HTS versus LTS: physics, technology, and application prospects

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Acknowledgments

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- TU Wien: Johannes Bernardi, Thomas Baumgartner

Financial support:
Hundreds of superconducting elements and compounds are known...
Motivation

Hundreds of superconducting elements and compounds are known...

... but we mostly use niobium and its compounds in applications.

\[
\begin{align*}
\text{Nb, NbN (electronics)} \\
\text{NbTi, Nb}_3\text{Sn (wires, magnets)}
\end{align*}
\]
Motivation

However, there are many promising candidates...
Motivation

However, there are many promising candidates...

... which could become attractive superconductors (HTS) for applications.

- Cuprates
- Iron-based compounds
- MgB$_2$
- ...
What are the hurdles....

...for becoming an "important" superconductor?
Comparison of the superconducting properties of the materials most promising for or used in applications

Prediction of the critical current densities after optimization

State-of-the-art performance

Current activities and issues

Application prospects
Requirements

Application: current (density), power, weight and space restrictions, mechanical properties, maintenance, efficiency, operation conditions (temperature, magnetic field), etc.
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Basic superconducting properties
Requirements

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Processing: long length, cost effective, high yield...

Basic superconducting properties

Superconductors
Requirements

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Technological issues: thermal, mechanical, chemical, and electric stability, quench protection etc.

Processing: long length, cost effective, high yield...

Basic superconducting properties

Superconductors
Requirements

Application: current (density), power, weight and space restrictions, mechanical properties, maintenance, efficiency, operation conditions (temperature, magnetic field), etc.

Alternative solutions: cost!

Technological issues: thermal, mechanical, and electric stability, quench protection etc.

Processing: long length, cost effective, high yield...

Basic superconducting properties

Superconductors
Basic superconducting properties

Three basic parameters:

- **Critical temperature** $T_c$
- **Upper critical field** $B_{c2}$
  (coherence length $\xi$)
- **Critical current density** $J_c$
  (defect structure, magnetic penetration depth $\lambda, \xi$)

Spoilsports:

- Inter-grain connectivity
- Anisotropy
Critical temperature

- $T_c$ defines the maximum operation temperature
- Robustness of superconducting state against thermal energy

https://en.wikipedia.org/wiki/Superconductivity
Upper critical field

\[ B_{c2} = \frac{\phi_0}{2\pi\xi^2} \]

Cuprates, some iron based compounds

MgB\(_2\), NbTi, (Nb\(_3\)Sn)

http://www.oettinger-physics.de/vortex.html
Critical current density: flux pinning

- Thermodynamic limit: depairing current density
  \[ J_d = \frac{\phi_0}{3\pi\sqrt{3}\mu_0\lambda^2\xi} \]
- Energy of vortex core per meter: \( E_{\text{core}} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2} \)
  \[ f_p^{\text{max}} = \frac{E_{\text{core}}}{\xi} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2\xi} \]
- Critical state: \( F_p = F_L = |J_c \times B| \)
- Highest possible pinning force per vortex and unit length: cylindrical defect with \( r_D \geq \xi \)
- Force balance for one vortex (\( B \perp J_c \)): \( f_L = f_p \)
  \[ f_L = \iint F_L dA = \iint J_c \times BdA = J_c\phi_0 \leq f_p^{\text{max}} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2\xi} \]
- \( J_c^{\text{max}} = \frac{f_p^{\text{max}}}{\phi_0} = \frac{\phi_0}{16\pi\mu_0\lambda^2\xi} = \frac{3\sqrt{3}}{16} J_d \approx 0.32 J_d \)
- \( \eta = \frac{J_c}{J_d} \) ... pinning efficiency
- \( \eta_{\text{max}} \approx 32\% \)

\( J_d \) sets the scale for the achievable critical current density!
Critical current density: neutron irradiation

$r_D \approx 2-3$ nm

MgB$_2$: $r_D \ll \xi \approx 10$ nm $\rightarrow$ Pinning efficiency reduced by $\left(\frac{r_D}{\xi}\right)^2 \approx \left(\frac{2.5}{10}\right)^2 \approx 0.06$

Similar defect structure results in similar pinning efficiency in all materials.

