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UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

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Swiss Accelerator Research and Technology

MuCol

Super EMFL

Swiss National Science Foundation

HFM
High Field Magnets

Advancing Superconductor Technology for High Field Applications: Current State and Emerging Trends

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With special thanks to Amalia Ballarino, Bernardo Bordini, Luca Bottura and Thierry Boutboul (CERN) for the exciting collaborations in view of future colliders, to Davide Nardelli (Bruker) and Davide Uglietti (EPFL) for the very instructive exchanges and to my great team at UNIGE, Romain Babouche, Marco Bonura, Gianmarco Bovone, Florin Buta, Pablo Cayado, Francesco Lonardo, Celia Lucas and Damien Zurmuehle

Outline

- **What we do today and aim to achieve in the near future with superconductors**
  - Focus on high magnetic field applications
- **Which future for Low Temperature Superconductors (LTS) ?**
  - Towards the ultimate performance of Nb_3Sn for a Future Circular Collider
- **Which future for High Temperature Superconductors (HTS) ?**
  - The technology-pull towards magnetic fields beyond the reach of LTS and the opportunity for higher operating temperatures
- **Conclusions**

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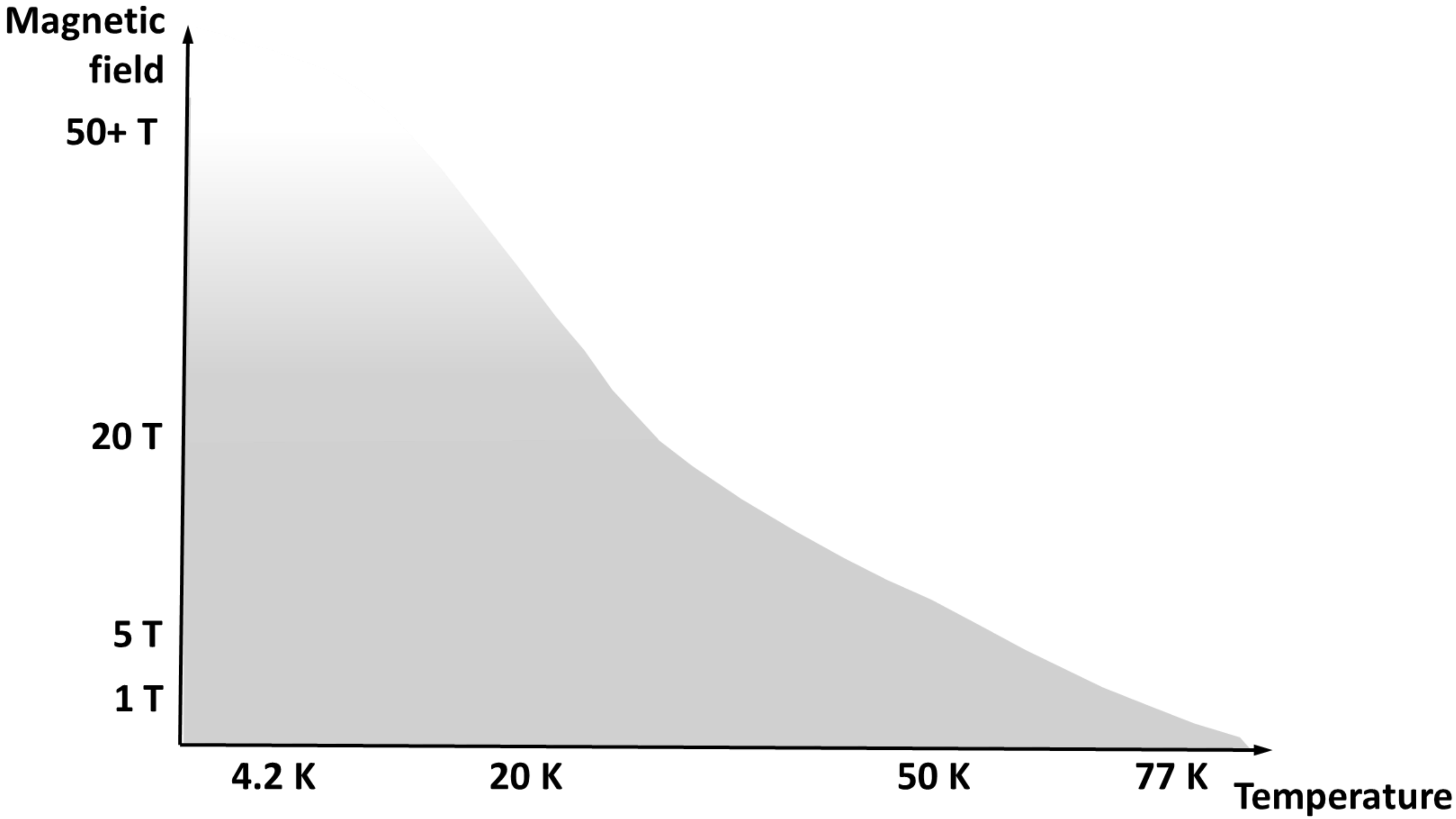
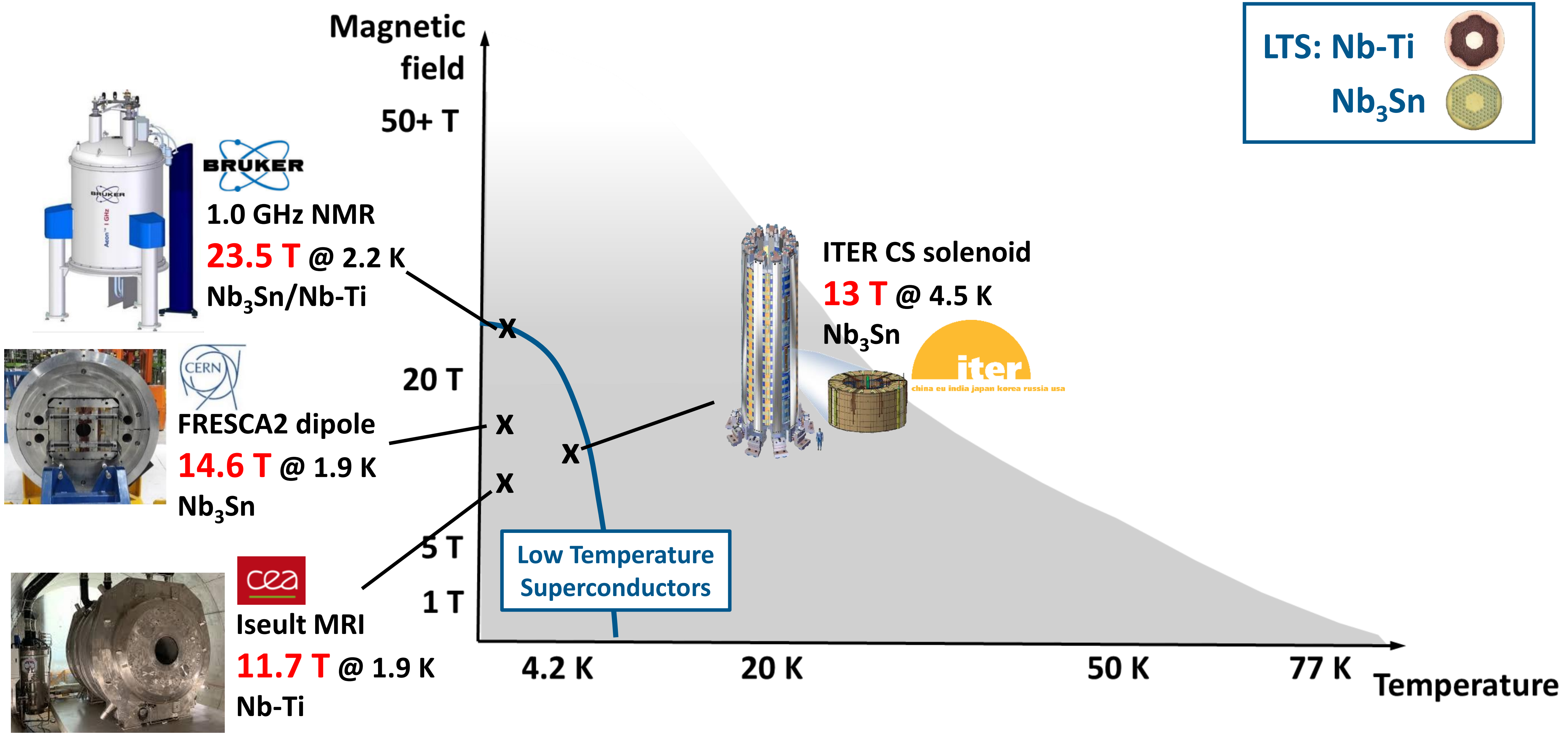
Field-temperature phase diagram of technical superconductors



High field applications of Low Temperature Superconductors

Field-temperature phase diagram of technical superconductors



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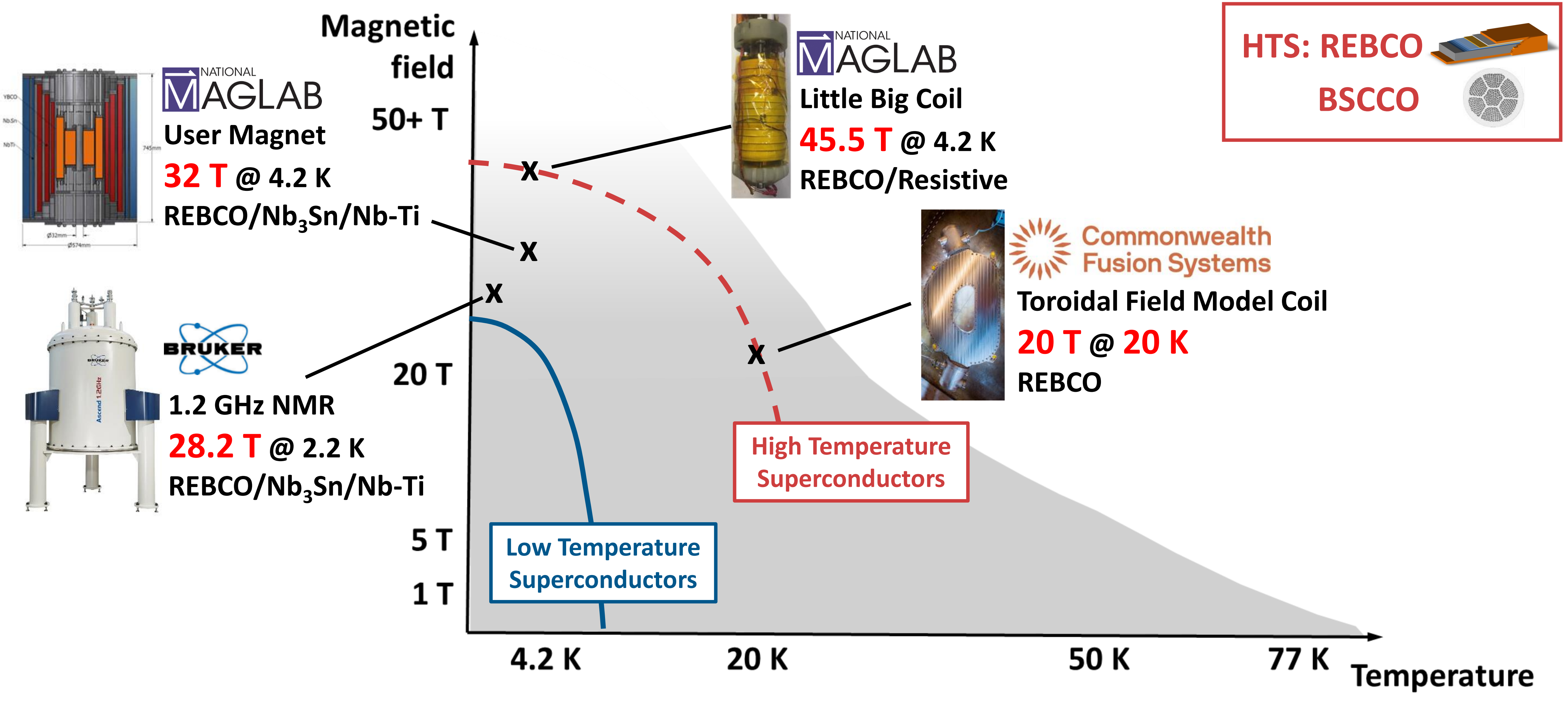
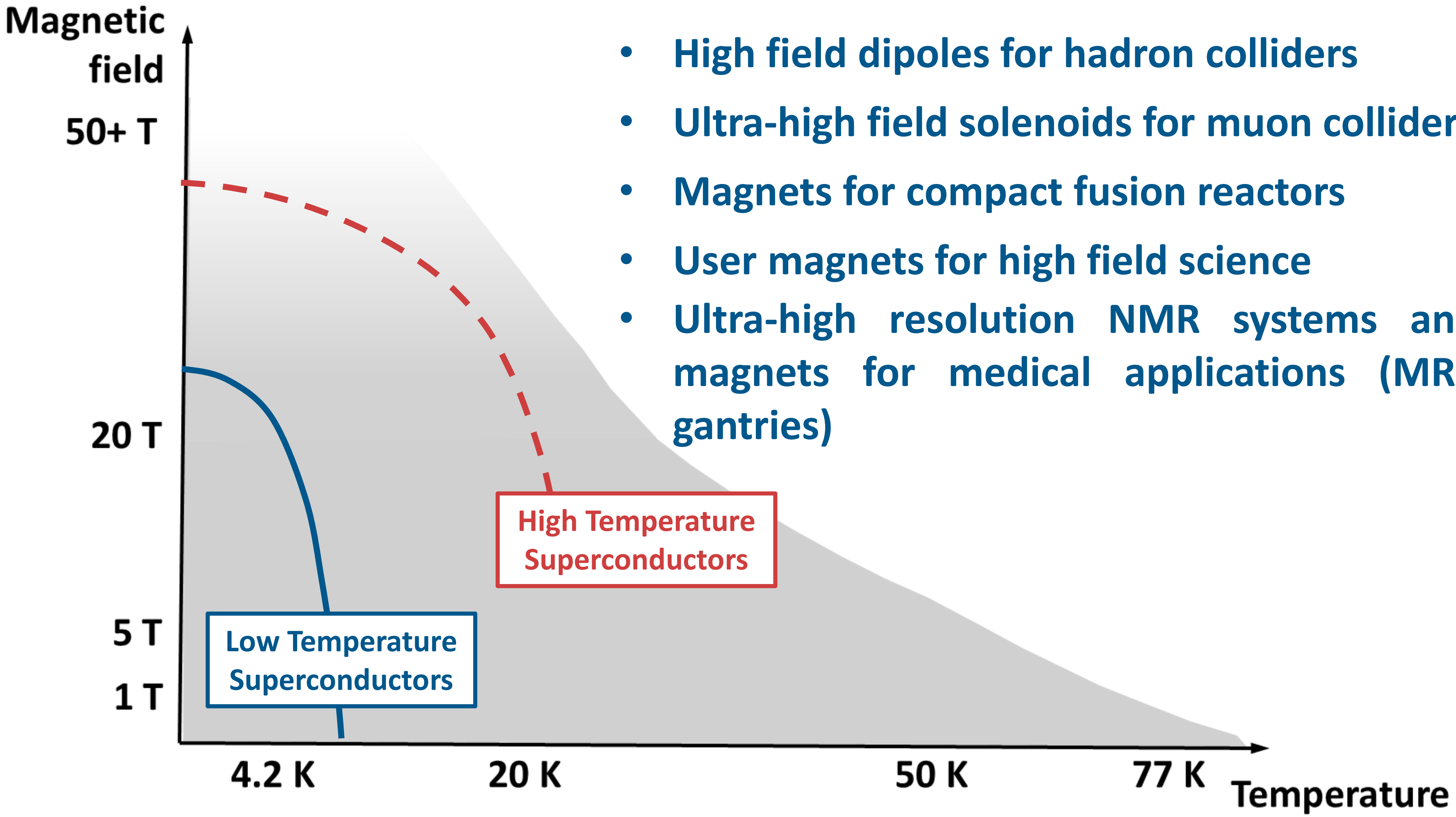


The application's pull towards higher magnetic fields

Field-temperature phase diagram of technical superconductors

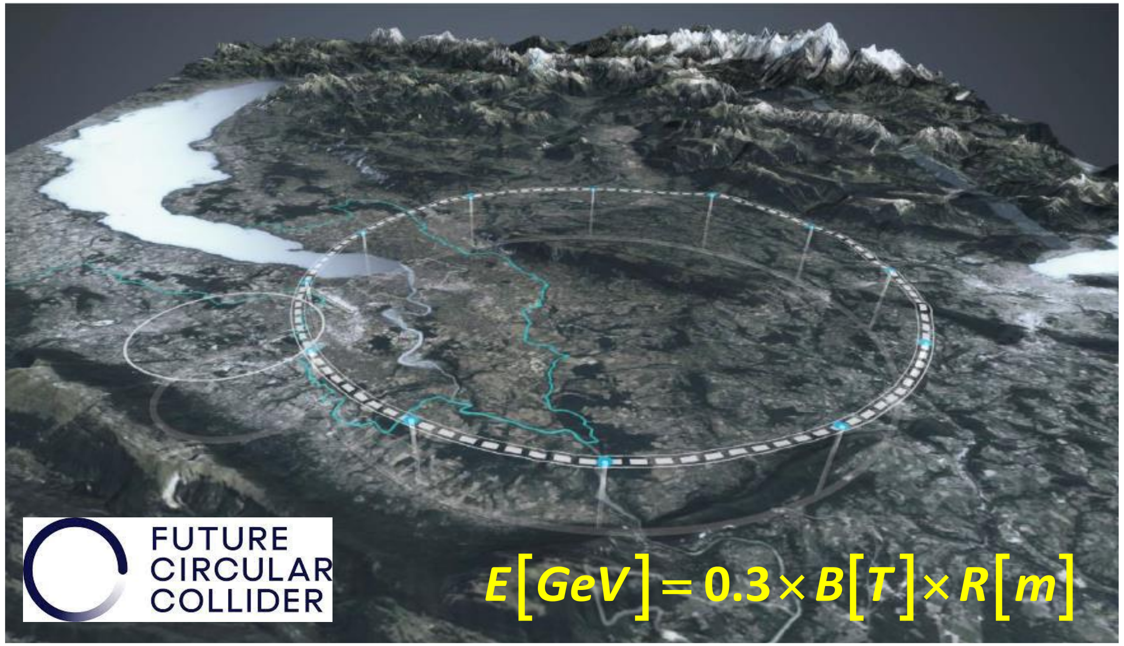


- High field dipoles for hadron colliders
- Ultra-high field solenoids for muon colliders
- Magnets for compact fusion reactors
- User magnets for high field science
- Ultra-high resolution NMR systems and magnets for medical applications (MRI, gantries)

The call for High Field Magnets from High Energy Physics

Targets for a future 100 TeV hadron collider

Next-generation Energy-Frontier Particle Accelerators are intended to collide particles at energies of ~10 TeV pCM (parton center-of-mass energy), corresponding to proton-proton collisions in the 100 TeV range.



