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Swiss National
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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

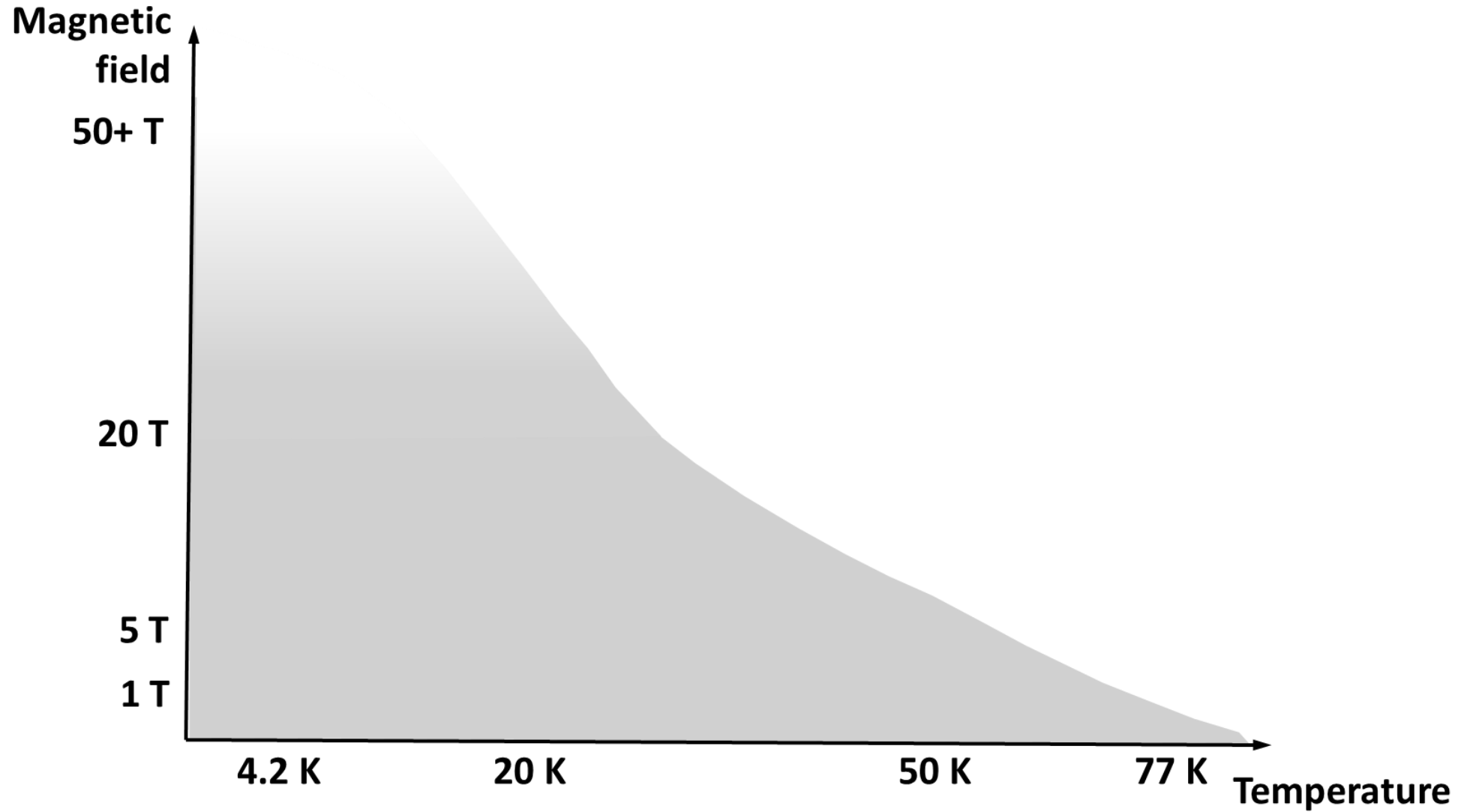
Outline

- **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 Nb₃Sn 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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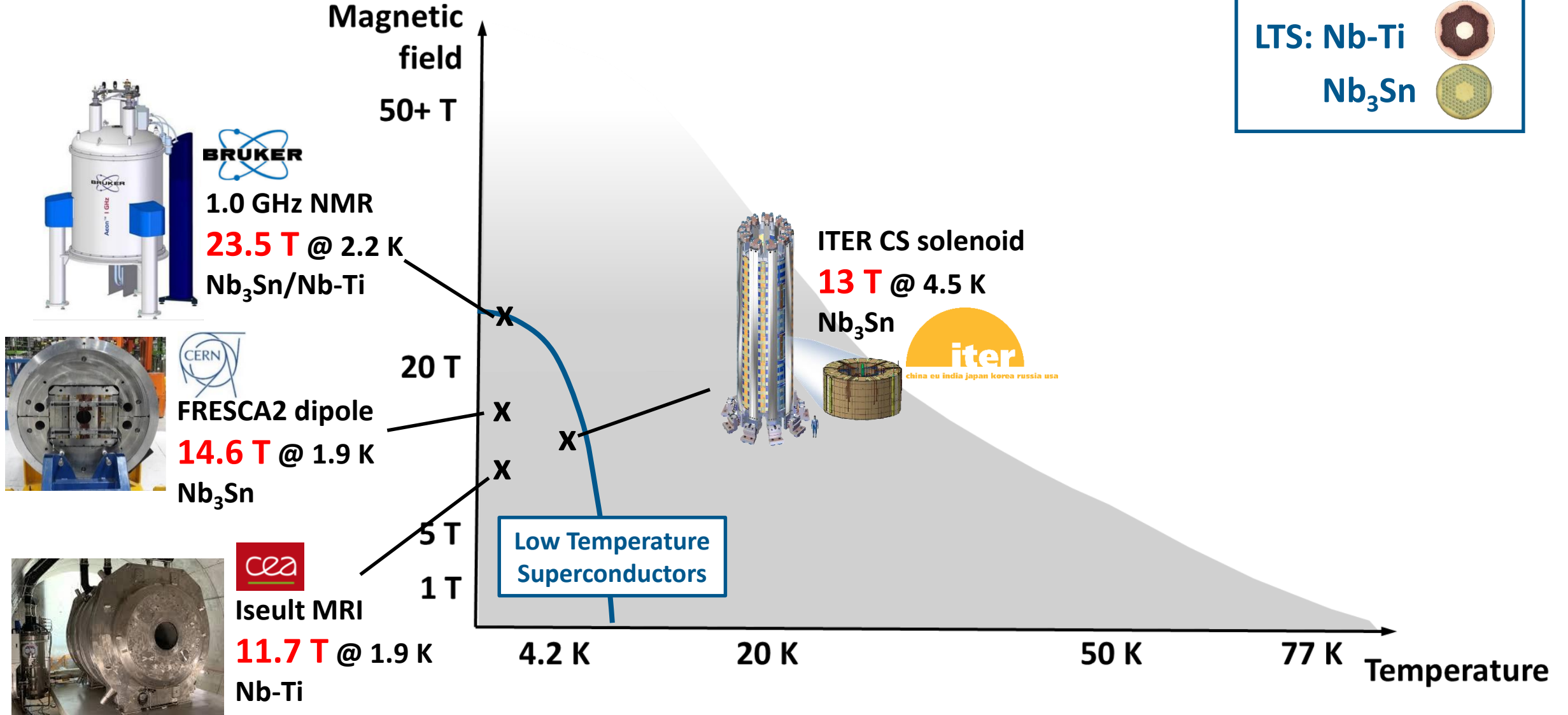
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Field-temperature phase diagram of technical superconductors



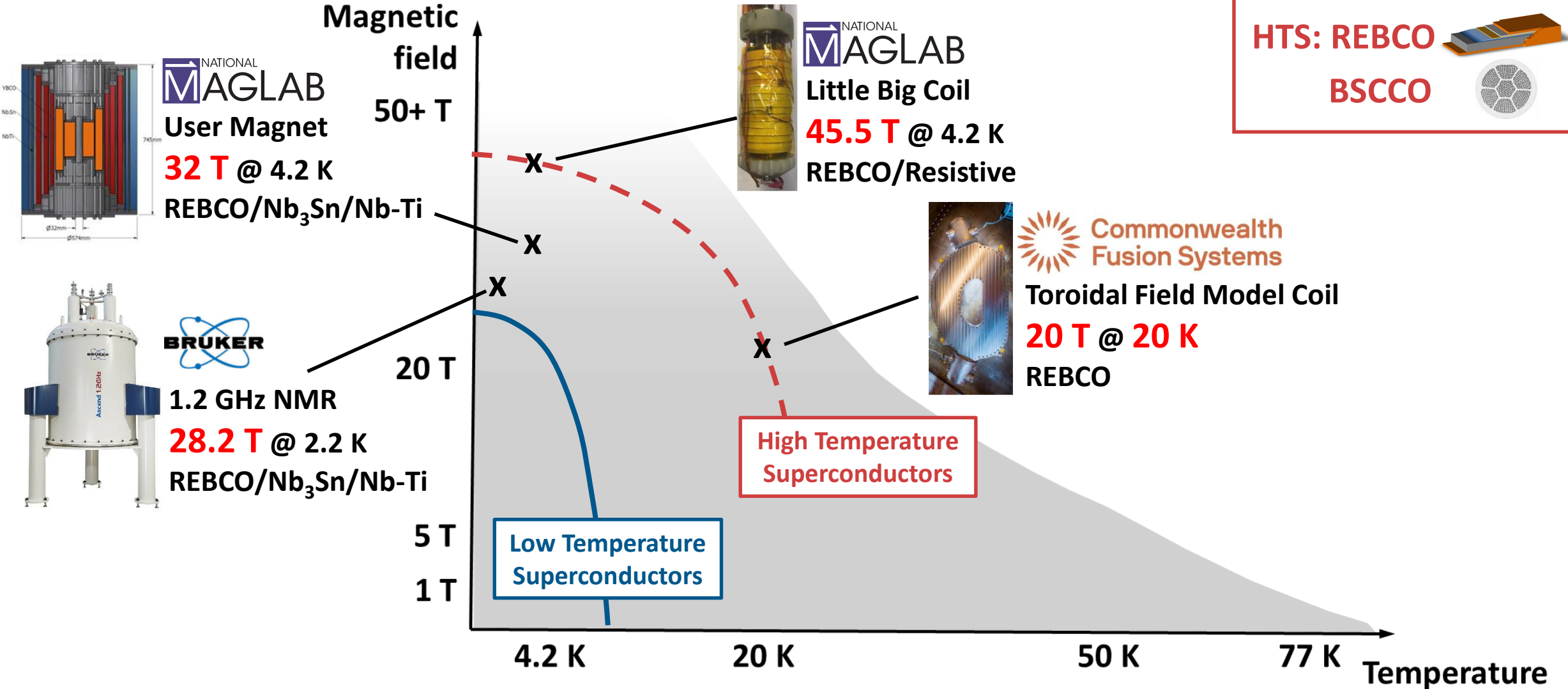
High field applications of Low Temperature Superconductors

Field-temperature phase diagram of technical superconductors



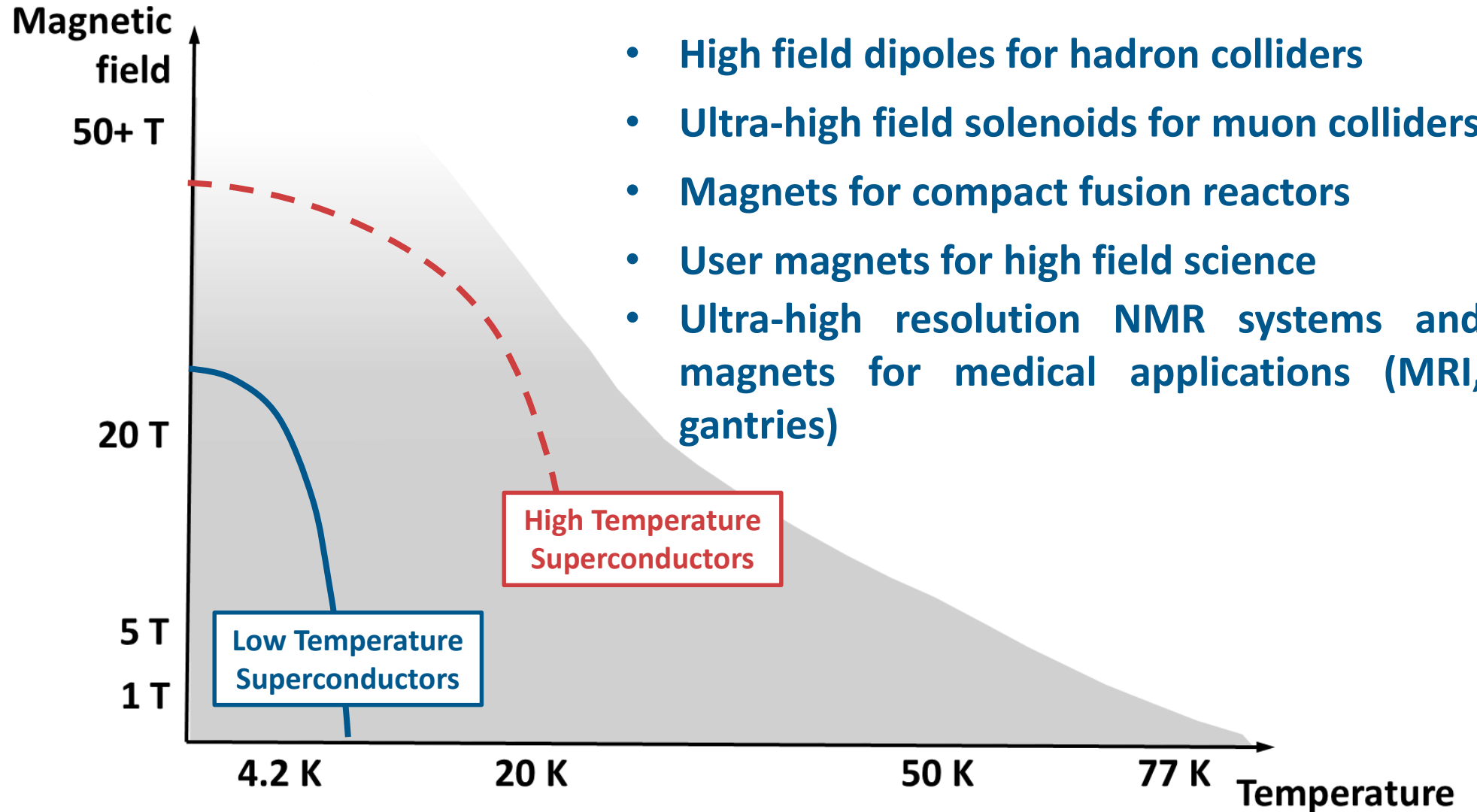
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The application's pull towards higher magnetic fields

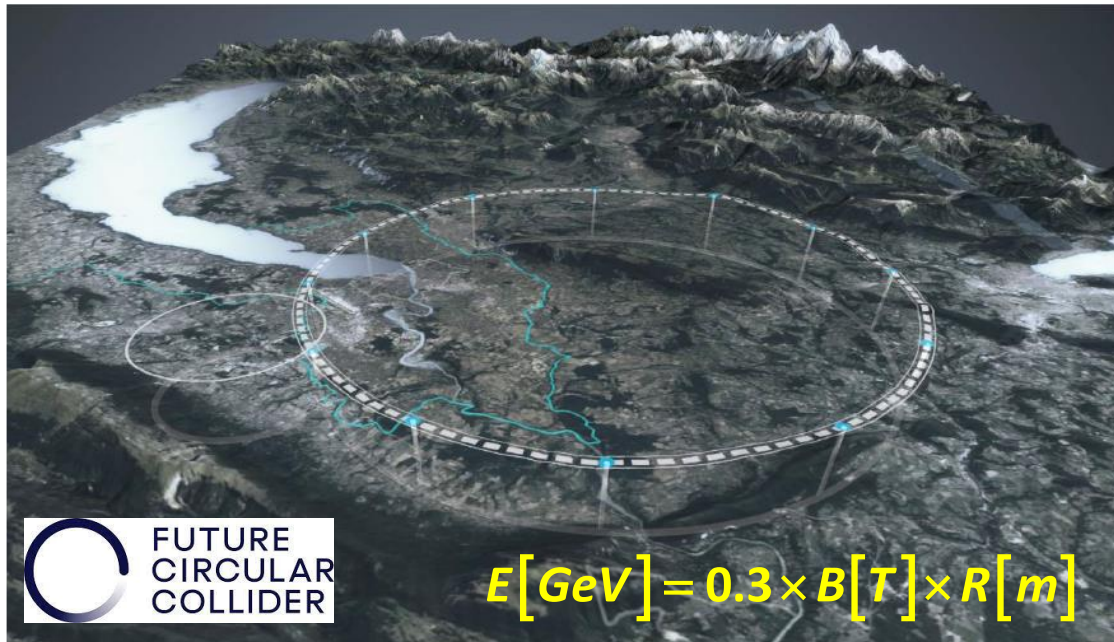
Field-temperature phase diagram of technical superconductors



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 **Nb₃Sn** would give **85-90 TeV**
- **20 T-dipoles** based on **HTS** would give **~120 TeV**

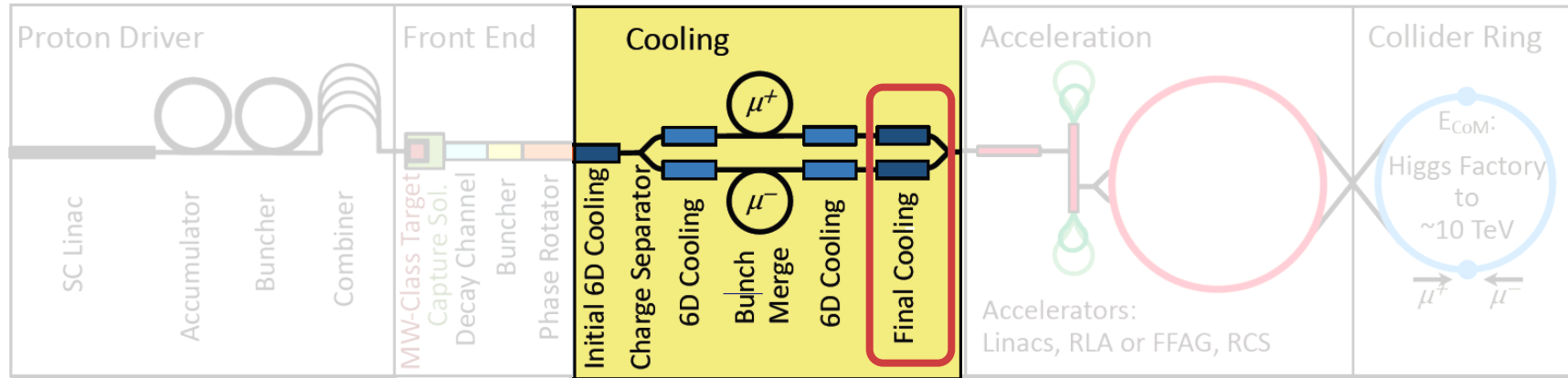
parameter	FCC-hh
collision energy cms [TeV]	85 - 120
dipole field [T]	14 (Nb₃Sn) – 20 (HTS)
circumference [km]	90.7
arc length [km]	76.9
beam current [A]	0.5
bunch intensity [10 ¹¹]	1
bunch spacing [ns]	25
synchr. rad. power / ring [kW]	1020 - 4250
SR power / length [W/m/ap.]	13 - 54
long. emit. damping 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](#)

