Superconducting Cables

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Superconducting cables
CAS, Erice, April 29th 2013

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Outline

Cables vs. multi-filamentary composites

Historical milestones for superconducting cables

Transposition

Strand movement

Degradation

Manufacturing aspects

A chart about cabled conductor design

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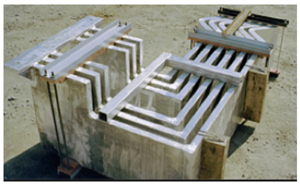
Why Cables?

The word "cable", opposite to "wire" is associated to high current.

However, very large current in the range of several ten kA, can be carried by bulky (non-cabled) Cu or Al profiles, with cross section exceeding several hundreds cm²…



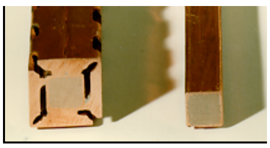
So why do we need cables?

In normal conductor technology, cables are used in AC application (eddy current issue) and to allow long conductor sections to be transported and installed (flexibility / bending).

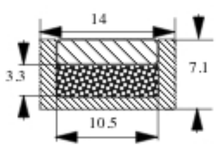
Why *Superconducting* Cables?

Opposite to normal conductors, a superconductor is not a section of bulk metal, but a multi-filamentary composite, i.e. superconducting filaments embedded into a normal metal matrix, assembled by extrusion of billets.

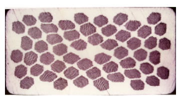
The limited size of the extrusion billets (<300 kg) and the need to achieve thin filaments (flux jump issues) sets boundaries to the maximum realistic cross section of a superconducting composite, typically < 50 mm²



NbTi square composite for MFTF coils, 42 mm² (≈1976)



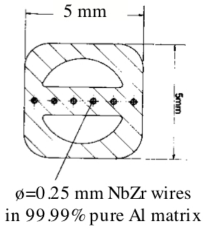
Nb_3Sn flat composite for TRIAM, 35 mm² (≈1986)



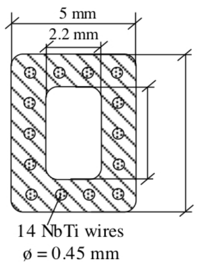
NbTi/CuNi/Cu composite for Tore Supra, 16 mm² (≈1987)

Force flow composites

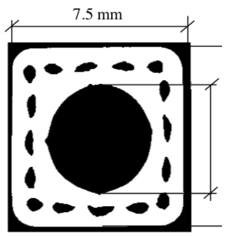
In the late 60', with increasing demand for force flow conductors, hollow composites were manufactured by extrusion, with limited length, up to 100m – 300m. Beside the lack of transposition, the low extrusion ratio (thick filaments) was an issue.



Supercon, US, 1967



IMI, UK, 1968



MFO, CH, 1968

Cables vs. Composites

Large composites require R&D, are expensive and have little market. *Today*, composites are mostly round strands with cross section < 2 mm^2. For operating current > 1 kA, cables are preferred to large composites.

Large Composites	**Cabled Conductors**
High engineering current density	Unbalanced current distribution
Excellent current distribution	Complex joining technology
Easy joining	Modular assembly
Easy application of insulation	Lost cross section (voids)
Potentially high ac loss	Mechanically unstable (if not impregnated)
Potentially poor transient stability	Large operating current
Limited operating current	

The broad family of cabled superconductors

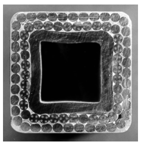
Bath cooled
Co-axial
Hybrid
Insulated
MULTISTAGE
Co-extruded
Cable-in-conduit
Wind & React
Braided
React & Wind
Forced flow
Soldered
Armored

Three historical milestones of cables

The OMEGA magnet (early 70', cern)

Forced flow single channel, fully transposed, soldered, outer shell of copper wires

-> over 20 years of operation!



The T-7 Tokamak (mid 70', Kurchatov)

Electrolytic copper assembly, non-transposed,
Force flow in 9 parallel channels

-> e.m. instability, blocked channels issues

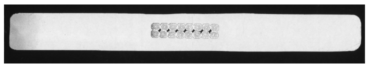
The Tevatron (late 70', Fermilab)

Flat "Rutherford" single stage cable, bath cooled, wrapped, semi-transparent insulation

-> strand movement, training

Another two important milestones of cables

The ALEPH detector (mid 80', cern)



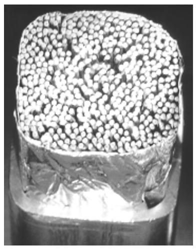
NbTi single stage flat cable of 16 strands, co-extruded with pure Al stabilizer, conduction cooled, self-protected for quench

The mother of all modern detector conductors

The LCT-WH TF coil (early 80', Oak Ridge)

Nb_3Sn Cable-in-conduit, wind&react&transfer, superalloy conduit

The aunt of most fusion conductors



Requirements for superconducting cables

The catalogue of requirements is the top level of specification. Requirements must be strictly enforced before choosing the various options for layout. The *top requirements are dictated by the application*, not by the magnet design.

