Superconducting Magnets - 2

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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

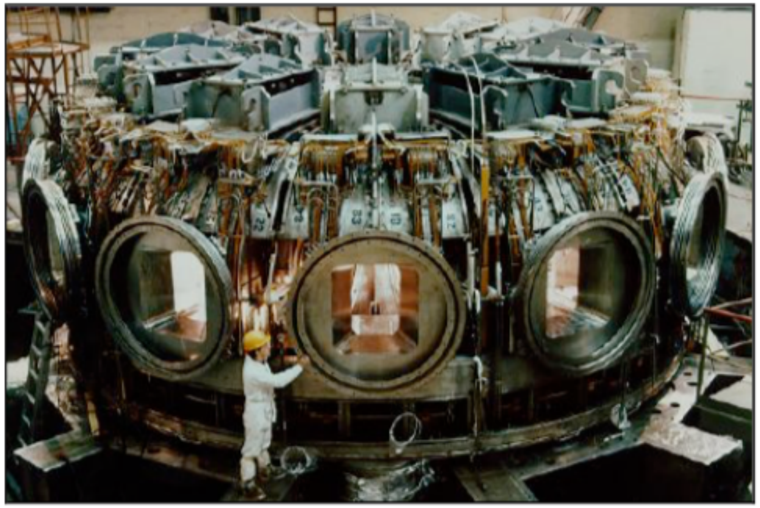
3. The ITER Conductors and Coils

4. Toward DEMO - HTS

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

First, large Nb_3Sn based device (25 t strand)

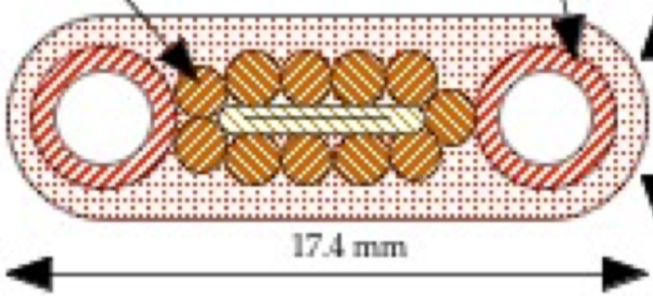
Conductor manufacture ≈ 1980-1983



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

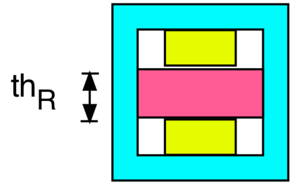
One of the first large scale use of the **react and wind** technique.

???



Coils made with Nb_3Sn strands

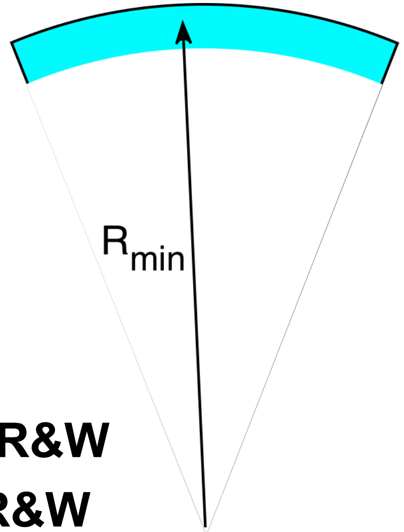
- As Nb_3Sn is very brittle, the strands cannot be bent/deformed after the heat treatment. **Cabling** must be done **before** the heat treatment.
- On the other hand, **Winding** can be done either *before* the heat treatment (Wind&React) or *after* the heat treatment (React&Wind), provided that the 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 ➔ $\varepsilon_b = 1\%$ ➔ **no R&W**

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

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

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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

