IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2022.
Plenary presentation PL2 was given at HTS 2022, 14 – 16 June 2022, Nancy, France (Hybrid).

High Temperature Superconductors and Their Applications

A summary of the current status…

Arno Godeke

Plenary Lecture – HTS Modelling 2022 – Nancy, France – June 15, 2022

What has been done before?

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. 32 (2019) 053001 (29pp) https://doi.org/10.1088/1361-6668/ab06a2

Topical Review

A review of commercial high temperature superconducting materials for large magnets: from wires and tapes to cables and conductors

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TOHOKU UNIVERSITY
EUCAS 2019 GLASGOW
14th European Conference on Applied Superconductivity
1st-5th September 2019, SEC, Glasgow

Superconductors in High Magnetic Fields
- Now and the future -

Satoshi Awaji

High Field Laboratory for Superconducting Materials (HFLSM),
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HFLSM
Research

High Temperature Superconductors for Commercial Magnets

Contemplations from a magnet perspective…

Arno Godeke – ICSM2021 Plenary – Milas-Bodrum, Turkey – Oct. 22, 2021

→
(In progress)

Topical Review

High Temperature Superconductors for Commercial Magnets

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29 May 2022

Abstract. The steadily increasing magnetic fields that can be generated with superconducting magnets are reaching the limits of what is achievable with low- … what is currently available, and what is missing, is therefore considered timely and appropriate in this context.

Keywords: high temperature superconductor, magnet, Bi-2223, Bi-2212, REBCO

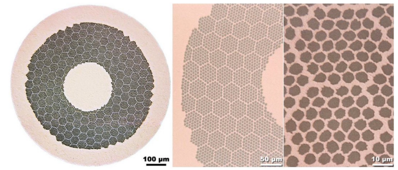
Submitted to: *Supercond. Sci. Technol.*

Agenda

- Low Temperature Superconductors
  - Why higher temperatures are cooler
- High Temperature Superconductors
  - Types, production, main properties, price
- Applications
  - Magnets, rotating machines, energy,…
- An outlook for HTS

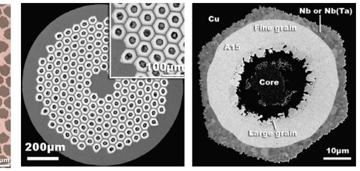
Low Temperature Superconductors

Present performance boundaries



Nb-Ti

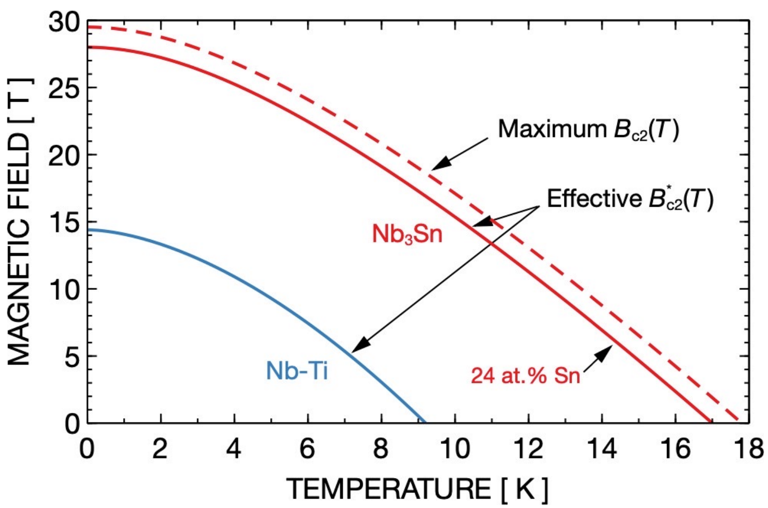
Lee, in "*100 years of Superconductivity*" (2011)



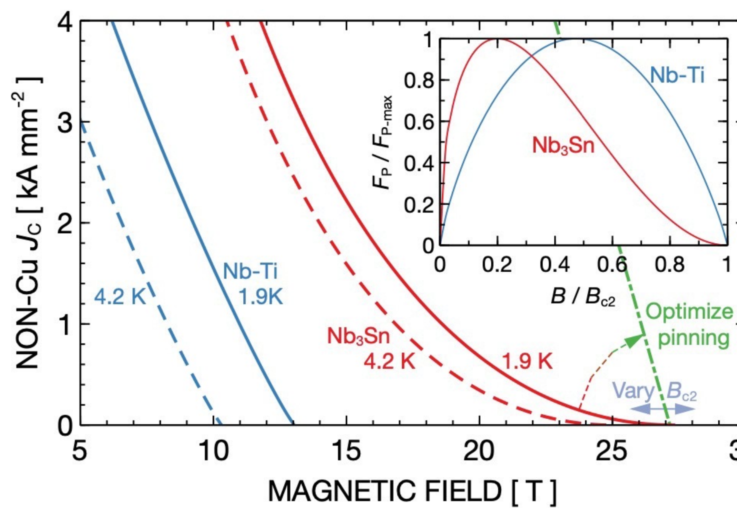
Nb_3Sn

Godeke, Cryogenics 48, 308 (2008)

- Magnetic field and temperature



- Current density



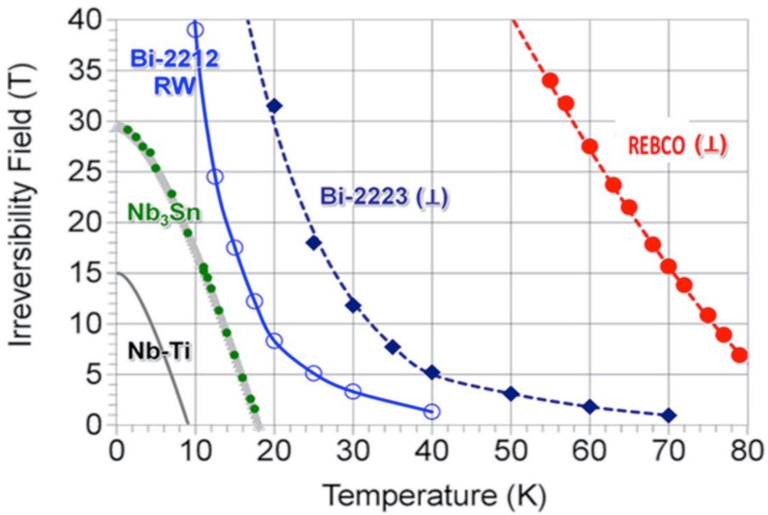
Godeke, *J. Appl. Phys.* 97, 093909 (2005)
Godeke, *IEEE Trans. Appl. Supercond.* 17, 1149 (2007)

Nb-Ti → Fully optimized
Nb_3Sn → Further potential (upcoming topical review)

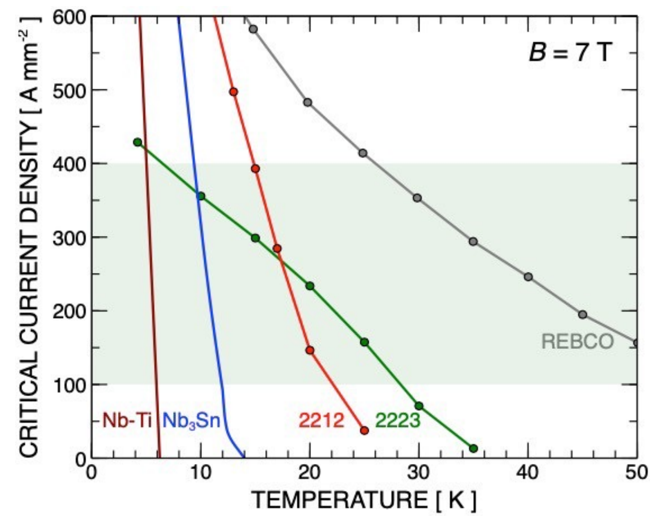
Why higher temperatures are cooler (1)