E.g. "high field quality" is a requirement for the accelerators (*application*).

In terms of *winding*, it means "*precise position of the conductors*".

In terms of *cable*, it means "*homogenous current distribution*"

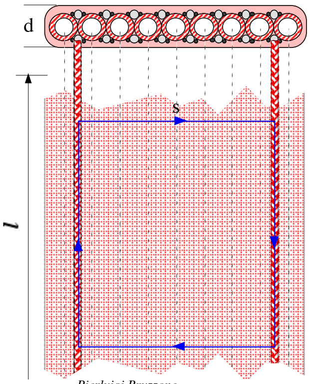
In terms of *strand*, it means "*low residual magnetization*"

The conductor designer translates the requirement into specifications for a particular design. In the case of "high field quality requirement", the designer may specify thin filaments, monolithic conductor (large composite or soldered cable).

Typical cable requirements – Full Transposition

"each current carrying element exchanges its position in the cable"

Full transposition is an illusion in a superconductor (the filaments are not transposed in a strand). *Transposition provides uniform current distribution* during the charge (but not necessarily in steady state).



The case of T-7. The parallel, non-transposed strands form a huge loop of coupling currents for self field or external field change:

$$I_{cc} = \frac{V}{R} = \frac{\dot{B}(l \cdot s)}{\rho_{cu}(s/d \cdot l)} = \frac{\dot{B}\, l^2 d}{\rho_{cu}}$$

With $\ell \approx$ 200m, even at dB/dt = 0.1G/s, the induced current is in MA range, leading to saturation / flux jumps. Nonetheless, the very low J_{cu} and transverse resistance helps recovery and T7 achieved 80% of the nominal current.

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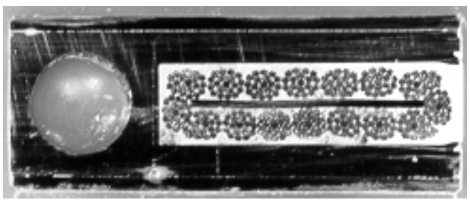
Transposition and current re- distribution - 1

In multifilament composites the outer shell of filaments quickly saturate at charging, but smooth re-distribution is achieved through the low resistivity matrix.

The effect of non-perfectly transposition in cables is mitigated by low transverse resistance.

SULTAN, high grade Nb_3Sn conductor, R&W (1985):

The 1. and 2. cable stage are non-transposed, core+6x(1+6)+12x(1+6), but the solder matrix promotes current re-distribution. The 1. and 2. cable stages behave as a composite with ø = 1.7 mm



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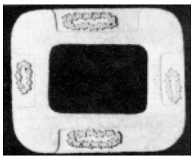
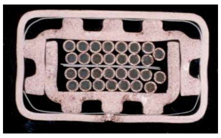
Transposition and current re- distribution - 2

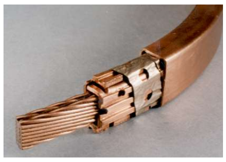
Two Nb_3Sn **non-transposed** cabled conductors from ETL (JA) are reported to satisfactorily operate in model coils:

ETL 1978, four rotary braids of Nb_3Sn strands, R&W, soldered in slots of a rectangular copper pipe



ETL mid 80', two flat cables of Nb_3Sn strands, R&W, encased between shells of copper stabilizer



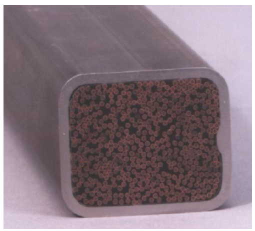


Transposition and current re- distribution - 3

Two NbTi **fully-transposed** cabled conductors did not achieve 100% performance in coils

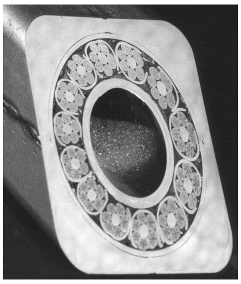
DPC-U (JA), late 80', CICC of 486 insulated NbTi strands, 3x3x3x3x6, fully transposed.

