Luca.Bottura@cern.ch

Fils et câbles supraconducteurs du futur

ASSOCIATION FRANÇAISE DU FROID

AFF Commission Cryogénie et Supraconductivité.
Les Journées Thématiques au CERN:
LHC, premiers résultats et perspectives.
June 6th-7th, 2013

CERN

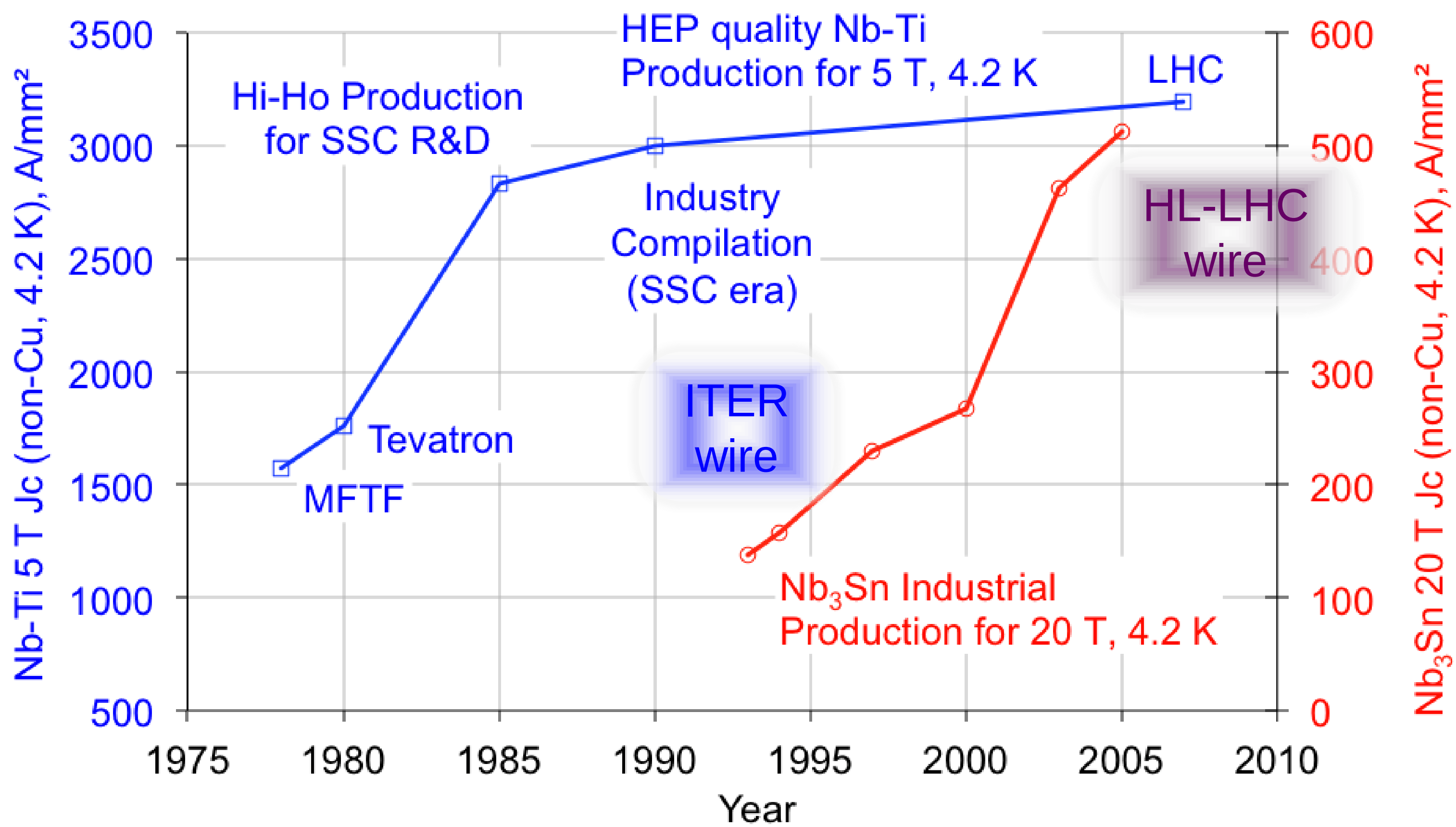
Overview

- The drive from the LHC
  - LTS wires and cables at 50
  - HTS conductors at 25
- Beyond the LHC
- Summary and conclusions

Overview

- **The drive from the LHC**
  - **LTS wires and cables at 50**
  - HTS conductors at 25
- Beyond the LHC
- Summary and conclusions

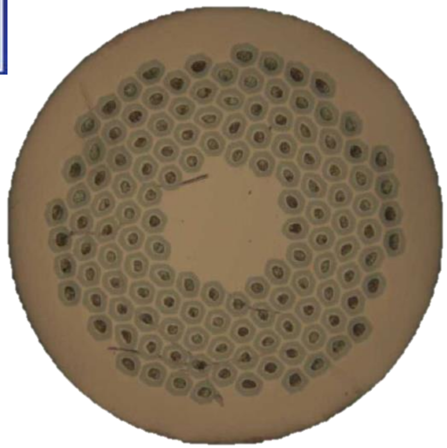
At 50, LTS's have reached maturity ?

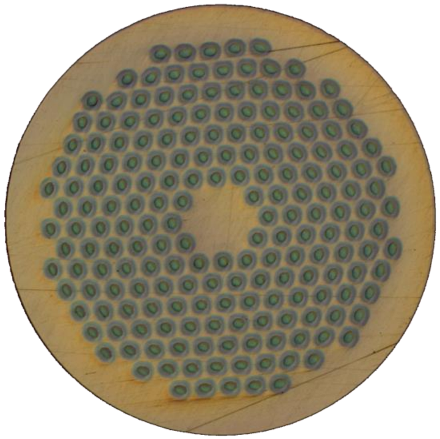


Data by courtesy of J. Parrell (OST)

Micrographs by A. Bonasia (CERN)

Typical HEP-grade Nb_3Sn wires



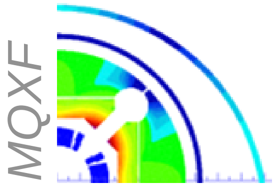


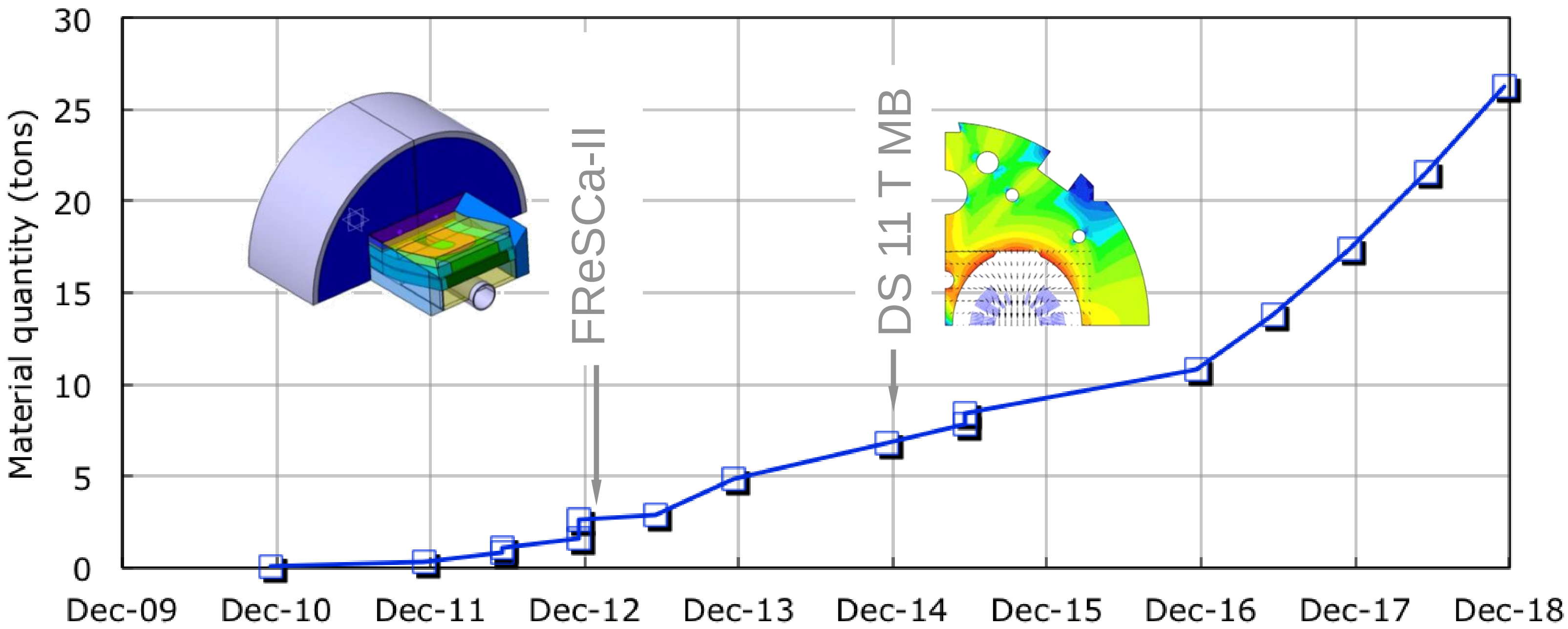
Strand diameter: 1.0 mm
Cu:non-Cu: 1.25
Filament diameter: 58 μm
Number of filaments: 132
J_C (15 T. 4.2 K) > 1575 A/mm²
RRR > 150
UL > 400 m … 800 m

Strand diameter: 1.0 mm
Cu:non-Cu: 1.25
Filament diameter: 48 μm
Number of filaments: 192
J_C (15 T. 4.2 K) > 1350 A/mm²
RRR > 150
UL > 400 m … 800 m

NOTE: procurement assisted by the special in-kind contribution from France

Material needs – Nb_3Sn





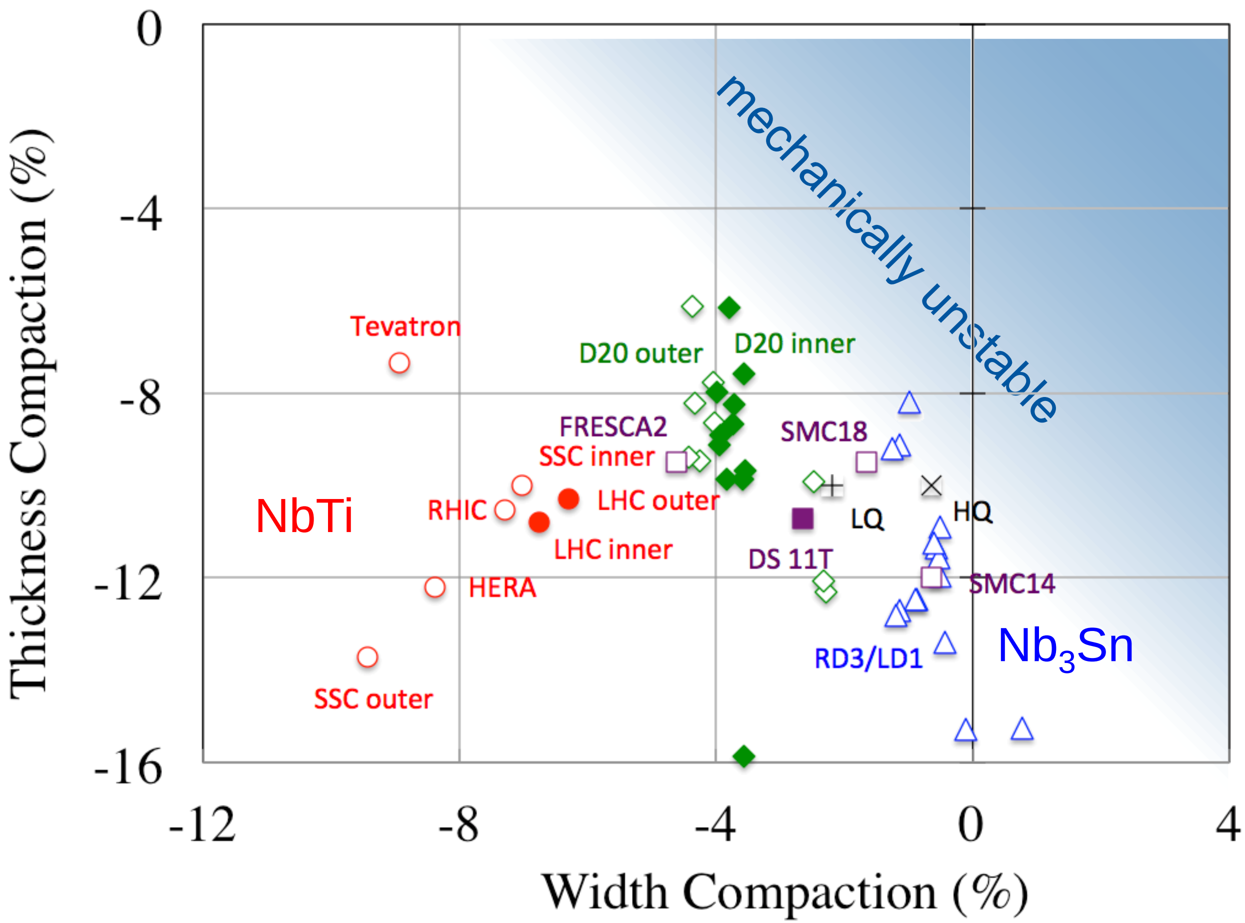
- Approximately 26 tons of *HEP-grade* Nb_3Sn will be needed in the coming 5 years

Cabling by A. Bonasia, L. Oberli; graphics by M. Brice (CERN)

