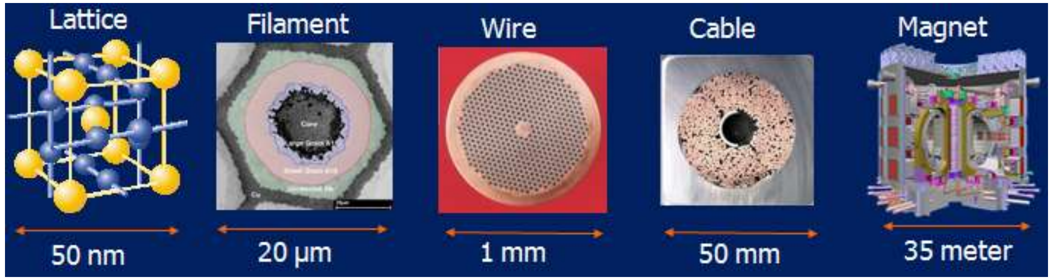
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Mo-Mo-PL1-01 given at MT26, 22 – 27 September 2019; Vancouver, Canada.

UNIVERSITY OF TWENTE.

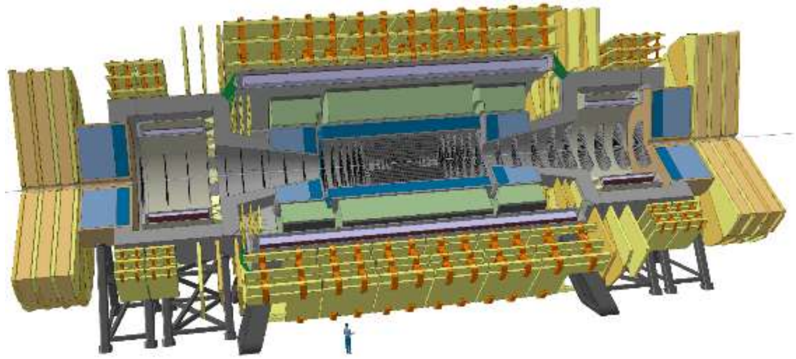
Super-Conductors for Successful Magnets



Herman ten Kate

Content

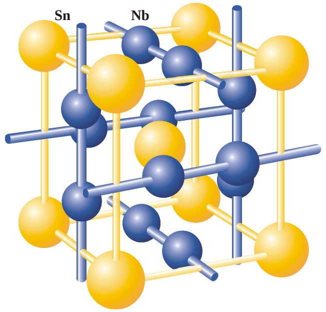
1. Conductor requirements
2. Case Fusion CICC
3. Case Nb_3Sn Rutherford cables
4. Case *Re*BCO cables
5. Conclusion



Disclaimer: can't present all, selected cases only!

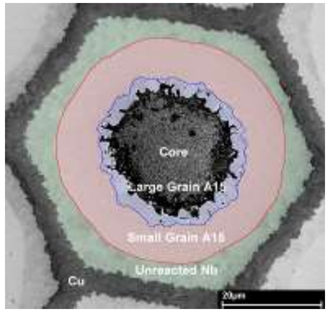
From material to magnet

Lattice



50 nm

Filament



20 µm

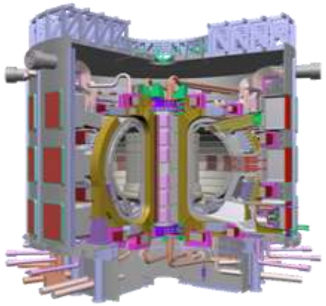
Wire

1 mm

Cabled conductor

50 mm

Magnet



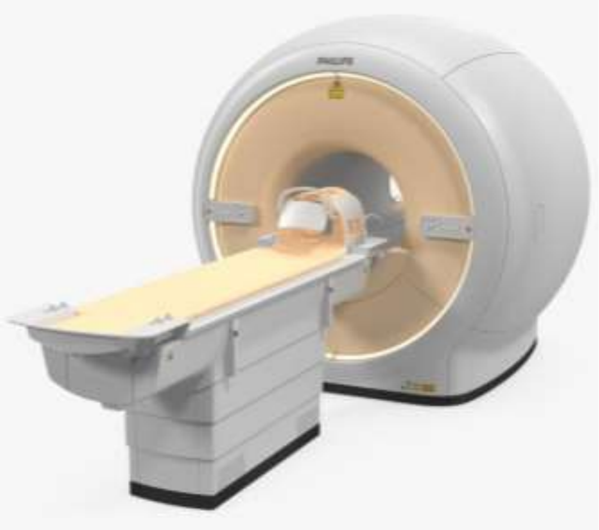
35 meter

- 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

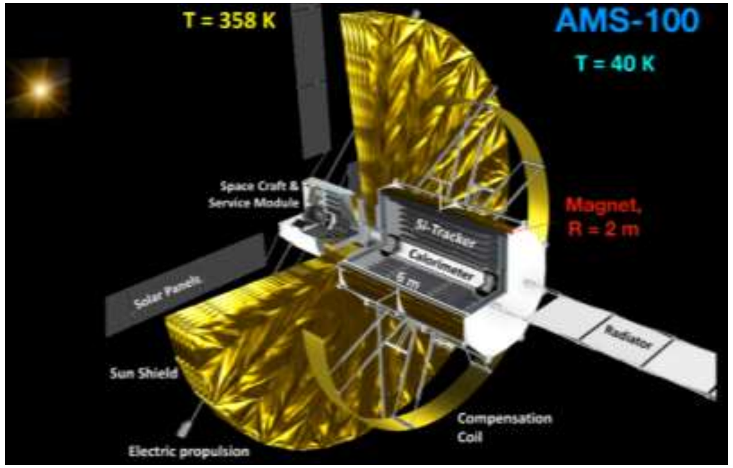
What is a successful magnet? Depends on whom you ask…

- **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)



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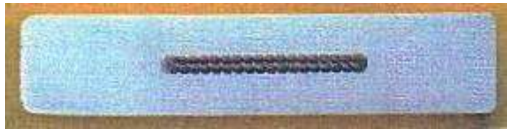
For large-scale magnets - Cables are what we need!

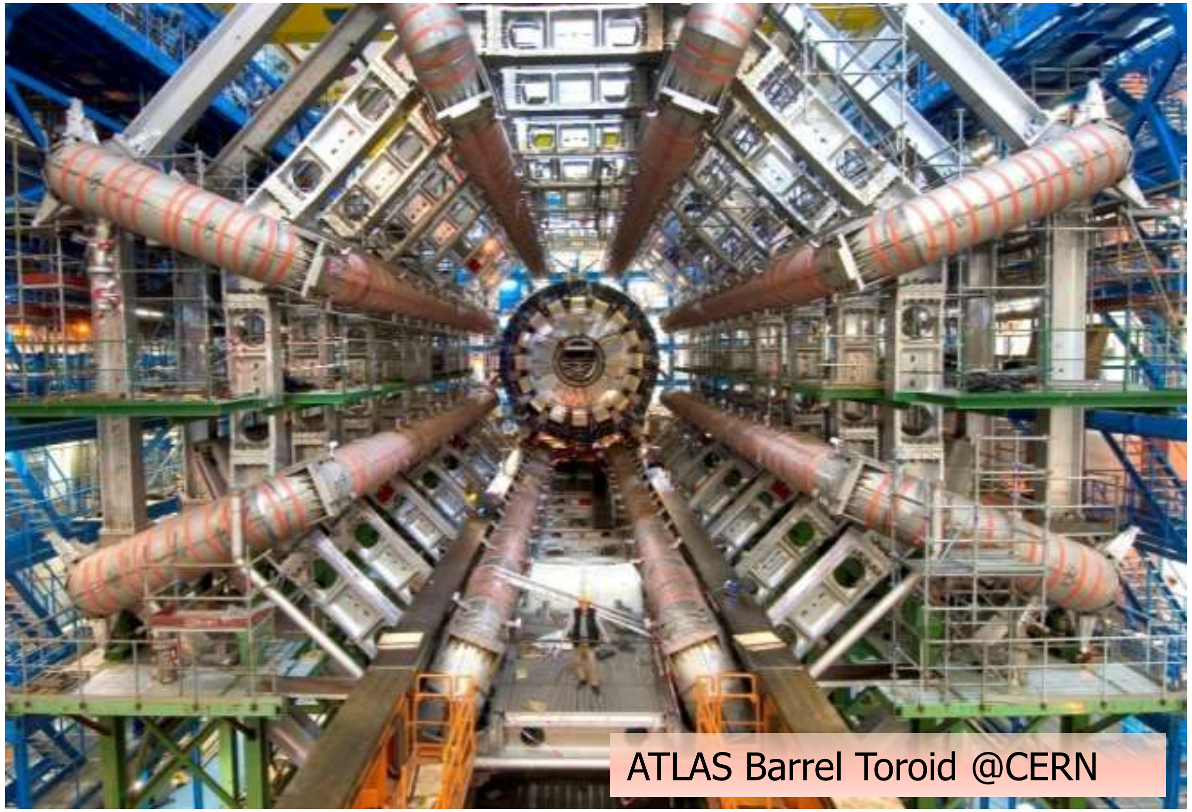
200 A HTS tape

✗

65000 A@5T Al-NbTi/Cu



✓



ATLAS Barrel Toroid @CERN

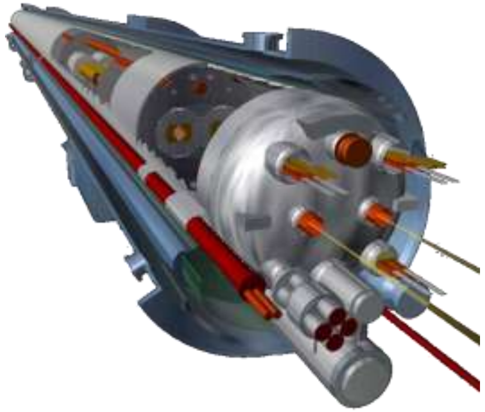
- Can not build **large scale magnets** from single NbTi, Nb_3Sn, B2212 wires, or ReBCO tapes
- Superconductors required **that can be cabled and still perform**!

Scaling - $I_{safe} \propto J \times B^2 \times$ Volume

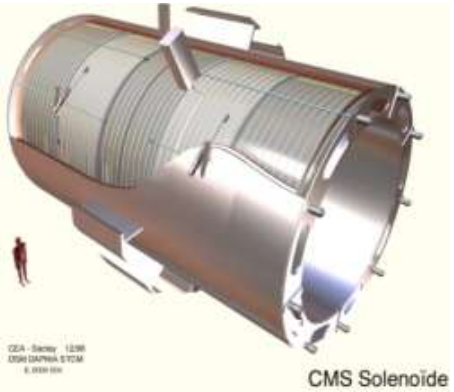
0.0001 m³ *HF insert model*
200 A

2 m³ *MRI magnet*
200-800 A *@ 1-3 T, ~10 MJ*

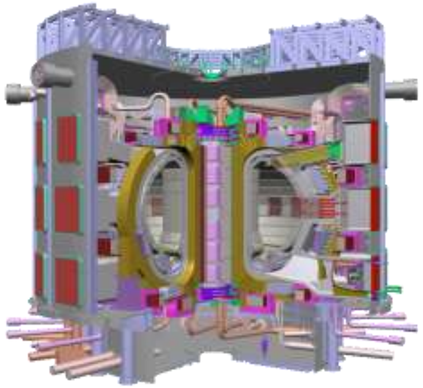
25 m³ *ATLAS Solenoid*
8 kA *@ 2 T, 40 MJ*