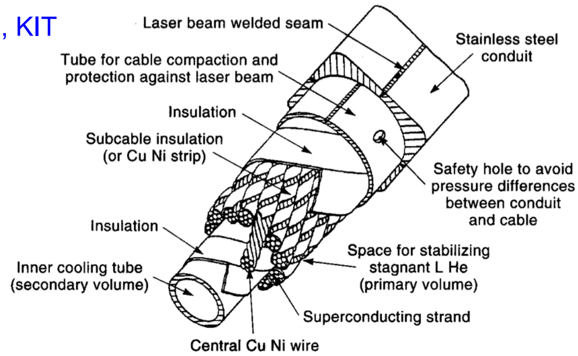
The coil quenched 1 s after full current charge due to unbalanced current re-distribution: from the "inductive", balanced distribution, the current re-distributes in steady state according to joint resistance distribution. When an overloaded strand hits the critical current, another current re-distribution should take place, but the diffusion time from the weak spot to the joint is much too long compared to the quench propagation



Transposition and current re- distribution - 4

The Polo conductor/coil, ≈86, KIT





Two separate channels, stagnant supercritical and forced flow 2-phase. 78 NbTi strands, fully transposed, (core +6)x13. Insulation between subcables. The joints preserve the separation among subcables.

Excellent performance for transient field (1000T/s) and ac loss (τ = 0.2 ms), but only 70% of I_c achieved in dc, likely due to current unbalance at the coil terminal

Conclusion on transposition and current re- distribution

Despite dogmatic statements about transposition, *non-transposed cables may work* in steady state, provided that low transverse resistance is granted for current re-distribution.

The performance of fully transposed cables with *very large (infinite) transverse resistance* is limited by the homogeneity of the resistance distribution at the joints/terminals.

Full transposition remains mandatory for pulsed and AC applications.

Transverse resistance for local current re-distribution is a design parameter of paramount importance: it must be targeted as low as the ac loss allows.

Conductor movement

Conductor movement, either slip-stick of individual strands inside a cable or full conductor movement in a winding, may be easily *restricted by solder / epoxy impregnation*.

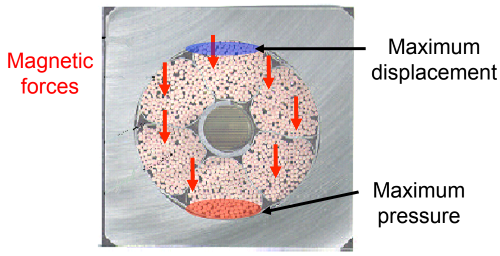
In case of bath cooling and cable-in-conduit, impregnation is not applicable.

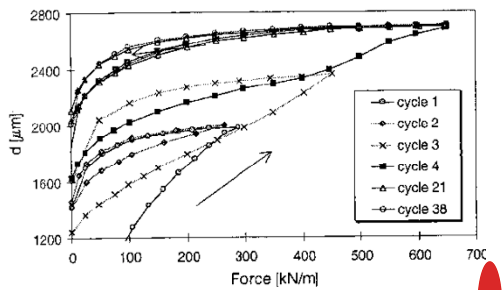
Any displacement, ΔL, of a current carrying element in a background magnetic field causes a change of stored energy, e.m. ($B \cdot I \cdot \Delta L$) and, if applicable, elastic. Depending on the friction coefficient, a fraction of ΔE can be locally dissipated.

Slow displacements do not generate a quench because the dissipated power is lower than the heat removal rate.

Strand movements in a cable in conduit - 1

The internal e.m. forces push the strand bundle to one side of the conduit. The energy over one load cycle is measured as “mechanical hysteresis”. Energy and power are smaller than the magnetization hysteresis loss, ≈ 5 mJ/cm^3 -> **no issue for conductor stability**





Less than 5% of the work done on the strand bundle is dissipated as frictional energy

Strand movements in a cable in conduit - 2

Slip-stick of an individual strand. With I_{strand} of the order of 100-200 A and displacement ΔL of the order of 0.1 mm, the energy is

$$\Delta E / \ell = \Delta L \cdot I_{strand} \cdot B \approx 0.2\ J/m$$

Assuming than 1 cm long section of strand is involved in the slip-stick, the actual change of stored energy is $\Delta E \approx 2\ mJ$

We assume that 5% of ΔE is dissipated by friction in the strand, leading to $\Delta E / V \approx 10\ mJ/cm^3$

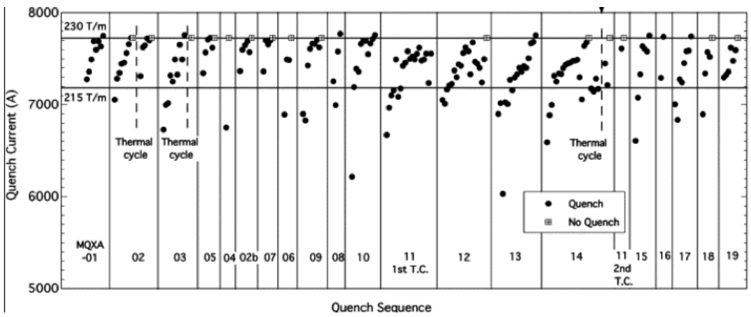
which on the time scale of ms, i.e. strictly adiabatically, *could lead to a local quench*. However, the local helium enthalpy and the current sharing to neighboring strands promote a safe recovery.