Increased performance boundaries with HTS

- Higher magnetic fields are accessible



- Usable at higher temperatures
  - Helium is becoming scarce

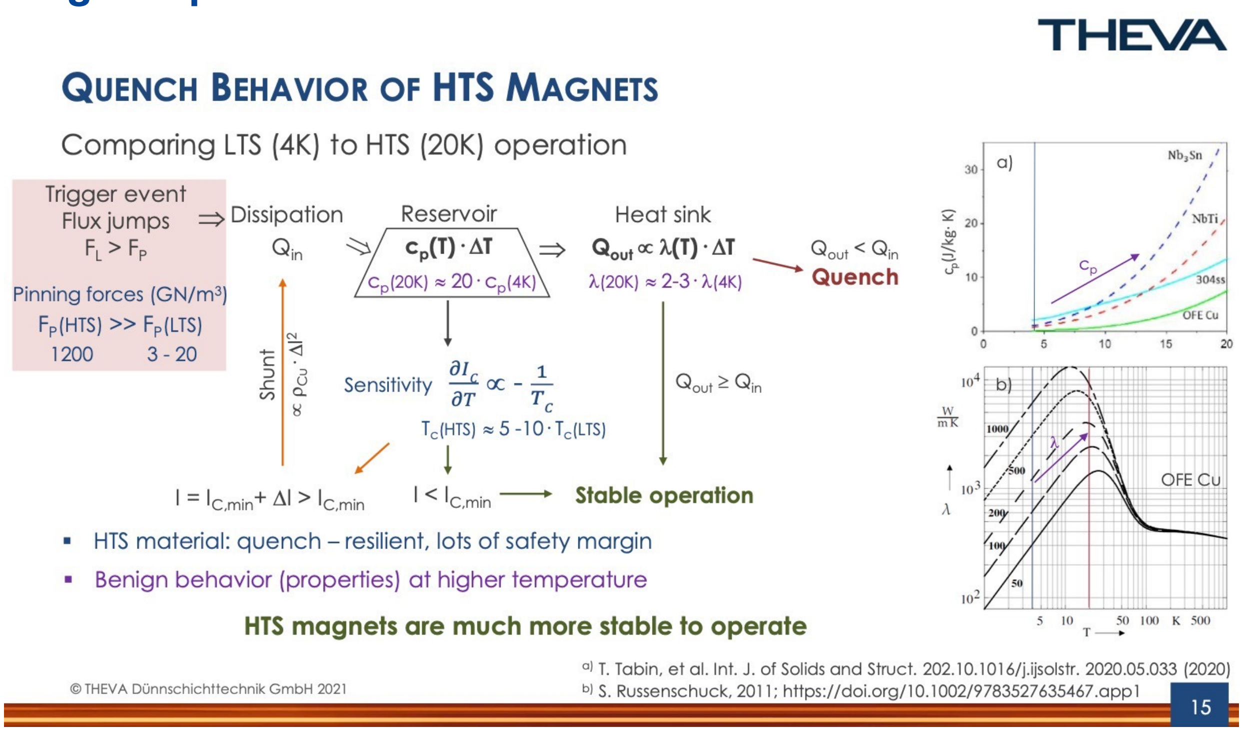


Larbalestier, *Nat. Mat.* 13, 375 (2014)
Godeke, *Supercond. Sci. Technol.* 33, 064001 (2020)

Gains in magnetic field and operating temperature

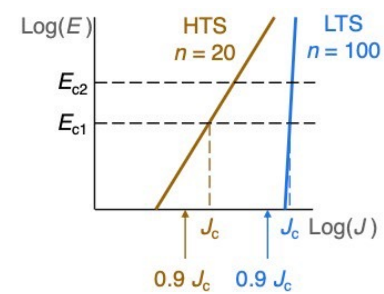
Why higher temperatures are cooler (2)

Magnet operation becomes easier



Reproduced with permission from W. Prusseit, *Virtual CCA conference*, 14-10-2021

- Lower n-values in HTS
  - LTS → "Quench"
  - HTS → Slow runaway



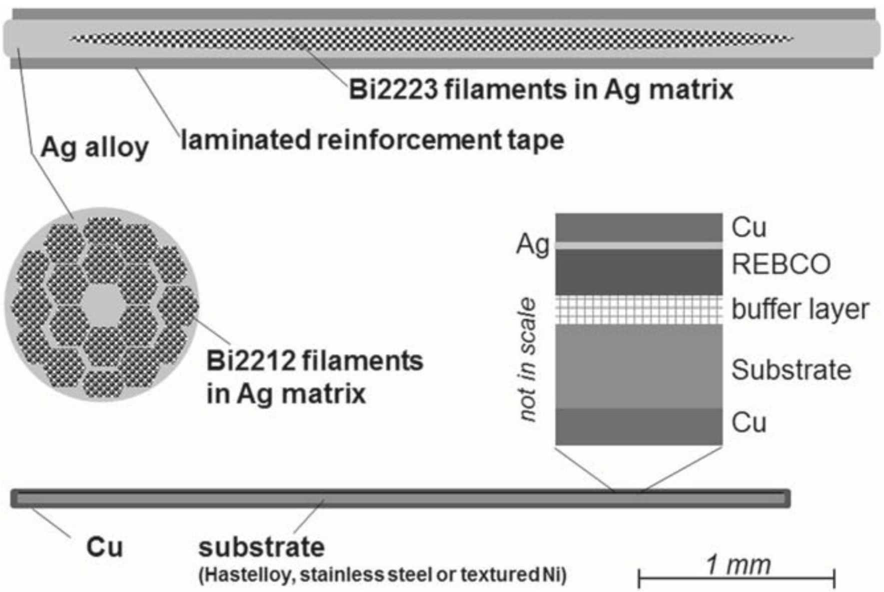
Upcoming Topical Review

Agenda

- Low Temperature Superconductors
  - Why higher temperatures are cooler
- High Temperature Superconductors
  - Types, production, main properties, price
- Applications
  - Magnets, rotating machines, energy,…
- An outlook for HTS

High Temperature Superconductors

Three commercially available options

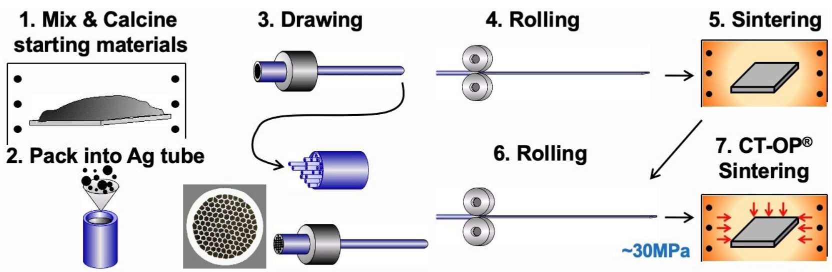


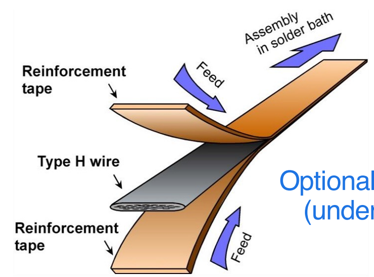
- Bi-2223 ($[Bi\text{-}Pb]_2Sr_2Ca_2Cu_3O_x$)
  - 1 (?) manufacturer
  - 4.2 or 4.5 mm wide, 0.23…0.35 mm thick tapes
  - Ag/Ag-alloy matrix with optional reinforcement
  - Multifilamentary, untwisted
  - Pre-reacted
- Bi-2212 ($Bi_2Sr_2Ca_1Cu_2O_x$)
  - 2+ (?) manufacturers
  - Round and rectangular wires of various dimensions
  - Ag/Ag-alloy matrix with optional reinforcement
  - Multifilamentary, twisted or untwisted
  - Wind & React or pre-reacted
- REBCO ($[RE]Ba_2Cu_3O_x$)
  - 10+ (?) manufacturers
  - 2…40 mm wide, about 0.05…0.2 mm thick tapes
  - High-strength substrate with variable Cu plating
  - Single- or double REBCO layer
  - Pre-reacted

Uglietti, *Supercond. Sci. Technol.* 32, 053001 (2019)

SUMITOMO ELECTRIC DI-BSCCO

Bi-2223 conductors

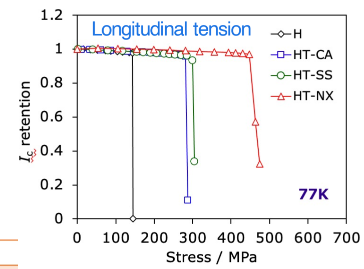




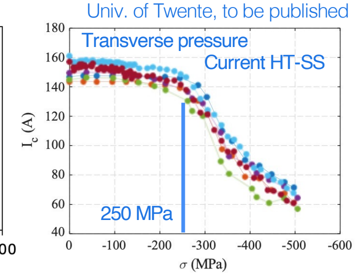
Specifications	Type H	Type G
Average Width	4.2 ± 0.2 mm	4.2 ± 0.2 mm
Average Thickness	0.23 ± 0.01 mm	0.23 ± 0.01 mm
Length / Matrix	Up to 1000 m	Ag-Au 5.4wt%
I_c (77 K, Self Field)	≧ 170 A	≧ 170 A
Critical Wire Tension* (RT)	80 N **	80 N **
Critical Tensile Strength* (77 K)	130 MPa **	130 MPa **
Critical Tensile Strain* (77 K)	0.2% **	0.2% **
Critical Double Bend Diameter* (RT)	80 mm **	80 mm **