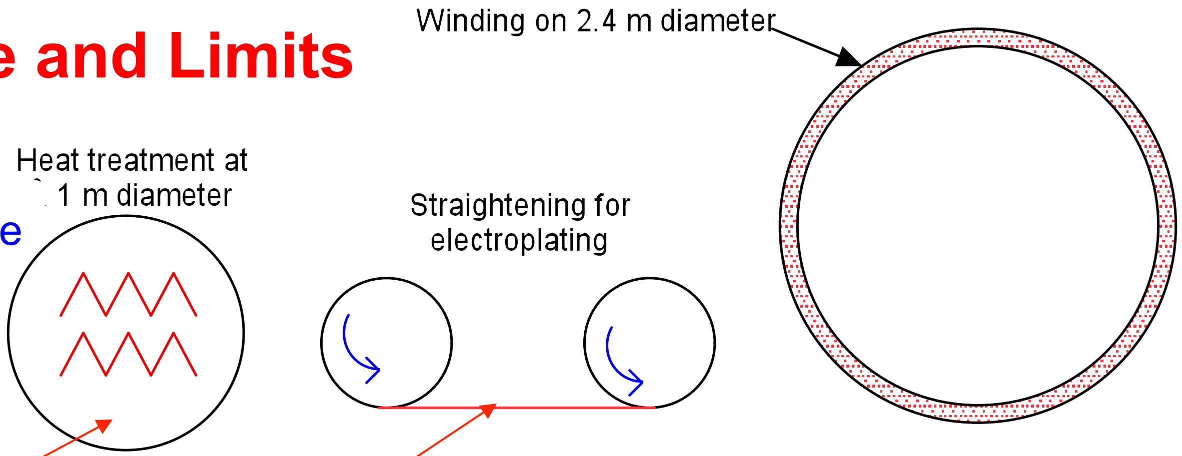
T-15: Performance and Limits

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.

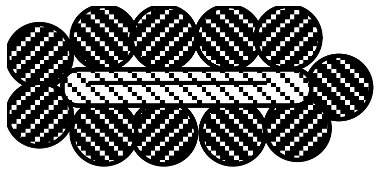
$R_{min} = 0.5$ m

$R_{max} = \infty$

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

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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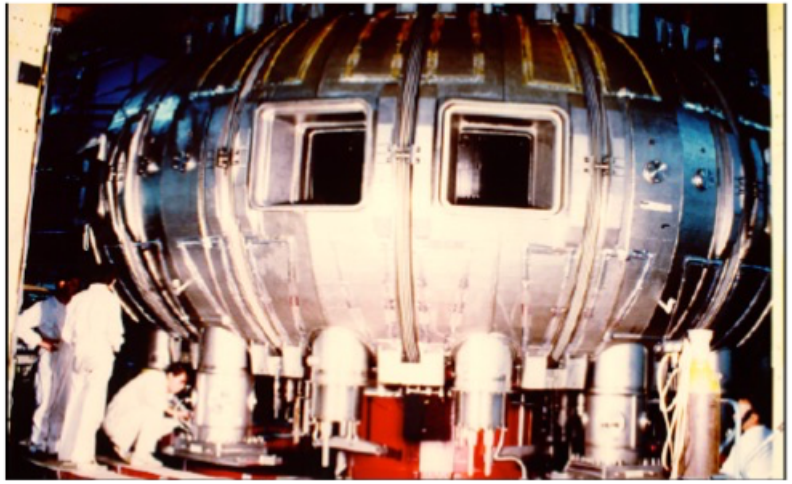
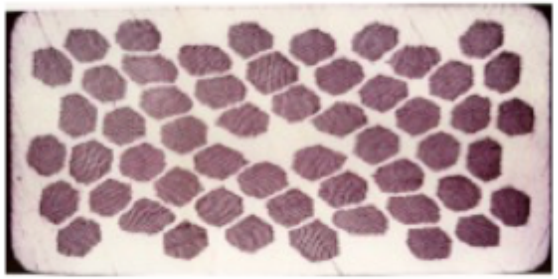
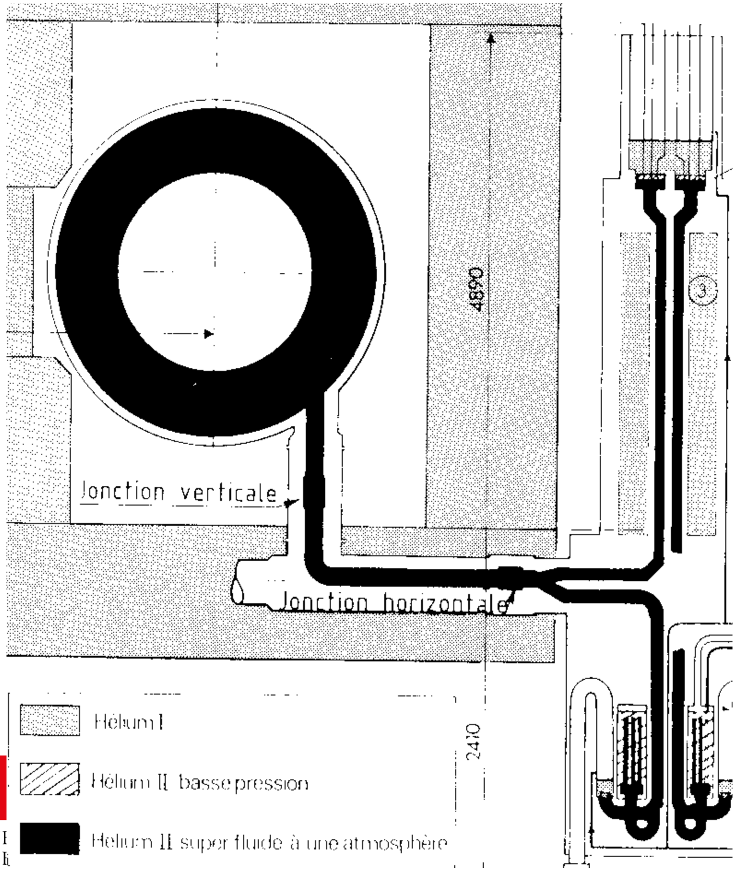