Cabling challenges

14 strands, 1.25 mm Powder-in-Tube (PIT) SMC cable

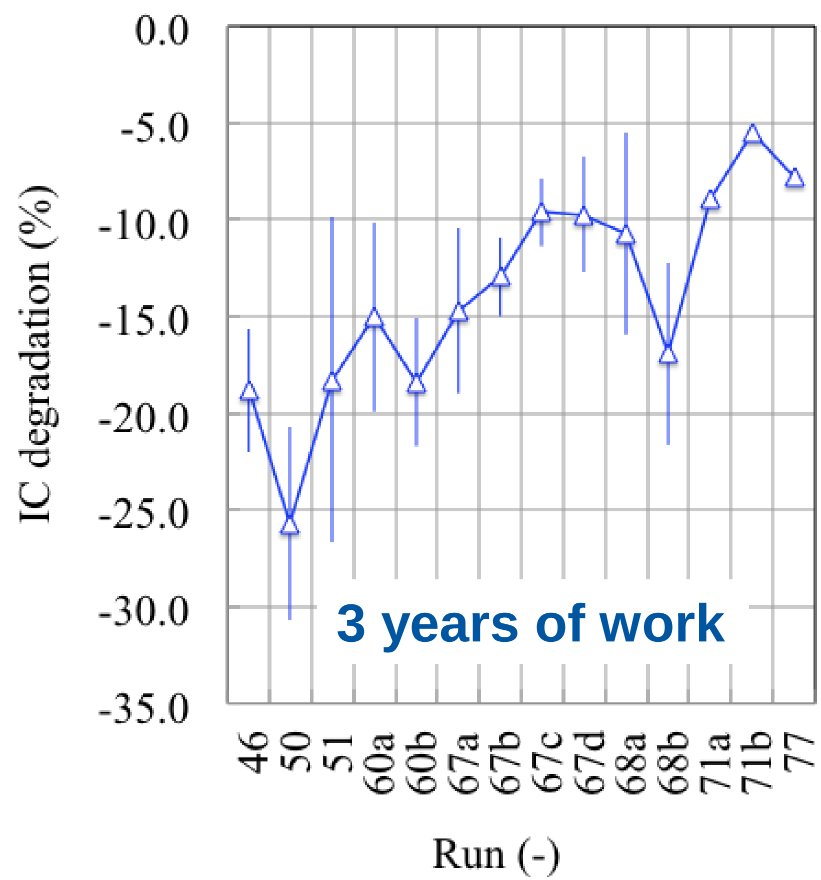
Range of Cabling Parameters

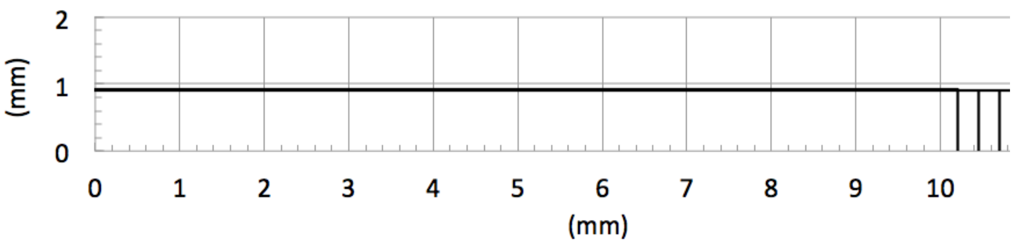


Data by courtesy of R. Scanlan, D. Dietderich, H, Highley (LBNL, Berkeley) and L. Oberli (CERN)

The case of the FRESCA2 cable

Run	Billet	Condition	Width (mm)	Thickness (mm)	Pitch (mm)	C_w (%)	C_t (%)	C (%)	Degradation (%)
46	PIT0905	dry	21.4	1.82	120	-2.5	-9.0	88.7	-18.8
50	PIT0905	dry	22	1.82	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
51	PIT0905	dry	21.4	1.82					
60a	PIT10402	dry	20.9	1.82					
60b	PIT10402	dry	20.9	1.82					
67a	PIT10402	dry	20.4	1.806					
67b	PIT10402	dry	20.4	1.806					
67c	PIT10402	dry	20.4	1.86					
67d	PIT10402	dry	20.4	1.86					
68a	PIT0904	ethanol	21.4	1.82					
68b			21.4	1.82					
71a	PIT11403	ethanol	20.9	1.82					
71b	PIT11403	oil	20.9	1.82					
77	PIT23258,	buthanol	20.9	1.82					

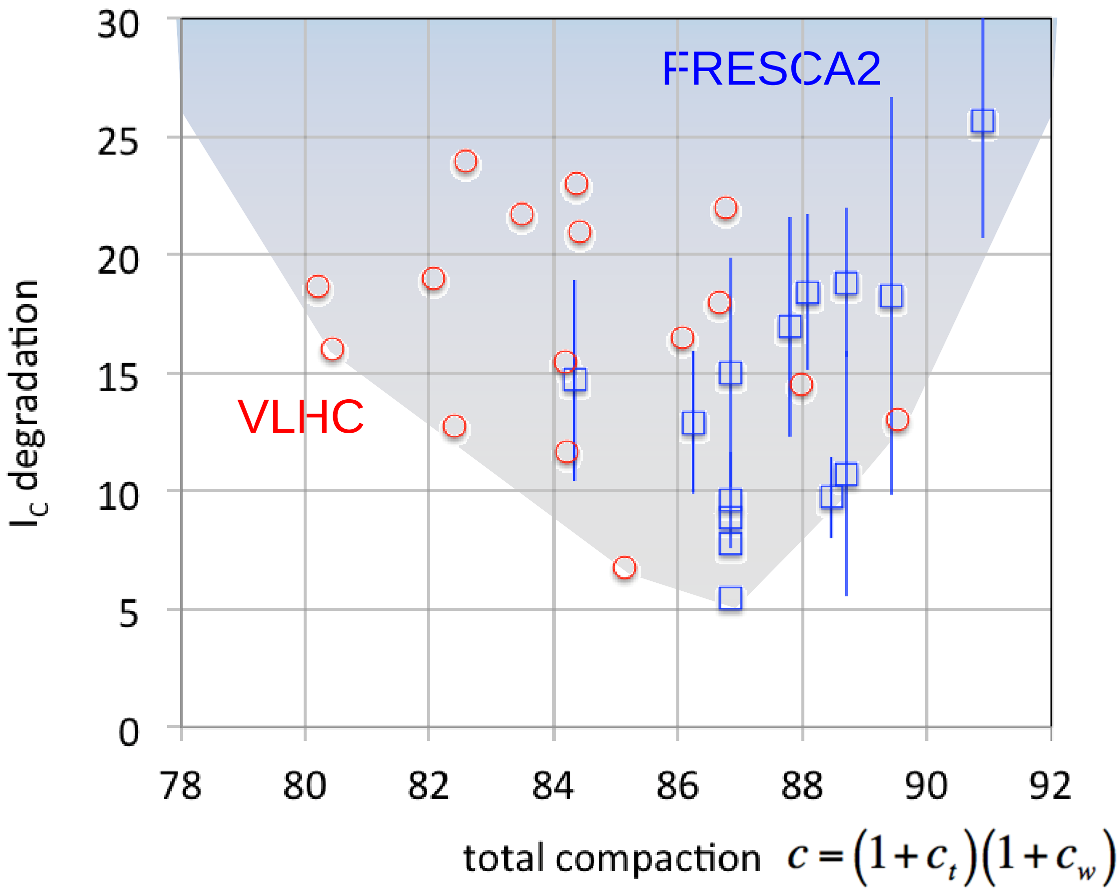




Data by courtesy L. Oberli (CERN)

Compaction vs. Degradation

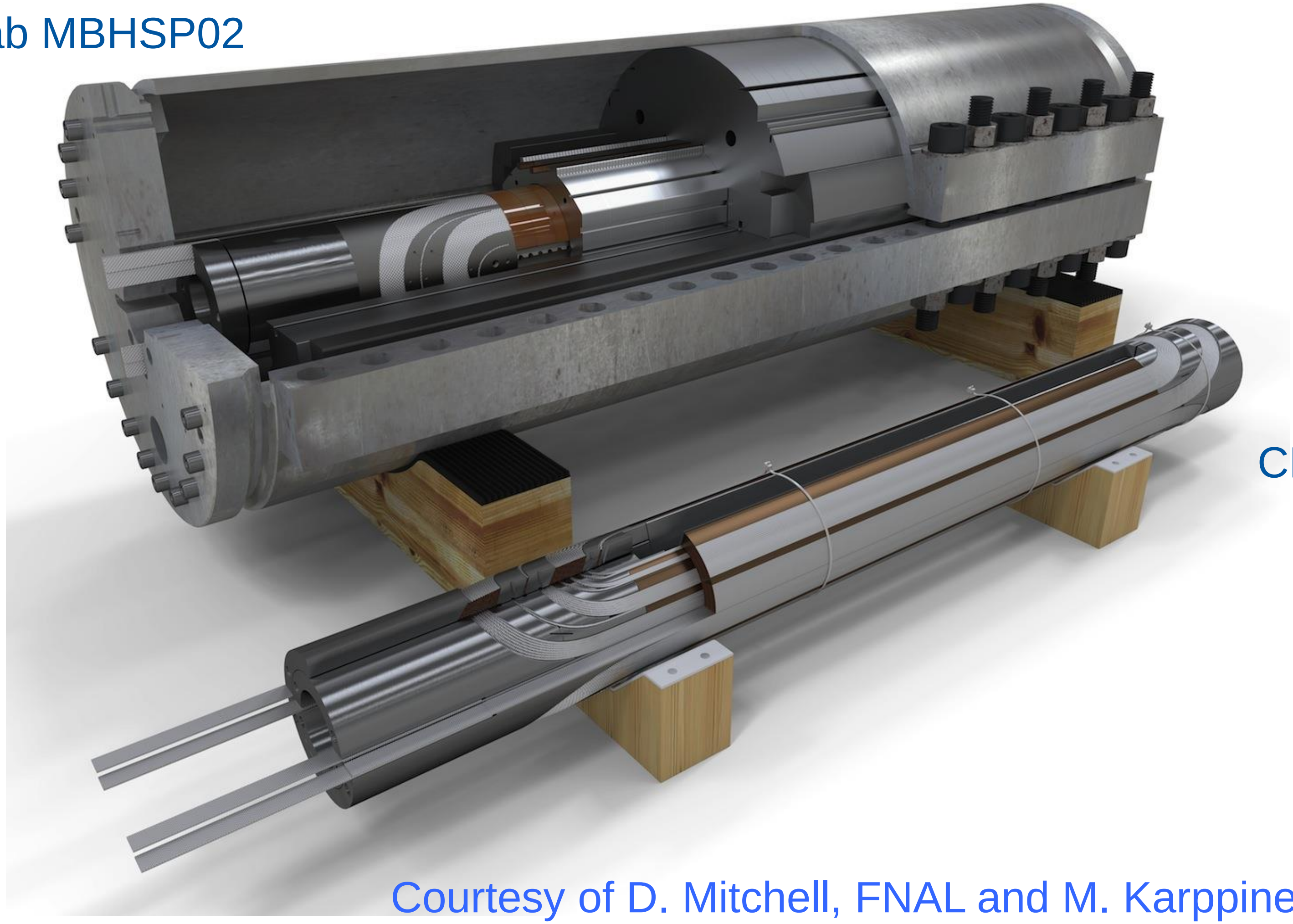
- Lowest degradation is obtained when the compaction is in the range of 85%...86%
- This is a delicate, lengthy and difficult optimization



Data by courtesy L. Oberli (CERN) and E. Barzi (FNAL)

DS 11 T MB models

Fermilab MBHSP02

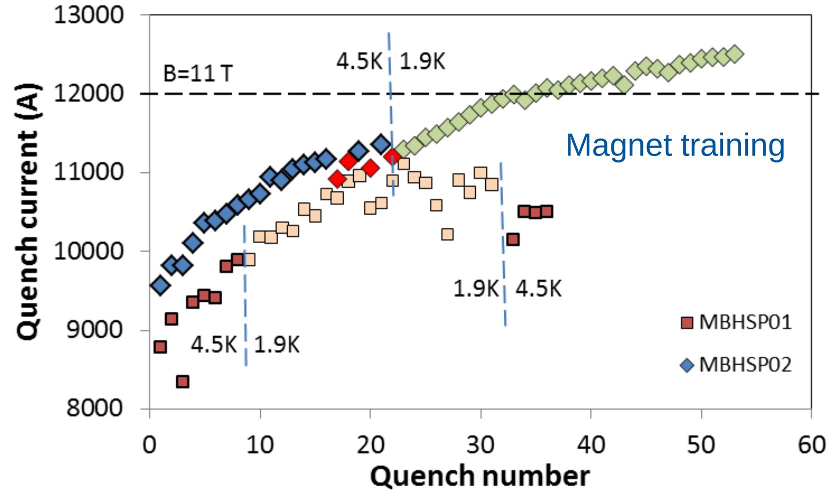


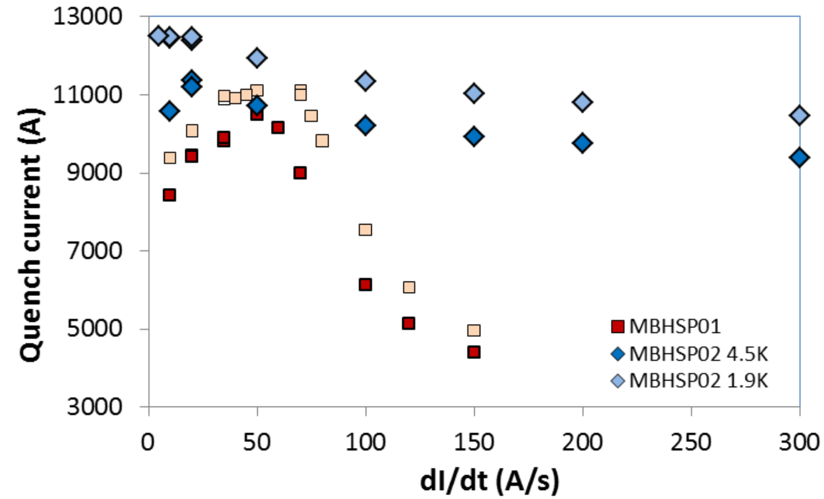
CERN coil

Courtesy of D. Mitchell, FNAL and M. Karppinen, CERN

MBHSP02 Performance

- Test completed in April 2013
  - Bmax= 11.7 T – 97.5% of design field B=12 T (78% of SSL at 1.9 K)
- Issues to be addressed
  - Long training
  - Conductor degradation
  - Negative ramp rate dependence at dI/dt<20 A/s and 4.5 K