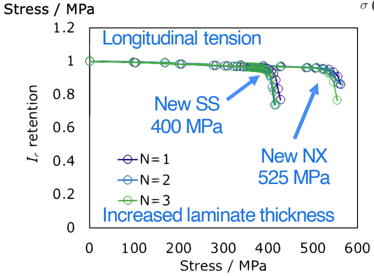
Specifications

	Type HT-SS	Type HT-CA	Type HT-NX
Average Width	4.5 ± 0.1 mm	4.5 ± 0.1 mm	4.5 ± 0.2 mm
Average Thickness	0.29 ± 0.02 mm	0.35 ± 0.02 mm	0.31 ± 0.03 mm
Reinforced Material	Stainless Steel (20μm)	Copper Alloy (50μm)	Nickel Alloy (30μm)
Length		Up to 500m	
I_c (77 K, Self Field)		170 A, 180 A, 190 A, 200 A	
Critical Wire Tension* (RT)	230 N **	280 N **	410 N **
Critical Tensile Strength* (77 K)	270 MPa **	250 MPa **	400 MPa **
Critical Tensile Strain* (77 K)	0.4% **	0.3% **	0.5% **
Critical Double Bend Diameter* (RT)	60 mm **	60 mm **	40 mm **



Univ. of Twente, to be published





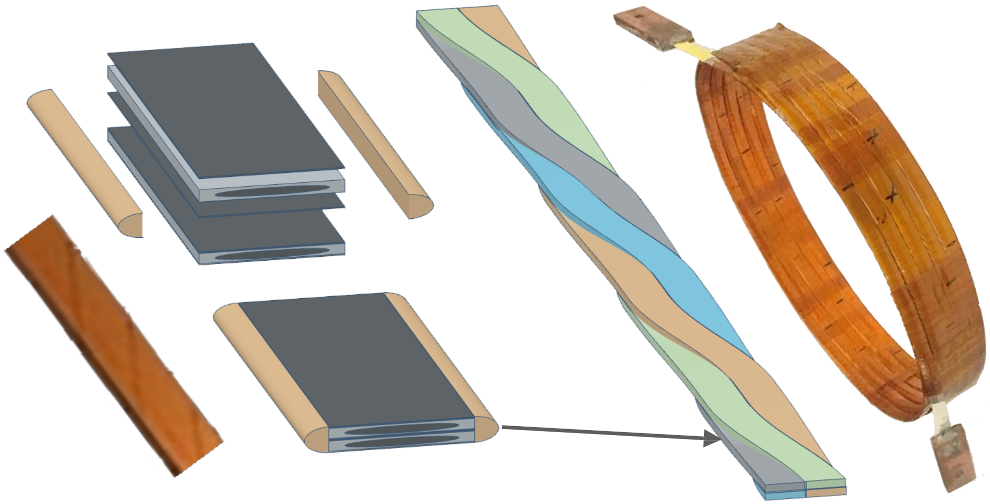
Sumitomo Electric product flyer (2021) – Hayashi, *33rd ISS* (2020) – Hayashi, *3rd Asian Supercond. Summer School* (2018)

Solid Material Solutions, LLC

Bi-2223 cables

Large magnets need cables → Limit L (→V) and winding cost

- Magnet cables
  - Dense → High J_E
  - Mechanically stable
  - Transposed
  - Flexible
  - Scalable
- Bi-2223 → Magnum NX® cable
  - Solid Material Solutions
  - Sumitomo HT-NX tape
    - 2 or more tapes bundled and wrapped
    - Wrapped bundles are cabled



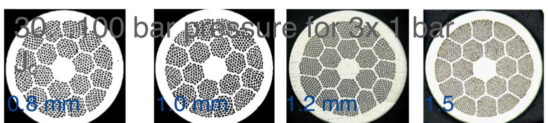
Cabling high aspect ratio conductors is not trivial

Saraco, *Appl. Supercond. Conf.* (2020)
Otto, *Low Temp. Supercond. Workshop* (2022)
Upcoming topical review

Bi-2212 conductors

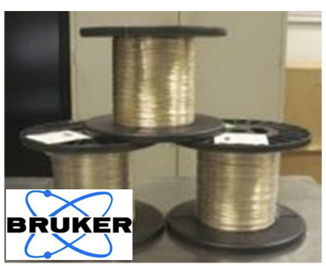
Manufactured by Bruker-OST and by Solid Material Solutions

- Powder-in-Tube process similar to Bi-2223
  - Reaction at 890 ! 1…5"C in O_2
    - → Challenge for materials
  - Highest J_c with overpressure reaction
    - 30 … 100 bar pressure for 3x 1 bar J_c



72 mm OD, 28 mm ID, h = 50 mm

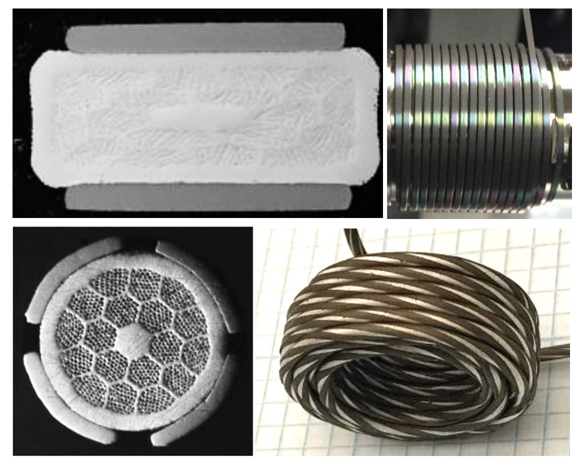
OD 72 mm x ID28 mm x L50 mm



Huang, *13th EUCAS conf.* (2017)

- Novel designs
  - With strengthening
    - Rectangular and round
  - Cost reductions
  - High J_c without overpressure

Solid Material Solutions, LLC



Otto, *33th ISS* (2020)

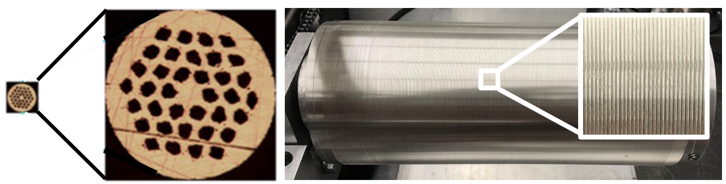
Bi-2212 wires for AC applications

Solid Material Solutions, LLC

Rotating machines, energy, and fast ramping magnets require low AC-loss

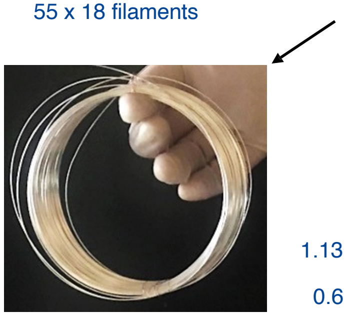
- Reduction of AC-losses using LTS experience
  - Small ∅filaments, ∅wire, and twist-pitch (loops) + resistivity

∅1 mm standard
55 x 18 filaments



∅0.16 mm
36 filaments

300 m spool at ∅0.236 mm
36 filaments

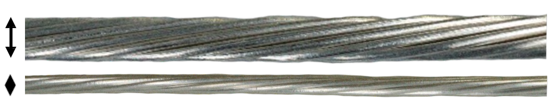


Cabled at ∅0.236 mm 36 filaments

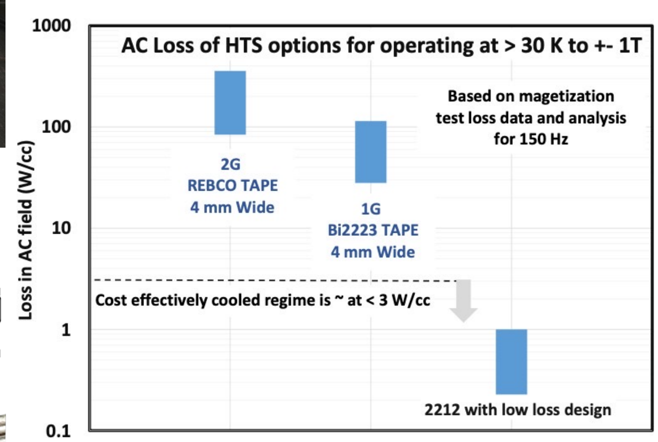
Round wire | Consolidated | Reinforced

1.13 mm

0.6 mm



- Comparison of losses for B⊥ tapes
  - 2 orders of magnitude lower AC-loss



Otto, *Low Temp. Supercond. Workshop* (2022)

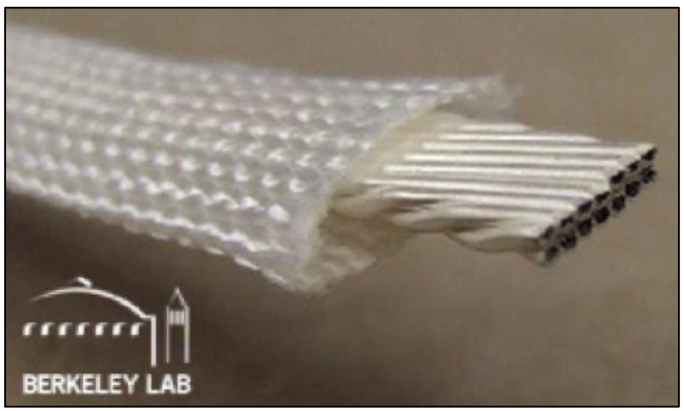
Low losses are key for cryogen-free: Power density gains can be cancelled by cooling needs