- The baseline of the FCC study is a 91 km-ring
- 14+ T-dipoles based on Nb_3Sn would give 85-90 TeV
- 20 T-dipoles based on HTS would give ~120 TeV

parameter	FCC-hh
collision energy cms [TeV]	85 - 120
dipole field [T]	14 (Nb_3Sn) – 20 (HTS)
circumference [km]	90.7
arc length [km]	76.9
beam current [A]	0.5
bunch intensity [10^{11}]	1
bunch spacing [ns]	25
synchr. rad. power / ring [kW]	1020 - 4250
SR power / length [W/m/ap.]	13 - 54
long. emit. damping time [h]	0.77 – 0.26
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30
events/bunch crossing	~1000
stored energy/beam [GJ]	6.1 - 8.9
Integrated luminosity/main IP [fb^{-1}]	20000

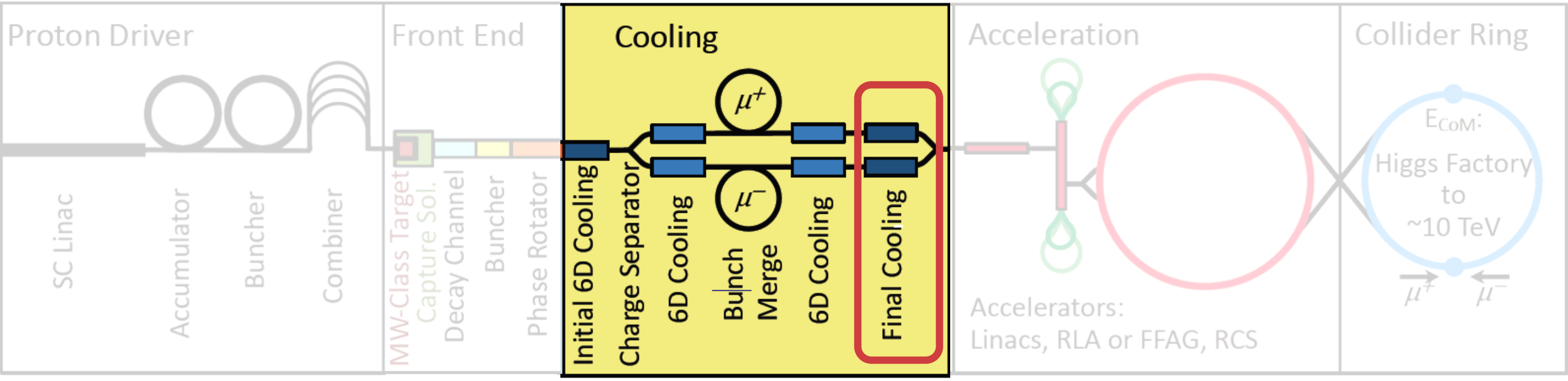
Adapted from M. Benedikt, FCC Week 2024

European Strategy for Particle Physics - Accelerator R&D Roadmap
https://doi.org/10.23731/CYRM-2022-001

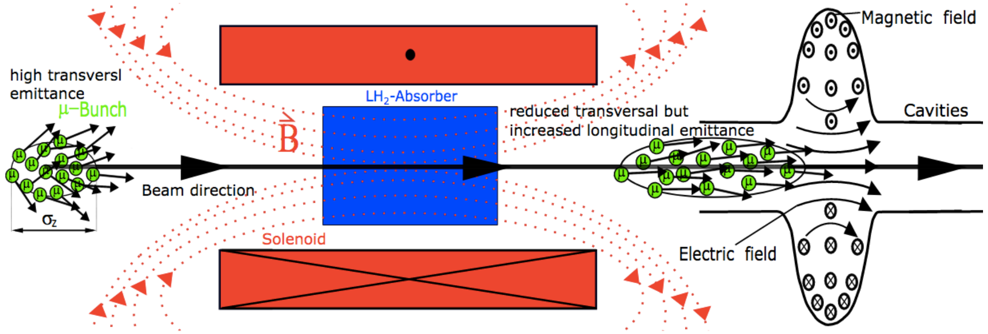
The call for High Field Magnets from High Energy Physics

The concept for a high-energy muon collider

The Muon Collider is a particle collider for searches of new physics based on collisions of muons, particles with a lifetime of 2.2 μs! Muon beams require rapid capture and acceleration within their short lifetime



An entire zoo of superconducting magnets is needed for capturing pions, cooling muons and for the acceleration and collision rings



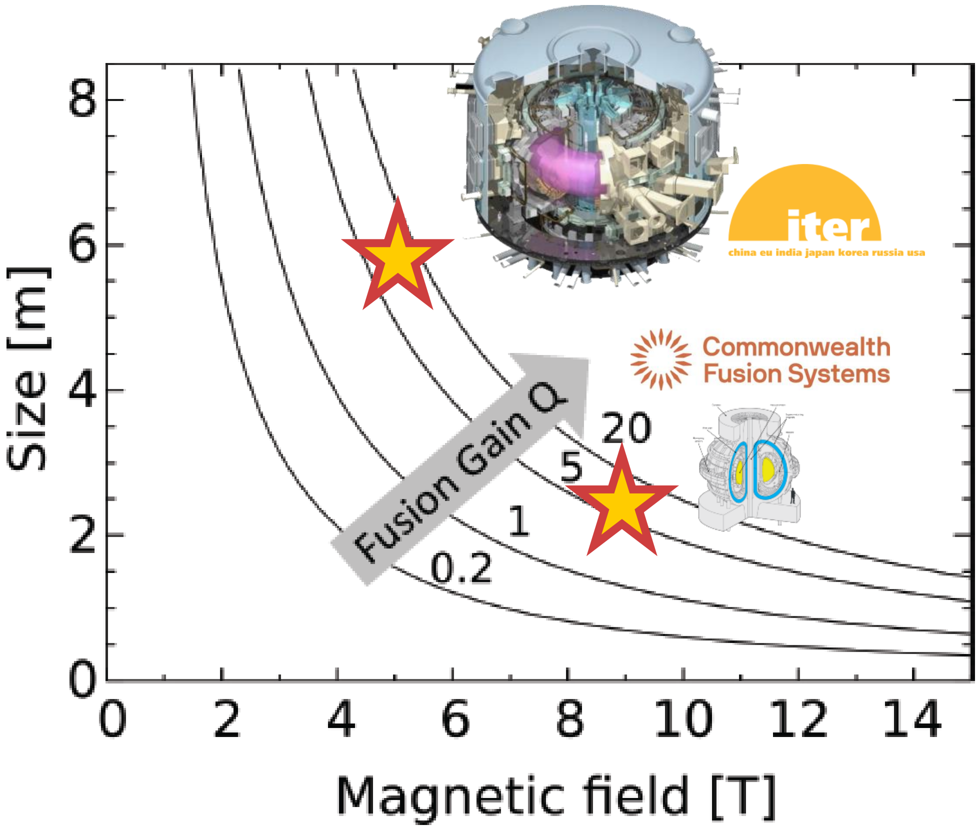
Muons are cooled through interaction with light matter and subsequent acceleration by RF cavities. Solenoids of 40 T to 60 T with a bore of 50 mm, only achievable with HTS, are required to meet the specification on the transverse emittance

According to the last P5 report, a 10 TeV muon collider is considered as an option for bringing energy frontier colliders back to US

Report of the 2023 Particle Physics Project Prioritization Panel
https://doi.org/10.2172/2368847

The call for High Field Magnets from Fusion

Towards high-gain small-size fusion reactors



HTS are making possible new designs of compact fusion reactors because of **two technical advantages** with respect to LTS

1. Higher critical fields, as the **fusion power density** in a tokamak is **proportional to B^4**
2. The possibility to **operate at higher temperatures**, > 4 K, with a large margin that would allow withstanding the neutron heating and lower the cryogenic costs

Two examples: Commonwealth Fusion Systems and Tokamak Energy are both developing magnets for plasma confinement with **peak fields at 20 T** on the superconductor and operation in the **20 K range**

Energy from Fusion: an emerging industrial business

FUSION INDUSTRY ASSOCIATION

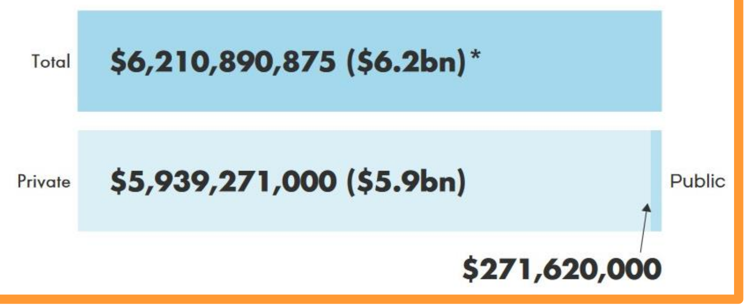
ABOUT

Members

Commonwealth Fusion Systems · TYPE ONE ENERGY · THEA ENERGY · RENAISSANCE FUSION · nT-tao Compact Fusion Power · Proxima Fusion · Tokamak Energy · GAUSS FUSION · STELLAREX · Helical Fusion

Companies adopting magnetic fusion confinement systems

Funding for Fusion Companies



https://www.fusionindustryassociation.org/

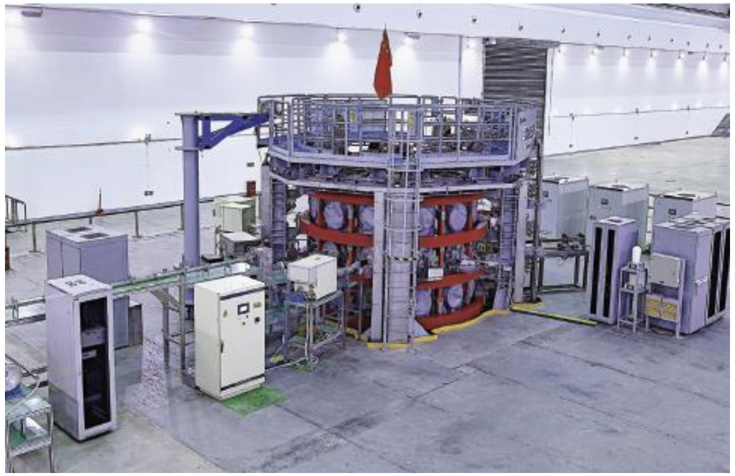
Compact fusion Start-ups in China

Growing competitors in the race to fusion power

Test of HH70 at Energy Singularity in June 2024

Company	Founded in	Technology	Fund rising
ENN	2019	Spherical Tokamak	120 M€
Startorus	2021	Spherical Tokamak	n/a
Energy Singularity	2021	Compact Tokamak	100 M€
Neo Fusion	2023	N/A	640 M€

NIO

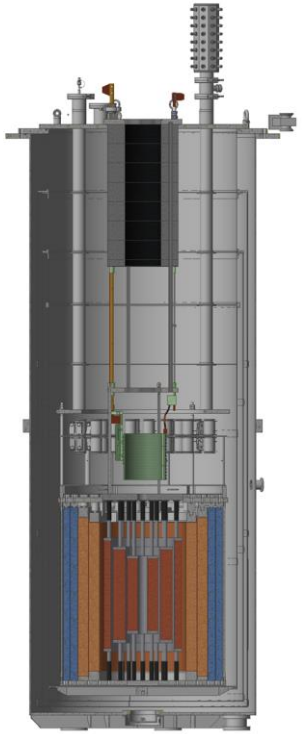


ENN's Spherical Tokamak device EXL-50

The call from High Field Science

Superconducting magnets for sustainable user facilities

High Magnetic Field Laboratories have as a goal to develop all-superconducting user magnets in the 40 T range. These magnets are intended to replace the current resistive ones, leading to a significantly lower energy consumption and to new scientific possibilities



NATIONAL MAGLAB

U.S. National Science Foundation

LNCMI

anr agence nationale de la recherche

A common strategy towards 40 T

- **REBCO high field insert**
- **commercial LTS outsert 12-15 T**

I. Dixon, [IMCC Annual Meeting 2022]
K. Amm, [FCC Week 2024]

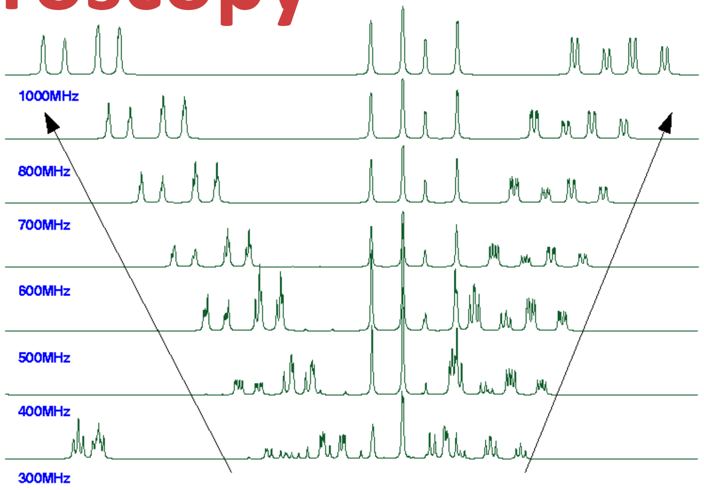
F. Debray, [HiTAT Workshop 2023]

The call for higher resolution in NMR spectroscopy

A commercial application of ultra-high fields

Higher fields in NMR magnets lead to

- better resolution, i.e. better peak separation in the NMR spectra
- better signal to noise ratio

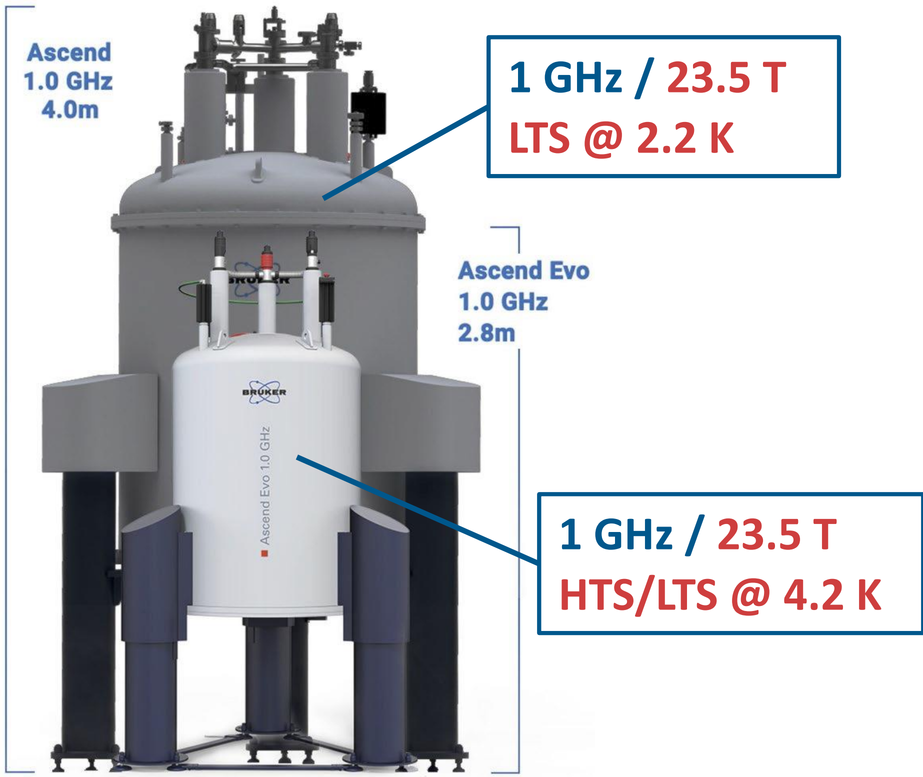


REBCO is the enabling technology for NMR magnets up to 28.2 T (HTS/LTS hybrid, 2.2 K)

proton resonance frequency of 1.2 GHz

Next target is 1.3 GHz, 30.5 T

REBCO enables also NMR systems with reduced footprint compared to all LTS solutions



P. Vonlanthen, ASC 2022

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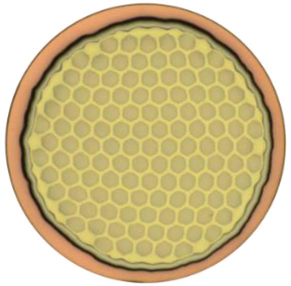
Industrial fabrication of multifilamentary Nb_3Sn wires

Three technologies developed at industrial scale



Bronze Process

Sn source: Cu-Sn alloy

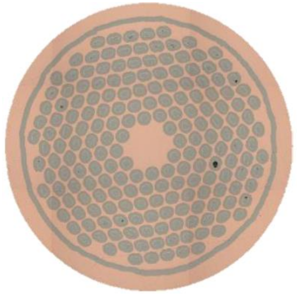
Low Critical Current Density (J_c)

Limited by the solubility of Sn in Cu

Internal Sn Diffusion Process

Sn source: metallic Sn

High Critical Current Density (J_c)



Powder-In-Tube (PIT) method

Sn source: $NbSn_2$ and Sn powders

Presently produced by

BRUKER

FURUKAWA ELECTRIC

Kiswire

LUVATA

JASTEC SUPERCONDUCTOR

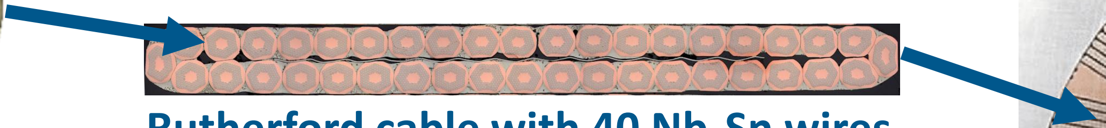
Western Superconducting Technologies Co.,Ltd.

Used for NMR spectrometers, ITER magnets, HL-LHC magnets, laboratory magnets

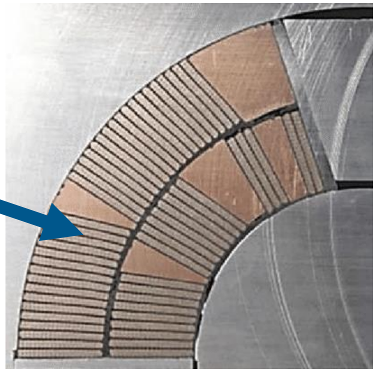
The experience of HL-LHC on Nb_3Sn accelerator magnets

- HL-LHC represent the first experience with a production of Nb_3Sn-based accelerator magnets
- More than 150 coils built at CERN and in the US
- The scaling of the MQXF quadrupole up to 7 m-long prototypes was successful
- Magnets are working also at 4.5 K

https://home.cern/news/news/accelerators/hilumi-news-72-m-long-niobium-tin-quadrupole-magnet-manufactured-cern



Rutherford cable with 40 Nb_3Sn wires

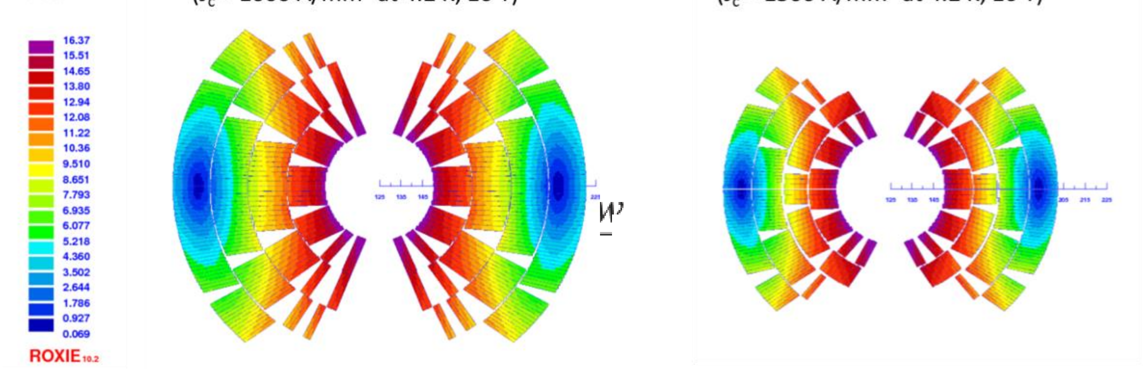


Section of a Nb_3Sn dipole magnet

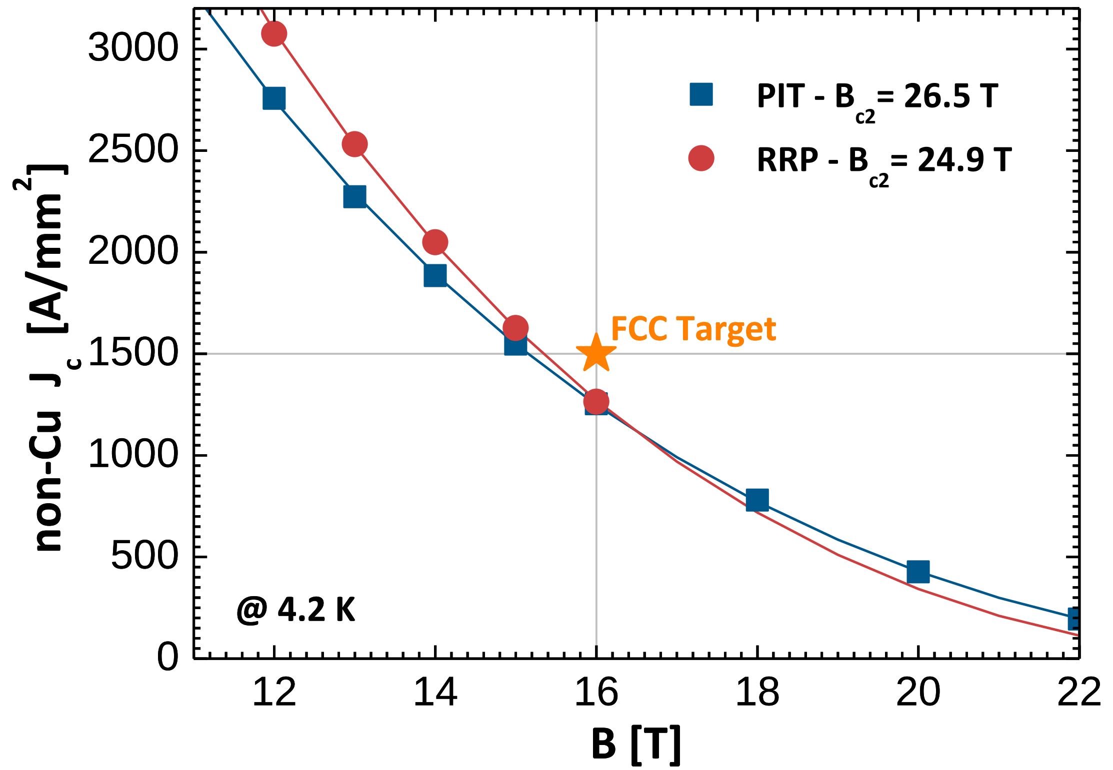
Towards the ultimate performance of Nb_3Sn for the FCC-hh

