Super-Conductors for Successful Magnets

Content
1. Conductor requirements
2. Case Fusion CICC
3. Case Nb$_3$Sn Rutherford cables
4. Case ReBCO cables
5. Conclusion

Disclaimer: can’t present all, selected cases only!
From material to magnet

• How to make cabled conductors that guarantee the magnet not to quench or degrade?
• Essential area of research, to avoid surprises and degraded magnets
• Need to understand and control the entire chain
• Striking examples exist of missing understanding putting large projects at risk!
Conductor Requirements

What is a successful magnet? Depends on whom you ask...

- **Company**: making financial profit in a highly competitive market (MRI)
- **Physicist**: reaching ultimate user performance whatever it cost (detector magnet in space)
- ... or anything in between

Depends on application

- Commercial magnet (MRI, standard lab magnets)
- Quasi-commercial small series (accelerators, special lab magnets)
- Single unique, one-off magnets (detectors, space applications, HFM facilities)
For large-scale magnets - Cables are what we need!

- Can not build **large scale magnets** from single NbTi, Nb$_3$Sn, B2212 wires, or ReBCO tapes
- Superconductors required **that can be cabled and still perform**!
Scaling - $I_{safe} \propto J \times B^2 \times Volume$

0.0001 m$^3$ HF insert model
200 A

2 m$^3$ MRI magnet
200-800 A @ 1-3 T, ~10 MJ

25 m$^3$ ATLAS Solenoid
8 kA @ 2 T, 40 MJ

50 m$^3$ LHC Dipole magnet
13 kA @ 8 T

400 m$^3$ HEF Detector Magnet
20 kA @ 4 T, 2.6 GJ

1000 m$^3$ ITER Magnets
40-70 kA @ 10-13 T, 50 GJ
• What is thermal –, and load cycling doing with AC Loss and temperature margin $T_{cs}$
• Any type of high-$J_c$ strand OK, or strand properties matter? Mechanics of contact points....
• Twist pitches effect on AC loss, temperature margin $T_b-T_{cs}$, and stability
• Can we measure cable-in-magnet performance in short-section cable tests?
• So far most effort was on AC loss, He cooling, hydraulics, but we have seen surprises!
• Thermo-electric-mechanical dynamics, charging and thermal cycling & stability are key
• Representative measurements and full-size 2D-3D modelling required!
• Smart testing and realistic simulation software are requested................................. etc.
Multifilament strand versus Multi-strand cables

- **Multi-filament wire**
  - Filaments on rings, not fully transposed
  - Uniform properties in section
  - Easy in AC loss and stability

- **Multi-strand cable**
  - Full transposition for uniform current sharing
  - *Multistage twisting*
  - *Crossing strands with discrete X-contacts*
  - Point-like current and heat transfer
  - Strongly affected by local strain
  - Complex in AC loss and Stability

➢ Learnt the hard way: unexpected problems arising from uncontrolled twisting and pressure & interface conditions at strand crossing-over points
Case I: **Fusion CICC - ITER superconductors**

**International Thermonuclear Experimental Reactor**
- Aiming at 500 MW fusion energy
- Initiated in 1995, sited in 2005 in Cadarache, France
- At ~ 60% of construction
- Closed for 1\textsuperscript{st} plasma ~2027, ready for 1\textsuperscript{st} fusion ~2035

**Superconductors used in 48 coils & leads**
- 18 Toroidal Field (TF) Coils
- 6 Central Solenoid (CS) Modules
- 6 Poloidal Field (PF) Coils
- 9 pairs of Correction Coils (CC)
- Current leads
**Fusion CICC – ITER superconductors**

![Toroid coil windings pack](image)