Bi-2212 cables

Easier to cable round and low-aspect ratio conductors

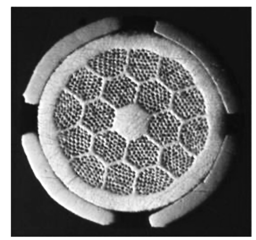
Solid Material Solutions, LLC

- Traditional Rutherford cables
  - For round Bi-2212 wires
    - With braided ceramic fiber insulation
  - Ag is soft after reaction heat-treatment



Godeke, *LBNL, unpublished* (2008)

- Cables from reinforced Bi-2212 conductors



Round reinforced cable (6 wires)

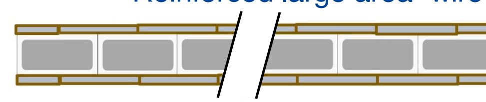
∅5 mm

Roll-consolidated reinforced cable

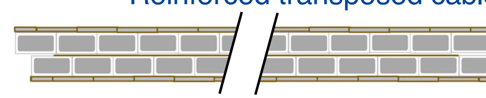
4.32 mm

2.41 mm

Reinforced large area "wire"



Reinforced transposed cable



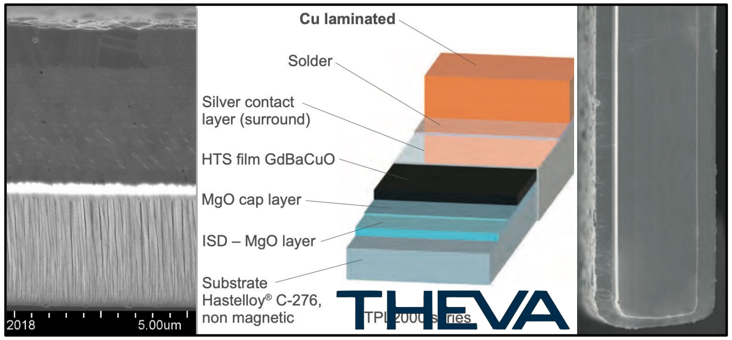
Transposed top view

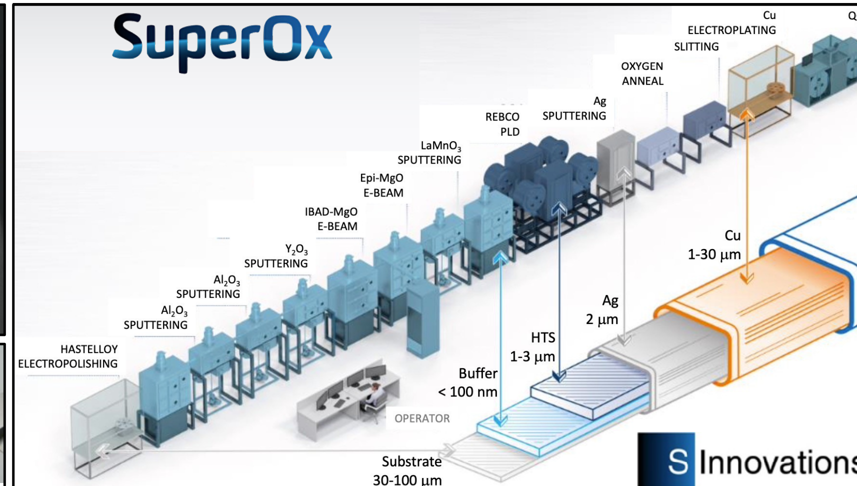
Otto, *Low Temp. Supercond. Workshop* (2022)

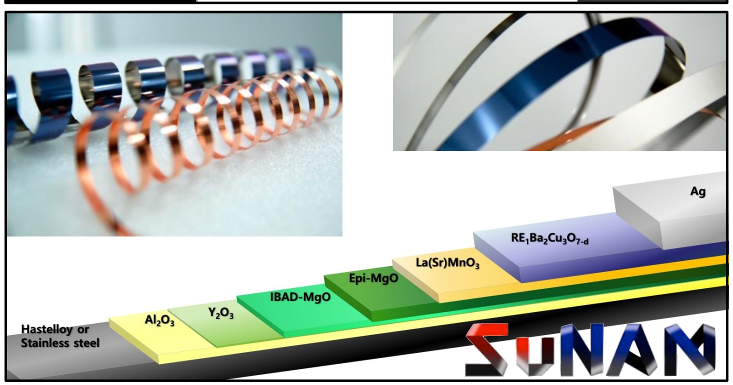
REBCO conductors

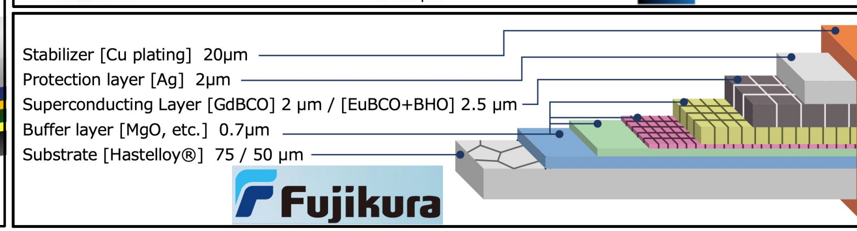
A non-exclusive selection…

THEVA Product flyer (2021)
W. Prusseit, *Virtual CCA conference* (2021)
Molodyk, *15th EUCAS* (2021)
Lee, Virtual CCA (2021)
https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/2052504_12808.html (2021)









REBCO cables

Some examples…

- Four main configurations
  - Roebel
    - KIT and IRL
    - Full transposition
  - Stacks in slotted core
    - ENEA
  - Cable On Round Core
    - ACT
  - Twisted Stack
    - Swiss Plasma Center

Goldacker, *Supercond. Sci. Techn.* 27, 093001 (2014)
van der Laan, *Supercond. Sci. Techn.* 28, 124001 (2015)
Chiesa, *Appl. Supercond. Conf.* (2014)
Uglietti, *13th EUCAS* (2017)

Global specifications of HTS

Upcoming Topical Review

Cost of application

Performance of application

Property	Bi-2212	Bi-2223	REBCO
Physical properties			
Current manufacturers	Bruker-OST Solid Material Solutions	Sumitomo Electric Industries	> 10 companies
Superconductor	$Bi_2Sr_2CaCu_2O_{8+x}$	$Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10-y}$	$[RE]Ba_2Cu_3O_{7-\delta}$
Construction	Ag/Ag-alloy matrix Optional reinforcement	Ag/Ag-alloy matrix Optional reinforcement	High-strength substrate Variable Cu-plating
Superconductor fraction	20–35%	30–40%	< 5%
Ag/Ag-alloy fraction	65–80%	60–70%	< 1%
Substrate fraction	—	—	50–98%
Copper fraction	—	—	0–50%
Form-factor	Twisted multi-filamentary wire	Non-twisted multi-filamentary tape	Single- or dual-layer tape
Typical dimensions	∅ 0.15–1.5 mm and squared	$4.2 \times 0.23\,mm^2$ (bare) $4.5 \times 0.29–0.35\,mm^2$ (reinforced)	$2–40 \times 0.05–0.2\,mm^2$
State	Wind & React or pre-reacted	Pre-reacted	Pre-reacted
Piece length [m]	> 500	> 500	< 300
Electrical properties			
$J_E(15\,T, 4.2\,K)$ [$A\,mm^{-2}$]	200[a]–700[b]	350–500[c]	400–1500[c,d]
Mechanical properties			
Critical axial tensile stress [MPa]	100-130 (bare) > 250 (reinforced)	130 (bare) 250–525 (reinforced)	400–800
Usable axial strain window	0% to 0.3–0.6%	−0.1% to 0.25% (bare) −0.1% to 0.57% (1%[e]) (reinforced)	−1.2% to 0.4–0.7%
Critical transverse compressive stress [MPa]	70 (bare, impregnated)[f]	70–100 (bare) 150–250 (reinforced)	300–750

Conductor mechanics, not J_E, is the main driver for application performance

→ J_E is much less dependent on field (vs LTS), so J_E mainly determines application cost