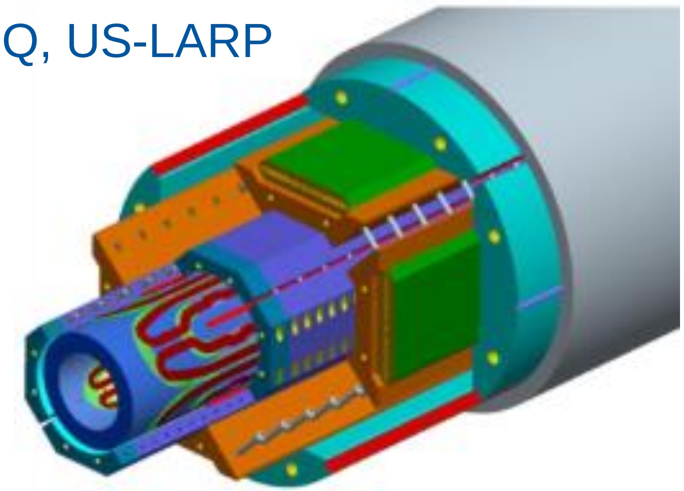


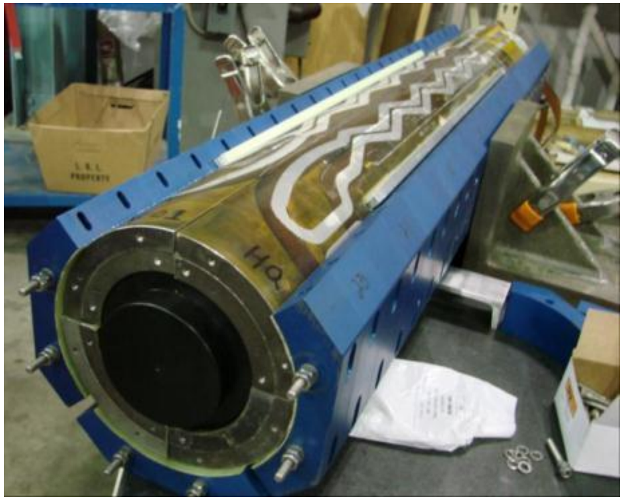
Tests at Fermilab, reported by courtesy of M. Karppinen, CERN

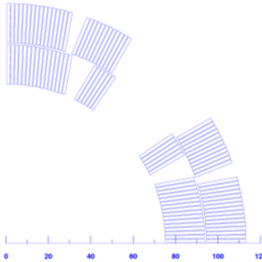
Ramp rate dependence

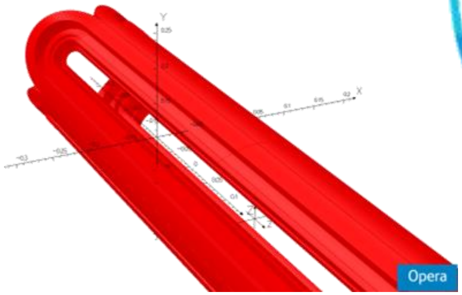
From HQ to MQXF

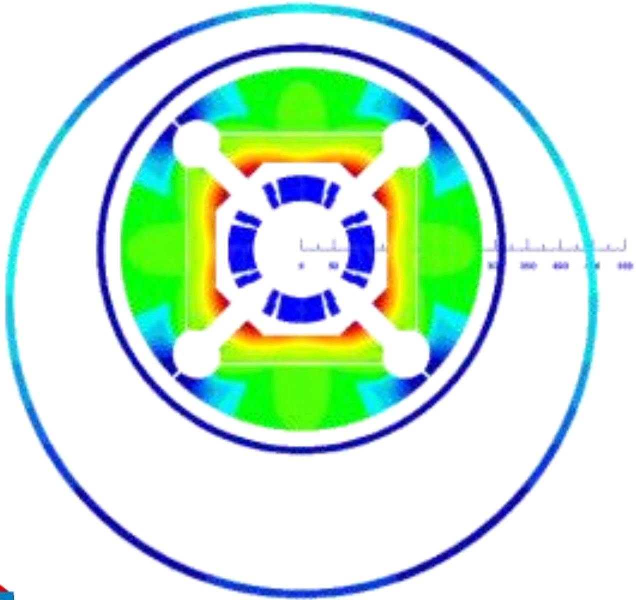
HQ, US-LARP



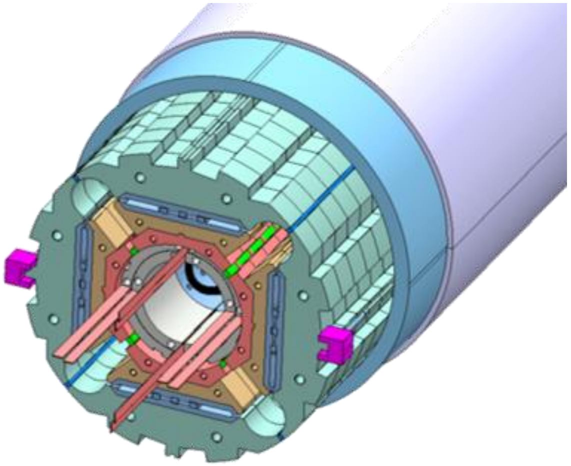






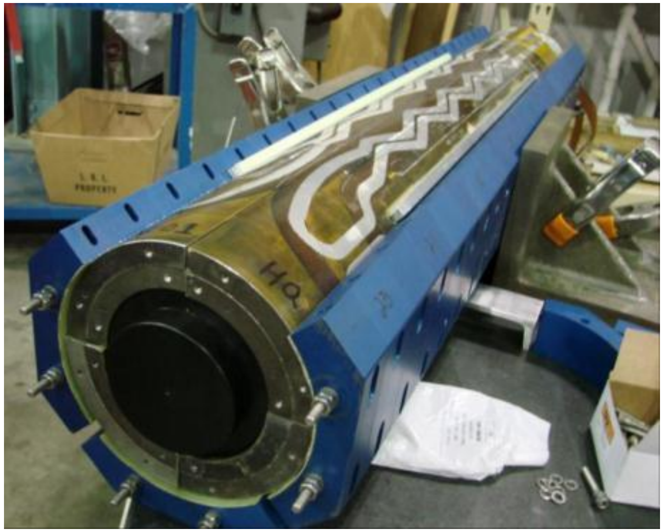


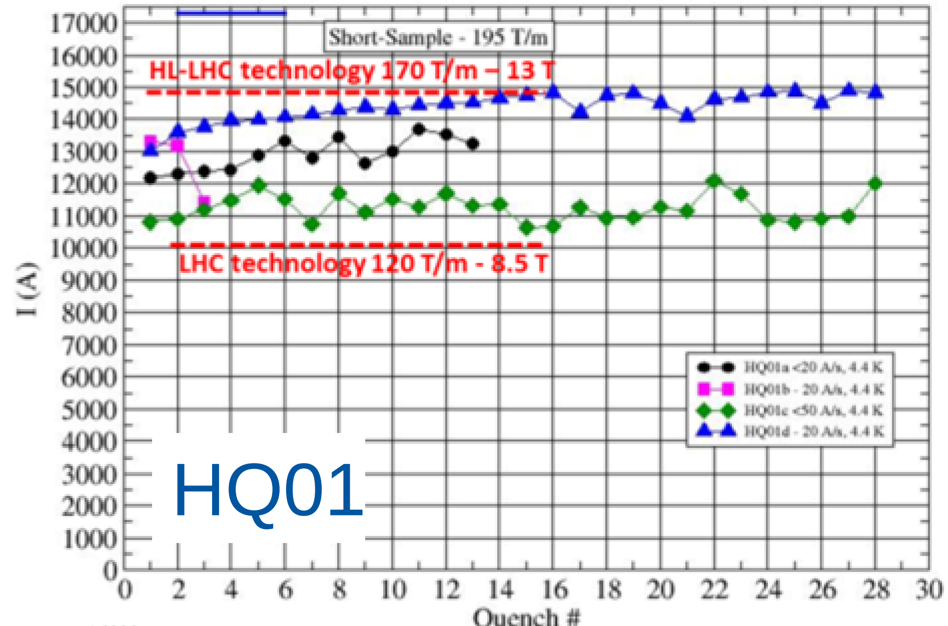
MQXF, joint development US-LARP and CERN



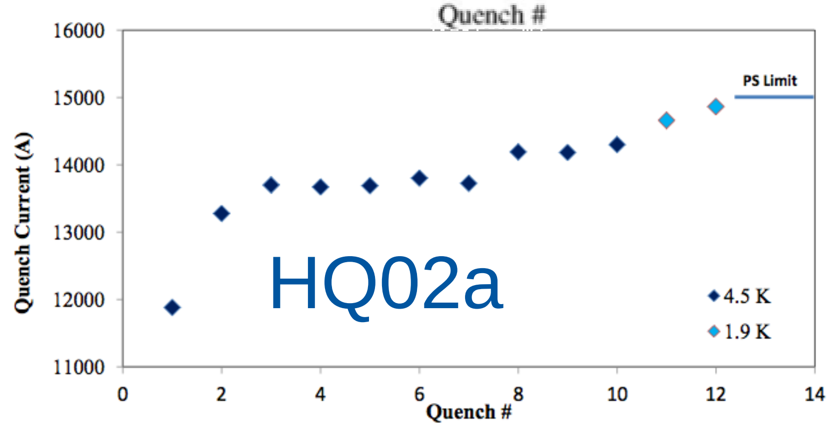
Courtesy of G. Chlachidze, FNAL

LARP HQ performance

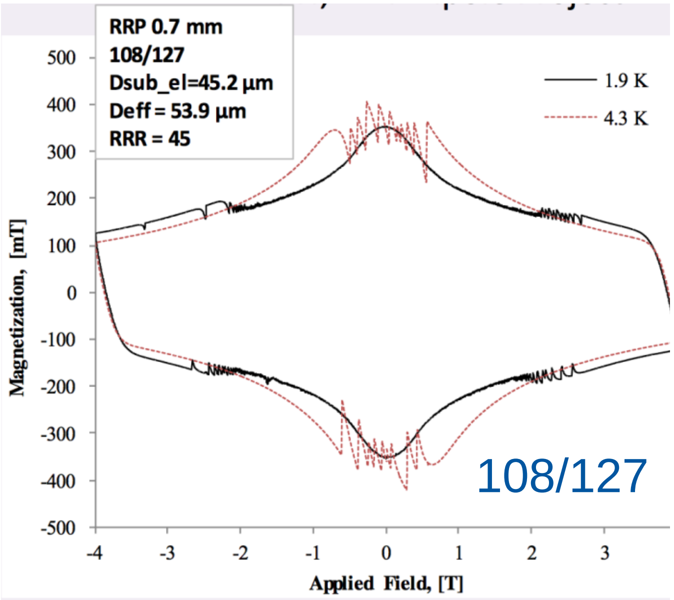




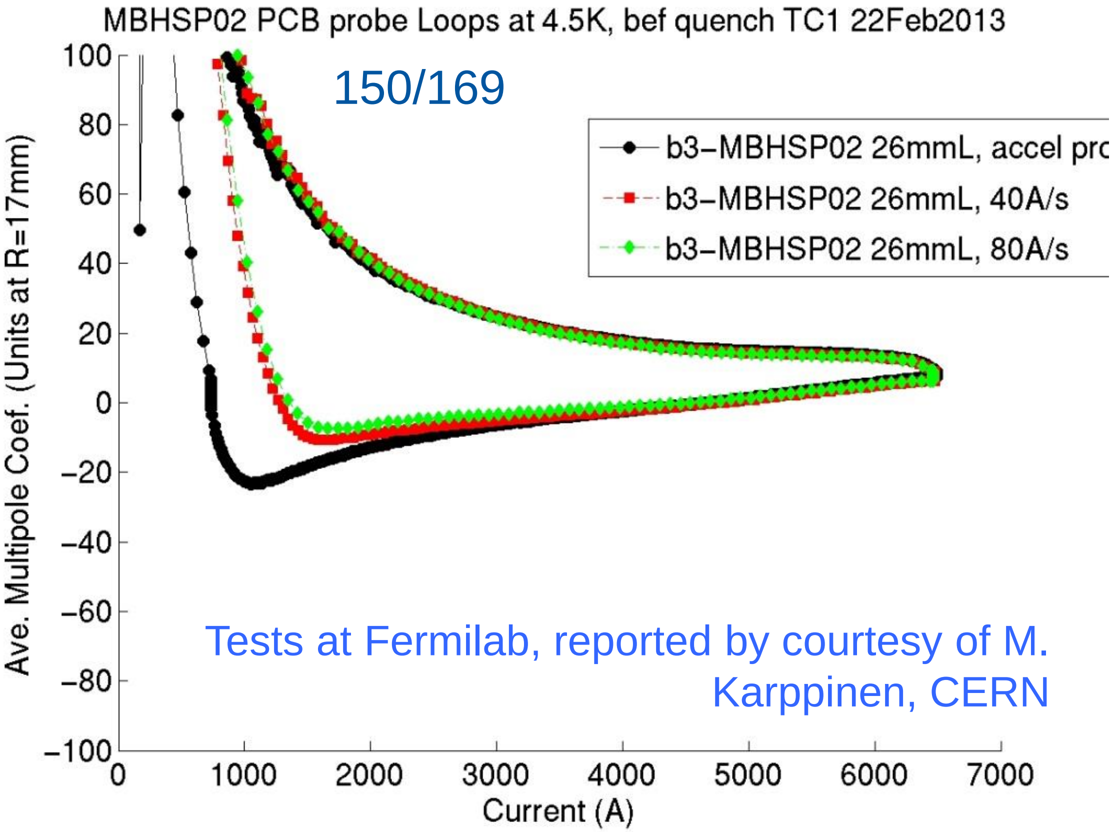
- The test of HQ02 is on-going, but we see very promising results !