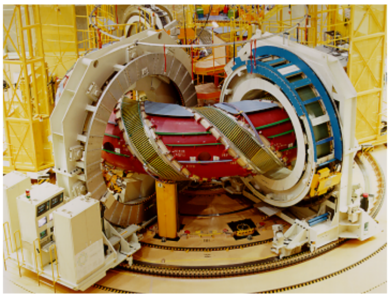
(Slip-stick cannot occur in solder filled cables)

Conductor movements in bath cooled windings

Training in accelerator magnets can be considered as a particular case of slip stick, involving more than one strand.

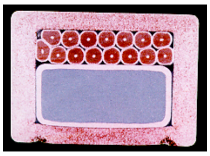
Opposite to the cable-in-conduit, the *limited local helium inventory*, the *cable insulation* and the *high current density* may lead to a stability issue, i.e. to a quench. As most of the slip sticks are irreversible events, a "training" effect is observed, i.e. the same slip stick will not occur again at next charge and the winding learns to behave at each lesson at increasing *I·B* load.

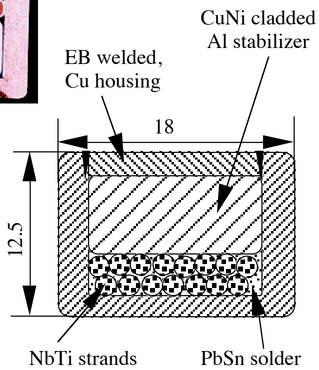




The case of LHD *NIFS 1996, Japan*

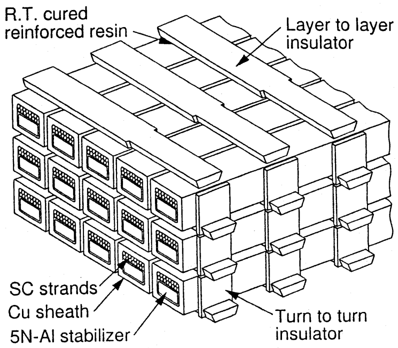
Highly engineered conductor, **13 kA, 6.9 T**





Bath cooled, flat cable of 15 NbTi strands, high RRR Al stabilizer, sheathed by CuNi. 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 loads and the large wet surface for 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).

In LHD, no strand movement is possible (soldered cable), but a collective sliding of the winding pack happens, with large dissipated energy.

The expected cryo-stability by cold-end recovery was actually not achieved. The operating current had to be limited to 11.3 kA due to observed propagating normal zone. A limited improvement is obtained by sub-cooling the bath.

Degradation

Performance below design is stigmatized as "degradation": it can be due either to *accidental event in the manufacture* or to *intrinsic feature of the design*.

Coil Degradation: winding movement (LHD), training (LHC), insufficient cooling, radiation damage, insulation failure

Conductor Degradation: mechanical irreversibility (Nb_3Sn), self-field instability, flux jumps, lack of transposition, unbalanced current distribution

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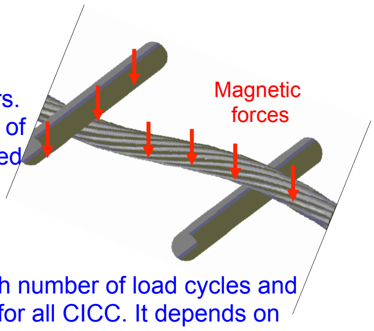
Conductor degradation examples – Nb_3Sn in CICC

The transverse load on the strand bundle leads locally to stress concentration at the strand crossovers and to deflection between crossovers. When the stress exceeds the reversibility range of the Nb_3Sn strands, filament breakage is observed and the conductor performance degrades by broadening of the transition (reduced n-index).



The transverse load degradation progresses with number of load cycles and thermal cycles. The degradation is not identical for all CICC. It depends on

- Robustness of the strand (reversible range)
- Void fraction in the strand bundle
- Size / Aspect ratio of the strand bundle
- Sequence of the twist pitches