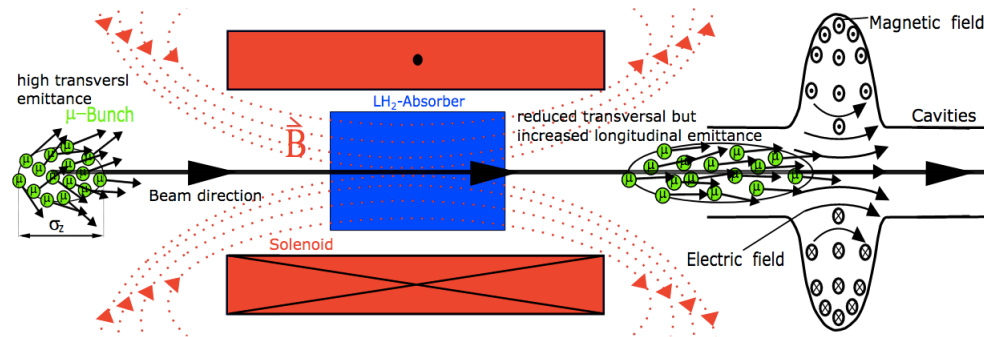
The call for High Field Magnets from High Energy Physics

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 $2.2 \mu\text{s}$! 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



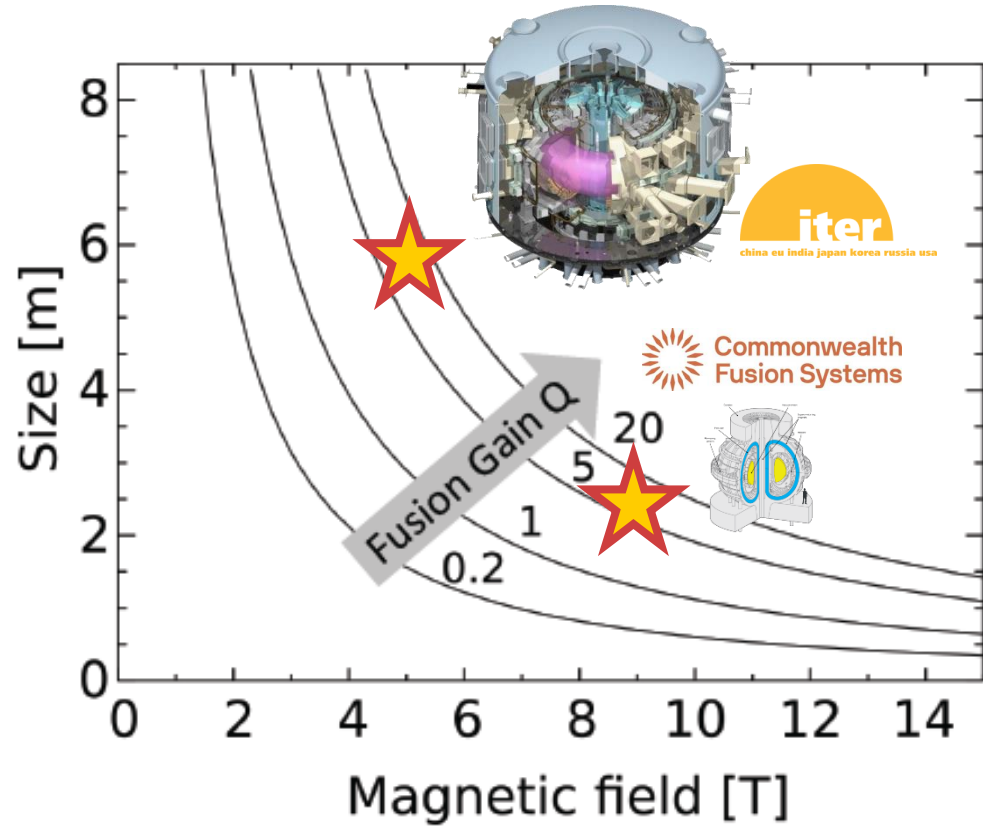
Muons are cooled through interaction with light matter and subsequent acceleration by RF cavities. Solenoids of 40 T to 60 T with a bore of 50 mm, only achievable with HTS, are required to meet the specification on the transverse emittance

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



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



ABOUT Members



Companies adopting magnetic fusion confinement systems

<https://www.fusionindustryassociation.org/>

Funding for Fusion Companies



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€

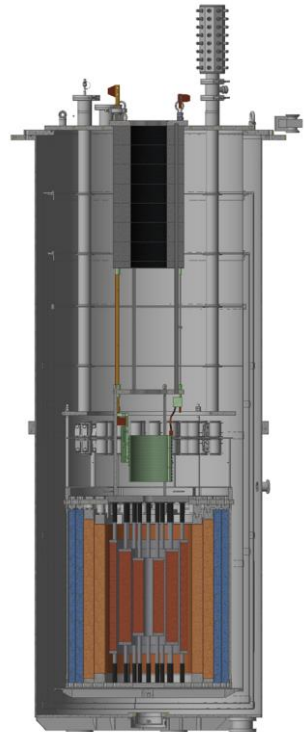


ENN's Spherical Tokamak device EXL-50

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



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Science
Foundation

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



anr[®]
agence nationale
de la recherche

F. Debray, [HiTAT Workshop 2023](#)



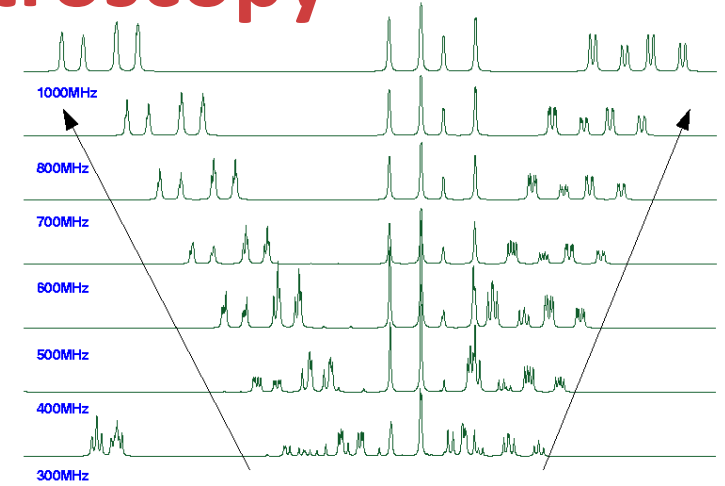
- A common strategy towards 40 T**
- REBCO high field insert
 - commercial LTS outsert 12-15 T

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

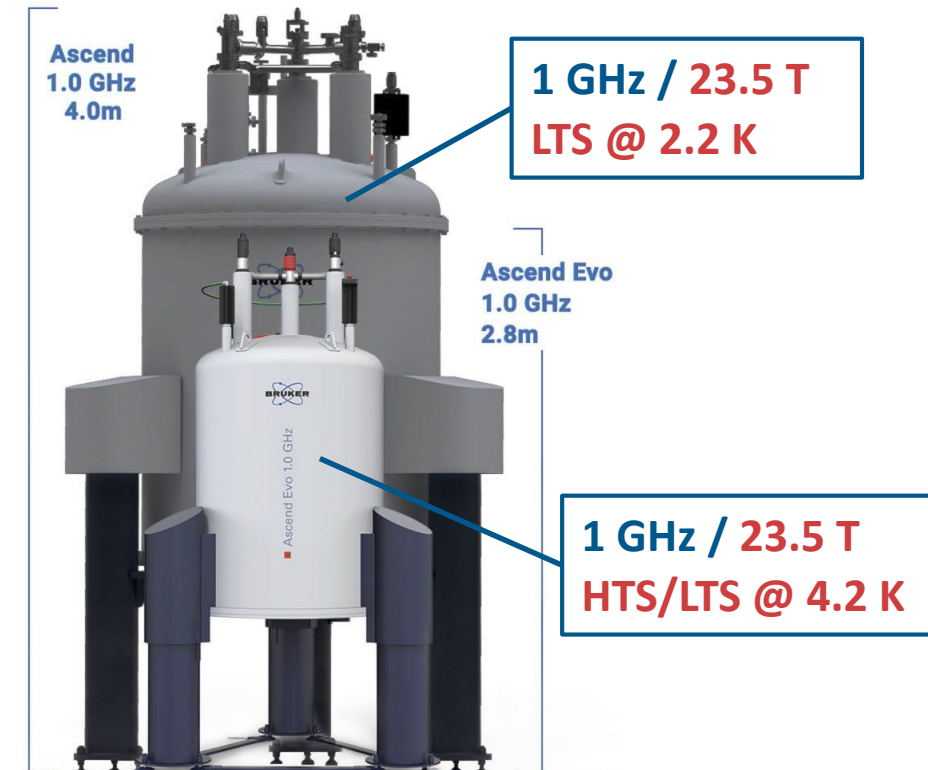


REBCO is the enabling technology for NMR magnets up to **28.2 T** (HTS/LTS hybrid, **2.2 K**)
proton resonance frequency of 1.2 GHz

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](#)

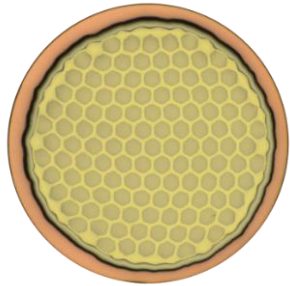


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Industrial fabrication of multifilamentary Nb₃Sn wires

Three technologies developed at industrial scale



Bronze Process

Sn source: Cu-Sn alloy

Low Critical Current Density (J_c)

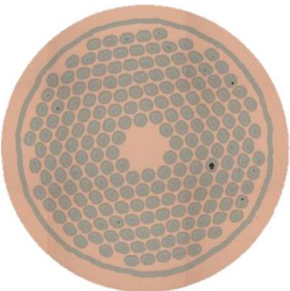
Limited by the solubility of Sn in Cu



Internal Sn Diffusion Process

Sn source: metallic Sn

High Critical Current Density (J_c)



Powder-In-Tube (PIT) method

Sn source: NbSn₂ and Sn powders

Presently produced by



FURUKAWA
ELECTRIC



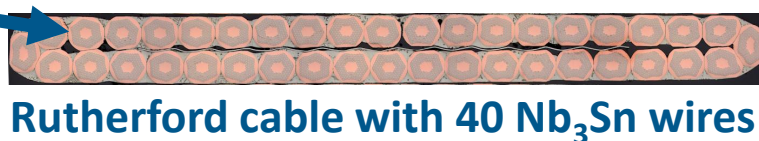
LUVATA



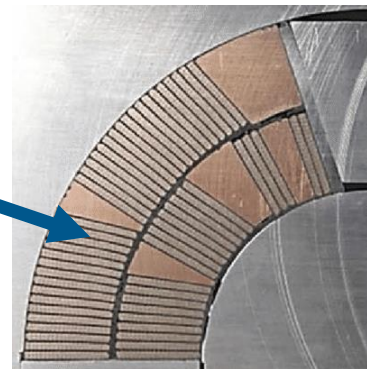
Used for NMR spectrometers, ITER magnets, HL-LHC magnets, laboratory magnets

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**



Rutherford cable with 40 Nb_3Sn wires

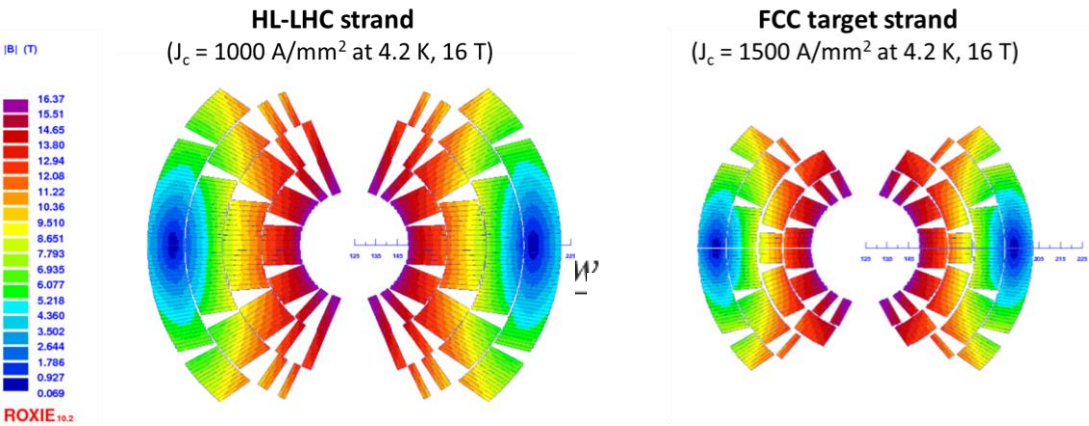


Section of a Nb_3Sn dipole magnet



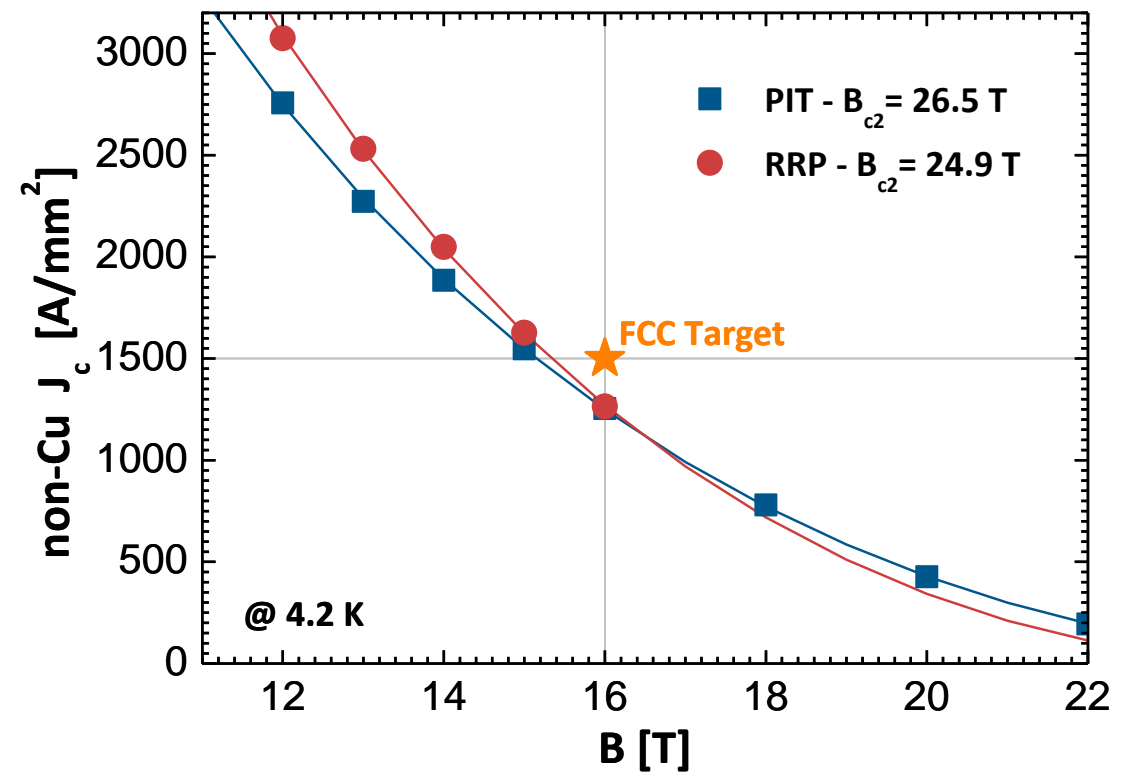
<https://home.cern/news/news/accelerators/hilumi-news-72-m-long-niobium-tin-quadrupole-magnet-manufactured-cern>

Towards the ultimate performance of Nb₃Sn for the FCC-hh Dipoles at B = 16 T based on Nb₃Sn with a non-Cu J_c(4.2K, 16 T) = 1'500 A/mm²



B [T]	16	16
J _{op} [A/mm ²]	300	600
w [mm]	76	38
A _{coil} [mm ²]	20'000	7'000

2x →



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

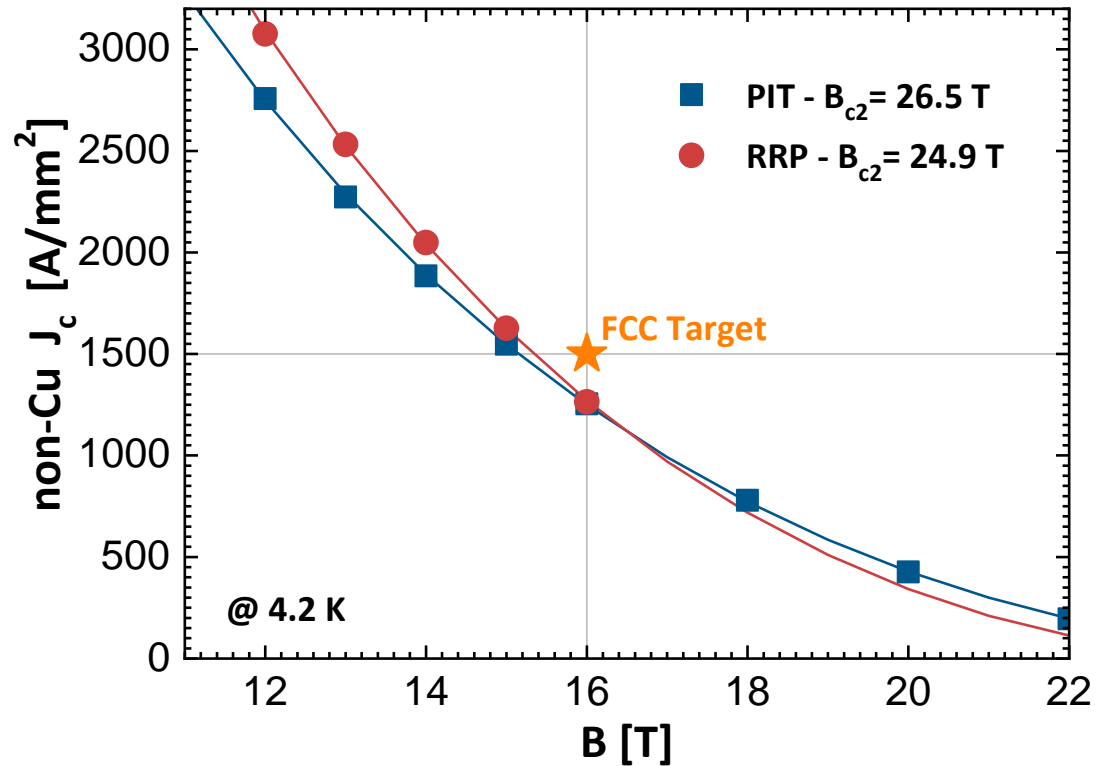
$A_{coil} \propto SC\ mass \propto$

J. Parrell et al., AIP Conf. Proc. 711 (2004) 369
T. Boutboul et al., IEEE TASC 19 (2009) 2564

DOI: [10.1063/1.1774590](https://doi.org/10.1063/1.1774590)
DOI: [10.1109/TASC.2009.2019017](https://doi.org/10.1109/TASC.2009.2019017)