50m³ *LHC Dipole magnet*
13 kA *@ 8 T*

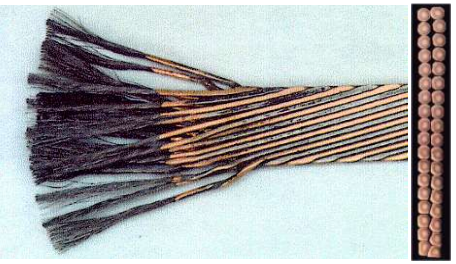


400 m³ *HEF Detector Magnet*
20 kA *@ 4 T, 2.6 GJ*



1000 m³ *ITER Magnets*
40-70 kA *@ 10-13 T , 50 GJ*

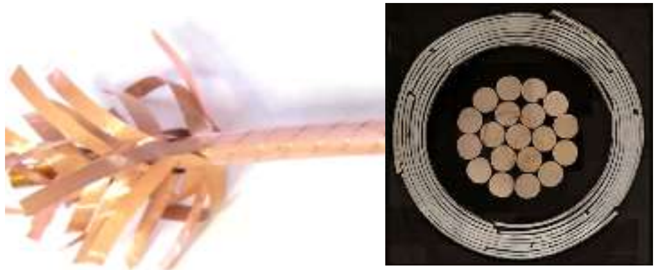
Understanding cables



Rutherford cable

CICC

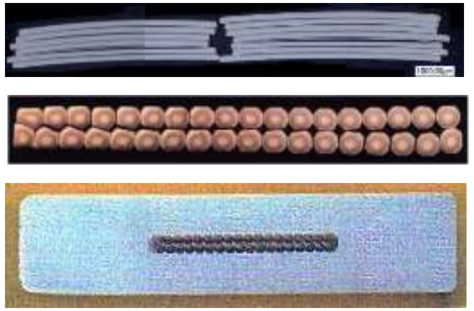
ReBCO-Roebel cable



ReBCO-CORC

- 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

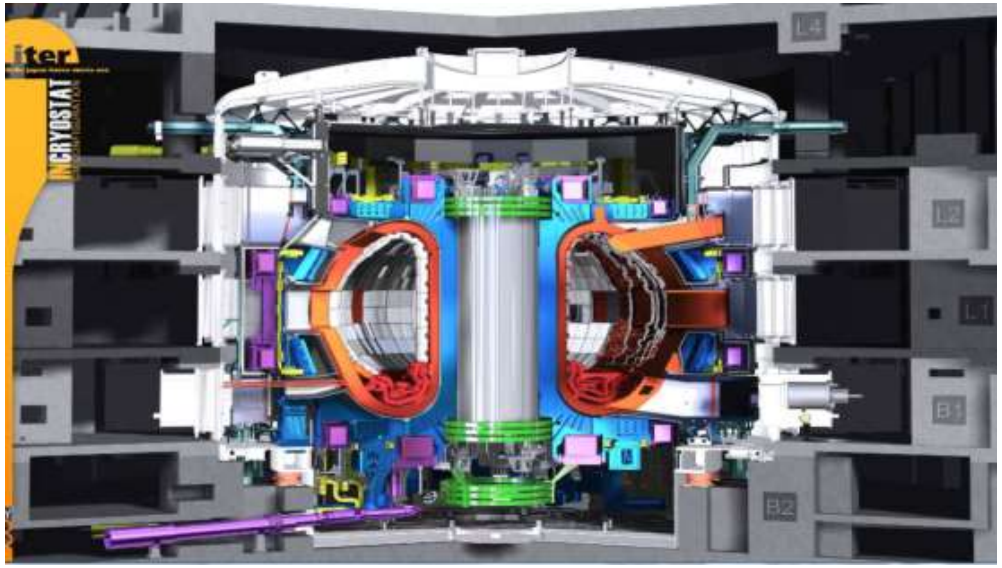


- **Multi-filament wire**
- Filaments on rings, not fully transposed
- Uniform properties in section
- Easy in AC loss and stability

- **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 1st plasma ~2027, ready for 1st 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

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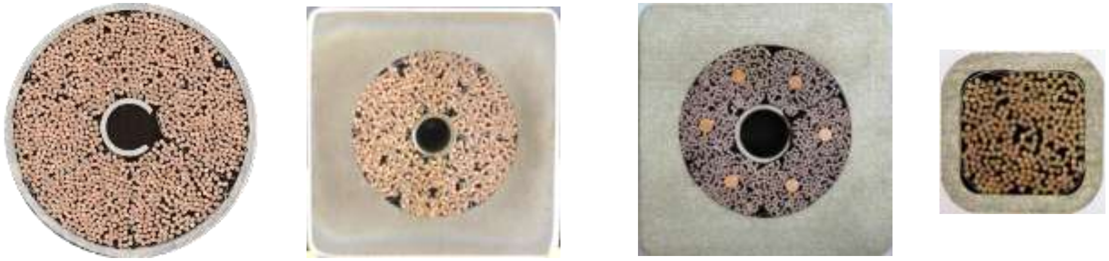
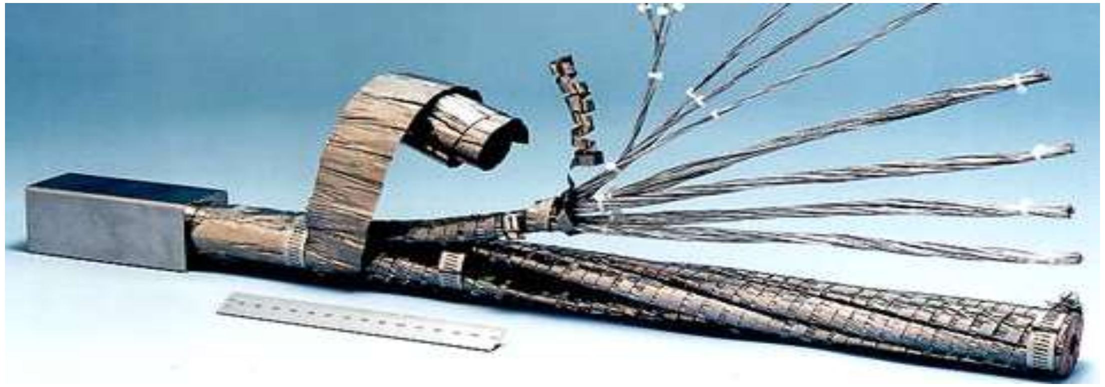
Fusion CICC – ITER superconductors

System	# units	Energy GJ	Peak field T	Conductor length km	Weigth t
Toroidal Field	**18 coils**	**41**	**11.8**	**82.2**	**6540**
Central Solenoid	**6 modules**	**6.4**	**13.0**	**35.6**	**974**
Poloidal Field	**6 coils**	**4**	**6.0**	**61.4**	**2163**
Correction Coils	9 pairs	-	4.2	8.2	85
	48 coils	52	4-13	130 km	

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 **Nb_3Sn** (TF&CS) versions exist

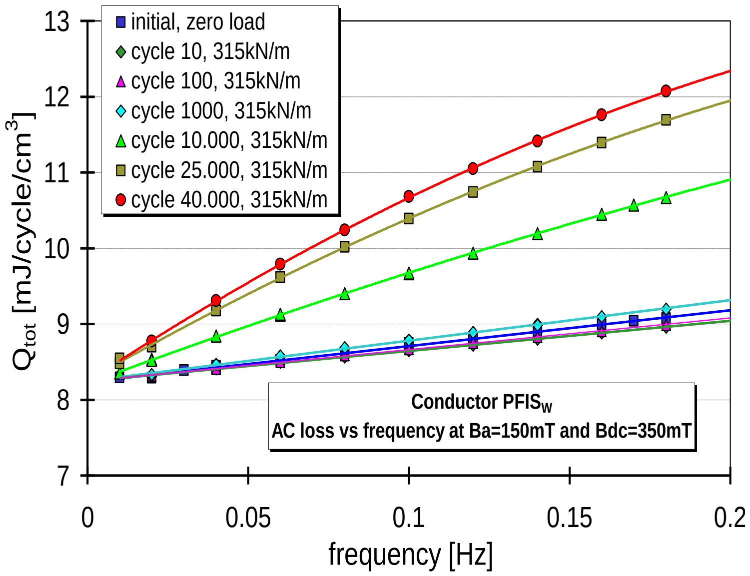


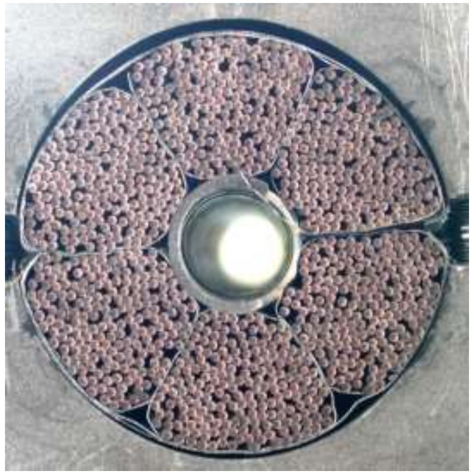


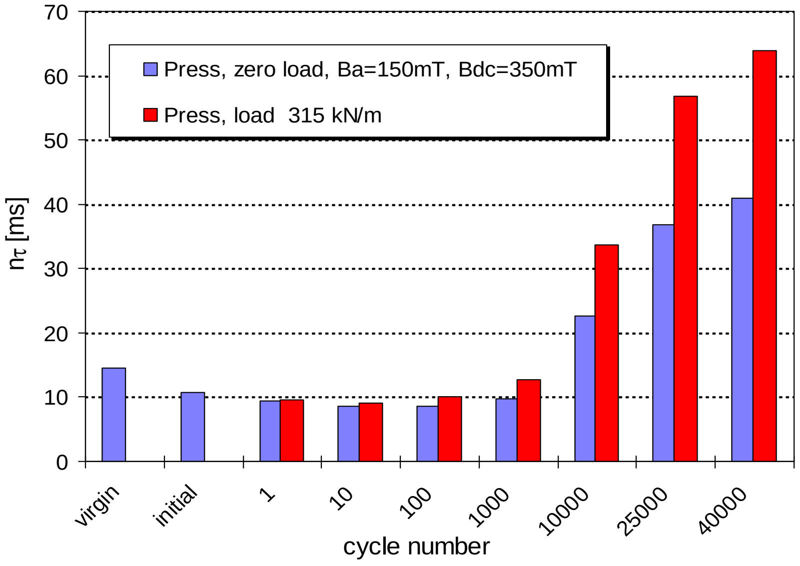
Issue 1: Inter-strand contact resistance ageing in a CICC

- **? 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**

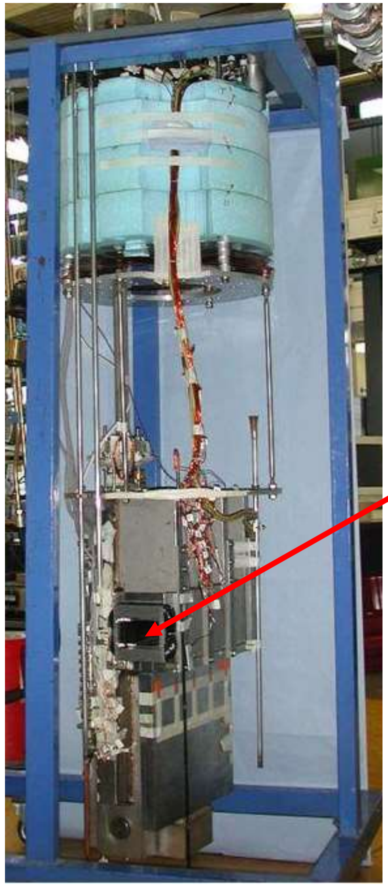


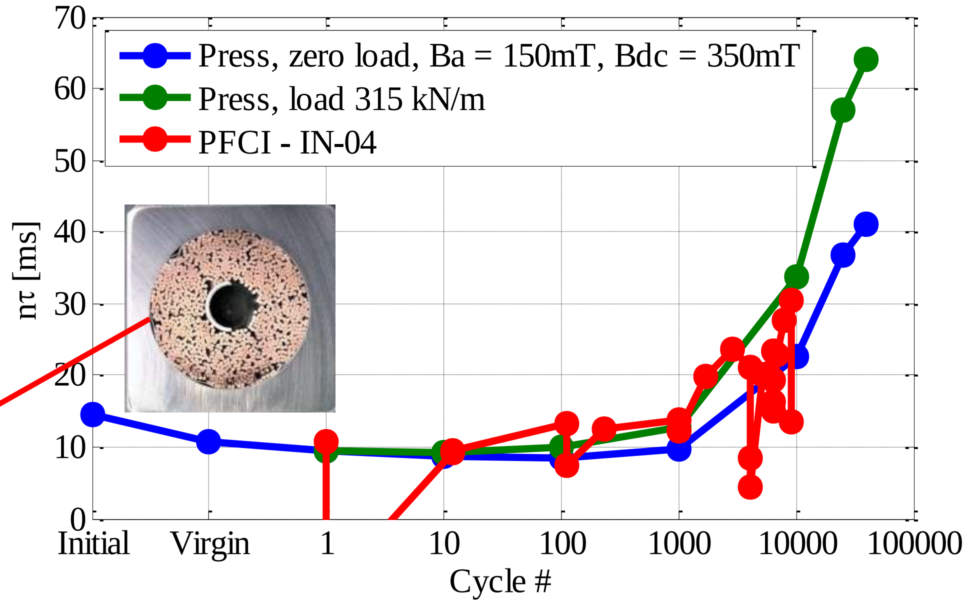


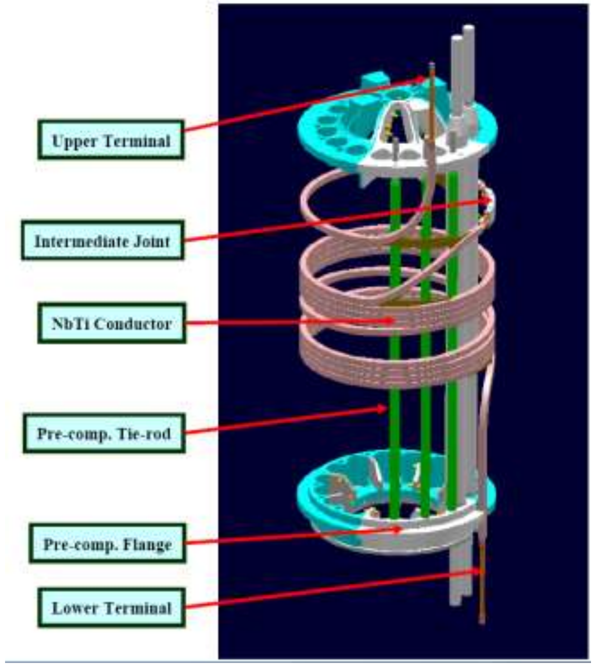


AC loss ageing measured in a demo coil - verification

- ITER PF insert coil AC loss test in CSMC-Naka Japan (2008) and comparison to *“Uni Twente Cable Press AC loss results”*