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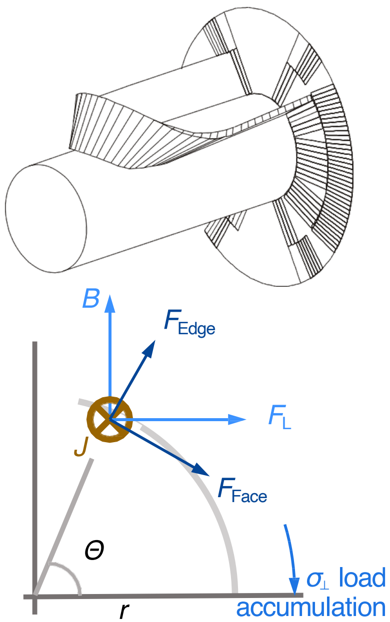
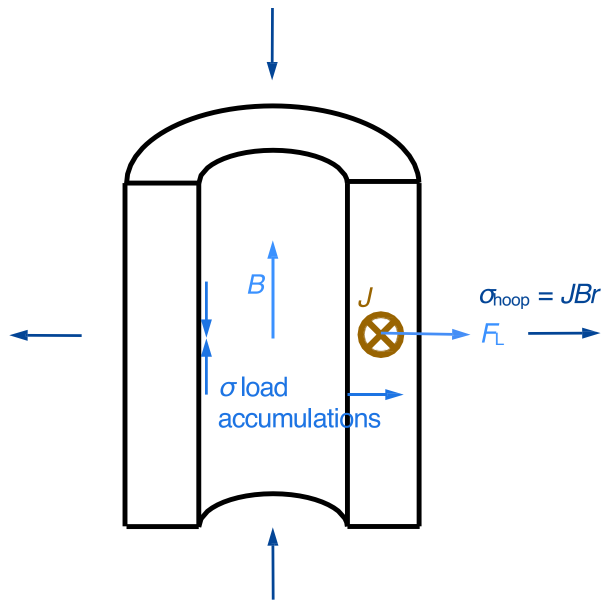
Mechanical loads on conductors

Complex 3D loads → Tension, compression, shear, torsion, buckling,…

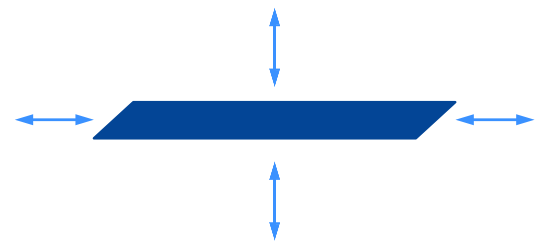
- Dipole magnets



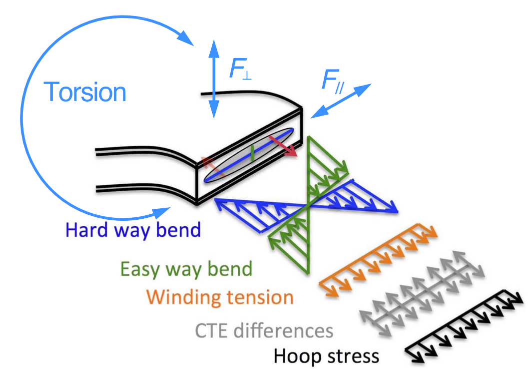
- Solenoid magnets



- Conductor tests



- Reality

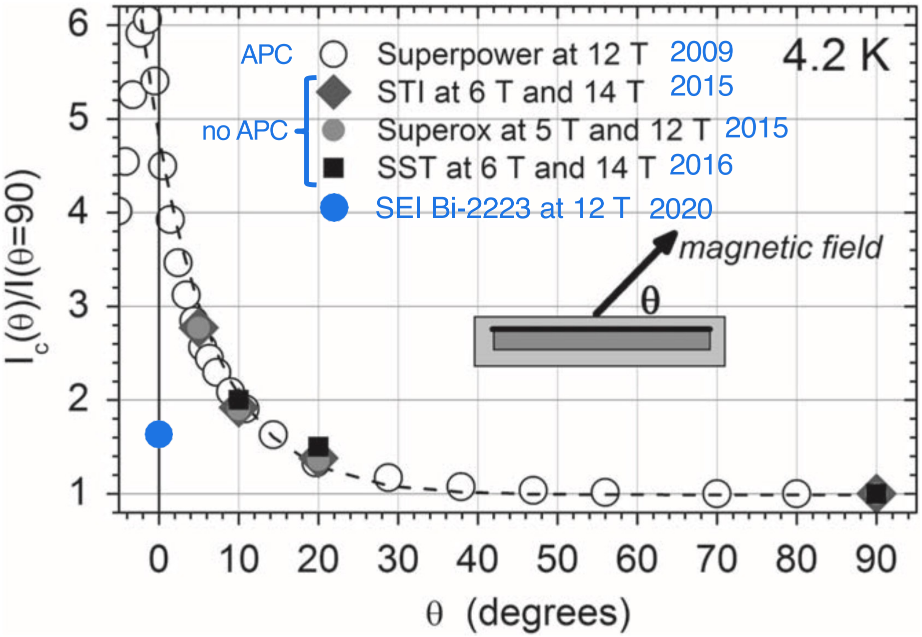


3D loads are key to successful applications. In AC applications also cyclic loads (fatigue)

Anisotropy in HTS tape conductors

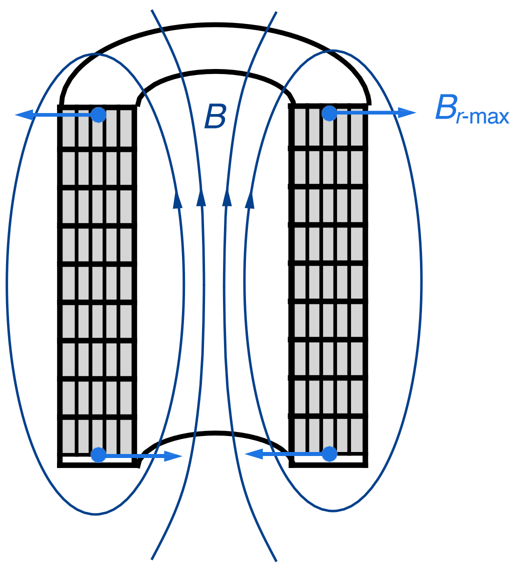
Critical current depends on angle

- Angular dependence of the critical current



Uglietti, *Supercond. Sci. Technol.* 32, 053001 (2019)

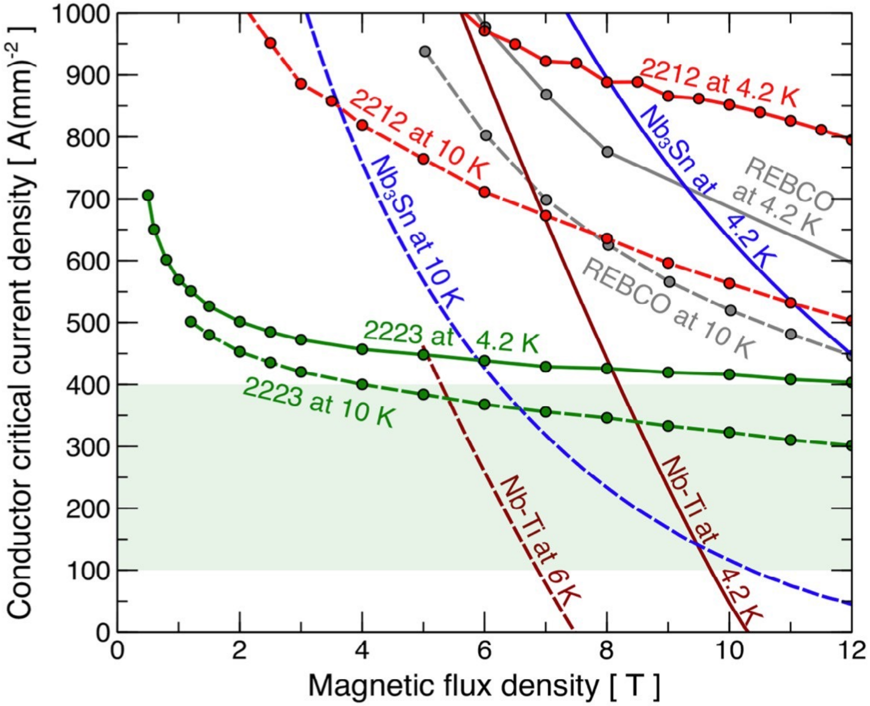
- Practical consequence
  - Localized limitations of J_c



Angular dependencies are an important aspect of application design

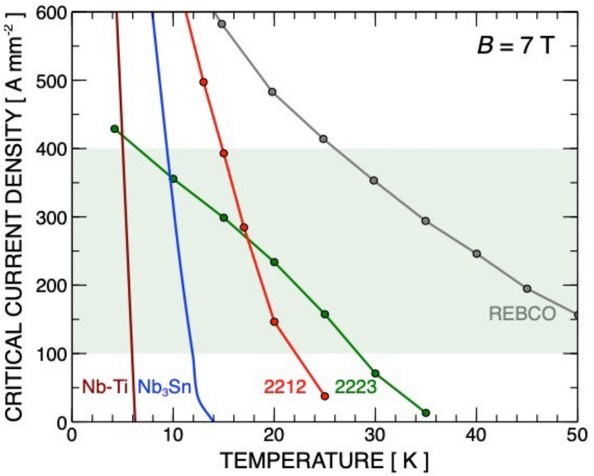
Critical current of HTS

Compared to LTS



Cryogen-free designs → Driven by economics and mechanics

- **Key takeaways**
  - All HTS have sufficient J_E
    - For <u>safe</u> operation in the indicated field-range
  - Dependence on B is less than LTS
  - Cryogen-free: LTS has little or no margin