Strategies to increase the critical current density of Nb₃Sn

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



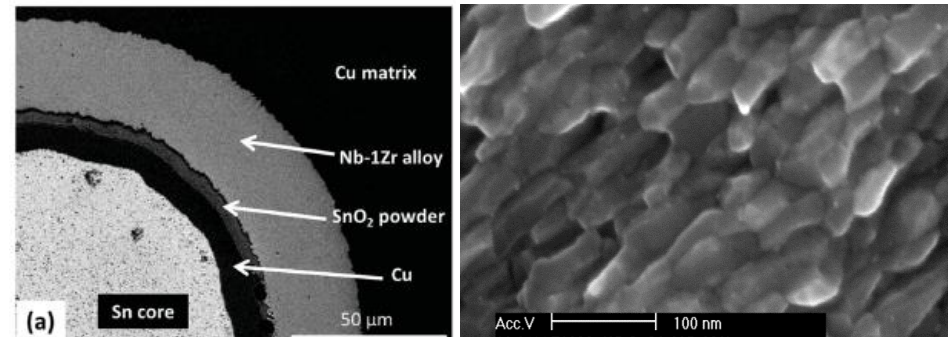
Idea from Benz (1968) of an **Internal Oxidation** to form fine precipitates in Nb to impede the Nb₃Sn grain growth Benz, Trans. Metall. Soc. AIME, 242 (1968) 1067-1070

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-ZrO₂ (HfO₂)



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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](https://doi.org/10.1063/1.4866865)

X. Xu et al., Adv. Mat. 27 (2015) 1346

DOI: [10.1002/adma.201404335](https://doi.org/10.1002/adma.201404335)

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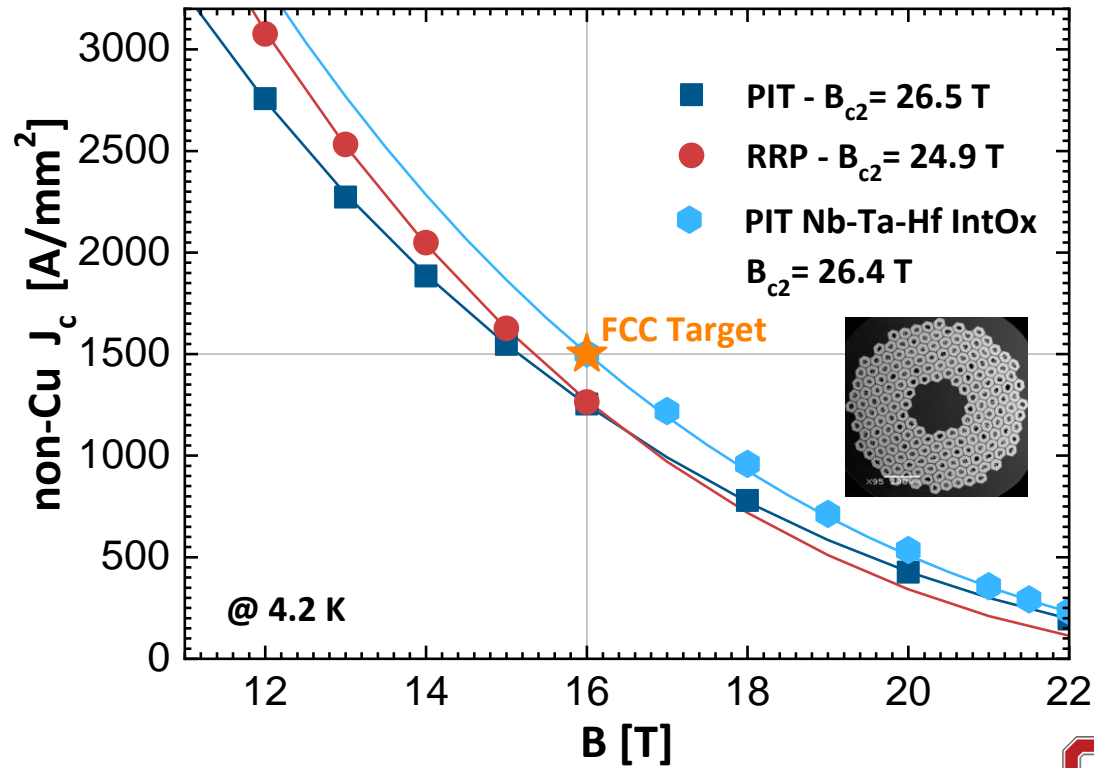
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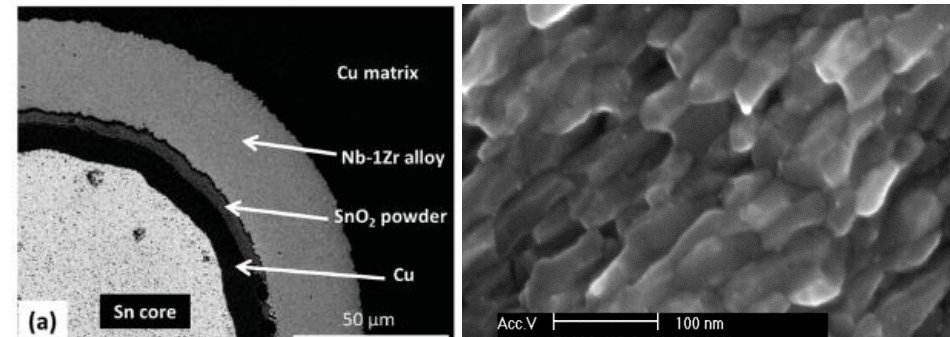
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DOI: [10.1002/adma.201404335](https://doi.org/10.1002/adma.201404335)

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](https://doi.org/10.1088/1361-6668/acb17a)

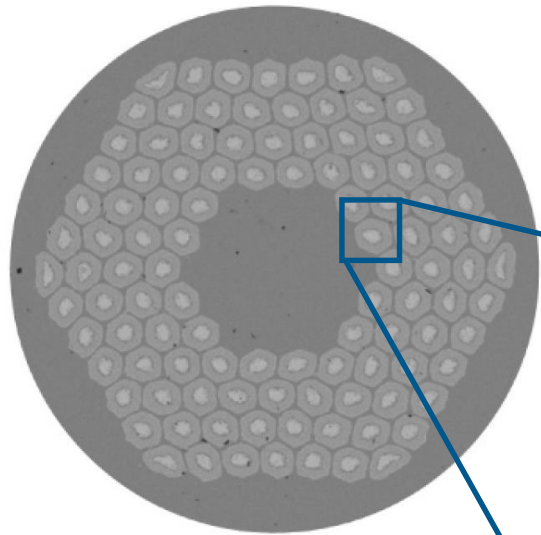
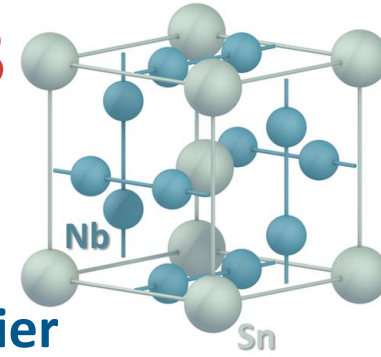


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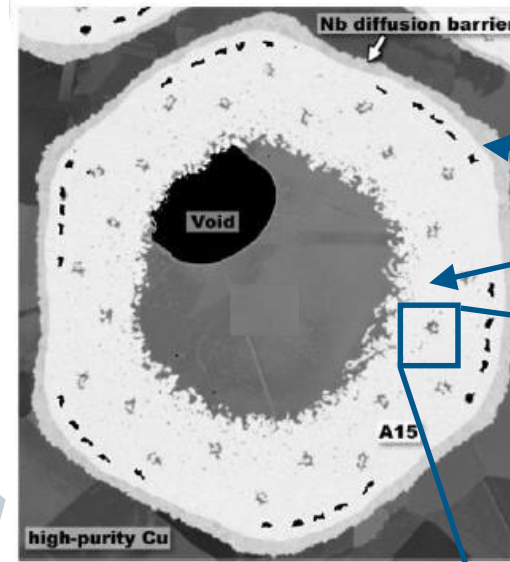
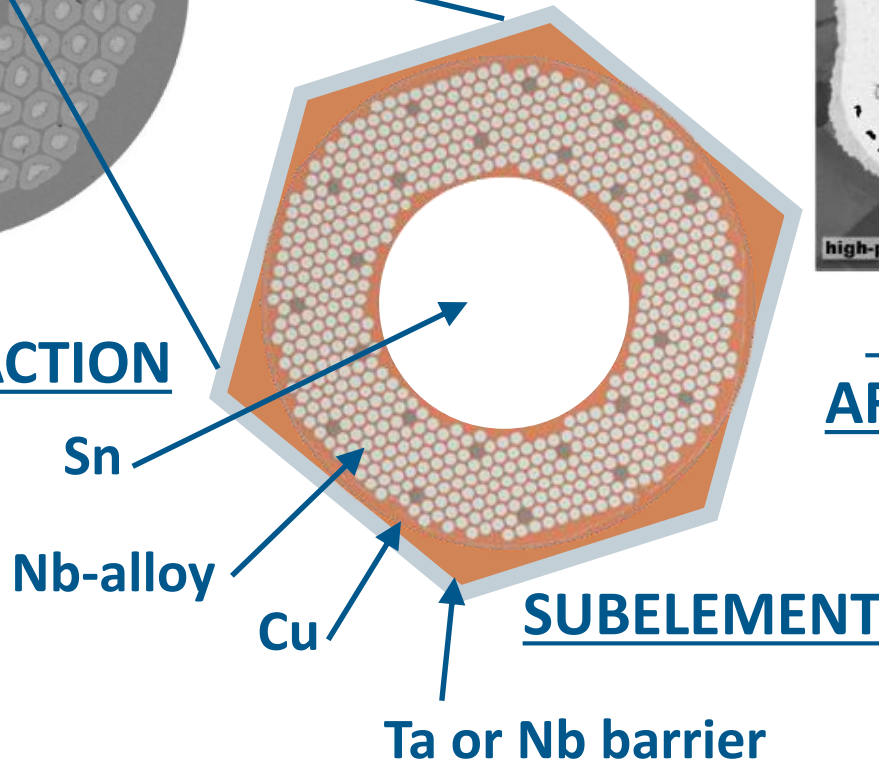
Hyper Tech

Fermilab

The structure of high- J_c internal Sn Nb_3Sn wires

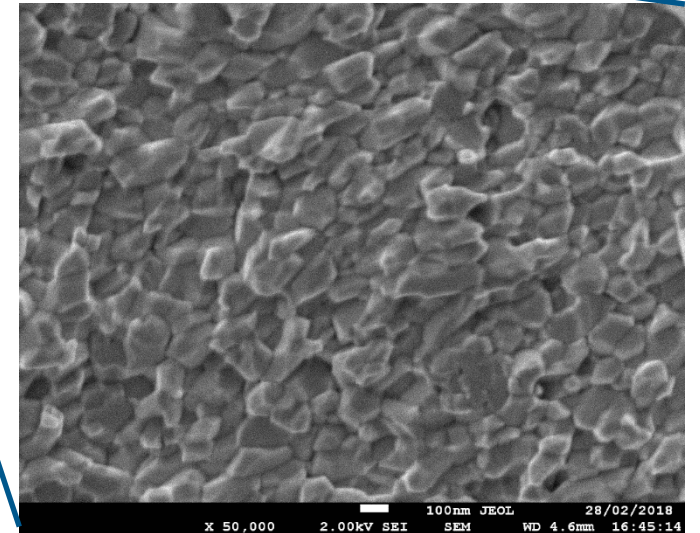


WIRE
BEFORE REACTION



SUBELEMENT
AFTER REACTION

Ta or Nb barrier
Nb₃Sn layer

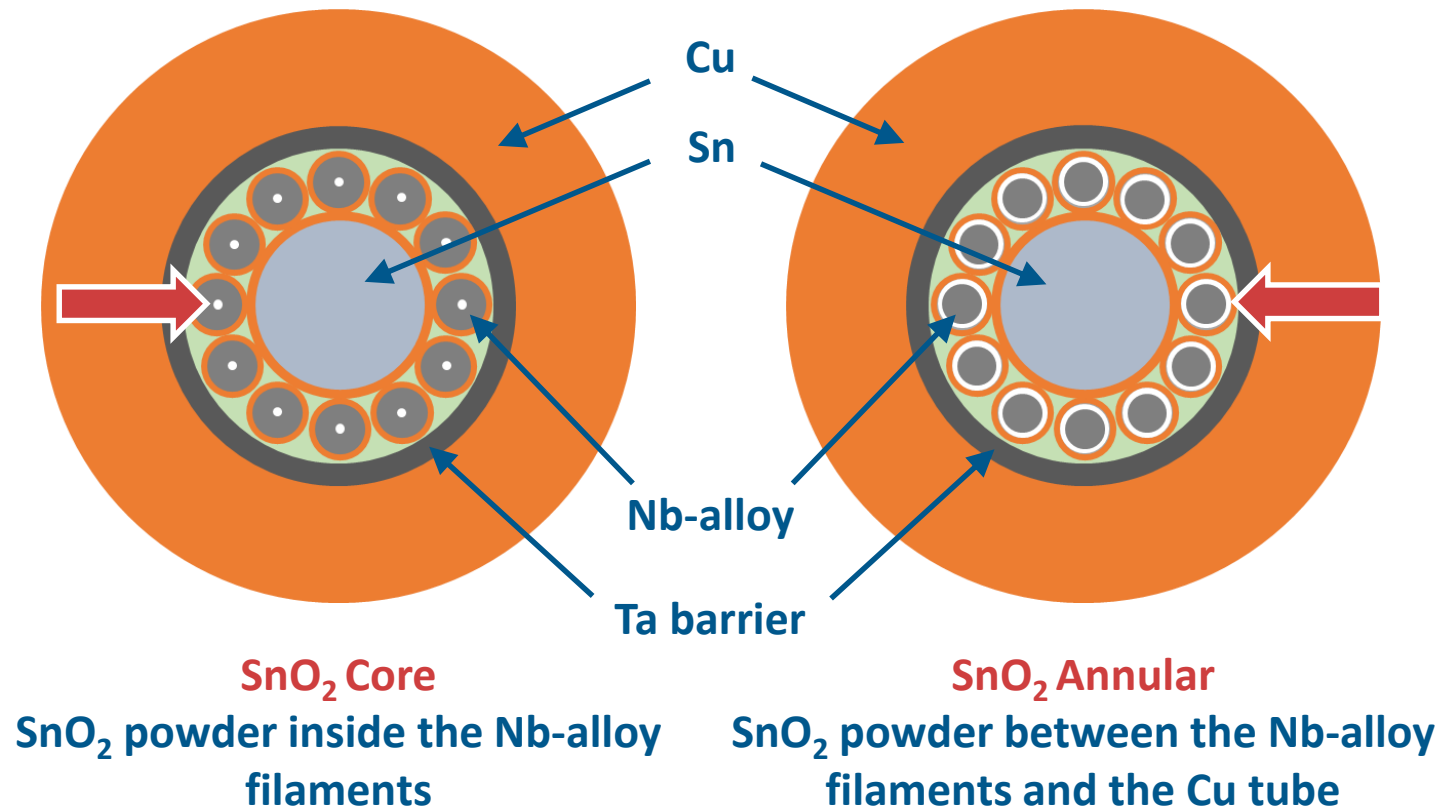


Nb₃Sn microstructure
Critical current density $\propto 1/(\text{grain size})$

Internal Oxidation of test-bed Internal Sn subelements

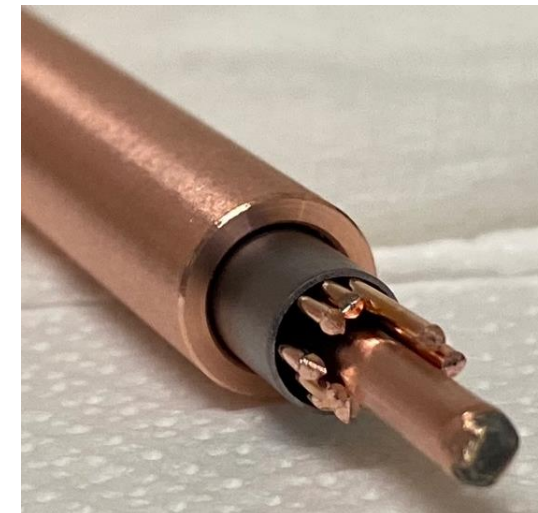
12-filament wires with an internal Sn source

