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:
Motivation

Hundreds of superconducting elements and compounds are known...

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

Nb, NbN (electronics)

NbTi, Nb3Sn (wires, magnets)
Motivation

However, there are many promising candidates...

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

- Cuprates
- Iron-based compounds
- MgB$_2$
- ...

Plenary presentation 2P1-01 given at EUCAS, 17-21 September 2017, Geneva, Switzerland.
Motivation

What are the hurdles....

...for becoming an "important" superconductor?
Outline

- 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.

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

Smiley face: \( \text{MgB}_2, \text{NbTi}, (\text{Nb}_3\text{Sn}) \)

Sad face: \( \text{MgB}_2, \text{NbTi}, (\text{Nb}_3\text{Sn}) \)
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 \((B \perp J_c)\): \( f_L = f_p \)

\[ f_L = \iint F_L dA = \iint J_c \times B dA = J_c \phi_0 \leq f_p^{\text{max}} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2\xi} \]

\[ J_c^{\text{max}} = \frac{f_p^{\text{max}}}{\phi_0} = \frac{\phi_0}{16\pi\mu_0\lambda^2\xi} = \frac{3\sqrt{3}}{16} J_d \approx 0.32 J_d \]

- \( \eta = \frac{J_c}{J_d} \) ... pinning efficiency

- \( \eta_{\text{max}} \approx 32\% \)

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

TRIGA reactor

YBCO  MgB$_2$

$r_D \approx 2-3$ nm

$T_c$ (K)

$\eta_{irr}$ (%)

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.

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

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

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

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

- NbTi wire
- \( \text{MgB}_2 \) film
- \( \text{Ba(P)}122 \) film
- \( \text{Sm-1111 sc 1.4GeV Pb} \)
- \( \text{Ba(Co)}122 \) film
- \( \text{Fe(Se,Te) film p-irr} \)
- \( \text{Ba(K)}122 \text{ sc 1.4GeV Pb + p} \)
- \( \text{Gd123 cc} \)
- \( \text{H}_3\text{S 155 GPa 50 K} \)
- \( \text{H}_3\text{S 203 K} \)

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

- Assumption: $J_{c}^{sf} = 0.15J_{d}$
- 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: $J_c = \frac{F_p}{B}$
- $J_c \propto B^{-\alpha}$, $\alpha = 0.5$

$F_p$ vs $B$:
- $J_c \propto B^{-0.5}$
- $J_c \propto B^{-1}$
Achievable in-field performance

- Assumption: $J_{c}^{sf} = 0.15J_{d}$
- Critical state: $F_{p} = F_{L} = |J_{c} \times B|$
- Maximum Lorentz force configuration: $J_{c} = \frac{F_{p}}{B}$
- $J_{c} \propto B^{-\alpha}(1 - B/B_{c2})^{2}$, $\alpha = 0.5$

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

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

$REBa_2Cu_3O_{7-\delta}$ (REBCO) has by far the best $J_c$-properties.
(Nevertheless, NbTi is used by far most frequently)
State-of-the-art

MATERIAL PROPERTIES: LTS
NbTi

LHC conductor

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

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

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

Layer \( J_c \) (RRP)

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

- 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 Nb$_3$Sn)
• Technological issues
**Actual challenges**

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

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** Nb₃Sn for FCC: the CERN conductor program**

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

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>mm</td>
<td>~1</td>
</tr>
<tr>
<td>Non-Cu Jc (16 T, 4.2 K)*</td>
<td>A/mm²</td>
<td>≥1500</td>
</tr>
<tr>
<td>μoΔM (1 T, 4.2 K)</td>
<td>mT</td>
<td>≤150</td>
</tr>
<tr>
<td>σ(μoΔM) (1 T, 4.2 K)</td>
<td>%</td>
<td>≤4.5</td>
</tr>
<tr>
<td>Deff</td>
<td>μm</td>
<td>(≤20)</td>
</tr>
<tr>
<td>RRR</td>
<td>-</td>
<td>≥150</td>
</tr>
<tr>
<td>Unit length</td>
<td>km</td>
<td>≥5</td>
</tr>
<tr>
<td>Cost</td>
<td>Euro/kA m**</td>
<td>~5</td>
</tr>
</tbody>
</table>

Total quantity required: ~8000 tons

(≈1200 tons of Nb-Ti in LHC, ~500 tons of Nb₃Sn in ITER)

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A. Ballarino

**Four years program – started in 2017**
Nb$_3$Sn optimization: flux pinning

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

- 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

**Graphical representation:**
- Plot showing $J_c$ versus $B$ for neutron-irradiated and non-Cu $J_c$ (RRP) materials.
- FCC specifications indicated.