Dipoles at B = 16 T based on Nb_3Sn with a non-Cu J_c(4.2K, 16 T) = 1'500 A/mm²

HL-LHC strand (J_c = 1000 A/mm² at 4.2 K, 16 T) — **FCC target strand** (J_c = 1500 A/mm² at 4.2 K, 16 T)



	HL-LHC		FCC
B [T]	16		16
J_{op} [A/mm²]	300	2x →	600
w [mm]	76		38
A_{coil} [mm²]	20'000		7'000



Doubling the operating current density brings a reduction of the superconductor area to one third

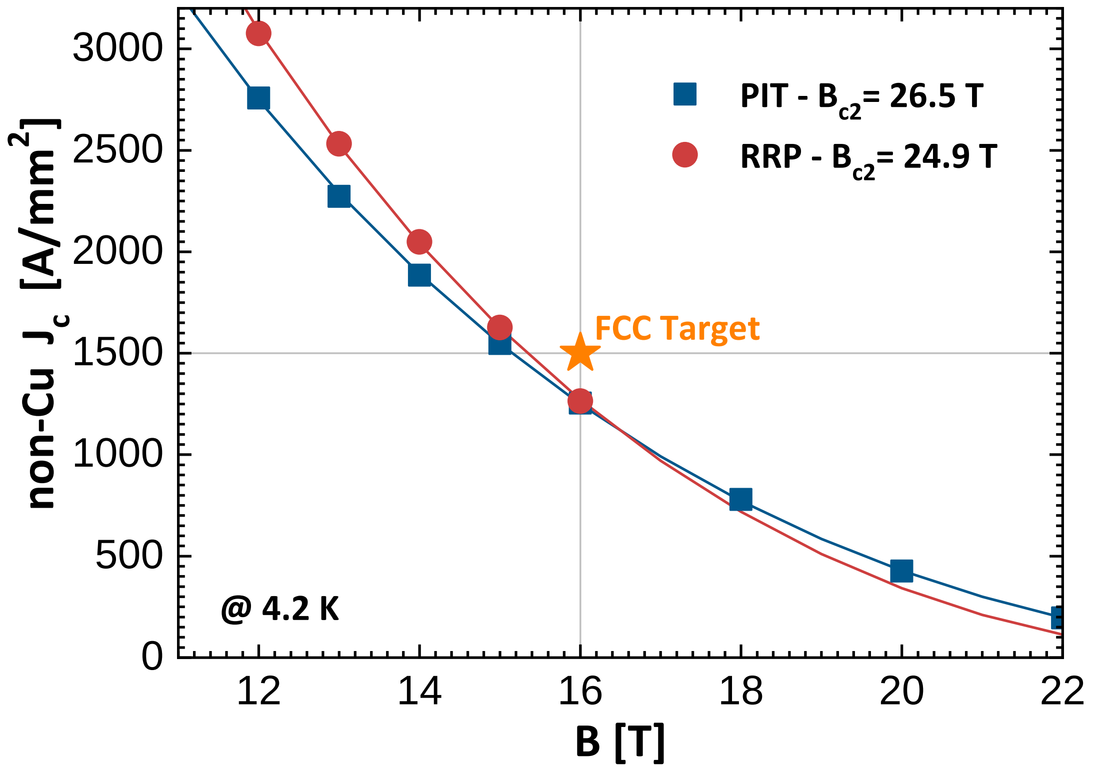
$A_{coil} \propto$ SC mass $\propto$

J. Parrell et al., AIP Conf. Proc. 711 (2004) 369 — DOI: 10.1063/1.1774590

T. Boutboul et al., IEEE TASC 19 (2009) 2564 — DOI: 10.1109/TASC.2009.2019017

Strategies to increase the critical current density of Nb_3Sn

The Internal Oxidation method - Critical current density $\propto$ 1/(grain size)



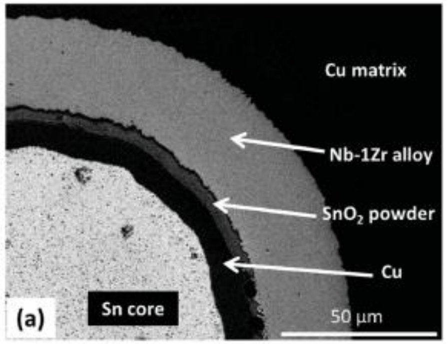
J. Parrell et al., AIP Conf. Proc. 711 (2004) 369 DOI: 10.1063/1.1774590
T. Boutboul et al., IEEE TASC 19 (2009) 2564 DOI: 10.1109/TASC.2009.2019017

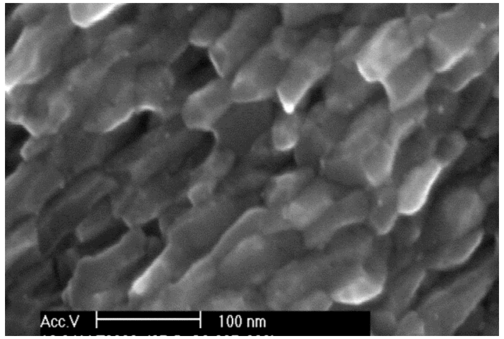
Idea from Benz (1968) of an Internal Oxidation to form fine precipitates in Nb to impede the Nb_3Sn grain growth Benz, Trans. Metall. Soc. AIME, 242 (1968) 1067-1070

Use of a Nb-alloy containing Zr or Hf: Zr and Hf have stronger affinity to oxygen than Nb

Oxygen supply added to the composite: oxidation of Zr (Hf) and formation of nano-ZrO_2 (HfO_2)

THE OHIO STATE UNIVERSITY





The first evidence of average grain size reduced down to ~ 50 nm (vs ~ 100 nm in regular wires)

X. Xu et al., APL 104 (2014) 082602 DOI: 10.1063/1.4866865
X. Xu et al., Adv. Mat. 27 (2015) 1346 DOI: 10.1002/adma.201404335

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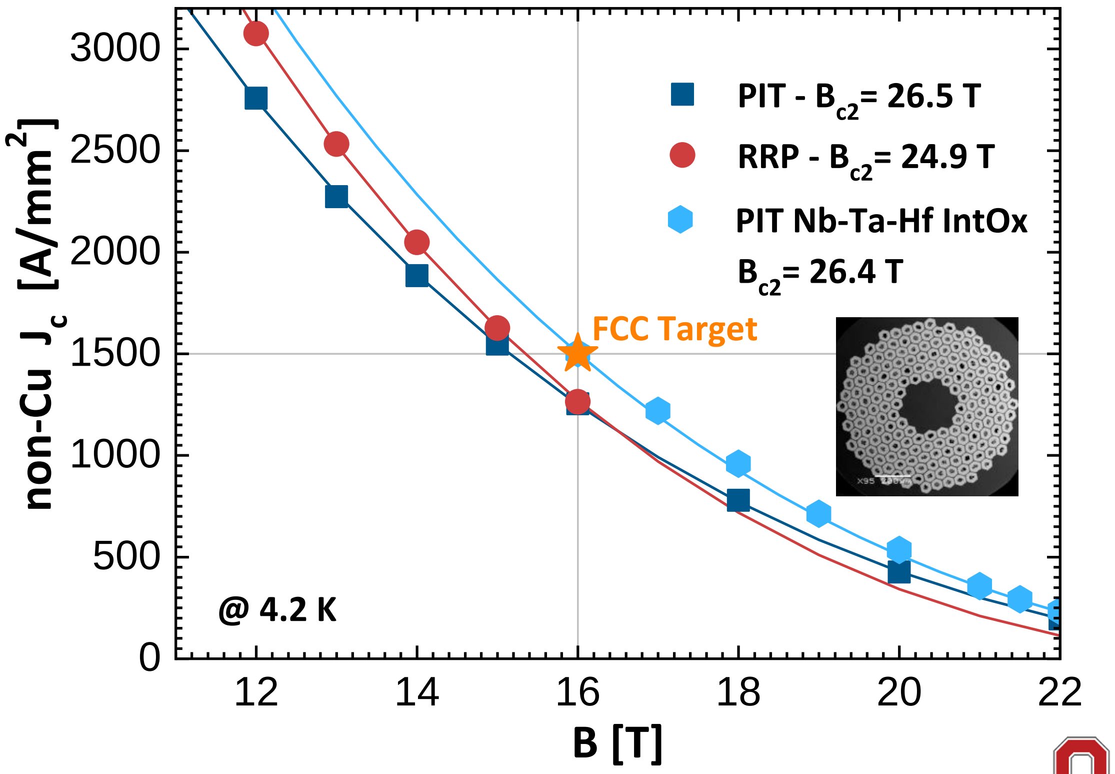

First report on a PIT multifilamentary wire that reaches the FCC specifications

X. Xu et al., Supercond. Sci. Technol. 36 (2023) 035012
DOI: 10.1088/1361-6668/acb17a

The Ohio State University

Hyper Tech

Fermilab

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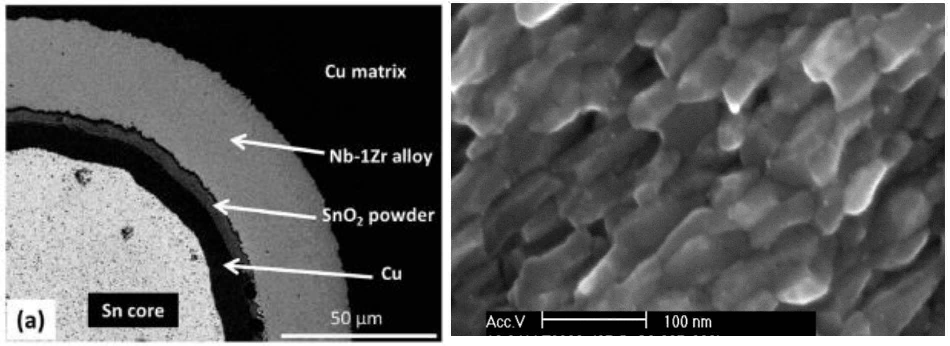

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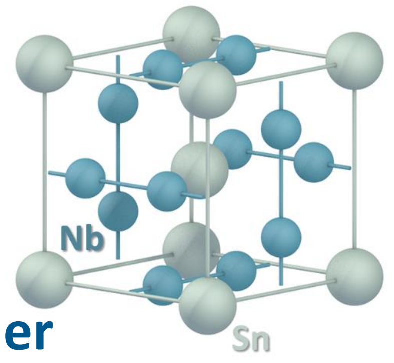
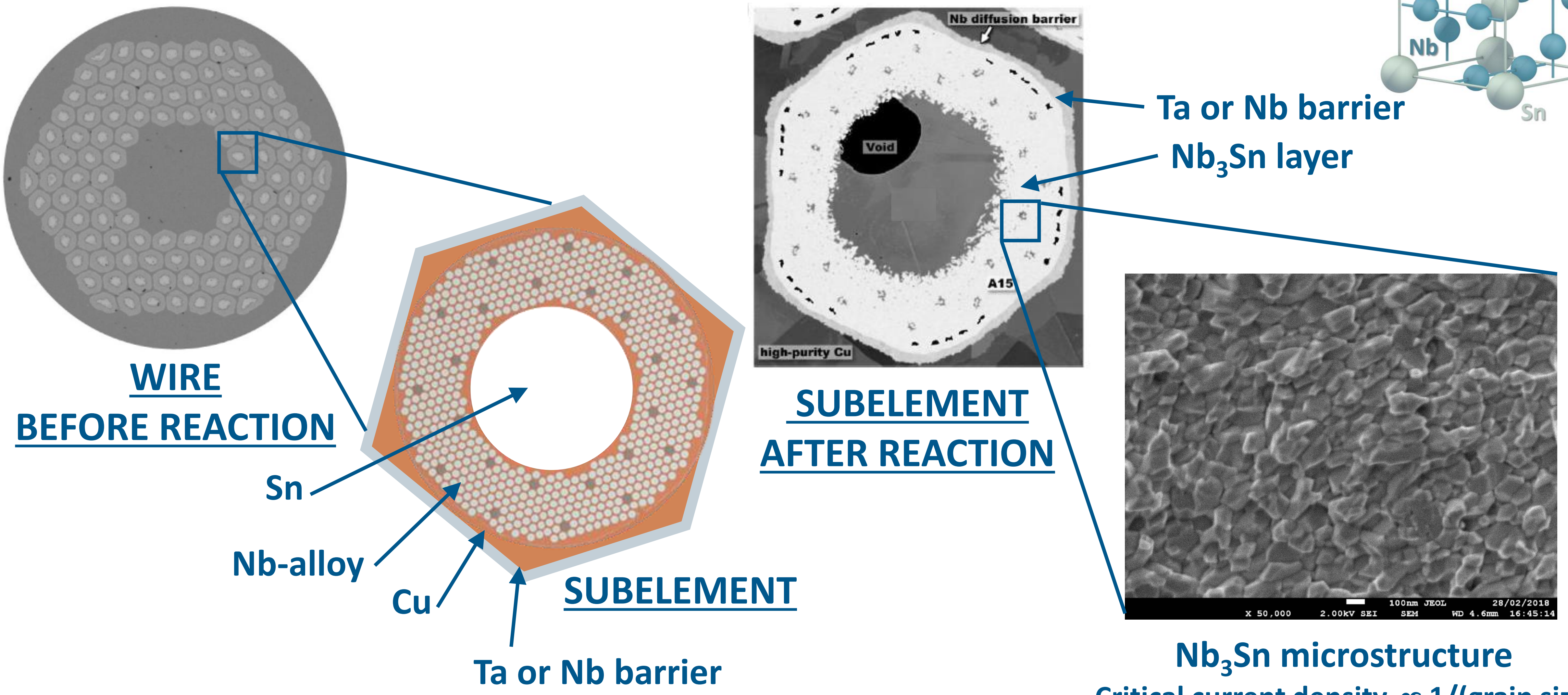
The structure of high-J_c internal Sn Nb_3Sn wires





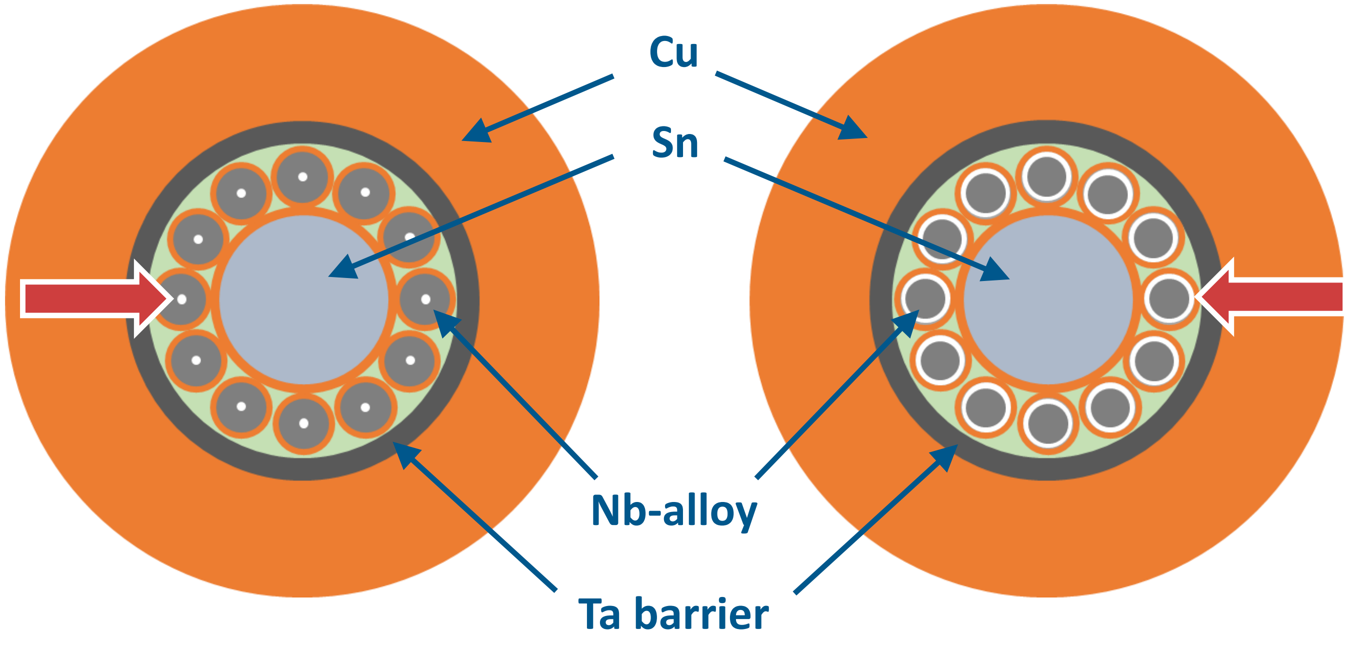
Nb_3Sn microstructure

Critical current density $\propto$ 1/(grain size)

Internal Oxidation of test-bed Internal Sn subelements

12-filament wires with an internal Sn source

Two possible configurations for the oxygen source

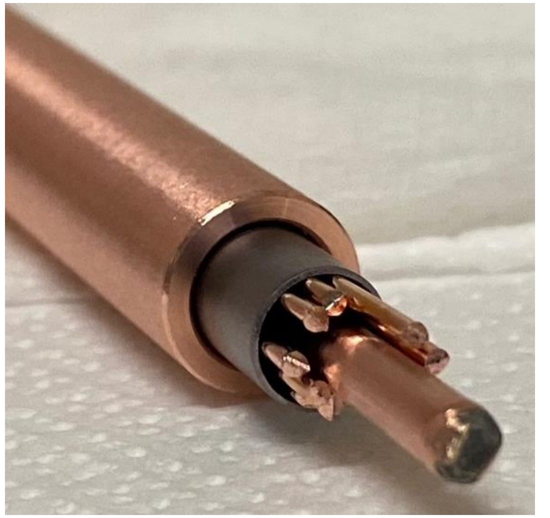


SnO_2 Core
SnO_2 powder inside the Nb-alloy filaments

SnO_2 Annular
SnO_2 powder between the Nb-alloy filaments and the Cu tube

Nb-alloy	Oxide configuration
Nb-7.5wt%Ta (REF.)	None
Nb-7.5wt%Ta-1wt%Zr	None
	SnO_2 Core
Nb-7.5wt%Ta-2wt%Hf	None
	SnO_2 Core
	SnO_2 Annular

