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?

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

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High Temperature Superconductors for Commercial Magnets
Contemplations from a magnet perspective...


Superconductors in High Magnetic Fields
- Now and the future -

Satoshi Awaji
High Field Laboratory for Superconducting Materials (HFLSM), Institute for Materials Research, Tohoku University

High Temperature Superconductors for Commercial Magnets

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20 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 mpulsion, and what is missing, is constant commercial unity and appropriate in this context.

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

- Magnetic field and temperature
  - Maximum $B_{c2}(T)$
  - Effective $B_{c2}(T)$
  - Nb$_3$Sn
  - Nb-Ti
  - 24 at.% Sn

- Current density
  - $F_n / F_{n,\text{max}}$

Nb-Ti $\rightarrow$ Fully optimized
Nb$_3$Sn $\rightarrow$ Further potential (upcoming topical review)


Lee, in “100 years of Superconductivity” (2011)
Godeke, Cryogenics 48, 308 (2008)
Why higher temperatures are cooler (1)

Increased performance boundaries with HTS

- Higher magnetic fields are accessible
- Usable at higher temperatures
  - Helium is becoming scarce

Gains in magnetic field and operating temperature

Larbalestier, Nat. Mat. 13, 375 (2014)
Why higher temperatures are cooler (2)

Magnet operation becomes easier

Quench Behavior of HTS Magnets

Comparing LTS (4K) to HTS (20K) operation

- **Lower n-values in HTS**
  - LTS → “Quench”
  - HTS → Slow runaway

- **HTS material:** quench – resilient, lots of safety margin
- **Benign behavior (properties) at higher temperature**

HTS magnets are much more stable to operate

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  • Why higher temperatures are cooler

■ High Temperature Superconductors
  • Types, production, main properties, price

■ Applications
  • Magnets, rotating machines, energy,…

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High Temperature Superconductors

Three commercially available options

- **Bi-2223 ([Bi-Pb]₂Sr₂Ca₂Cu₃Oₓ)**
  - 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 (Bi₂Sr₂Ca₁Cu₂Oₓ)**
  - 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]Ba₂Cu₃Oₓ)**
  - 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
**Bi-2223 conductors**

1. Mix & Calcine starting materials
2. Pack into Ag tube
3. Drawing
4. Rolling
5. Sintering

---

**Specifications**

<table>
<thead>
<tr>
<th>Type of Bi-2223</th>
<th>Type H</th>
<th>Type G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Width</td>
<td>4.2 ± 0.2 mm</td>
<td>4.2 ± 0.2 mm</td>
</tr>
<tr>
<td>Average Thickness</td>
<td>0.23 ± 0.01 mm</td>
<td>0.23 ± 0.01 mm</td>
</tr>
<tr>
<td>Length / Matrix</td>
<td>Up to 1000 m</td>
<td>Ag-Au 5.4wt%</td>
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<tr>
<td>$I_c$ (77 K, Self Field)</td>
<td>≈ 170 A</td>
<td>≈ 170 A</td>
</tr>
<tr>
<td>Critical Wire Tension* (RT)</td>
<td>80 N **</td>
<td>80 N **</td>
</tr>
<tr>
<td>Critical Tensile Strength* (77 K)</td>
<td>130 MPa **</td>
<td>130 MPa **</td>
</tr>
<tr>
<td>Critical Tensile Strain* (77 K)</td>
<td>0.2% **</td>
<td>0.2% **</td>
</tr>
<tr>
<td>Critical Double Bend Diameter* (RT)</td>
<td>80 mm **</td>
<td>80 mm **</td>
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</table>

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

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*Note: All values are given in standard specifications for Bi-2223 conductors.*

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**Optional lamination (under tension)**

- Univ. of Twente, to be published
**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**
Bi-2212 conductors
Manufactured by Bruker-OST and by Solid Material Solutions

- Powder-in-Tube process similar to Bi-2223
  - Reaction at 890 °C in O₂
  - → Challenge for materials
  - Highest Jₖ with overpressure reaction
  - 300°-150 bar pressure for 3x 1 day

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

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Bi-2212 wires for AC applications

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

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

- Comparison of losses for $B_\perp$ tapes
  - 2 orders of magnitude lower AC-loss