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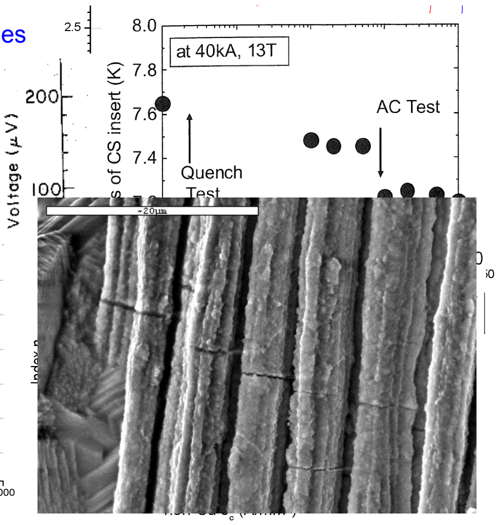
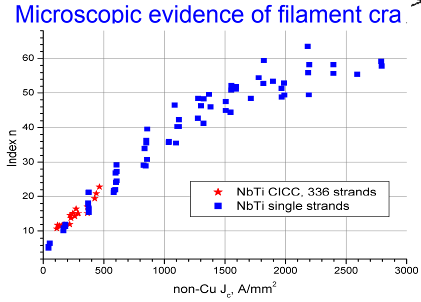
Evidence of irreversible degradation – Nb_3Sn in CICC

- I_c test on strands extracted from cables
- Resistive behavior upon cyclic load
- T_{cs} degradation on ITER CSMC
- N-index comparison, strand vs CICC
- Microscopic evidence of filament cra





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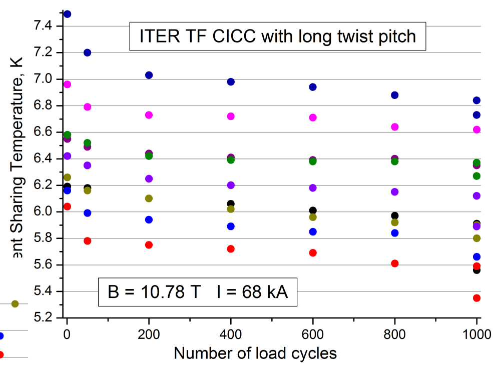
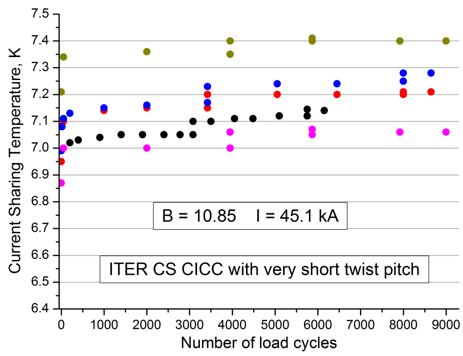
The ITER CICC

The TF CICC (long pitches) degrade





The recent "very short" pitch is ok

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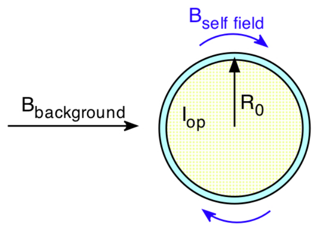
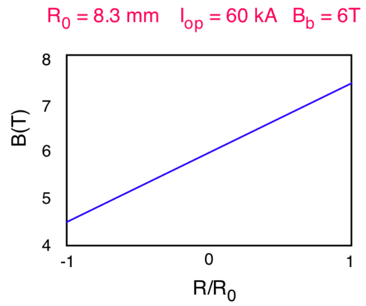
Conductor degradation examples – NbTi self field effect

In cabled conductors with *high operating current* and *low background field*, the superconducting transition may be "sudden", without visible current sharing. The correct name for these case is "**self-field instabilities**".

Example: NbTi medium size CICC





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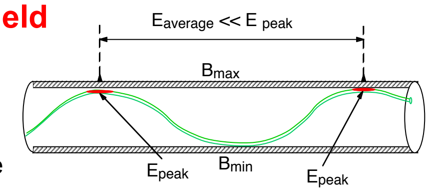
Local and Average Electric Field

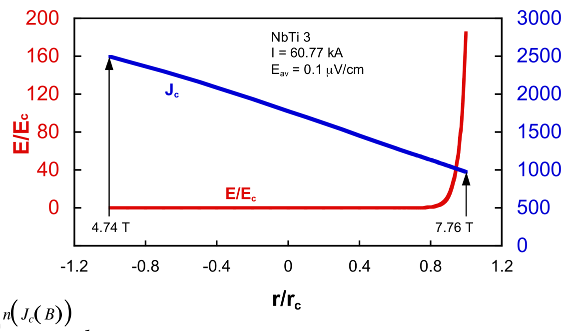


In twisted superconductors, the strands travel continuously from the low field to the high field. The field gradient can be several Tesla and the strands hit the critical surface and develop voltage only at a very short length

The *local electric field*,

$$E(R) = E_c\left(\frac{J}{J_c(R)}\right)^n$$

may vary substantially over few mm.



