High current superconductors: overcoming the materials challenges to achieve power applications

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> 100 years of superconductivity

I have a dream!

• Electricity transport at long distances without losses
• Generate high magnetic fields (10 T at that time). Can we jump to the 40 – 50 T magnets?
• Massive electrical energy storage?

Are we close to Onne’s dreams?

K. Onnes (1911)
A new electrical energy paradigm

The Energy Future: new paradigm
- Change in Energy Production
- Increase in Electricity Generation
- Increase in Renewables

Will result in
- More energy exchange and transport
- More energy storage
- More flexible generation
- Demand for new solutions

What could be the benefit, the application and the future of HTS energy applications?

Is superconductivity a solution to a problem? Are we ready?
Superconductivity: a timely opportunity?

• Where our electrical system requires the use of superconductivity?

• Real advantages versus other technologies? Where are we essential?

• Are we ready? Right materials and a reliable engineering?

• What can we achieve with the existing materials and technologies? How far are we from the required cost/performance ratio?

• Do we still need new materials? What performances would make real breakthroughs?
HTS in power engineering: conventional vs novel systems with new functionalities

- Highest current densities without (dc) or reduced losses (ac)
- High magnetic fields can be generated

Reduced Weight/Volume
Reduction of Losses

Higher Power Densities
Better Efficiencies

Optimization of Conventional Systems

- Cable
- Trans-former
- Motor Generator

Novel Applications

- Flywheel
- Fault Current Limiter

Higher Power Density
Retrofit

Energy Savings
Life Safety

Volume, Weight
Energy Savings

Energy Density
Energy Savings
Safety

Availability
Savings of Ressources

Savings of Ressources
Power Quality

Courtesy of H.C. Freyhardt
The long and winding road: from discovery to applications

Academia

Physicist

Electrical / electronic engineer

Devices / systems / Cryogenics

Industry

Final use industry (services)

Users (people) / Market / Investors / Environment (climate)/ Politicians / Social groups / Scientific facilities / Hospitals

Materials Engineer

Materials Manufacturing (industry)

Chemist

Materials Scientist

Utilities, energy generation, transport...
HTS main issues: grain boundary problem

\[ J_{c,GB} = J_0 \exp(-\phi/\phi_c) \]

Charge imbalance at the GB depresses \( J_c \) at the interface (t-J model calculations)

- Charging of \( \text{CuO}_4 \) squares: screening length similar to interatomic distances
- Supercurrents flow through regions between distorted regions
- Conductors rely on current percolation through grain boundaries

**HTS main issues: vortex physics**

**Control of vortex motion → Nanometric defects ~ \( \xi \) (nm)**

**Intrinsic upper limit of Irreversibility line: loss of vortex line tension**

\[
U(T, H) = A \frac{\Phi_0^2 \gamma}{4\pi^2 \kappa \lambda_{ab}} \left( \frac{H_{c2}(T) - H}{H_{c2}(T)} \right)
\]

Energy cost of deformation at different \( H \)

\[
U(T, H) \approx kT
\]

Maximal excitation of a bulge

**YBCO: \( T=77K \) : \( H_l H 1.5 H_m \sim 14 T \)**

\[
H_l(T) = H_{c2}(T)[1 - (g / A)t(1-t)^{-1/2}]
\]

Superconducting Wires & Tapes

Metallic

*NbTi* (*Nb_3Sn* etc.)

Metallic

*MgB_2* / *Fe based*

Oxide

*Bii223*

*Bii2212*

Oxide

*YBCO*

Only a few materials allows wire manufacturing!

Courtesy of T. Izumi
New frontiers for applications

- LHe
- Cryocoolers
- LN$_2$

Temperature (K) vs. Magnetic Field (T)

- REBCO
- YBCO
- BSCCO
- NdFeAsOF
- Nb$_3$Sn
- MgB$_2$
- NbTi

Adapted from M. Matsumoto
Conductors at ultrahigh fields and low temperatures

Several HTS conductors can be suitable for ultrahigh field magnets.

YBCO has the highest $J_c$.

Bi2212 round wire is also very appealing.