Godeke, *Supercond. Sci. Technol.* 33, 064001 (2020)

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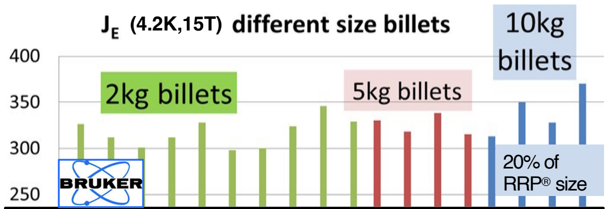
Manufacturing yield

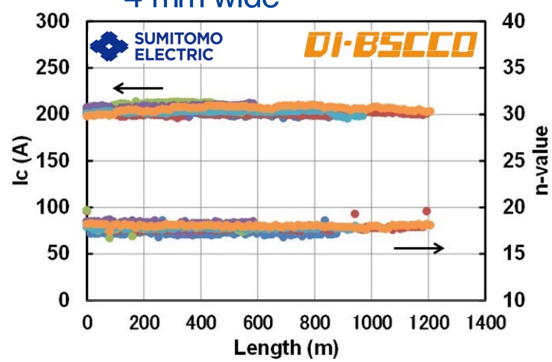
Bi-2212



10 kg → 800 m @1.3 mm / 1,300 m @1.0 mm / 2,400 m @0.8 mm

Huang, *13th EUCAS conf.* (2017)

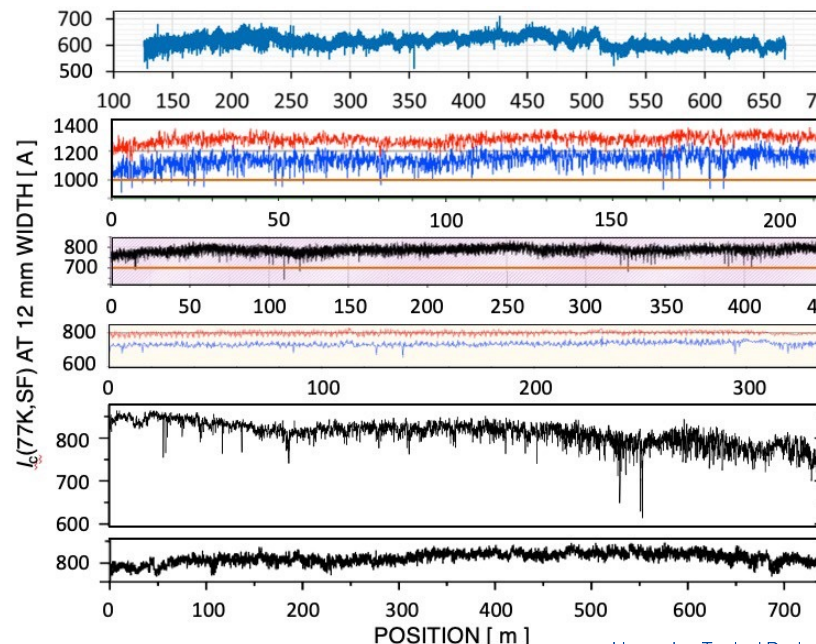
Bi-2223 4 mm-wide



1 km class, 77 K SF I_c Standard Deviation of 3% over 7 productions

Hayashi, *3rd Asian Supercond. Summer School* (2018)

REBCO



Upcoming Topical Review

Bi-conductors: Traditional wire drawing
REBCO: Harder to produce in long lengths

Generic conductor price

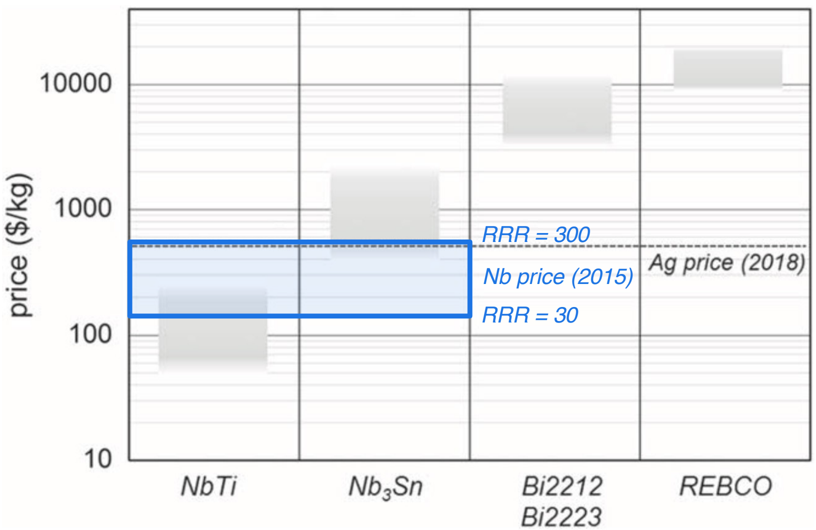
Compared to LTS

Indicative $/m
∅0.8 mm wire
4 mm wide tape

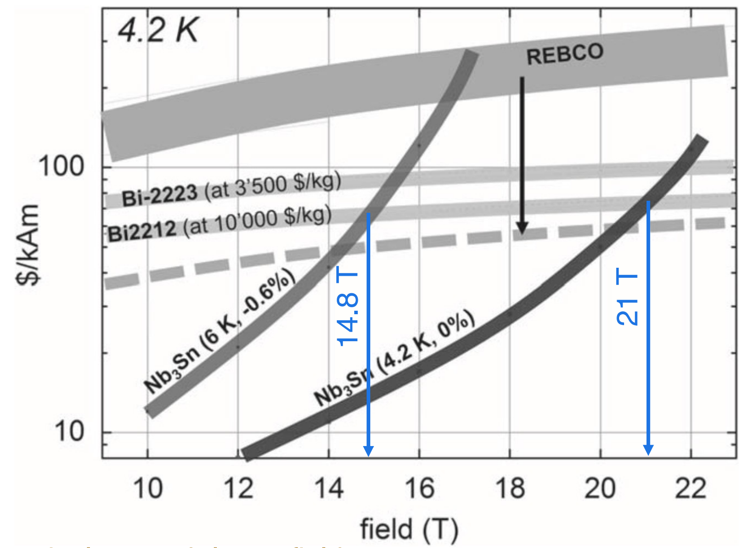
Nb-Ti	Nb_3Sn	Bi-2223	Bi-2212	REBCO
1	3.5	20 ↕	75? ↕	40 ↕

Price ≠ cost:
How much?
Market potential?
Unit lengths?
Performance?
Quality control?

- Price per kg



- Price per kAm



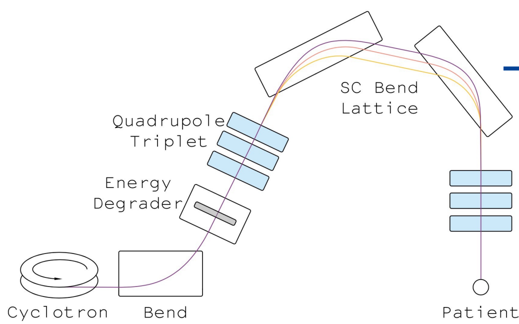
Uglietti, *Supercond. Sci. Technol.* 32, 053001 (2019)

HTS becomes more economical at much lower field at increased T or when Nb_3Sn is affected by strain

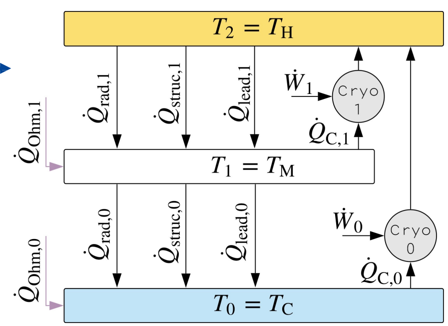
Thermo-economic cost case study

Cryogen-free proton therapy magnet with a 20-year lifespan

- 4 T gantry bend magnet



- Thermo-economic model



- Findings

Conductor	T_{OP} [K]	Cost [k$]
Nb-Ti	6.8	116
Nb_3Sn	9.4	112
Bi-2223	12.8	196
REBCO	5.7	414

- $ Nb-Ti > $ Nb_3Sn (!)
  - Higher cooling needs
  - Low thermal margin
- $ Bi-2223 = $ Nb_3Sn + 80 k$
  - But no reaction needed for HTS
  - HTS is more stable: No training
- $ REBCO ≅ 2x $ Bi-2223
  - Higher conductor capital cost

HTS is more economical for cryogen-free applications

Teyber, *Supercond. Sci. Technol.* 33, 105005 (2020)

Agenda

- Low Temperature Superconductors
  - Why higher temperatures are cooler
- High Temperature Superconductors
  - Types, production, main properties, price
- Applications
  - Magnets, rotating machines, energy, …
- An outlook for HTS

neoscan solutions

Magnet applications (1)