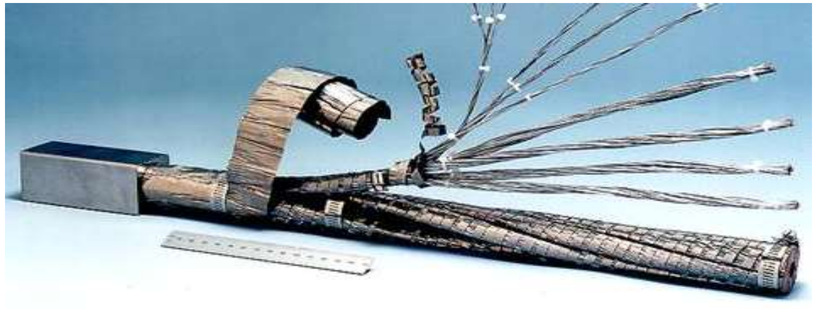


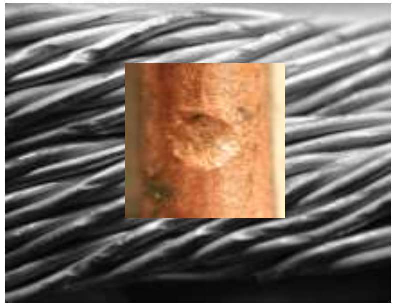


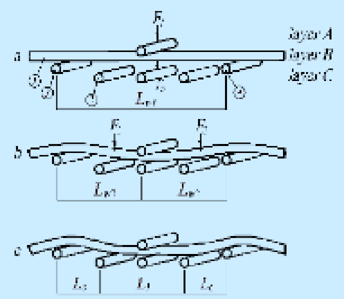


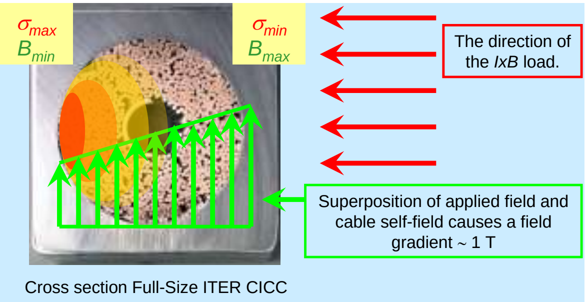
- ✓ Excellent agreement is found showing that full size cables can be correctly tested in a small scale test facility based on 500mm samples
- ✓ Demonstrating importance of “smart” testing

Issue 2: Nb_3Sn CICC - current sharing temperature ageing



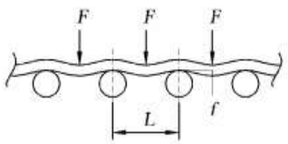


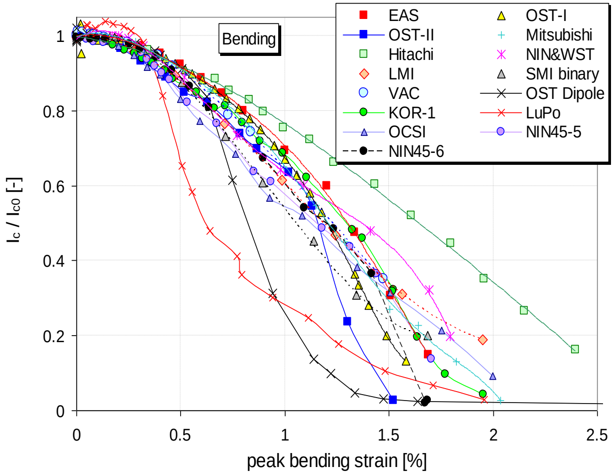


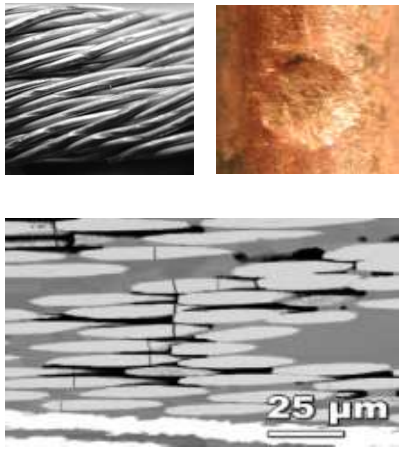


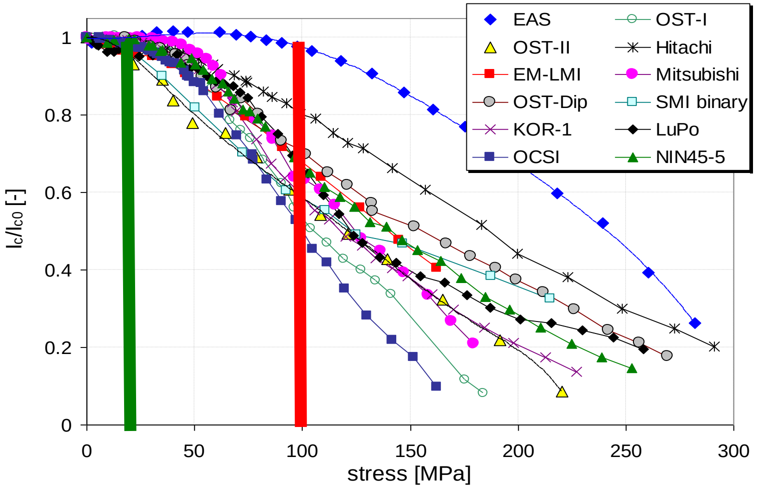
- Initially, naïve idea that a CICC is simply bundling 1000 Nb_3Sn strands in a conduit…
- Body force of magnet is taken by the conduit, not transmitted to the strands
- Still, local Lorentz Force = JxB [N/m] causes cable compression within the conduit
- Enhanced transverse load on crossing strands --> 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:** $\{T_{cs}(B,I) - T_b\} = \{T_c(B) - T_b\} . \{1 - I/I_c\}$
- Explore operational limits to arrive at predictable and durable operation

Susceptibility to Periodic bending and Contact Pressure





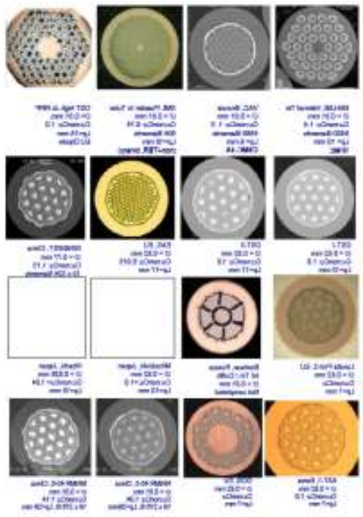




- Significant spread in I_c- susceptibility to bending strain and contact stress
- Contact stress depends strongly on cabling pitch length
- Relevant range 20 - 100 MPa for short and long cabling twist pitches
- These loads change ‘reversible’ strain state and causing cracks, thus Ic!

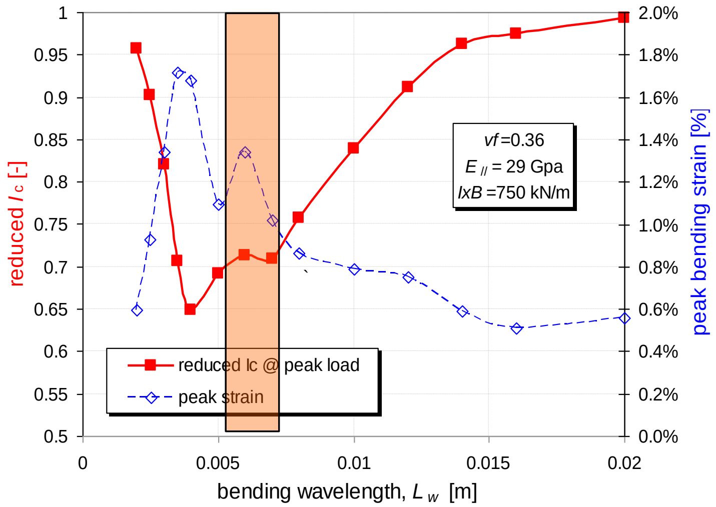
✓ **Really expect large spread in CICC performance**

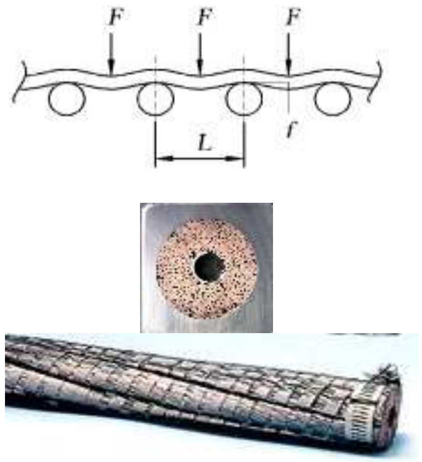
✓ **Optimization is strand type dependent!**

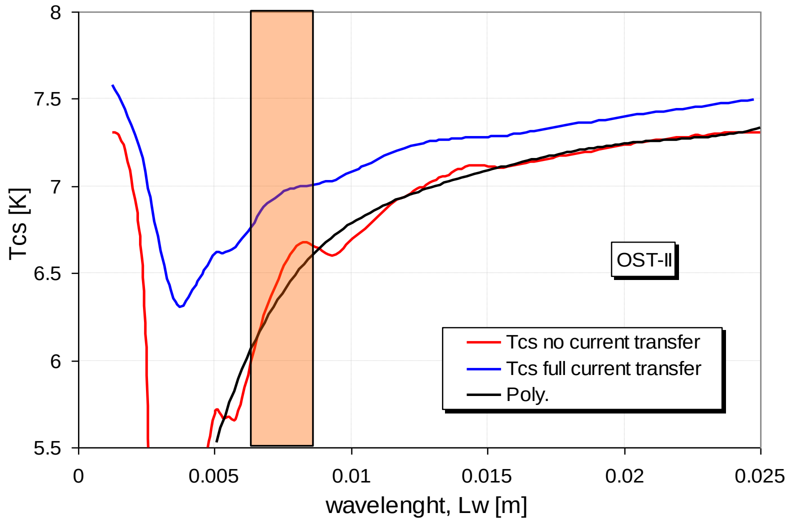


Simulation is Key for predicting conductor performance

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



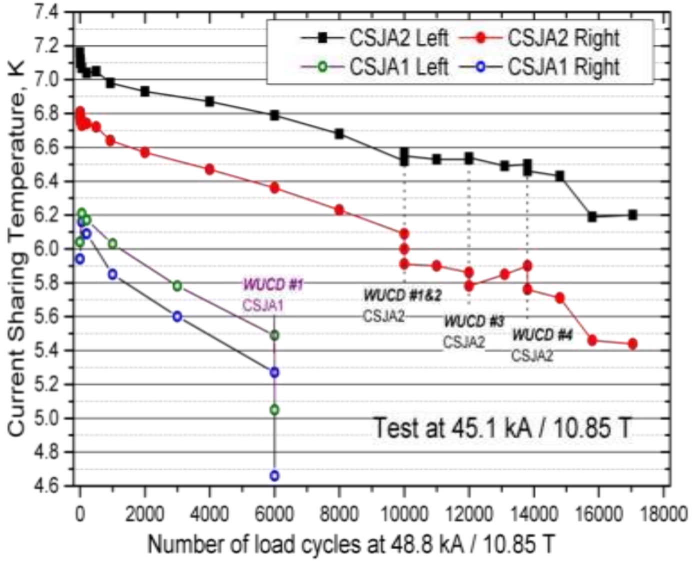




- Badly chosen twist pitches leads to maximum degradation (few ITER cables in this trap)
- Strong minimum found when wrong twist-pitches and void fractions are chosen

✓ **This T_{cs} ageing causes a reduced stability margin risking entire ITER to fail when ignored.**

Example - ITER’s Central Solenoid conductor



Issues with CSJA1

ITER'S BEATING HEART

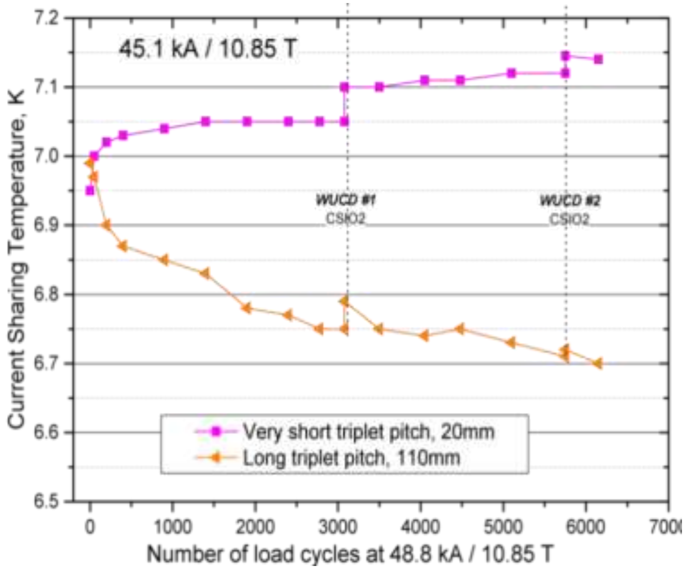
The superconducting cables of the central solenoid are a crucial part of the fusion reactor.