32 T magnet at Tallahassee.

4.2 K

Courtesy of D. Larbalestier
CC’s: HTS materials for power applications

J_c breakthroughs

Critical Current Density (MA/cm²)

Magnetic Field (T)

NbTi (4.2 K)

Nb_3Sn (4.2 K)

Epitaxial YBCO film

Polycrystalline YBCO tape

Long length Biaxial Texturing

APC-Introduced YBCO film

Nanotechnology

77 K

Courtesy M. Matsumoto
10 years of coated conductors

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
YBa$_2$Cu$_3$O$_{7-x}$ is able to push all the power applications up to the present limits. Length, allowed cost and required performances strongly differ (~1 km to 300 km).
Coated Conductor research in Europe

Xavier Obradors
Coordinator EUROTAPES
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EUROTAPES: European development of Superconducting Tapes: integrating novel materials and architectures into cost effective processes for power applications and magnets (2012-2016)
European main SC activities

- EUROTAPES
  - http://www.eurotapes.eu/
  - 20 EU partners (9 countries)
  - ~20 M (13.5 M - EU)
  - 2012-2016
YBCO COATED CONDUCTORS: EPITAXIAL ARCHITECTURE

Nanostructure control on km length materials: very close to real power applications
YBCO COATED CONDUCTORS: EPITAXIAL ARCHITECTURE

Nanoengineering of the vortex landscape defines the properties

Cap layer: Ag thickness $\approx 0.2 - 0.5 \, \mu m$

SC layer: YBCO $\sim 1.0 - 2.0 \, \mu m$

Buffer layers: CeO$_2$, YSZ, STO, ... $\sim 0.1 \, \mu m$

Metallic substrate: RABiTS Ni, SS-IBAD, thickness $\sim 80 \, \mu m$

Grain boundaries should not be an issue

Nanostructure control on km length materials: very close to real power applications
Fundamental materials science knowledge
Manufacturing methodologies

Material science / Nanoscience maximizing performance

Vacuum deposition → Metallic substrates Buffer layers → Chemical Solution Deposition

Process

HTS Epitaxial Film Growth

Multi layers → Nano structure

Defining process to achieve structure with optimum property

Develop stable and fast processes, identify key properties

Long length, high throughput manufacturing, quality control

Property Scaling

Develop well grounded property-structure relationships

Structure

High-throughput / high-yield Low cost manufacturing processes

CC’s: A tough S&T issue!
Interdisciplinary know-how required!

Solution chemistry Colloidal solutions Self-assembling Nanoengineering

Vortex pinning landscape vs nanoscale properties

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
Plenty of room for improvement: self-field $J_c(T)$

**Self-field $J_c$**

For $T \rightarrow 0$, $J_{c, sf}/J_0 \sim 0.2$

At 77 K, $J_{c, sf}/J_0 \sim 0.1$

$J_{c, sf}(77K) \leq 6-7$ MA/cm$^2$

$J_0(77K) \sim 70$ MA/cm$^2$

Theoretical limit for self-field $J_c$: depairing current density

Can we multiply by 5 the self-field $J_c(77K)$?
Plenty of room for improvement: $I_c(T,B)$

- Increase of $I_c$ through $J_c$ and thickness enhancement
- Reduce the magnetic field dependence $J_c(H)$: vortex pinning
- Practical processes to achieve high $I_c(H)$ values

Present

Future?

Japanese program

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
Specifications and cost for applications

- High In-field $I_c$
- High Mechanical Strength
- Low AC Loss

Applications:
- NMR
- Accelerator
- Wind Generation
- Trans.
- SMES
- Cable
- Motor

Low cost

Courtesy of T. Izumi
Search for breakthroughs

Simplified architectures? / All chemical? / Large thickness

- AMSC
- Evico/Nexans/D-Nano
- Superpower
- Fujikura
- Bruker / Oxolutia
- SuNAM

Rolling Assisted Biaxial Texturing (RABiT)

• Urgent need for simplified conductors and reduced cost/performance ratio (similar needs in photovoltaic industry)
EUROTAPES project

