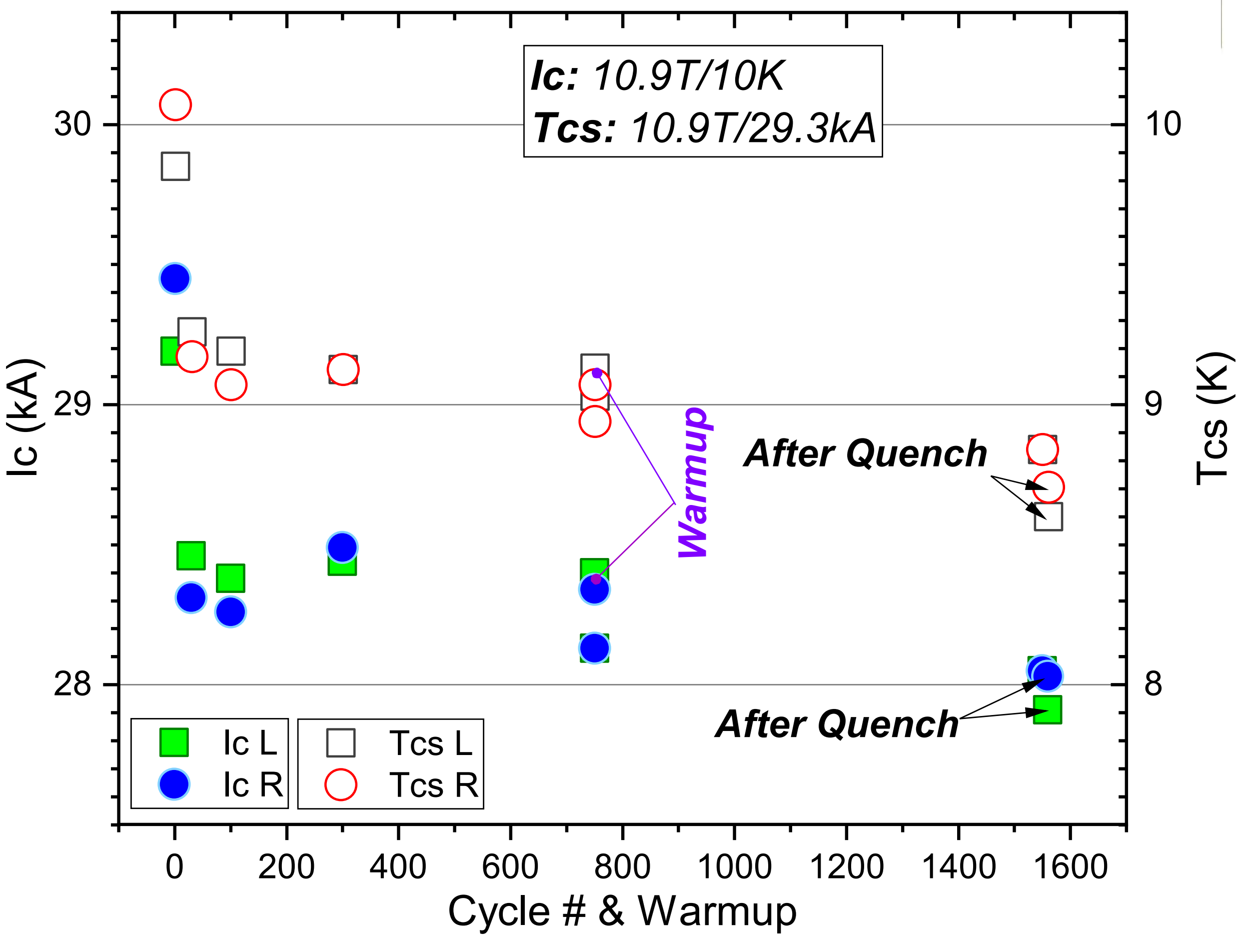
2019 (later improved)
Good initial results (zero resistance).
Performance loss upon cyclic loading.