Cable test raises fears at fusion project. Degradation of superconducting cables for the heart of the ITER fusion machine 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.

……….problem developed during the *Swiss* tests, which mimicked ITER's operating conditions by placing the cable in a strong but non-uniform magnetic field……….

Published online 8 March 2011 | Nature 471, 150 (2011) | doi:10.1038/471150a



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)

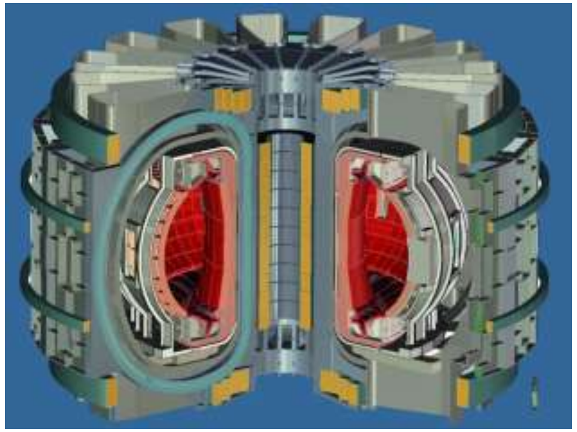
- ‘Last minute’ recovery program to understand and tweak the conductors parameters such that it may work, solution found, solenoid rescued!

✓ **New conductor with very short twist pitches now implemented**

Lessens learnt - and next, DEMO

It was demonstrated:

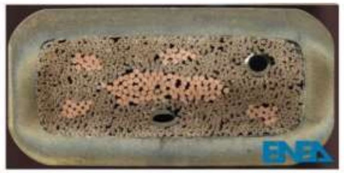
- **AC loss ageing**: very much depends (factor 5 seen) on the inter-strand resistances, thus on number of load and thermal cycles!
- **Temperature margin ageing:** very strain dependent and thus depends and strand-type, cabling pitches and thermal cycling, a nasty disadvantage of Nb_3Sn-CICC.



- 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…..

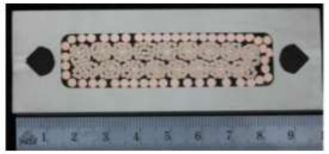
- DEMO conductors are now being developed:

ENEA-WR1



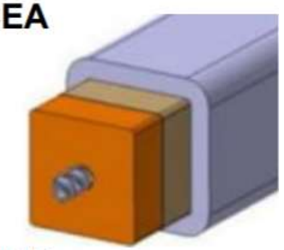
W&R
ε_{eff} -0.50%~ -0.55%

SPC-RW1



R&W
ε_{eff} -0.28%~ -0.32%

CEA



W&R
ε_{eff} -0.66% (design)

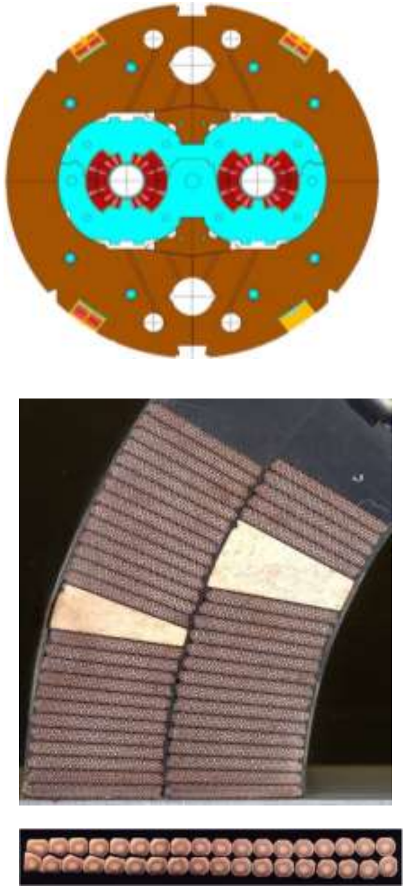
Case II : Nb_3Sn Rutherford cables for accelerator magnets

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

- 8 T at LHC, 11 T for HL-LHC and 16 T for FCC
- Conductor Jc development underway for 1500 A/mm^2 at 16T, 1.9K
- Goal almost reached in short wire sections

- Next step: maturing production, further increase to some 1800 A/mm^2 for achieving margin and robustness, and making long lengths

Main issue is Sustaining Transverse Pressure on cable wide face

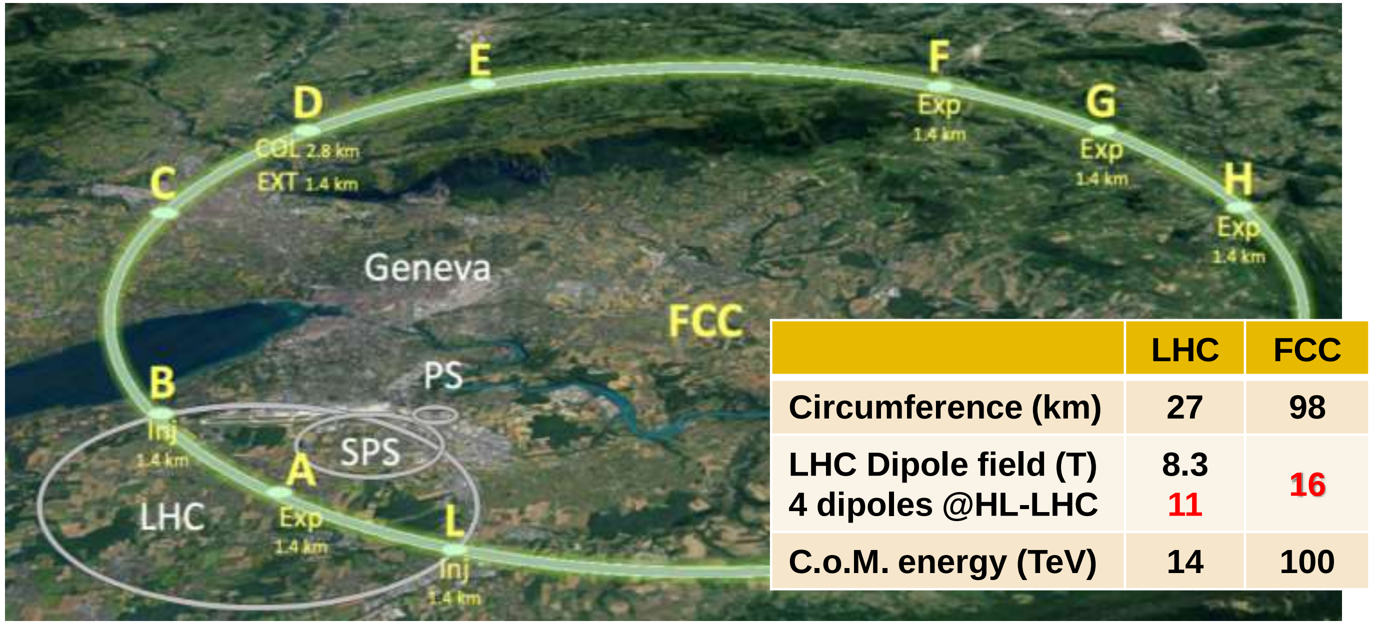


Cos θ dipole magnet layout, winding pack and cable

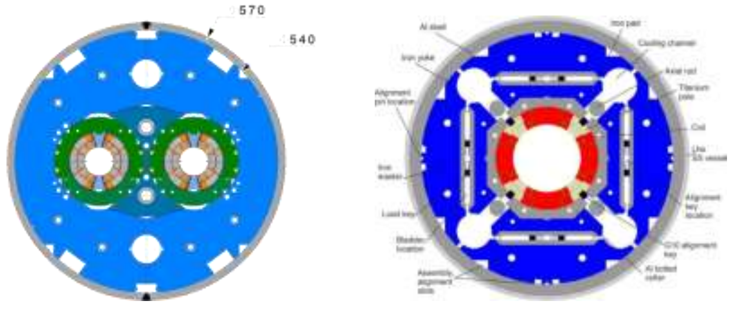
High-Field Nb_3Sn magnets - for HL-LHC and FCC

- **HL-LHC magnets** under construction, some 40 cold masses **under construction** at CERN and at FNAL

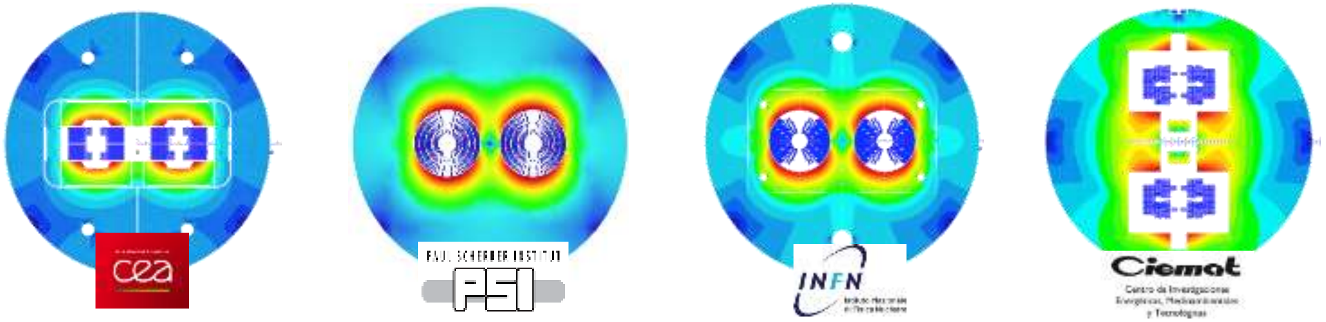
- **FCC 16 T dipole magnets** conceptual magnet designs being developed with partners,
- Long term R&D 2020-2040



	LHC	FCC
Circumference (km)	27	98
LHC Dipole field (T) 4 dipoles @HL-LHC	8.3 11	16
C.o.M. energy (TeV)	14	100



HL-LHC dipole and quad construction design



Flavor of FCC type 16 T dipole magnet conceptual designs by collaborators

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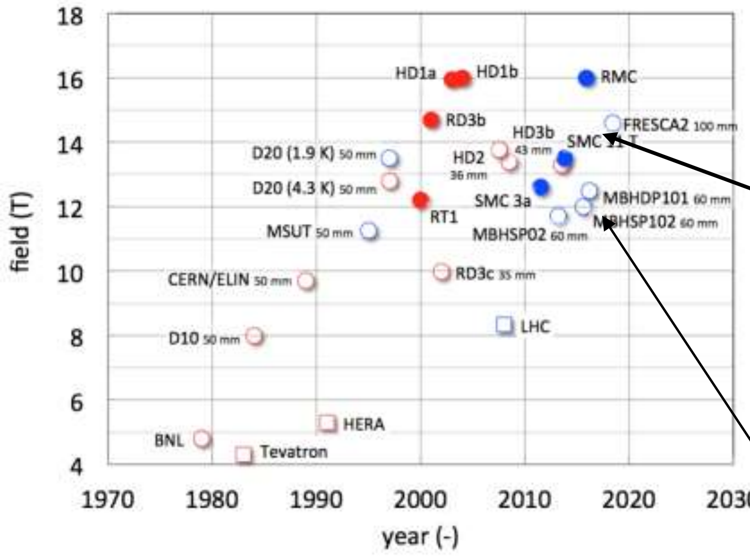
Record magnets – recent achievements



R&D magnet

15T cosθ dipole at FNAL, 1st test 14.1 T @4.5 K
*More after strain adjustment…. **very promising result** !*