M. C. Frischherz et al., Physica C 232 (1994) 309
M. Zehetmayer et al., PRB 69 (2004) 054510
Depairing current density

Quantitative determination of $\lambda$ is difficult.

$$J_d = \frac{\phi_0}{3\pi\sqrt{3}\mu_0\lambda^2\xi}$$

- $\text{YBCO, } \text{Nb}_3\text{Sn}$
- $\text{NbTi, Fe(Se,Te)}$
Pinning efficiency: highest(?) reported values

\[ \frac{J_c^{sf}}{J_d} \text{ at low temperatures} \]

\[ T \sim 4.2 \text{ K} \]

\[ J_c = 0.15J_d \ (\eta = 15 \%) \text{ can be achieved realistically at low fields.} \]
Achievable in-field performance

- Assumption: $J_c^{sf} = 0.15 J_d$
- Critical state: $F_p = F_L = |J_c \times B|$
- Maximum Lorentz force configuration: $J_c = \frac{F_p}{B}$
- $J_c \propto B^{-\alpha}$, $\alpha = 0, 1$

A. Xu et al., APL Materials 2 (2014) 046111
Achievable in-field performance

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- Maximum Lorentz force configuration: $J_c = \frac{F_p}{B}$
- $J_c \propto B^{-\alpha}(1 - B/B_{c2})^2$, $\alpha = 0.5$

Decrease of condensation energy, overlapping vortices
Optimum performance of various superconductors

Underlying assumptions:

- \( J_{csf} = 0.15J_d \)
- \( J_c(B) \propto B^{-0.5}(1 - B/B_{c2})^2 \)

\[ \text{REBa}_2\text{Cu}_3\text{O}_{7-\delta} \text{(REBCO)} \text{ has by far the best } J_c \text{-properties.} \]
(Nevertheless, NbTi is used by far most frequently)
State-of-the-art

MATERIAL PROPERTIES: LTS
+ Easy to produce (drawing)
+ Highly optimized conductor (α-Ti precipitates)
+ Good mechanical properties (flexible)
+ MRI, accelerator, laboratory magnets
- Modest superconducting properties
  \( T_c \approx 9.6 \text{ K}, \; B_{c2}(0 \text{ K}) \approx 17 \text{ T}, \; J_d \approx 38 \text{ MA/cm}^2 \)

P.J. Lee and D.C. Larbalestier, Presentation at Interwire (Atlanta, GA, 2001)
\[
J_c \sim B^{-0.5}(1-B/B_{c2})^2, \quad J_c(sf)=0.15J_d
\]

layer \( J_c \) (RRP)

\( B_{c2}(4.2\, K) \sim 27\, T, \quad J_d \sim 190\, MA/cm^2 \)

- High field magnets (10-23 T)
- Brittle material (wind & react)
- Grain boundary pinning
- Room for optimization
Actual challenges

Fusion magnets (ITER/DEMO)

- Thermomechanical properties (500 tons Nb₃Sn)
- Technological issues

9×17 m²
4.3×18 m²

Pair of TF Coils
CS Coil

www.iter.org
Actual challenges

Future Circular Collider (FCC-hh)
- Demanding superconducting properties and production costs

### Nb$_3$Sn for FCC: the CERN conductor program

- **CERN-Bochvar** (Russia)
- **CERN-KEK** (Japan)
- **CERN-KAT** (Korea)

**Figure:**
- Graph showing non-Cu $J_c$ at 15 T for various samples
- Legend: Sample A, Sample B, Sample C
- Data points marked with arrows

**Text:**
- Four years program – started in 2017

### Superconductor for FCC (100 km, 100 TeV)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>mm</td>
<td>~ 1</td>
</tr>
<tr>
<td>Non-Cu $J_c$ (16 T, 4.2 K)</td>
<td>A/mm$^2$</td>
<td>$\geq$ 1500</td>
</tr>
<tr>
<td>$\mu_0\Delta M$ (1 T, 4.2 K)</td>
<td>mT</td>
<td>$\leq$ 150</td>
</tr>
<tr>
<td>$\sigma(\mu_0\Delta M)$ (1 T, 4.2 K)</td>
<td>%</td>
<td>$\leq$ 4.5</td>
</tr>
<tr>
<td>Deff</td>
<td>$\mu$m</td>
<td>($\leq$ 20)</td>
</tr>
<tr>
<td>RRR</td>
<td>-</td>
<td>$\geq$ 150</td>
</tr>
<tr>
<td>Unit length</td>
<td>km</td>
<td>$\geq$ 5</td>
</tr>
<tr>
<td>Cost</td>
<td>Euro/kA m**</td>
<td>$\sim$ 5</td>
</tr>
</tbody>
</table>

**Total quantity required:** ~ 8000 tons

- (~1200 tons of Nb-Ti in LHC, ~500 tons of Nb$_3$Sn in ITER)

_A. Ballarino_
Nb$_3$Sn optimization: flux pinning

\[ J_c \sim B^{-0.5}(1-B/B_c)^2, \quad J_c(\text{sf}) = 0.15J_d \]

- non-Cu $J_c$ (RRP)
- FCC specifications

Fast neutron irradiation

Introduced defects (?)