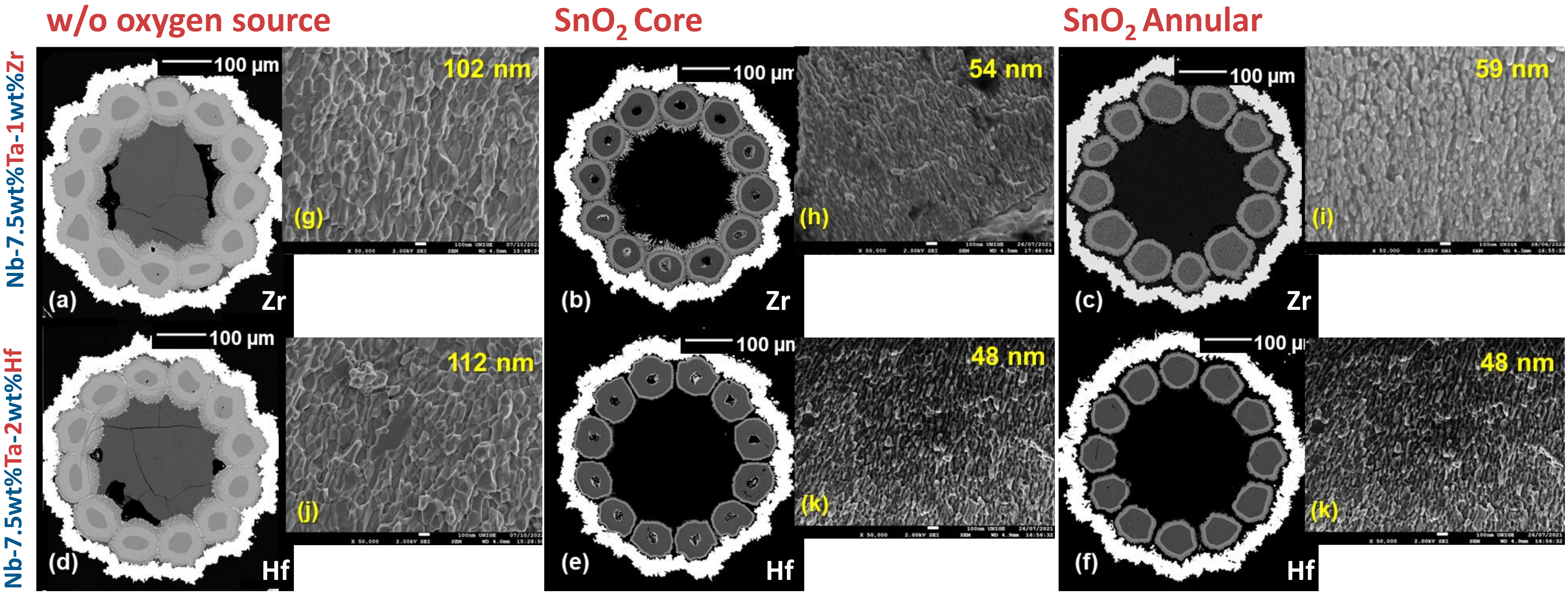
Two commercial ternary alloy were tested with 1wt%Zr and 2wt%Hf



HT: 550°C x 100h + 650°C x 200h

Internal Oxidation of test-bed Internal Sn subelements

12-filament wires with an internal Sn source

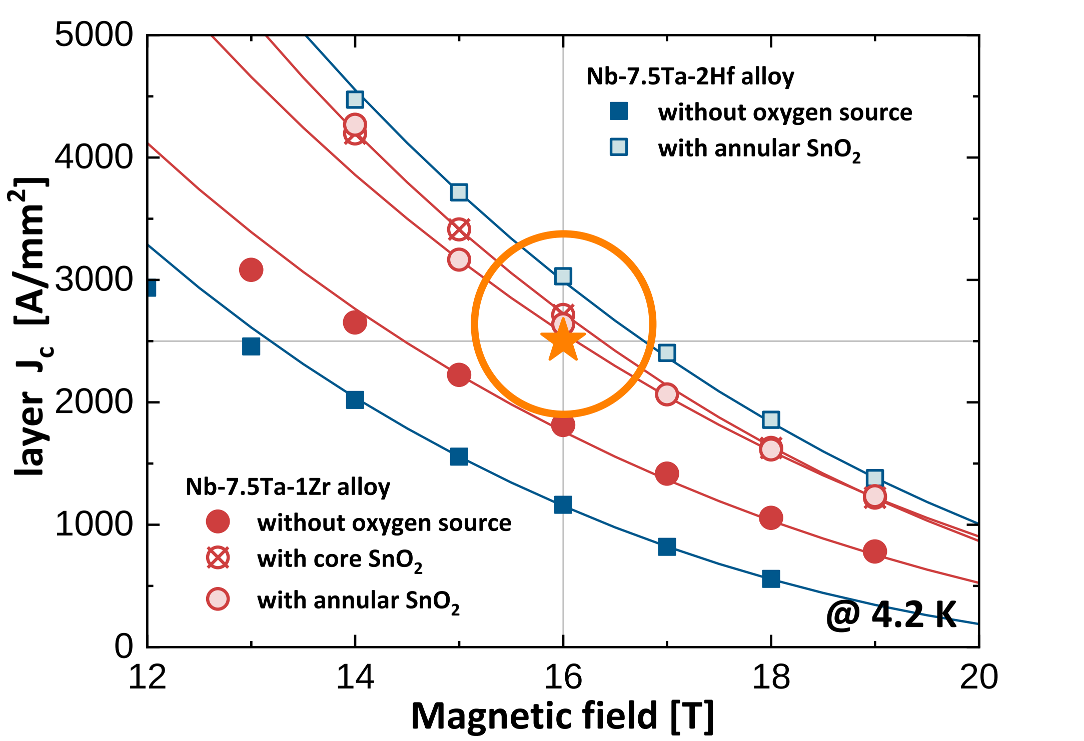


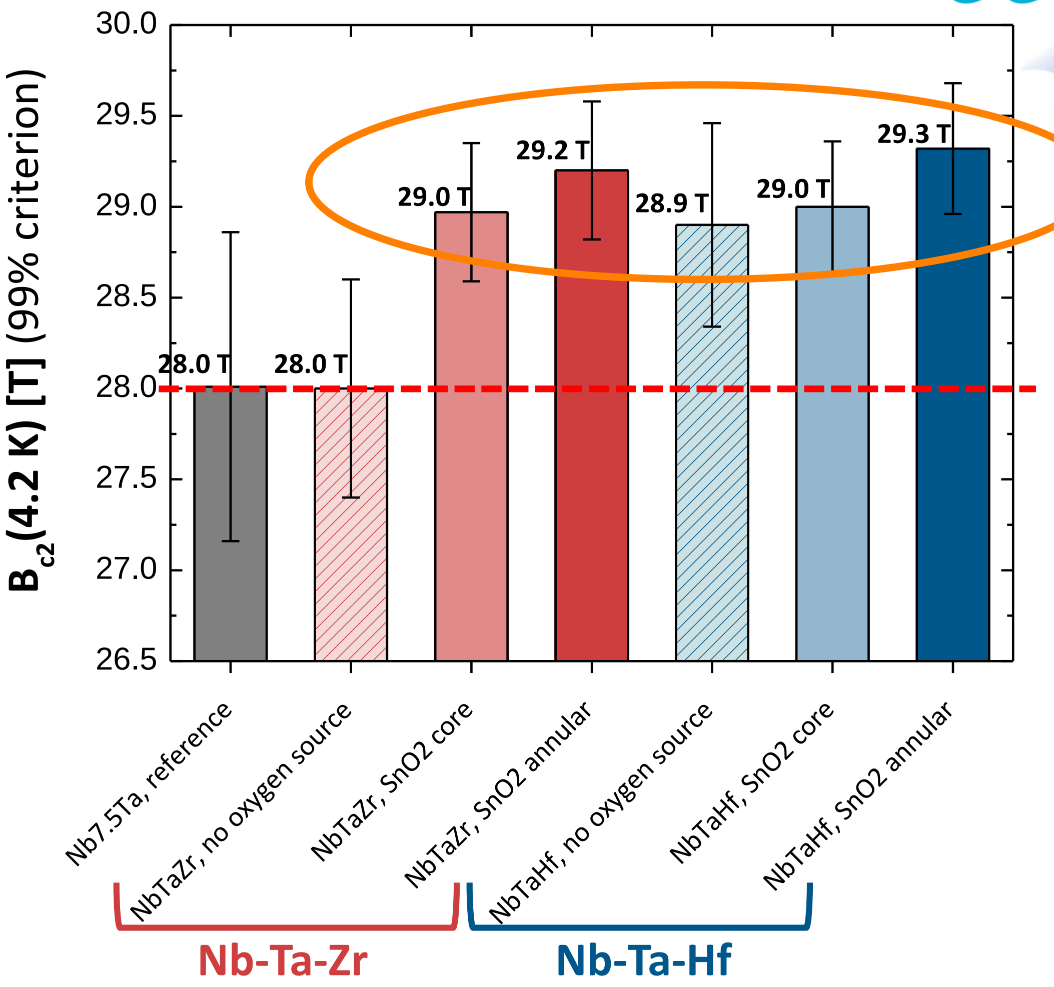
Internal oxidation leads to a refinement of the grain size from ~100 nm to ~50 nm regardless of the oxygen source configuration

G. Bovone *et al.*, Supercond. Sci. Tech. 36 (2023) 095018
DOI: 10.1088/1361-6668/aced25

Internal Oxidation of test-bed Internal Sn subelements

Transport I_c and B_{c2} measurements





Layer J_c determined from transport measurements

FCC layer J_c (4.2K,16T) = 2'500 A/mm^2 considering 60% of Nb_3Sn in the non-Cu area

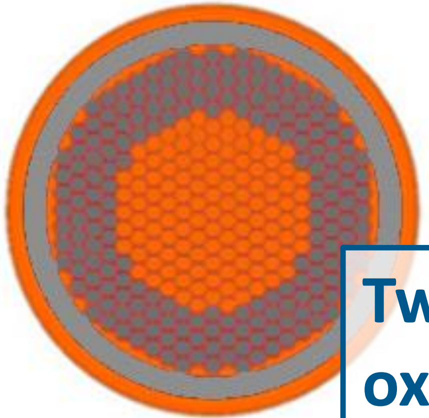
G. Bovone *et al.*, Supercond. Sci. Tech. 36 (2023) 095018

DOI: 10.1088/1361-6668/aced25

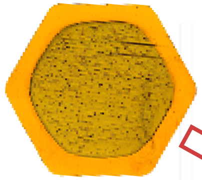
R(B) tests performed up to 33 T at LNCMI-Grenoble confirm that the record high B_{c2} values are achieved both with Hf and Zr

Towards the development of multifilamentary wires

From test-bed subelements to prototype wires with Internal Oxidation



192 Cu/Nb-alloy filaments
121 Cu filaments



Cu and Cu/Nb filaments produced and assembled at UNIGE

Billet e-Beam weld at CERN

Ø = 71 mm

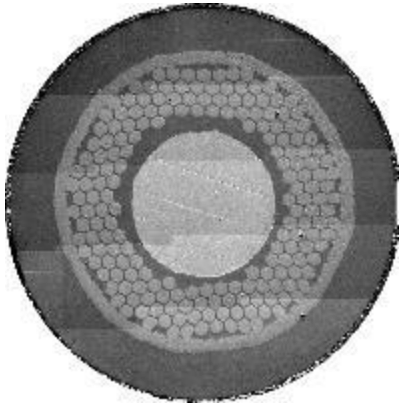
HIP to remove voids

Hot Isostatic Extrusion

Ø = 18 mm

Two methods for introducing an oxygen source are being now tested

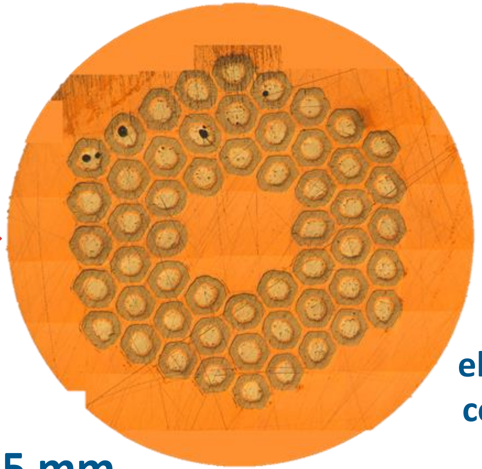
Cold-deformation, gun-drilling of the subelement Cu core to insert the Sn rod



Ø = 6.05 mm

Cold-deformation to reach restack size

1.5 – 1.0 mm



Ø = 15 mm

54/61 wire

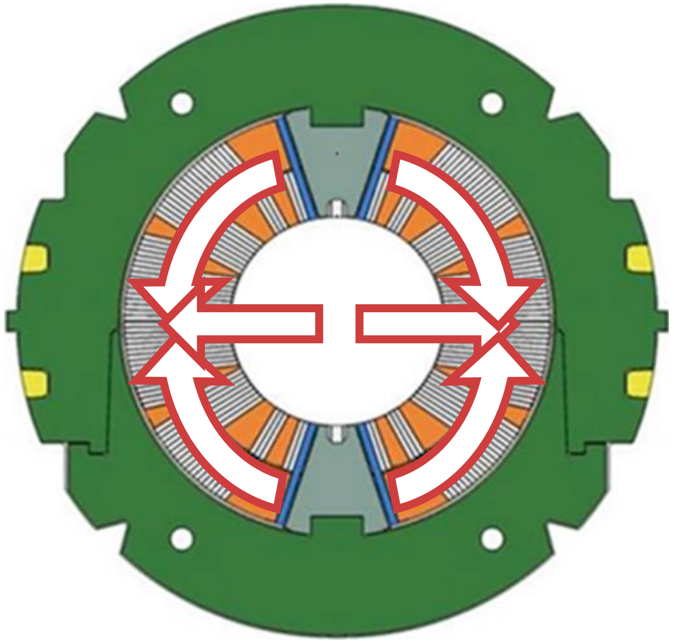
Restack of the sub-element in a Cu tube, and cold-deformation to final wire size (1 – 0.7 mm)

Increasing the non-Cu J_c beyond state of the art is a necessary condition to get 16 T dipoles, but it is not sufficient

Other crucial conductor requirements:

- Have high tolerance to stress
- Be safe in case of magnet quench
- Have low magnetization
- Have a low price...

Stress management is key for Nb_3Sn-based accelerator magnets

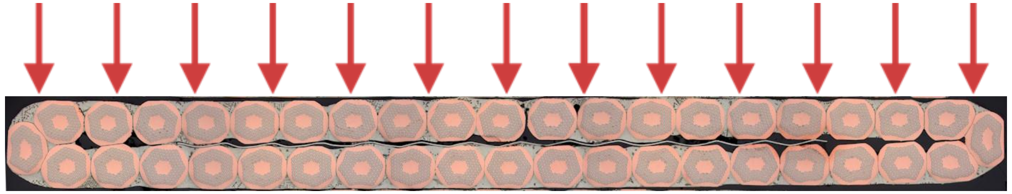


Electromagnetic forces in an accelerator magnet

- The azimuthal component accumulates at the midplane of the coil, with a magnitude of many hundreds kN/m
- The radial component pushes the coil outwards with a maximum displacement localized again at the midplane
- The longitudinal component tends to elongate the coil

The combination of these forces with the pre-compression and the thermomechanical effects exposes the brittle and strain sensitive Nb_3Sn to the risk of degradation

All design options developed for the 16 T dipoles for a future 100 TeV collider share a peak stress in the range of 150-200 MPa at operation, with the main component in the transverse direction of the Nb_3Sn Rutherford cables

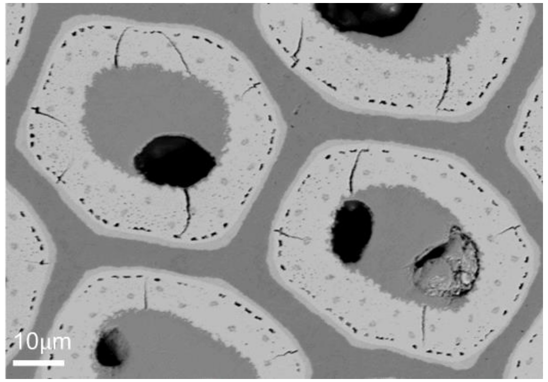


Irreversible reduction of the critical current after unload

Mechanisms responsible for the performance degradation

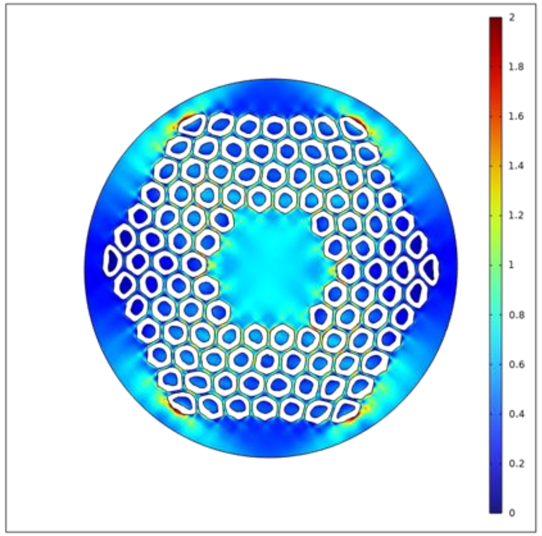
Two mechanisms govern the permanent reduction of the critical current

- **Formation of cracks in the Nb_3Sn filaments**



Cracks generate a reduction of the current carrying cross section $\Rightarrow$ I_c^{unload}/I_{c0} is independent of the magnetic field

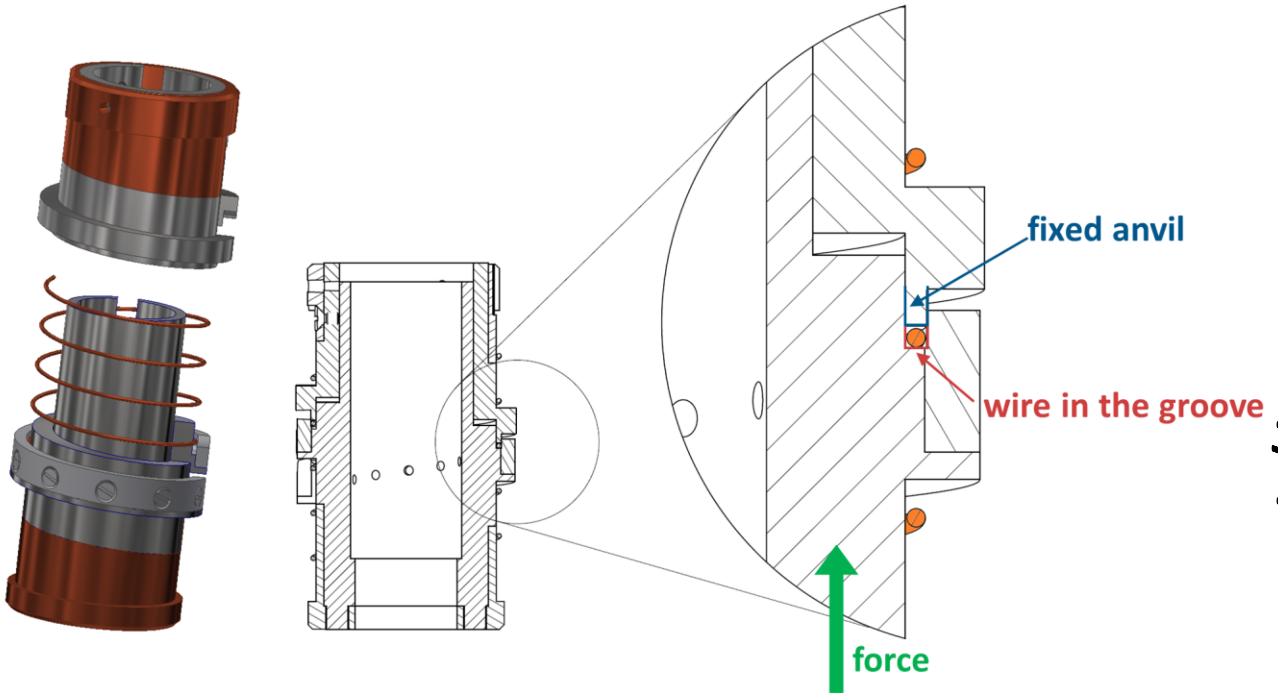
- **Plastic deformation of the Cu matrix and residual stress on the Nb_3Sn filaments**



