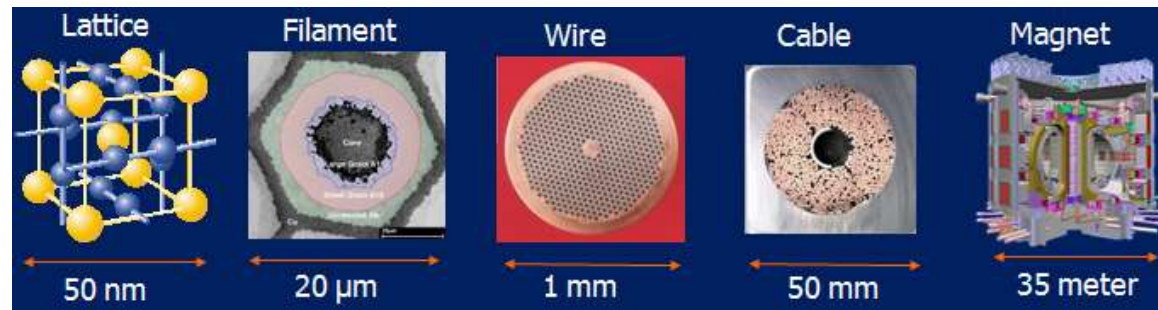


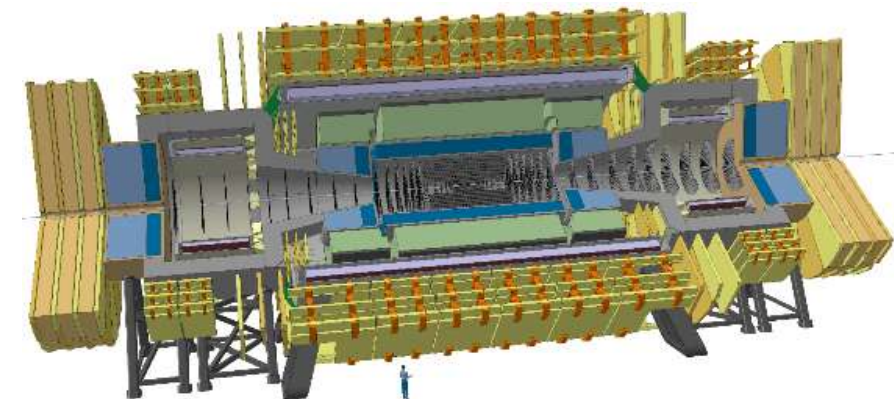
Super-Conductors for Successful Magnets



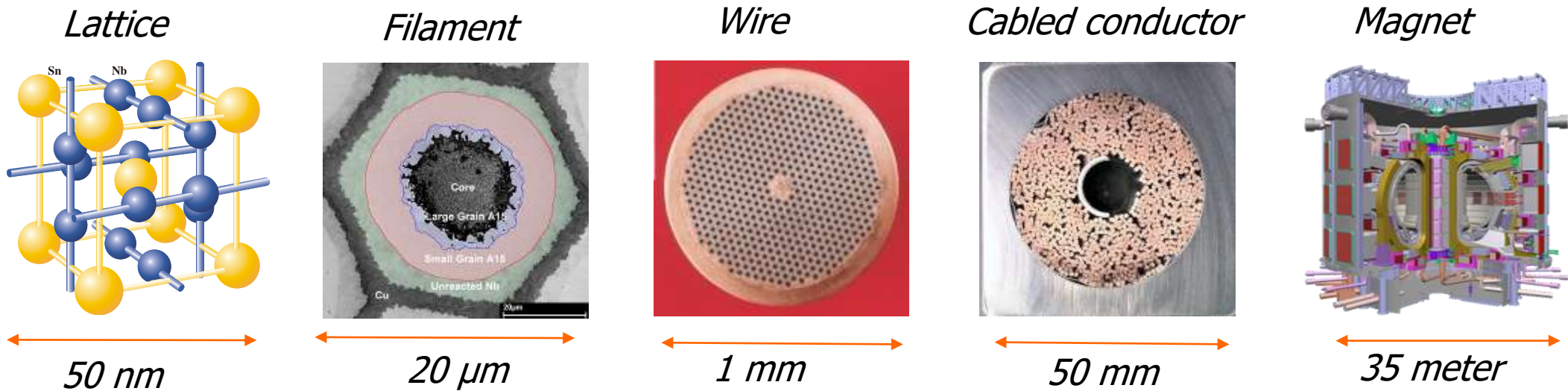
Content

1. Conductor requirements
2. Case Fusion CICC
3. Case Nb₃Sn Rutherford cables
4. Case *ReBCO* cables
5. Conclusion

Herman ten Kate



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 !

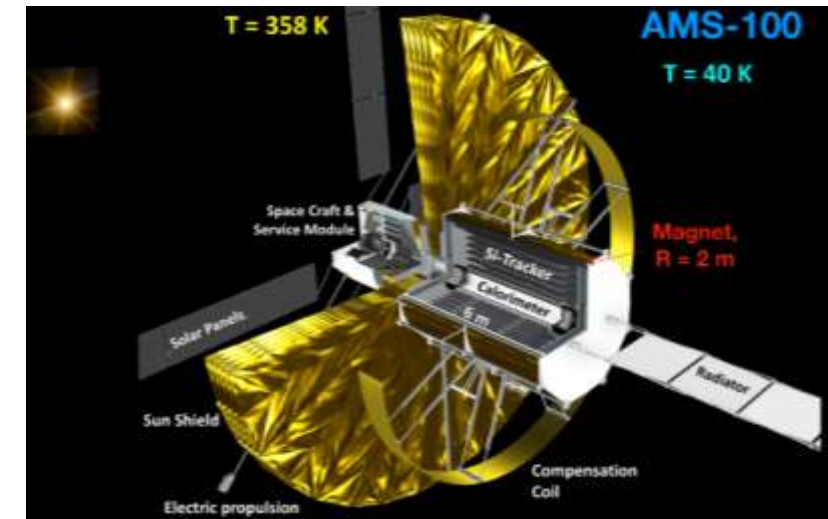
Conductor Requirements

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

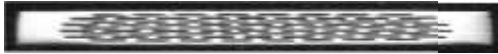
Depends on application

- 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!

200 A HTS tape

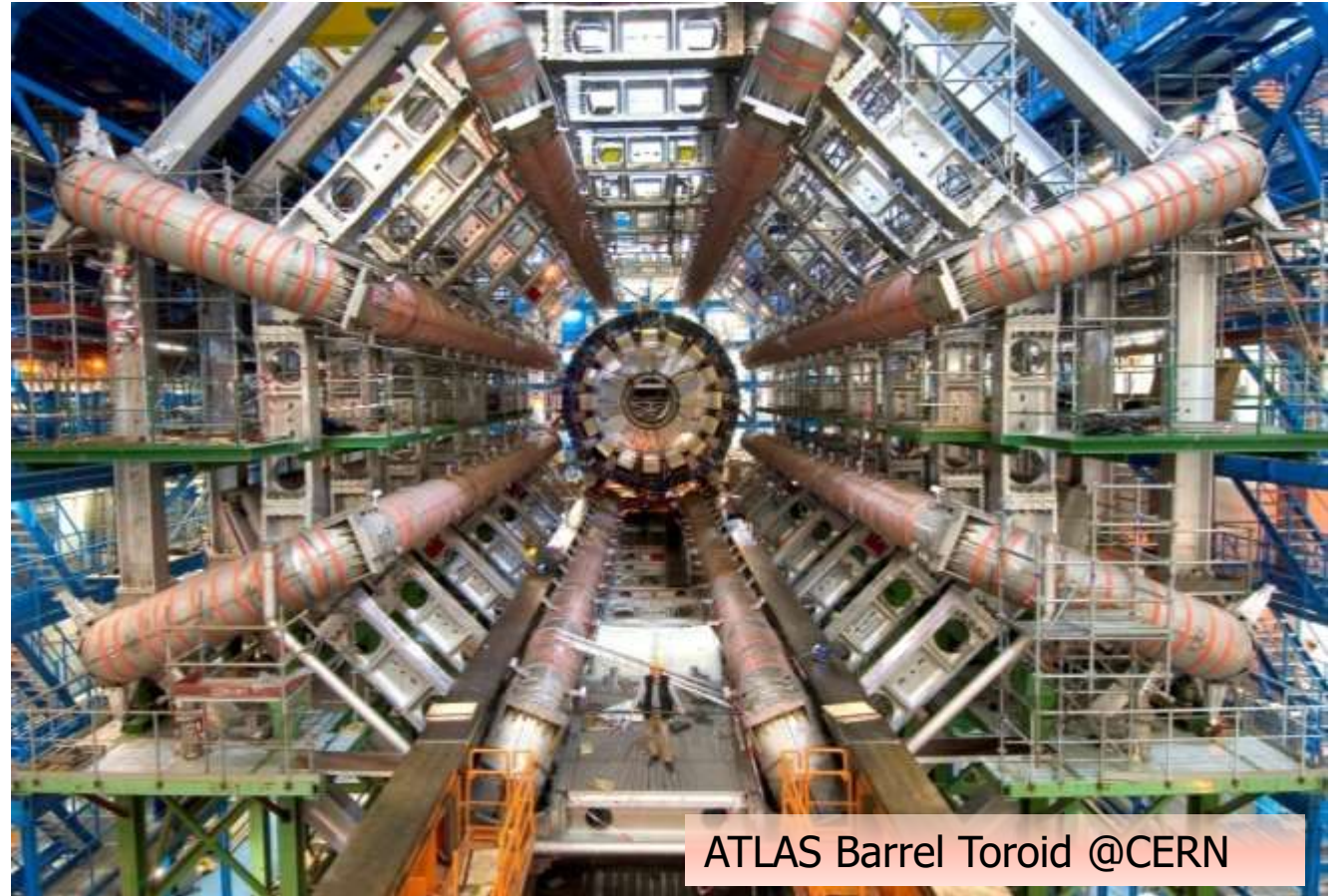


X

65000 A@5T Al-NbTi/Cu



✓



- Can not build **large scale magnets** from single NbTi, Nb₃Sn, B2212 wires, or ReBCO tapes
- Superconductors required **that can be cabled and still perform!**



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



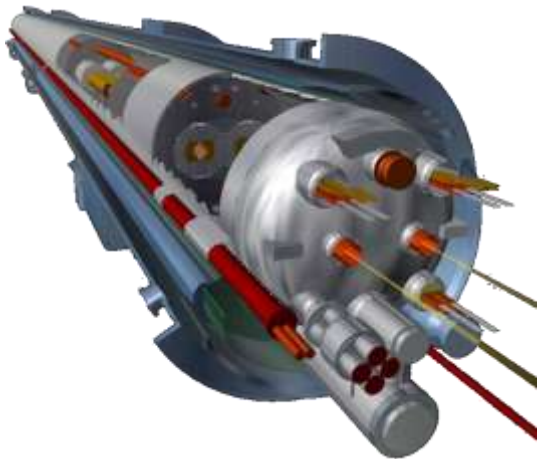
0.0001 m³ HF insert model
200 A



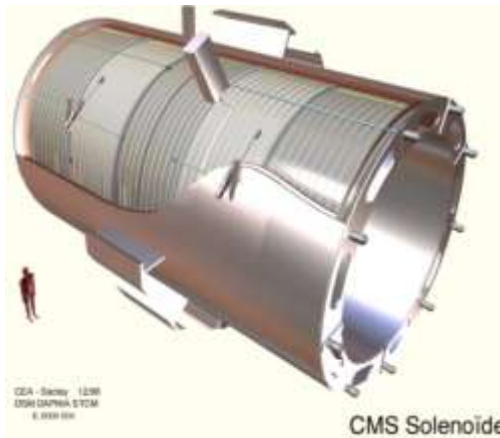
2 m³ MRI magnet
200-800 A @ 1-3 T, ~10 MJ