USTEM, TU Wien; S. Pfeiffer et al., 1MP4-01
**Nb₃Sn optimization: flux pinning**

Fast neutron irradiation
- Introduction of small defects
- Point pinning contribution

\[ J_c \sim B^{-0.5}(1-B/B_{c2})^2, \ J_c^{(sf)}=0.15J_d \]

non-Cu \( J_c \) (RRP)

\( J_c \) (MA/cm²)

B(T)

neutron irradiated

FCC specifications

1/3
1/2
+50%

T. Baumgartner et al., Sci. Rep. 6 (2015) 10236; 1MP1-09
APC: flux pinning/grain refinement

Internal oxidation method

- Nb-1% Zr
- Sn source + O source
- Heat treatment
- Nb$_3$Sn with ZrO$_2$ particles
- Residual core
- Residual Nb

Nb$_3$Sn grain size: 100-150 $\rightarrow$ 35-50 nm

Activities at:
Hyper Tech, Ohio State University, FNAL, NHMFL (FSU), University of Geneva

X. Xu et al., Adv. Mat. 27 (2015) 1346
**Nb$_3$Sn optimization**

- **Useful Nb$_3$Sn layer**
  - 40-60% of subelement
  - Unreacted Nb

**Sn-gradients:**
- In sub-elements
- Inside grains

- Increasing fraction of current carrying layer (e.g. heat treatment)
- Improving stoichiometry (e.g. heat treatment)
- Quaternary wires (Ti, Ta)

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**References:**
- Tarantini et al., SUST 27 (2014) 065013
- USTEM, TU Wien, S. Pfeiffer et al., 1MP4-01
Nb₃Sn: Summary

- Nb₃Sn is the favorite conductor for high field magnets (10-23 T).
- Brittle material, demanding wind and react technology
- Performance push by accelerator project (High Luminosity LHC, FCC)
- Demanding ITER magnet technology
Cuprate Superconductors (HTS)

- Layered structure
- CuO$_2$-planes (1-3 per unit cell)

- Complex electronic phase diagram
- Competing orders (charge, spin, sc)
- Quantum critical point(s) in sc dome?

Superconducting condensate essentially behaves as in conventional superconductors.


N. Barišić et al., PNAS 110 (2013) 12235
RE-123 coated conductors

\[ J_c (B||c) > \min_{\theta} J_c \, ? \]

- Highly optimized artificial pinning: Self assembling nano-particles, nano-rods etc.
- Further improvement possible?

Actual status of conductor development: B. Holzapfel 2MO1

A. Xu et al., APL Materials 2 (2014) 046111

Microstructure

- Firework-shape defect structure (BZO)
- CuO-chain intergrowths

Courtesy of G. Van Tendeloo et al. University of Antwerp
Coated conductor technology

Hilgenkamp and Mannhart, 

A. Gurevich, Nature Mat. 10 (2011) 255

+ High critical current densities
+ Flexible tapes
- Slow and expensive technology
- Small superconducting volume fraction (1-2%)
- Monofilament conductors
Engineering current density

Superconducting volume fraction: wires 30 %, coated conductors 2%

**Ideal performance**

**Critical Current Density**

**Engineering Current Density**

- Single filament: ac losses, no current sharing between the filaments within one strand (high current densities, large temperature margin, small quench propagation velocity → high risk of damage)
Anisotropy of the upper critical field:

\[ \gamma = \frac{B_{c2}(H||ab)}{B_{c2}(H||c)} \]

\[ \lambda_{ab}(0 \text{ K}) \approx 140 \text{ nm}, \lambda_{c}(0 \text{ K}) \approx 1 \text{ μm!} \]

Soft vortex lattice is prone to **thermal fluctuations**.