Effect of magnetization in dipoles



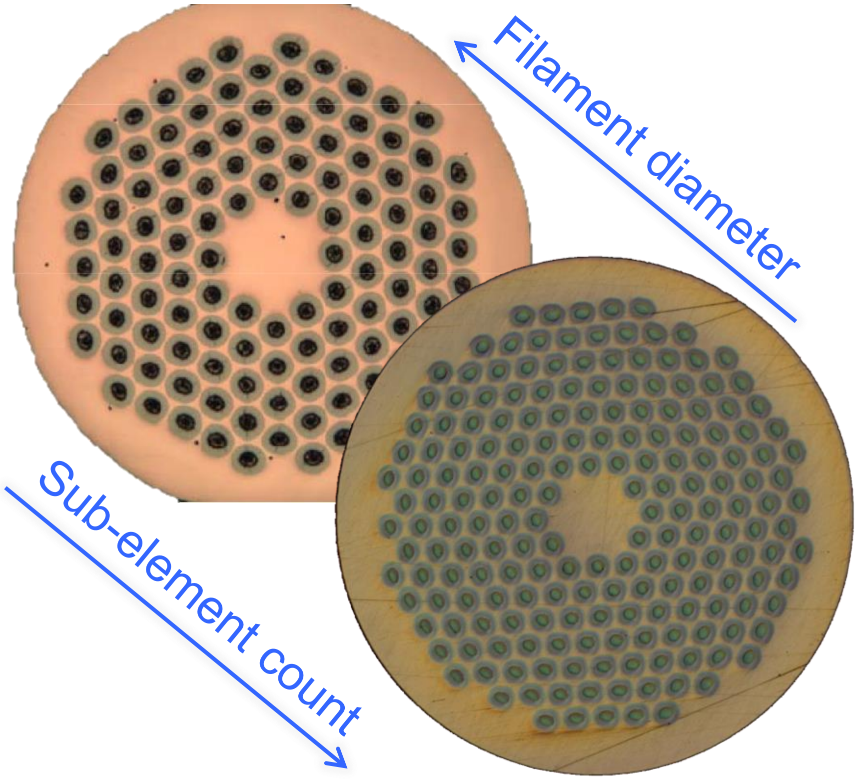
Measurement by D. Richter, CERN

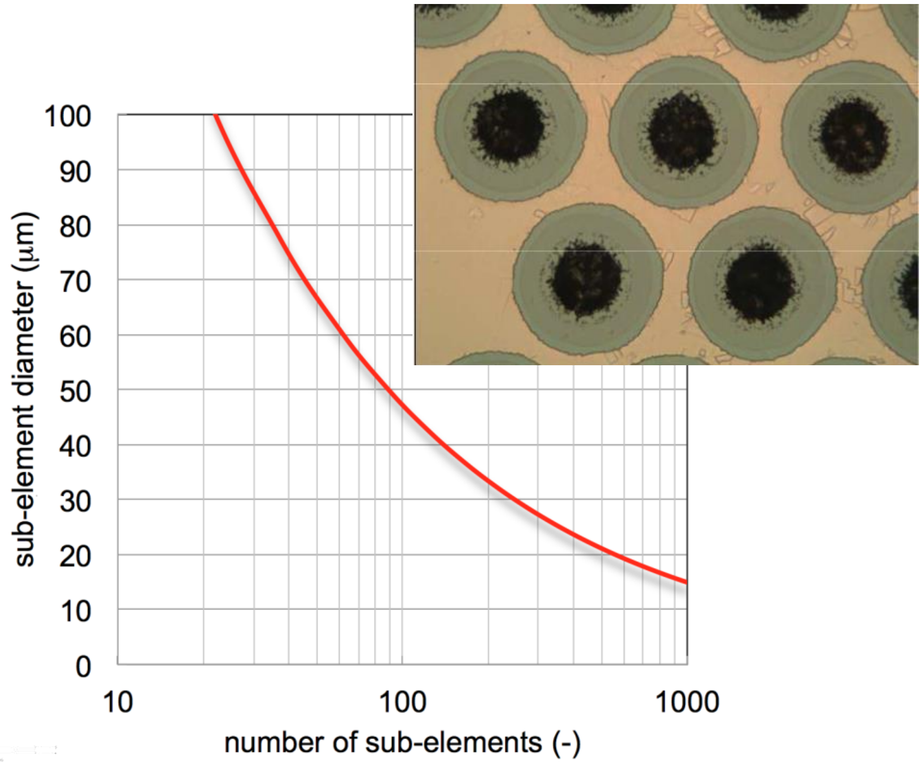


Tests at Fermilab, reported by courtesy of M. Karppinen, CERN

Nb_3Sn magnetization is large, and affects field quality at injection: **reduce filament diameter !**

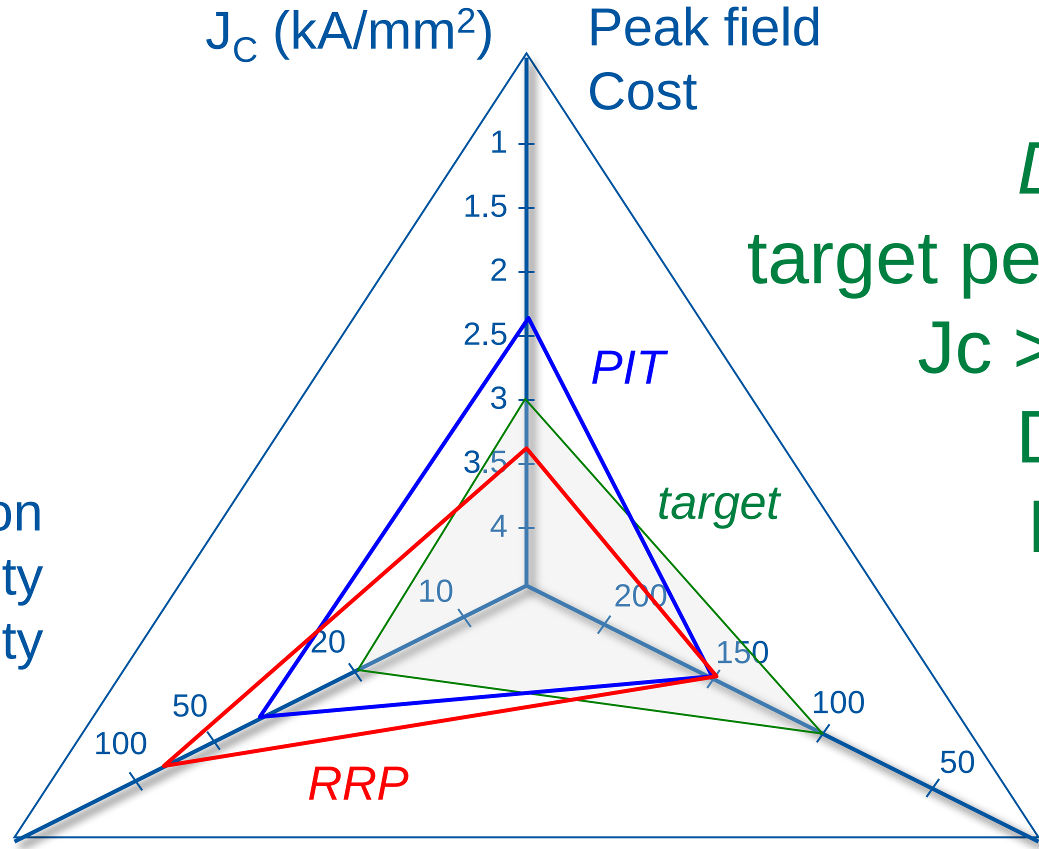
Sub-element diameter vs. counts





- Small sub-elements (filament diameter) implies complex, costly and risky stacking

A Nb_3Sn dream wire for the LHC



Performance
Peak field
Cost

Magnetization
Field Quality
Stability

Stability
Protection

Dream wire

target performance:

$J_c > 3$ kA/mm²

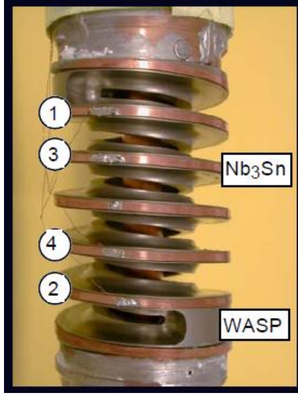
$D_{fil} < 20$ μm

RRR > 100

Longitudinal strain effects

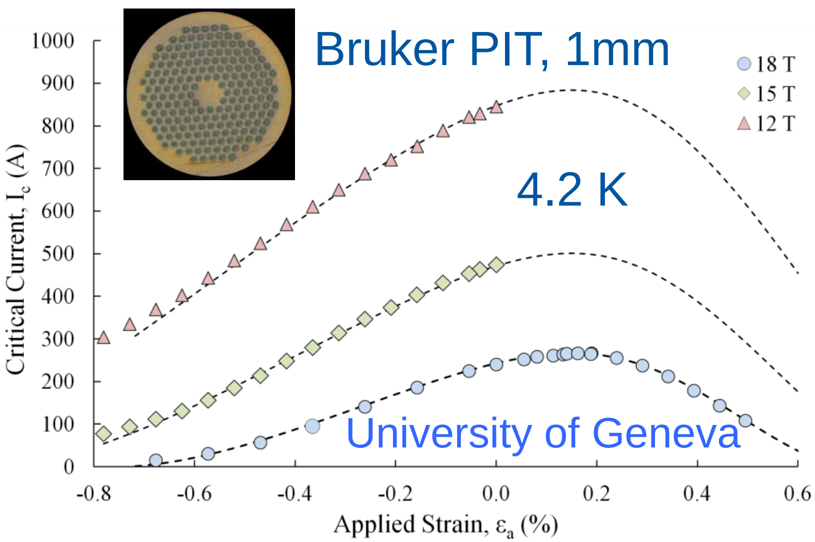
I_c vs. axial strain, B, T

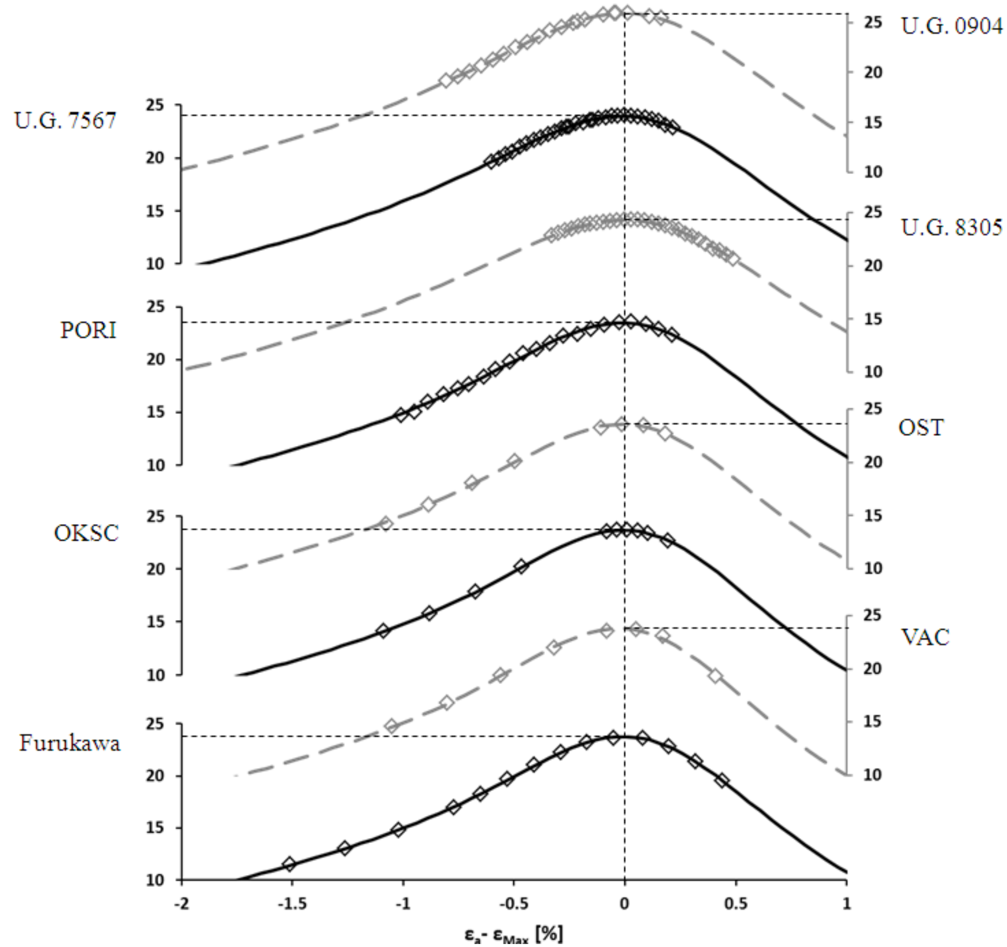
University of Geneva



Specification

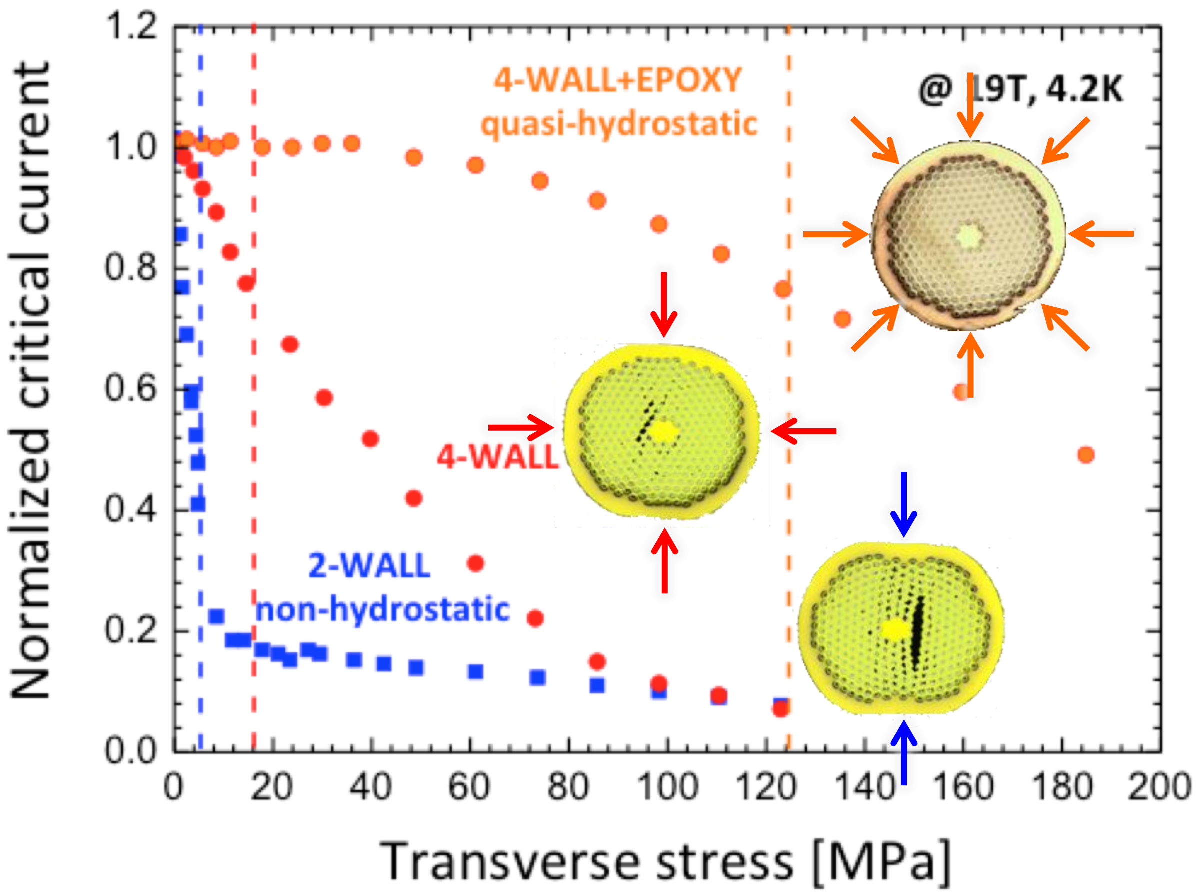
- **Axial strain: ± 1.0%**
- **Magnetic field: ≤ 21 T**
- **Temperature: 2.2 K - 100 K**
- **Critical currents: ≤ 1000 A**