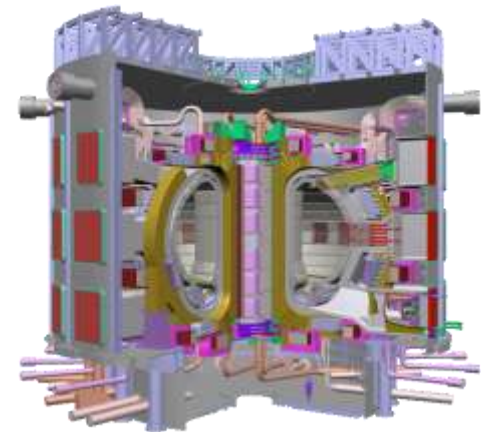
25 m³ ATLAS Solenoid
8 kA @ 2 T, 40 MJ



50m³ LHC Dipole magnet
13 kA @ 8 T

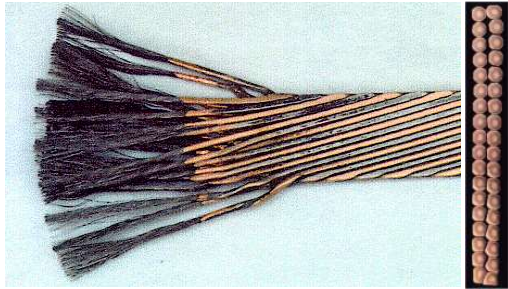


400 m³ HEF Detector Magnet
20 kA @ 4 T, 2.6 GJ



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

Understanding cables



Rutherford cable



CICC



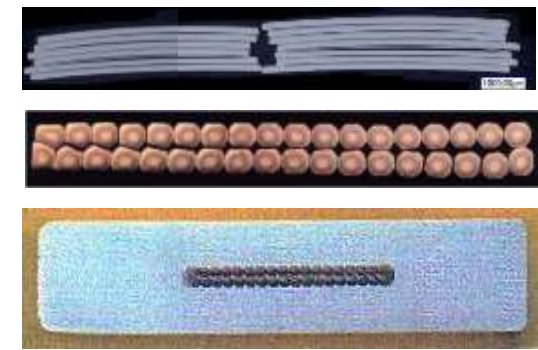
ReBCO-Roebel cable



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

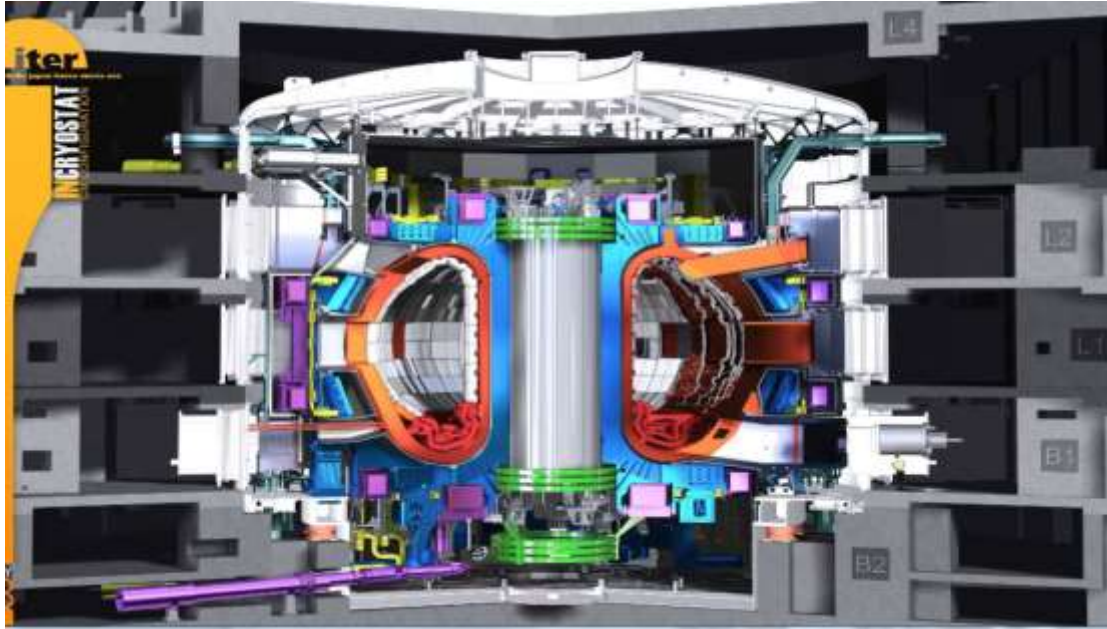


- **Multi-filament wire**
- Filaments on rings, not fully transposed
- Uniform properties in section
- Easy in AC loss and stability

- **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

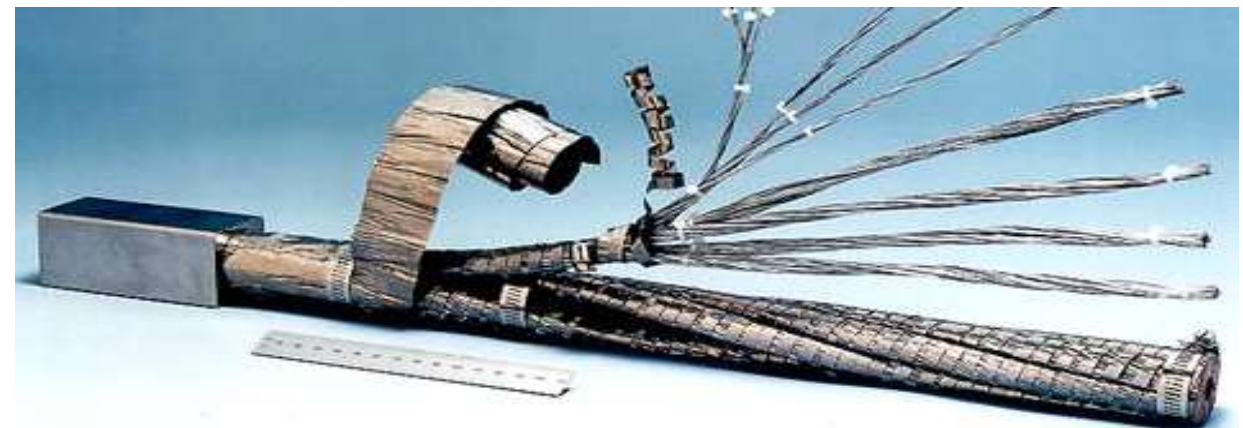
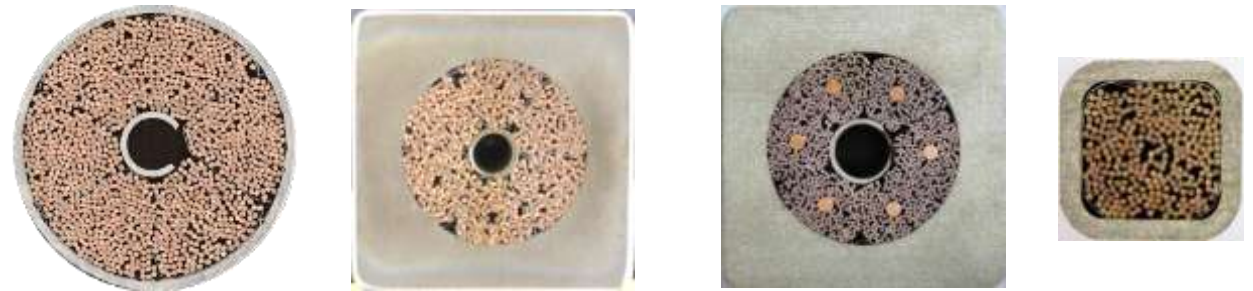
Fusion CICC – ITER superconductors



System	# units	Energy GJ	Peak field T	Conductor length km	Weight 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	

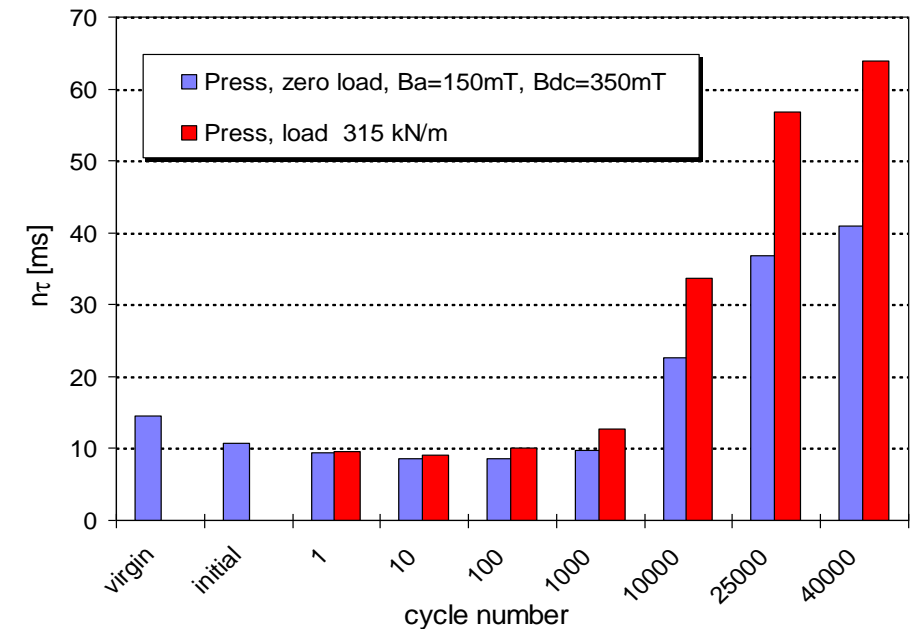
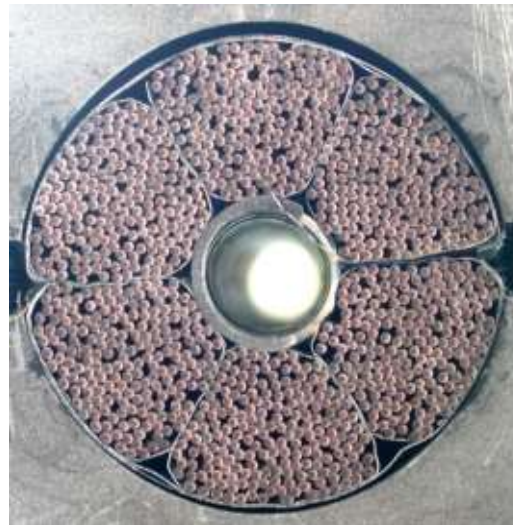
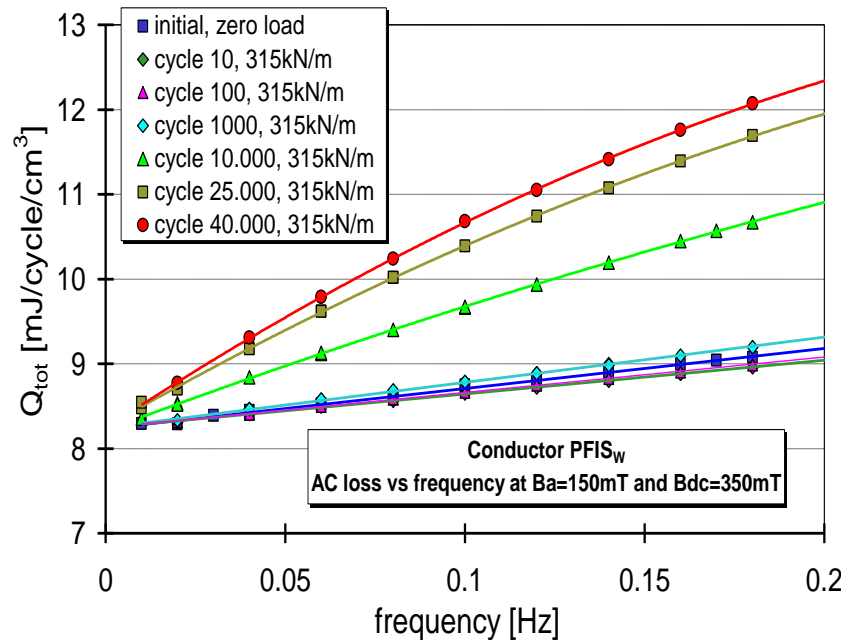
Initial conductor concept:

- ✓ 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 **Nb₃Sn** (TF&CS) versions exist



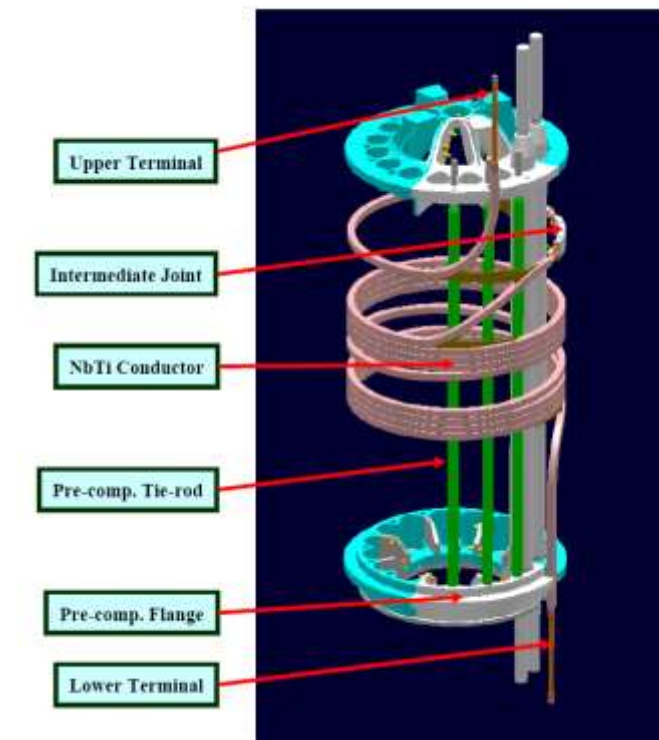
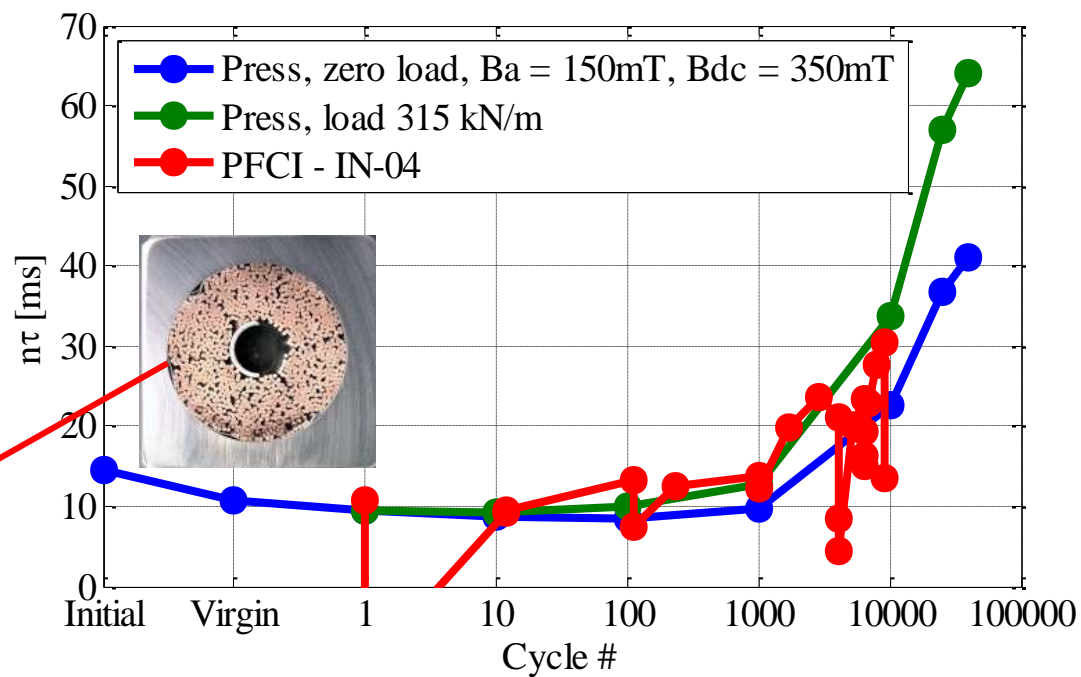
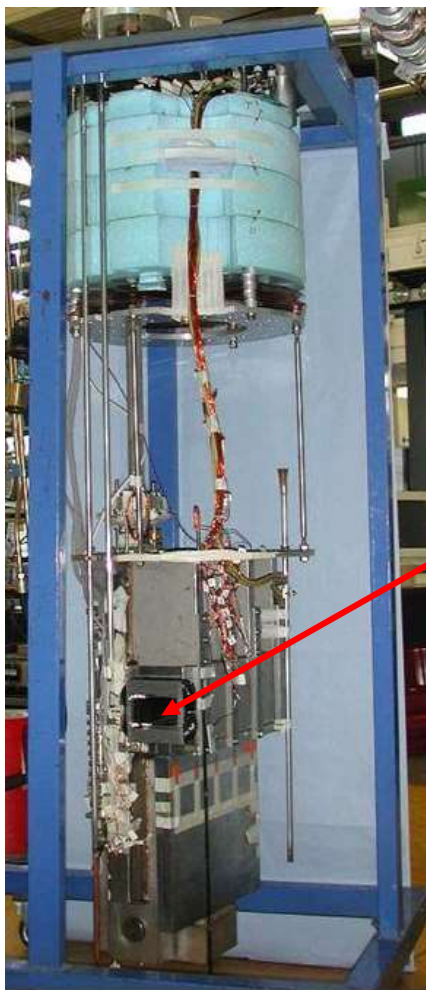
Issue 1: Inter-strand contact resistance ageing in a CICC