**High operation temperatures:**
- The maximum operation field is reduced
- The field dependence of \( J_c \) increases
- Low superconducting volume fraction of coated conductors becomes problematic at high temperatures
RE-123: current efforts

- Optimization of **pinning** for the respective operational conditions
  - Nano-precipitates: $\text{BaZrO}_3$ (BZO), $\text{BaHfO}_3$ (BHO), $\text{Ba}_2\text{YNb}_{0.5}\text{Ta}_{0.5}\text{O}_6$ etc.
- Increasing RE-123 layer **thickness**


- Lowering production **cost** (upscaling, higher yield)
  - Chemical solution deposition, CSD
Efforts at ICMAB-Barcelona for improving pinning in scalable, low cost CSD-CC

Nanocomposites with pre-formed non-reactive nanoparticles for first time worldwide

BZrO$_3$, BHfO$_3$ with controlled size and shape

Up to 20% M BHO or BZO can be reached with no decrease on $T_c$ and $J_c^{sf} = 4$ MA/cm$^2$ to be published
Outstanding properties of CSD nano-composites with rich pinning landscapes

Rich microstructures full of defects and disorder inducing vortex pinning (nano-particles, 248-intergrowths, partial dislocations, Cu and O cluster vacancies, lattice distortions,..).

Latest approach is investigating liquid assisted growth of CSD (pre-formed) nanocomposites with 100 x faster growth rates

RE-123: current efforts

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  - Nano-precipitates: BaZrO$_3$ (BZO), BaHfO$_3$(BHO), $\text{Ba}_2\text{YNb}_{0.5}\text{Ta}_{0.5}\text{O}_6$ etc.
- Increasing RE-123 layer thickness
- Lowering production cost (upscaling, higher yield)
  - Chemical solution deposition, CSD
- Development of (superconducting) joints
- Quench detection/protection
- Filamentation (ac losses, field quality)
- Mechanical properties (delamination)
- High current wires/cables

Current distribution in filametted conductor

TRATOS - ENEA
CroCo - KIT
Fusion cable - EPFL
RACC - KIT
CORC® - Advanced Conductor Technologies LCC
Bi-2212

\[ J_c \sim B^{-0.5}(1-B/B_{c2})^2 \]

- Particular growth mode results in local texture
- Macroscopically isotropic
- Surprisingly large currents despite of grain misalignment
- Multi-filamentary wire (25 % sc)
- Successful prototype magnets
  - High pressure (~100 bar) treatment needed
  - Silver sheath (expensive)
  - Bi-2212 only applicable at low temperatures

D. C. Larbalestier
Nature Mat. 13 (2014) 375
HTS Applications: High Field Magnets

- 32 T at Tallahassee (NbTi, Nb$_3$Sn, RE-123)  
  Huub Weijers - 3P1

- 24.6 T cryogen free  
  S. Awaji, 1P2

- Accelerator magnets

- 26.7 T, all RE-123  
  no insulation coils  
  (radial current sharing)  
  S. Awaji et al., SUST 30 (2017) 065001

- 27.6 T demonstrator for 1.3 GHz  
  (30.5T) NMR project  
  S. Yoon et al., SUST 29 (2016) 04LT04

- 17.6 T @ 26 K  
  $\phi = 2.5$ cm  
  J.H. Durrell et al., SUST 27 (2014) 082001
(Possible) HTS applications

- High current cables
- Power transmission lines (Ampacity: 1 km, 10 kV, 40 MW)
- Motors, generators, (e.g. Ecoswing M. Bauer 2LO2)
- Fault current limiters (e.g. FastGrid P. Tixador 1LO1)
- Electric Aircrafts (cables, propulsion, generators)

3.6 MW wind turbine, 128 m rotor diameter

https://ecoswing.eu/project

M. Stemmle et al., talk at CIRED 2015
Medium Temperature Superconductors

ALTERNATIVE MATERIALS
MgB$_2$

Upper critical field anisotropy: 5-6

Critical current in polycrystalline materials

Calculated by a percolation model: $J_c = \int_0^{J_c^{\max}} \left( \frac{p(J) - p_c}{1 - p_c} \right)^{1.78} dJ$

M. Eisterer et al., PRL 90 (2003) 247002
**MgB₂**

Upper critical field anisotropy: 5-6

Critical current in polycrystalline materials

- Thin films: max. $B_{c2}(H\parallel ab) \sim 70$ T, $B_{c2}(H\parallel c) \sim 40$ T
- Bulk materials: max. $B_{c2}(H\parallel ab) < 40$ T, $B_{c2}(H\parallel c) \sim 10$ T
- Difference is not yet understood.