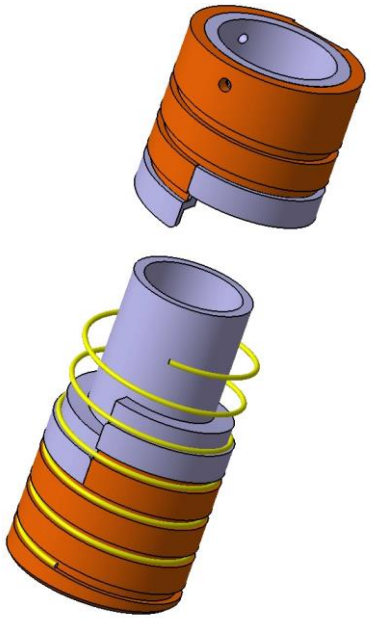




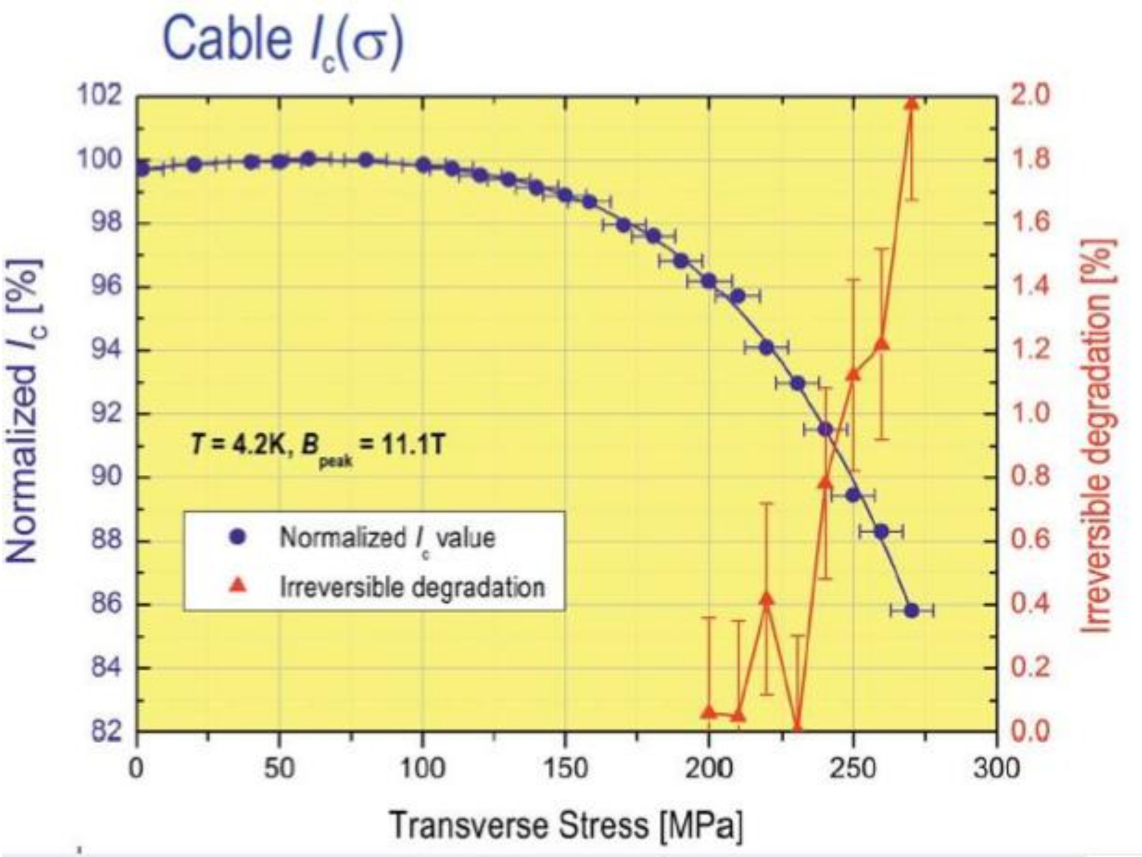
B Bordini *et al* 2013 *Supercond. Sci. Technol.* **26** 075014 doi:10.1088/0953-2048/26/7/075014

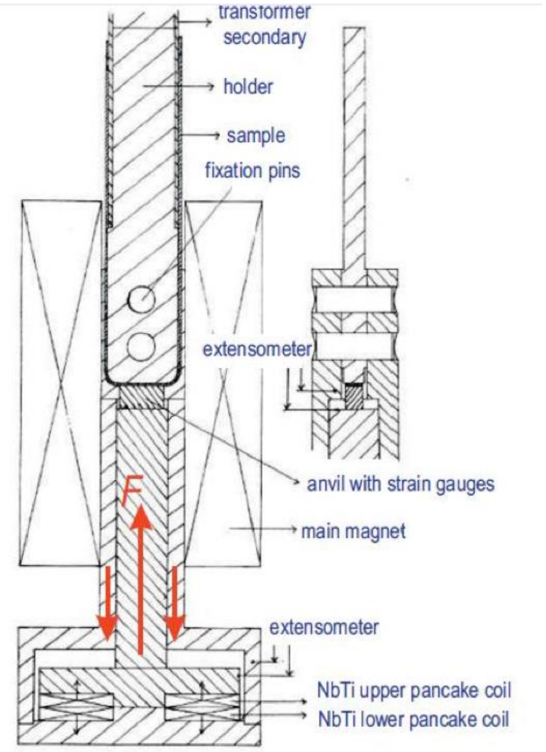
Transverse strain effects…





… more on transverse stress…

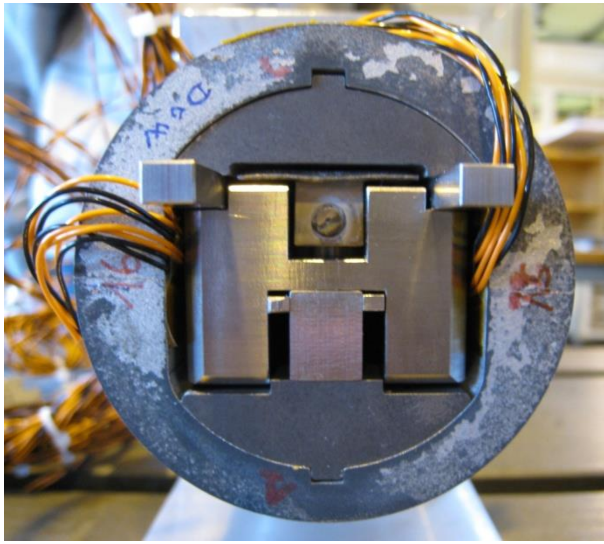


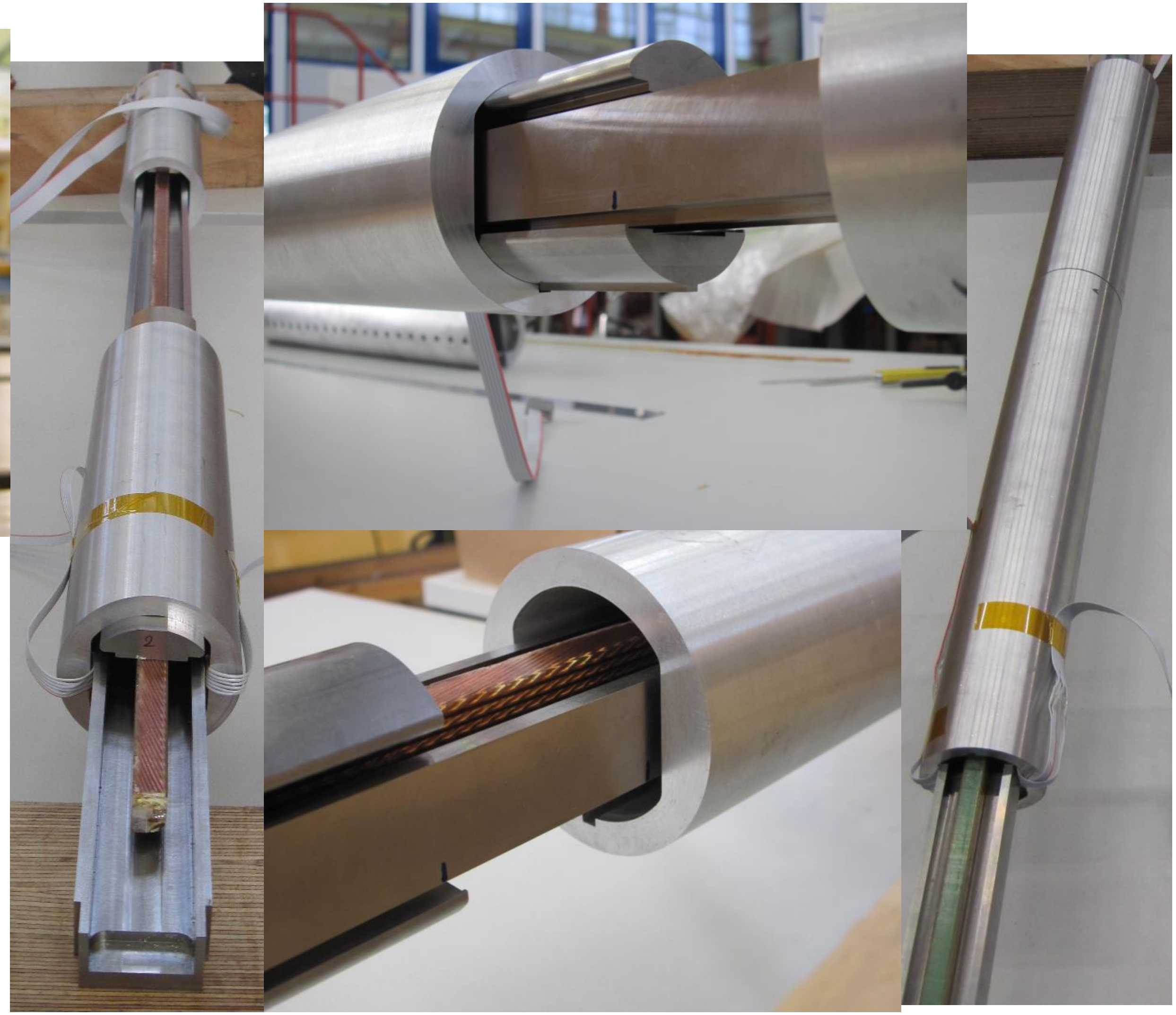


No irreversible degradation till 200 MPa

By courtesy of B. Bordini (CERN)

… and even more



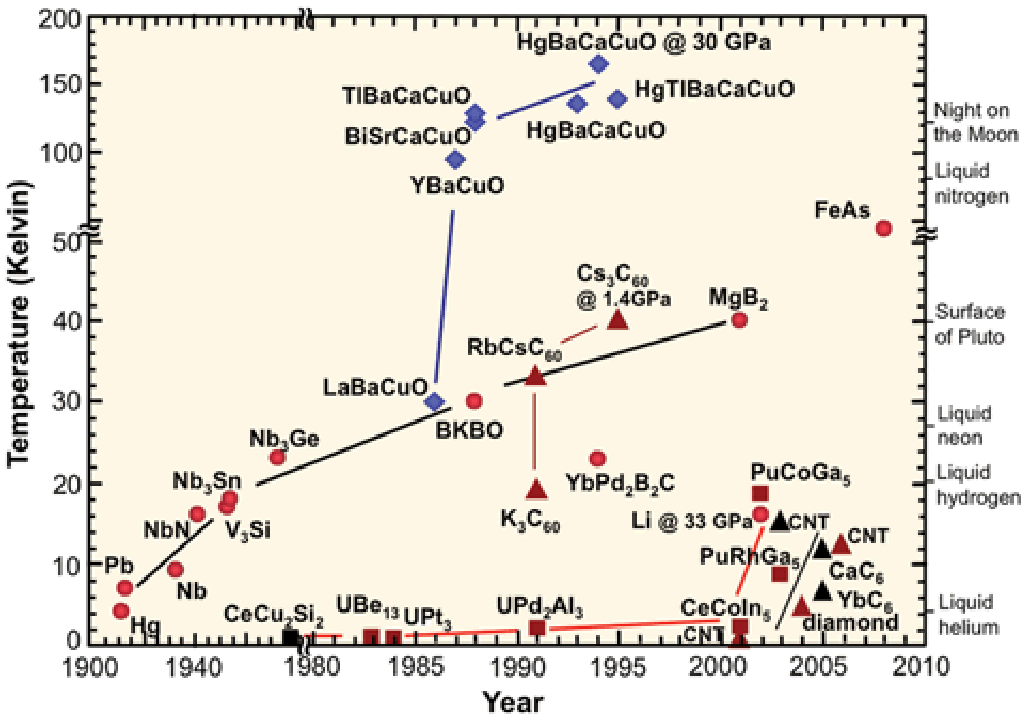


Transverse stress sample holder in construction for the FReSCa-1 test facility, at CERN, 200 MPa capability in 10 T field and 32 kA (60 kA) current.