<table>
<thead>
<tr>
<th>System</th>
<th># units</th>
<th>Energy GJ</th>
<th>Peak field T</th>
<th>Conductor length km</th>
<th>Weight t</th>
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<tbody>
<tr>
<td>Toroidal Field</td>
<td>18 coils</td>
<td>41</td>
<td>11.8</td>
<td>82.2</td>
<td>6540</td>
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<tr>
<td>Central Solenoid</td>
<td>6 modules</td>
<td>6.4</td>
<td>13.0</td>
<td>35.6</td>
<td>974</td>
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<tr>
<td>Poloidal Field</td>
<td>6 coils</td>
<td>4</td>
<td>6.0</td>
<td>61.4</td>
<td>2163</td>
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<tr>
<td>Correction Coils</td>
<td>9 pairs</td>
<td>-</td>
<td>4.2</td>
<td>8.2</td>
<td>85</td>
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<tr>
<td></td>
<td>48 coils</td>
<td>52</td>
<td>4-13</td>
<td>130 km</td>
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</table>

**Initial conductor concept:**

- Maximum stability by He on the strands
- Cost efficient production (?) through “simple” multi-stage cabling, cable pull into long jacket, rolling down for a close fit, and spooling for coil winding
- **NbTi (PF&CC) and Nb₃Sn (TF&CS)** versions exist
Issue 1: Inter-strand contact resistance ageing in a CICC

- Is AC loss in CICC predictable and durable during the lifetime of ITER?
- Build a cryogenic press with in-situ AC loss measurement and run cycles up to 100,000!
- Example of what was found: initially a decrease of the loss and after some 1000 cycles, the coupling loss increases exceeding by far the virgin level

✓ Thus AC loss may become too high and lead to instability, and it loads the cryosystem
ITER PF insert coil AC loss test in CSMC-Naka Japan (2008) and comparison to “Uni Twente Cable Press AC loss results”

- Excellent agreement is found showing that full size cables can be correctly tested in a small scale test facility based on 500mm samples
- Demonstrating importance of “smart” testing
Issue 2: Nb$_3$Sn CICC - current sharing temperature ageing

• Initially, naïve idea that a CICC is simply bundling 1000 Nb$_3$Sn strands in a conduit...
• Body force of magnet is taken by the conduit, not transmitted to the strands
• Still, local Lorentz Force = JxB [N/m] causes cable compression within the conduit
• Enhanced transverse load on crossing strands --> tensile, compressive & bending deflection
• Strand properties, surface coating, cabling pattern and void fraction will affect $I_c$ and thus the cable’s temperature margin and magnet performance
• **Ageing margin temperature margin:** $\{T_{cs}(B,I) - T_b\} = \{T_c(B) – T_b\} \cdot \{1 - I/I_c\}$
• Explore operational limits to arrive at predictable and durable operation
• Significant spread in $I_c$-susceptibility to bending strain and contact stress
• Contact stress depends strongly on cabling pitch length
• Relevant range 20 - 100 MPa for short and long cabling twist pitches
• These loads change ‘reversible’ strain state and causing cracks, thus $I_c$!
✓ Really expect large spread in CICC performance
✓ Optimization is strand type dependent!
Simulation is Key for predicting conductor performance

- TEMLOP code (@UT) developed to study the effect of characteristic bending wavelength, essentially confirming the effects seen (thus naive cabling is risky!)

- Badly chosen twist pitches leads to maximum degradation (few ITER cables in this trap)
- Strong minimum found when wrong twist-pitches and void fractions are chosen
  ✓ This $T_{cs}$ ageing causes a reduced stability margin risking entire ITER to fail when ignored.
Example - ITER’s Central Solenoid conductor

### Problem (2011): Conductor test shows “dead” after only 1000 charging cycles, 60000 needed!

### Cure (2012): Use short twist pitch in 1st stage triplet thereby minimizing strand bending (but higher AC loss)

- ‘Last minute’ recovery program to understand and tweak the conductors parameters such that it may work, solution found, solenoid rescued!

- New conductor with very short twist pitches now implemented

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**Legend:***
- **Test at 45.1 kA / 10.85 T**
- **Temperature, K**
- **Number of load cycles at 45.8 kA / 10.85 T**
- **Current Sharing Temperature, K**
- **Cable test raises fears at fusion project**
- **Degradation of superconducting cables for the heart of the ITER fusion machines threatens to cause further delays.**
- **Scientists on three continents are scrambling to understand a potentially serious problem with superconducting cables destined for ITER, the world’s largest fusion experiment.**

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*Published online 8 March 2011 | Materials Today, 15(1), 2011 | doi: 10.1016/j.mattod.2011.01.001*

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**References:**
- Plenary presentation Mo-Mo-PL1-01 given at MT26, 22 – 27 September 2019; Vancouver, Canada.
Lessens learnt - and next, DEMO

It was demonstrated:

- **AC loss ageing**: very much depends (factor 5 seen) on the inter-strand resistances, thus on number of load and thermal cycles!