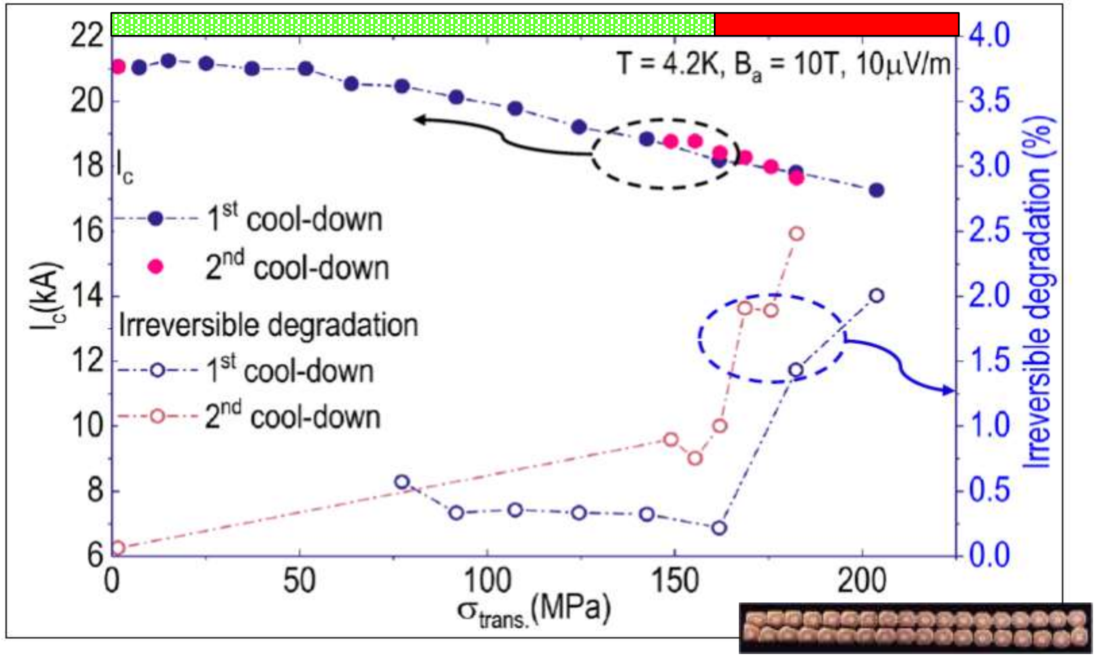
Production magnet

11 T Dipole magnet windings for HL-LHC

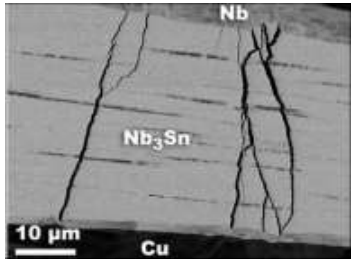
Nb_3Sn Rutherford cables under transverse pressure

- 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.



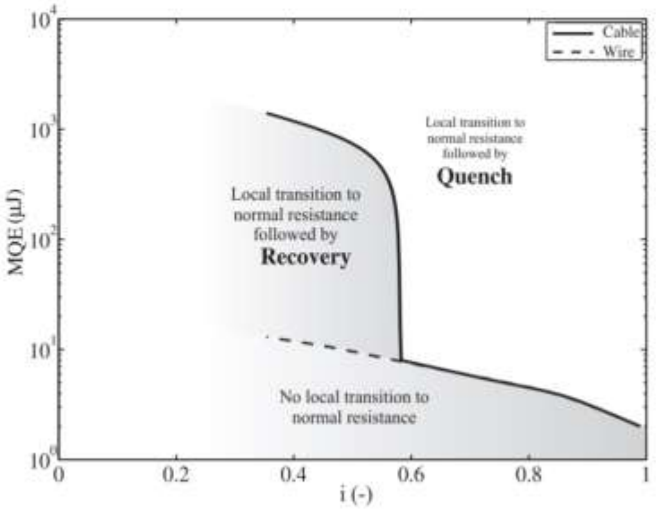
- ✓ **Transverse pressure of some 150 MPa OK** in perfectly impregnated cables, but Ic then some 20% less, eating from the margin, thus reduced stability!
- ✓ Strand and cable mechanical optimization possible to some extend, not more, a **principle limit for not-reinforced Rutherford cables** !

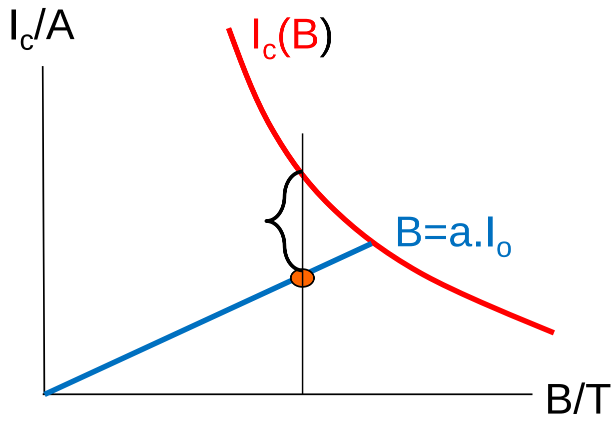


Filament cracking

Issue 2: Nb_3Sn Rutherford - Cable stability versus I_c

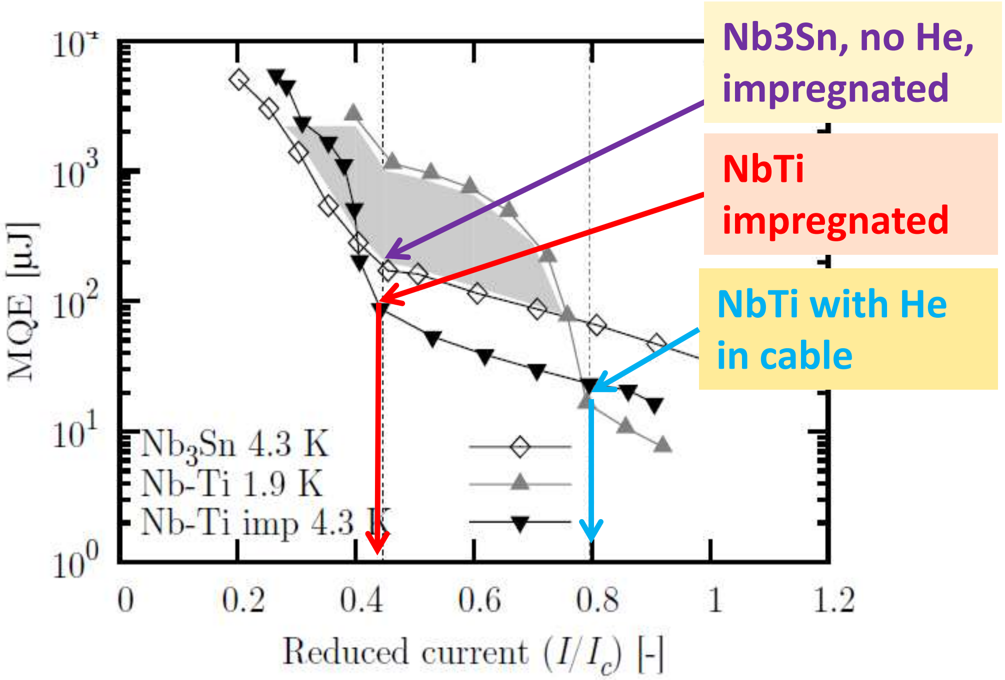
- Operate cable at value of I/Ic not too high.
- **Profit from collective strand stability to gain robustness and be less susceptible to wire motion and resin carking!**
- The transition is characterized mainly by single strand level (heat capacity) and the “kink value”, I/Ic value $i_{\_kink}$
- **Systematically all effects determining the $i_{\_kink}$ were investigated experimentally and verified by simulation using CUDI**
- Trivial factors are Cp (sf He presence); cooling sf He and inter-strand contact resistances!





Nb_3Sn - 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 Nb_3Sn 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 !



Nb3Sn, no He, impregnated

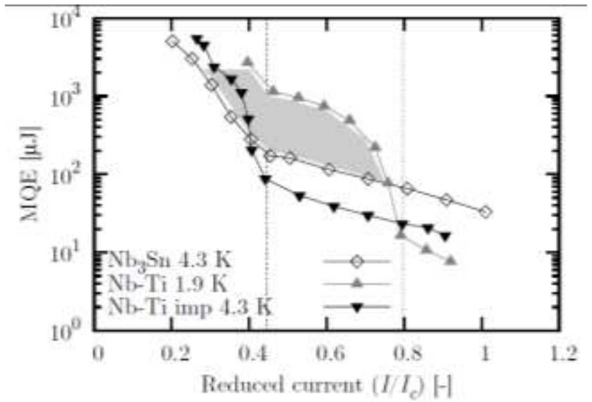
NbTi impregnated

NbTi with He in cable

- ✓ **Conclusion? What to do ? Ignoring and hoping for the best, or…?**
- ✓ It is not credible to make some 4000 (FCC) full-size Nb_3Sn magnets in industry with current technology (impregnated) based on single strand stability

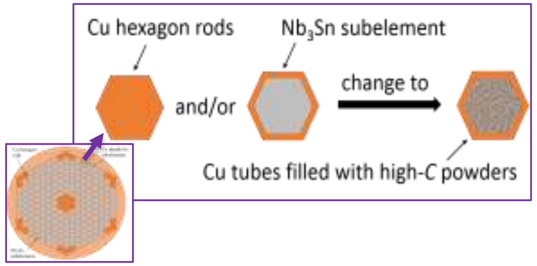
Nb_3Sn - Stability cliff disaster

- The present design ideas of operating 10-16T Nb_3Sn 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/Ic to some 0.4
2. Dramatically increase heat capacity of the conductor.
3. Bring He cooling back in the conductor (shifting $I_{\_kink}$ to right)
4. Reduce inter-strand contact resistance (shifting $I_{\_kink}$ to right).
5. **A well-balanced combination of 1 to 4!**



Example FNAL initiative:

- High-C_p materials: $CeCu_6$, Gd_2O_3
- Adding 1 vol.% of Gd_2O_3 to a Nb_3Sn wire can increase its C_p by several times.
- **Good, but more, try 10 to 15 %!**

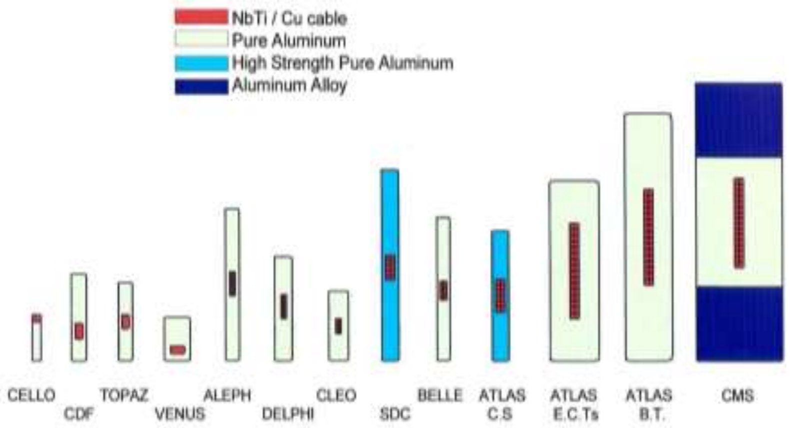
✓ We need improvements and new strategy, high priority!

(or use switch to HTS €€€)

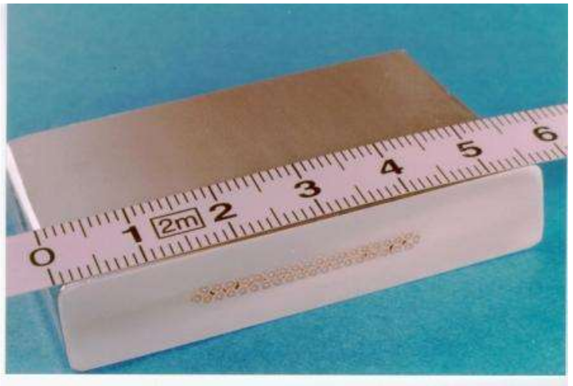
Case III: Al stabilized conductors for Detector Magnets

Why Al?