The E field distribution is

$$\frac{E}{E_c} = \int_{-r_c}^{r_c} 2\frac{\left(r_c^2 - r^2\right)^{1/2}}{\pi r_c^2}\left(\frac{J}{J_c(B)}\right)^{n(J_c(B))} dr$$

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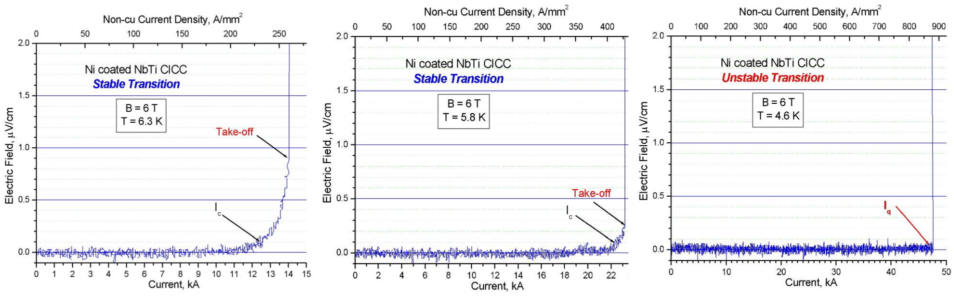
The V-I Transition



At low current density, i.e. low self field, the V-I curve is smooth with extended current sharing range.
At increasing current (e.g. decreasing the temperature), the take-off electric field decreases till it disappears in the noise and the transition looks “unstable”, but actually well reproducible.

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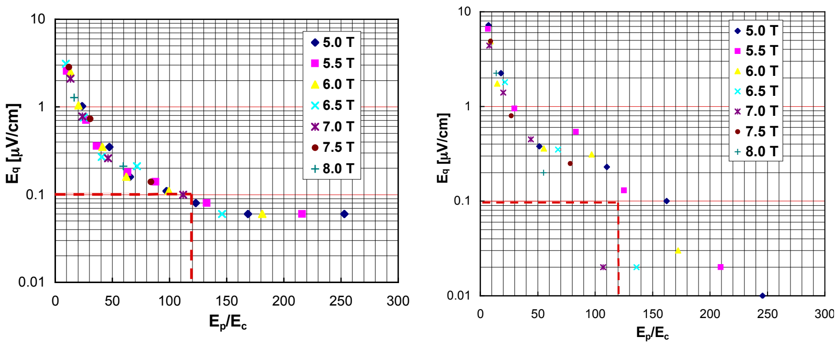
Sudden take-offs are peak field induced quench



Ni coating *Solder coating*

As the take-off electric field, E_q, decreases, the ratio of peak-to-average electric field increases. In our example, the E_c = 10 μV/m criterion for I_c cannot be reached when E_p/E_c > 120. The interstrand resistance in CICC (solder / Ni coating) has a marginal impact on the E_p/E_c threshold

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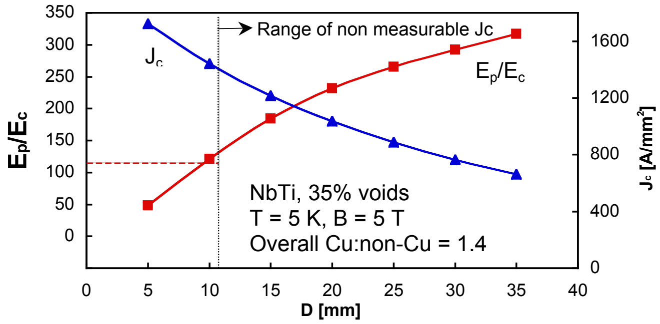
The role of the cable size



With increasing cable size, the expected J_c is smaller than the sum of the individual strands at the same background field because of the large self field.

The ratio E_p/E_c increases above 120 for round cable size > 11 mm: the E_q becomes smaller than 10 μV/cm and the "expected" J_c cannot be achieved

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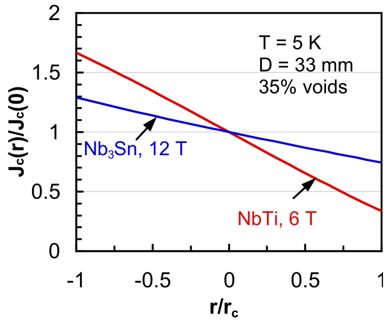
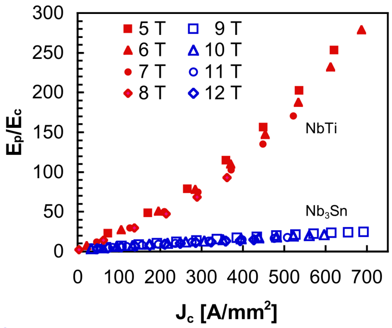
Self field impact on J_c for NbTi vs. Nb_3Sn

NbTi @ 6 T vs. Nb_3Sn @ 12 T. For same Cu:non-Cu, void fraction, T_{op} and cable diameter, the I_c is respectively 85 and 116 kA. Despite the higher self field in Nb_3Sn, the J_c variation over the cable cross section is much higher for NbTi than Nb_3Sn and the E_p/E_c ratio is much smaller.