Tore Supra *Cadarache, 1987*

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.



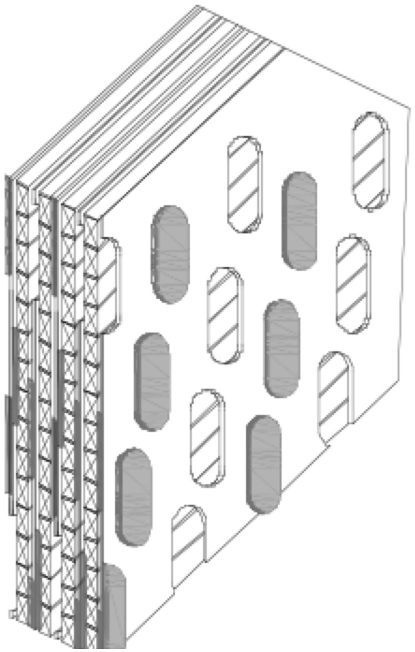


Quench Protection: Little copper is used in the cross section. In case of quench, the He pressure building at the top of the coil case expels all the liquid He through the bottom port: within 3 s the winding is dry and all the conductor is normal

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).

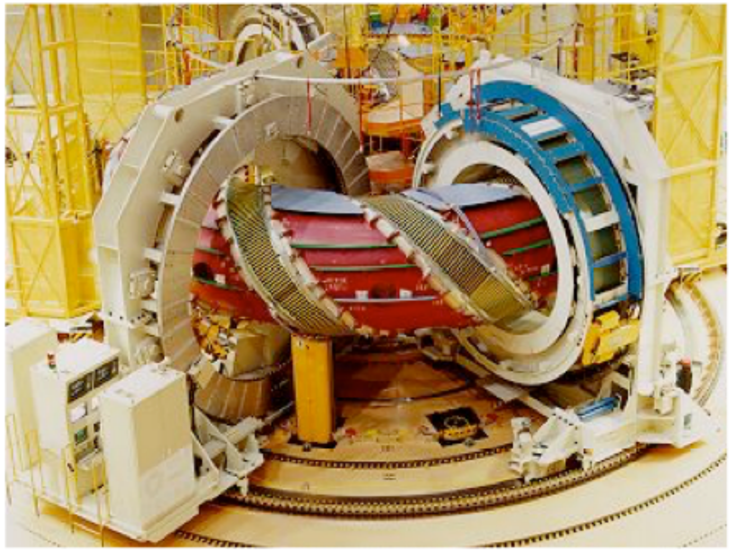


Nonetheless, a short occurred at a current dump and destroyed one coil, possibly due to some microscopic metallic chip, causing a high electric field peak