Overview

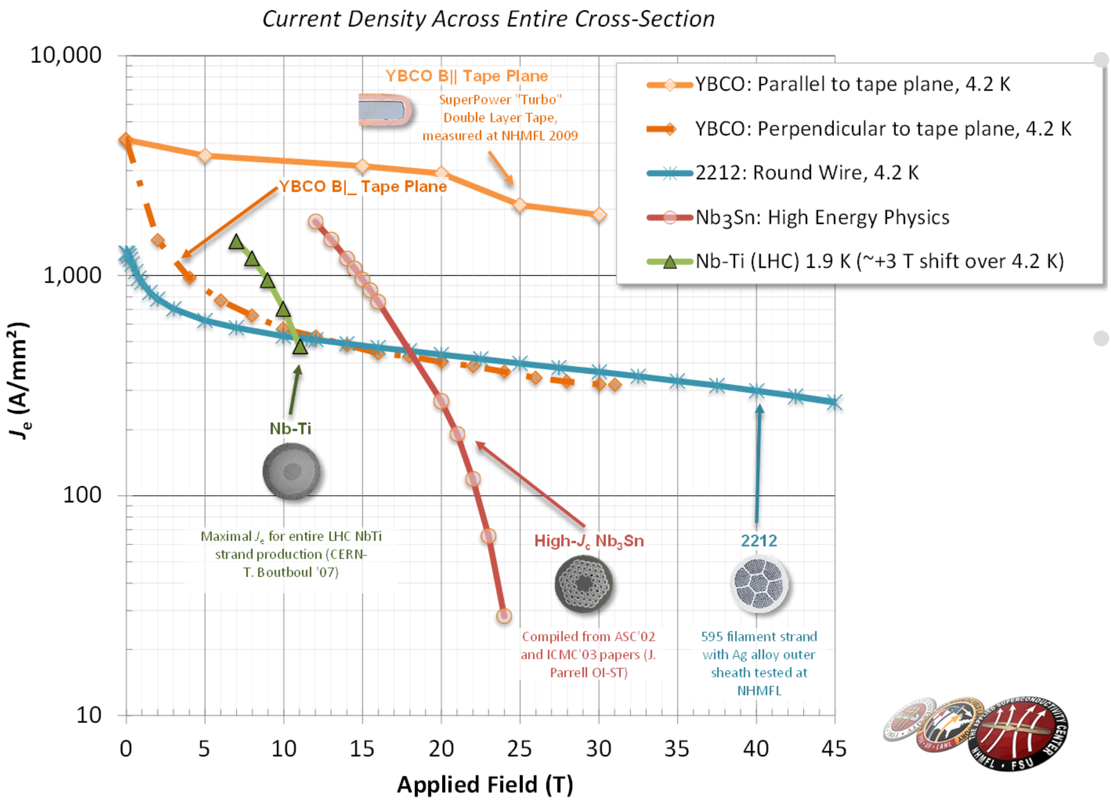
- **The drive from the LHC**
  - LTS wires and cables at 50
  - **HTS conductors at 25**
- Beyond the LHC
- Summary and conclusions

From materials to applications



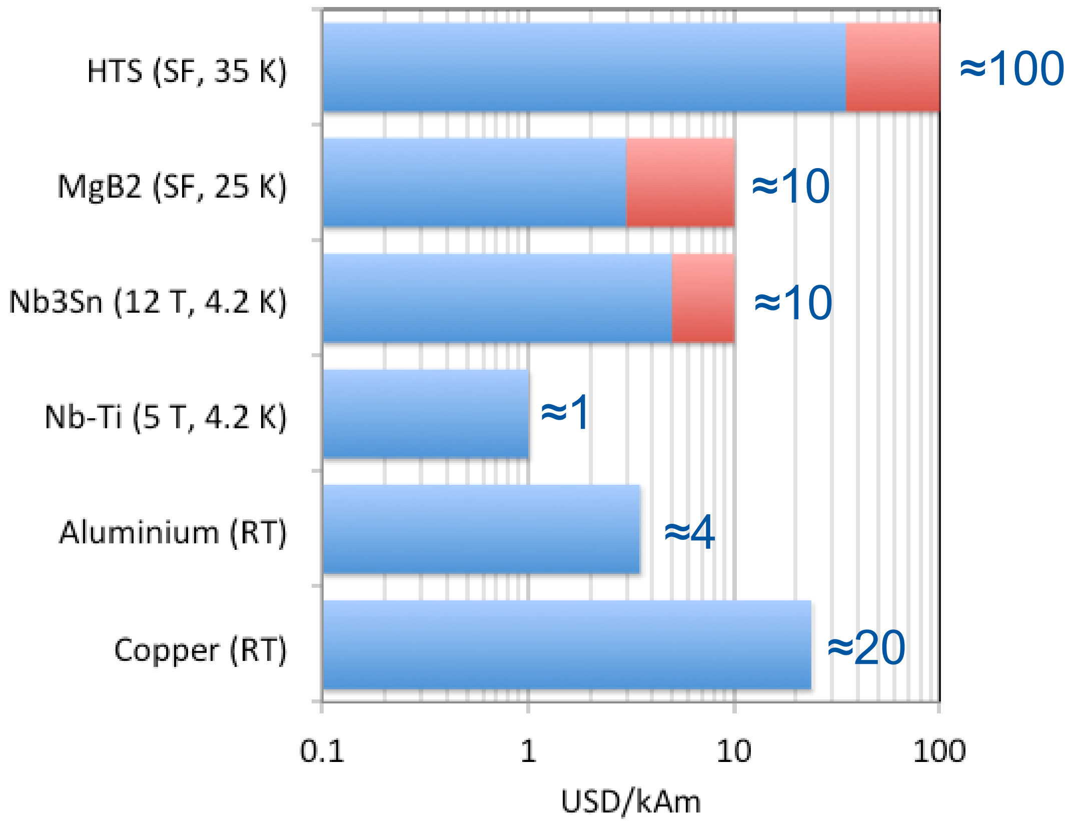
- Superconductors as seen by the eye of a physicist
- The grand challenge of today is to find the **room temperature superconductors**

From materials to applications



- Superconductors as seen by the eye of an engineer
- The grand challenge of today is to develop the technology of **high-field superconductors**

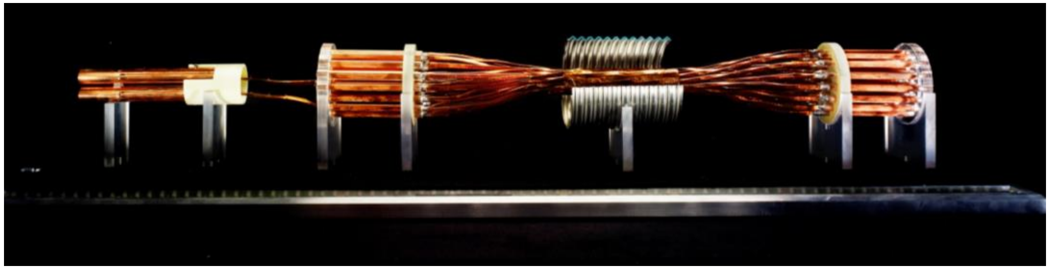
From materials to applications



- Superconductors as seen by the eye of a manager
- The grand challenge of today is availability of **long lengths of reasonably priced commercial materials**

A future for HTS at the LHC

A model of link by A. Ballarino and the TE-MSC-SCD team (CERN)



- SC links for the LHC
  - Quasi-DC operation
  - GHe operation (5 K … 25(35) K)
  - Single cables operated at up to 20 kA
  - Multi-cable (□ 50 high-current cable) assemblies
  - Horizontal + Vertical (□ 80 m) configuration
  - 2 kV electrical insulation
- Potential for use of MgB_2, or other HTS materials in specific location demanding for more margin and/or tolerance

More details in the talk of L. Rossi on HL-LHC

Superconductors for the LHC SC Links

		Φ (mm)	W (mm)	Th (mm)	Tmax (K)	Ic [‡] (A)
[†] MgB_2	wire	< 1	-	-	25	≥ 400
MgB_2	tape	-	3.7	0.67	25	≥ 400
YBCO	tape	-	4	0.1	35	≥ 400
BSCCO 2223	tape	-	4	0.2	35	≥ 400

Within reach today

[†] bending radius $R_B \leq 80$ mm
[‡] applied field $B \leq 0.5$ T

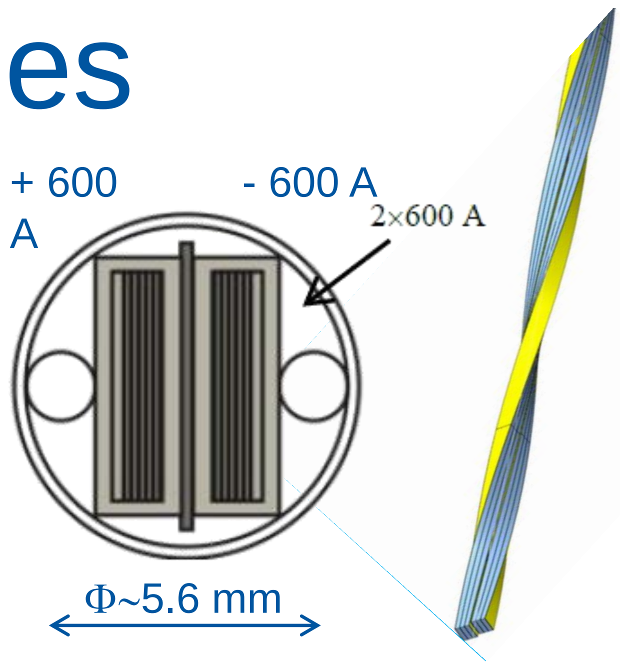
Reacted wires

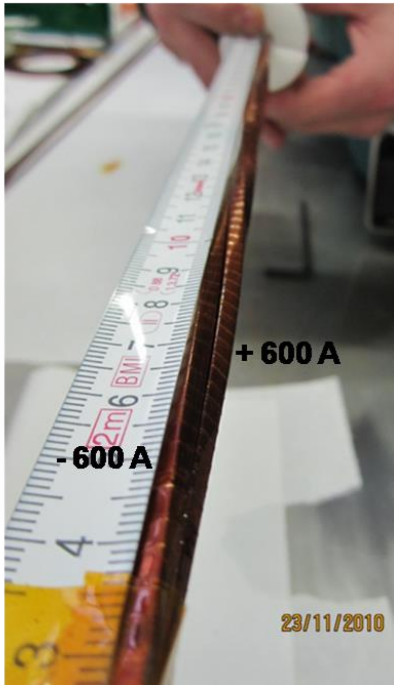
Ltot ~ 1000 km of conductor for series production

By courtesy of A. Ballarino (CERN)

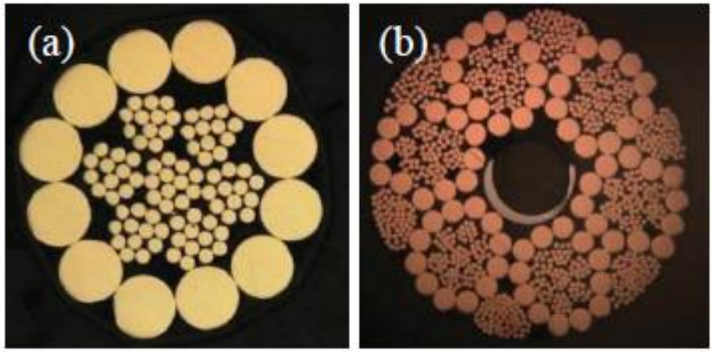
SC Link cables

Insulated and twisted tapes, for cables of modest amperage (can be assembled into larger cables for higher current)



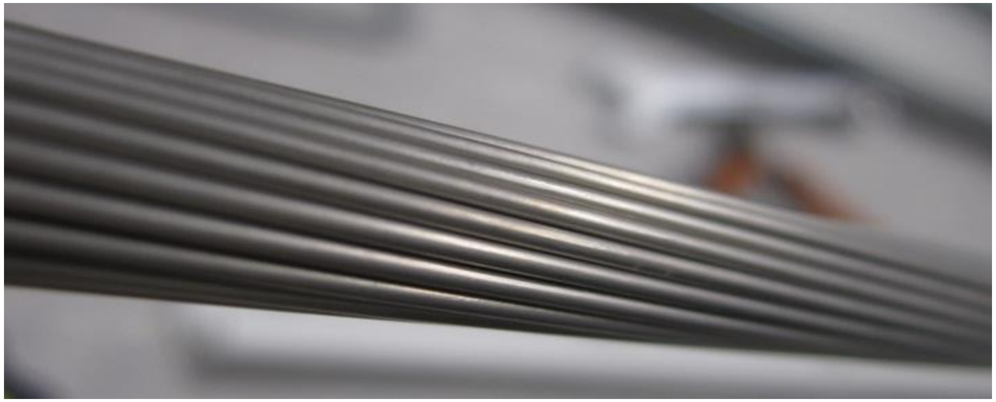


Twisted wires for high current



3 kA @ 25 K 20 kA @ 25 K

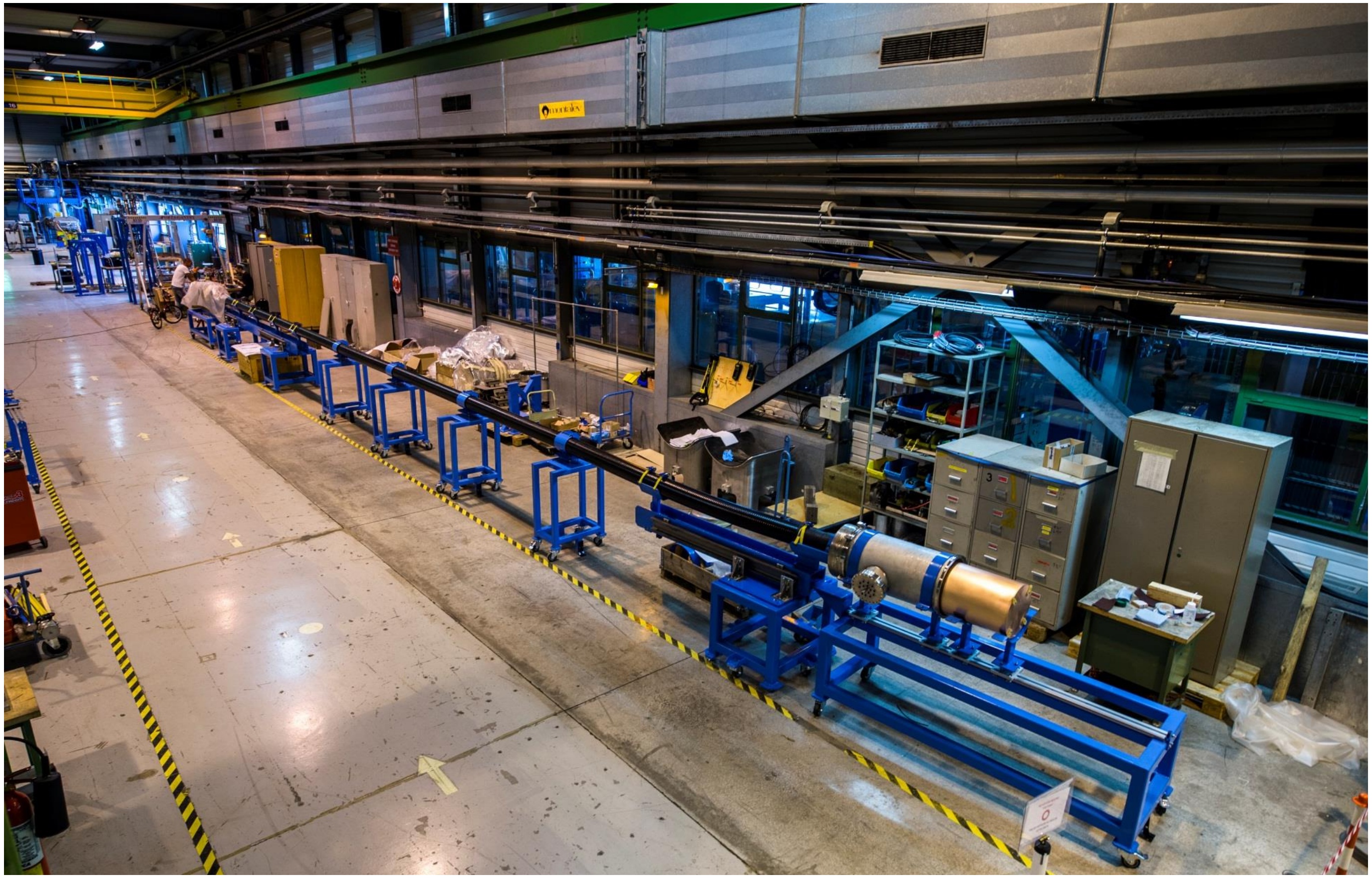
(Dummy cables)