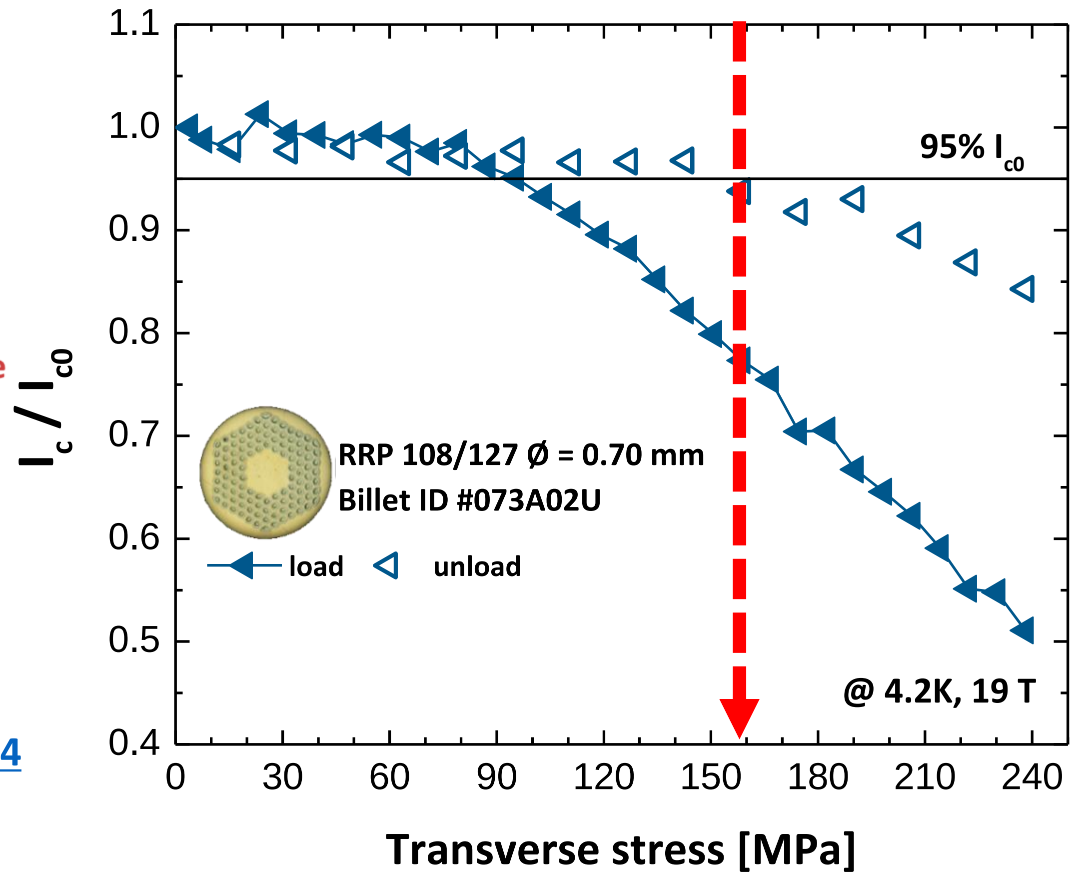
Residual stress induces a permanent reduction of B_{c2} after unload $\Rightarrow$ I_c^{unload}/I_{c0} depends on of the magnetic field

Tolerance to transverse stress of a single wire

Electromechanical tests on Nb_3Sn wires impregnated with epoxy



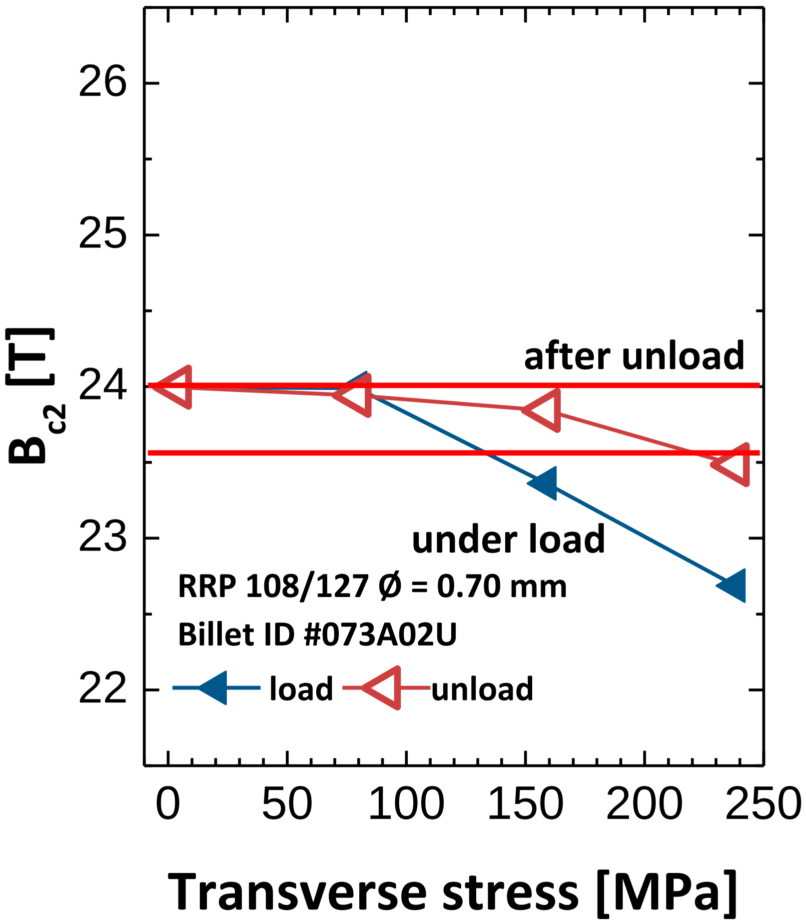
The WASP concept was adapted to transverse loads by
B. Seeber et al., IEEE TAS 17 (2007) 2643, DOI: 10.1109/TASC.2007.897934



The irreversible limit is defined at the force level leading to a 95% recovery of the initial I_c after unload

Here the irreversible stress limit is σ_{irr} (B=19T)= 155 MPa (force dived by groove area)

Comparison of B_{c2} under load and after unload

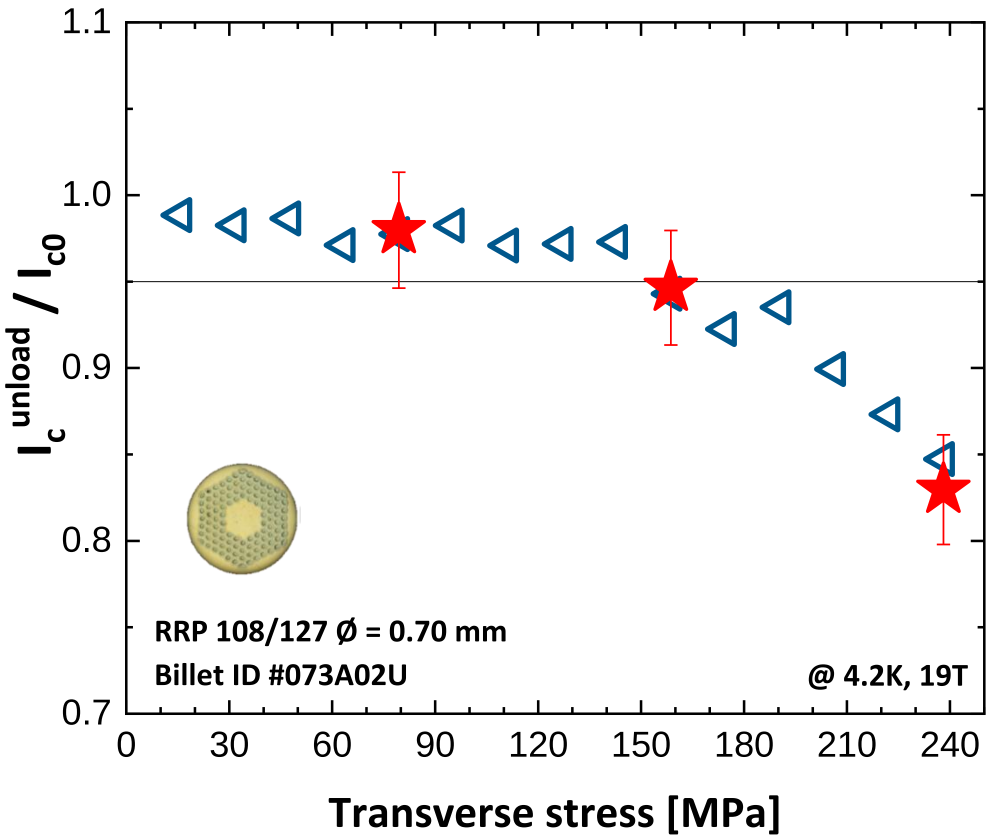


After unload from σ = 240 MPa

$\Delta B_{c2}^{unload} \approx 0.5$ T

CS *et al.*, Supercond. Sci. Technol., 36 (2023) 075001
DOI: 10.1088/1361-6668/acca50

Measured I_c^{unload} (open blue points) vs expected degradation from residual stress (solid red stars)



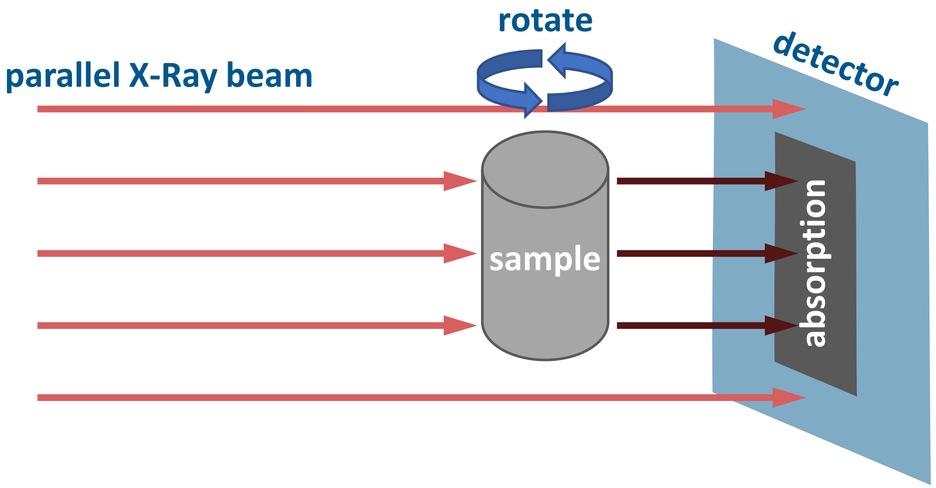
$$I_c^{unload}(B) = f\,C\left[\frac{B_{c2}^{unload}}{B}\right]^{0.5}\left[1-\frac{B}{B_{c2}^{unload}}\right]^2$$

The observed permanent degradation of I_c after unload originates mainly from the residual stress

The effect of cracks seems negligible up to very high transverse stress values

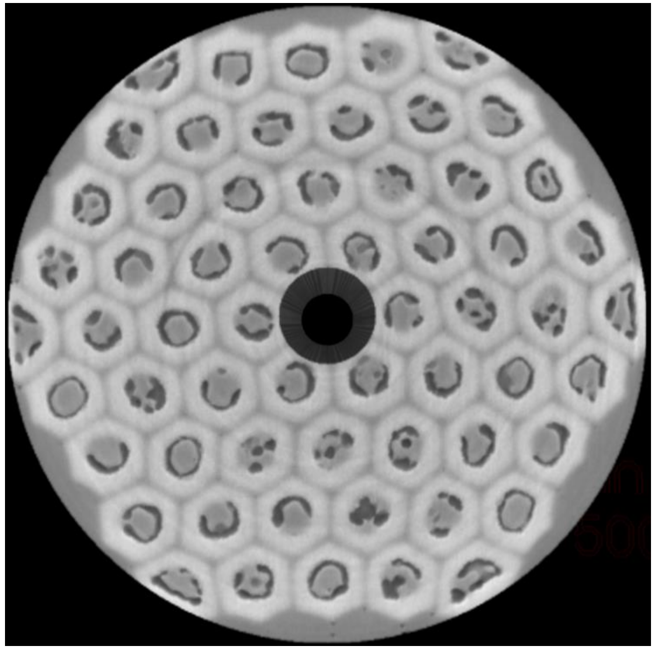
X-ray tomography and Machine Learning for crack detection

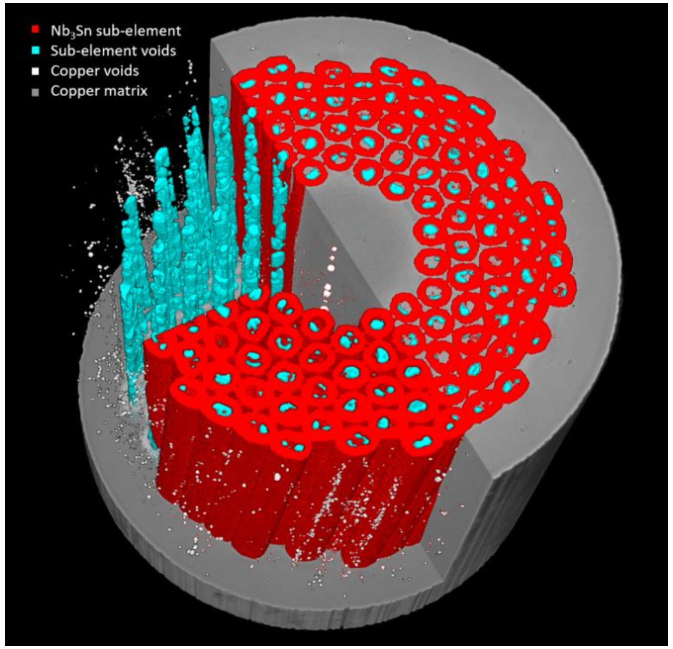
An independent confirmation of the conclusions



- X-ray photon energy = 80 keV
- 360° rotation of the sample
- 10’000 projections
- 2560 x 2160 pixels
- 0.57 μm/pixel resolution

Marta MAJKUT
Alexander RACK



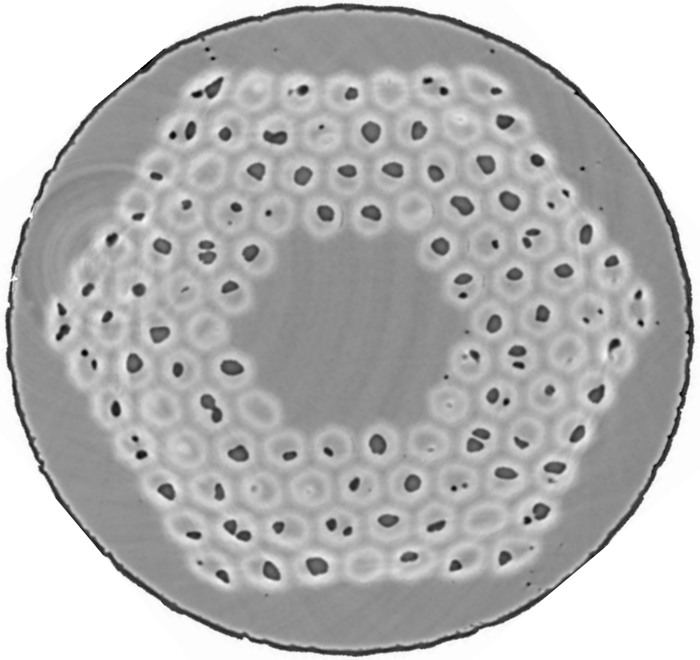


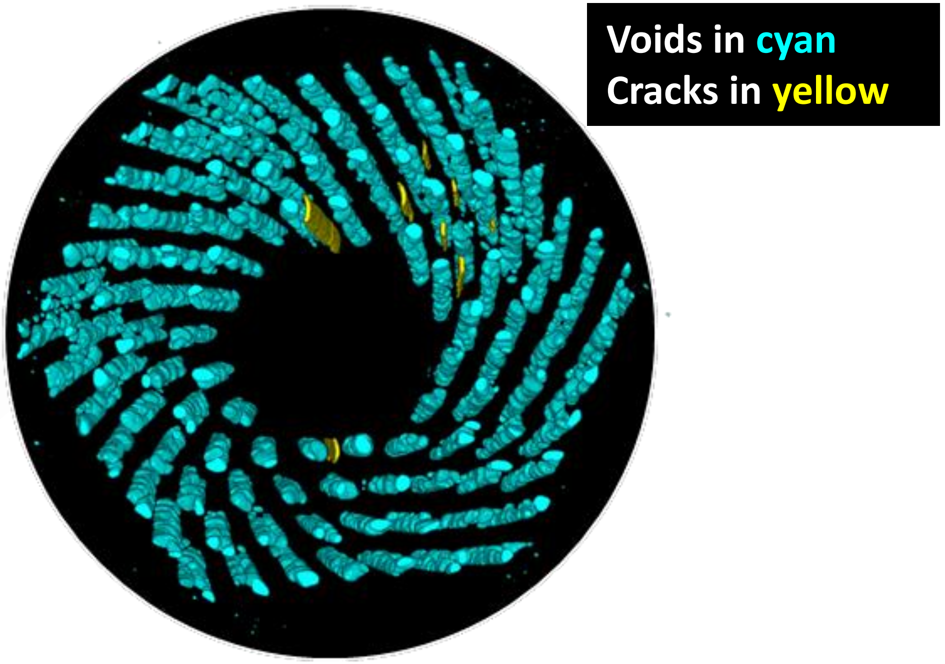
A novel, non-destructive and non-invasive method to investigate the internal structure of high-performance Nb_3Sn wires combines X-ray microtomography with machine-learning algorithms

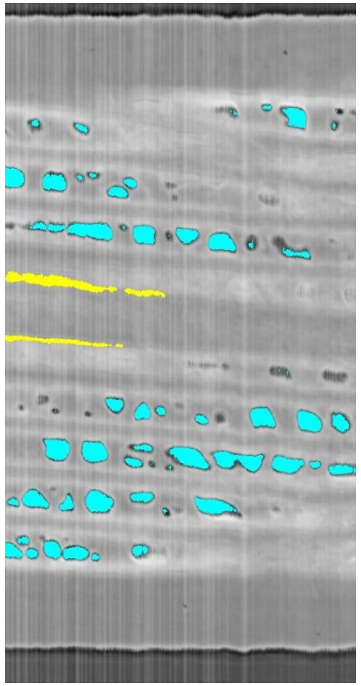
T. Bagni *et al.*, Sci. Reports 11 (2021) 7767 DOI: 10.1038/s41598-021-87475-6

X-ray tomography and Neural Networks for crack detection

An independent confirmation of the conclusions







An analysis based on Convolutional Neural Networks was performed on the tomographic scan of the exact same sample used for the I_c vs σ test, after unload from 240 MPa

Very few cracks were detected, none of them interrupting the subelements and responsible for the measured degradation by 15% of I_c

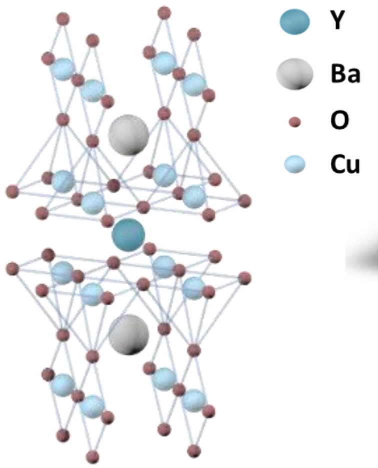
T. Bagni *et al.*, Supercond. Sci. Technol., 35 (2022) 104003 DOI: 10.1088/1361-6668/ac86ac