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

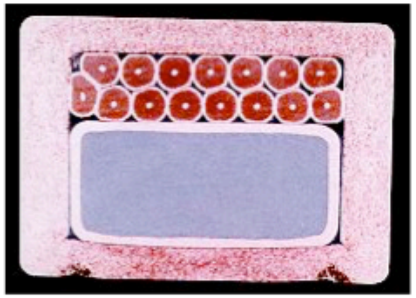
- most advanced cryogenic system to obtain 1.8 K
- improved I_c and stability due to superfluid helium
- high current density thank to low protection copper
- monolithic conductor with low ac loss

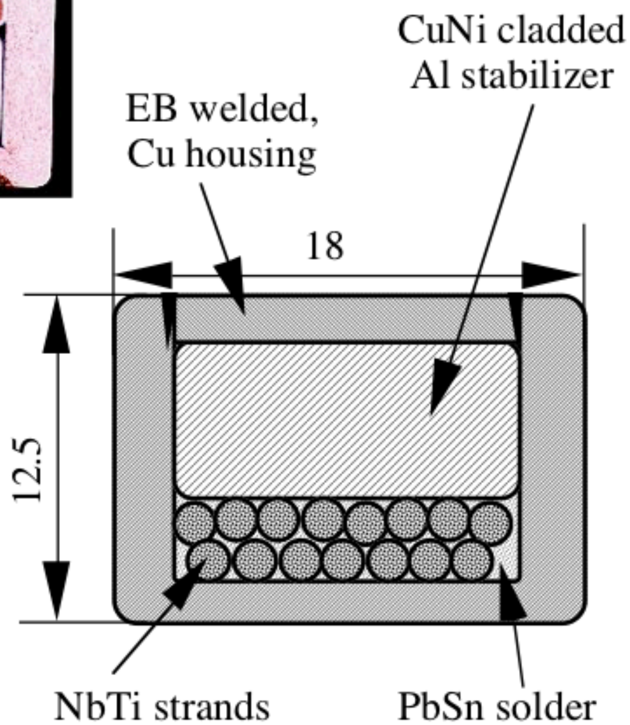
The design features are not scalable to higher energy devices. Only the "bad" lesson (pool cooling = short circuit) remains in the common memory



Helical Coils of LHD *NIFS, Toki, Japan*

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





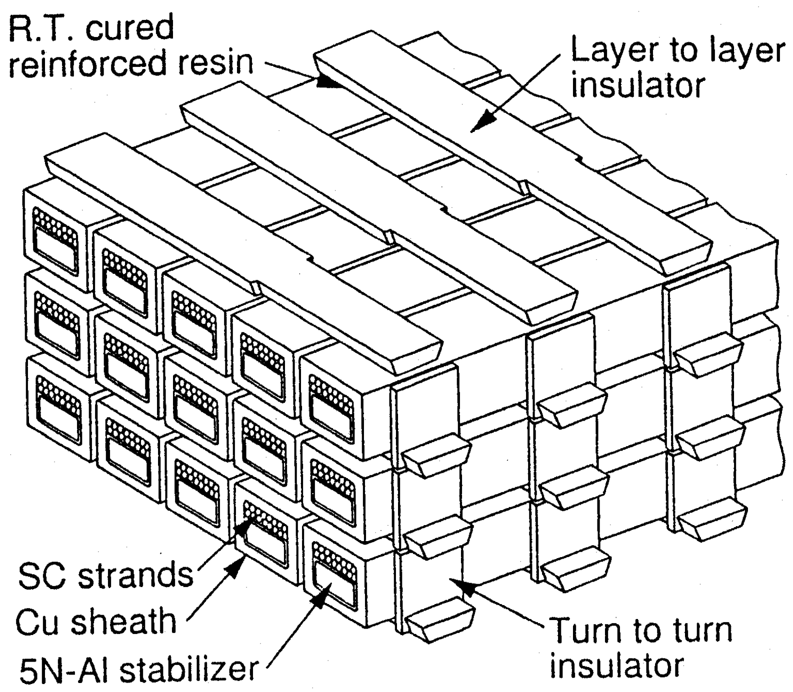
Cooling: helium bath @ 4.2K.