Work in TE-MSC-SCD, by courtesy of A. Ballarino (CERN)

SC Link prototype test

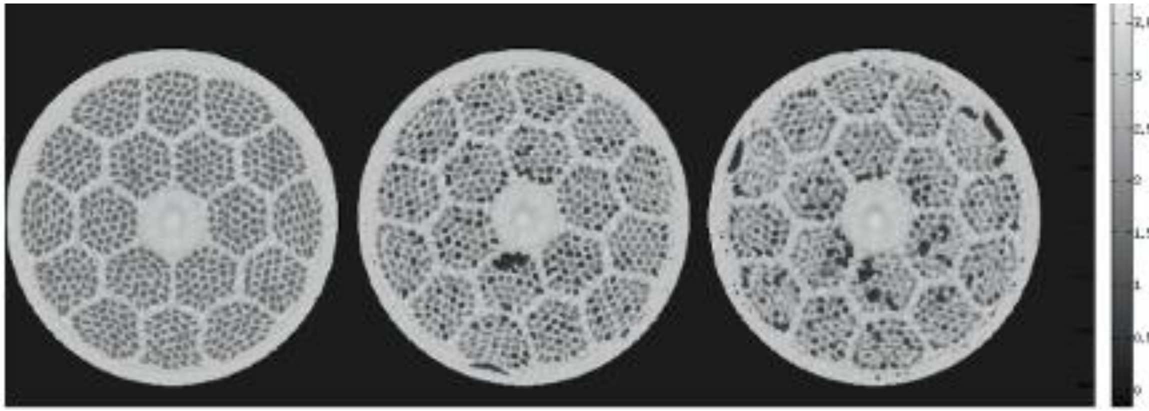
- New feed-box for supercritical helium (10 g/s) variable temperature (5 K … > 77 K) and high current (13 kA)
- Flexible cryostat to host various cable types and materials, up to 20 m length



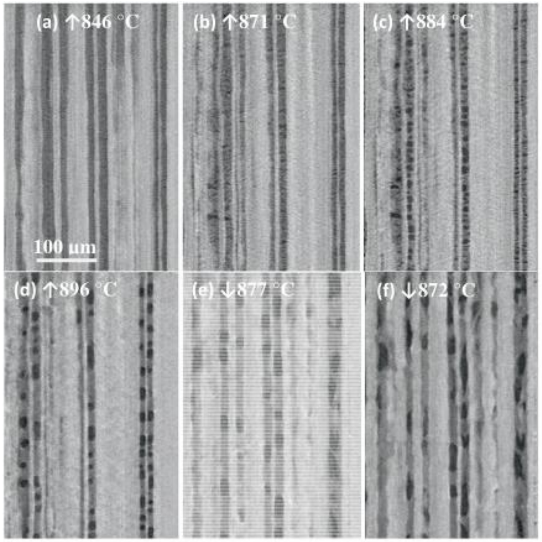
Overview

- The drive from the LHC
  - LTS wires and cables at 50
  - HTS conductors at 25
- **Beyond the LHC**
- Summary and conclusions

BSCCO-2212



As drawn — Quenched at 888 C — Fully processed

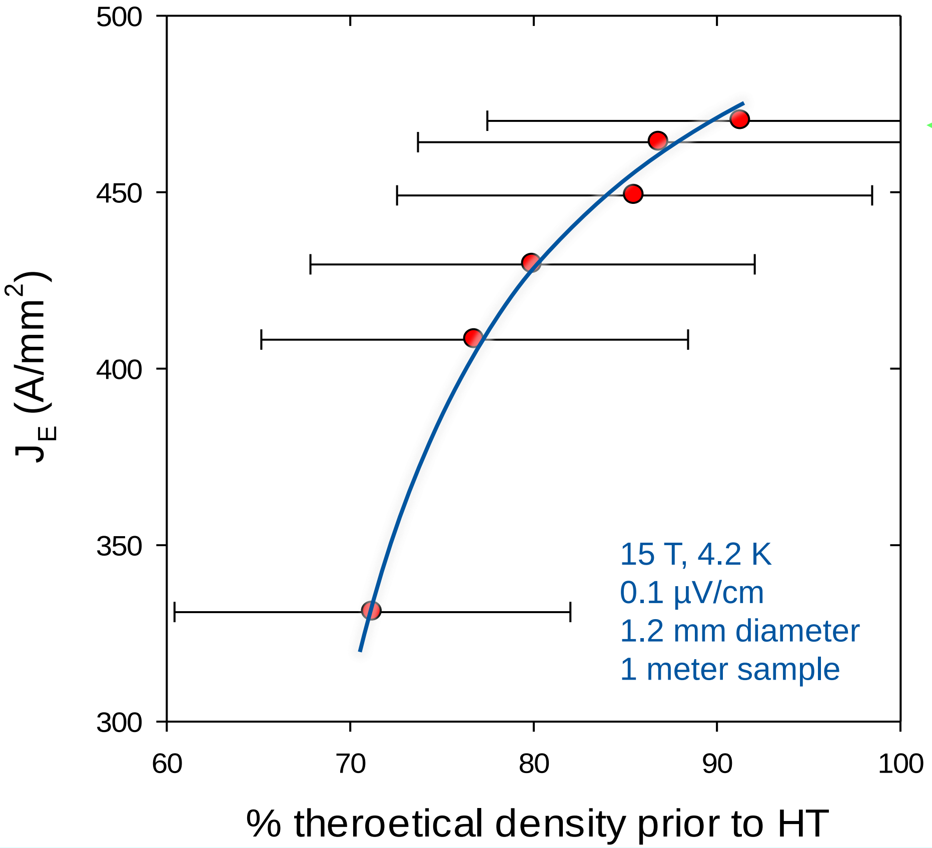


In-situ tomography

- Voids in 2212 are a clear issue, that has been recently understood, but not yet mastered
  - Is it originated by intrinsic or extrinsic sources ?
  - What is a practical means to overcome it ?

F. Kametani, et al., Superconductor Science and Technology, 24, 075009(7pp) (2011)

Improvement by CIPping

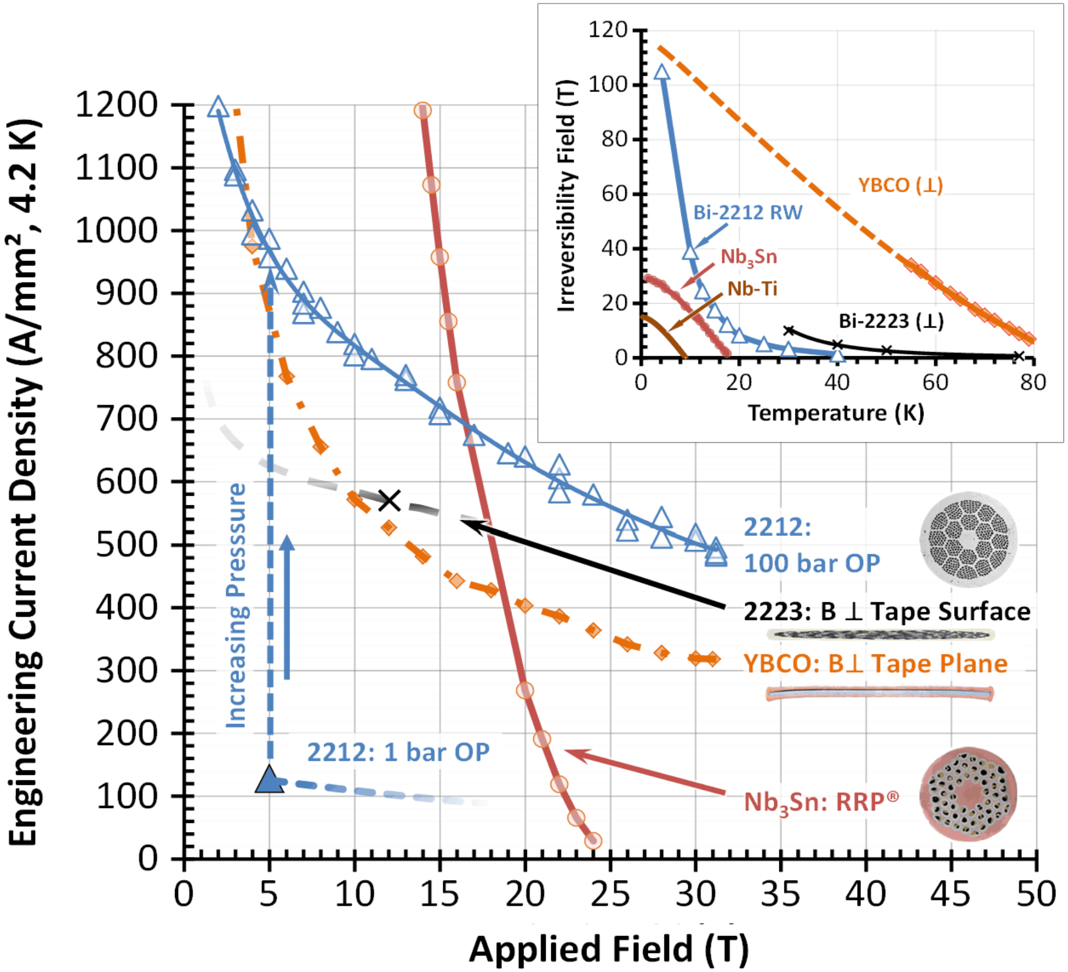


- Core densification result in double J_E values to ~470 A/mm^2 at 15 T

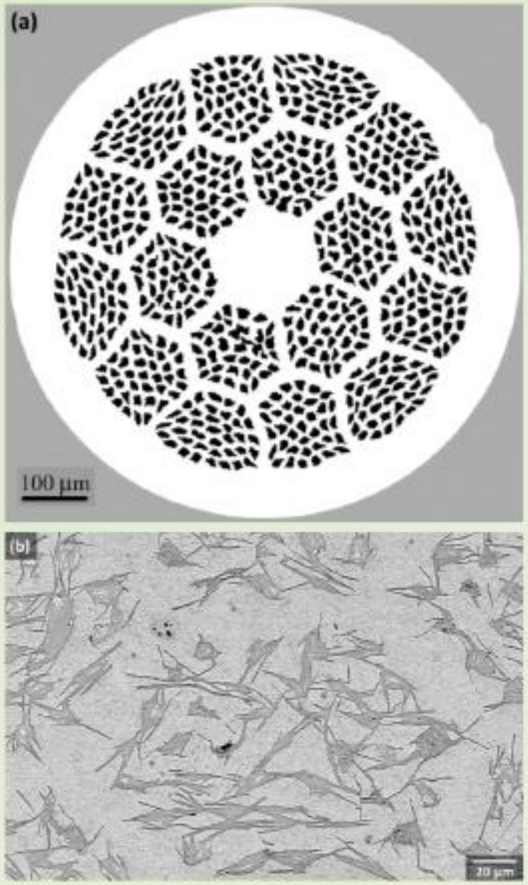
By courtesy of Y. Huang (OIST)

J. Jiang, E. Hellstrom, D. Larbalestier et al., NHMFL-FSU

Improvement by OPHT

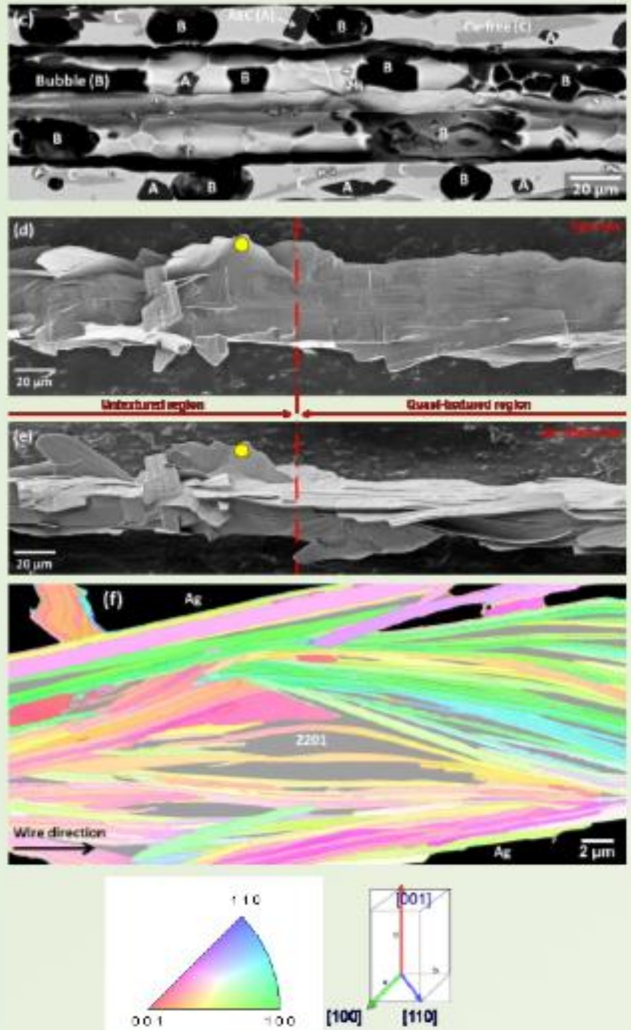


2212 Filaments contain many HAGBs – and (without bubbles) have high Jc



Kametani and Jiang unpublished

Transverse section images



Longitudinal section images

Polished sections of filaments in their surrounding Ag

Exposed filaments show their plate-like nature and frequent strong misalignments.