- **Temperature margin ageing**: very strain dependent and thus depends and strand-type, cabling pitches and thermal cycling, a nasty disadvantage of Nb$_3$Sn-CICC.

- It may work when carefully tweaking cabling parameters and minimize thermal cycling, but robustness missing

- Better not to repeat for next machines like DEMO, mitigate these flaws.....

- DEMO conductors are now being developed:
Case II: \(\text{Nb}_3\text{Sn} \) Rutherford cables for accelerator magnets

For efficiency-cost-volume reasons current density in accelerator windings must be at least some \(400 \text{ A/mm}^2\) at requested field:

- 8 T at LHC, 11 T for HL-LHC and 16 T for FCC
- Conductor \(J_c\) development underway for \(1500 \text{ A/mm}^2\) at 16T, 1.9K
- Goal almost reached in short wire sections
- Next step: maturing production, further increase to some \(1800 \text{ A/mm}^2\) for achieving margin and robustness, and making long lengths

Main issue is Sustaining Transverse Pressure on cable wide face
High-Field \( \text{Nb}_3\text{Sn} \) magnets - for HL-LHC and FCC

- **HL-LHC magnets** under construction, some 40 cold masses **under construction** at CERN and at FNAL
- **FCC 16 T dipole magnets** conceptual magnet designs being developed with partners,
- Long term R&D 2020-2040

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<th>FCC</th>
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<tr>
<td>Circumference (km)</td>
<td>27</td>
<td>98</td>
</tr>
<tr>
<td>LHC Dipole field (T)</td>
<td>8.3</td>
<td>11</td>
</tr>
<tr>
<td>4 dipoles @HL-LHC</td>
<td>8.3</td>
<td>11</td>
</tr>
<tr>
<td>C.o.M. energy (TeV)</td>
<td>14</td>
<td>100</td>
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**HL-LHC dipole and quad construction design**

**Flavor of FCC type 16 T dipole magnet conceptual designs by collaborators**
Record magnets – recent achievements

R&D magnet

15T $\cos\theta$ dipole at FNAL, 1st test 14.1 T @4.5 K
More after strain adjustment… very promising result!

Production magnet

11 T Dipole magnet windings for HL-LHC
**Nb$_3$Sn Rutherford cables under transverse pressure**

- Critical current affected by pressure
- **Reversible part** due to lattice deflection
- Reversible part some 10-20% at 150 MPa!
- **Irreversible damage**, filament cracking
- Starts at some 150-200 MPa

**Note:** measured with pressure uniformly applied, in real coil not the case, thus worse to expect.

- **Transverse pressure of some 150 MPa OK** in perfectly impregnated cables, but $I_c$ then some 20% less, eating from the margin, thus reduced stability!

- Strand and cable mechanical optimization possible to some extent, not more, a **principle limit for not-reinforced Rutherford cables**!
Issue 2: Nb$_3$Sn Rutherford - Cable stability versus $I_c$

- Operate cable at value of $I/I_c$ not too high.

- Profit from collective strand stability to gain robustness and be less susceptible to wire motion and resin carking!

- The transition is characterized mainly by single strand level (heat capacity) and the “kink value”, $I/I_c$ value $i_{kink}$

- Systematically all effects determining the $i_{kink}$ were investigated experimentally and verified by simulation using CUDI

- Trivial factors are $C_p$ (sf He presence); cooling sf He and inter-strand contact resistances!
**Nb₃Sn - Stability cliff disaster**

- Using collective cable stability yields factor 10 to 50 more MQE!
- NbTi 1.9 K, sf-He inside, *need margin* to profit from collective strand stability, I/Ic<0.75 !
- **Impregnated Nb₃Sn is in single strand regime when at >75% on load line**! Need to reduce I/Ic down to <0.4 to profit again!
- We see the same in impregnated NbTi 1.9 K (watch coil heads!), “lost” stability, need to reduce to I/Ic<0.45 !