Two possible configurations for the oxygen source



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



Internal Oxidation of test-bed Internal Sn subelements

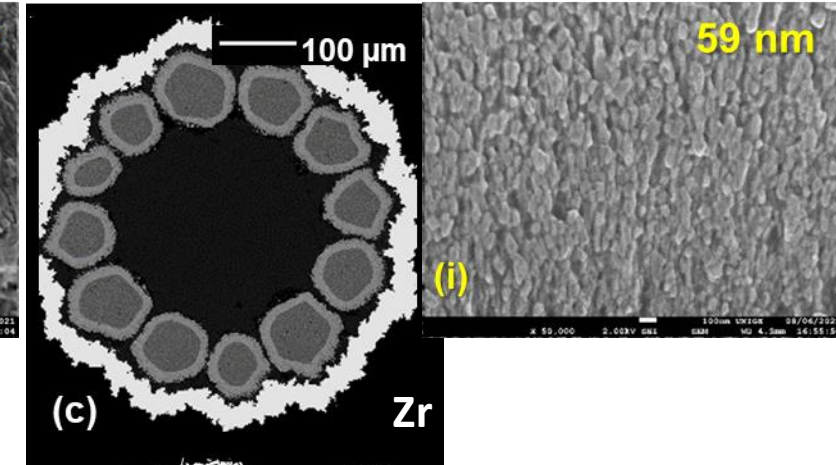
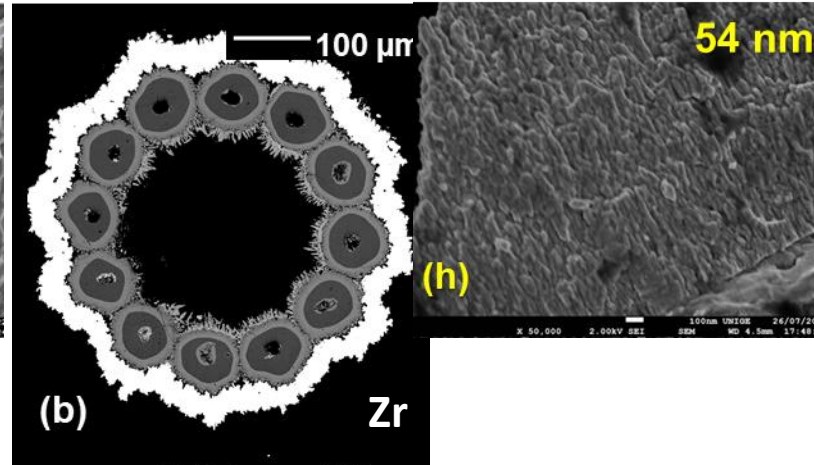
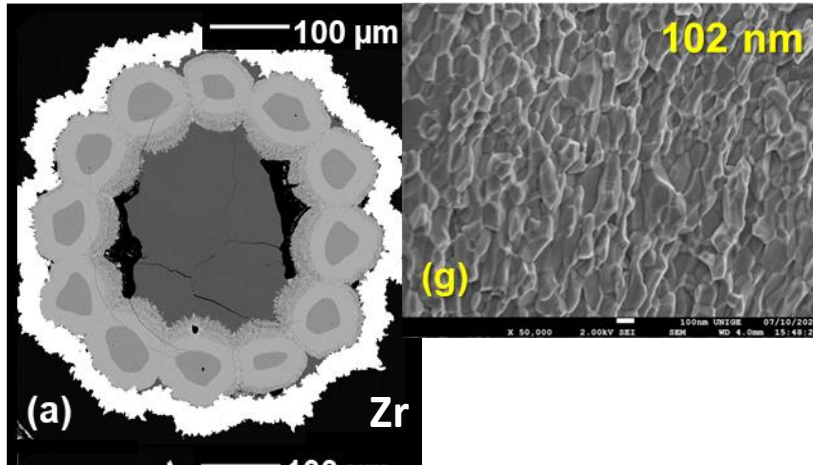
12-filament wires with an internal Sn source

w/o oxygen source

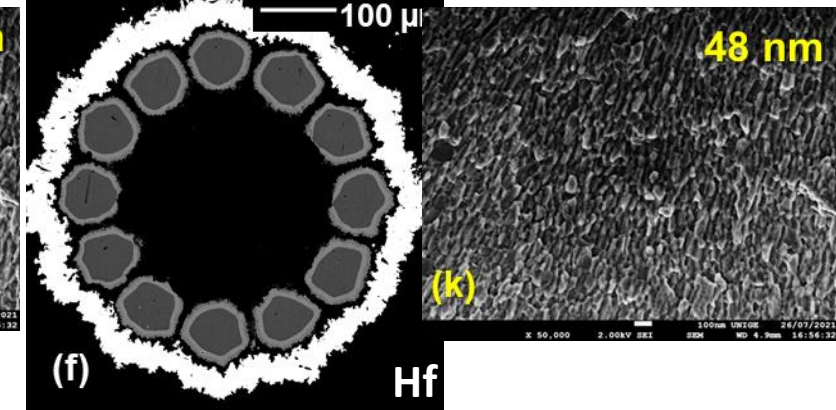
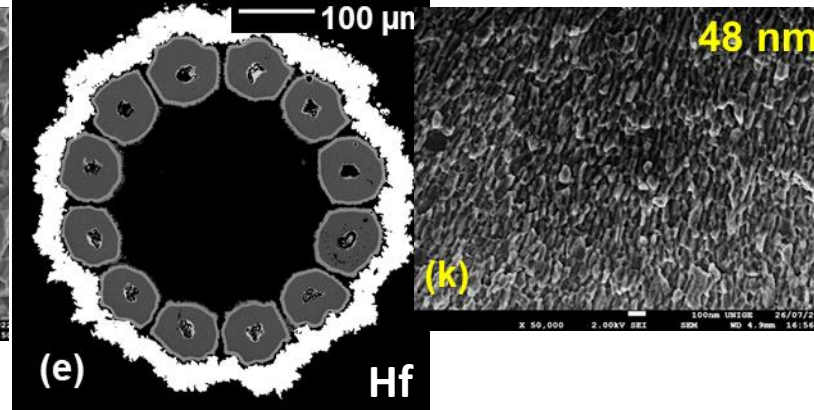
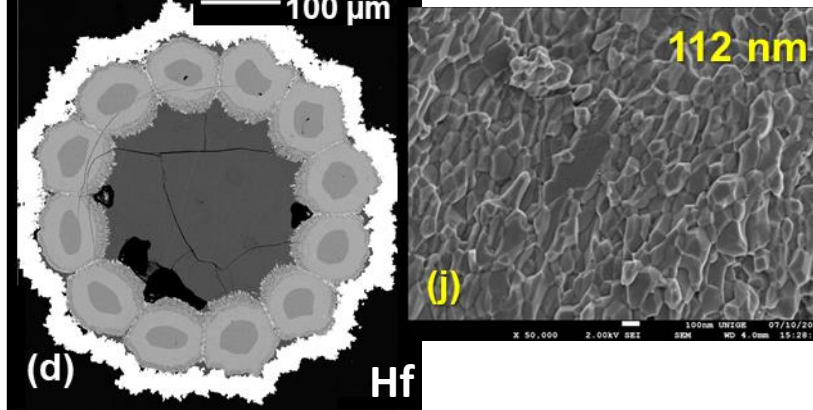
SnO₂ Core

SnO₂ Annular

Nb-7.5wt%Ta-1wt%Zr



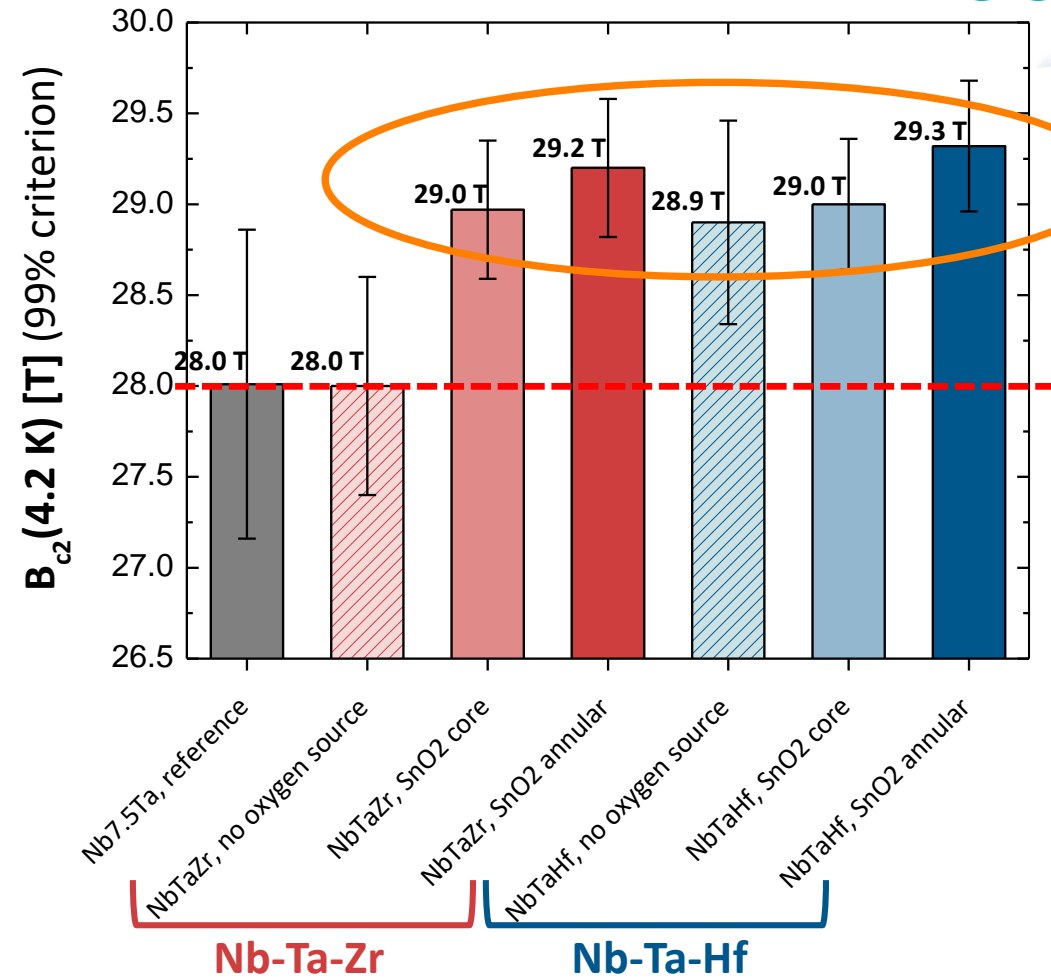
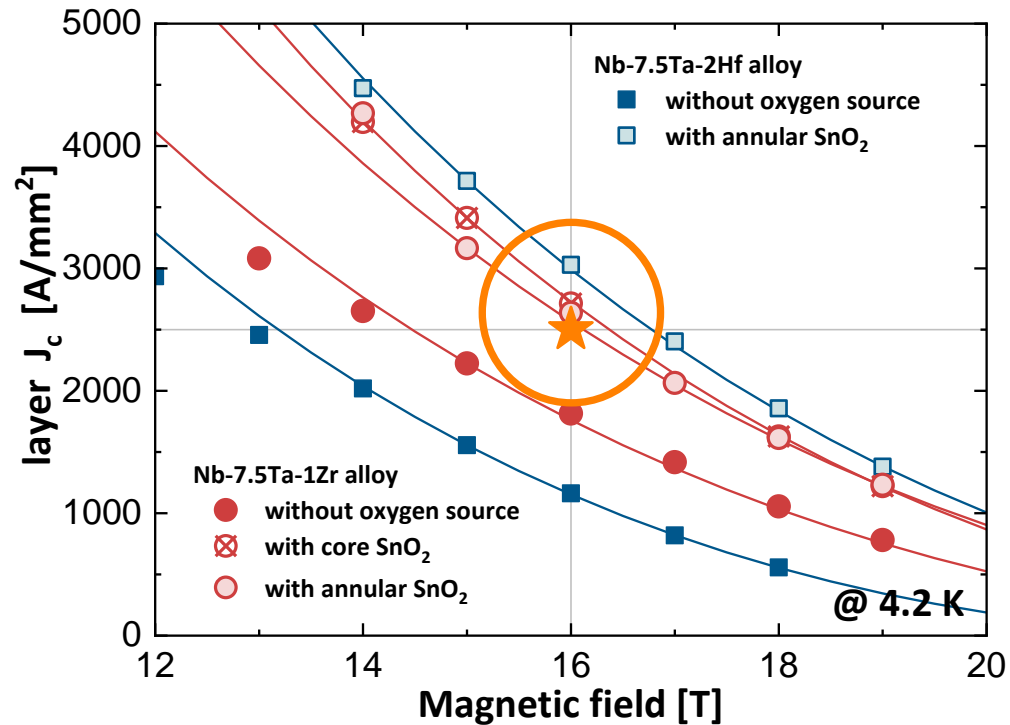
Nb-7.5wt%Ta-2wt%Hf



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

Internal Oxidation of test-bed Internal Sn subelements

Transport J_c and B_{c2} measurements



Layer J_c determined from transport measurements

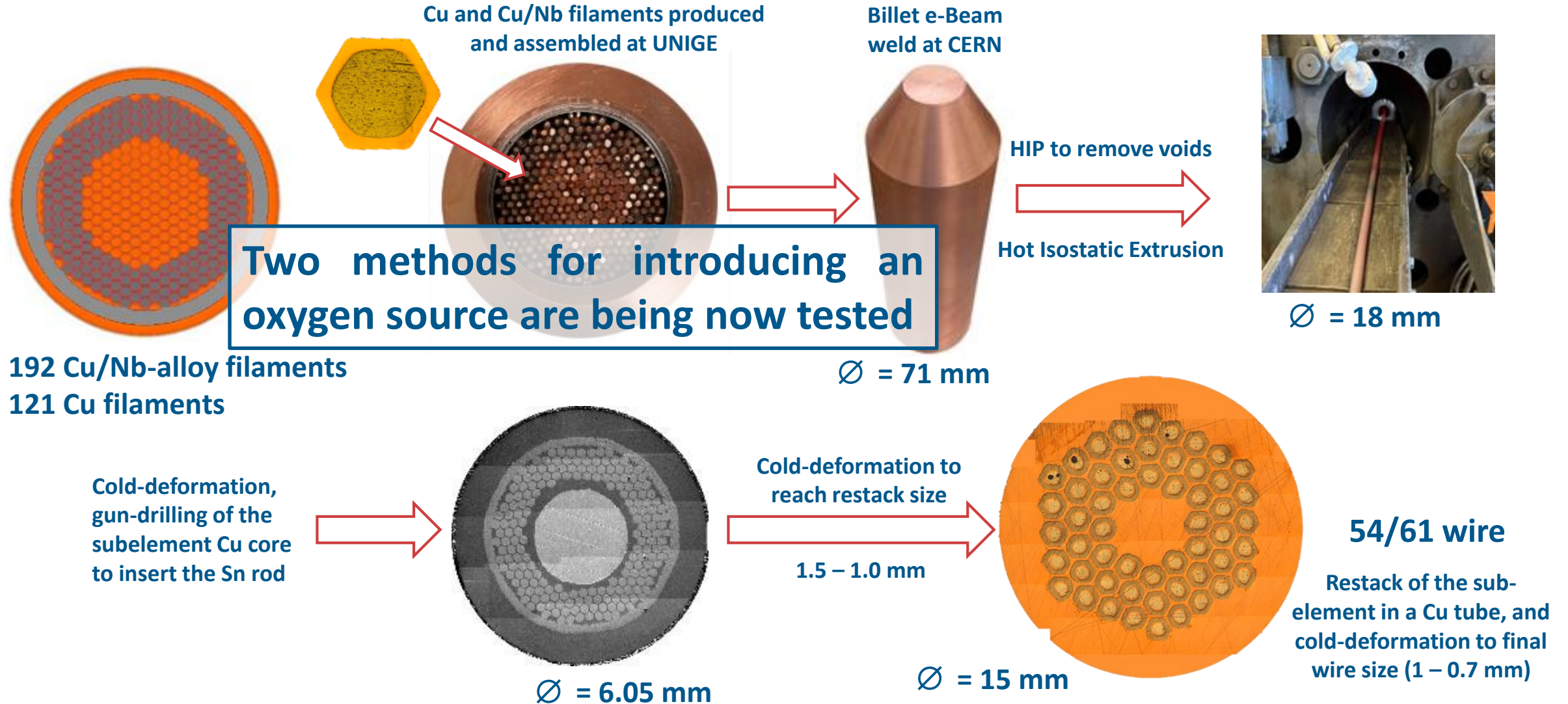
FCC layer J_c (4.2K,16T) = 2'500 A/mm²
 considering 60% of Nb₃Sn in the non-Cu area

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

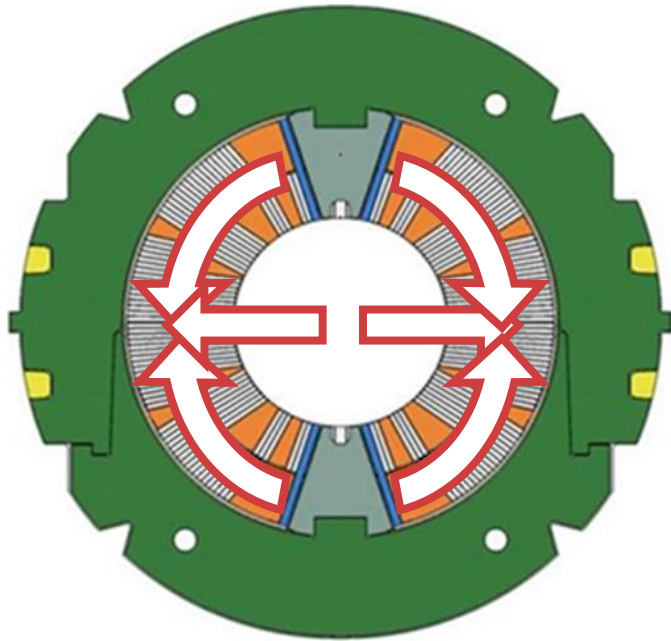


Increasing the non-Cu J_c beyond state of the art is a necessary condition to get 16 T dipoles, but it is not sufficient

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 Nb₃Sn-based accelerator magnets

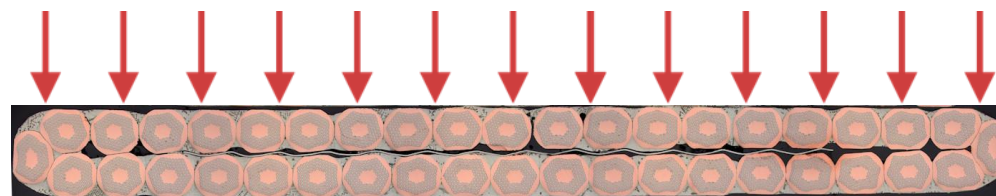


Electromagnetic forces in an accelerator magnet

- 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 Nb₃Sn** 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 Nb₃Sn Rutherford cables



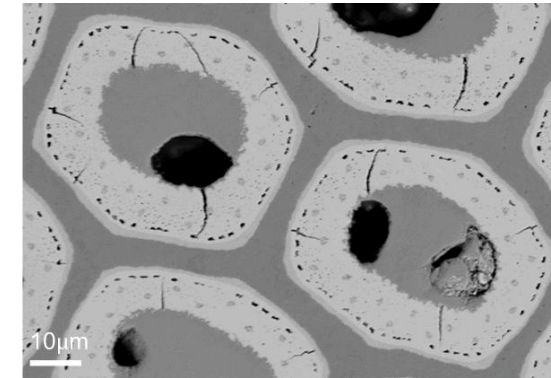
Irreversible reduction of the critical current after unload

Mechanisms responsible for the performance degradation

Two mechanisms govern the permanent reduction of the critical current

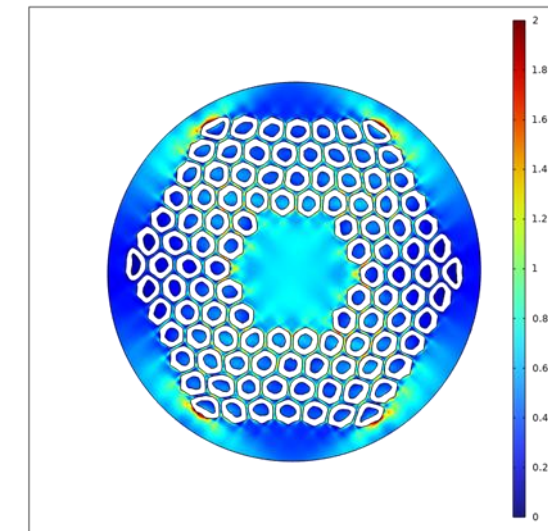
- Formation of **cracks** in the Nb₃Sn filaments