- ? 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



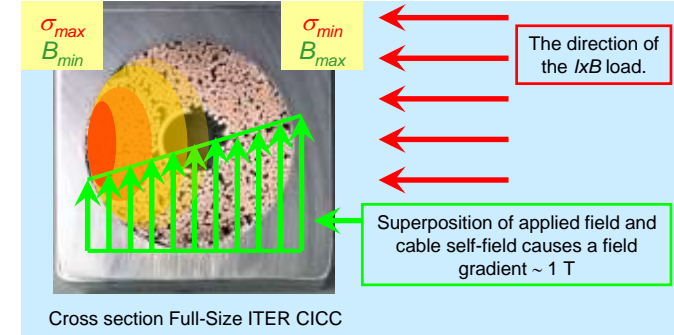
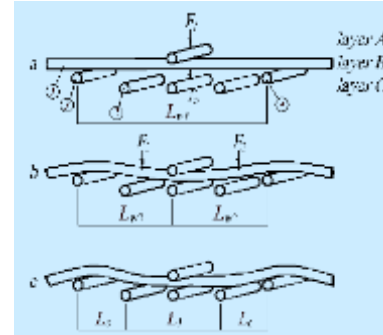
AC loss ageing measured in a demo coil - verification

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



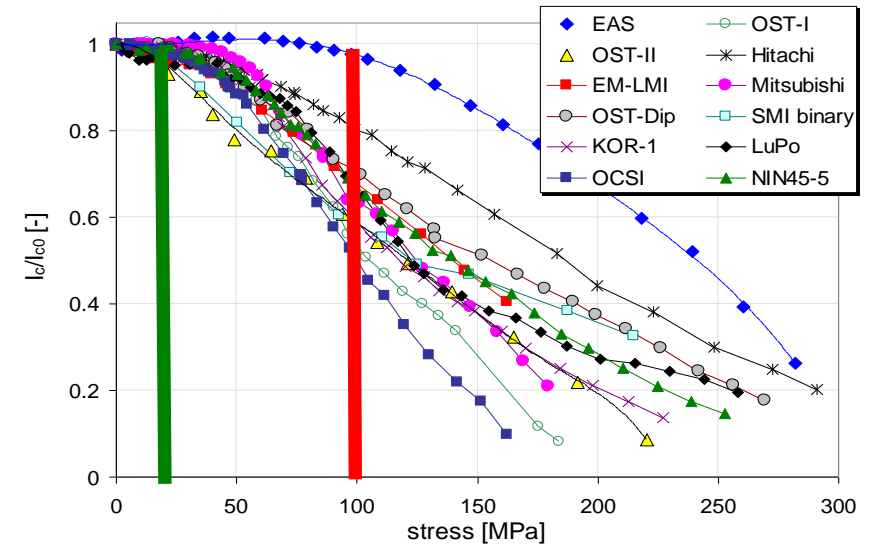
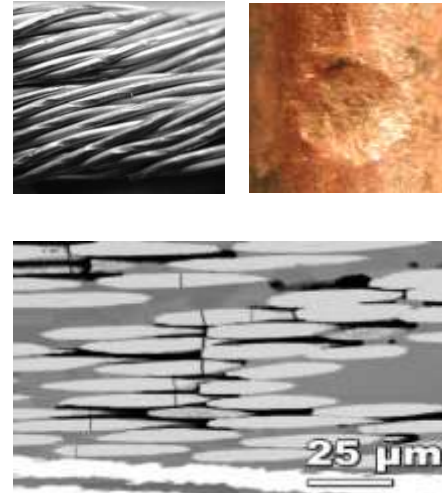
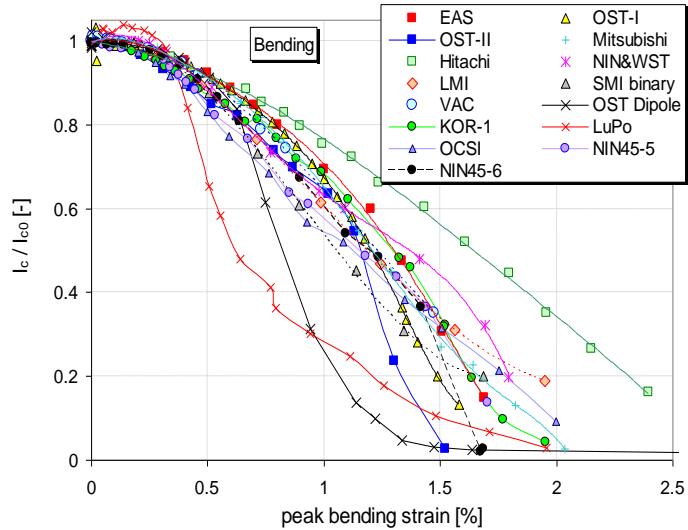
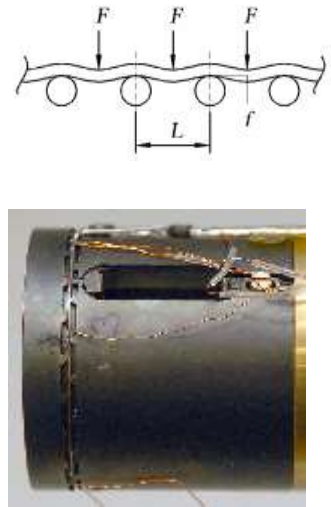
- ✓ Excellent agreement is found showing that full size cables can be correctly tested in a small scale test facility based on 500mm samples
- ✓ Demonstrating importance of “smart” testing

Issue 2: Nb₃Sn CICC - current sharing temperature ageing

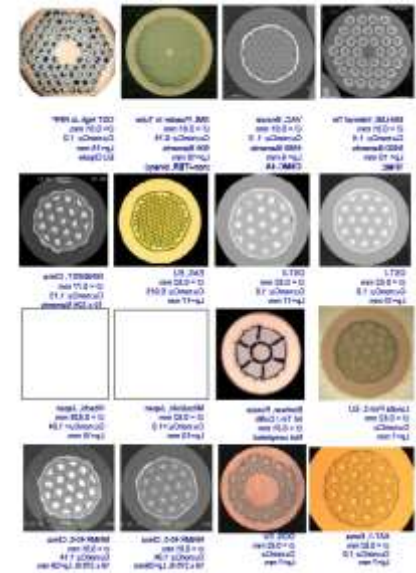


- Initially, naïve idea that a CICC is simply bundling 1000 Nb₃Sn strands in a conduit...
- Body force of magnet is taken by the conduit, not transmitted to the strands
- Still, local Lorentz Force = $J \times B$ [N/m] causes cable compression within the conduit
- Enhanced transverse load on crossing 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

Susceptibility to Periodic bending and Contact Pressure

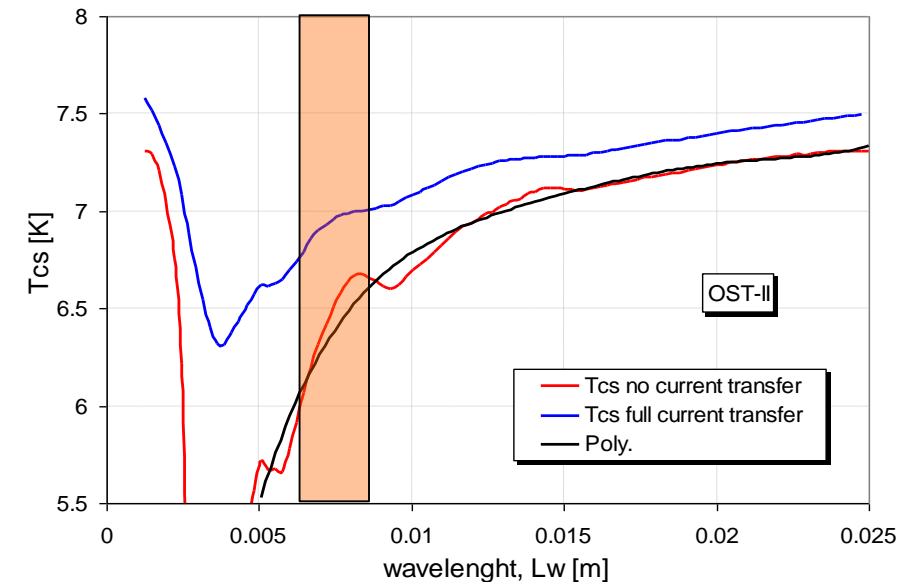
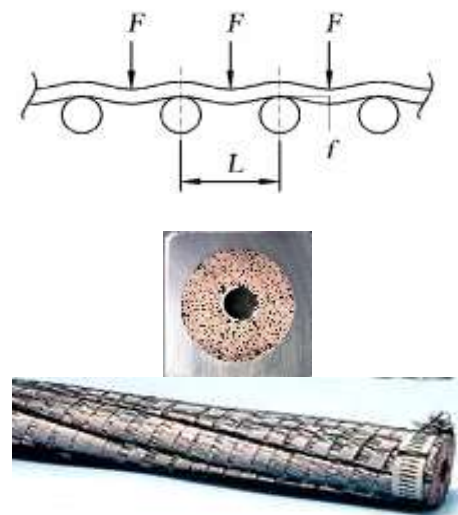
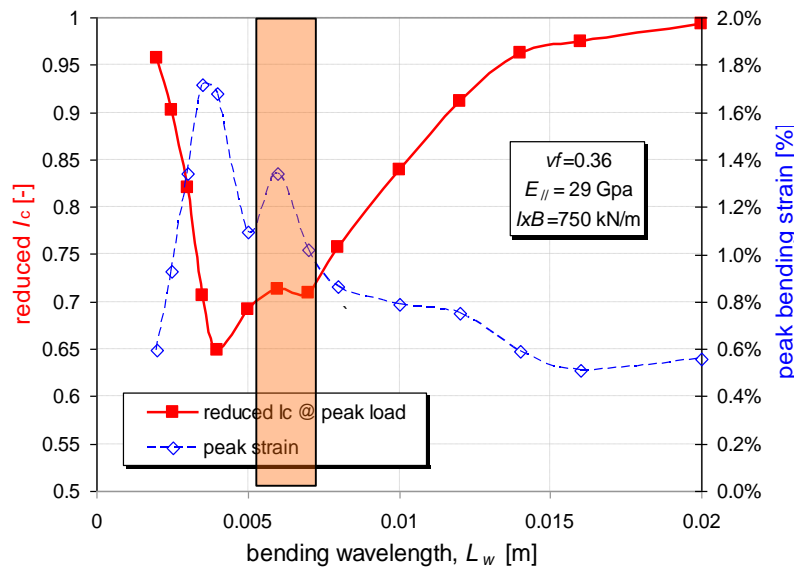


- Significant spread in I_c - susceptibility to bending strain and contact stress
- Contact stress depends strongly on cabling pitch length
- Relevant range 20 - 100 MPa for short and long cabling twist pitches
- These loads change 'reversible' strain state and causing cracks, thus I_c !
- ✓ **Really expect large spread in CICC performance**
- ✓ **Optimization is strand type dependent!**