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

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

- Cables from reinforced Bi-2212 conductors

  Round reinforced cable (6 wires)
  \( \varnothing 5 \text{ mm} \)
  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)
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

Uglietti, 13th EUCAS (2017)
Global specifications of HTS

<table>
<thead>
<tr>
<th>Property</th>
<th>Bi-2212</th>
<th>Bi-2223</th>
<th>REBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current manufacturers</td>
<td>Bruker-OST</td>
<td>Sumitomo Electric Industries</td>
<td>&gt; 10 companies</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Bi₂Sr₂Ca₂Cu₃O₇₋ₓ</td>
<td>Bi₂₋ₓPbₓSr₂Ca₂Cu₃O₁₀₋ᵧ</td>
<td>[RE]Ba₂Cu₃O₇₋δ</td>
</tr>
<tr>
<td>Construction</td>
<td>Ag/Ag-alloy matrix</td>
<td>Ag/Ag-alloy matrix</td>
<td>High-strength substrate</td>
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<td>Superconductor fraction</td>
<td>20–35%</td>
<td>30–40%</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Ag/Ag-alloy fraction</td>
<td>65–80%</td>
<td>60–70%</td>
<td>&lt; 1%</td>
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<tr>
<td>Substrate fraction</td>
<td>—</td>
<td>—</td>
<td>50–98%</td>
</tr>
<tr>
<td>Copper fraction</td>
<td>—</td>
<td>—</td>
<td>0–50%</td>
</tr>
<tr>
<td>Form-factor</td>
<td>Twisted multi-filamentary wire</td>
<td>Non-twisted multi-filamentary tape</td>
<td>Single- or dual-layer tape</td>
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<tr>
<td>Typical dimensions</td>
<td>Φ 0.15–1.5 mm and squared</td>
<td>4.2 x 0.23 mm² (bare)</td>
<td>2–40 x 0.05–0.2 mm²</td>
</tr>
<tr>
<td>State</td>
<td>Wind &amp; React or pre-reacted</td>
<td>Pre-reacted</td>
<td>Pre-reacted</td>
</tr>
<tr>
<td>Piece length [m]</td>
<td>&gt; 500</td>
<td>&gt; 500</td>
<td>&lt; 300</td>
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<tr>
<td>Electrical properties</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( J_E (15 T, 4.2 K) [A mm⁻²] )</td>
<td>200⁹–700⁹</td>
<td>350–500⁹</td>
<td>400–1500⁹–d</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Critical axial tensile stress [MPa]</td>
<td>100–130 (bare)</td>
<td>130 (bare)</td>
<td>400–800</td>
</tr>
<tr>
<td>Usable axial strain window</td>
<td>0% to 0.3–0.6%</td>
<td>0% to 0.3–0.6%</td>
<td>–0.1% to 0.25% (bare)</td>
</tr>
<tr>
<td>Critical transverse compressive stress [MPa]</td>
<td>70 (bare, impregnated)</td>
<td>70–100 (bare)</td>
<td>300–750</td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
Mechanical loads on conductors

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

- Dipole magnets
- Solenoid magnets
- Conductor tests

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

Practical consequence

- Localized limitations of $J_c$

Angular dependencies are an important aspect of application design


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Critical current of HTS

Compared to LTS

- All HTS have sufficient $J_E$
  - For safe operation in the indicated field-range
- Dependence on B is less than LTS
- Cryogen-free: LTS has little or no margin

Cryogen-free designs → Driven by economics and mechanics

Manufacturing yield

**Bi-2212**

- $J_E$ (4.2K,15T) different size billets
- 10 kg billets
- 2 kg billets
- 5 kg billets
- 20% of RRP size
- 10 kg → 800 m @ 1.3 mm / 1,300 m @ 1.0 mm / 2,400 m @ 0.8 mm

**Bi-2223**

- 4 mm-wide

**REBCO**

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

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**Upcoming Topical Review**

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

Compared to LTS

<table>
<thead>
<tr>
<th></th>
<th>Nb-Ti</th>
<th>Nb₃Sn</th>
<th>Bi-2223</th>
<th>Bi-2212</th>
<th>REBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRR = 300</td>
<td>1</td>
<td>3.5</td>
<td>20</td>
<td>75</td>
<td>40</td>
</tr>
<tr>
<td>Price per kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price per kAm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HTS becomes more economical at much lower field at increased T or when Nb₃Sn is affected by strain