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.



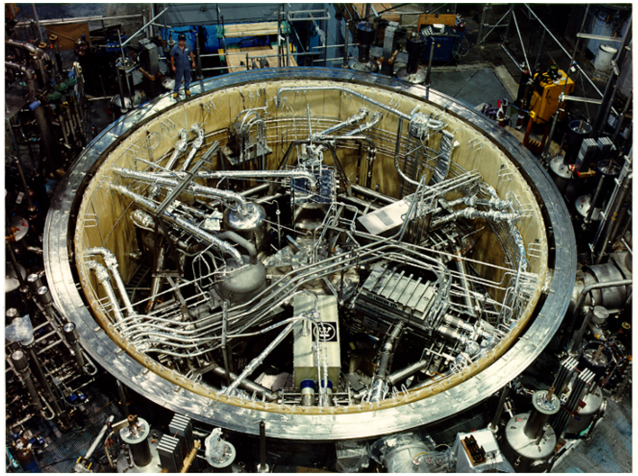
Helical Coil Winding

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).

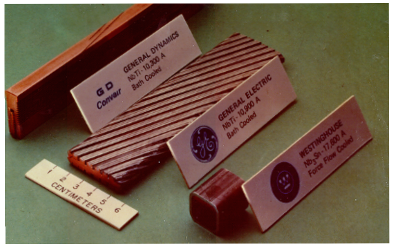
The expected cryo-stability was actually not achieved. The operating current had to be limited to 11.3 kA due to observed propagating normal zone.

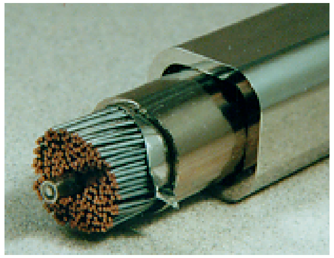
The lessons from Tore Supra (unreliable use of helium as dielectricum) and LHD (inadequate mechanical stiffness of a helium transparent winding) led to a serious prejudice against pool-cooled conductors for high energy windings, with high voltage at current dump (to extract as much as possible energy 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.

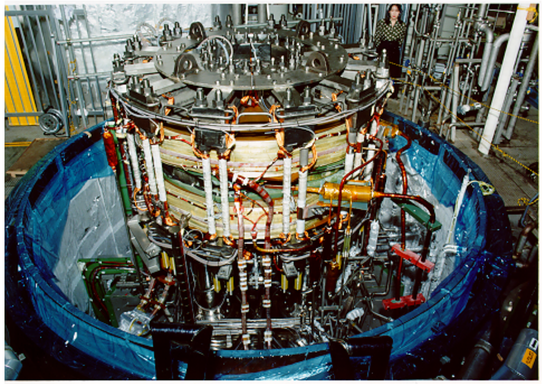
Other Large Development Magnets in last Century