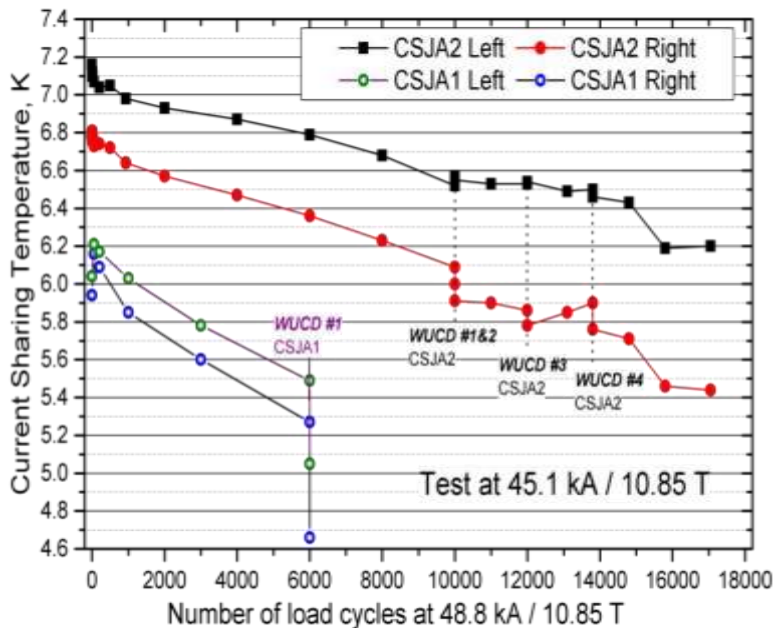
Simulation is Key for predicting conductor performance

- 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



Issues with CSJA1

naturenews

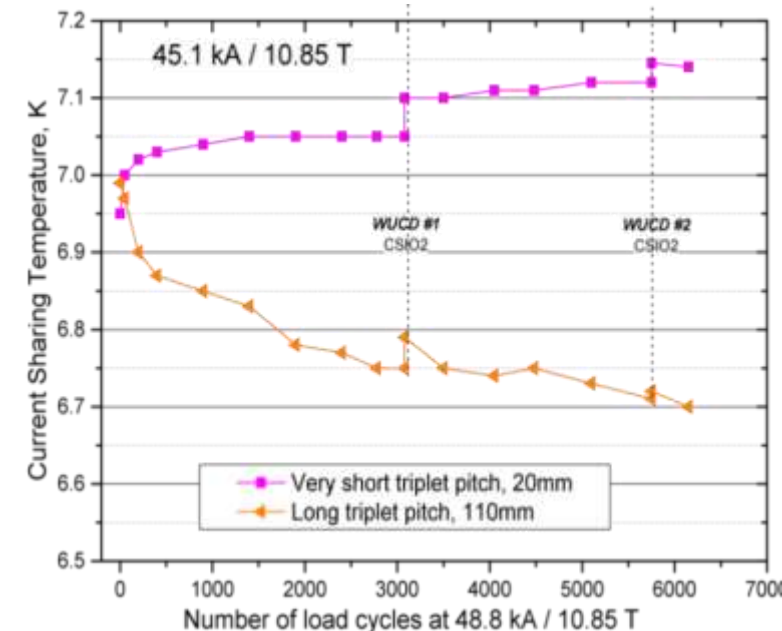
ITER'S BEATING HEART
The superconducting cables of the central solenoid are a crucial part of the fusion reactor.

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)

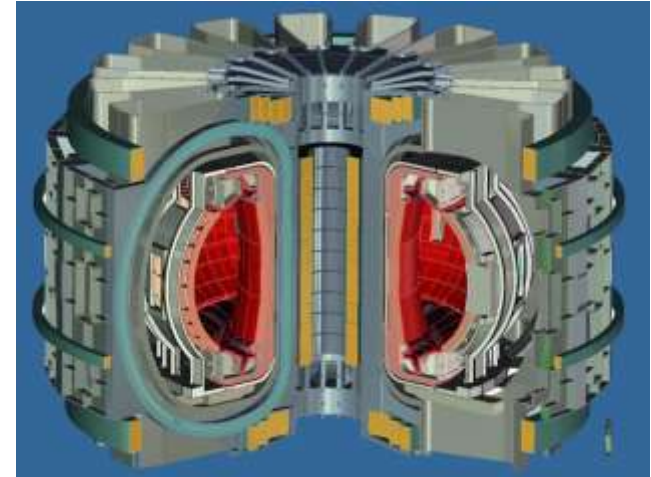
- ‘Last minute’ recovery program to understand and tweak the conductors parameters such that it may work, solution found, solenoid rescued!

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

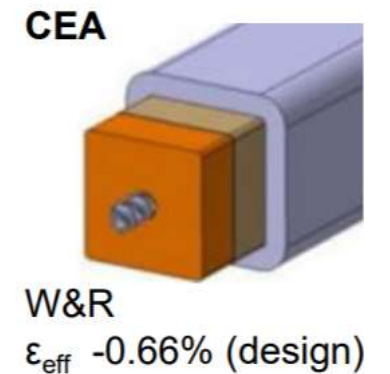
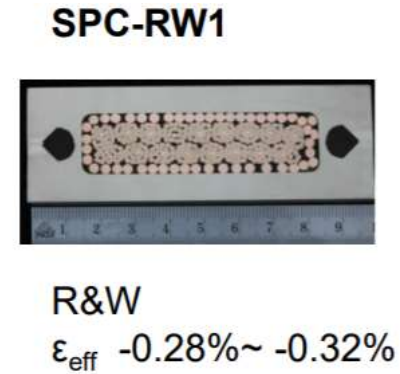
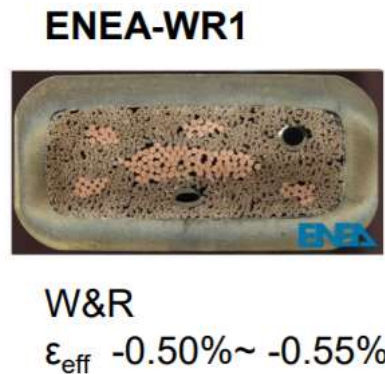
Lessens learnt - and next, DEMO

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 on strand-type, cabling pitches and thermal cycling, a nasty disadvantage of Nb₃Sn-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:

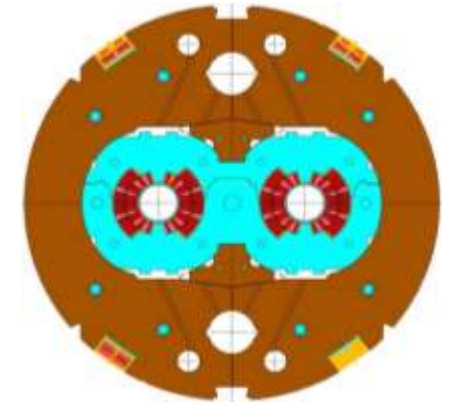


Case II : Nb_3Sn Rutherford cables for accelerator magnets

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 J_c 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

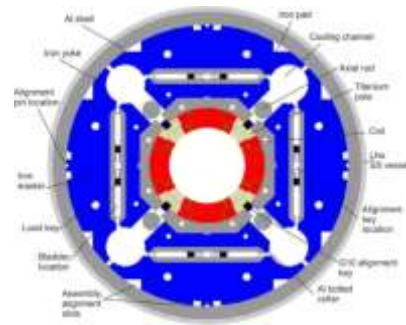
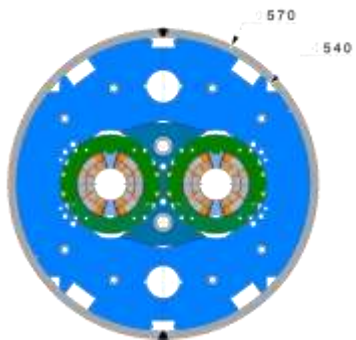
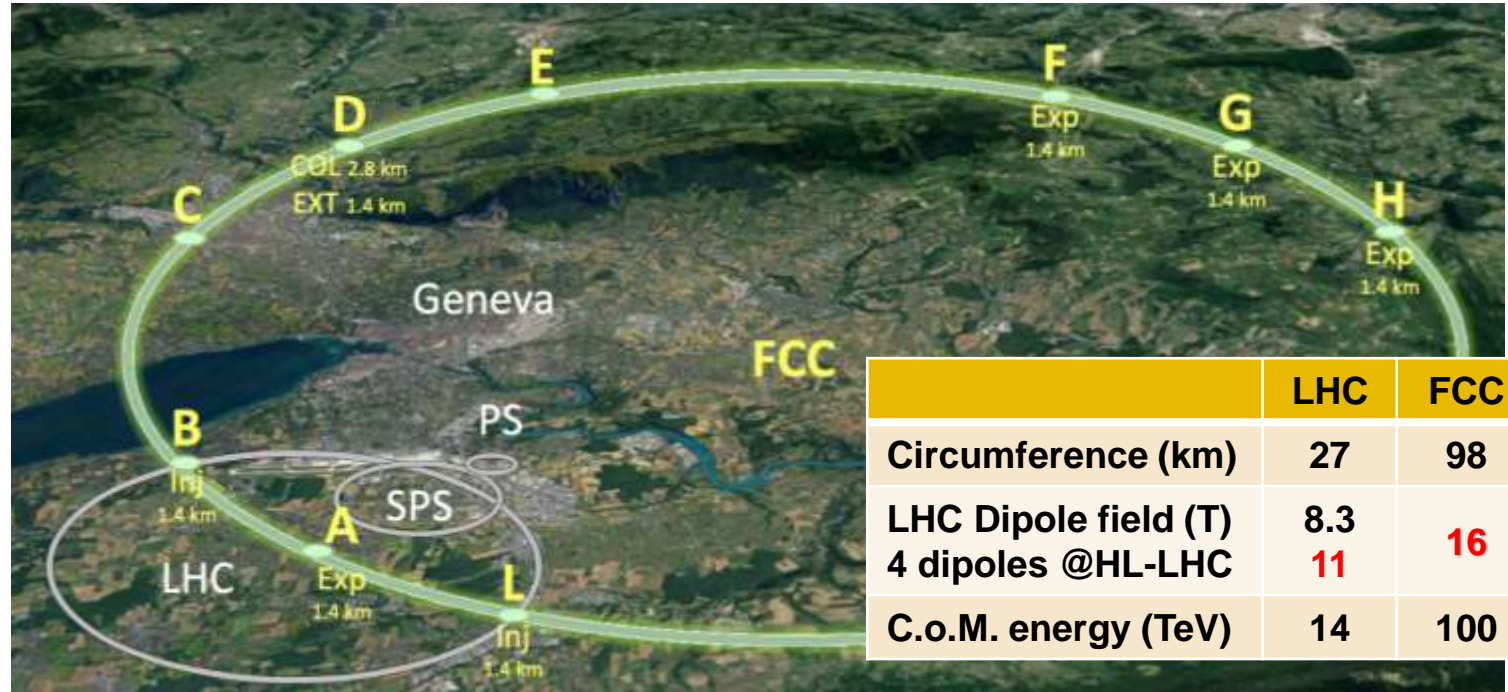
Main issue is Sustaining Transverse Pressure on cable wide face



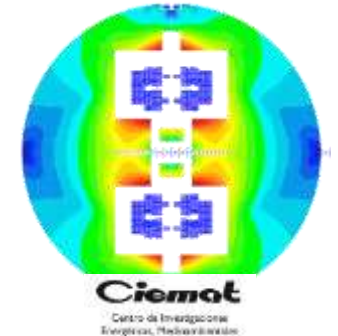
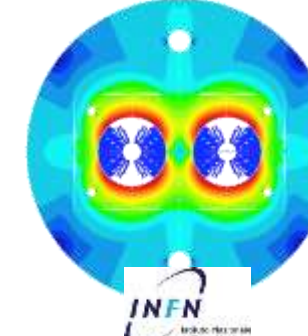
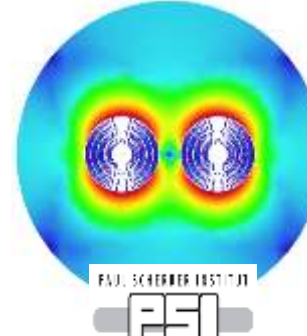
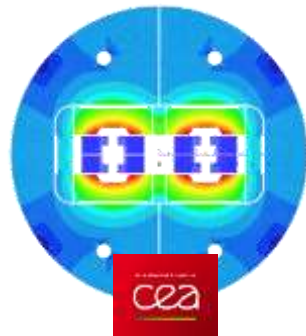
Cos θ dipole magnet layout, winding pack and cable

High-Field Nb₃Sn 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

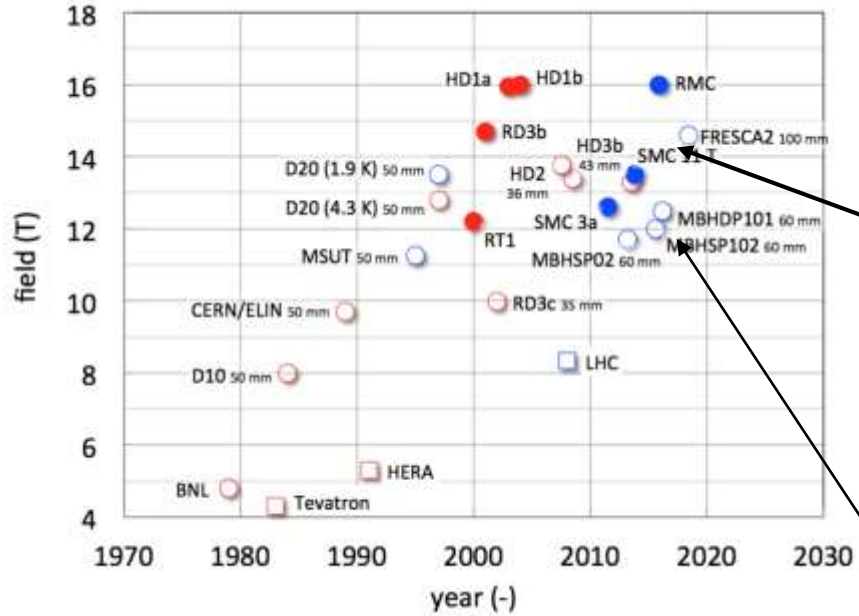


HL-LHC dipole and quad construction design



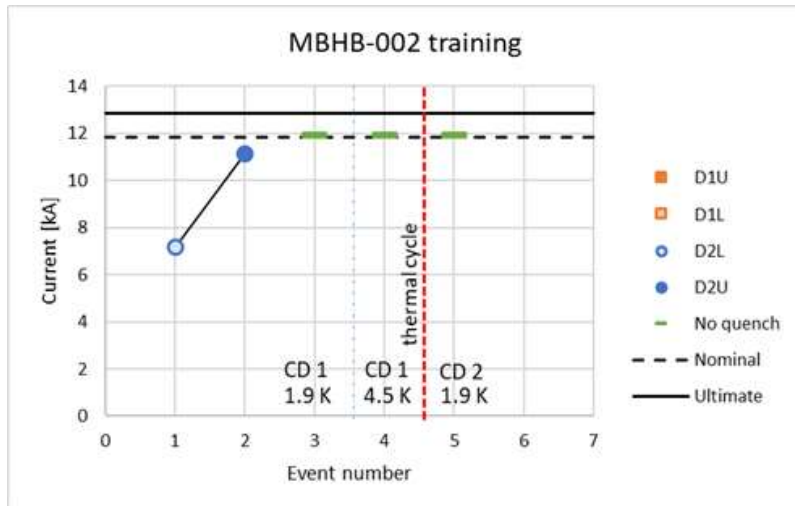
Flavor of FCC type 16 T dipole magnet conceptual designs by collaborators

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 !