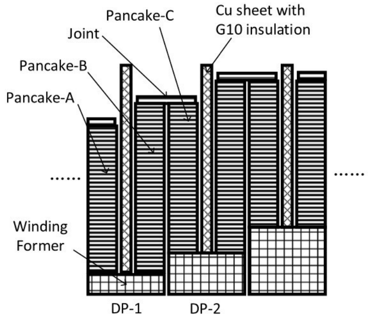
Magnetic Resonance Imaging (MRI)

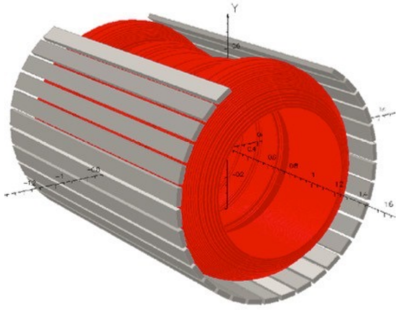
- Cryogen-free pediatric 1.5 T MRI
  - For babies and infants

  - Sumitomo Bi-2223
  - Actively shielded, stray field < 10 m^2
  - Magnet mass < 2 tons

https://www.neoscan-solutions.com (2021)

- Design for a cryogen-free 14 T whole body MRI





  - Sumitomo Bi-2223 HT-NX
  - Magnet → Length 1.9 m by 1.3 m OD
    - Half the size of 11.7 T LTS solution
    - Shorter than commercial 7 T LTS solution
  - Compactness due to mechanical- and field-margins

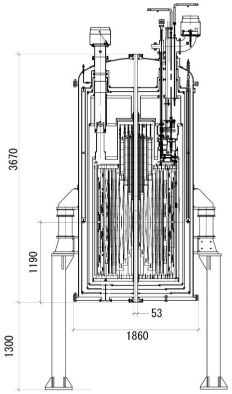
Commercial medical application of HTS
Compact high-field MRI with HTS

Li, *Supercond. Sci. Techn.* 34, 125005 (2021)

Magnet applications (2)

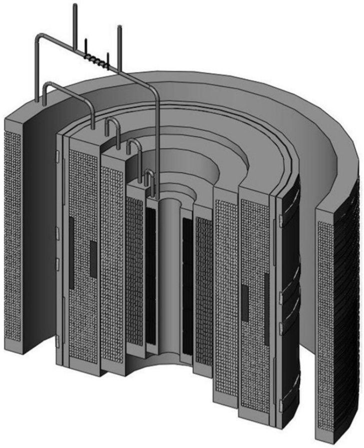
High-field NMR

- NIMS 1.02 GHz NMR
  - LTS limit is 1 GHz (23.5 T)
  - 920 MHz LTS system as basis
    - Inner coil replaced with Sumitomo Bi-2223
  - 1.02 GHz (24 T, driven) achieved at 1.8 K



Hashi, *J. Magn. Res.* 256, 30 (2015)

- Bruker 1.2 GHz (28.2 T) NMR
  - LTS outer with REBCO insert at 2 K
  - Actively shielded
  - Commercial product
  - Persistent



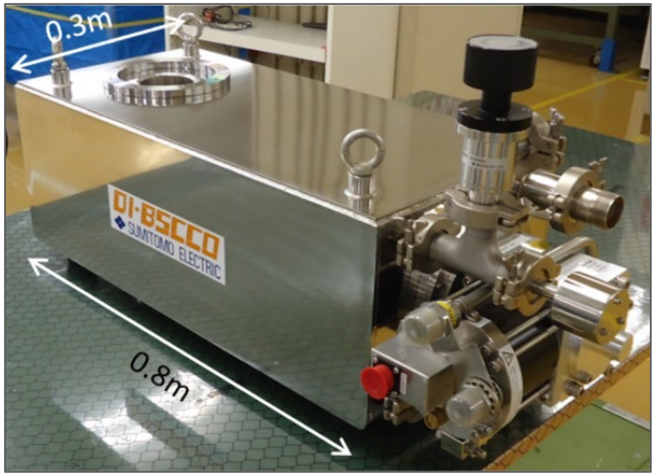
Wikus, *Supercond. Sci. Technol.* 35 033001 (2022)
https://www.bruker.com/en/products-and-solutions/mr/nmr/ascend-ghz-class.html

1.3 GHz (30.5 T) under development (JST Mirai Program, Japan)

Magnet applications (3)

Laboratory magnets

- 5…10 T cryogen-free RT magnets
  - Sumitomo Electric Industries, Ltd.
  - Bi-2223



https://sumitomoelectric.com/super/applications/hts-magnet

- 6 T cryogen-free fast ramping VSM
  - Toei Industry Co.,Ltd
  - Industrial magnetization measurements
  - +/- 6 T operating at 20 K, 70 mm RT bore
  - B-H loop in 3 minutes
    - B-H loop with LTS is 30…40 minutes

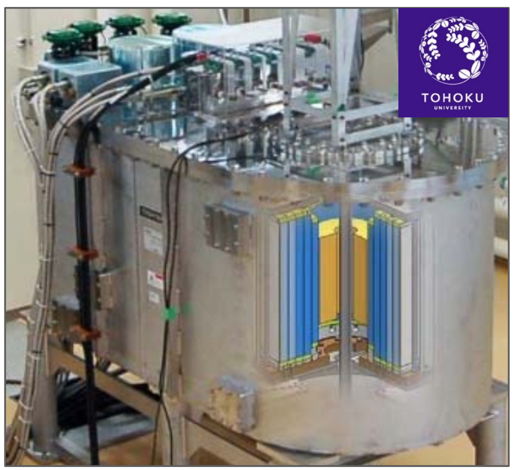
http://www.toeikogyo.co.jp/products/sei-01/vsm-5hsc.html

Magnet applications (4)

“Green” high field user magnets

Copper “Bitter” magnets
31…35 T = 18…20 MW
41…45 T = 30…33 MW
LHC accelerator + detectors: 120 MW

- Superconducting cryogen-free 25 T
  - Tohoku University, Japan
  - Nb-Ti + CuNb reinforced Nb_3Sn LTS section
  - Sumitomo Bi-2223 HT-NX HTS section



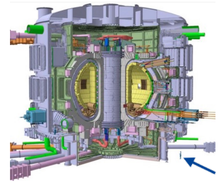
Awaji, *Supercond. Sci. Technol.* 30, 065001 (2017)

- Superconducting 32 T
  - NHMFL, Tallahassee, FL
  - Oxford instruments LTS outer section
  - Superpower REBCO HTS section

https://nationalmaglab.org

Magnet applications (5)

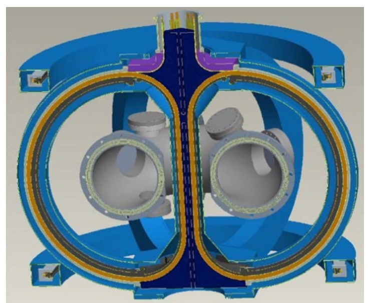
Compact fusion reactors



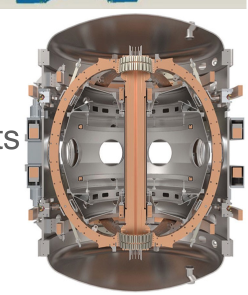
International Thermonuclear Fusion Reactor
→ 3+ decades of international development
Reactor scales with B^4 → Compact high-B Tokamaks

↖ Person

- Tokamak Energy (UK)
  - REBCO

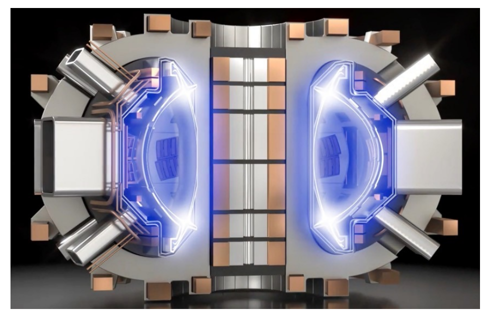


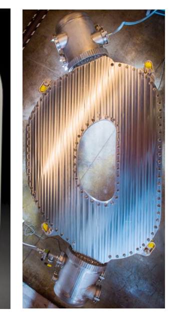
  - Plasma demonstrated in REBCO demo
  - Large private investments
  - Significant government support



Melhem, *IEEE Trans. Appl. Supercond.* 25, 4202304 (2015)
https://www.tokamakenergy.co.uk

- Commonwealth Fusion Systems (USA)
  - REBCO
  - 20 T demonstrated in full-size coil
    - This triggered 1.8B US$ in private funding
    - Unprecedented levels in superconductivity





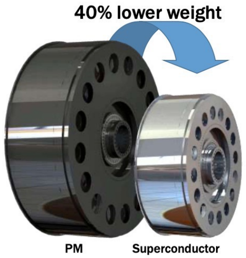
Thousands of km REBCO per system + huge funding
+ potential market size if successful =
Incentives for large-scale REBCO production