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



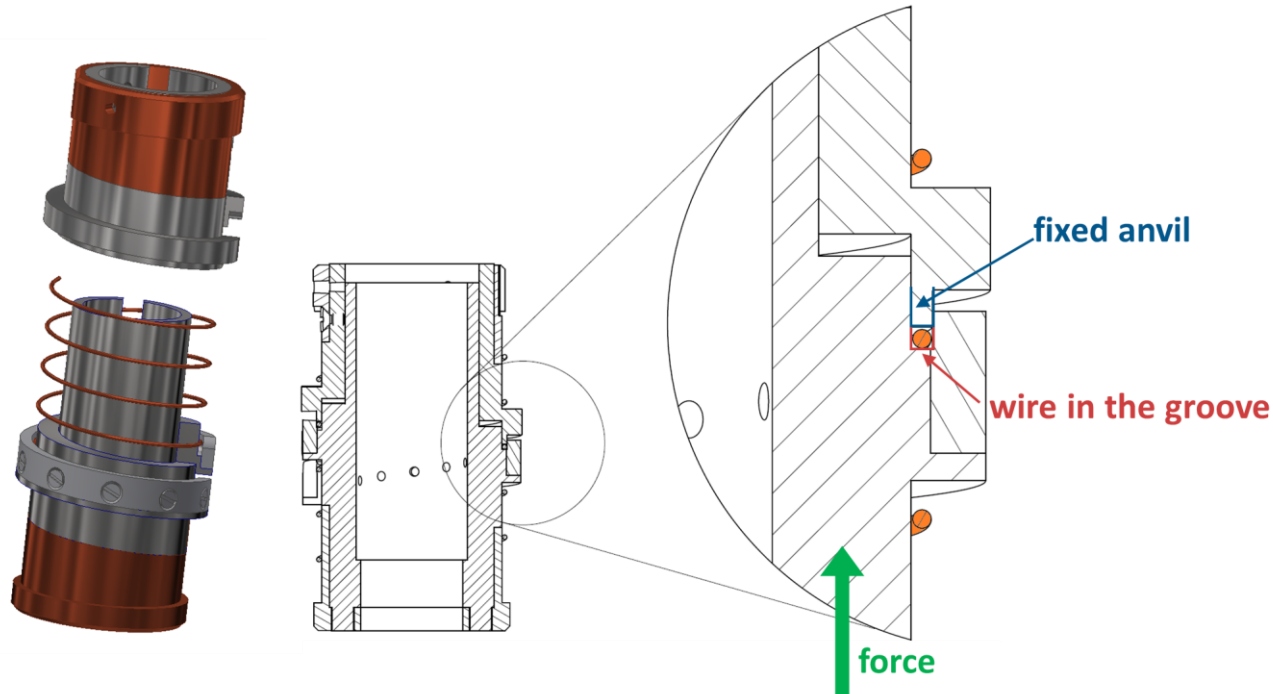
- **Plastic deformation** of the Cu matrix and residual stress on the Nb₃Sn filaments

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

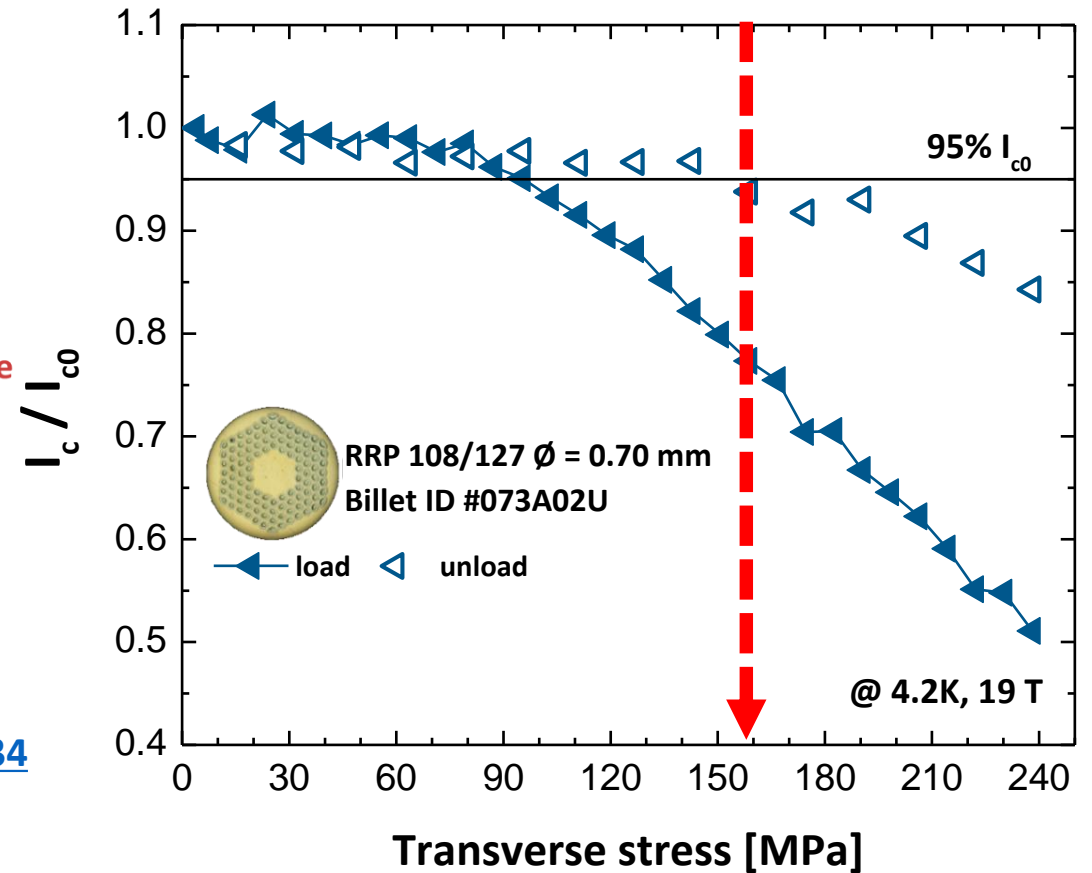


Tolerance to transverse stress of a single wire

Electromechanical tests on Nb₃Sn wires impregnated with epoxy



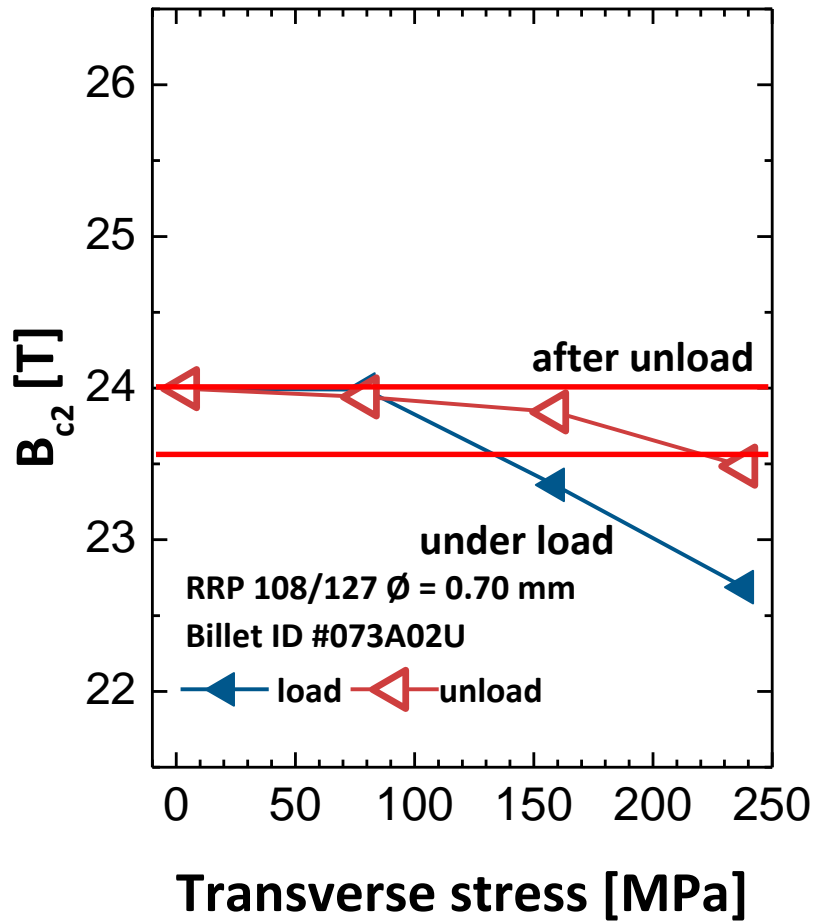
The WASP concept was adapted to transverse loads by
 B. Seeber et al., IEEE TAS 17 (2007) 2643, DOI: [10.1109/TASC.2007.897934](https://doi.org/10.1109/TASC.2007.897934)



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 $\sigma_{irr} (B=19T) = 155 \text{ MPa}$ (force dived by groove area)

Comparison of B_{c2} under load and after unload

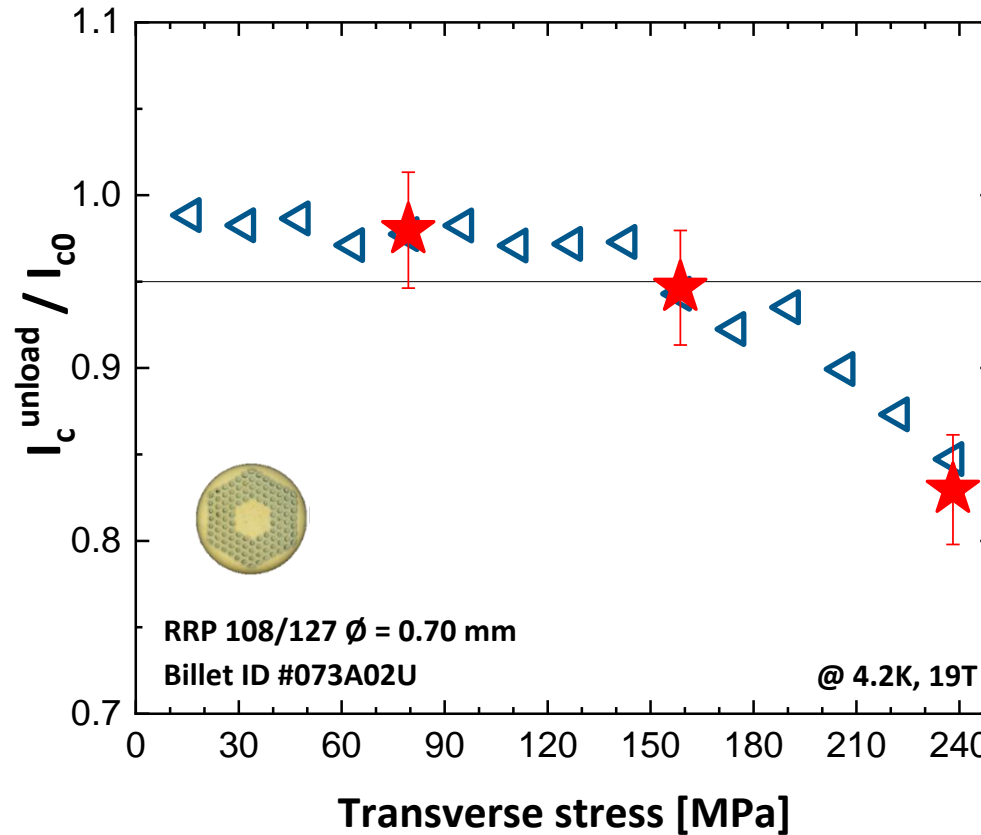


After unload from $\sigma = 240$ MPa

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

Measured I_c^{unload} vs expected degradation from residual stress

(open blue points) (solid red stars)



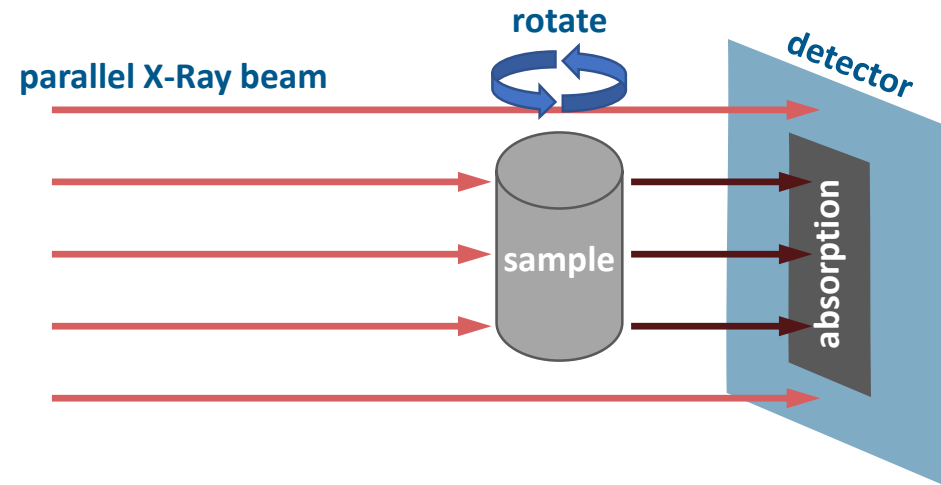
$$I_c^{\text{unload}}(B) = f C \left[\frac{B_{c2}^{\text{unload}}}{B} \right]^{0.5} \left[1 - \frac{B}{B_{c2}^{\text{unload}}} \right]^2$$

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

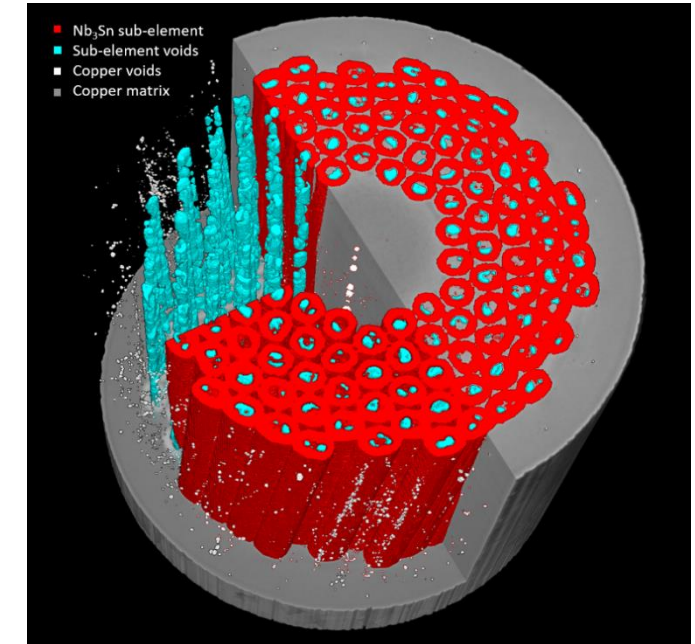
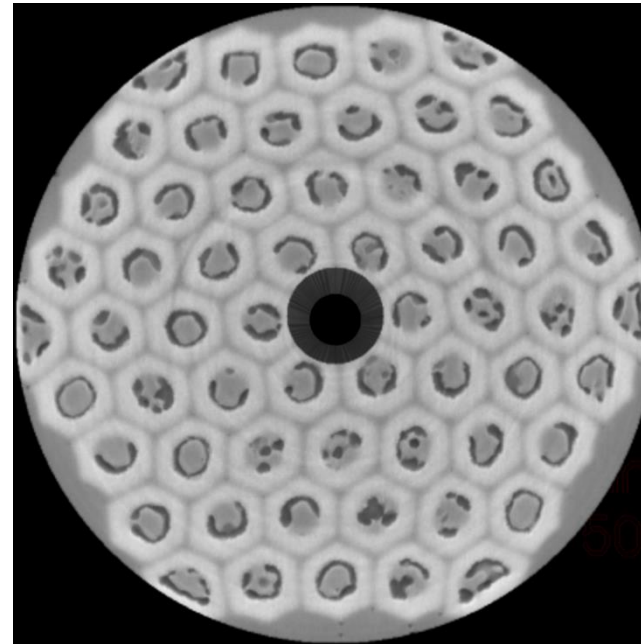
The effect of cracks seems negligible up to very high transverse stress values

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



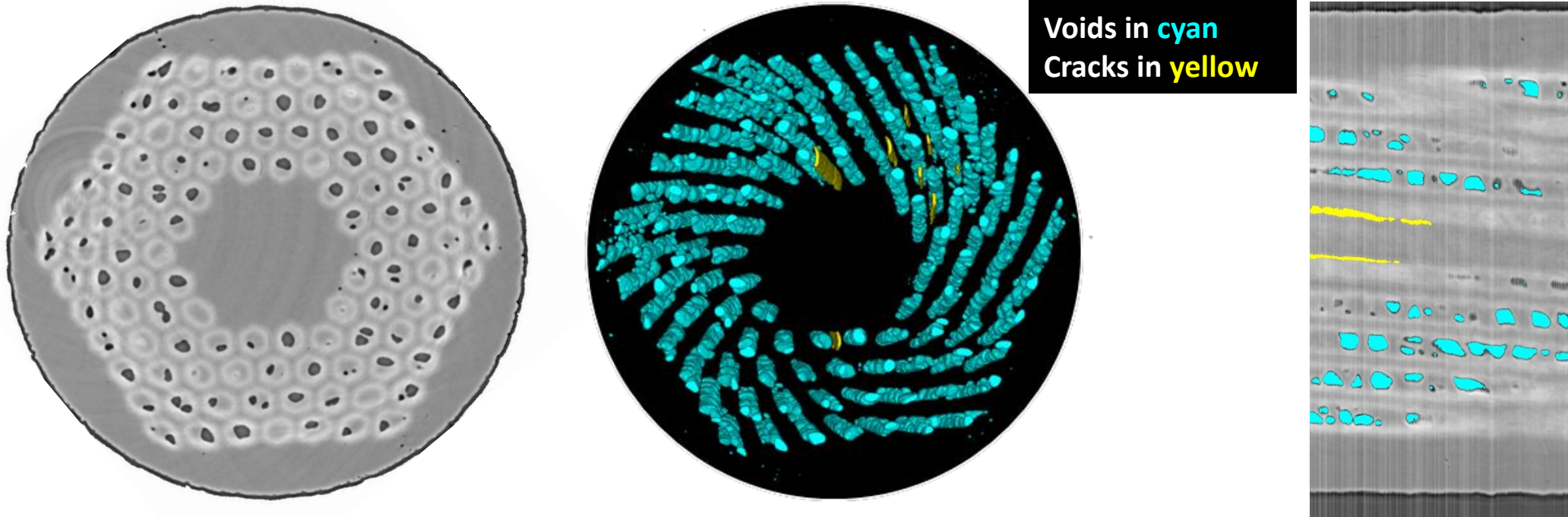
A novel, non-destructive and non-invasive method to investigate the internal structure of high-performance Nb₃Sn wires combines **X-ray microtomography** with **machine-learning algorithms**