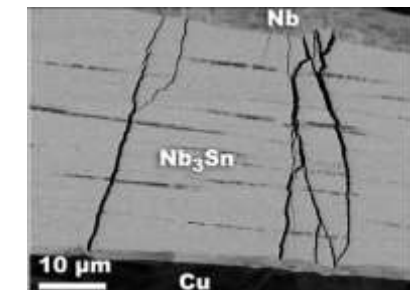
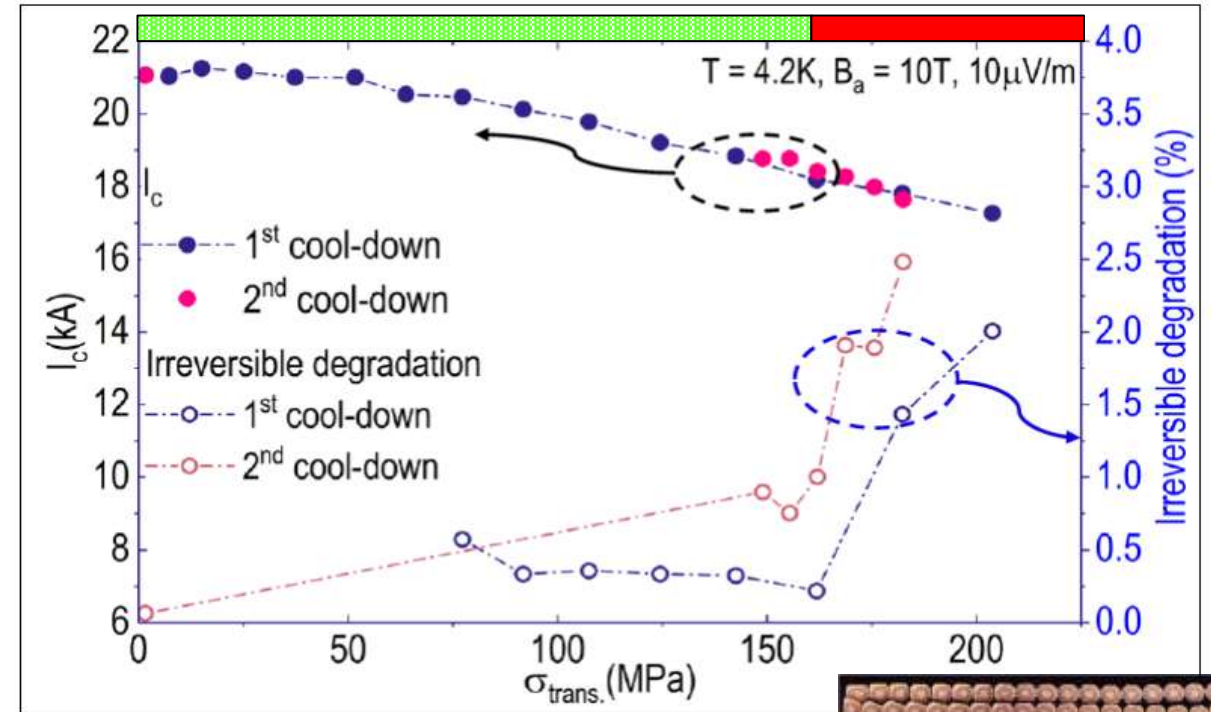
Production magnet

11 T Dipole magnet windings for HL-LHC

Nb₃Sn 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.

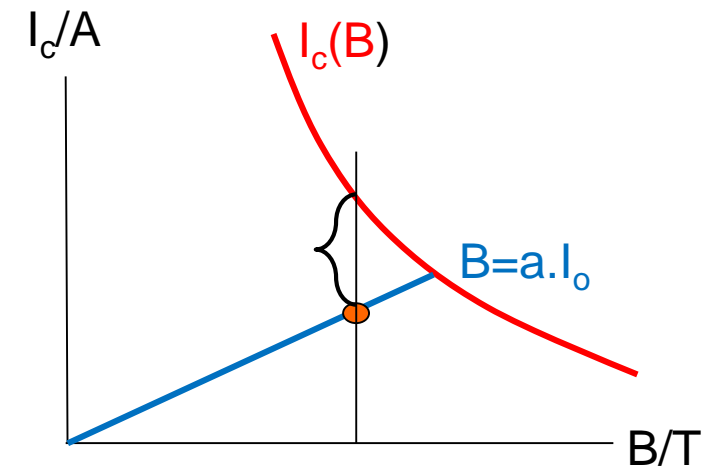
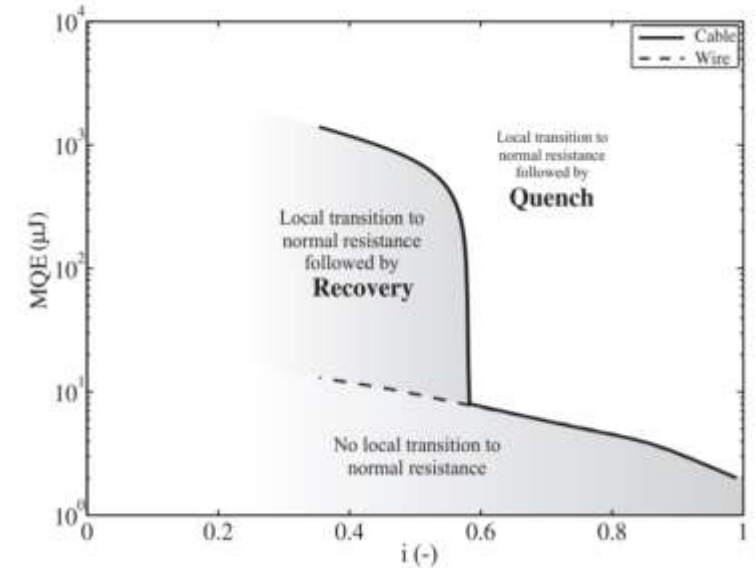


Filament cracking

- ✓ **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** !

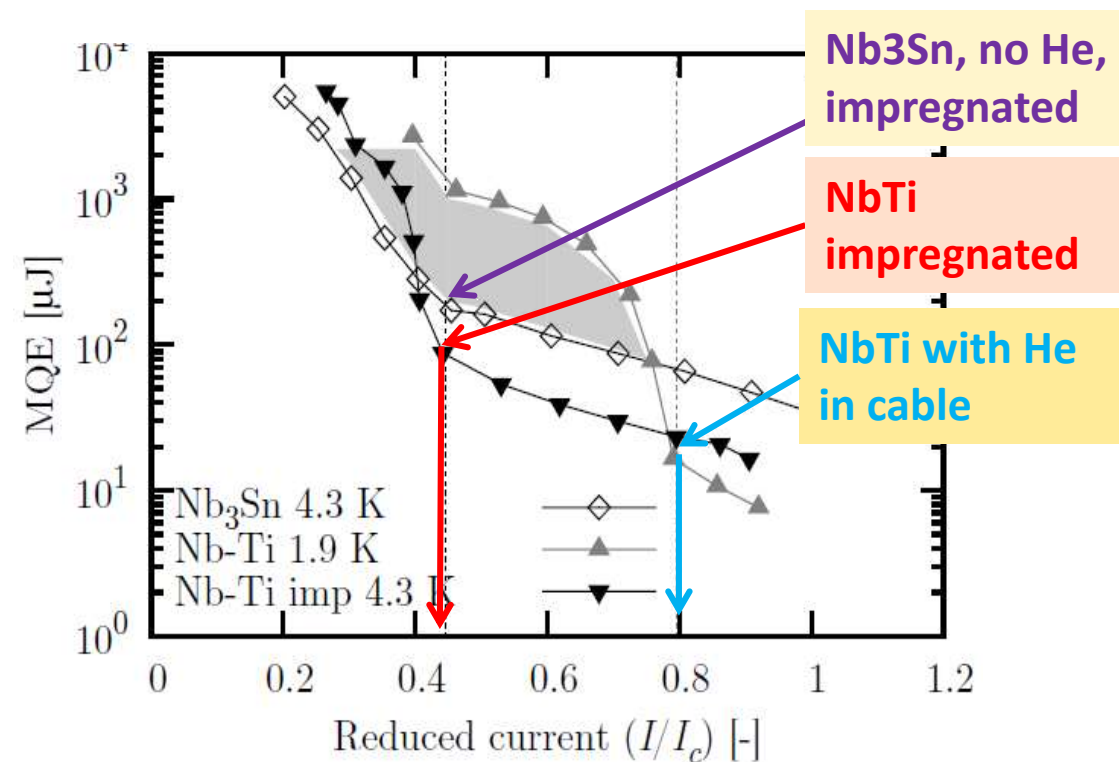
Issue 2: Nb₃Sn Rutherford - Cable stability versus I_c

- 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 Cp (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, $I/I_c < 0.75$!
- **Impregnated Nb₃Sn is in single strand regime when at >75% on load line!** Need to reduce I/I_c 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 $I/I_c < 0.45$!



- ✓ **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

Nb₃Sn - Stability cliff disaster

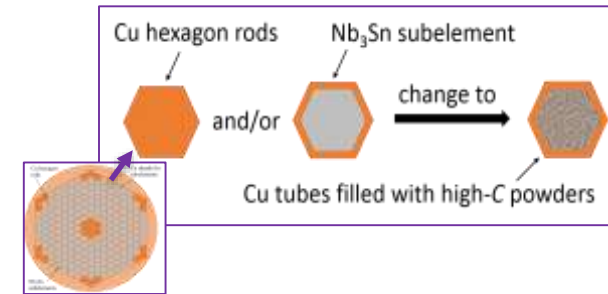
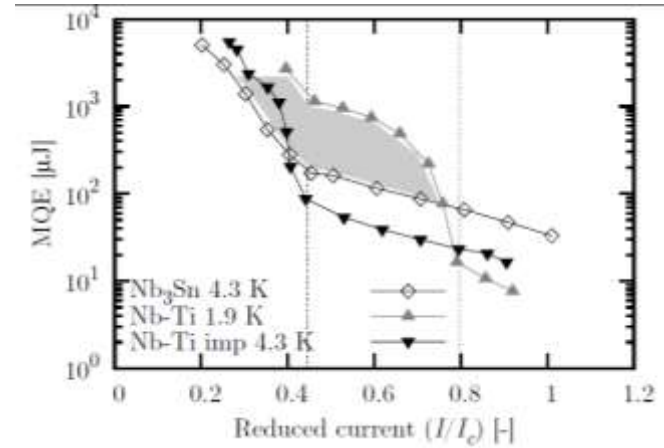
- The present design ideas of operating 10-16T Nb₃Sn magnets at >80% on load line is not robust, is not a credible solution!
- We can not make large scale series based on lucky-few magnets.
This will kill projects and funding!

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_{kink} to right)
4. Reduce inter-strand contact resistance (shifting I_{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 €€€)



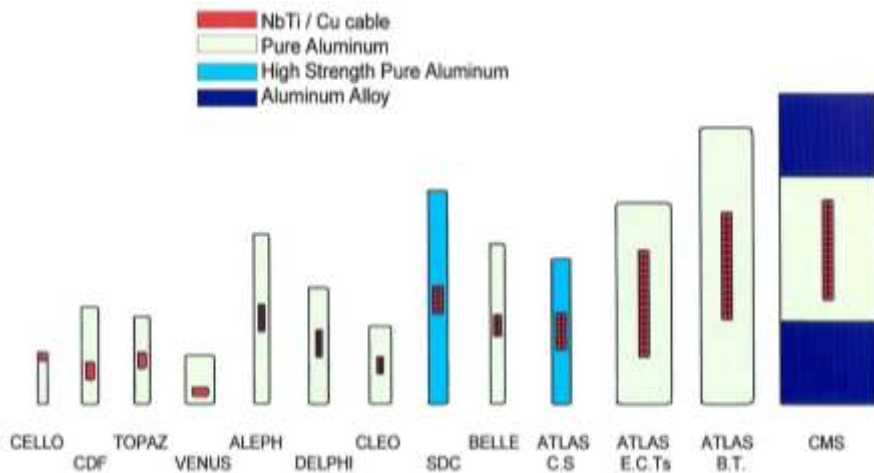
Example FNAL initiative:

- High-C_p materials: CeCu₆, Gd₂O₃
- Adding 1 vol.% of Gd₂O₃ to a Nb₃Sn wire can increase its C_p by several times.
- **Good, but more, try 10 to 15 %!**

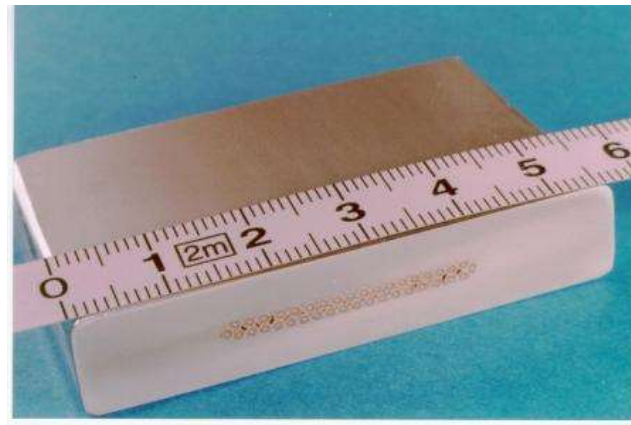
Case III: Al stabilized conductors for Detector Magnets

Why Al?