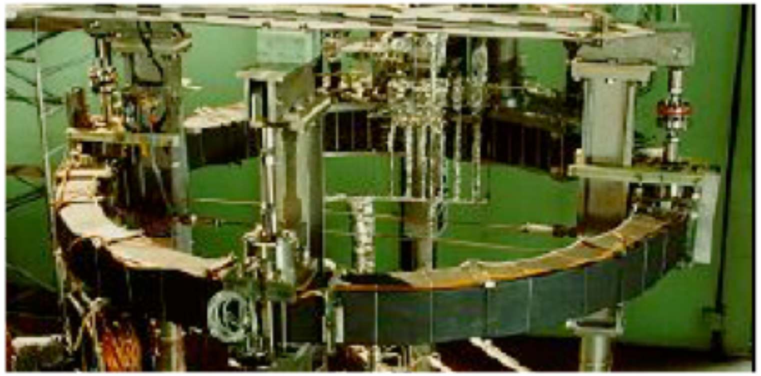
- Large Coil Task, Oak Ridge, 1981







- 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*

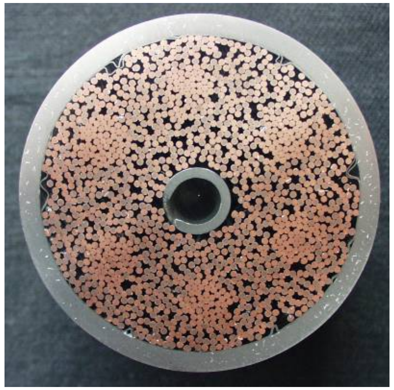
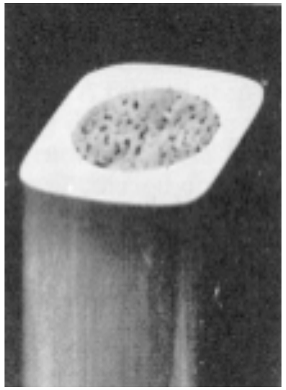
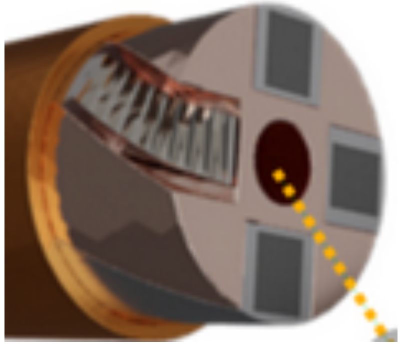
- From the very large composite to the cabled conductors
  - *Technical confidence, stability, ac loss, cost*

- In Nb_3Sn, react&wind is more frequent than wind&react
  - *Risk perception of the designer, furnace size, insulation issue*