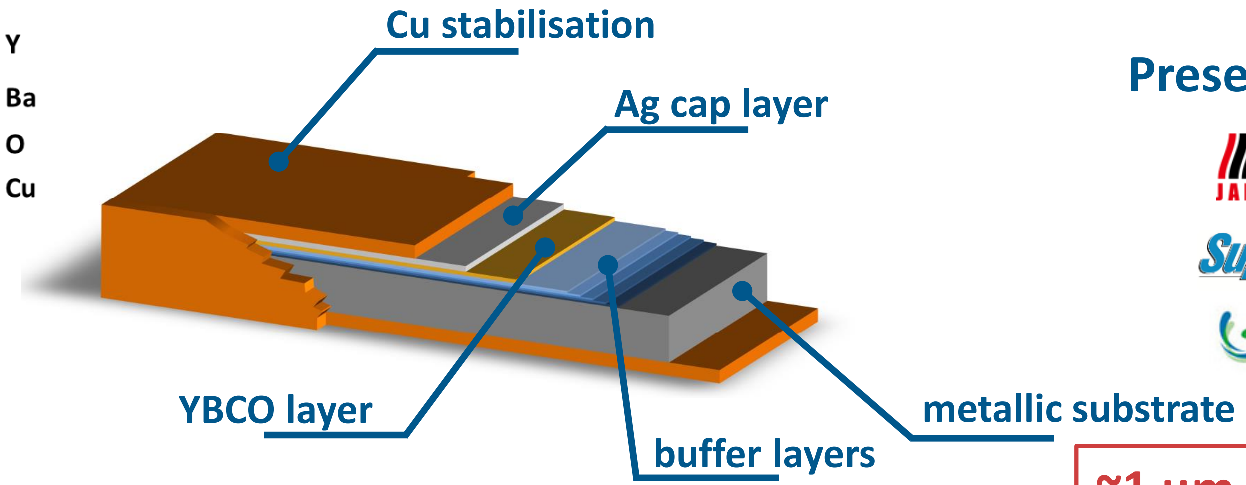
Outline

- What we do today and aim to achieve in the near future with superconductors
  - Focus on high magnetic field applications
- Which future for Low Temperature Superconductors (LTS) ?
  - Towards the ultimate performance of Nb_3Sn for a Future Circular Collider
- **Which future for High Temperature Superconductors (HTS) ?**
  - **The technology-pull towards magnetic fields beyond the reach of LTS and the opportunity for higher operating temperatures**
- Conclusions

Industrial fabrication of REBCO coated conductors

$REBa_2Cu_3O_{7-\delta}$, RE = Y, Gd, Eu, Nd, Sm, Yb, …

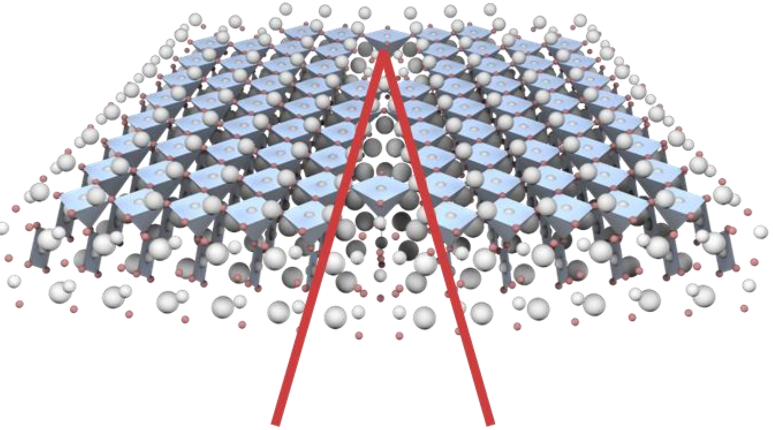




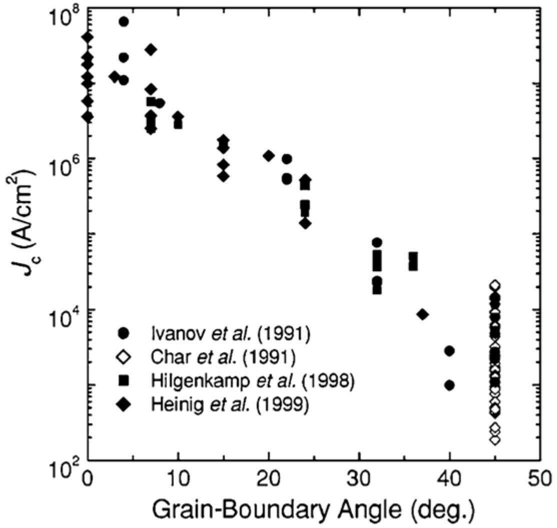
Presently produced by

Faraday Factory Japan, Fujikura, 上海超导 Shanghai Superconductor, SuperPower Inc. A Furukawa Company, SuNAM Zero to Infinity, THEVA, Shanghai, METOX, American Superconductor®

~1 µm of YBCO in a ~100 µm thick tape



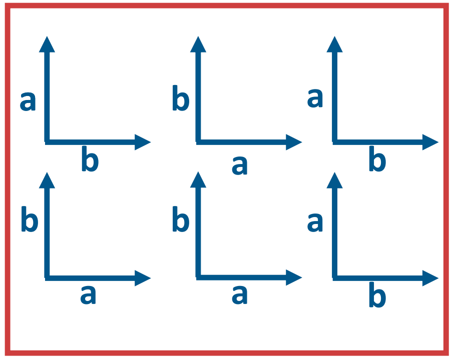
[001] tilt grain boundary



H. Hilgenkamp and J. Mannhart, RMP 74 (2002) 485

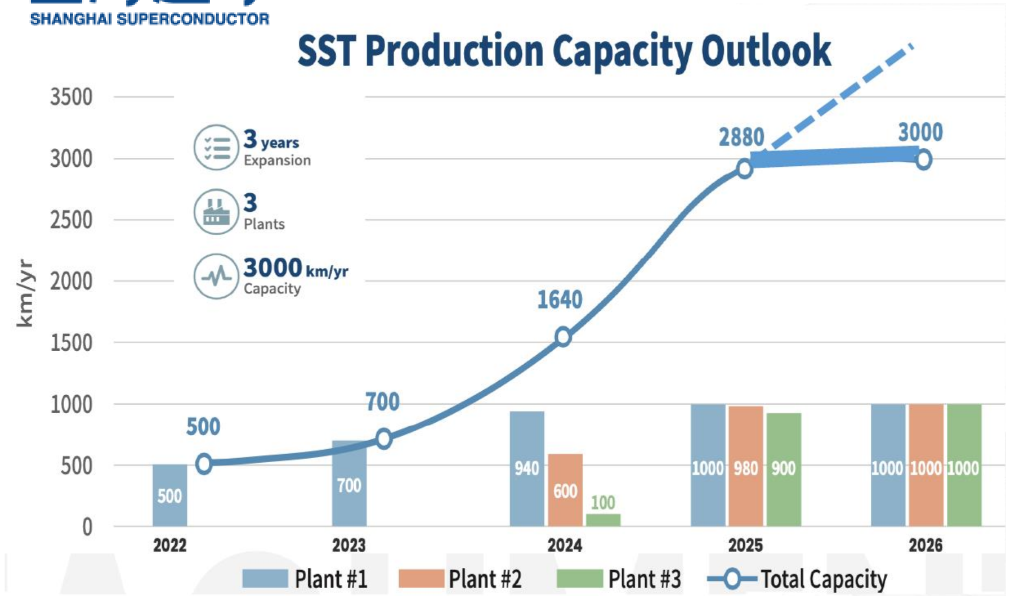
DOI: 10.1103/RevModPhys.74.485

A metallic substrate coated with a multifunctional oxide barrier is the template to grow biaxially textured REBCO with in-plane alignment within 5°



Fusion-driven expansion of REBCO production capacity

上海超导™
SHANGHAI SUPERCONDUCTOR



1600 km_{12}/yr (2024) → 3000 km_{12}/yr (2026)

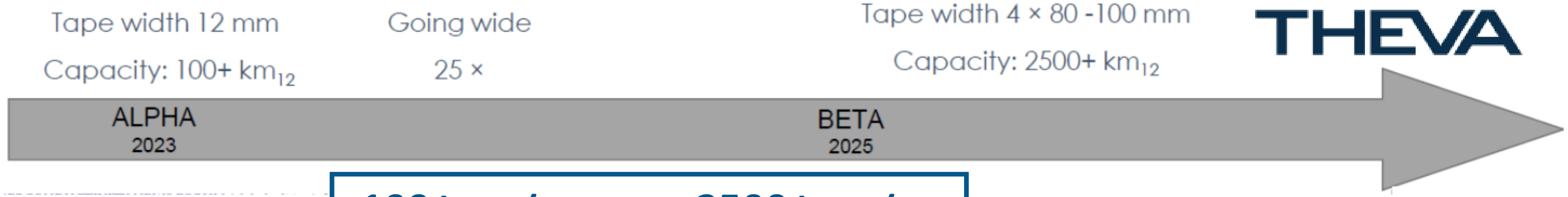
FARADAY FACTORY JAPAN

1300 km_{12}/yr (2024) → 25000 km_{12}/yr (2028)

SuperPower Inc.
A Furukawa Company

200 km_{12}/yr (2024) → 1200 km_{12}/yr (2026)

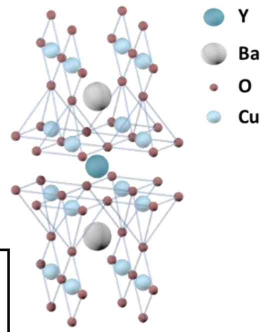
THEVA



100 km_{12}/yr (2023) → 2500 km_{12}/yr (after 2025)

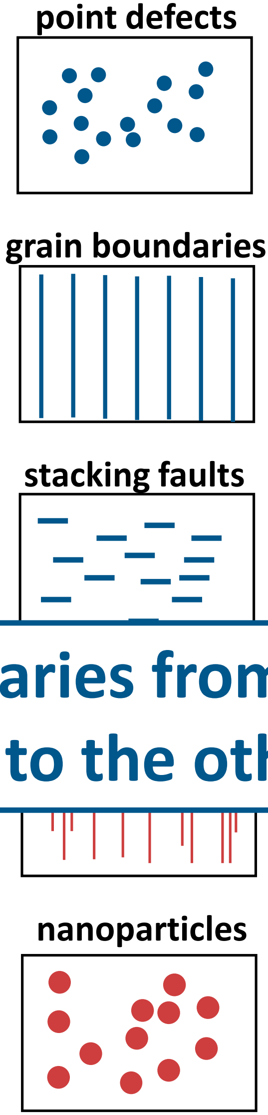
Tailoring the critical current density of REBCO

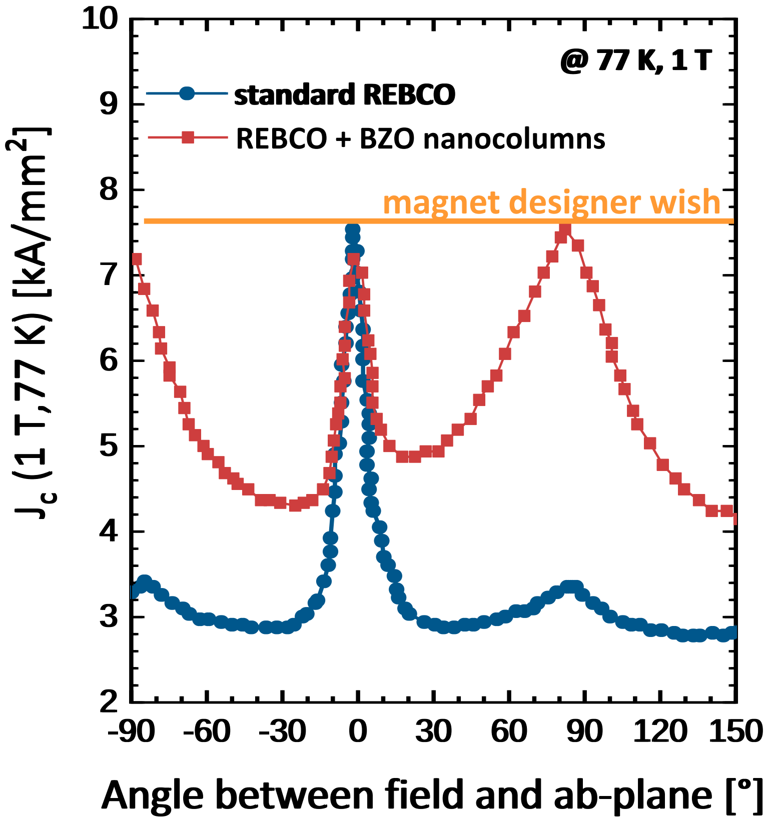
Anisotropy, Intrinsic and Artificial defects and their Dimensionality



Intrinsic defects, e.g. point defects (0D), grain boundaries (2D), stacking faults (3D), are native pinning centers

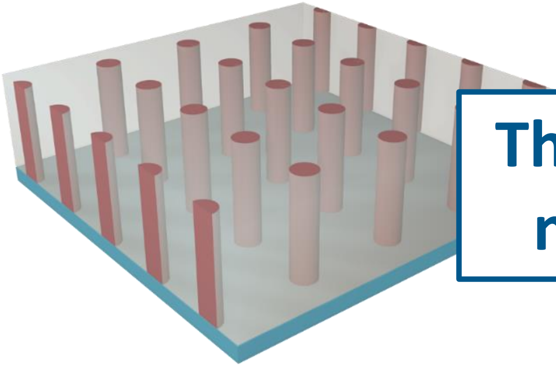
Tailored artificial defects, e.g. nanocolumns (1D) and nanoparticles (3D), can be introduced to reduce anisotropy and enhance performance





V. Selvamanickam *et al.*, IEEE TAS 21 (2011) 3049 – DOI: 10.1109/TASC.2011.2107310

$BaZrO_3$ (BZO) and $BaHfO_3$ (BHO) precipitate in the form of nanocolumns oriented along the c-axis of REBCO



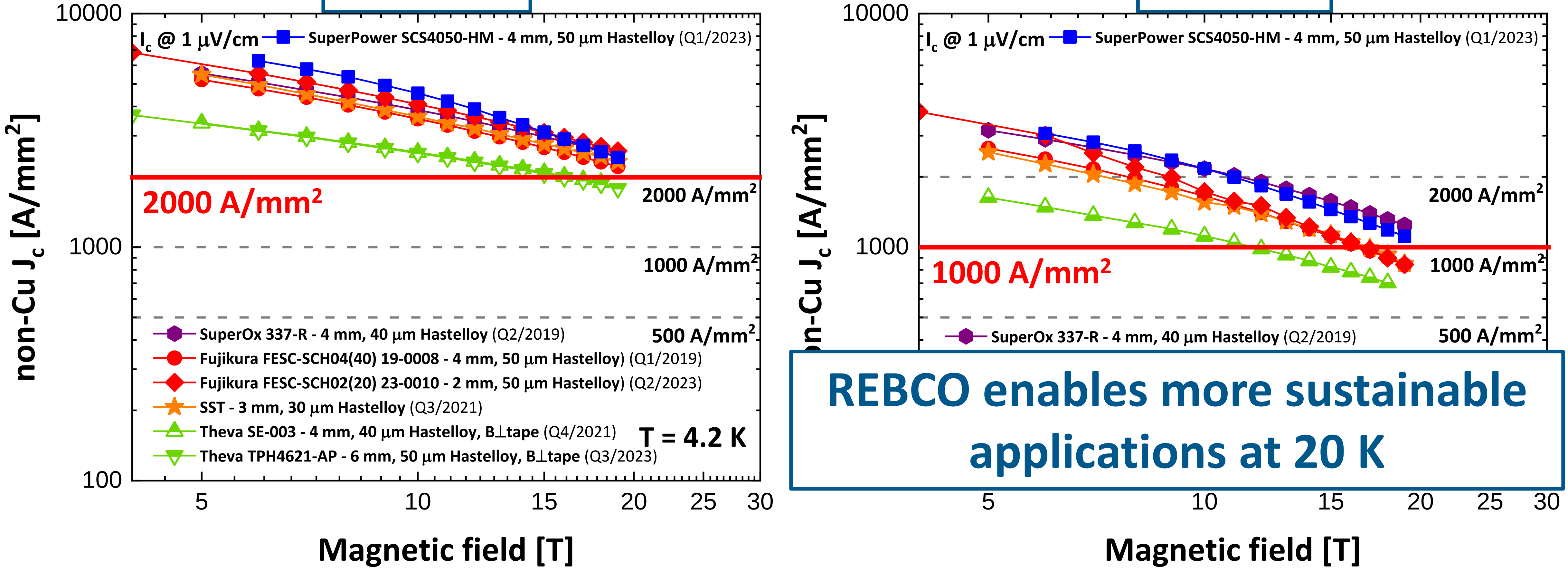
The approach varies from one manufacturer to the others

J. Driscoll *et al.*, Nat. Mat. 3 (2004) 439
DOI: 10.1038/nmat1156
A. Goyal *et al.*, SUST 18 (2005) 1533
DOI: 10.1088/0953-2048/18/11/021

Comparison of the performance: non-Cu J_c

The non-Cu J_c corresponds to the critical current divided by the tape cross-section area minus the Cu area

$$\text{non-Cu } J_c = \frac{I_c}{A_{tot} - A_{Cu}}$$



REBCO enables more sustainable applications at 20 K

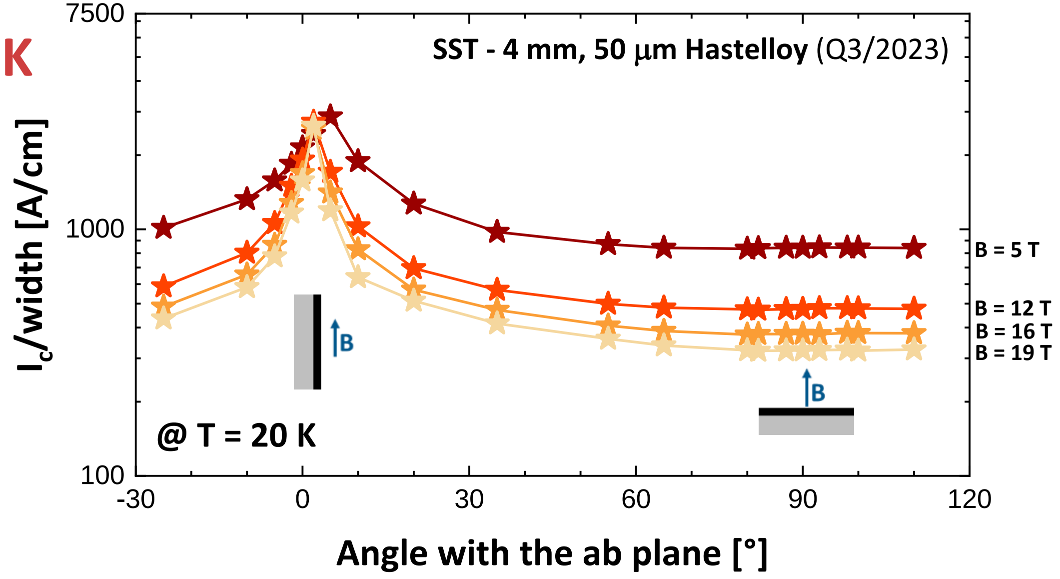
Angular dependence of I_c: very fresh results