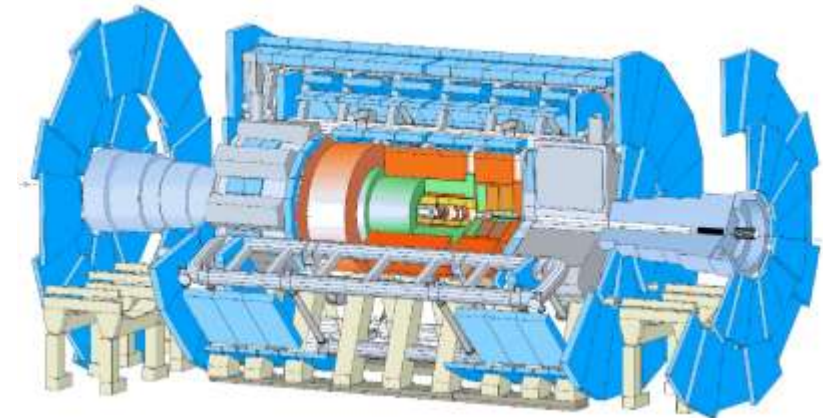
- *Simplicity of conduction cooling*, affordable since no dynamic operation, quasi stationary
- High-purity Al stabilized, RRR 2000, *maximum MPZ* (m), much larger λ/ρ than copper!
- *Particle transparency* for minimum particle scattering
- **But higher collision energy implies larger dimension**, tracking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

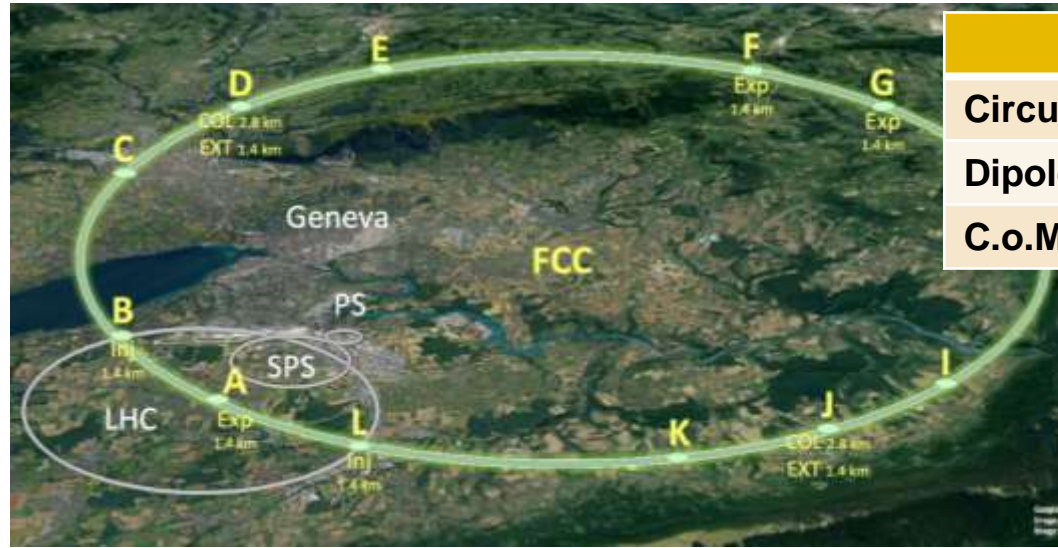
Magnets for FCC ee & hh collision detectors

Proposed Future Circular Collider

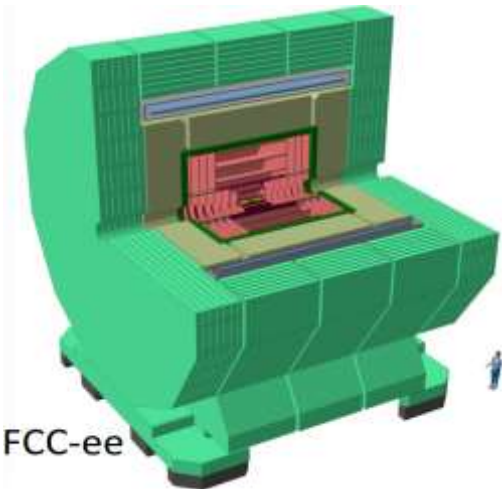
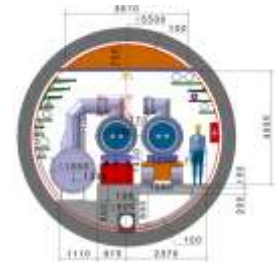
Stage 1: ee collisions (~2040)

Stage 2: 100 TeV hh collisions (~2070)

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

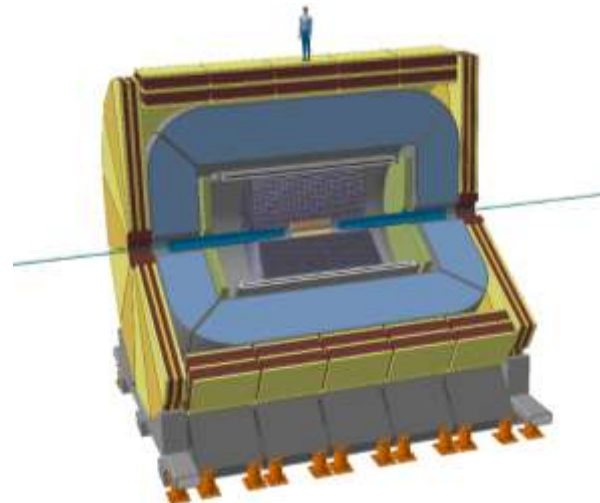


	LHC	FCC
Circumference (km)	27	98
Dipole field (T)	8.3	16
C.o.M. energy (TeV)	14	100

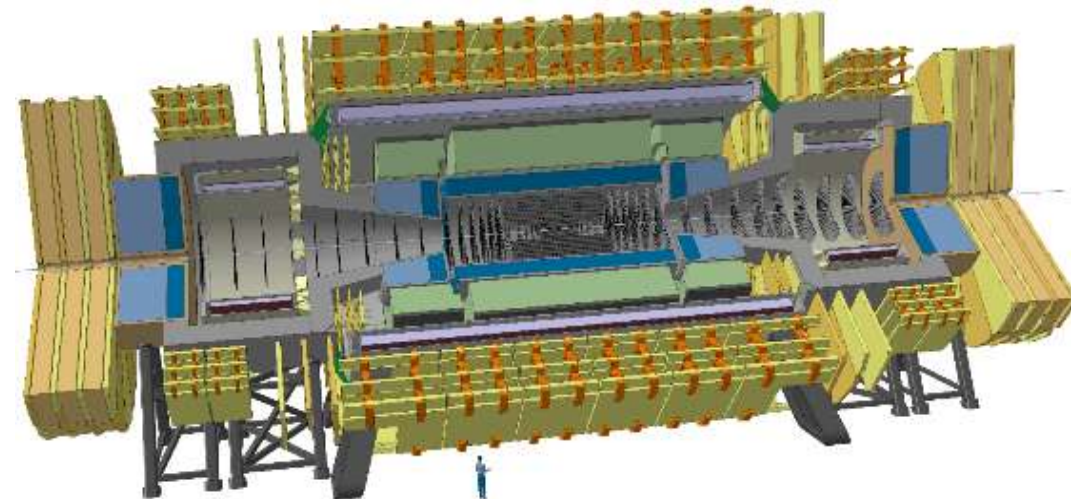


FCC-ee

Classical 2 T Solenoid



IDEA, innovative **thin** Solenoid around tracker

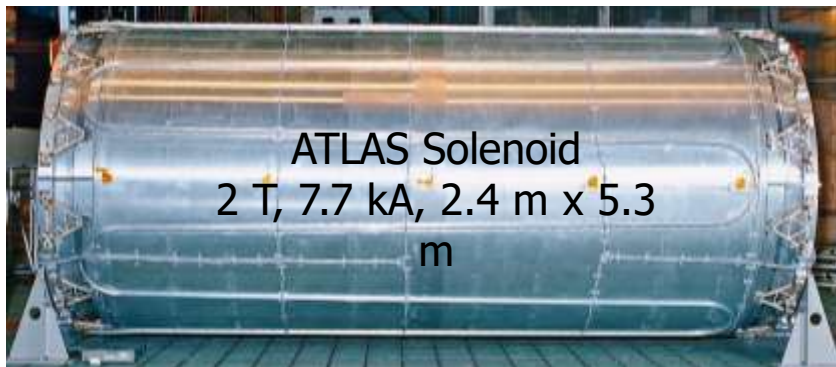
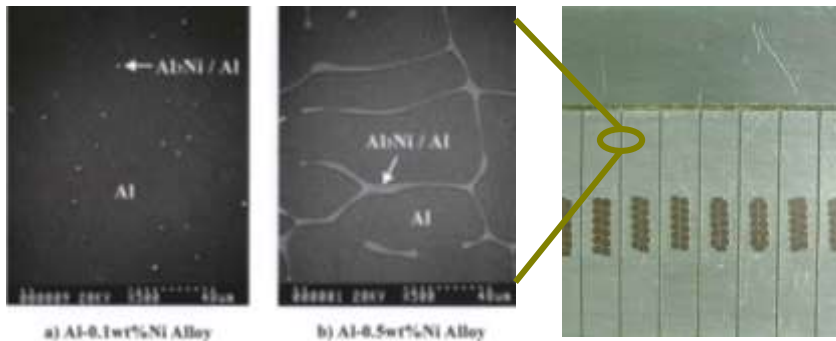


FCChh Detector, **4T/10m** main & 2 3T forward solenoids

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

Option 1

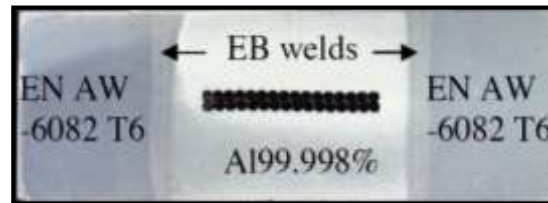
Micro-alloy pure Al with Ni or Zn
Used in the ATLAS Solenoid



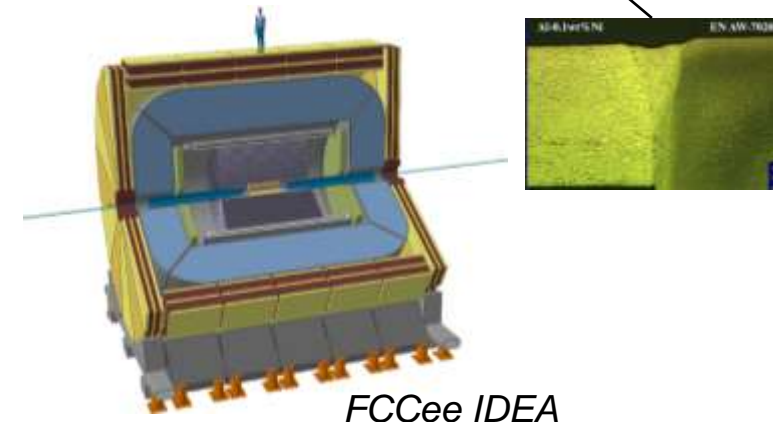
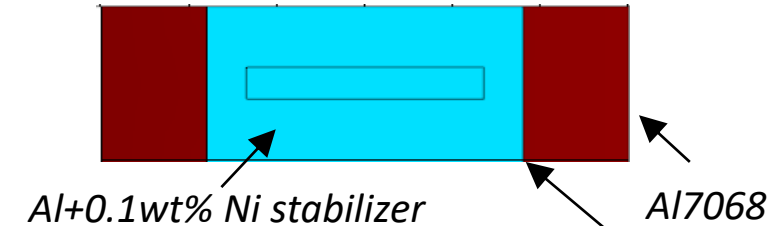
Option 2