**Additional information:**
- $J_c \sim B^{-0.5}(1-B/B_{c2})^2$, $J_c$ (sf) = 0.15$J_d$
- RRP (recoil-recoil production)

**Reference:**
T. Baumgartner et al., SUST 27 (2014) 015005; 1MP1-09
APC: flux pinning/grain refinement

Internal oxidation method

Nb-1%Zr
Sn source + O source

Heat treatment

Nb₃Sn with ZrO₂ particles
Residual core

Residual Nb

Nb-1%Zr
Cu+Sn+SnO₂

 Courtesy of X. Xu, FNAL

Nb₃Sn grain size: 100-150 → 35-50 nm

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

Activities at:
Hyper Tech, Ohio State University, FNAL, NHMFL (FSU), University of Geneva
Nb$_3$Sn optimization

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

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

Sn-gradients:

In sub-elements

Inside grains

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

$J_c(B||c) > \min J_c$?

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

$J_c = 0.15 J_d (1-B/B_c)^2$

$J_c \sim B^{-0.5}(1-B/B_c)^2$

Actual status of conductor development: B. Holzapfel 2MO1

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

https://commons.wikimedia.org/w/index.php?curid=8777295
Microstructure

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

Courtesy of G. Van Tendeloo et al.
University of Antwerp
RE-123: Granularity

Hilgenkamp and Mannhart, Rev. Mod. Phys. 74 (2002) 485

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

A. Gurevich, Nature Mat. 10 (2011) 255
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)
Cuprates: anisotropy

Anisotropy of the upper critical field:

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

\( \lambda_{ab}(0 \text{ K}) \sim 140 \text{ nm}, \lambda_c(0 \text{ K}) \sim 1 \mu\text{m}! \)

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: BaZrO$_3$ (BZO), BaHfO$_3$ (BHO), Ba$_2$YNb$_{0.5}$Ta$_{0.5}$O$_6$ etc.
- Increasing RE-123 layer **thickness**

![Graph showing the relationship between HTS film thickness and critical current density.]


- 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**

- **NPs**
- **YBCO precursors**
- **Ink jet printing solution deposition**
- **Growth process**
- **Nanocomposite with artificial pinning centers**

**BZrO₃, BHfO₃ 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/cm² to be published
Outstanding properties of CSD nanocomposites 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

- Optimization of pinning for the respective operational conditions
  - Nano-precipitates: BaZrO$_3$ (BZO), BaHfO$_3$ (BHO), Ba$_2$YNb$_{0.5}$Ta$_{0.5}$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 filamented conductor

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

- 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

- 26.7 T, all RE-123  no insulation coils (radial current sharing)  
  Y. Yanagisawa et al., SNF, STH42

- 27.6 T demonstrator for 1.3 GHz (30.5T) NMR project  
  S. Awaji et al., SUST 30 (2017) 065001

- 24.6 T cryogen free  
  S. Awaji , 1P2

- Accelerator magnets

- 24.6 T cryogen free  
  S. Awaji , 1P2

- 17.6 T @ 26 K  
  Ø = 2.5 cm


S. Yoon et al., SUST 29 (2016) 04LT04

Y. Yanagisawa et al., SNF, STH42

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:

\[
J_c = \int_0^{J_c^{\text{max}}} \left( \frac{p(J) - p_c}{1 - p_c} \right)^{1.78} dJ
\]

M. Eisterer et al., PRL *90* (2003) 247002
MgB$_2$

Upper critical field anisotropy: 5-6

Impurity scattering enhances $B_{c2}$

Critical current in polycrystalline materials

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

M. Eisterer, SUST 20 (2007) R 47
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

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MgB$_2$

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

- Significant potential for improvements
  - Conservative approach: connectivity, volume fraction
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T. Prikhna 4MP2

- Thin film performance ($B_{c2}$, $\gamma$, $T_c$)

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![Graph showing $J_c$ vs $B(T)$ for YBCO, Nb$_3$Sn, and MgB$_2$ with temperature and critical field values.](image)
MgB$_2$: Applications

• Power transmission
  • Superconducting cables for the HiLumi LHC

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

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

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

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

www-paramed.it

Full-size prototype coil
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

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

- 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$_2$

+ Cheap PIT process
+ Long wires (100m) were demonstrated
+ High upper critical fields
- Intrinsic connectivity problem (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

0.15$J_o B^{-0.5} (1-B/B_{c2})^2$, $B_{c2}=150$ T, $\lambda=200$ 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 superconducting 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.

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

\[ B(T) \]

- NbTi
- Nb$_3$Sn
- MgB$_2$
- Ba(K)-122, Sm-1111
- Bi-2212
- Bi-2223
- YBCO
- Bi-2223
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.

Thank you for your attention!