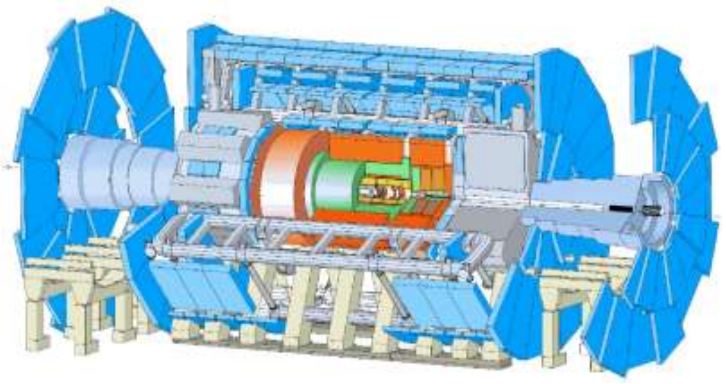
- *Simplicity of conduction cooling*, affordable since no dynamic operation, quasi stationary
- High-purity Al stabilized, RRR 2000, *maximum MPZ* (m), much larger λ/ρ than copper!
- *Particle transparency* for minimum particle scattering
- **But higher collision energy implies larger dimension**, tracking 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

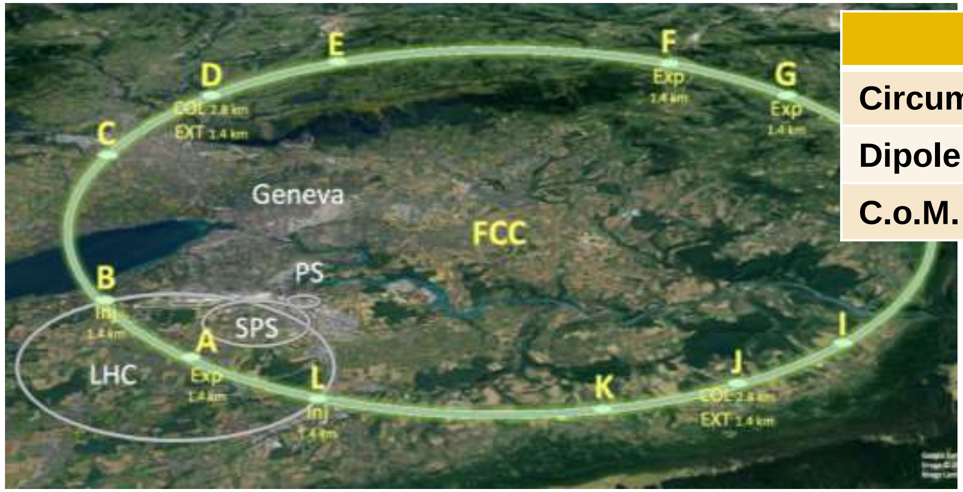
Magnets for FCC ee & hh collision detectors

Proposed Future Circular Collider

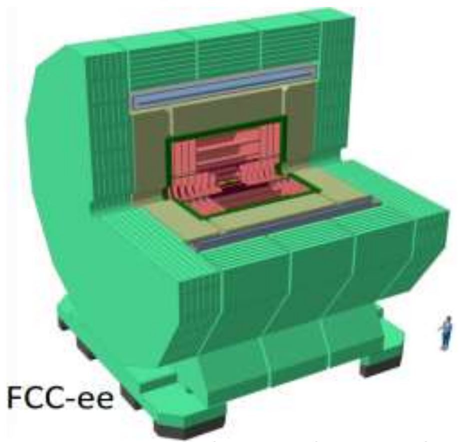
Stage 1: ee collissions (~2040)

Stage 2: 100 TeV hh collisions (~2070)

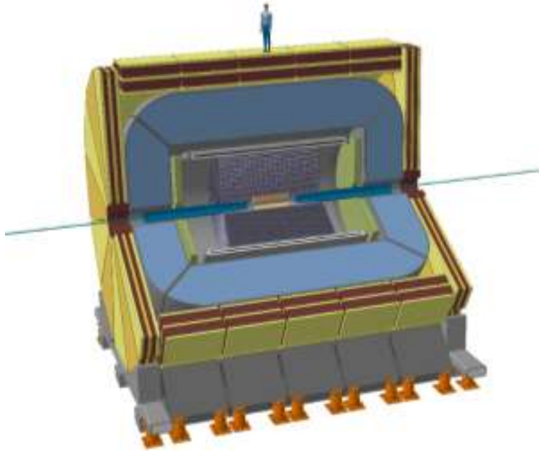
- 2 ee and 1 hh collision detectors proposed requiring reinforced Al stabilized conductors



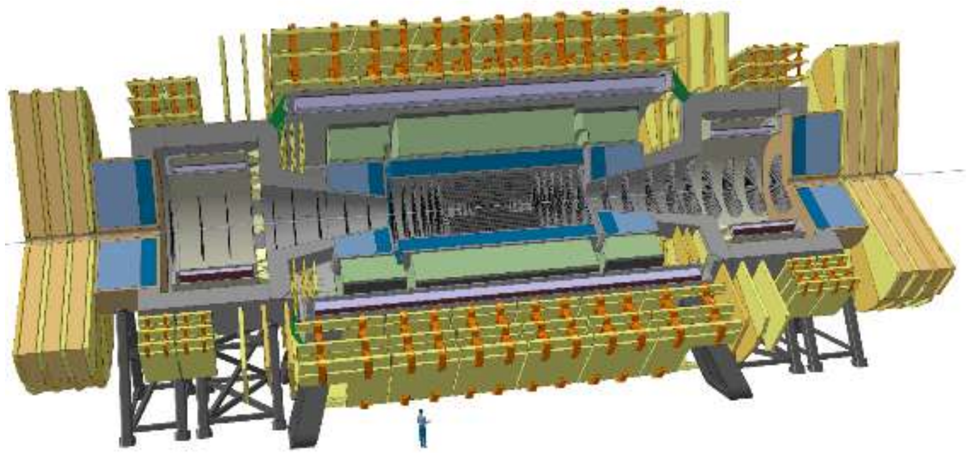
	LHC	FCC
Circumference (km)	27	98
Dipole field (T)	8.3	16
C.o.M. energy (TeV)	14	100



Classical 2 T Solenoid



*IDEA, innovative **thin** Solenoid around tracker*



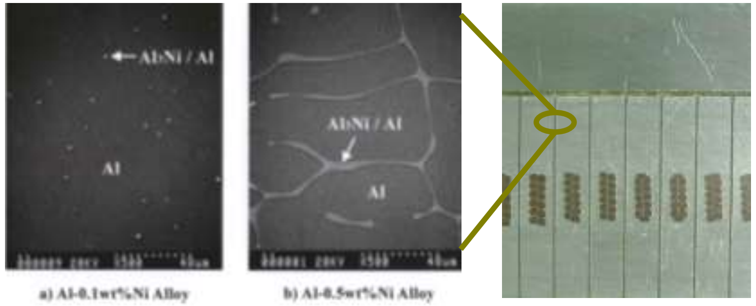
*FCChh Detector, **4T/10m** main & 2 3T forward solenoids*

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

Option 1

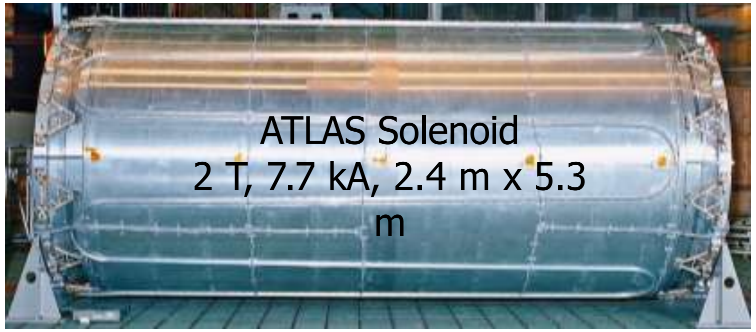
Micro-alloy pure Al with Ni or Zn

Used in the ATLAS Solenoid



a) Al-0.1wt%Ni Alloy

b) Al-0.5wt%Ni Alloy

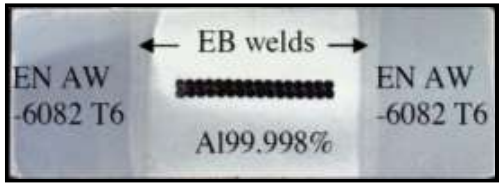


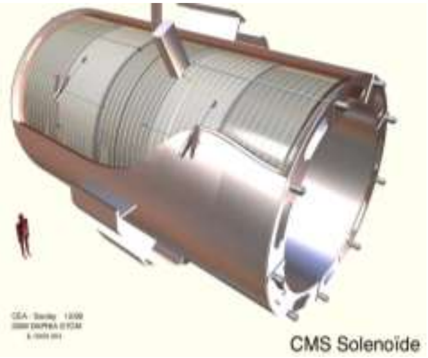
ATLAS Solenoid
2 T, 7.7 kA, 2.4 m x 5.3 m

Option 2

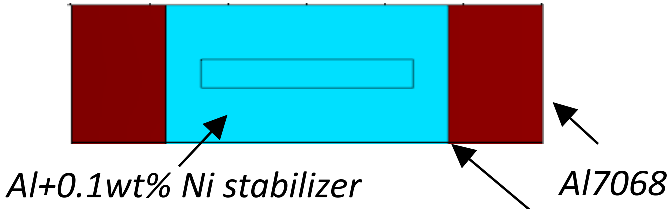
Reinforce with Al-alloy side bars, EB-welded to the pure Al of the NbTi/Cu/Al conductor

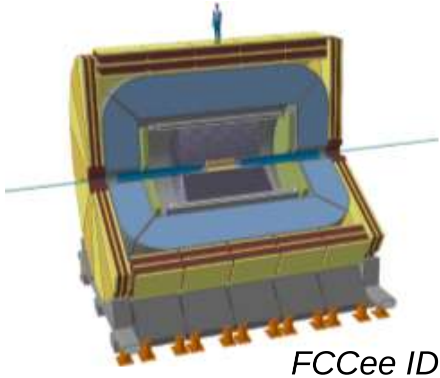
Using **Al 6082** T6
(Used in CMS Solenoid)

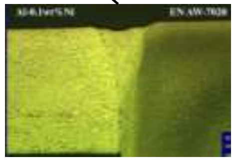




Using **Al 7020/7068**
(R&D for FCC-IDEA)

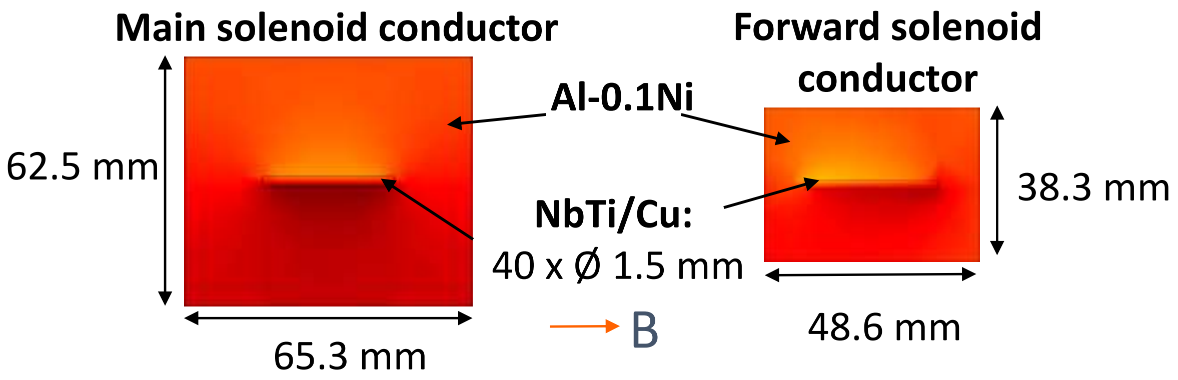






FCCee IDEA

Super-Conductors for 4T/10m detector solenoids



Main solenoid conductor

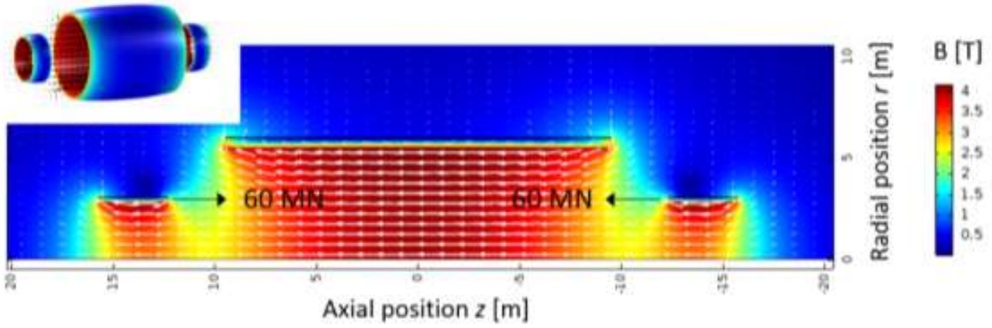
Forward solenoid conductor

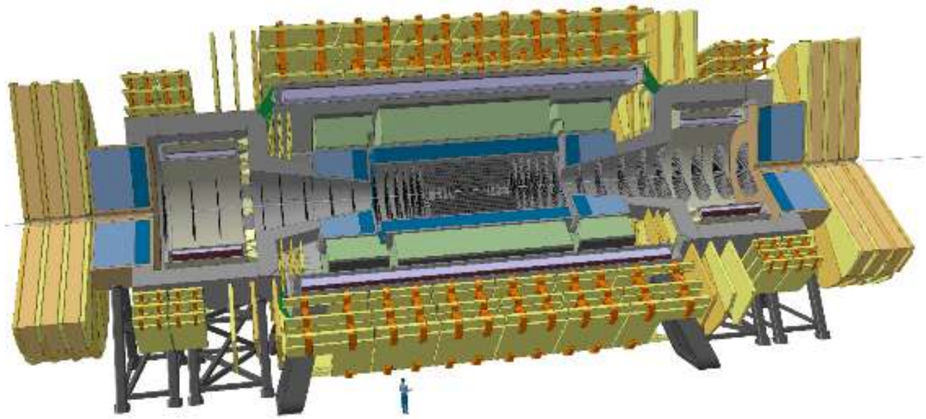
Al-0.1Ni

NbTi/Cu:
40 x Ø 1.5 mm

62.5 mm
65.3 mm
38.3 mm
48.6 mm

B





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

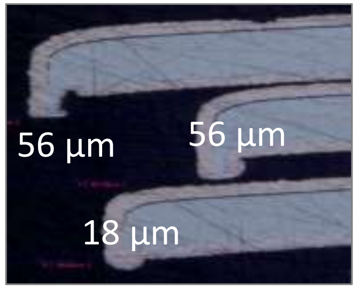
- Peak magnetic field on conductor 4.5 T
- Current sharing temperature 6.5 K
- 2 K temperature margin when operating at 4.5 K
- **Nickel-doped Aluminum (≥0.1 wt.%)** combining good electrical properties (RRR 600) with mechanical properties, 146 MPa conductor yield strength