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

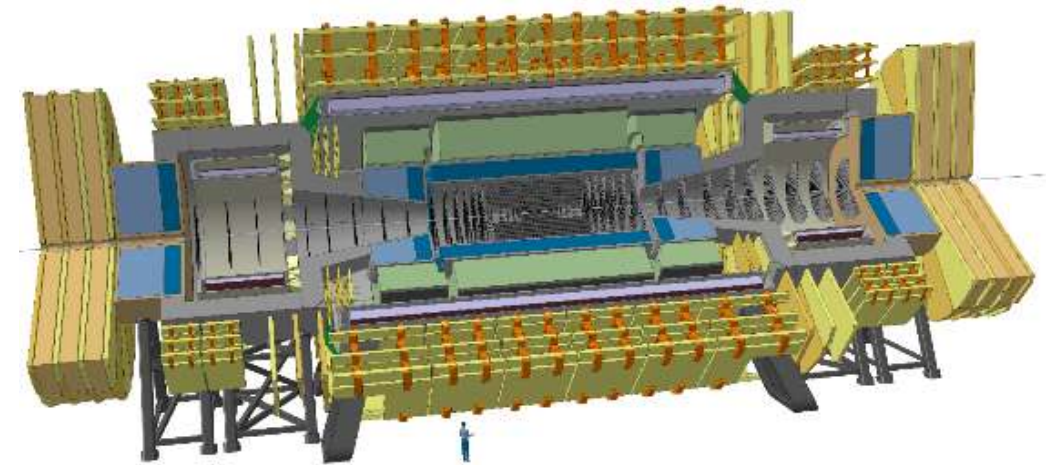
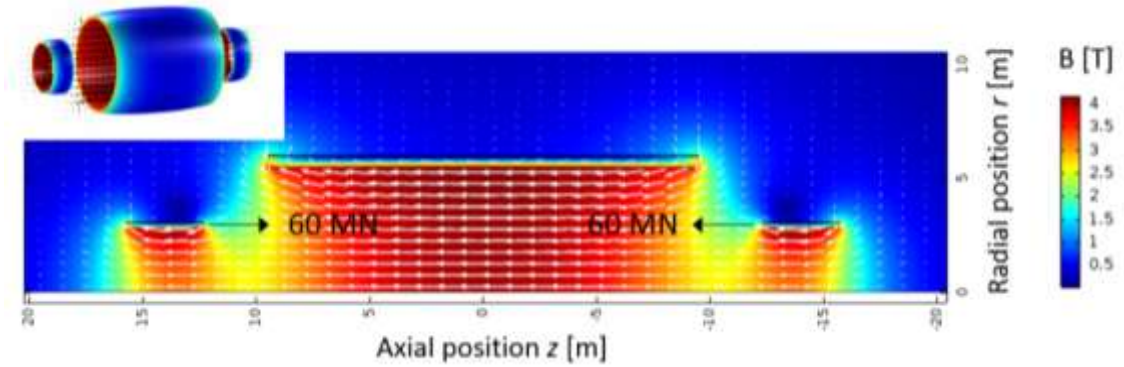
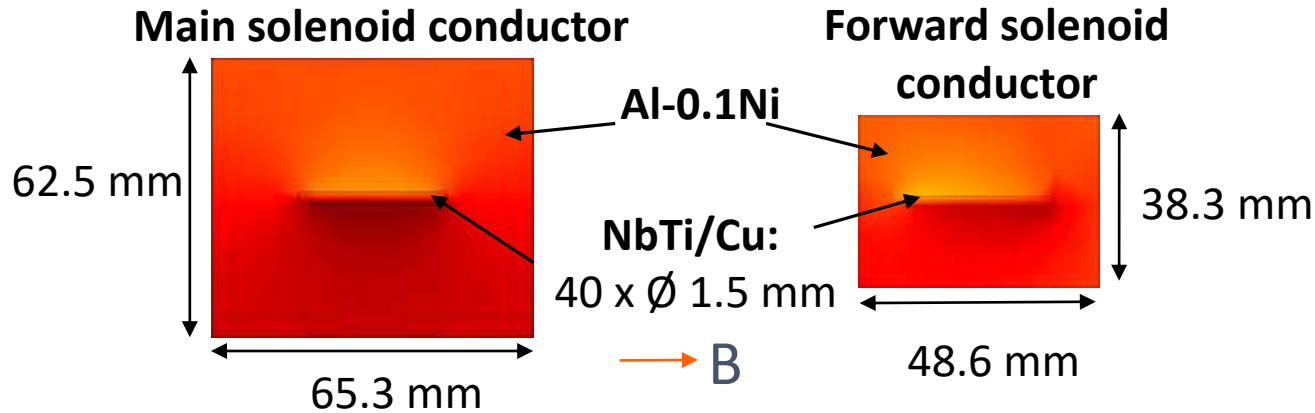
Using **Al 6082 T6**
(Used in CMS Solenoid)



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



Super-Conductors for 4T/10m detector solenoids



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

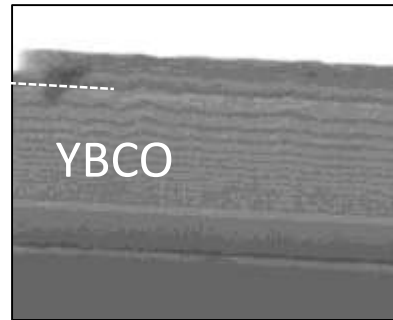
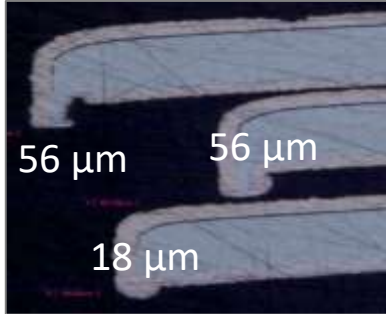
- Peak magnetic field on conductor 4.5 T
- Current sharing temperature 6.5 K
- 2 K temperature margin when operating at 4.5 K
- **Nickel-doped Aluminum (≥ 0.1 wt.%)** combining good electrical properties (RRR 600) with mechanical properties, 146 MPa conductor yield strength

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:

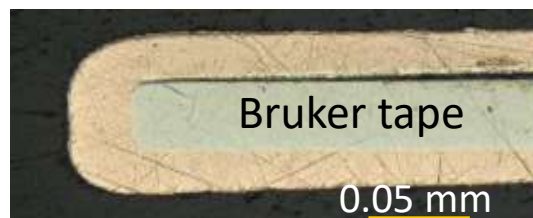
Punching or Laser cutting



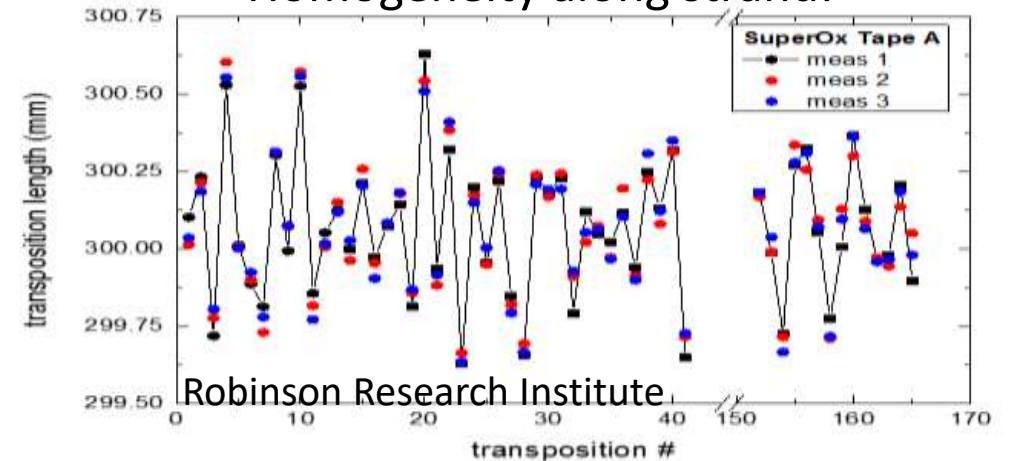
Magneto-optical imaging showing broken strands

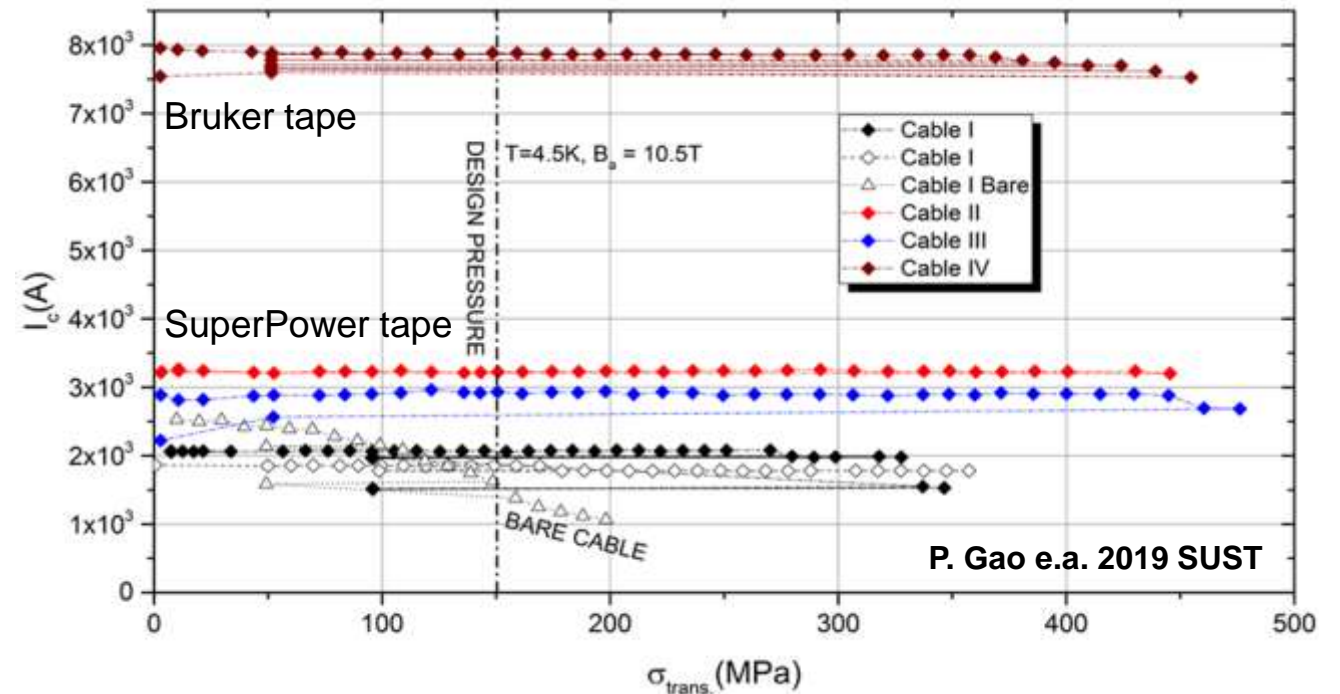
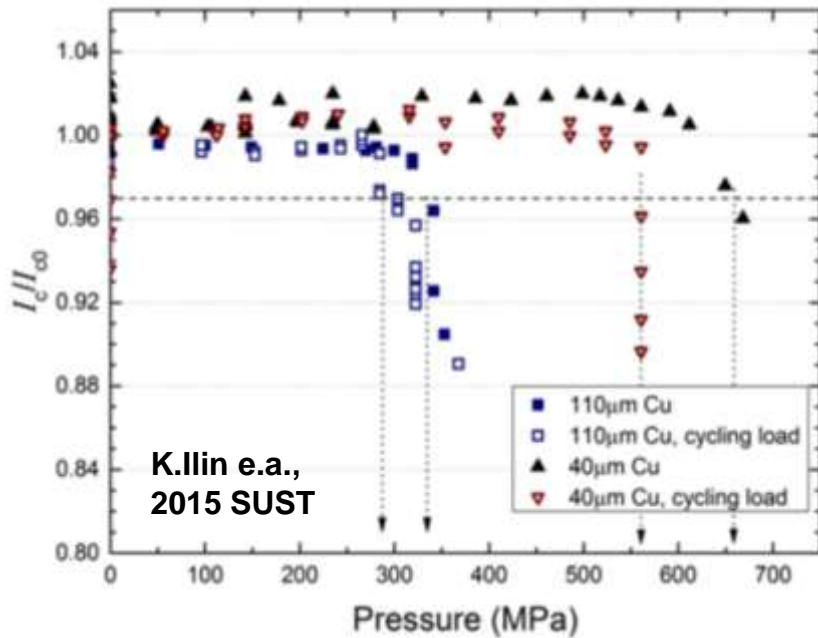


Punch & coat technique



Homogeneity along strand:





- 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

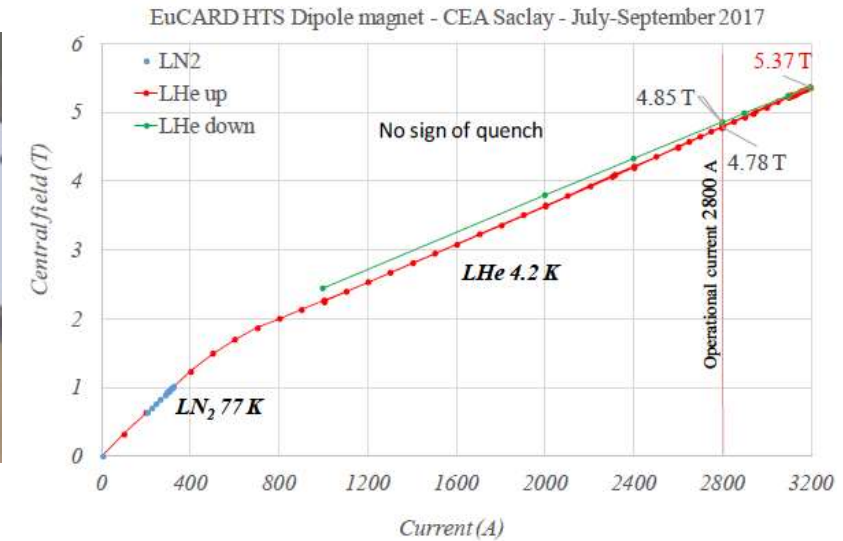
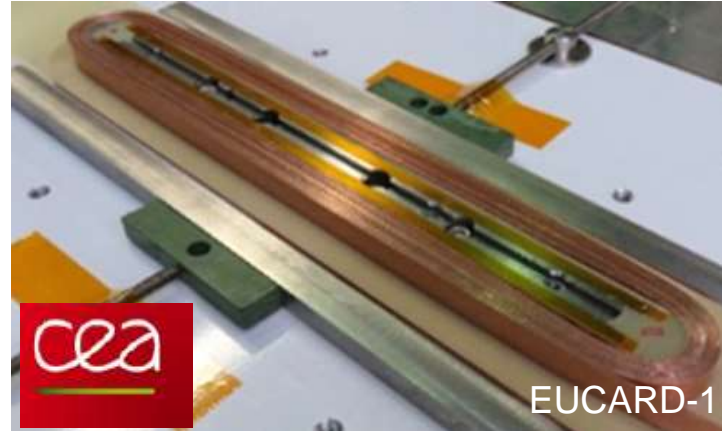