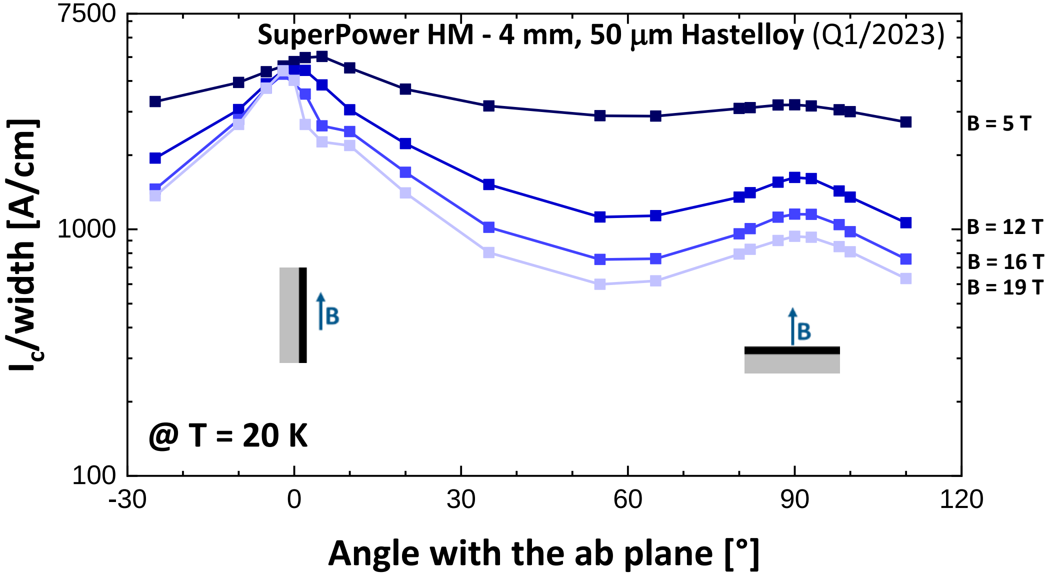
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
TOHOKU UNIVERSITY

上海超导 SHANGHAI SUPERCONDUCTOR **EuBCO + BHO nanocolumns**

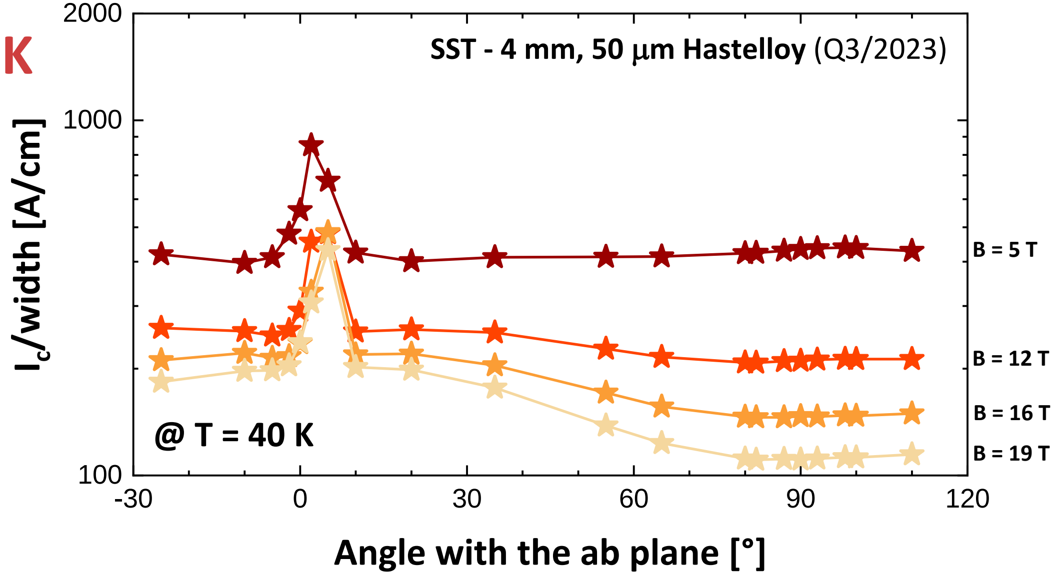
SuperPower Inc. A Furukawa Company **YBCO + BZO nanocolumns**

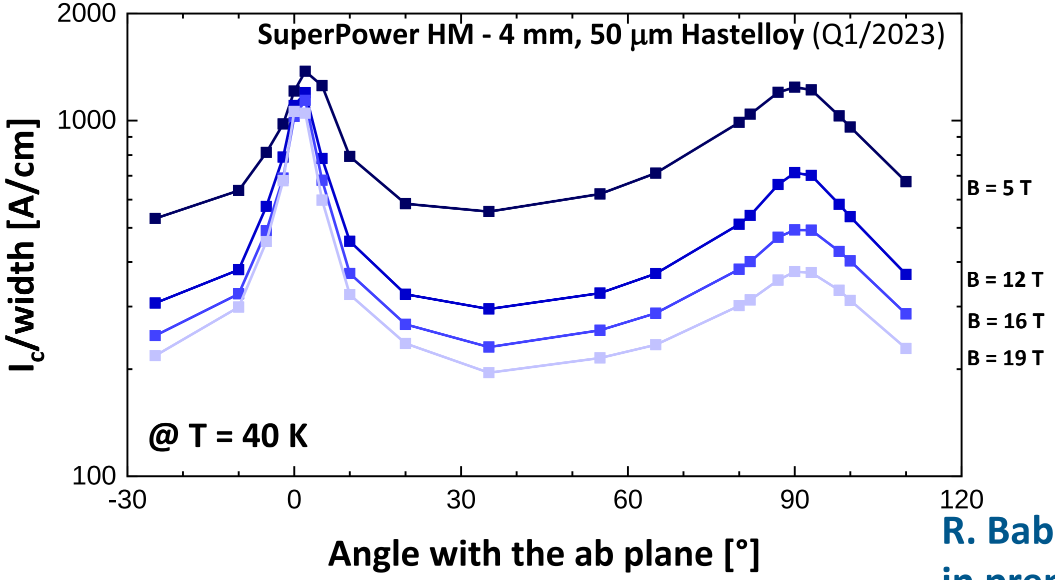
T = 20 K
5 T → 19 T





T = 40 K
5 T → 19 T

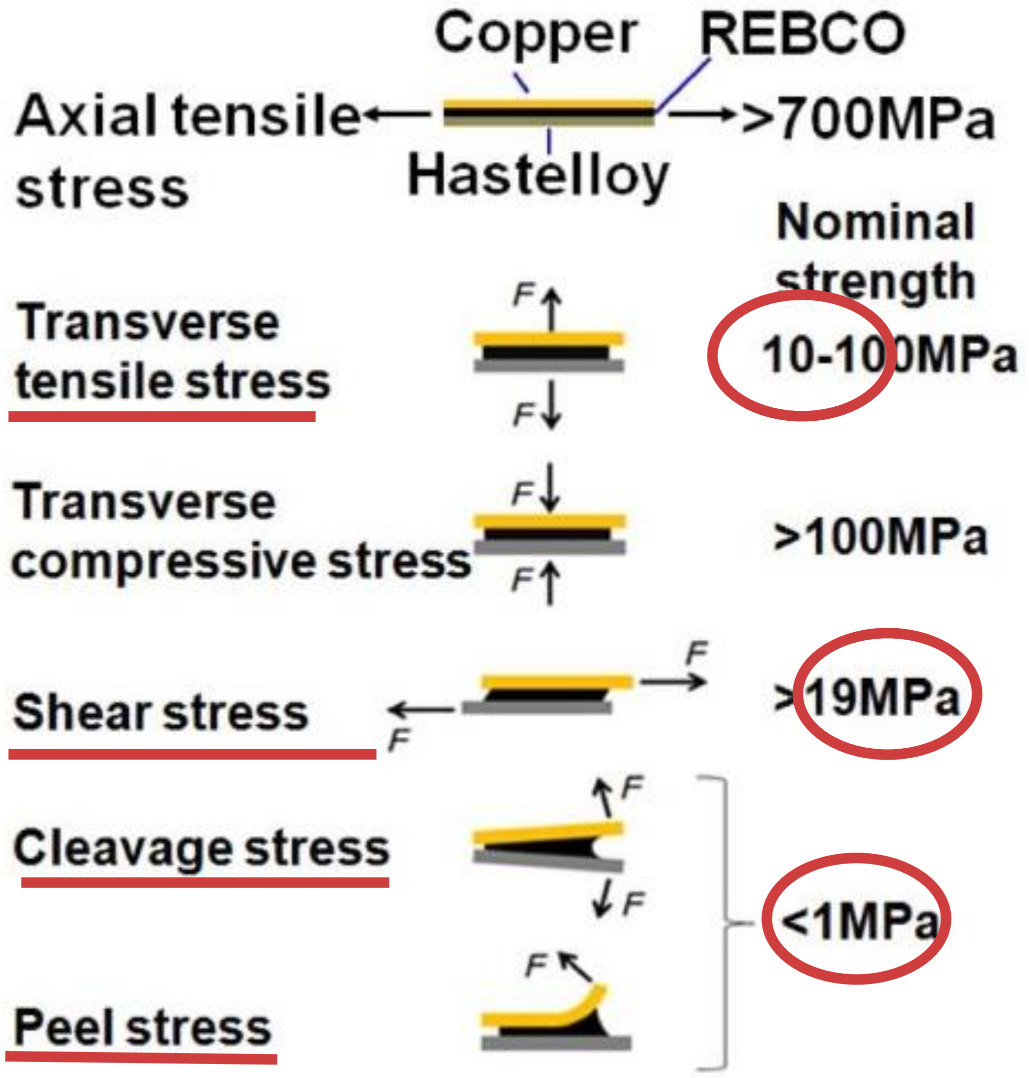




R. Babouche et al., in preparation

High in-field J_c is not sufficient for UHF magnets

A short note on the mechanical properties

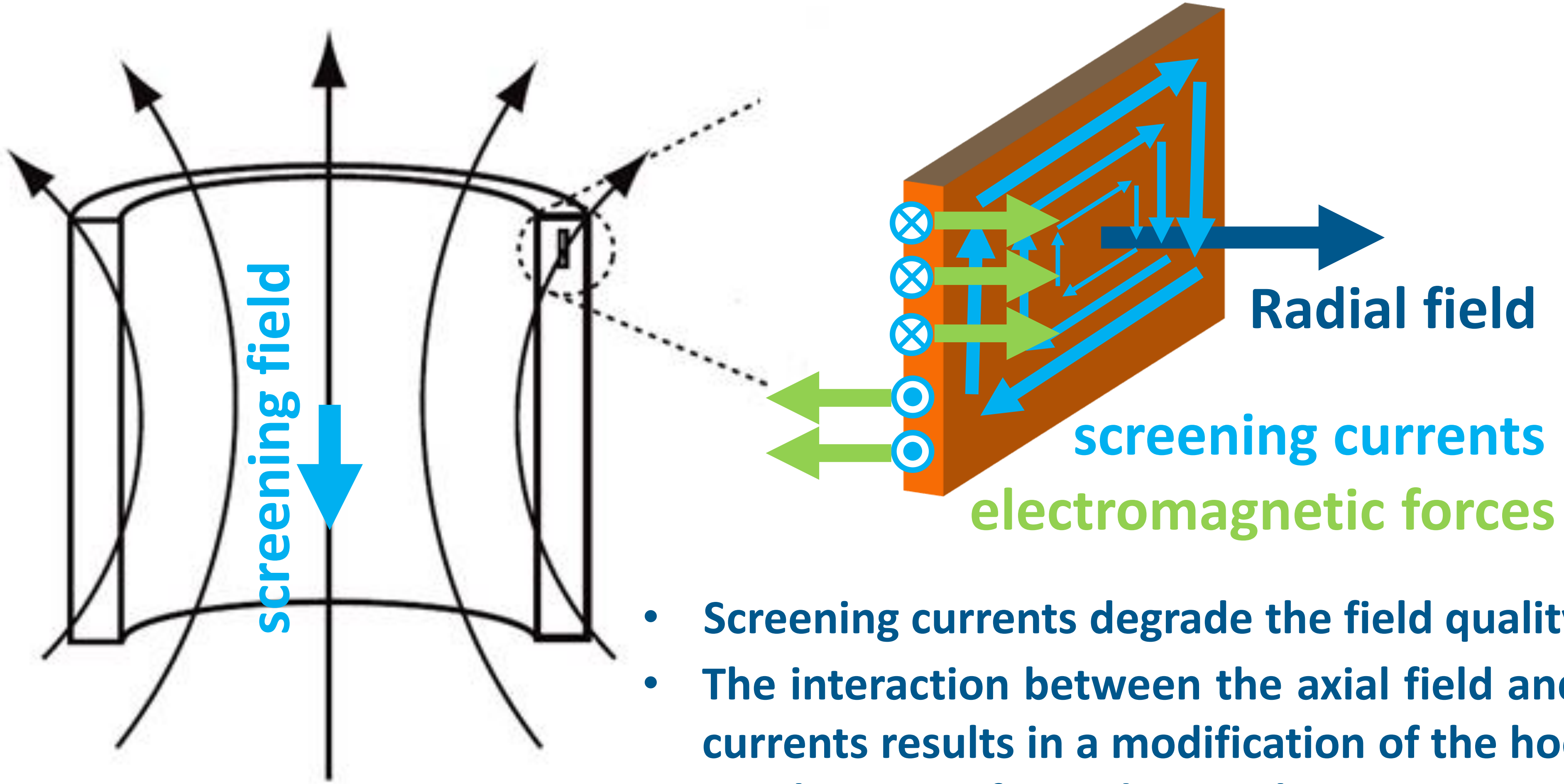


- **REBCO tapes are inherently prone to delamination**
- **Adhesion between layers seems to be process dependent**
- **A standardized process to determine the properties of the tapes is missing**

H. Maeda, and Y. Yanagisawa, IEEE Trans. Appl. Supercond., 24 (2014) 4602412
DOI: 10.1109/TASC.2013.2287707

High in-field J_c is not sufficient for UHF magnets

Screening Currents, Field Quality and Conductor Degradation

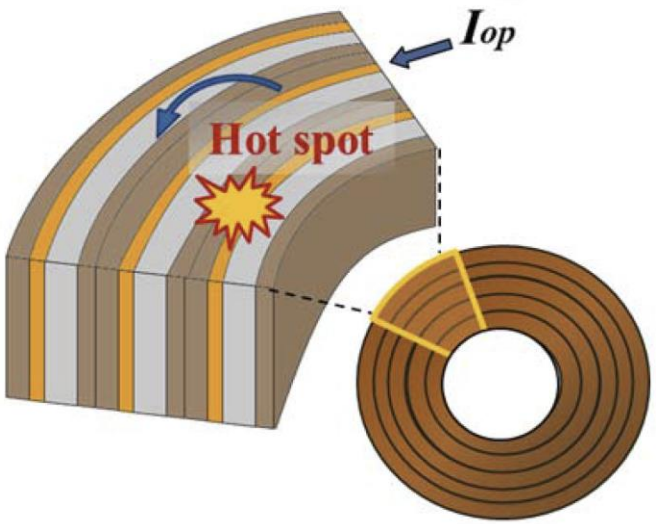


- Screening currents degrade the field quality
- The interaction between the axial field and the screening currents results in a modification of the hoop stress
- Local Lorentz force due to the screening currents can be source of delamination force

Some lessons learned from REBCO magnet R&D

The No-Insulation (NI) winding technique of REBCO coils

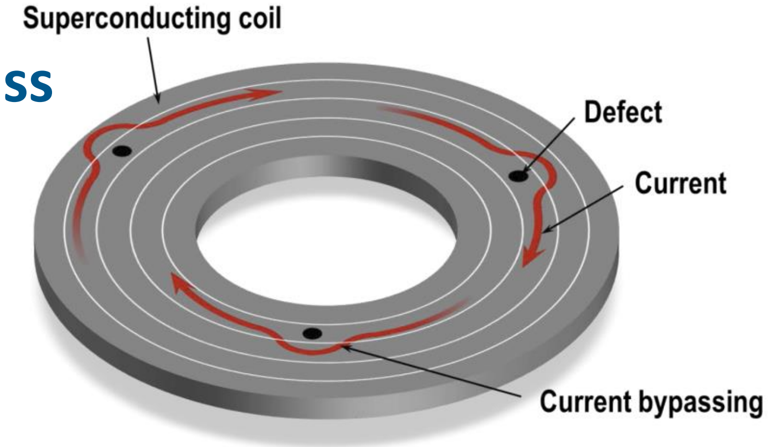
A new paradigm with advantages and drawbacks



Compact winding → very high current density in the winding

Self-protecting → turn-to-turn bypass of quench current
(in principle)

Defect-tolerant → turn-to-turn bypass of current in case of local I_c drop



S. Hahn et al., *IEEE Trans. Appl. Supercond.*, 21 (2011) 1592
DOI: 10.1109/TASC.2010.2093492

U. Bong et al., Supercond. Sci. Technol. 34 (2021) 085003
DOI: 10.1088/1361-6668/ac0759

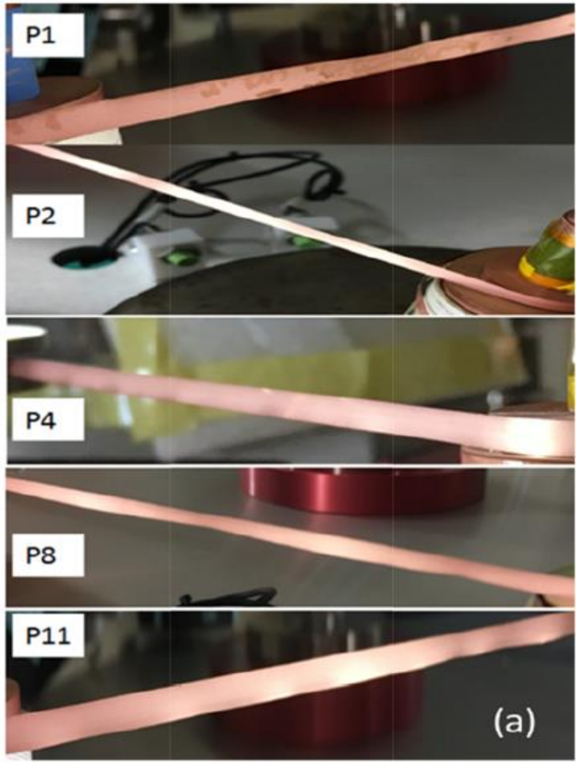
A major drawback comes from the charging delays, which can be mitigated by Partial/Metal/Smart Insulation

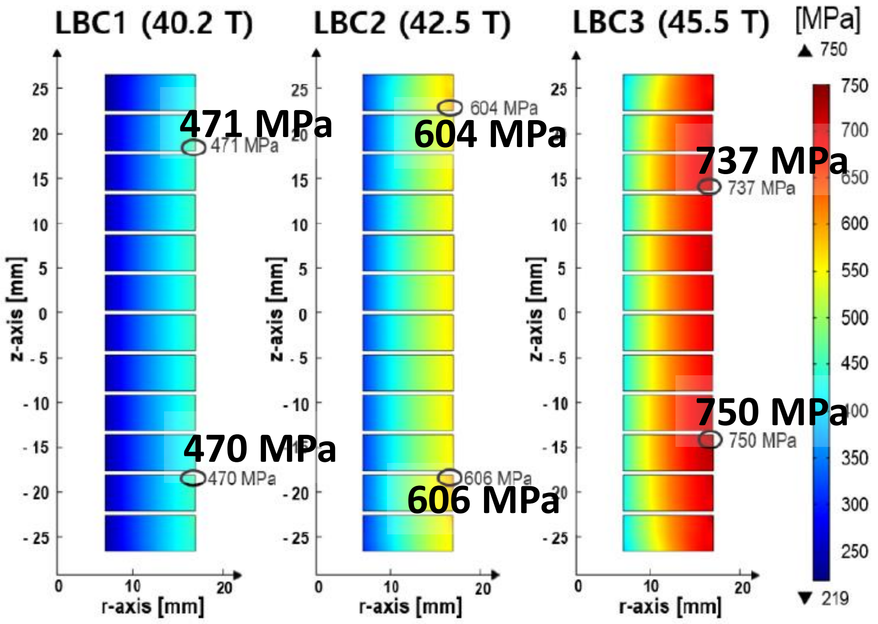
Other known drawbacks: unbalanced forces, induced overstresses