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Thermo-economic cost case study
Cryogen-free proton therapy magnet with a 20-year lifespan

■ 4 T gantry bend magnet

■ Thermo-economic model

■ Findings

<table>
<thead>
<tr>
<th>Conductor</th>
<th>$T_{OP}$ [K]</th>
<th>Cost [k$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-Ti</td>
<td>6.8</td>
<td>116</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>9.4</td>
<td>112</td>
</tr>
<tr>
<td>Bi-2223</td>
<td>12.8</td>
<td>196</td>
</tr>
<tr>
<td>REBCO</td>
<td>5.7</td>
<td>414</td>
</tr>
</tbody>
</table>

■ $\text{Nb-Ti} > \text{Nb}_3\text{Sn}$ (!)
  • Higher cooling needs
  • Low thermal margin

■ $\text{Bi-2223} = \text{Nb}_3\text{Sn} + 80 \text{k$}$
  • But no reaction needed for HTS
  • HTS is more stable: No training

■ $\text{REBCO} \equiv 2x \text{Bi-2223}$
  • Higher conductor capital cost

HTS is more economical for cryogen-free applications
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
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 m²
  - Magnet mass < 2 tons

- 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


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

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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

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

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

• 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

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

http://www.toeikogyo.co.jp/products/sei-01/vsm-5hsc.html
Magnet applications (4)

“Green” high field user magnets

- Superconducting cryogen-free 25 T
  - Tohoku University, Japan
  - Nb-Ti + CuNb reinforced Nb$_3$Sn LTS section
  - Sumitomo Bi-2223 HT-NX HTS section

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

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

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https://nationalmaglab.org
Magnet applications (5)

Compact fusion reactors

- Tokamak Energy (UK)
  - REBCO
  - Plasma demonstrated in REBCO demo
  - Large private investments
  - Significant government support
  - REBCO demo

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

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

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

https://www.tokamakenergy.co.uk

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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)

Successful, but high upfront development costs for follow-up
Rotating machines (2)

Electric motors

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

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

Electric planes

• Safran / Airbus / Univ. of Lorraine

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


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Dorget, EUCAS (2021)

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## Energy applications (1)

### Cables

- Sumitomo 3 phase cable
- Bi-2223

<table>
<thead>
<tr>
<th>Project (SEI supplied cable system)</th>
<th>V(kV)</th>
<th>I(kA)</th>
<th>L(m)</th>
<th>Site</th>
<th>Wire (Bi:DI-BSCCO)</th>
<th>Note</th>
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<tbody>
<tr>
<td>Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TEPCO/SEI</td>
<td>66</td>
<td>1.0</td>
<td>100</td>
<td>CRIEPI</td>
<td>Bi</td>
<td>Finished</td>
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<td>Chubu Univ. (DC)</td>
<td>20</td>
<td>2.0</td>
<td>200</td>
<td>Chubu. Univ.</td>
<td>Bi</td>
<td>In operation</td>
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<td>NEDO (MPACC)</td>
<td>66/275</td>
<td>5/0.38</td>
<td>15/30</td>
<td>Test yard</td>
<td>Y</td>
<td>Finished</td>
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<td>66</td>
<td>2.0</td>
<td>240</td>
<td>Asahi S.S.</td>
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<td>SEI in-house demo</td>
<td>3.3</td>
<td>0.2</td>
<td>70</td>
<td>SEI Osaka</td>
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<td>In Operation</td>
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<td>RTRI (DC)</td>
<td>1.5</td>
<td>5</td>
<td>30</td>
<td>Railway Lab</td>
<td>Bi</td>
<td>In Operation</td>
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<td>Ishikari-METI (DC)</td>
<td>10</td>
<td>5</td>
<td>500, 1,000</td>
<td>Data Center</td>
<td>Bi</td>
<td>On going</td>
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<td>0.8</td>
<td>350</td>
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<td>2.4</td>
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Renewable energies causing grid overflows: Trigger for cables?
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?
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!

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Referrals are given on the slides

Thanks!

Contact: agodeke@icloud.com