At all operating fields, the Nb_3Sn cable maintains a moderate Ep/Ec, below 25

No sudden take-off is expected, i.e Eq >> Ec

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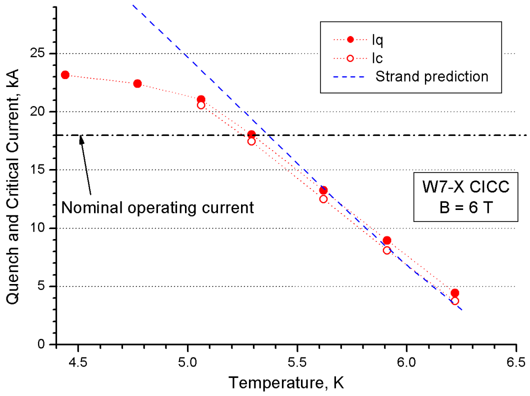
Should we care about Self Field induced take-off ?

As long as the cable current is perfectly balanced among the strands, the self-field induced take-off is just a curiosity, i.e. no degradation.

At the sudden take-off, no current re-distribution is possible because the voltage is too low, even when the peak electric field is sufficiently high to drive a quench.

In case of current unbalance, the performance loss is high and unpredictable. NbTi CICC must be designed to operate below the threshold of sudden take-off



In W7-X CICC, the threshold for sudden take-off is about 20 kA compared to an operating current of 18 kA

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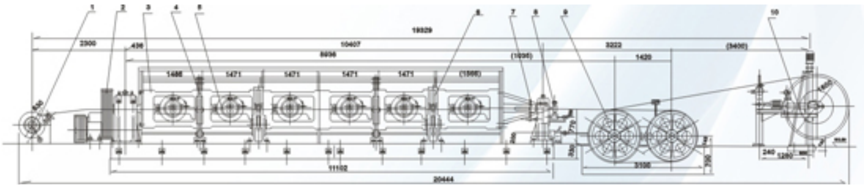
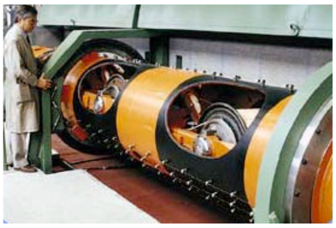
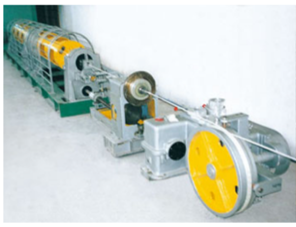
Manufacturing aspects – Tubular Stranding Machines

Suitable for small and medium size stranded cables, with short/medium twist pitch. The mass of the pay-off coils and take-up coil is not rotating. A “thin” cylinder surrounding the pay-off coils picks up the wire and rotates at high speed.







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Manufacturing aspects – Cage Stranding Machines

Suitable for large size stranded cables, with short/medium twist pitch. The mass of the pay-off coils is attached to one or more "planetary" holders and rotates. The production rate is limited by the rotating speed and cable pitch. The "cages" holding each pay-off coils can counter-rotate (back twist) to obtain a torsion-free cable.

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Manufacturing aspects – Drum Twisters

In a variation of the cage strander, the large individual pay-off coils are placed on ground on rotating holders. The cabling point is stationary and the take-up coil rotates.

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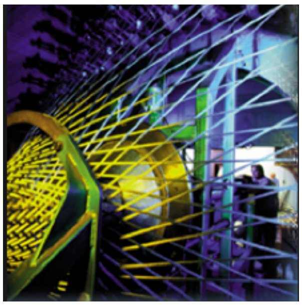
Manufacturing aspects – Braiders

Most common braiders are used for shielding / armoring of conductors (rotary braiders): the braid is a hollow cylinder made by two interleaved layers of parallel wires. Such braids are not transposed for parallel and transverse field.



The pay-off coils must move independently (must have small radius). It is impossible to build braiders with large number of wires and large size/inventory of material

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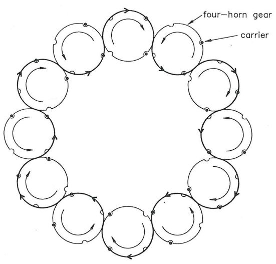
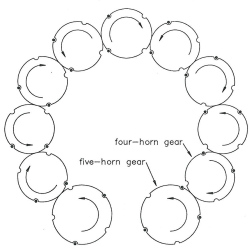
Manufacturing aspects – Special Braiders

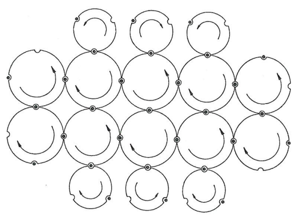
A modification of the rotary braider allows to produce a fully transposed flat braid (Isabelle, 80'). A further variation of the geometry/movements allow to produce a full braid (lattice braid) with fully transposed components.