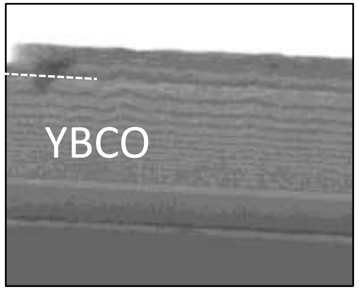
Case IV : *Re*BCO Roebel Cables

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

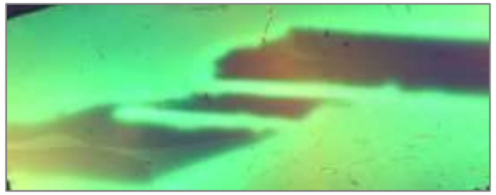
Further optimization required for strand cutting techniques and making long lengths:

Punching or Laser cutting

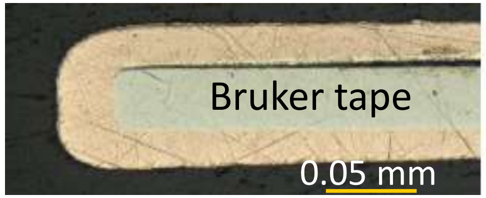




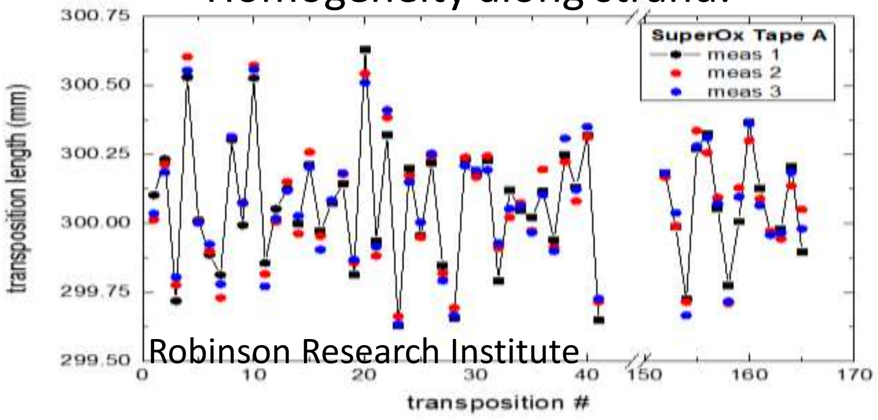
Magneto-optical imaging showing broken strands



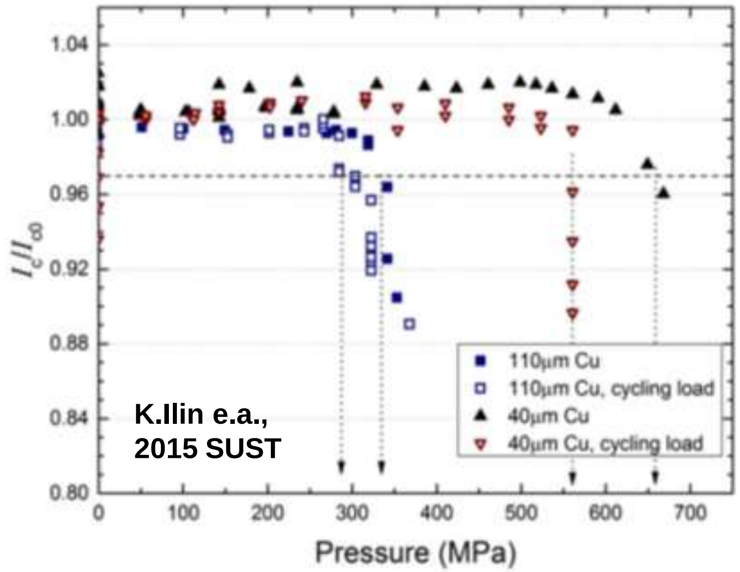
Punch & coat technique



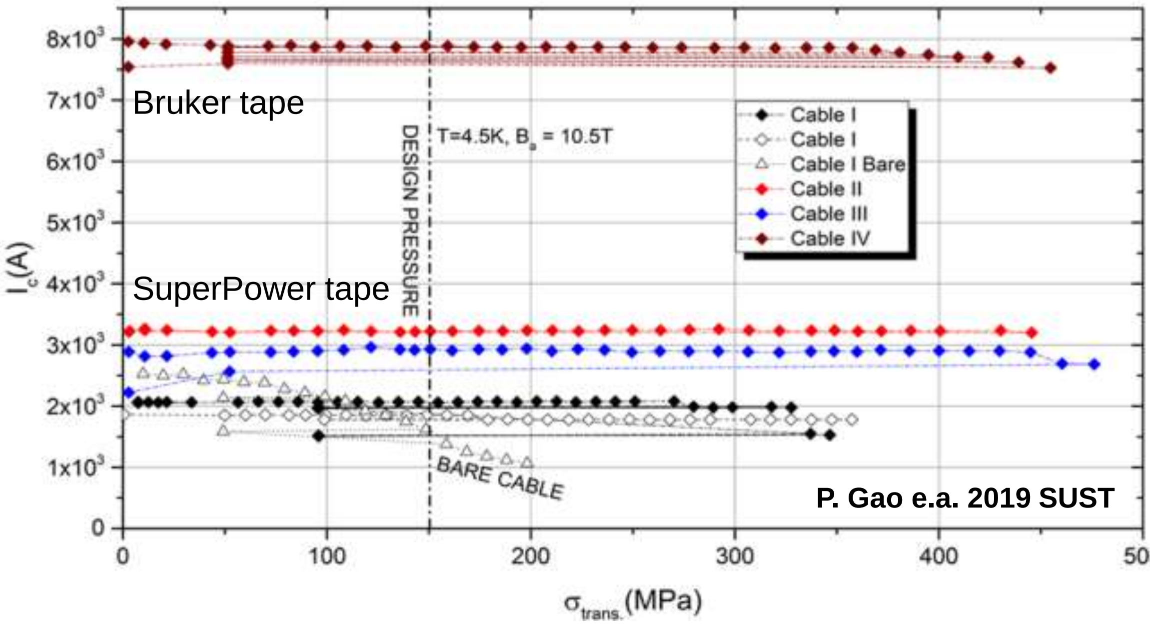
Homogeneity along strand:



Roebel Cable’s transverse pressure resistance



K.Ilin e.a.,
2015 SUST



P. Gao e.a. 2019 SUST

- Transverse pressure of *Re*BCO 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

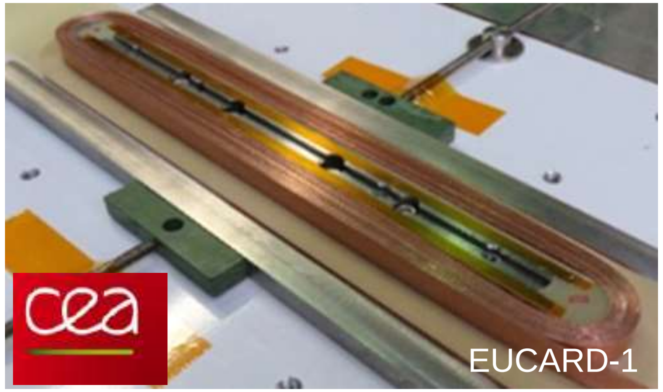
✓ **Impregnated Roebel cable can withstand transverse pressure in excess of 300 MPa !**

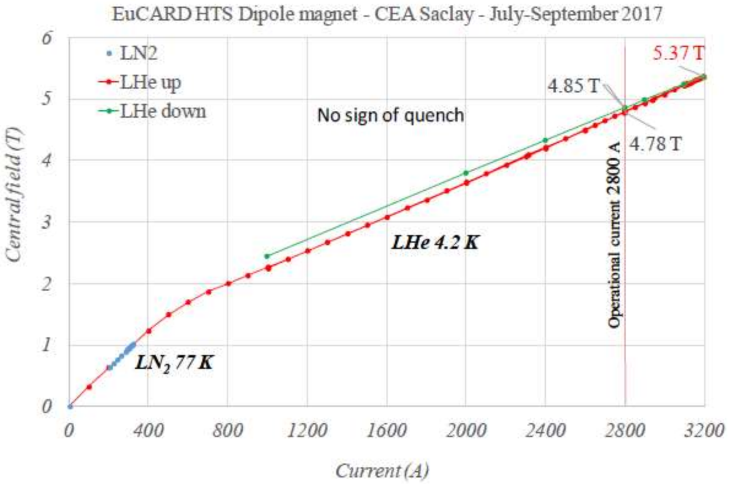
✓ **Very good for high-field magnets**

*Re*BCO dipole magnet developments - examples

*Re*BCO dipole development at CEA

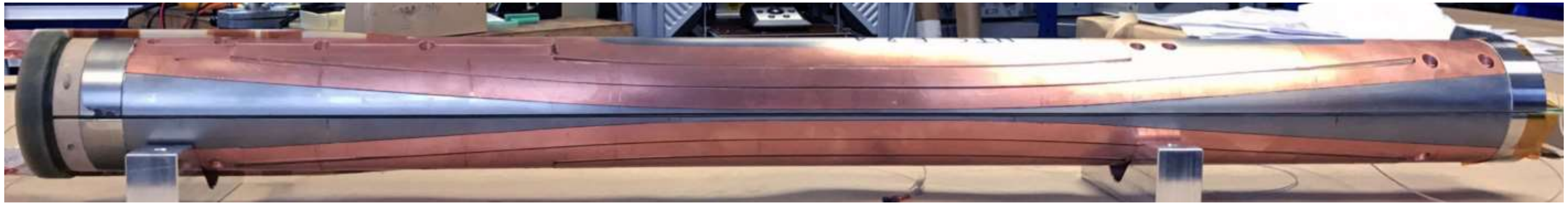
- Design for full-size dipole variants
- Demonstration racetrack coil reached 5.37 T



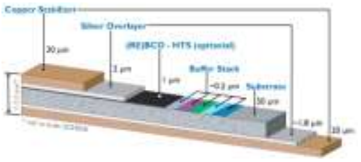


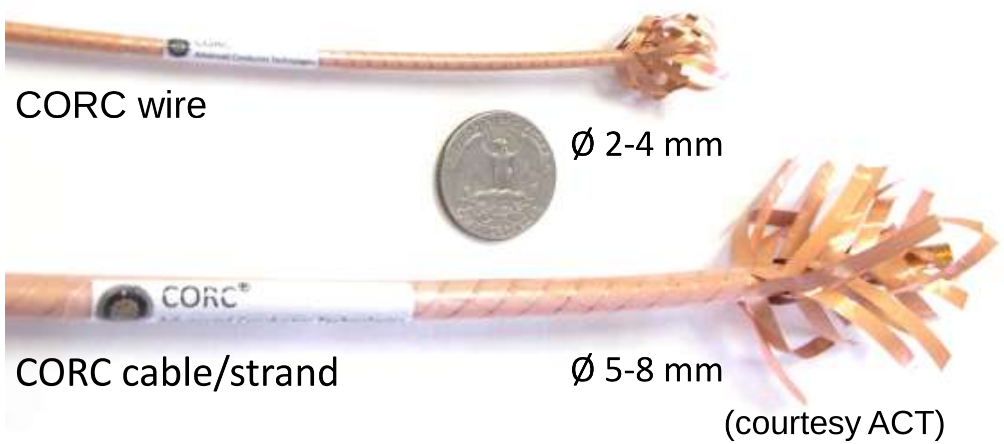
*Re*BCO Feather series dipole insert development magnets at CERN