**Impurity scattering enhances $B_{c2}$**

$B_{c2}(T)$ versus $T (K)$

$B(T)$ and $J_c (MA/cm^2)$

$B_{c2} = 14$ T, $\gamma = 6$ (clean limit)

Fraction of grains with $J_c > 0.05$ MA/cm$^2$
MgB$_2$

- Current issues
  - Low inter-grain connectivity (ex-situ & in-situ PIT)
  - Low mass density (in-situ PIT)
  - Small volume fraction (~10 % IMD)

- Significant potential for improvements
  - Conservative estimation: connectivity, volume fraction
  - Pinning: higher borides, Mg-B-O

T. Prikhna 4MP2

![Graph showing $J_c$ vs. $B$ for NbTi, Nb$_3$Sn, and MgB$_2$ at 4.2 K.](image)

$J_c$ (MA/cm$^2$)

$B$ (T)

4.2 K

IMD: Li et al., SUST 26 (2013) 095007
MgB$_2$

- **Current issues**
  - Low inter-grain connectivity (ex-situ & in-situ PIT)
  - Low mass density (in-situ PIT)
  - Small volume fraction (~10 % IMD)

- **Significant potential for improvements**
  - Conservative approach: connectivity, volume fraction
  - Pinning: higher borides, Mg-B-O

- **Thin film performance (B$_{c2}$, $\gamma$, $T_c$)**

![Graph showing Jc vs B(T) for MgB$_2$, YBCO, and Nb$_3$Sn]
MgB$_2$: Applications

- Power transmission
  - Superconducting cables for the HiLumi LHC

BEST PATHS project

- M. Tropeano 4MO2-06, A Marian 3LO4-06, C. Bruzek 3LP7-27

Demonstrator

- 20 kA at 25 K
- Total length: 40 m
- Record in current for MgB$_2$

1 phase, 5-10 kA, 200-320 kV (1-3.2 GW)

A. Ballarino et al., IEEE TAS 26 (2016) 5401705

Courtesy of A. Ballarino (CERN)
MgB$_2$: Applications

- Magnetic Resonance Imaging (MRI)
  - Commercial System
    - 0.5 T at 20 K
    - Cryocoolers

- Wind turbines
  - Suprapower (10 MW @ ~20 K)

J. Sun et al., IOPCS MSE 101 (2015) 012088
G. Sarmiento et al., IEEE TAS 26 (2016) 5203006
BaFe$_2$As$_2$

- Cheap PIT process
- Long wires (100m) were demonstrated
- High upper critical fields
  - Intrinsic connectivity problem
    (less severe than in the cuprates)

Polycrystalline materials:
Josephson coupled grains

- $J_c$ increases with decreasing grain size.
- Strong pinning within the grains reduces global $J_c$
  (increasing fields).

J. Hecher et al., SUST 29 (2016) 025004
BaFe$_2$As$_2$

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+ High upper critical fields
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    (less severe than in the cuprates)

Strategies for $J_c$ improvement (inter-grain connectivity):
- Extrinsic limitations
  - Reduction of secondary phases and cracks at the grain boundaries
- Intrinsic limitation (grain boundary angle):
  - Reduction of grain size
  - (Partial) texture

$J_c (\text{MA/cm}^2)$

\[ J_c(B) = 0.15J_0 B^{-0.5}(1-B/B_{c2})^2, \quad B_{c2} = 150 \text{ T}, \lambda = 200 \text{ nm} \]

Ba-122 tape, Huang et al., arXiv:1705.09788
Sm-1111 single crystal, 1.4 GeV Pb
Fang et al., Nature Comm. 4 (2013) 2655
Conclusions

- RE-123 compounds have the most favorable superconducting properties. Pinning is highly optimized in coated conductors.
- The sc properties have to fulfill only the minimum requirements of the respective application. The cheapest solution (conductor, required technologies) is usually chosen.
- The outstanding performance of CC is mandatory so far only for high field magnets, with Bi-2212 being an interesting competitor.
- Despite the many interesting activities, a sufficiently large market for CCs is still missing. If it cannot be established, we risk to lose this option for future applications, where the performance of established superconductors is insufficient.
Conclusions

- MgB$_2$ is an interesting alternative for low field applications, since it can be operated without liquid helium. The in-field properties of wires are poor. It is unclear how to achieve the high critical field demonstrated in thin films.

- The iron-based superconductors promise excellent high field properties. The central issue is currently the inter-grain connectivity.
Conclusions

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Thank you for your attention!