✔ **Conclusion? What to do ? Ignoring and hoping for the best, or...?**
✔ It is not credible to make some 4000 (FCC) full-size Nb₃Sn magnets in industry with current technology (impregnated) based on single strand stability
• The present design ideas of operating 10-16T Nb$_3$Sn magnets at >80% on load line is not robust, is not a credible solution!
• We can not make large scale series based on lucky-few magnets. **This will kill projects and funding!**

**What to do:**

1. Keep impregnated cables as is but reduce $I/I_c$ to some 0.4
2. Dramatically increase heat capacity of the conductor.
3. Bring He cooling back in the conductor (shifting $I_{\text{kink}}$ to right)
4. Reduce inter-strand contact resistance (shifting $I_{\text{kink}}$ to right).
5. **A well-balanced combination of 1 to 4!**

✓ We need improvements and new strategy, high priority! (**or use switch to HTS €€€**)
Case III: Al stabilized conductors for Detector Magnets

Why Al?

- *Simplicity of conduction cooling*, affordable since no dynamic operation, quasi stationary
- High-purity Al stabilized, RRR 2000, *maximum MPZ* (m), much larger $\lambda/\rho$ than copper!
- *Particle transparency* for minimum particle scattering
- *But higher collision energy implies larger dimension*, tracking length and field ($BL^2$), thus higher coil winding stress, requiring conductor reinforcement (pure Al yields at 17 MPa)

*Increase of section for larger detectors*

*ATLAS conductor 65kA@5T,4.2K*

*ATLAS magnet system, 4T/22m, 1.6 GJ*
Magnets for FCC ee & hh collision detectors

Proposed Future Circular Collider

Stage 1: ee collisions (~2040)
Stage 2: 100 TeV hh collisions (~2070)

• 2 ee and 1 hh collision detectors proposed requiring reinforced Al stabilized conductors

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**How to reinforce pure Al? - proven solution and R&D**

**Option 1**
Micro-alloy pure Al with Ni or Zn
Used in the ATLAS Solenoid

**Option 2**
Reinforce with Al-alloy side bars, EB-welded to the pure Al of the NbTi/Cu/Al conductor

Using **Al 6082 T6**
(Used in CMS Solenoid)

Using **Al 7020/7068**
(R&D for FCC-IDEA)

- Al+0.1wt% Ni stabilizer
- Al7068
- FCCee IDEA

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Next generation of Aluminum-stabilized Rutherford conductors for 30 to 40 kA at 5 T:

- Peak magnetic field on conductor 4.5 T
- Current sharing temperature 6.5 K
- 2 K temperature margin when operating at 4.5 K
- **Nickel-doped Aluminum (≥0.1 wt.%)** combining good electrical properties (RRR 600) with mechanical properties, 146 MPa conductor yield strength
Case IV: ReBCO Roebel Cables

Developed for highest current density in a flat cable, ‘ideal for racetrack-like coils for motors, generators, FCL, transformers……., and HEF accelerator coils

Further optimization required for strand cutting techniques and making long lengths:

- Punching
- Laser cutting

Magneto-optical imaging showing broken strands

Homogeneity along strand:

Robinson Research Institute

Transposition length

Roebel Cable’s transverse pressure resistance

- Transverse pressure of ReBCO tape shows much higher tolerance than bare Roebel cable (not impregnated)

- Cables I & II ‘KIT-type’
  - Araldite CY5538/HY5571
  - Filled with silica powder

- Cables III & IV ‘CERN-type’
  - CTD-101K
  - Glass rope & glass sleeve

☑ Impregnated Roebel cable can withstand transverse pressure in excess of 300 MPa!
☑ Very good for high-field magnets
ReBCO dipole developments - examples

ReBCO dipole development at CEA
• Design for full-size dipole variants
• Demonstration racetrack coil reached 5.37 T