- Coil 1: using SuperOx/SuNAM type Roebel cable, reached 3.35 T
- Coil 2: using Bruker type Roebel cable, presently at test

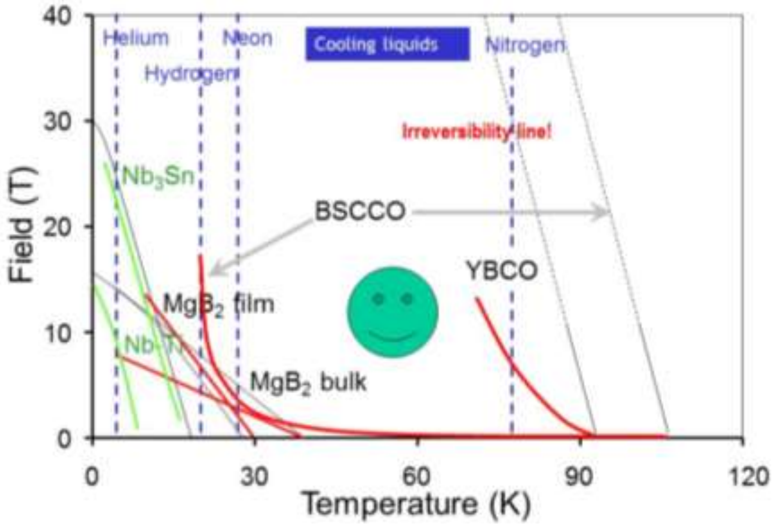


Case V : *Re*BCO CORC – cables and wires





(courtesy ACT)



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

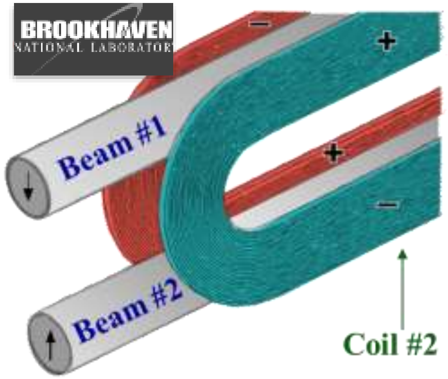
- Truly opening up massive magnet applications running at 30-50 K
- Today the only thin-round wire solution is CORC-'cable' (and variants)
- Multi layers of ReBCO tapes spiraled around a core
- Quest for thinner wire: thinner substrate > thinner core, 100>50>30>20 µm

*Re*BCO-CORC wire applications - examples

Flavor of demonstration coils in progress

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

Racetrack insert,
80 mm dia, 2 layers



Common coil insert
4T, 50m, 10kA, in 10T

74mm dia, insert
2 layers, 2T in 15T

100 mm bore insert,
2T in 14T, 17m wire, 5kA

Making of CCT2

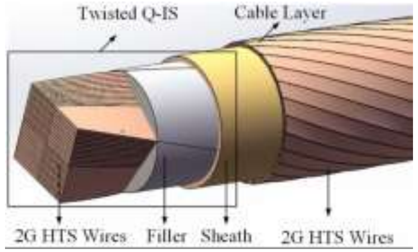
CCT3: 6 layers, 5T@4.2K, 10kA, 140m wire

*Re*BCO CORC - Cable-in-Conduit conductors

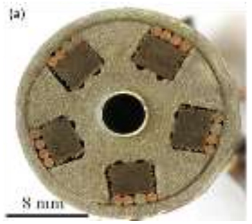
- **Cable-In-Conduit Conductors (CICCs),** designed for large-scale, high-current magnets as for large outsert coils, fusion magnets and particle detectors
- *NbTi* and *Nb_3Sn* conductor development close to their limits, also quest for higher temperature & no-helium operation **---> Development of *Re*BCO based CICCs**
- Dramatic increase in stability and enables operation at 20-50 K

Examples of several *Re*BCO based CICCs are in development around the globe:


CERN & ACT:
CORC 6-a-1 CICC



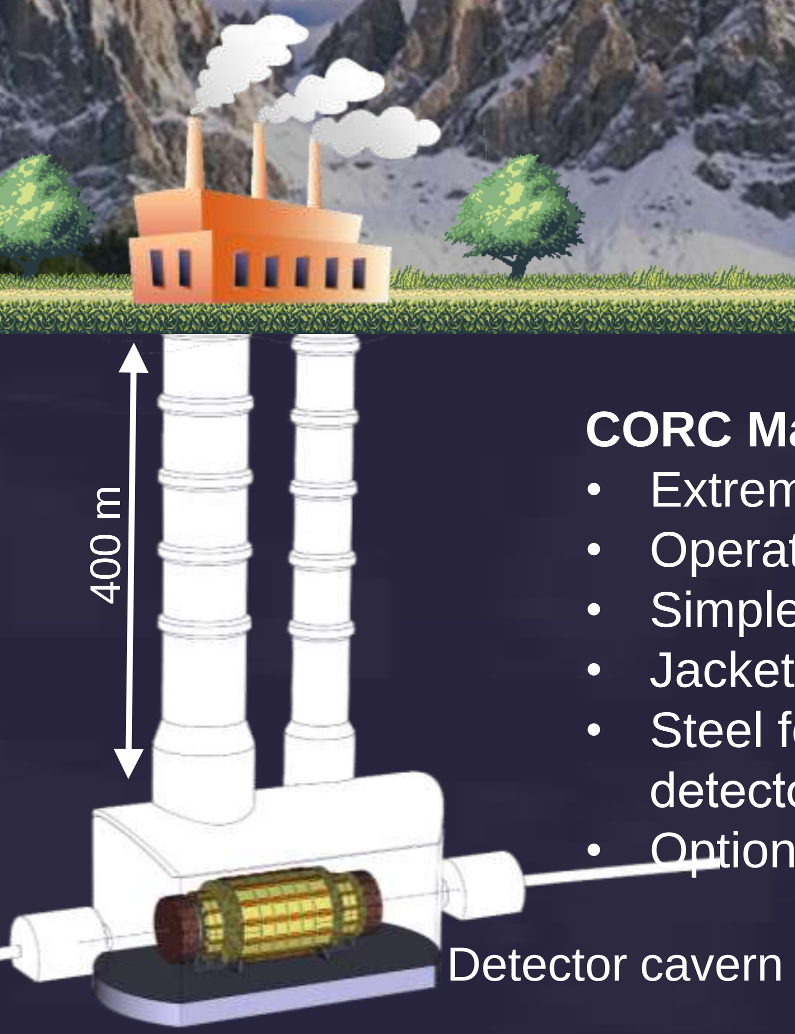
North China Electric Power
University Quasi-Isotropic Conductor



ENEA: Twisted Stacked
Round CICC

Swiss Plasma Center:
Twisted Stacked Rectangular CICC

CORC CICC for Bus Bars and Large Scale Magnets



Bus bars based on CORC CICC conductor, lighter, taking less space.

CORC Bus Lines:

- Reduce weight
- Reduce volume
- Reduce power converter requirements
- Allow power convertor placement on surface

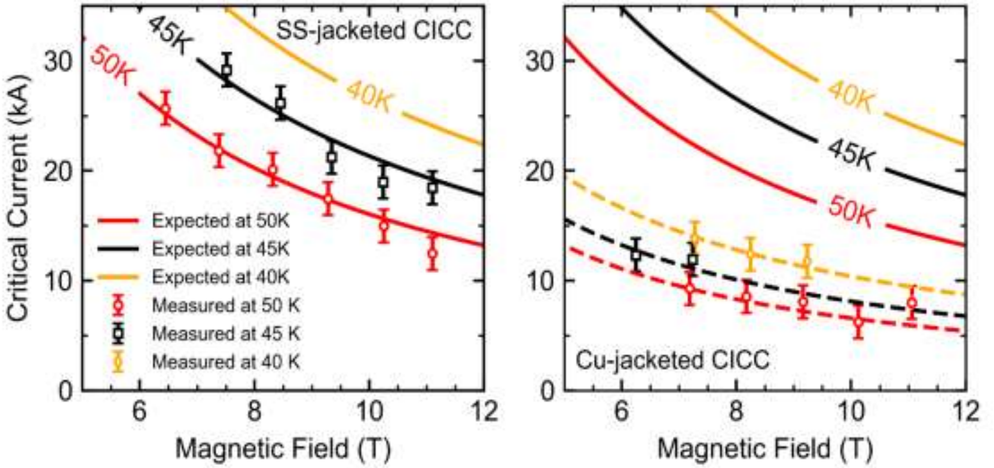
CORC Magnets:

- 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

SS and Cu jacketed CORC CICC samples – test results

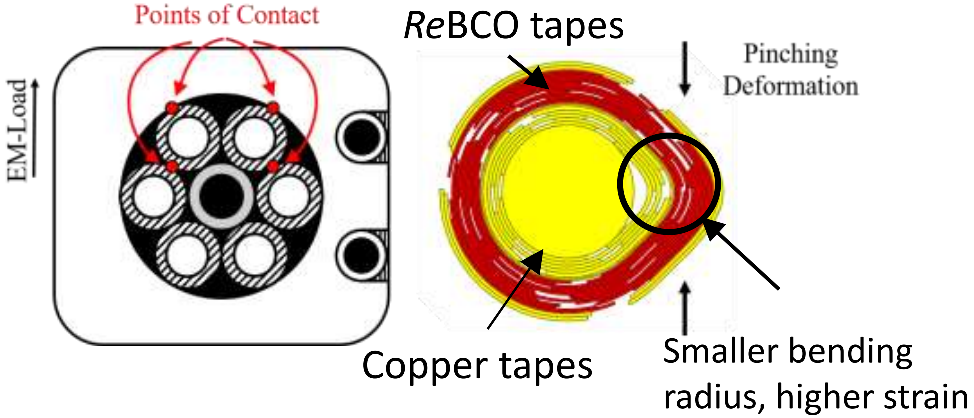
Typical result showing that R&D is needed

- 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! :

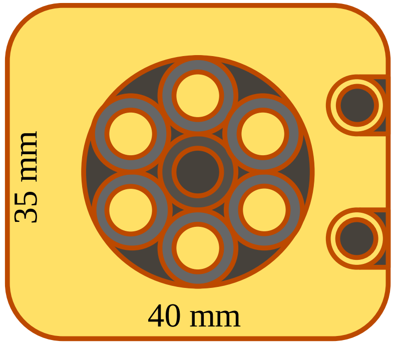
- Primary failure mode is a pinching effect
- Specific for this CORC production parameters
- Copper tapes layers around the core do not give sufficient mechanical support



CORC Cable-In-Conduit Conductor Design

Advanced Conductor Technologies LLC
www.advancedconductor.com

- 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

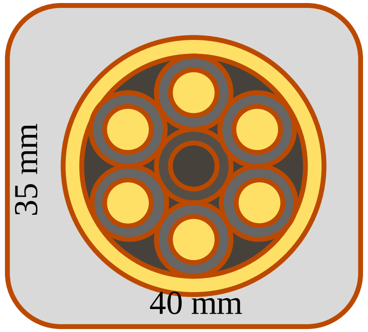


Magnets & Bus Bars:

- High thermal & electrical stability
- Practical conduction cooling

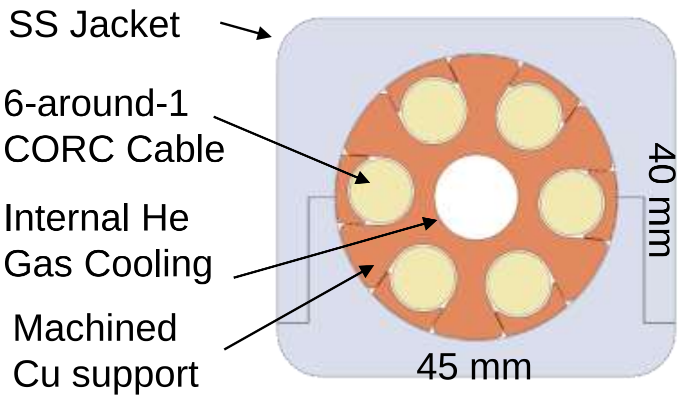
Fusion type magnets:

- Can sustains high stress
- For large heat load
- Internal forced-flow cooling



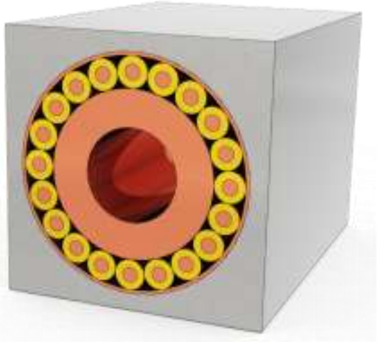
Next sample:

- 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!**