- ✓ Impregnated Roebel cable can withstand transverse pressure in excess of 300 MPa !
- ✓ Very good for high-field magnets

ReBCO dipole magnet developments - examples

ReBCO dipole development at CEA

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

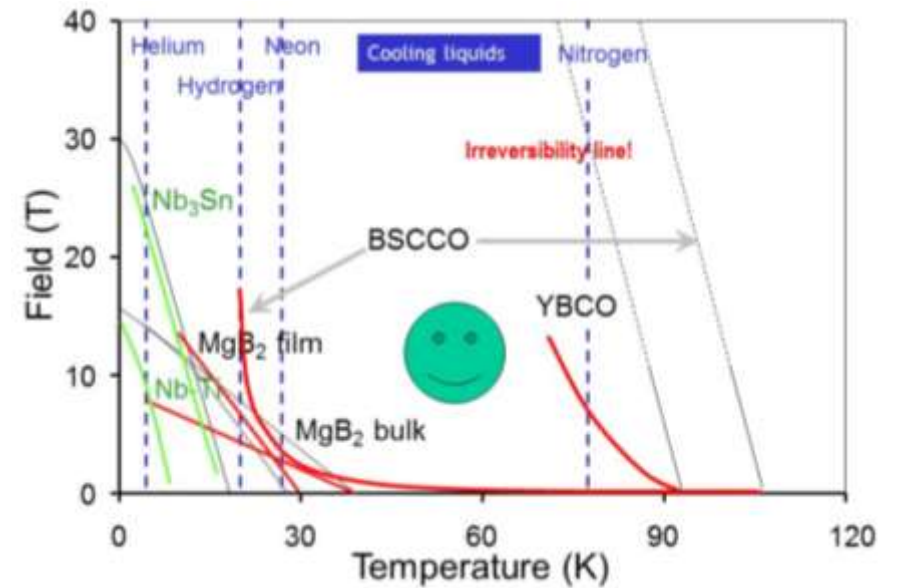
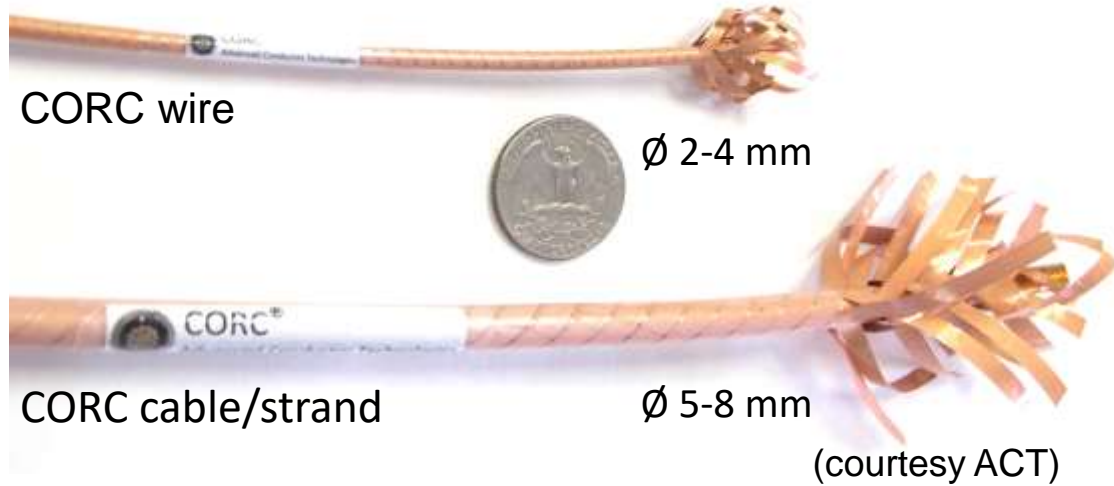
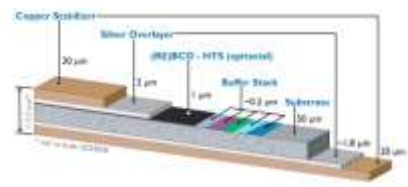


ReBCO Feather series dipole insert development magnets at CERN

- 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, can be 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

ReBCO-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



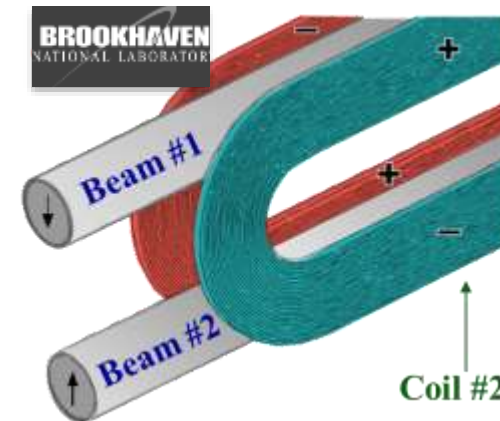
74mm dia, insert
2 layers, 2T in 15T



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



Racetrack insert,
80 mm dia, 2 layers



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



Making of CCT2

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

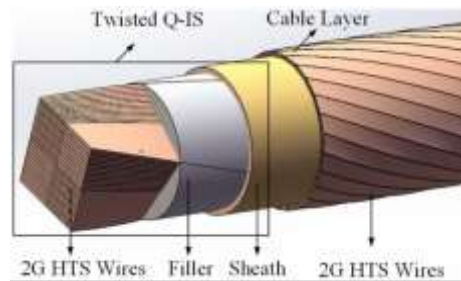
ReBCO CORC - Cable-in-Conduit conductors

- **Cable-In-Conduit Conductors (CICCs)**, designed for large-scale, high-current magnets as for large outsert coils, fusion magnets and particle detectors
- *NbTi* and *Nb₃Sn* 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

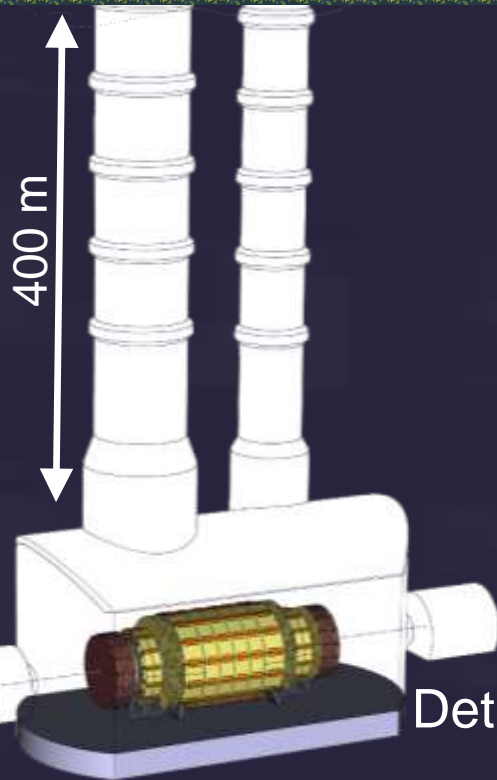
CORC CICC for Bus Bars and Large Scale Magnets



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



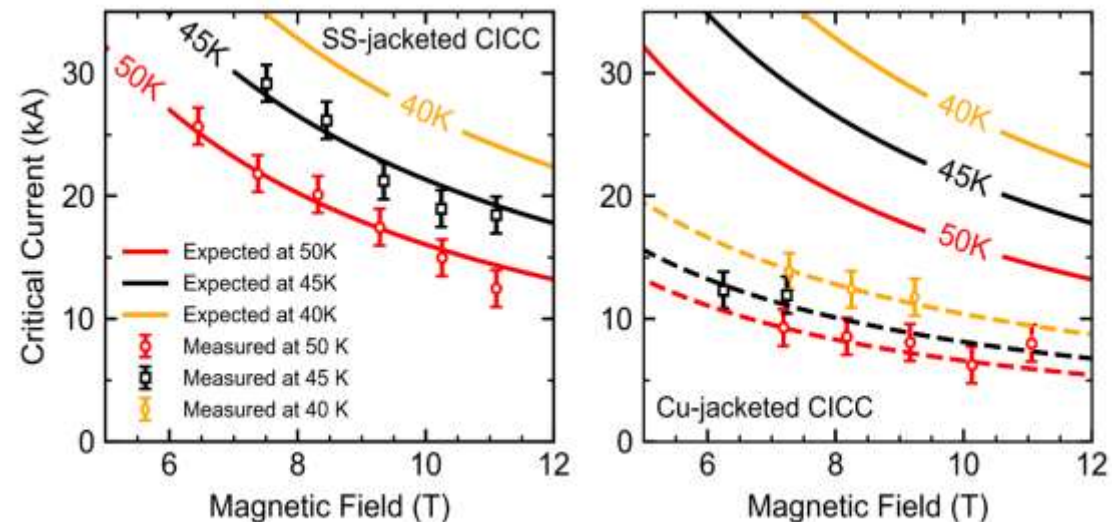
CORC Magnets:

- 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

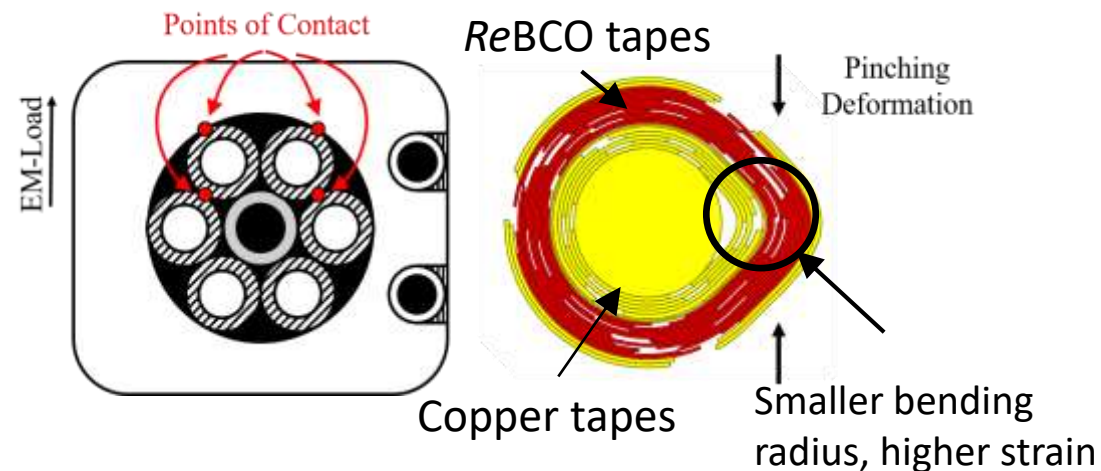
Typical result showing that R&D is needed

- 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,



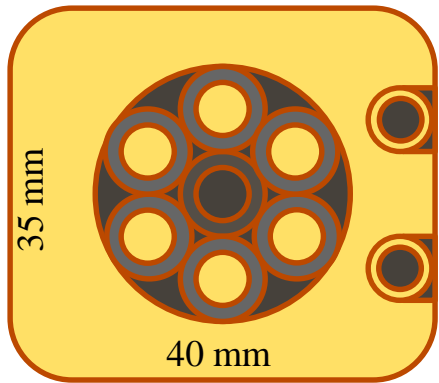
Why! :

- 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

- 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

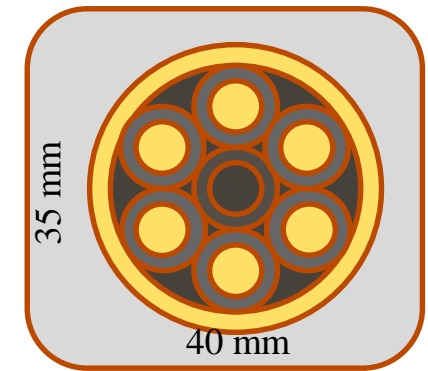


Magnets & Bus Bars:

- High thermal & electrical stability
- Practical conduction cooling

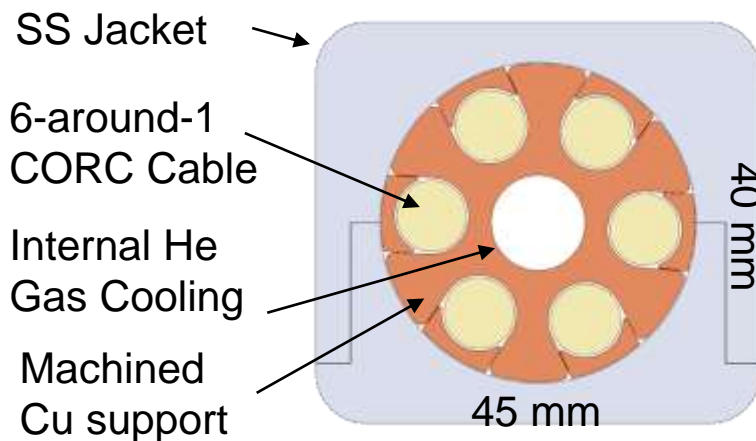
Fusion type magnets:

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



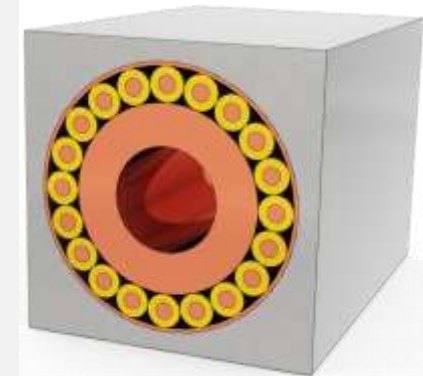
Next sample:

- 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



- 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!**