Rotary Braid



Flat Braid



Lattice Braid

Due to the interleaved structure, braids have a superior mechanical modulus compared to stranded cables with same void fraction. The strand crossovers are at sharper angles. Only limited compaction is possible.

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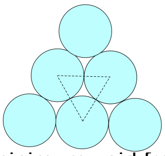
Manufacturing aspects – Rigid Compaction

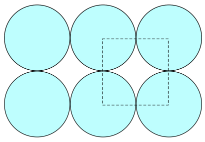
A bundle of round wires in a triangular array has a minimum void fraction of

$$1-\frac{\pi}{2\sqrt{3}}=0.093$$



For a square array, the minimum void fraction is

$$1-\frac{\pi}{4}=0.214$$



For single stage cables with “line contacts” between strands the nominal values of void fraction are realistic, except the issue of the twist angle. For multistage cables, with strand crossover, the minimum void fraction without plastic deformation is much larger, above 40%.

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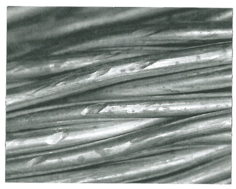
Manufacturing aspects – Plastic Compaction

In practical cables, plastic deformation occurs at the strand contacts, either lines or crossovers. The compaction of the strand bundle is substantially a plastic deformation.

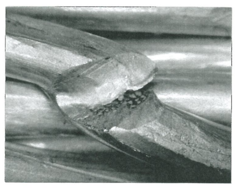
Most cable designs aim at low void fraction

- to restrict the strand movement (NbTi & Nb_3Sn)
- to avoid strand degradation (Nb_3Sn) under operating loads
- to enhance the engineering current density.



The practical lower limit for cable compaction is the strand damage. Such limit depends on the cable layout (number of stages, sequence of pitches) and on the deformation tolerance of the strand.

Beside “strand breakage”, other kinds of degradation are “broken diffusion barrier”, “disconnected filament array”.



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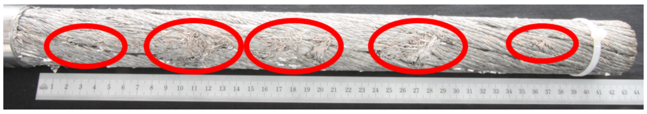
Manufacturing aspects – Compaction Limits

In multistage cables, the compaction process must be gradual, decreasing the void fraction at each cabling stage. In round CICC, practical lower limits are 25%-27%. Flat cables can go further down to 20%. Single stage cables are compacted down to 10% voids.

At large, cables made of NbTi and Bronze Nb_3Sn strands better withstand large compaction loads.



Strand damage is strictly forbidden by QA manuals, however it takes a lot of effort to substantial impair the conductor performance by “strand damage”!!

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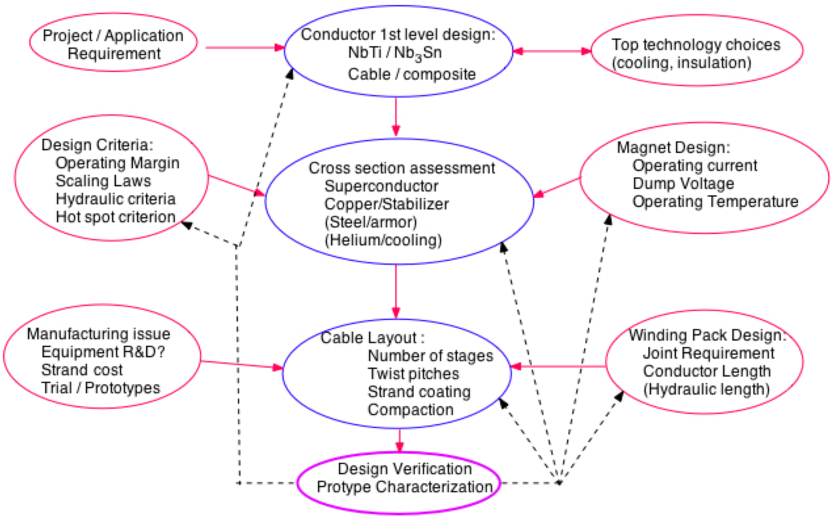
A chart for cabled conductor design



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Moral Recommendations

- Carefully read what is done in the past, learn from former lessons
- Fix the source of a problem rather than cure its consequence
- Keep an open mind for a broad range of
  - Designs/layouts
  - Manufacturers / suppliers
  - Methods / technology
- Be ready for feed-back, constructive criticism, self-criticism
- Do not get caught in the success-oriented loop
- Adjust to budget and schedule boundaries

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