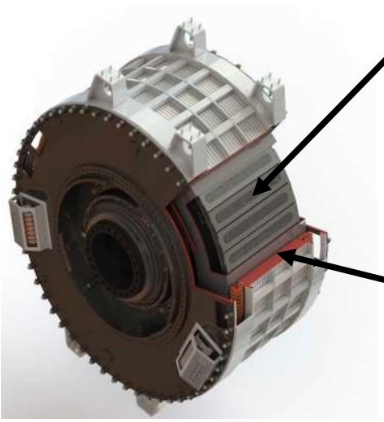
https://cfs.energy

Rotating machines (1)

Superconducting windmills

- 3 MW-class, 14 rpm, 128 m rotor
  - THEVA REBCO racetrack coils in rotor at 30 K
  - Ground tested, installed: Thyborøn, Denmark
- Traditional windmills moved on (> 10 MW)





Rotor

- 40 superconducting rotor poles
- Iron yoke as magnetic flux path
- Vacuum vessel for thermal insulation
- Cooled to 30 K (-243 °C)
- Rotating cryocoolers

Stator

- Conventional copper stator, w/ high current density

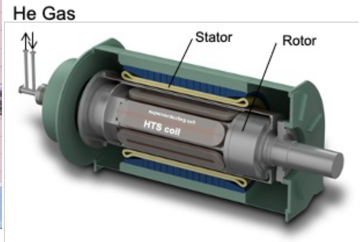
Successful, but high upfront development costs for follow-up

Kellers, *Univ. of Twente Symposium* (2018)

Rotating machines (2)

Electric motors

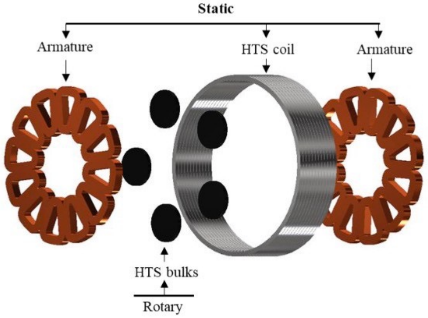
- 3 MW ship propulsion motor (Bi-2223)
  - Kawasaki Heavy Industries



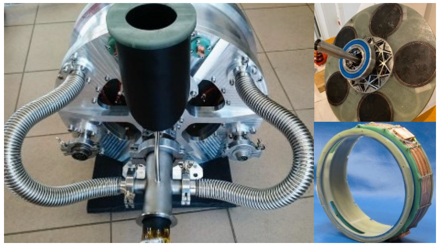
- Electric vehicles (Bi-2223)
  - Sumitomo Electric Industries

Hayashi, *3rd Asian Supercond. Summer School* (2018)

- Electric planes
  - Safran / Airbus / Univ. of Lorraine



- 50 kW prototype
  - 5,000 rpm, 52 kg
  - Bi-2223 stator, REBCO bulk rotor, T_{OP} = 30 K



Dorget, *EUCAS* (2021)

Cables: Allais, Tuesday plenary

Energy applications (1)

Cables

- Sumitomo 3 phase cable
  - Bi-2223

Hayashi, 3rd *Asian Supercond. Summer School* (2018)

	Project (SEI supplied cable system)	V(kV)	I(kA)	L(m)	Site	Wire (Bi:DI-BSCCO)	Note
Japan	TEPCO/SEI	66	1.0	100	CRIEPI	Bi	Finished
	Chubu Univ. (DC)	20	2.0	200	Chubu. Univ.	Bi	In operation
	NEDO (MPACC)	66/275	5.0/3.0	15/30	Test yard	Y	Finished
	NEDO (Yokohama)	66	2.0	240	Asahi S.S.	Bi	In Operation
	SEI in-house demo	3.3	0.2	70	SEI Osaka	Bi	In Operation
	RTRI (DC)	1.5	5	30	Railway Lab	Bi	In Operation
	Ishikari-METI (DC)	10	5	500, 1,000	Data Center	Bi	On going
USA	Albany	34.5	0.8	350	Grid	Bi/Y	Finished
	Ohio	13.8	3	200	Grid	Bi	Finished
	LIPA	138	2.4	600	Grid	Bi/Y	In operation
	Hydra	13.8	4	200	Grid	Y	On going
MEXICO	KASAT	13.8	1.75	17	Hydro P.S.	Bi	On going
EU	Denmark	30	0.2	30	Grid	Bi	Finished
	VNIIKP	20	1.4	200	Grid	Bi	Plan to Grid
	Essen	10	2.3	1,000	Grid	Bi	In operation
	St. Petersburg (DC)	20	2.5	2,500	Grid	Bi	On going
China	Yunnan	35	2	33.5	Puji S.S.	Bi	In operation
	Lánzhōu	10.5	1.5	75	Super - Substation	Bi	In operation
	IEE/CAS(DC)	1.3	10	360	Al mining factory	Bi	In operation
Korea	KEPCO	22.9	1.25	100	Lab	Bi	In operation
	DAPAS1	22.9	1.25	100	Lab	Bi	Finished
	DAPAS2	154	3.75	30	Lab	Y	Finished
	GENI	22.9	1.25	410	Icheon S.S.	Y	Finished
	Jeju	154	2.25	1,000	Grid	Y	On going
	Jeju (DC)	80	3.12	500	Grid	Y	In operation

Renewable energies causing grid overflows: Trigger for cables?

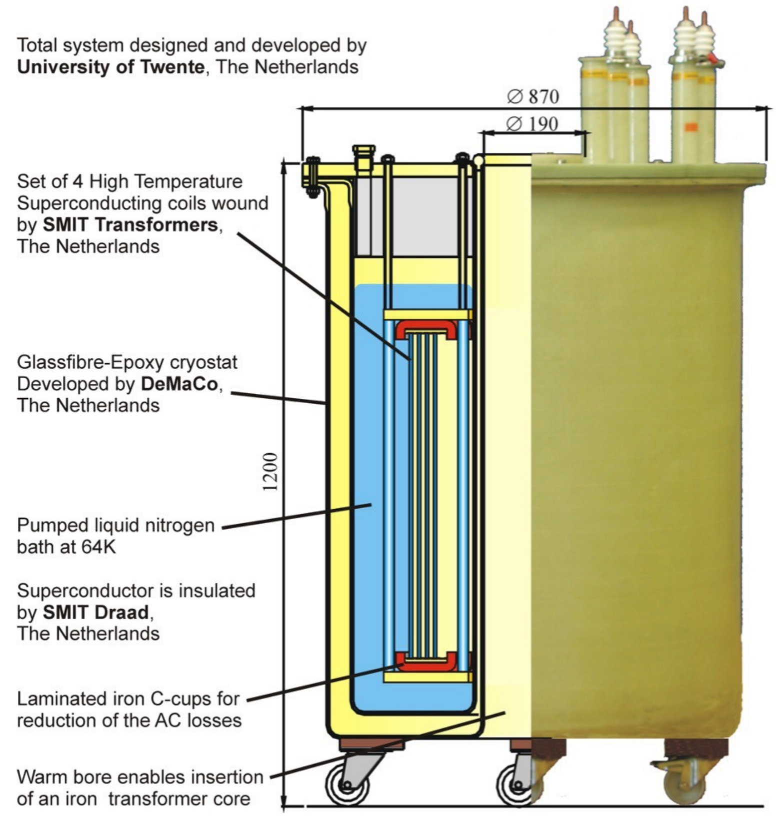
FCL: Allais, Tuesday plenary

Energy applications (2)

Transformers and Fault Current Limiters

- An early HTS "transformer" demo
  - Univ. of Twente around 2000
    - With SMIT Transformers and SMIT Draad
  - 4 concentric industry-wound Bi-2223 coils
    - Vacuumschmelze + American Superconductor tape
  - Configured as a 1 MVA resonator coil
  - Ferromagnetic reduction of radial field at ends
- Significant parallel efforts, same period
  - ABB, Siemens, AMSC,…

Will climate issues trigger revisiting such transformers?



Godeke, *Physica C* 372-376 1719 (2002)

An outlook for HTS

The dawn of commercial applications of HTS

- Climate
  - Private money → Public opinion (→ Legal → Money) → Governmental policy → **Funding** → **Action**
- Less fossil fuels
  - → Helium shortages → Helium **price** → **Action**
- Renewable energy
  - → Grid overloads → Incurred **costs** due to grid failures and lack of availability → **Action**

- Governmental policy changes & funding + bold investors and entrepreneurs = Action
  - Cryogen-free MRI and Compact Fusion → Today
  - Strong incentives for rotating machinery & utility industry → Tomorrow

- Commercial applications are inevitable (after 35 years) → Driven by climate + helium shortage

Thank you!

Contact: agodeke@icloud.com

Acknowledgements

Conductor manufacturers for providing their beautiful slides

Colleagues from around the globe that kindly provided inputs

Referrals are given on the slides

Thanks!