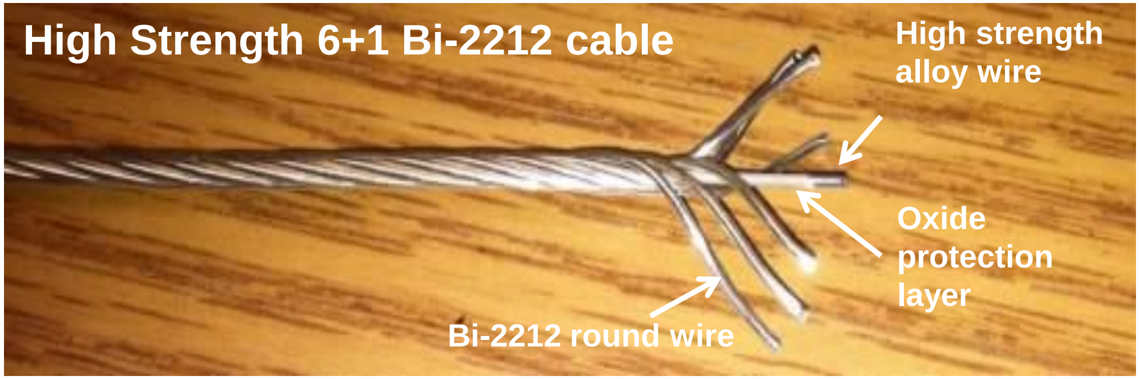
EBSD images show some local texture and significant 2nd phase content within filaments

The filaments cannot be fully connected – yet do have high Jc

BSCCO-2212, “easy” to cable

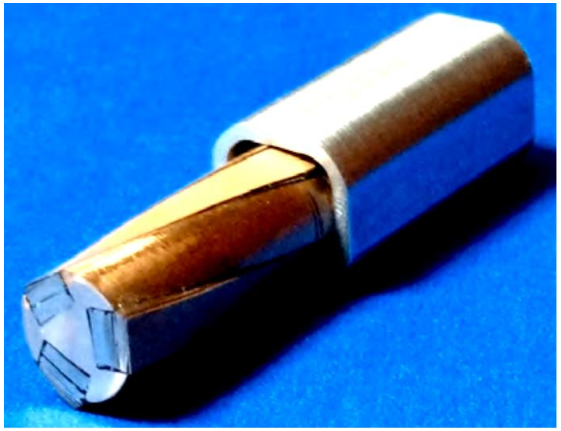
Bi-2212 Rutherford cables (Arno Godeke LBNL) with mullite insulation sleeve

R. Scanlan, D. Dietderich, A. Godeke, LBNL

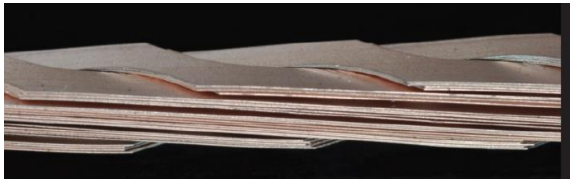


T. Shen, Strand and Cable Engineering Group, Fermilab
nGimat/NCSU

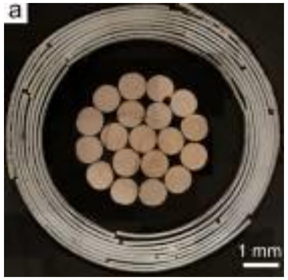
REBCO – how do you cable tapes ?



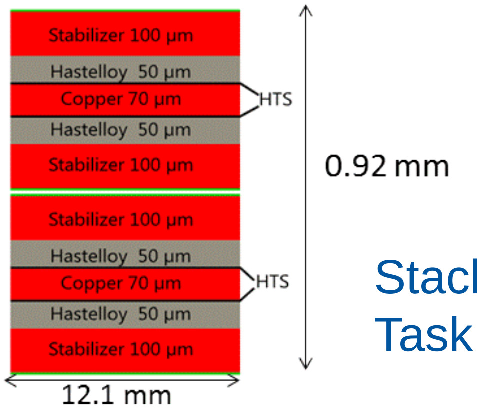
Stacks in Conduit Conductor
M. Takayasu, MIT



Roebels, W. Goldacker, KIT

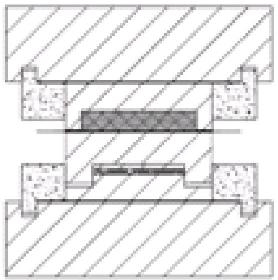


Cable-On-Round-Core
D. van der Laan

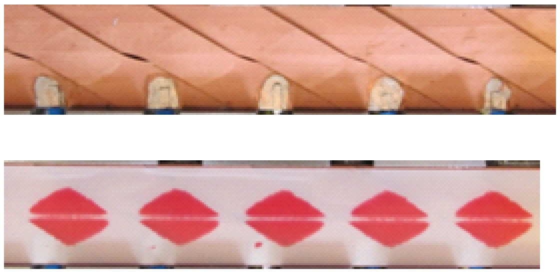


Stacked tapes conductors, EuCARD WP7
Task 4, Very High Field Dipole Insert

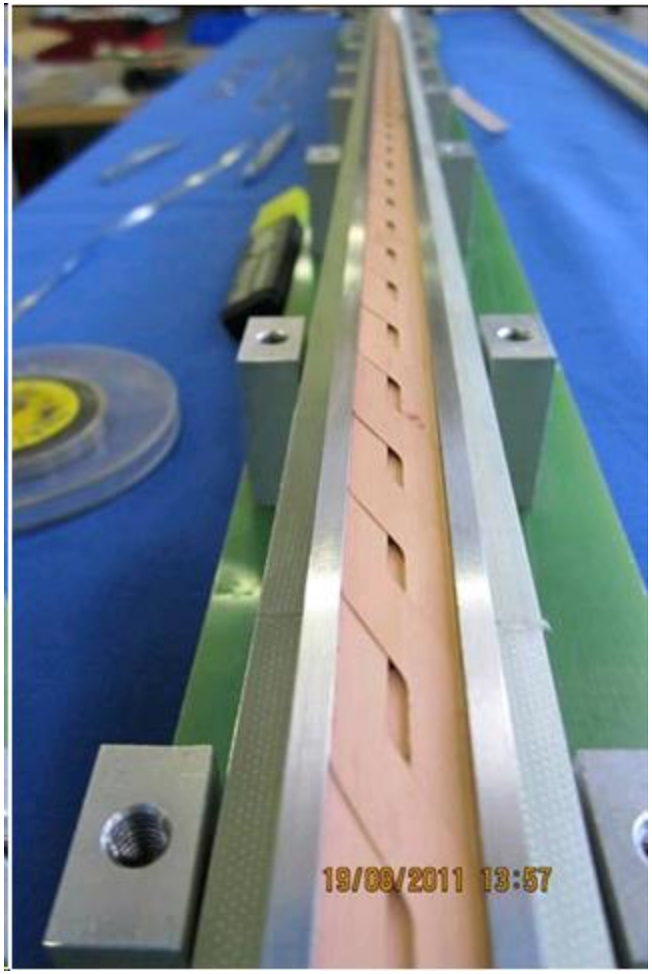
Roebel cables measured @ 4.2 K



Applied $\sigma_{trans.}$ = 40 MPa



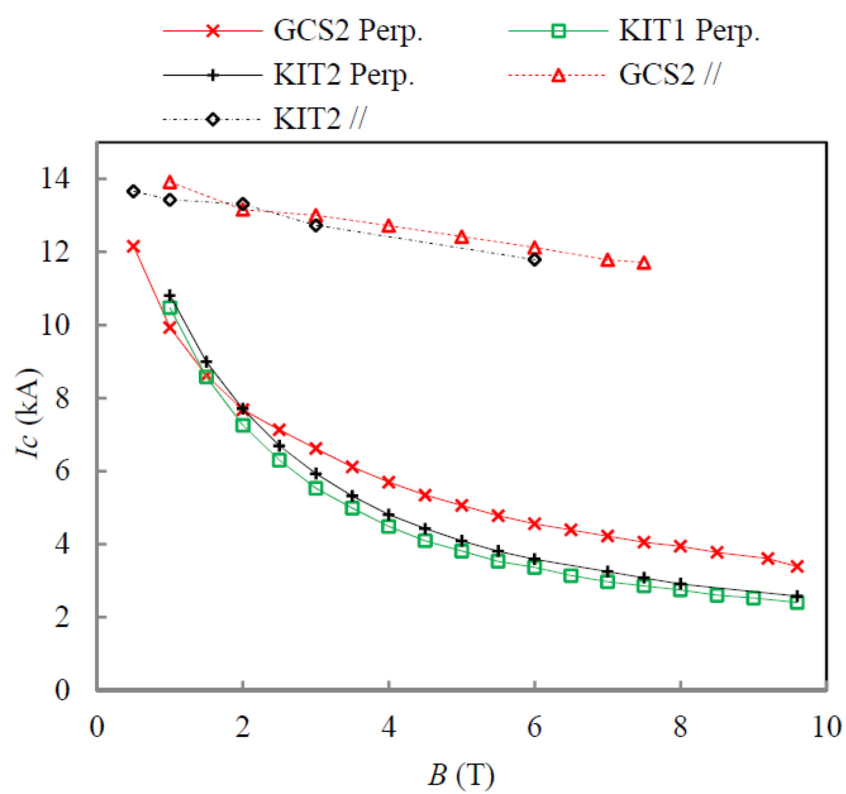
J. Fleiter, CERN,
PhD thesis of the
University of Grenoble

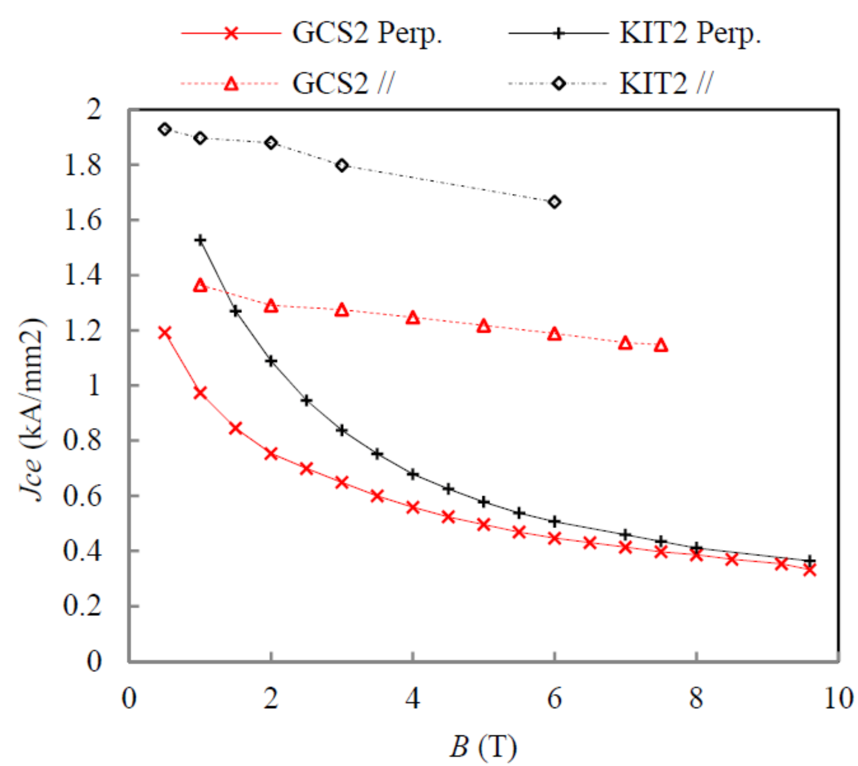


CERN, Superconductors Lab

Roebel cables results

Measurements @ CERN in the FReSCa-1 Test Station





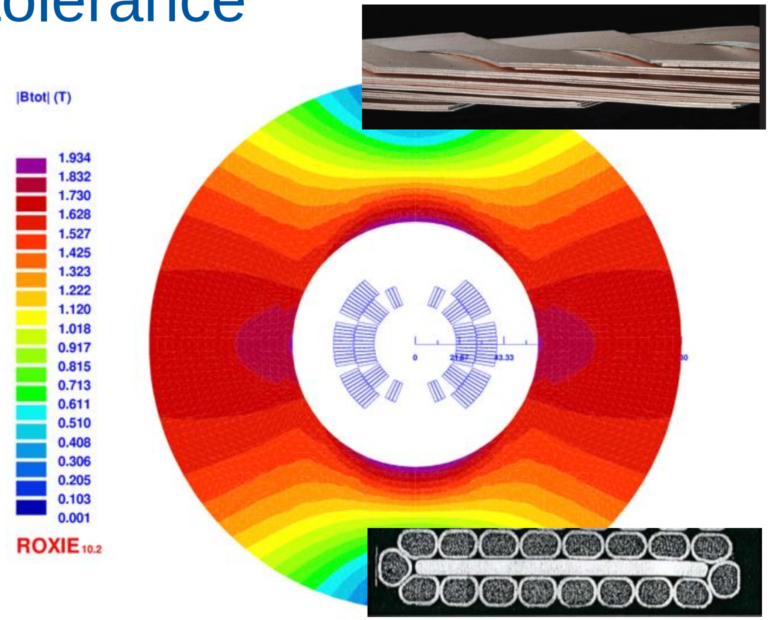
Ic (B⊥=9.6 T, 4.2 K) = 3.4 kA

Je (B⊥=9.6 T, 4.2 K) = 400 A/mm²

J. Fleiter, CERN, PhD thesis of the University of Grenoble

Beyond the LHC

EuCARD2: Develop 10 kA class HTS accelerator cable using Bi-2212 and YBCO. Test stability, magnetization, and strain tolerance



WP10: a 5 T, 40 mm bore HTS dipole

Summary - LTS

- Is Nb_3Sn mature ? Yes, and no
  - performance of Nb_3Sn wires has seen a great boost in the past decade (factor 3 in J_C w/r to ITER)
  - However, Nb_3Sn magnets were never built nor operated in accelerators. Manufacturing, quench, training, protection, strain tolerance, field quality are the focus today to make this new technology a reality
  - A dream wire will pave the way for the next step in circular accelerators

Summary - HTS

- Can HTS displace LTS ? Not today
  - Much needs to be done to bring this technology to a point where it can be sold as “mature”
    - Materials have potential that can be exploited
      - OPHT for BSCCO-2212
      - Thicker layer for YBCO tapes
      - The Holy Grail of a round YBCO wire
  - Production quantities, homogeneity and cost need to evolve
  - Step-up application demands, from self-field (SC-link is an ideal test-bed) to high-field accelerator magnets (feasibility)

www.cern.ch