Marta MAJKUT
Alexander RACK

X-ray tomography and Neural Networks for crack detection

An independent confirmation of the conclusions



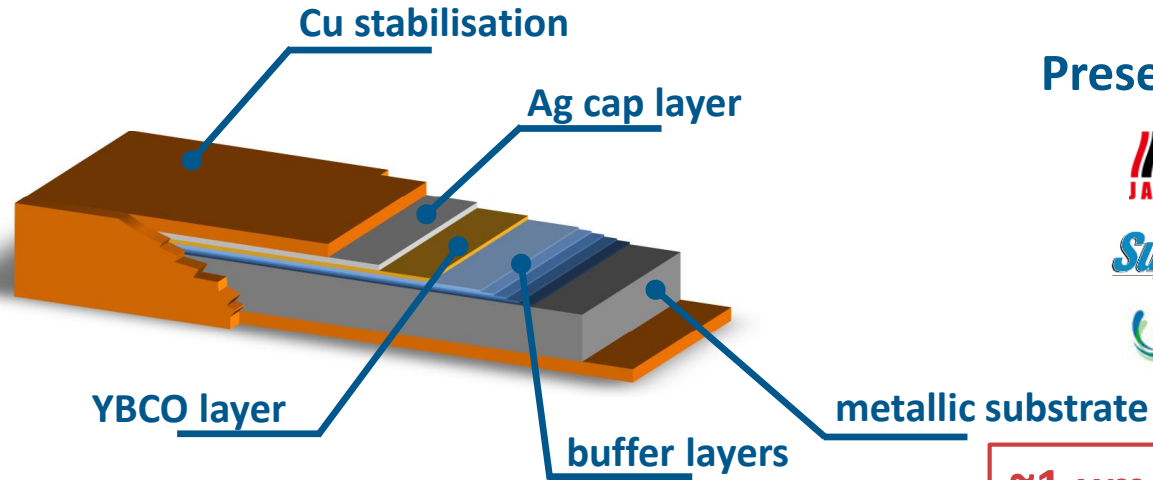
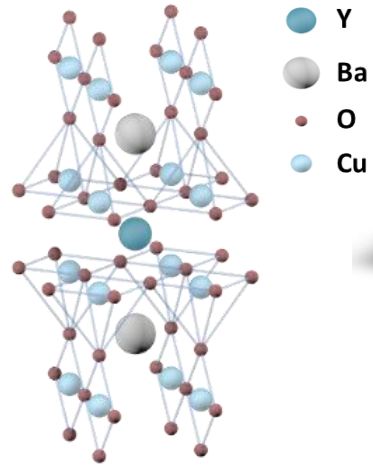
An analysis based on Convolutional Neural Networks was performed on the tomographic scan of the exact same sample used for the I_c vs σ test, after unload from 240 MPa

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

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 Nb₃Sn 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

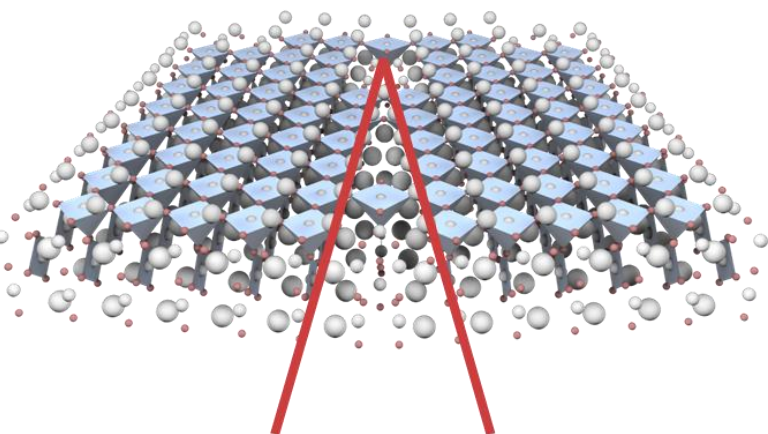
Industrial fabrication of REBCO coated conductors



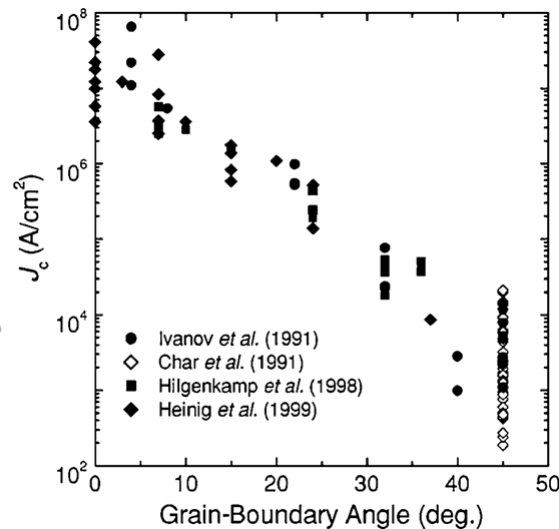
Presently produced by



~1 μm of YBCO in a ~100 μm thick tape



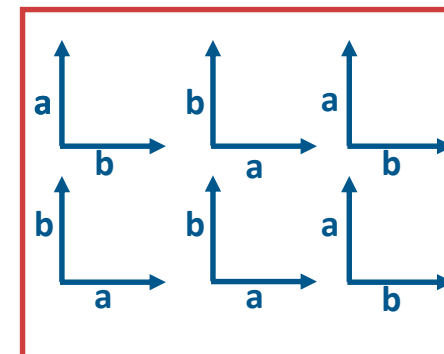
[001] tilt grain boundary



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

DOI: [10.1103/RevModPhys.74.485](https://doi.org/10.1103/RevModPhys.74.485)

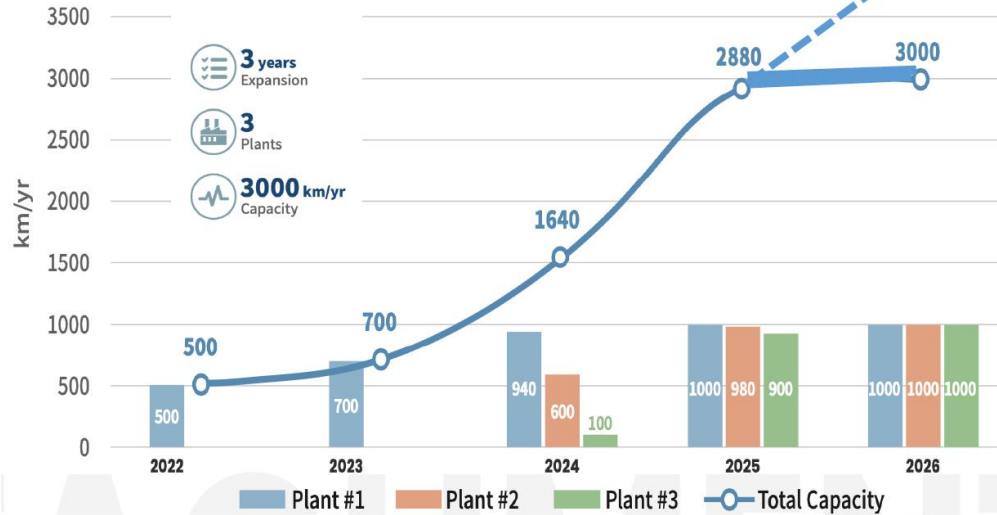
A metallic substrate coated with a multifunctional oxide barrier is the template to grow biaxially textured REBCO with in-plane alignment within 5°



Fusion-driven expansion of REBCO production capacity



SST Production Capacity Outlook



1600 km₁₂/yr (2024) → 3000 km₁₂/yr (2026)



1300 km₁₂/yr (2024) → 25000 km₁₂/yr (2028)



200 km₁₂/yr (2024) → 1200 km₁₂/yr (2026)

Tape width 12 mm
Capacity: 100+ km₁₂

Going wide
25 ×

Tape width 4 × 80 -100 mm
Capacity: 2500+ km₁₂



ALPHA
2023

BETA
2025

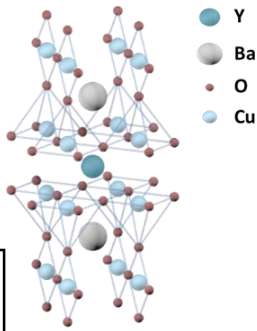
100 km₁₂/yr (2023) → 2500 km₁₂/yr (after 2025)

Tailoring the critical current density of REBCO

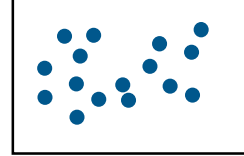
Anisotropy, Intrinsic and Artificial defects and their Dimensionality

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

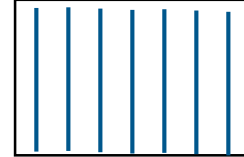
Tailored **artificial defects**, e.g. nanocolumns (1D) and nanoparticles (3D), can be introduced to reduce anisotropy and enhance performance



point defects



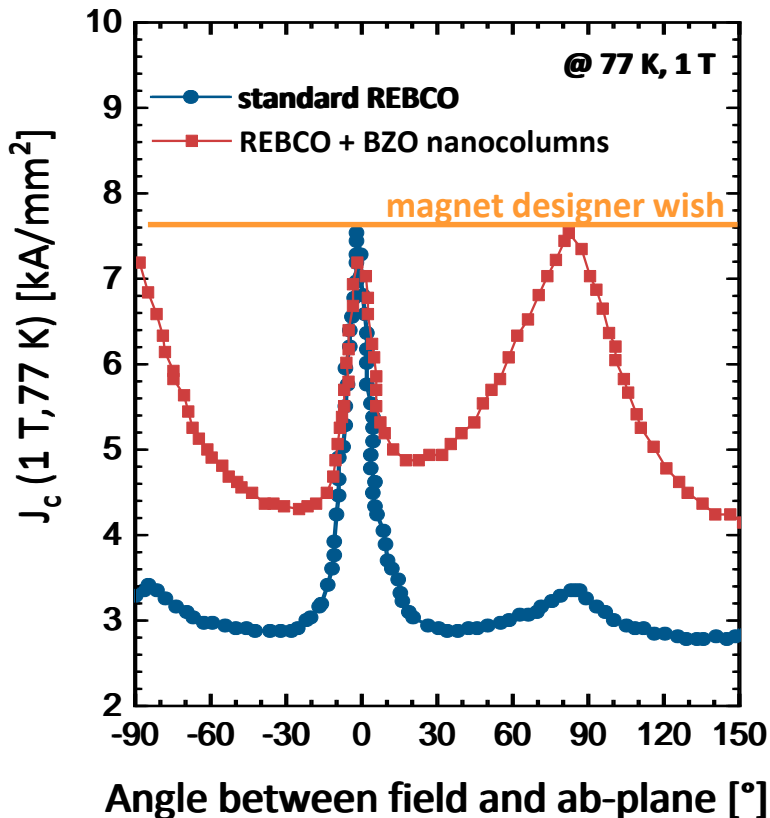
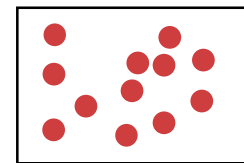
grain boundaries



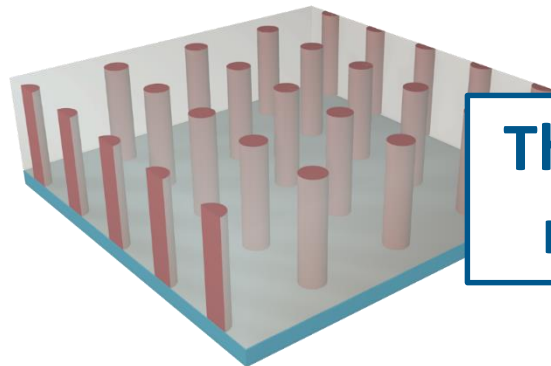
stacking faults



nanoparticles



BaZrO₃ (BZO) and BaHfO₃ (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](https://doi.org/10.1038/nmat1156)

A. Goyal *et al.*, SUST **18** (2005) 1533

DOI: [10.1088/0953-2048/18/11/021](https://doi.org/10.1088/0953-2048/18/11/021)

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

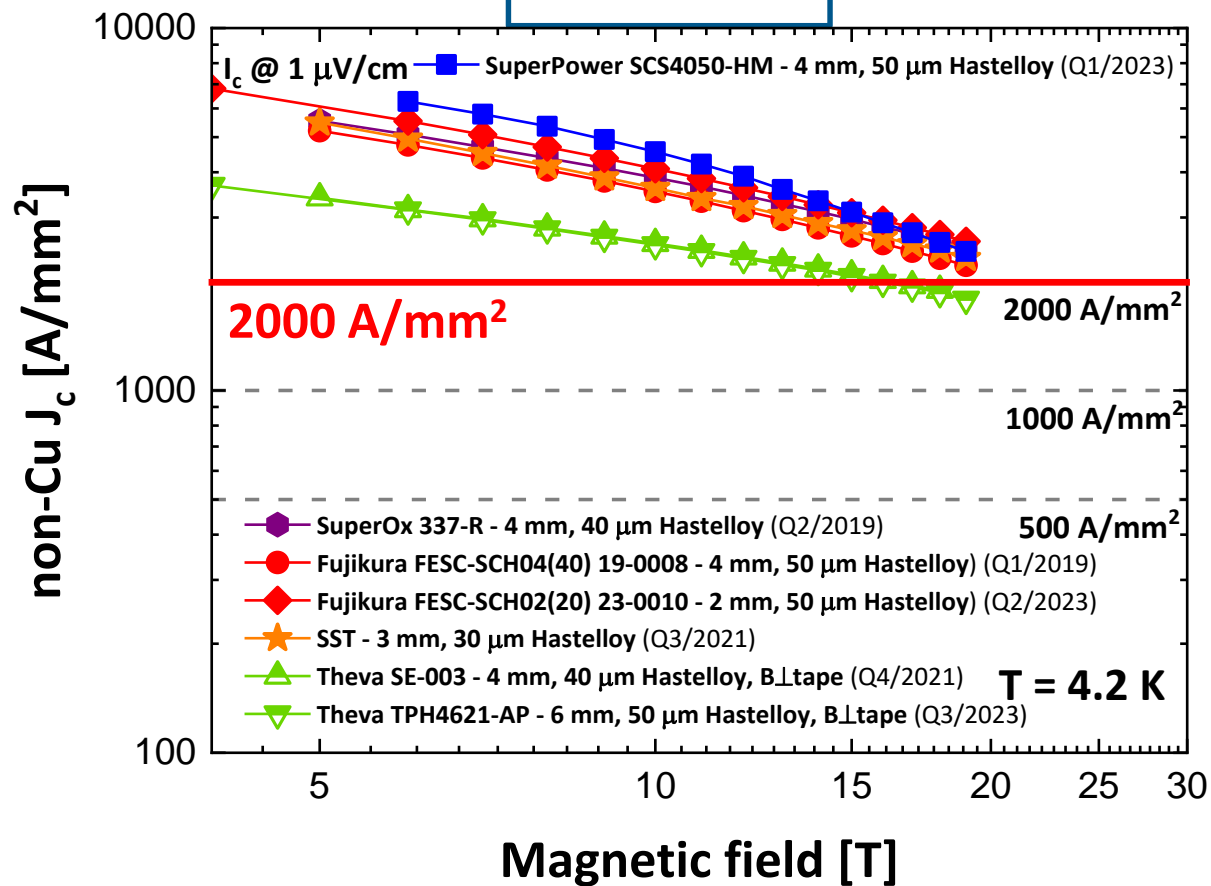


Comparison of the performance: non-Cu J_c

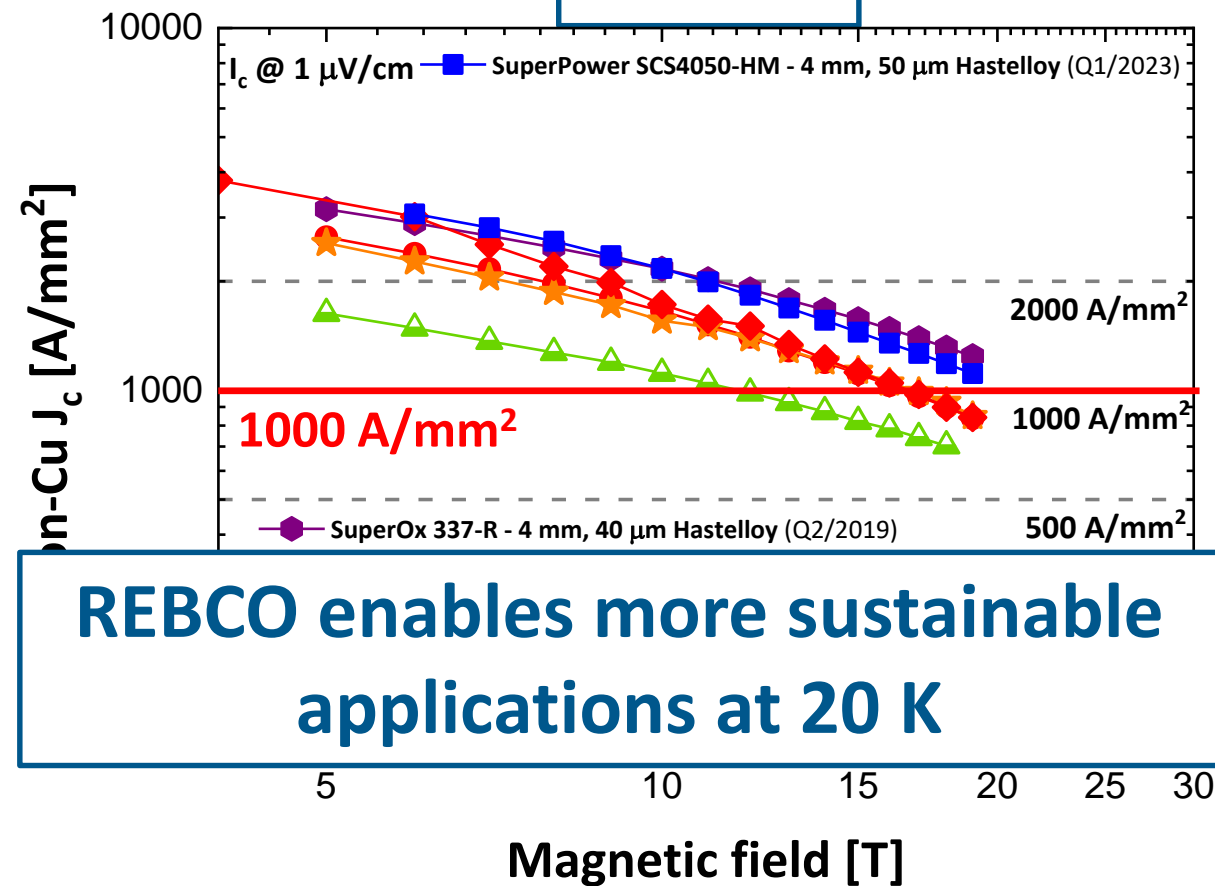
The non-Cu J_c corresponds to the critical current divided by the tape cross-section area minus the Cu area