Lesson learned from REBCO magnet R&D

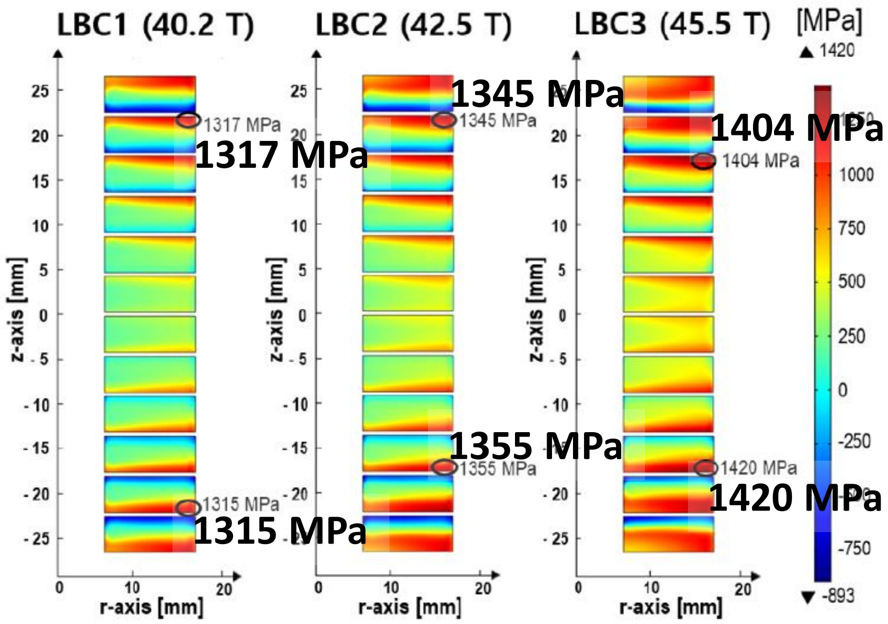
Post-mortem analysis of REBCO tapes from ultra-high field test coils at NATIONAL MAGLAB

Three non-insulated Little Big Coils (35 mm OD, 14 mm ID and 50 mm length) tested in the 37 mm diameter cryostat of the 31 T Bitter magnet at NHMFL





Calculated hoop stress distribution
without screening currents



Calculated hoop stress distribution
with screening currents

Conductor plastic deformation occurs at nominal JBR stress levels below the yield stress of Hastelloy, ~1 GPa @ 4 K

X. Hu *et al.*, SuST 33 (2020) 095012
DOI: 10.1088/1361-6668/aba79d

Lesson learned from REBCO magnet R&D

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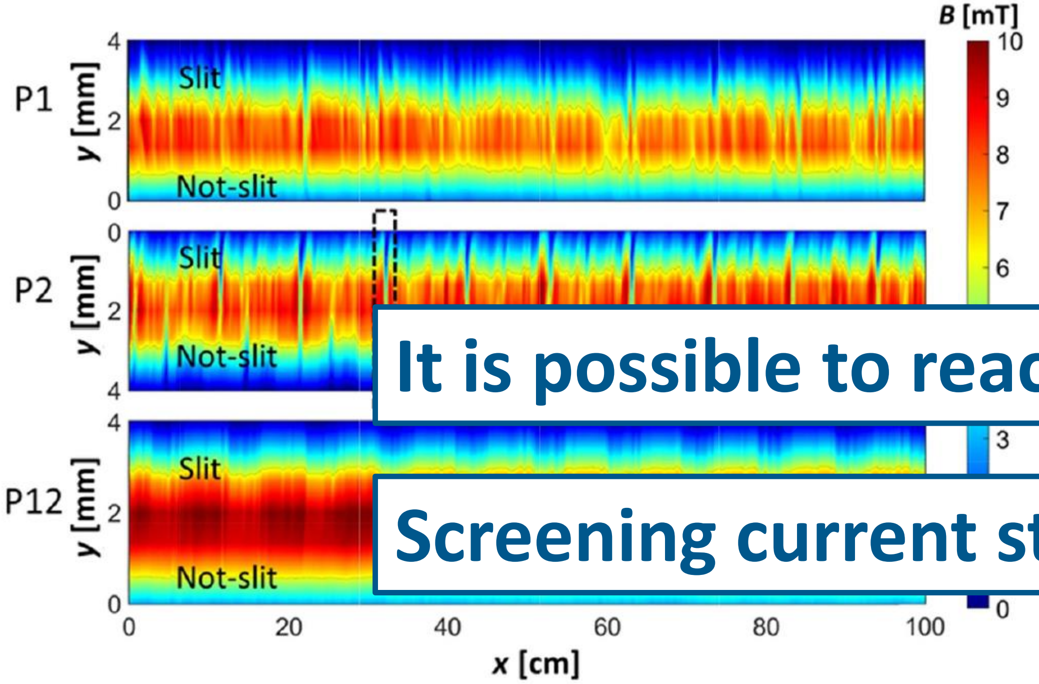


Magnetization maps of tapes extracted from LBC2 with evident signs of degradation

- I_c degradation due to plastic rippling occurs at coils edges
- All degraded edges occur at slit edges containing pre-existing micro-cracks
- … o observed … especially when the transport current is flowing along the slit edge

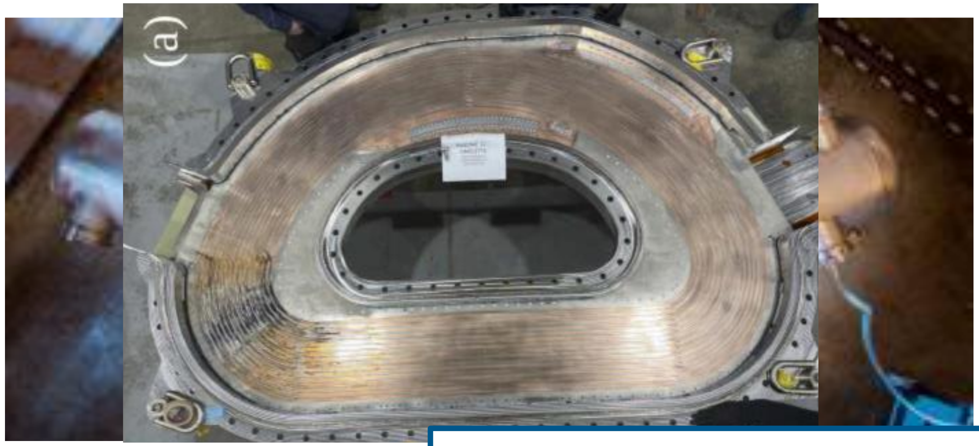
It is possible to reach and exceed 40 T with REBCO

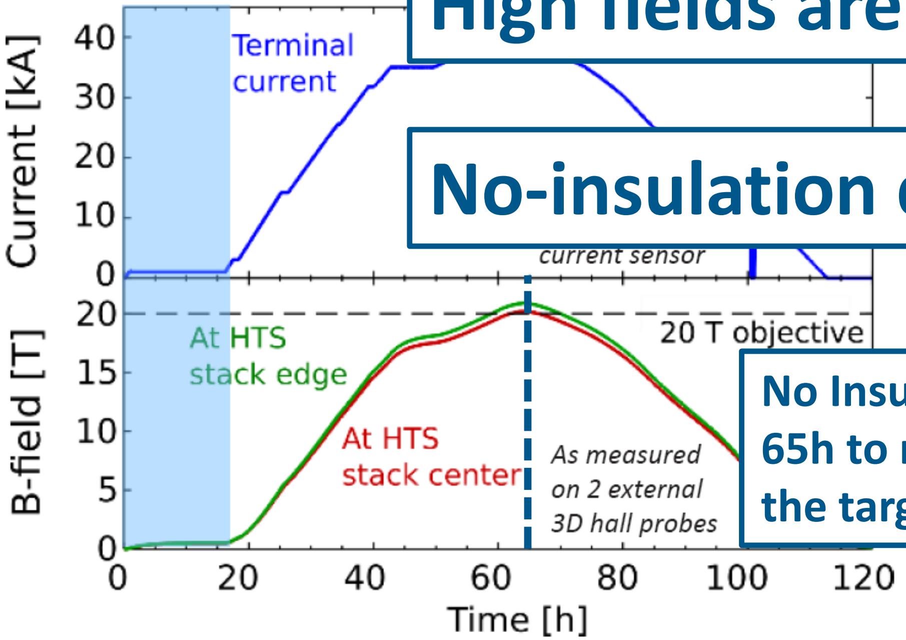
Screening current stresses cannot be neglected

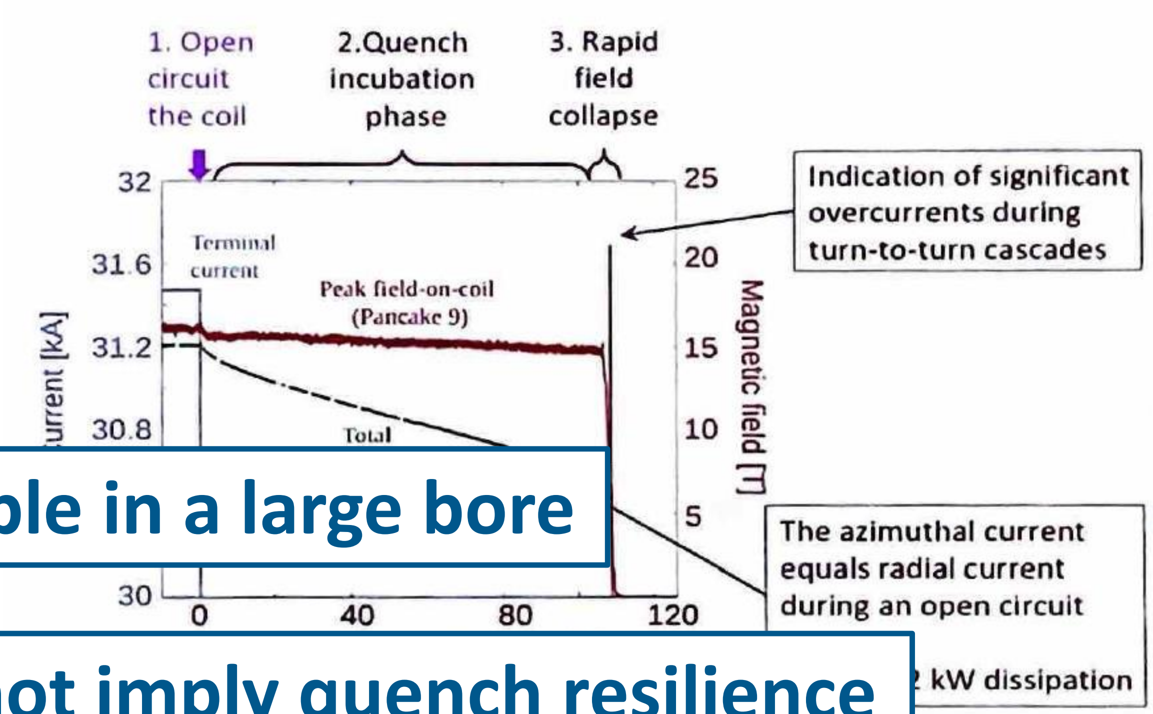
X. Hu *et al.*, SuST 33 (2020) 095012
DOI: 10.1088/1361-6668/aba79d

Lesson learned from REBCO magnet R&D

The quench test of the 20 T/ 20 K no-insulation SPARC Toroidal Field Model Coil







High fields are possible in a large bore

No-insulation does not imply quench resilience

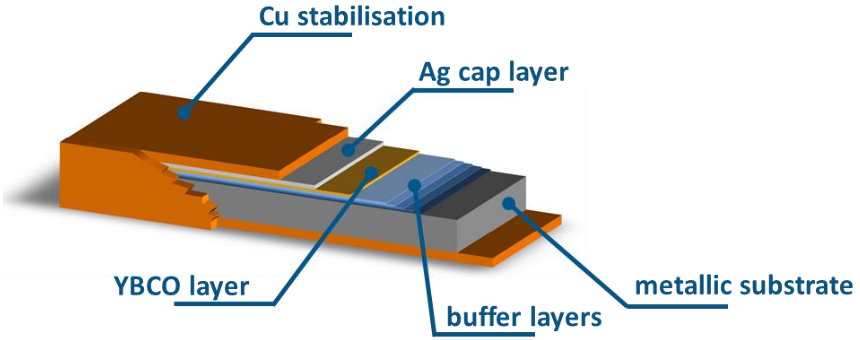
No Insulation: 65h to reach the target field

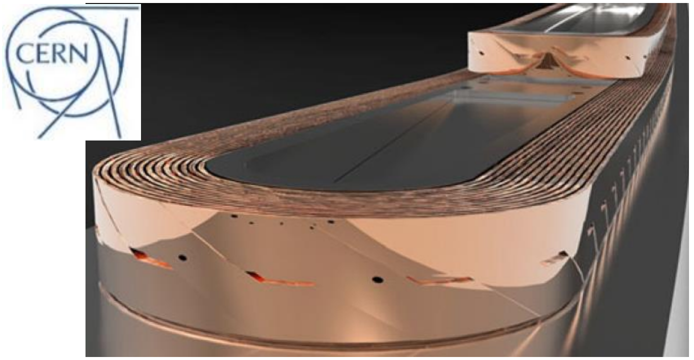
Quench test at 31.3 kA in open-circuit conditions

- Coil did not survive
- Localized energy deposition at levels high enough to damage the coil

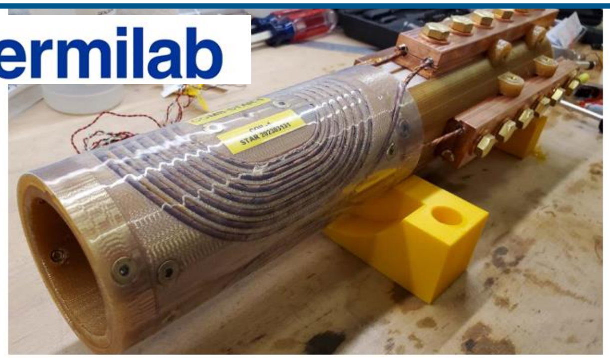
Z. Hartwig et al., IEEE TASC 34 (2024) 0600316
DOI: 10.1109/TASC.2023.3332613

From REBCO tapes to REBCO-based dipole magnets





Aligned block with Roebel cables



Roebel cables

W. Goldacker et al., SUST 27 (2
DOI: 10.1088/0953-2048/27/9/

Promising R&D ongoing, not yet consolidated solutions

CORC and STAR cables

D. Van der Laan et al., SUST 34 (2021) 10LT01
DOI: 10.1088/1361-6668/ac1aae

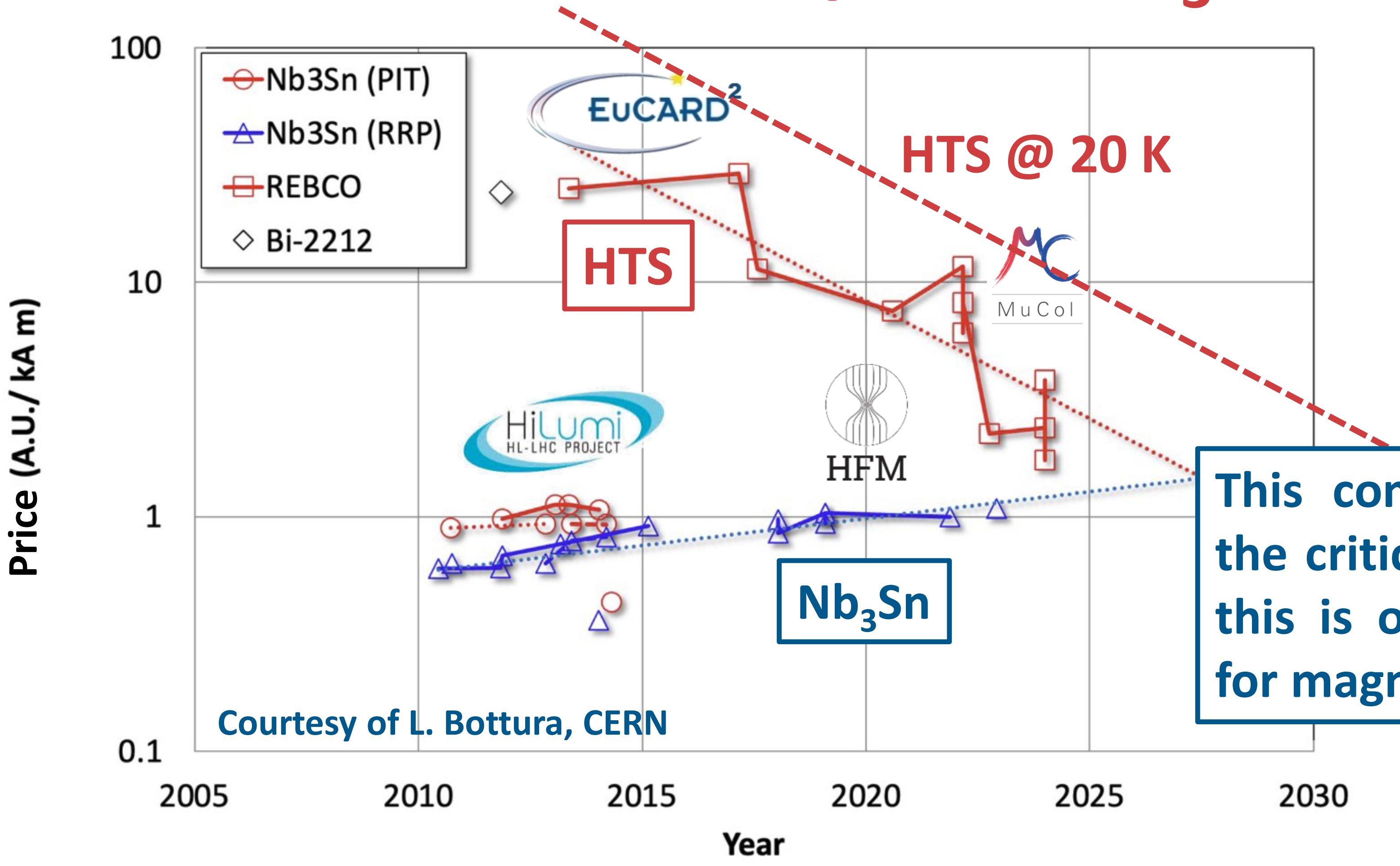
E. Galstyan et al., SUST 36 (2023) 055007
DOI: 10.1088/1361-6668/acc4ed

Tape stacks

Z. Hartwig et al., SUST 33 (2020) 11LT01
DOI: 10.1088/1361-6668/abb8c0

COMB with CORC cables

Some considerations on price: Nb_3Sn vs REBCO



This comparison is based only on the critical current performance but this is only one of the parameters for magnet applications

Price (arbitrary units) per unit length and current for Nb_3Sn and HTS (mainly REBCO), based on CERN orders and requests

The normalization is done for B = 12 T (// c-axis for REBCO) and T = 4.2 K

Conclusions

- LTS currently dominate the superconductor market, driven by MRI, NMR spectroscopy, and large-scale scientific projects. Nb_3Sn continues to lead in high-field applications.
- Efforts to achieve compact accelerator dipoles with B > 14 T for the Future Circular Collider are pushing Nb_3Sn to its ultimate performance.
- Internal oxidation has emerged as a practical solution to enhance J_c, with ongoing development to implement this technology in industrial wires. But the improved transport properties must be accompanied by mechanical robustness.
- The FCC would require a significant procurement of advanced Nb_3Sn wire (approximately 10’000 tons) and is the primary driver of this development. Who else could benefit from this advancement?
- HTS has the potential for higher operating fields and/or higher operating temperatures.
- REBCO is becoming available at affordable prices from multiple sources, driven by private fusion programs.
- There is still much to learn about using REBCO in magnets. Challenges include tape geometry, intrinsic anisotropy, layered structure, and large filament size.
- No major roadblocks have emerged so far, but there is still a long way to close the technology gap with LTS magnets. If we maintain momentum, breakthroughs will come.

Thank you for the attention !

Carmine SENATORE

carmine.senatore@unige.ch

http://supra.unige.ch

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