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

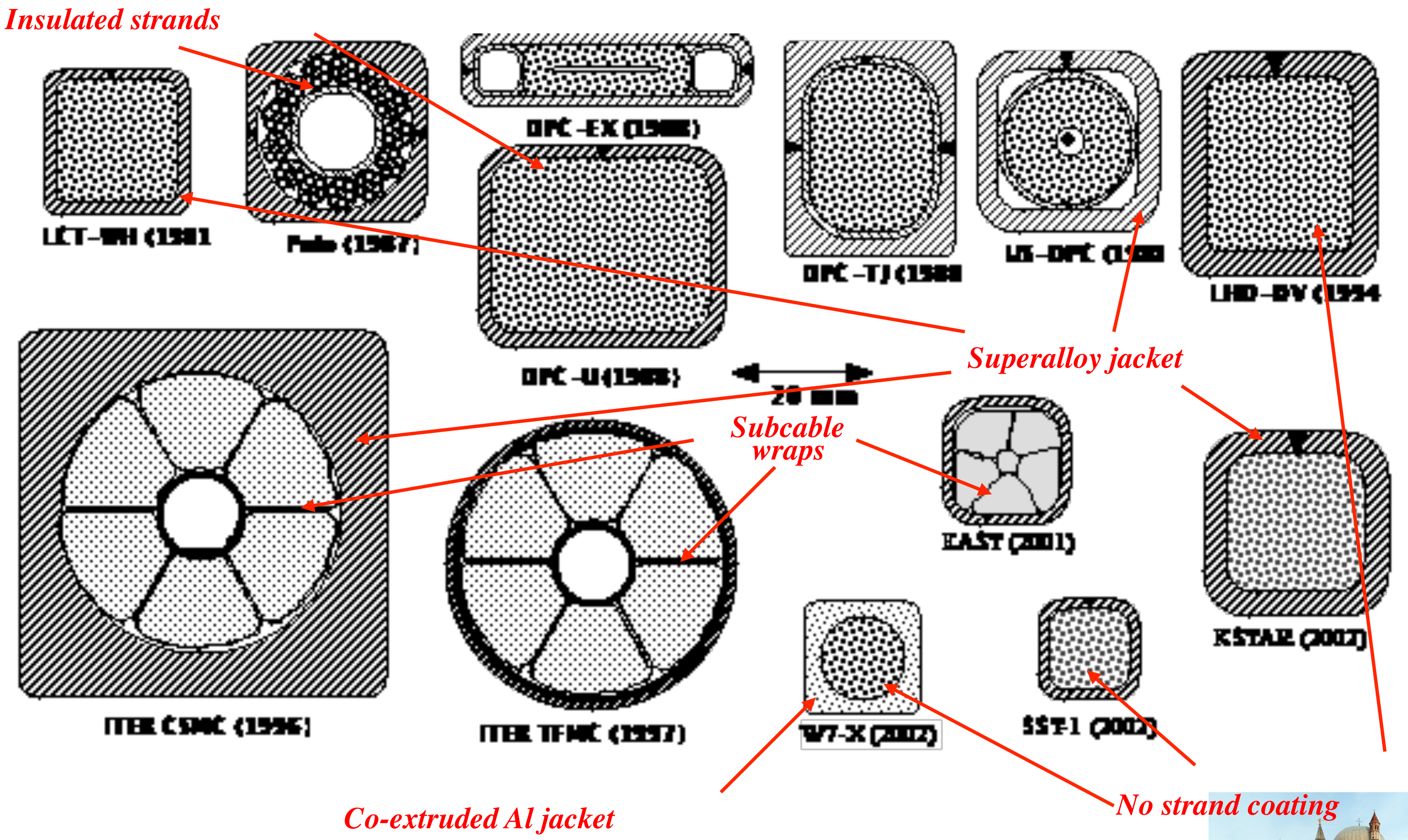
At large current (> 30kA) the size of a soldered conductor was judged to be inadequate for heat removal and ac loss

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

A Chart of most CICC's for Fusion



Insulated strands for CICC's ?

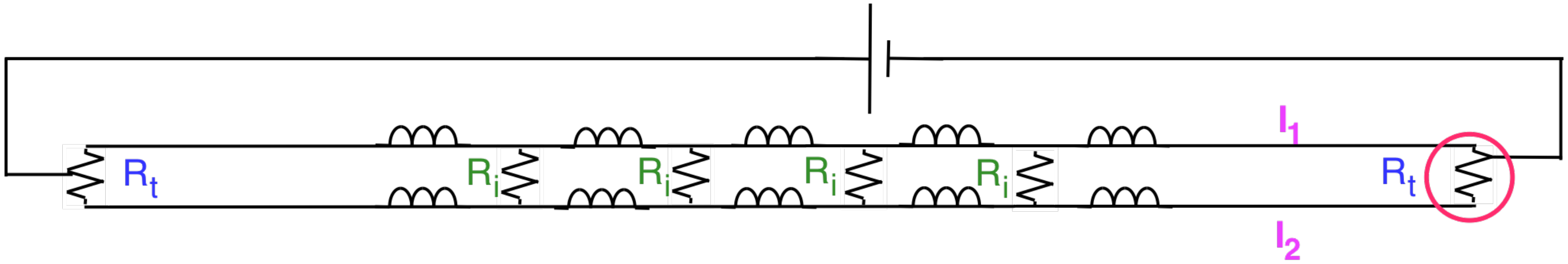
Aiming to 0 inter-strand coupling loss, Polo and DPC-U were made of insulated strands. Both CICC's achieved high pulsed current, but the DC properties were lower than predicted.