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

T = 4.2 K



T = 20 K



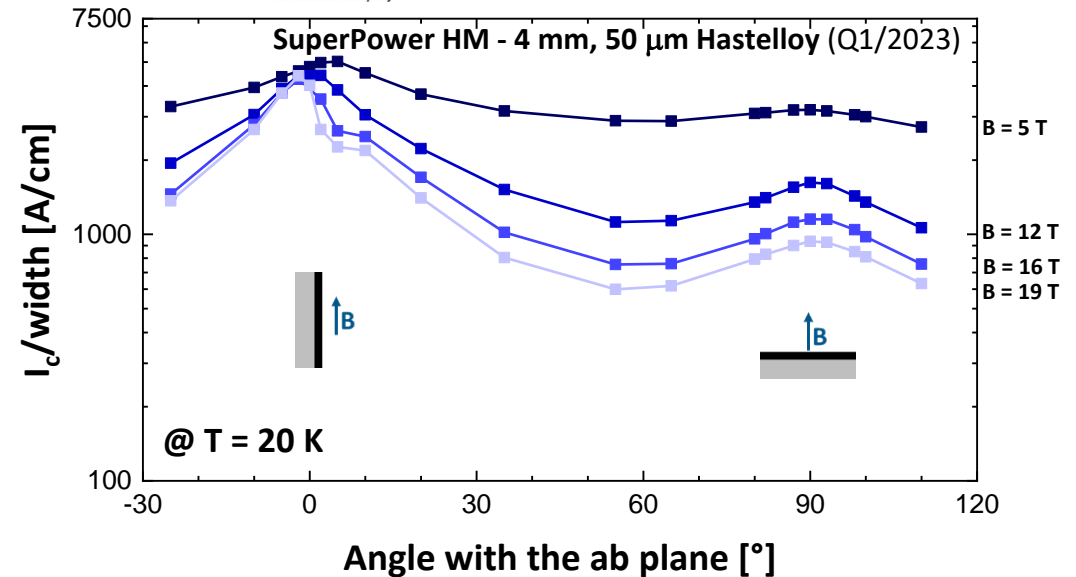
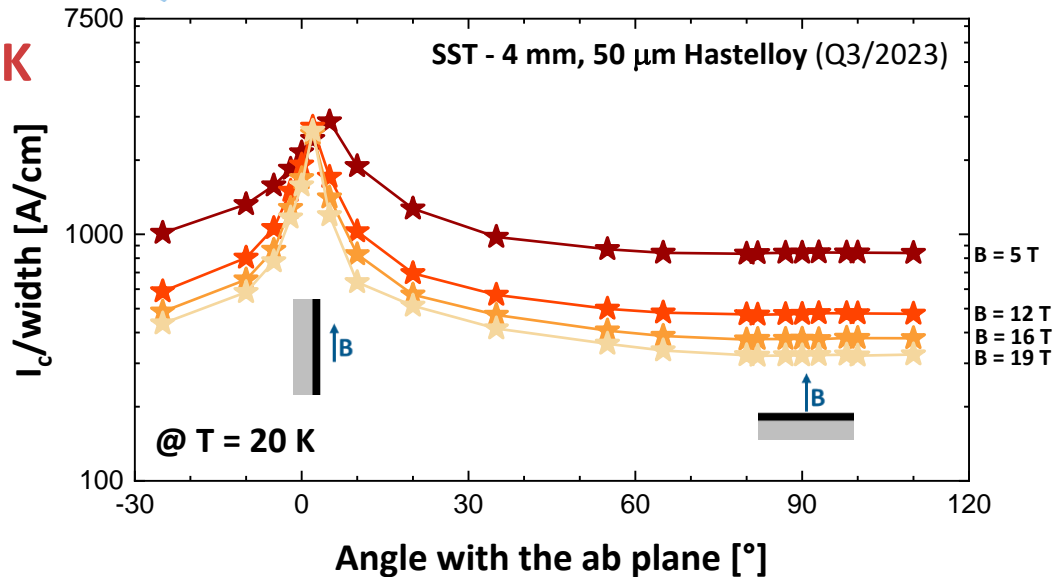
Angular dependence of I_c : very fresh results

上海超导™ SHANGHAI SUPERCONDUCTOR
EuBCO + BHO nanocolumns

SuperPower Inc. A Furukawa Company
YBCO + BZO nanocolumns

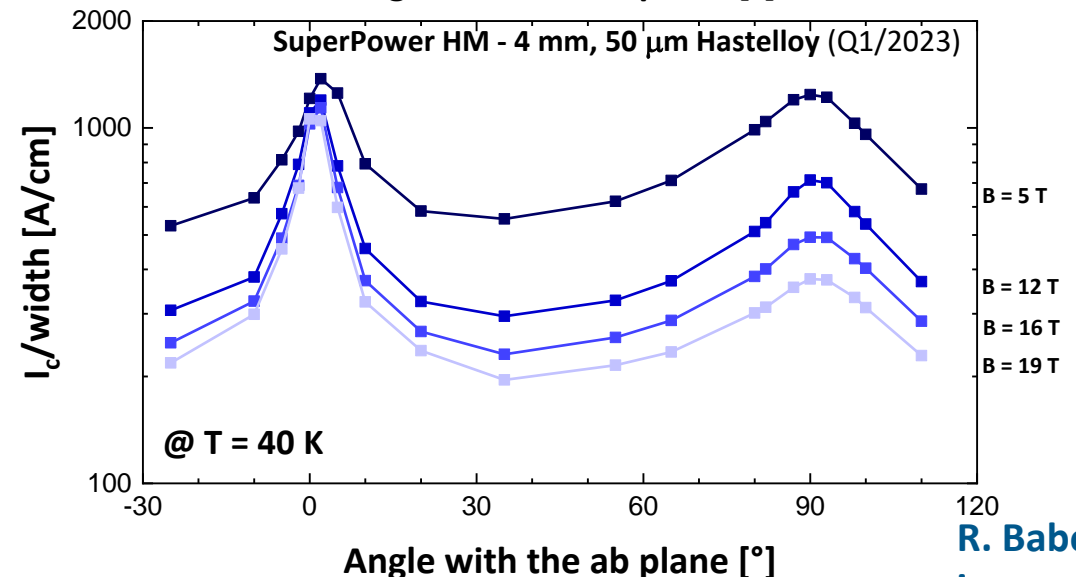
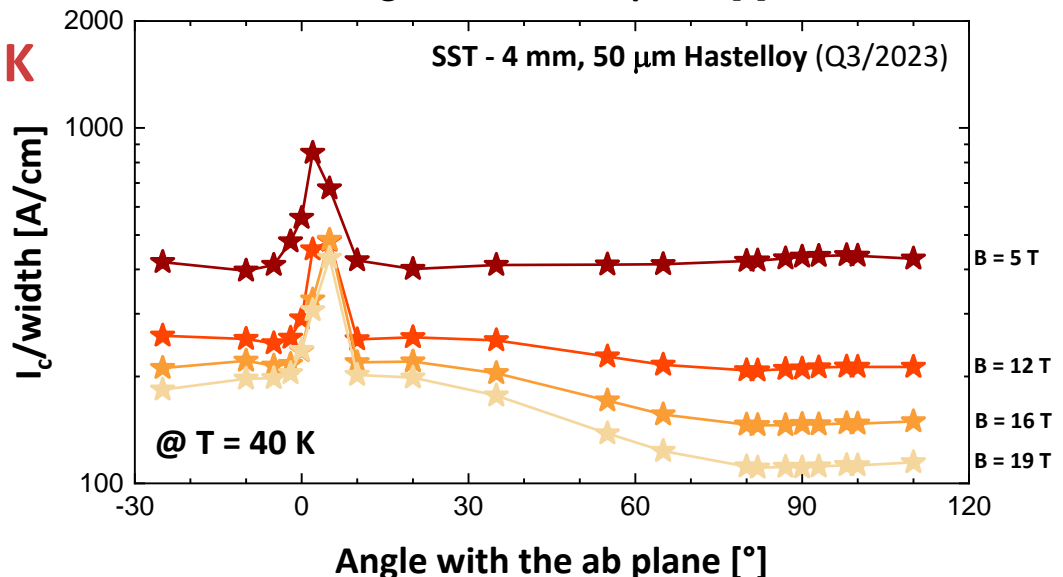
T = 20 K

5 T
↓
19 T



T = 40 K

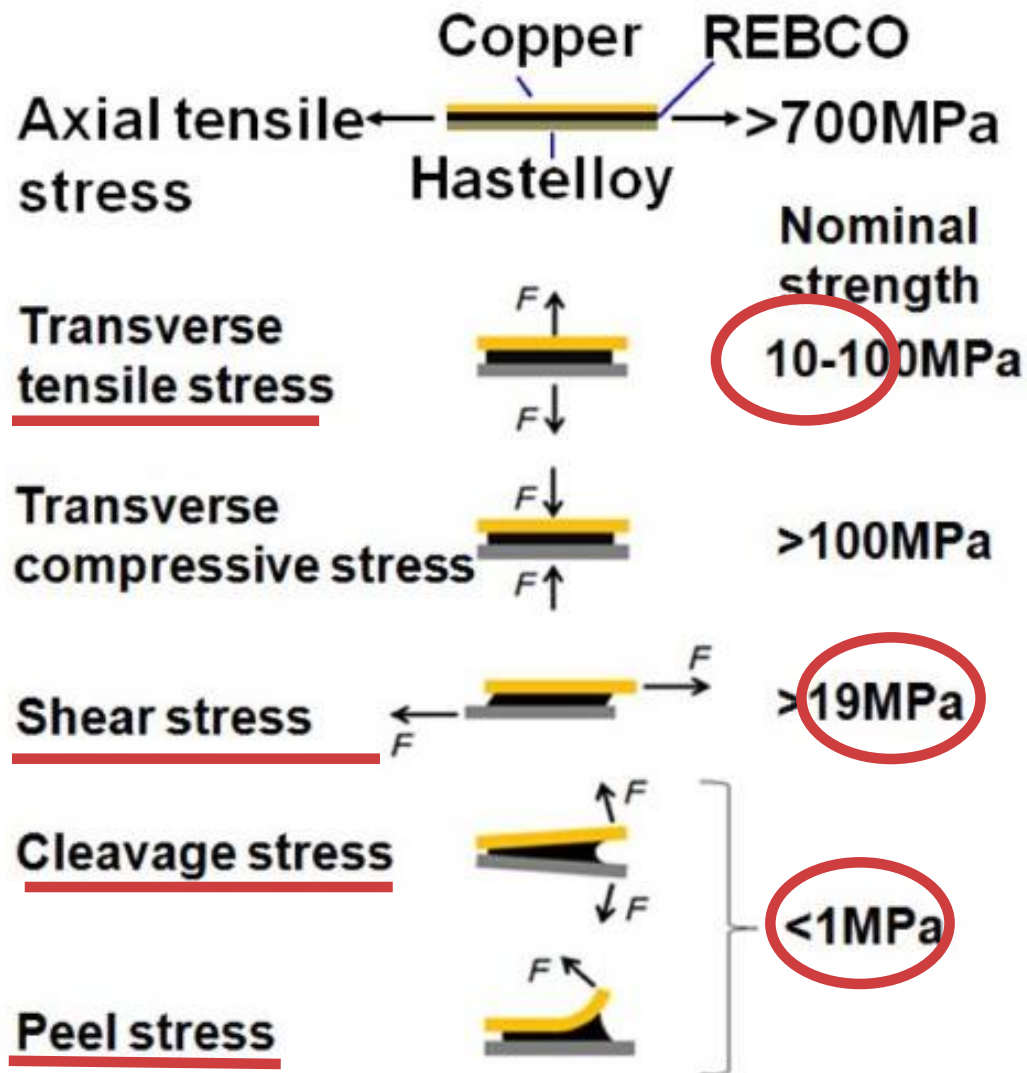
5 T
↓
19 T



R. Babouche et al.,
in preparation

High in-field J_c is not sufficient for UHF magnets

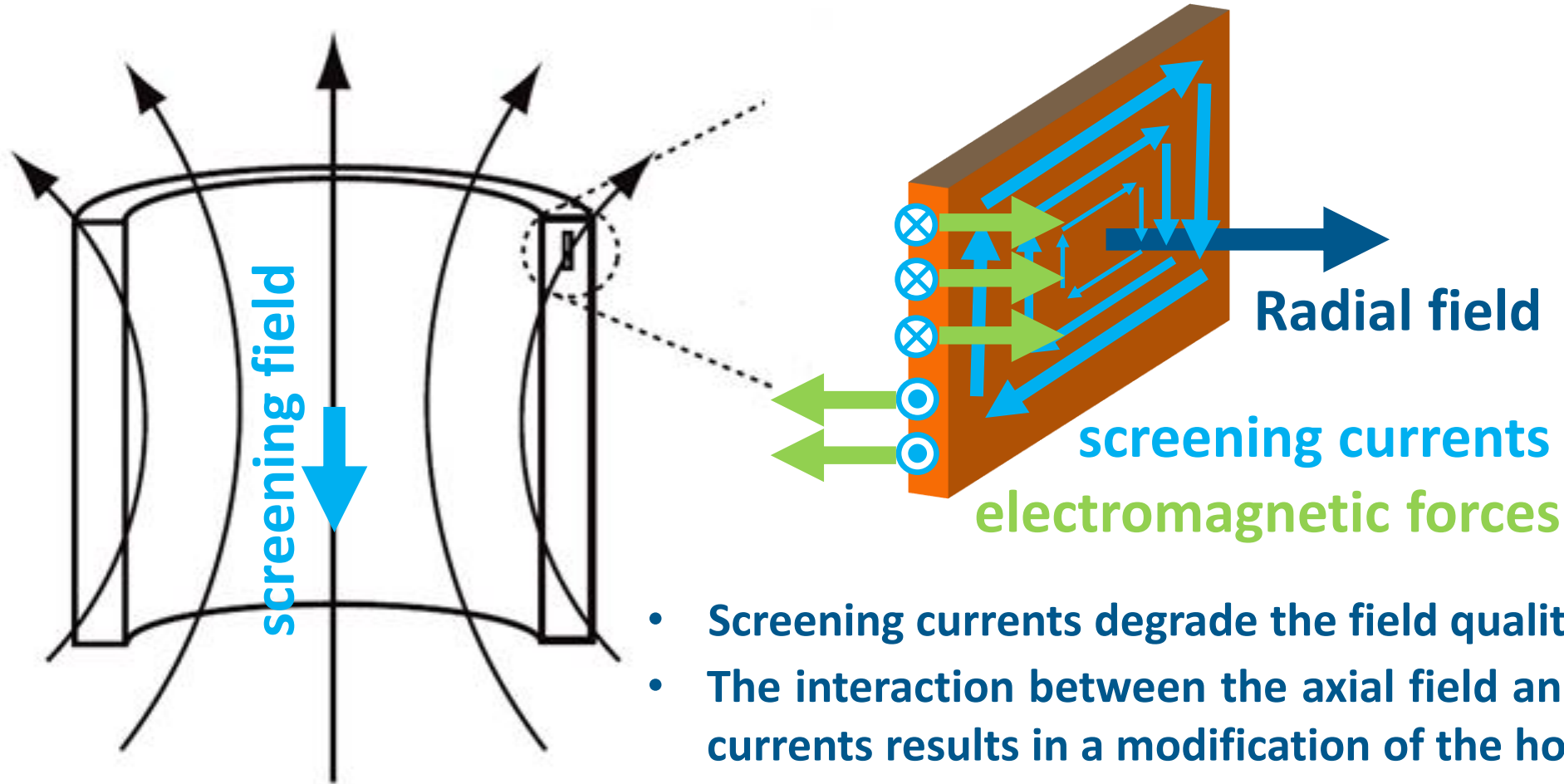
A short note on the mechanical properties



- 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

High in-field J_c is not sufficient for UHF magnets

Screening Currents, Field Quality and Conductor Degradation

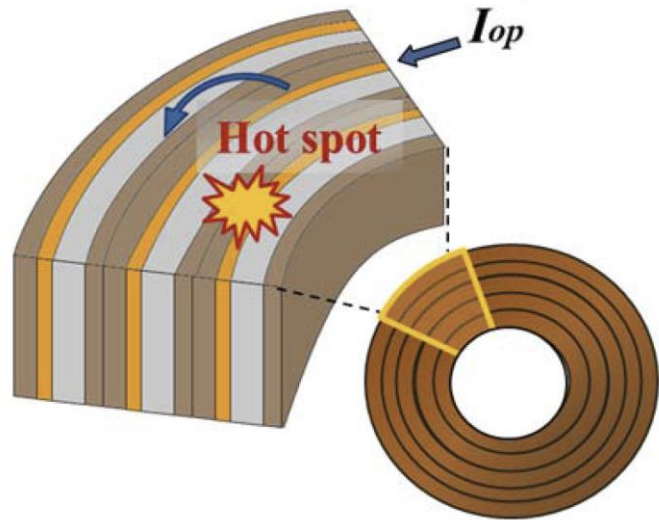


- Screening currents degrade the field quality
- The interaction between the axial field and the screening currents results in a modification of the hoop stress
- Local Lorentz force due to the screening currents can be source of delamination force

Some lessons learned from REBCO magnet R&D

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

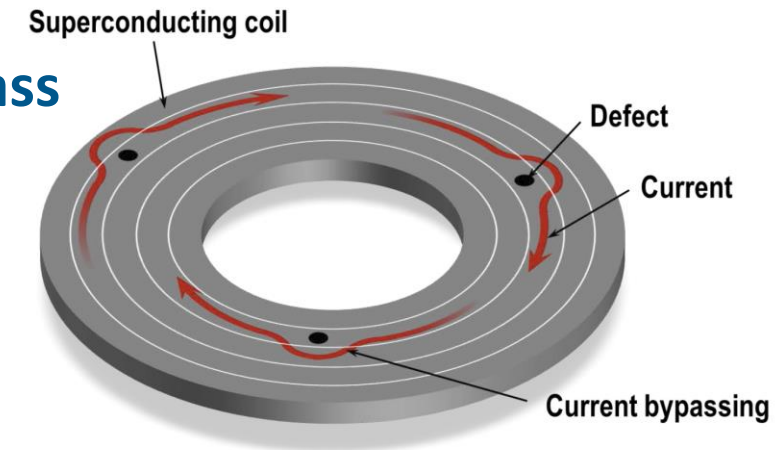
A new paradigm with advantages and drawbacks



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](https://doi.org/10.1109/TASC.2010.2093492)

U. Bong et al., *Supercond. Sci. Technol.* 34 (2021) 085003

DOI: [10.1088/1361-6668/ac0759](https://doi.org/10.1088/1361-6668/ac0759)

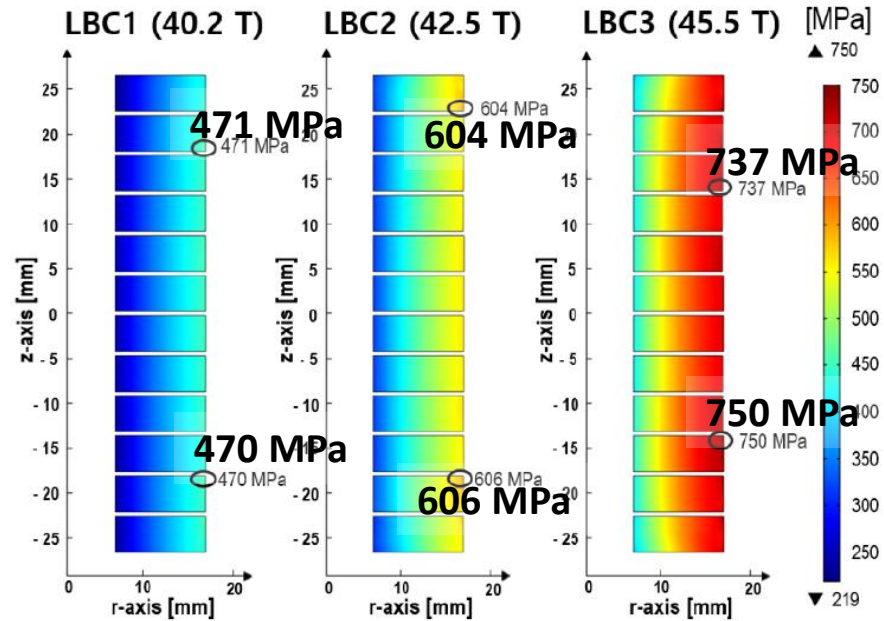
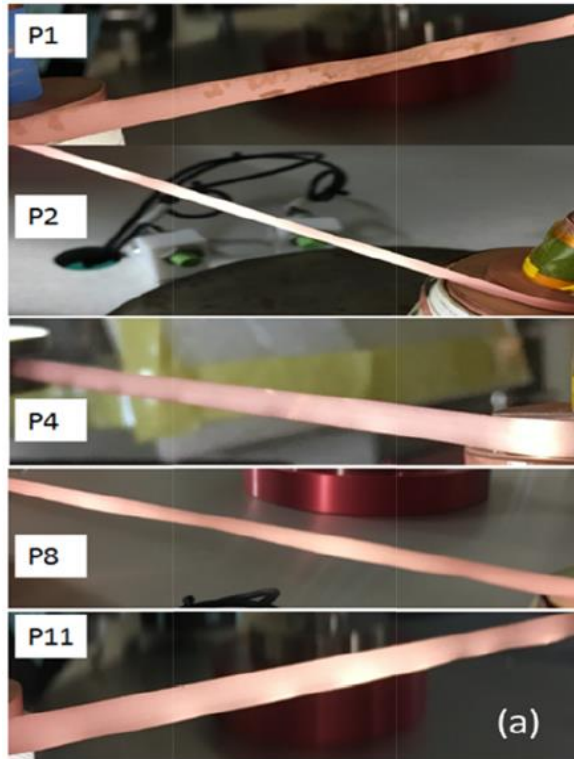
A major drawback comes from the **charging delays**, which can be **mitigated** by **Partial/Metal/Smart Insulation**