ReBCO Feather series dipole insert development magnets at CERN
• Coil 1: using SuperOx/SuNAM type Roebel cable, reached 3.35 T
• Coil 2: using Bruker type Roebel cable, presently at test
Case V: ReBCO CORC – cables and wires

Dreamed conductor: easy to make, off the reel, ready to use, no-heat treatment, ‘isotropic’, flexible, cab used like a thick NbTi wire but much better

- Truly opening up massive magnet applications running at 30-50 K
- Today the only thin-round wire solution is CORC-’cable’ (and variants)
- Multi layers of ReBCO tapes spiraled around a core
- Quest for thinner wire: thinner substrate > thinner core, 100>50>30>20 µm
Flavor of demonstration coils in progress

- Series of CCT coils at LBNL
- Insert solenoids at HFML and CERN/UT
- Racetracks at BNL and CERN

**ReBCO-CORC wire applications - examples**

- **CCT3**: 6 layers, 5T@4.2K, 10kA, 140m wire
  - 74 mm dia, insert, 2 layers, 2T in 15T
  - 100 mm bore insert, 2T in 14T, 17m wire, 5kA

- Making of CCT2
- Common coil insert
  - 4T, 50m, 10kA, in 10T
  - Racetrack insert, 80 mm dia, 2 layers

ReBCO CORC - Cable-in-Conduit conductors

- **Cable-In-Conduit Conductors (CICCs),** designed for large-scale, high-current magnets as for large outsert coils, fusion magnets and particle detectors

- $NbTi$ and $Nb_3Sn$ conductor development close to their limits, also quest for higher temperature & no-helium operation  --> **Development of ReBCO based CICCs**

- Dramatic increase in stability and enables operation at 20-50 K

Examples of several ReBCO based CICCs are in development around the globe:

- CERN & ACT: CORC 6-a-1 CICC
- North China Electric Power University Quasi-Isotropic Conductor
- ENEA: Twisted Stacked Round CICC
- Swiss Plasma Center: Twisted Stacked Rectangular CICC
Bus bars based on CORC CICC conductor, lighter, taking less space.

**CORC Bus Lines:**
- Reduce weight
- Reduce volume
- Reduce power converter requirements
- Allow power converter placement on surface

**CORC Magnets:**
- Extreme thermal & electric stability
- Operation at 20 to 50 K
- Simpler cooling with helium gas
- Jacket material application dependent
- Steel for fusion, Aluminum for detectors.....
- Options for internal or external cooling

Detector cavern
Typical result showing that R&D is needed
• Both, conduction - and inter cooling work
• SS-jacket version behaved as expected, 18 kA at 12 T and 45 K
• Cu jacket version showed 60% degradation,

Why! :
• Primary failure mode is a pinching effect
• Specific for this CORC production parameters
• Copper tapes layers around the core do not give sufficient mechanical support
CORC Cable-In-Conduit Conductor Design

- Since 2015 development at CERN and ACT of series of CICC variants, 4 done, 2 in pipeline
- **2.8 m long units**, rated for **80 kA at 12 T, 5K**, tested at CERN and at SULTAN

**Magnets & Bus Bars:**
- High thermal & electrical stability
- Practical conduction cooling

**Fusion type magnets:**
- Can sustain high stress
- For large heat load
- Internal forced-flow cooling

**Next sample:**
- 6-o-1 with better strand support
- Test in Sultan early 2020.

**In design:**
- x-o-1 with thinner strands
- Shorter twist pitch
- Internal He cooling
- Easy adjustable

Conclusion

• Understanding electromagnetic, thermal & mechanical behaviour of cables is key to the success of many magnets.

• A cable is more than putting many strands in parallel and ignoring this can lead to disappointing magnet performance and thus expensive mistakes.

• Most problems are related to high mechanical loading and load cycling of inter-strand contact points leading to changes in AC loss, stability and temperature margin.

• Critical current density is mostly not an issue, but maintaining transport properties & robustness are and often missing for allowing series production.

• Samples can often not be tested, for financial reasons, only subscale and in a limited parameter range, not covering the real operating conditions.

• In the past 10 years new tools, smart testing and dedicated test facilities were developed. These are essential for calibration simulation codes that can predict cable performance in a real magnet. **Use these!**