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.

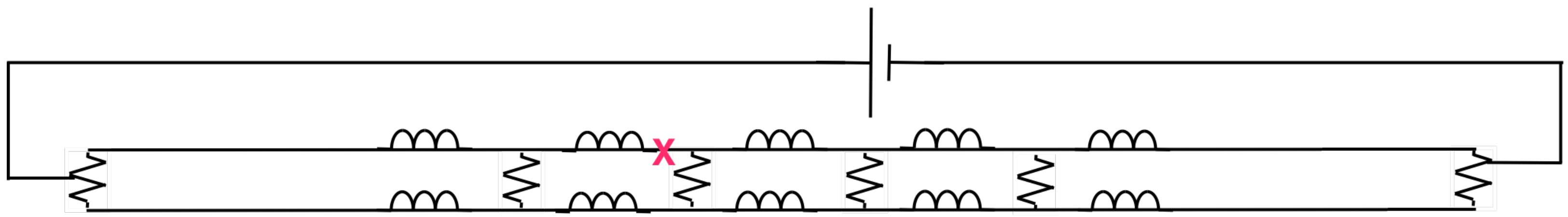
Current unbalance is unavoidable in CICC due to both transposition errors in the strand bundle and non-homogeneous contact resistance of the strands at the splices. As long as the current can locally re-distribute among strands within the stability limits, current unbalance does not lead to performance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

Current unbalance and Current re-distribution



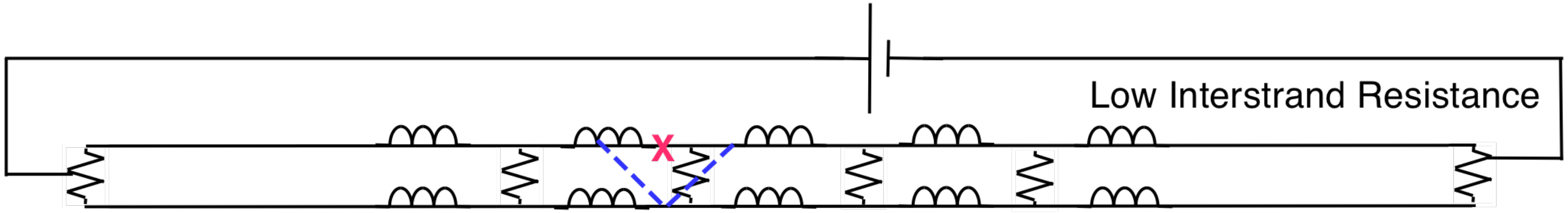
Unbalanced R_t -> Unbalanced DC Current, $I_1 > I_2$

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

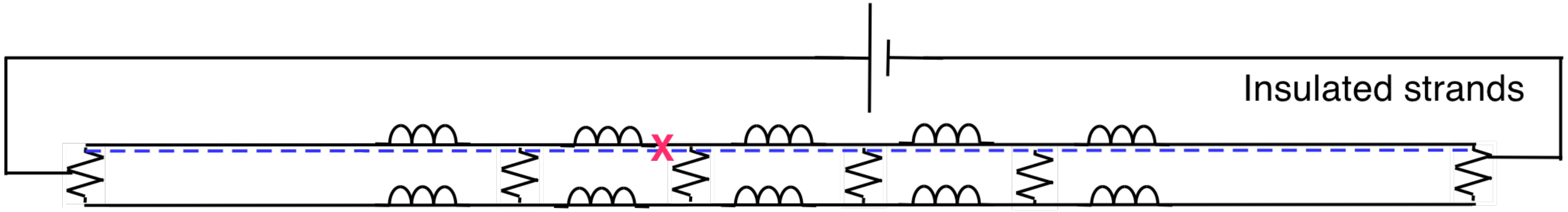
Current unbalance and Current re-distribution



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.

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