Other known drawbacks: **unbalanced forces**, induced overstresses

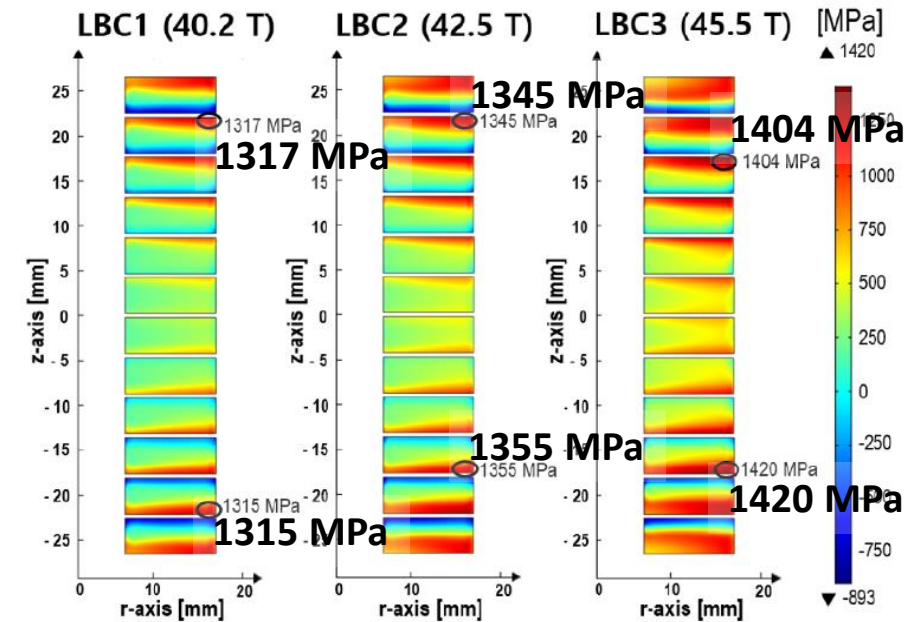
Lesson learned from REBCO magnet R&D

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

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



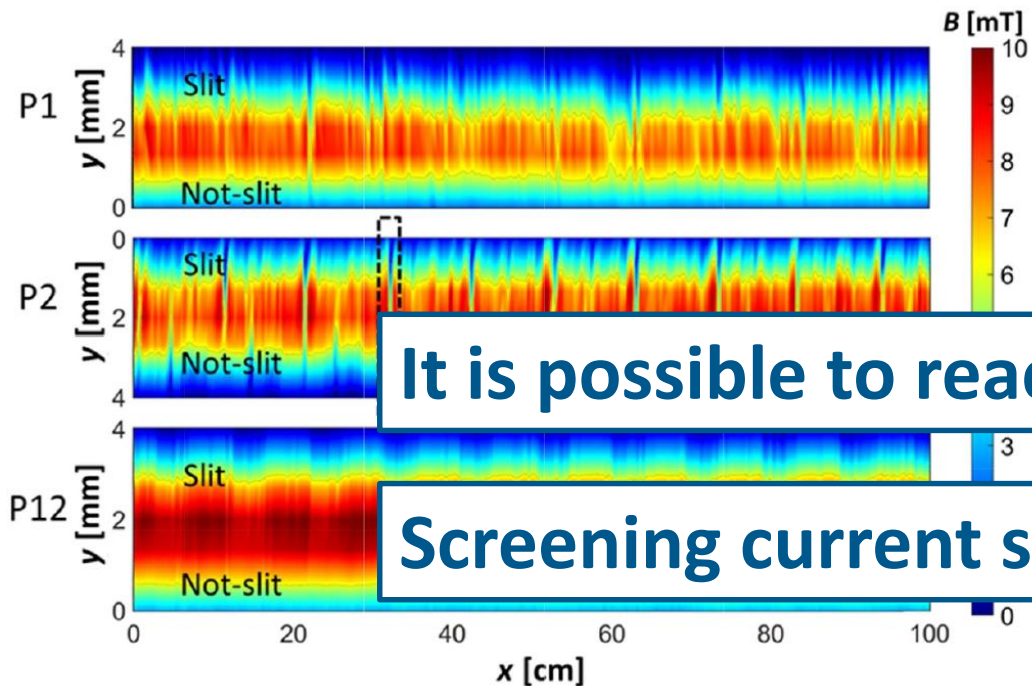
Calculated hoop stress distribution
with screening currents

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

Lesson learned from REBCO magnet R&D

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

Three **no-insulation** 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



- I_c degradation due to plastic rippling occurs at coils edges
- All degraded edges occur at slit edges containing pre-existing micro-cracks

It is possible to reach and exceed 40 T with REBCO

to be observed especially when the

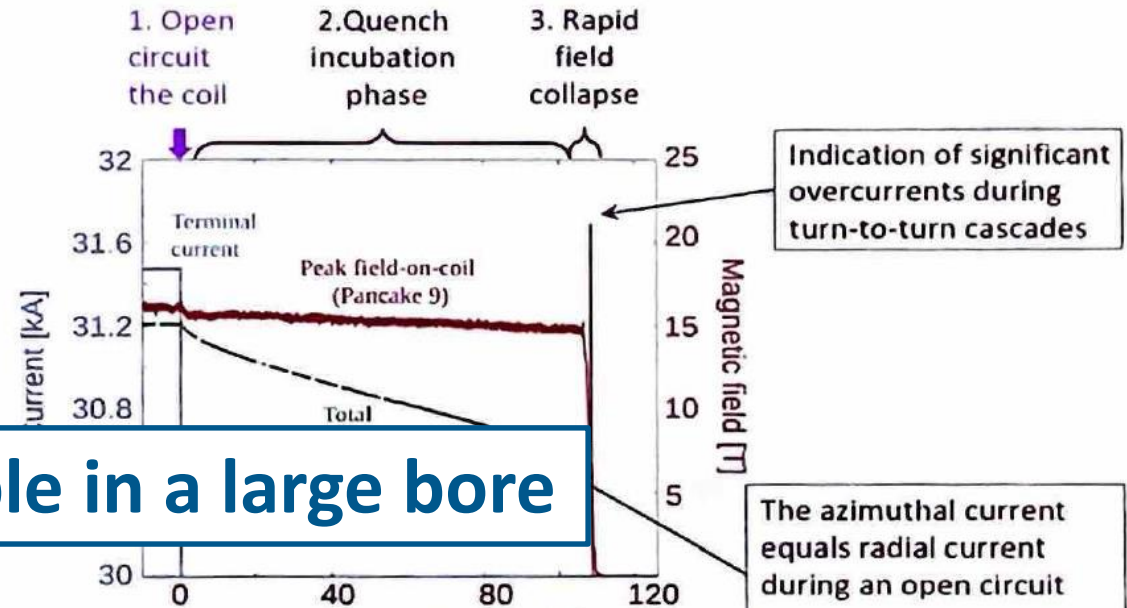
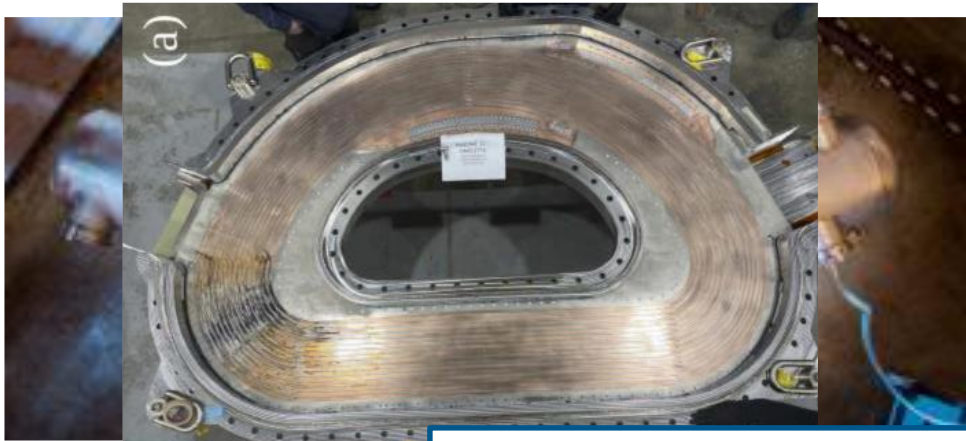
transport current is flowing along the slit edge

Screening current stresses cannot be neglected

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

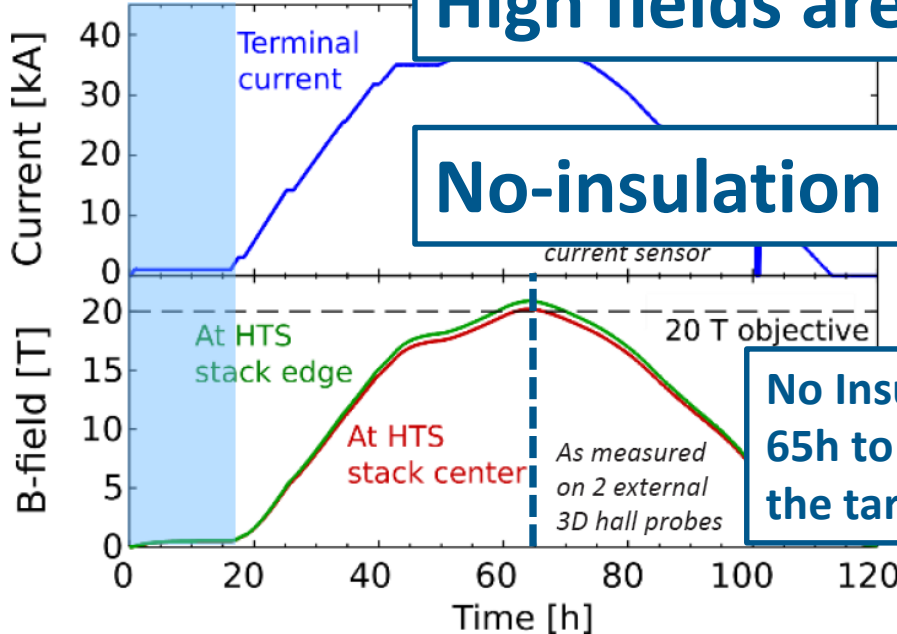
Lesson learned from REBCO magnet R&D

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

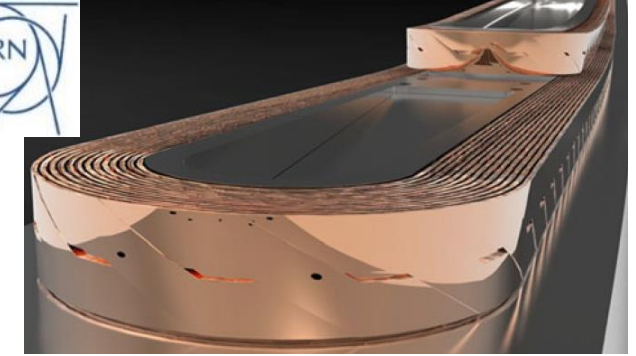
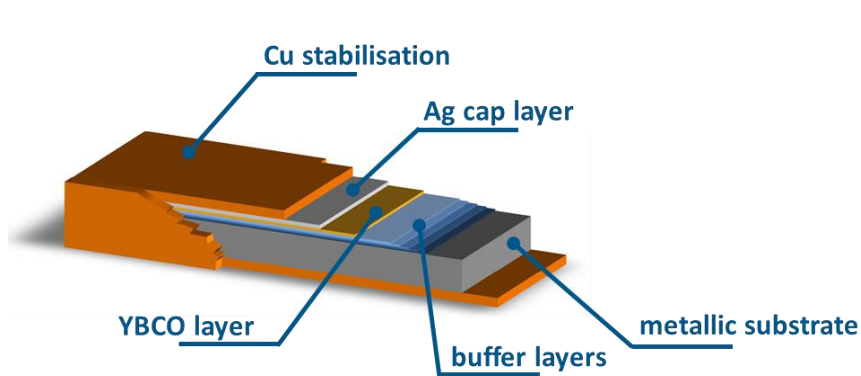


No Insulation: 65h to reach the target field

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

From REBCO tapes to REBCO-based dipole magnets



Aligned block with Roebel cables

Roebel cables

W. Goldacker et al., SUST 27 (2019) 10LT01
DOI: [10.1088/0953-2048/27/9/10LT01](https://doi.org/10.1088/0953-2048/27/9/10LT01)

Promising R&D ongoing, not yet consolidated solutions



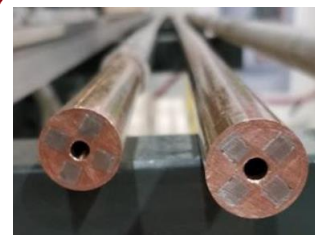
BERKELEY LAB



CORC and STAR cables

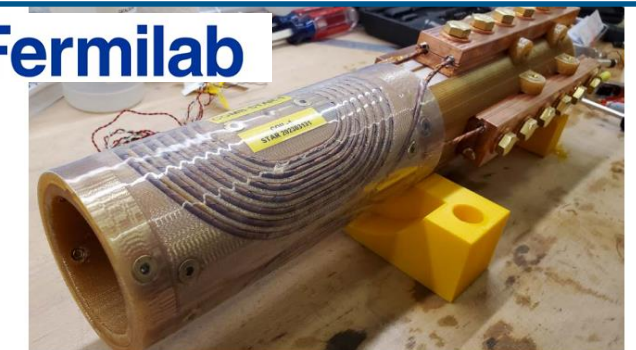
D. Van der Laan et al., SUST 34 (2021) 10LT01
DOI: [10.1088/1361-6668/ac1aae](https://doi.org/10.1088/1361-6668/ac1aae)

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



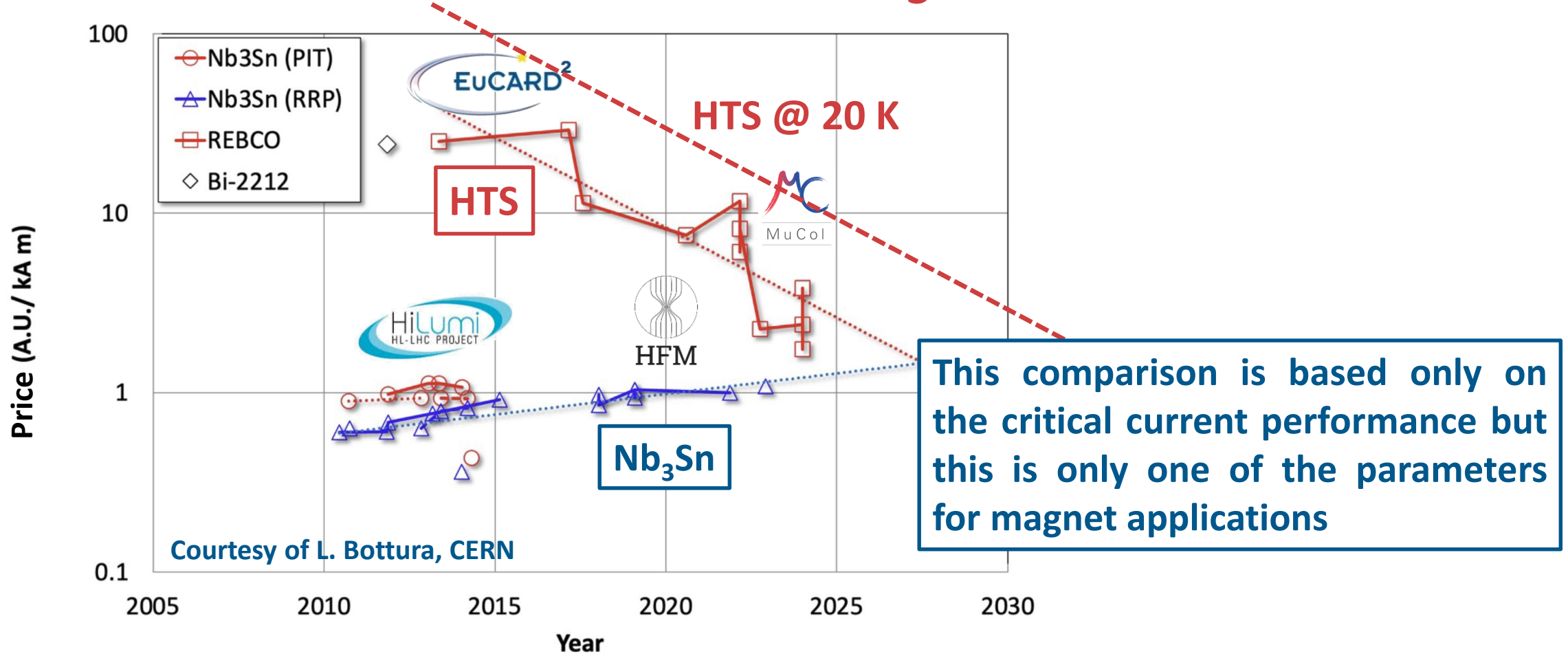
Tape stacks

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



COMB with CORC cables

Some considerations on price: Nb₃Sn vs REBCO



Price (arbitrary units) per unit length and current for Nb₃Sn 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. **Nb₃Sn** continues to lead in high-field applications.
- Efforts to achieve compact accelerator dipoles with $B > 14$ T for the **Future Circular Collider** are pushing **Nb₃Sn** 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 Nb₃Sn 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**.

ICEC/ICMC

29th International Cryogenic Engineering Conference
International Cryogenic Materials Conference 2024
July 22-26, 2024, Geneva, Switzerland

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, Sept 2024. Plenary presentation given at ICEC-ICMC 2024, July 2024, Geneva, Switzerland.



UNIVERSITÉ
DE GENÈVE

FACULTÉ DES SCIENCES



Swiss Accelerator
Research and
Technology



MuCol



Swiss National
Science Foundation



Thank you for the attention !

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<http://supra.unige.ch>

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