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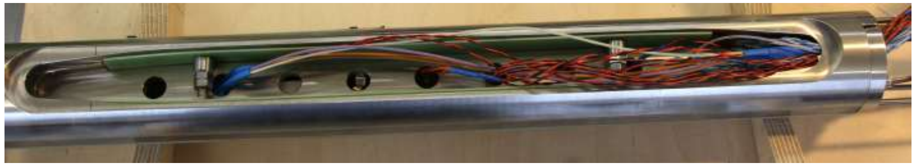
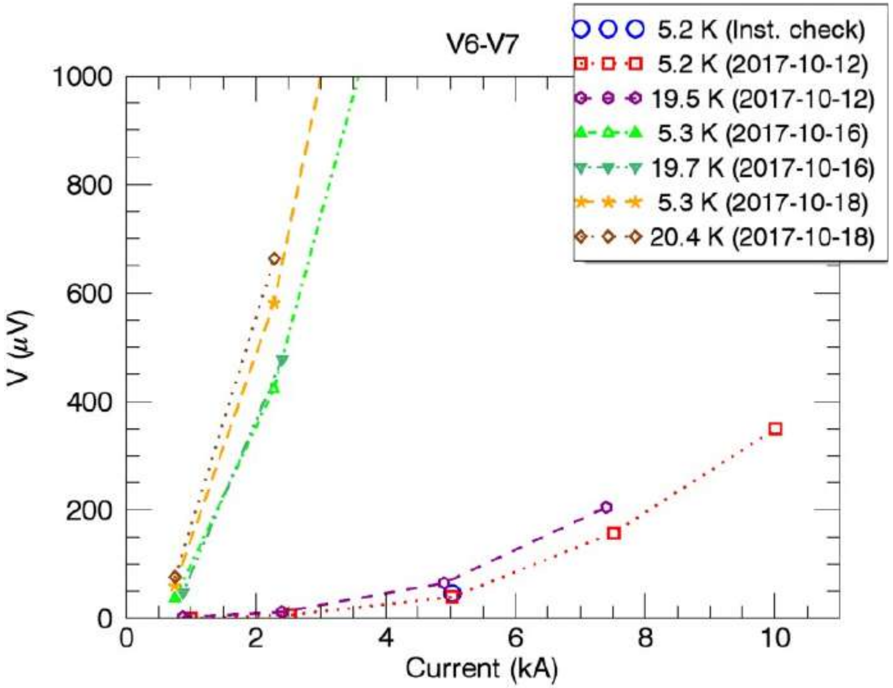
2017 (FM04) – 2019 (FM05)

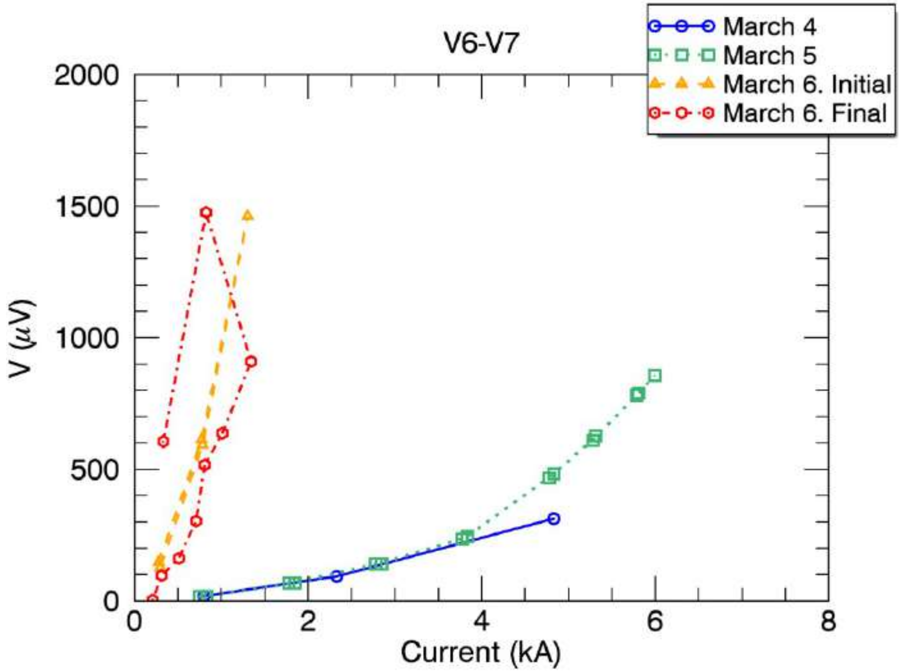


Two race-track insert coils made by Röbel cables show large voltage since the first run. The resistance increases by over one order of magnitude after test in field.

FM04 (2017)



FM05 (2019)



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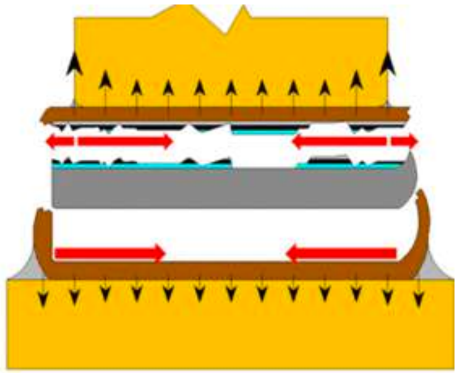
Summary on HTS cables (today)

- So far, the best (not perfect) performance is obtained by the VIPER cable of SPARC (CS coil), possibly due to the solder impregnation *under vacuum*, which suppress micro-bubbles.

- The typical failure mechanism for 2G tapes is the delamination of the REBCO film under shear load. Preventing "tape displacement" is not sufficient to avoid shear load.



- In CORC cables, the main issue is current injection / current sharing (apparent resistive behavior) together with sensitivity to transverse load.

As 2024, the only two examples of HTS coils made by sizeable cables (I_{op} > 30 kA) are the Model Coils of SPARC, TF (2019) and CS (2024)

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(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). Multi-CORC cable planned in CS high grade.

- **SPARC (CFS).** Up to 23 T, compact tokamak for technology demonstration, NI TF coils. (ARC, larger tokamak with demountable coils).

- FFHR (NIFS). Helical coils assembled by hundreds of segments (several thousands of joints). HTS is chosen for cryogenic economy.

- FNSF (PPPL). Spherical tokamak, field up to 16 T, HTS is proposed for the high current density.

- STEP (UKAEA). Compact spherical tokamak, with demountable HTS TF coils.