YBCO layers and nanocomposites

- PLD YBCO
- MOD YBCO
- PLD CeO$_2$
- MOD CeO$_2$
- IBAD YSZ, TiN
- Poly SS

- RABiTS: Ni-W, Cu-clad
- MOD YBCO
- MOCVD YBCO
- MOD LZO, CeO$_2$
- PVD CeO$_2$
- new MOD buffer layers

Metallic Substrates

- BRUKER, IFW, UCAM
- ICMAB, OXOLUTIA, TUC, UAB
- ENEA
- PerCoTech
- UGENT, CNRS
- BRUKER, IFW, UCAM
- ICMAB, OXOLUTIA
- UGENT, CNRS
- BRUKER, IFW, UCAM
- ICMAB, OXOLUTIA

Advanced characterization and in-situ monitoring: TUWien, UAntwerpen, THEVA
Striations, ac losses, round wire: UCAM, Bratislava, NEXANS
EUROTAPES objectives

- Metallic substrates with reduced ac –losses and lower cost ABAD templates
- Simplified architectures and cost effective CC
- Engineered nanocomposite CC (CSD, PLD) for high fields (3-10T, 60K) and ultrahigh fields (>20T, 5K).
- Eco-friendly chemical and colloidal solutions for nanocomposite CC’s
- New round wire low cost and low ac losses
- Multifilamentary striated conductors at low cost and low ac losses
- High throughput processing with high yield and performance
- Development of in-situ monitoring tools for process scalability
- Demonstrate (+500 m) manufacturing
EUROTAPES objectives

**TARGETS:**

- **Pre-comercial cost:** $\sim 100 \, \gamma/kAm$
- **Length:** +500 m
- **Performance:**
  - **For low fields** ($B < 1 \, T$):
    \[ I_c (77K, \text{sf}) > 400 \, A/cm-w \]
  - **For ultrahigh fields** ($B > 15 \, T$):
    \[ I_c (5K, 15 \, T) > 1000 \, A/cm-w \]
  - **For high fields** ($B \sim 3-5 \, T$):
    \[ F_p (60 \, K) > 100 \, GN/m^3 \]
ABAD metallic substrates

ABAD 40mm, YSZ/SS
(4mm/12mm also available)

Towards cost reduction:
Solution Deposition Planarization (SDP) process to substitute mechanical polishing

Targets:
- Substrate polishing:
  - 8 \Rightarrow 150 \text{ m/hour}
- ABAD:
  - 4 \Rightarrow 35 \text{ m/hour}
  - width 12 \Rightarrow 40 \text{ mm}
  - length 100 \Rightarrow 500 \text{ m}

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
All PLD approach: longest CC’s in Europe (~280 m)

6B-PLD machine with deposition area of 0.13m²
Multi plume HR-PLD for Large area HTS coated conductors

- Efficiency of material transfer is about 2 times higher as was expected
- Pulse energy of 600mJ is sufficient for 8 beams
- This indicates further increase cost efficiency and throughput

45m long, 4mm wide tape

Highest $I_c$ achieved in 6 m long tape: 500 A/cm-w at 77K, SF
Well-reproducible $I_c$ (~ 200 m): 250 A/cm-w at 77K, SF

WR (Fujikura) 572 A/ 816 m
**IBAD alternative: TiN based CC's**

**Application of IBAD-TiN on stainless steel: faster alternative to YSZ-ABAD?**

<table>
<thead>
<tr>
<th>a-Ta&lt;sub&gt;0.75&lt;/sub&gt;Ni&lt;sub&gt;0.25&lt;/sub&gt;</th>
<th>IBAD-TiN</th>
<th>homoepi TiN</th>
<th>SrZrO&lt;sub&gt;3&lt;/sub&gt;</th>
<th>YBCO 200 nm (ex-situ)</th>
</tr>
</thead>
</table>

RHEED:
- 5nm
- 15nm
- 200nm

**XRD**
- In-plane FWHM: ~6°
- YBCO (103)

**FIB cross section**
- J<sub>c</sub> = 2.85 MA/cm<sup>2</sup>
- T = 77 K
- H || c

Available products:

Ni5at%W - evico STANDARD

- > 98% cube texture fraction
- < 5 nm surface roughness
- high quality, stable process
- 80 µm thickness, 10 mm width, 10 - 250 m length

Ni7.5at%W - evico LOW AC LOSS

- > 96% cube texture fraction
- status: available, pilot production
- 80 µm thickness, 10 mm width, 1 - 100 m length

Ni9at%W - Research

- customized dimensions on request
- not available yet
- > 94% cube texture fraction
- Status: transfer to production soon

Spin-off from IFW- Dresden

The leading manufacturer of Ni-based RABiT in Europe
Non-magnetic RABiTS Ni-W tapes

Development of highly textured non-magnetic RABiTS tapes

YBCO coated conductor architecture validated by pulsed laser deposition

Fraction of cube texture: >95%
Deviation from (001)[100]
cube texture:

0° 62°


Typical $J_c$-values: 1.6 ... 1.8 MA/cm²

Ni-9 at.% W

Ni-9.5 at.% W

All-chemical CC’s: CSD buffer on NiW

100 nm La$_2$Zr$_2$O$_7$ are effective as metal diffusion barrier

Pyrolysis atmosphere

Full elimination of organic components with an air pyrolysis in a single coat of 100 nm

- 350 ºC Air pyrolysis
- 1050 ºC ArH$_2$ crystallization

YBa$_2$Cu$_3$O$_x$ CeO$_2$/LZO NiW

All chemical CC architecture

Roughness $R_{ms} = 3.5$ nm (2x2 um) (6.5 with standard annealing)
100 nm $\text{La}_2\text{Zr}_2\text{O}_7$ are effective as metal diffusion barrier

Effect of annealing temperature (980ºC - 1060ºC) - optimum for 1020 ºC

For 1020ºC: 99% of the scan points are indexed as LZO; No defects. The joints between crystals are all below 7º.

New buffer layer: $\text{YBiO}_3$

- YBCO deposition by PLD yields 3.6 MA/cm² on YBO-buffered single crystals
Understanding the thickness dependence of the CSD films

**Buffer layers by CSD: Gd$_2$Zr$_2$O$_7$**

Thickness gradient is very informative to study: i) morphology change associated with growth mode
ii) surface texture evolution

**CrystEngComm, 2012, 14, 3089**

*a multi-step annealing process*
TFA based CSD: Low cost YBCO and nanocomposites

Precursor solution synthesis
Y, Ba,Cu metal-organic precursors

Solution deposition
Ink-jet Printing

Pyrolysis
Removal organic precursors

Ex-situ Growth
Nucleation, crystallization and oxygenation

For Nanocomposites: In-situ

Addition of metal-organic salts (Zr, Ce, Ta, ...) in the TFA precursor solution: Spontaneous
Np segregation within the epitaxial YBa$_2$Cu$_3$O$_7$ matrix: Y$_2$O$_3$, BaZrO$_3$, Ba$_2$YTaO$_6$, BaCeO$_3$, ...


For Nanocomposites: Ex-situ

TFA colloidal precursor solutions: MFe$_2$O$_4$
(M=Co, Mn), CeO$_2$ (BaCeO$_3$), ...

CC strategy based on CSD

YBCO films multilayers

In-situ nanocomposites

TFA precursors (BaF₂ process)

Nucleation and growth control

Nanoparticles Stabilize solutions

Ex-situ nanocomposites

Low F precursors (BaF₂ process)

Robustness, R2R, large Ic, throughput, length

Non F precursors (Non BaF₂ process)

Explore capabilities

CSD Ink Jet Printing

ABAD / RABIT CSD Buffer layers

CeO₂/LZO NiW YBa₂Cu₃O₇

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2013
Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
Low fluorine / non-fluorine precursor solutions

<table>
<thead>
<tr>
<th>Carboxylate salts</th>
<th>+Solvent</th>
<th>+ Chelating Agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetate</td>
<td>Methanol</td>
<td>Triethanolamine (TEA)</td>
</tr>
<tr>
<td>Propionate</td>
<td>Propionic acid</td>
<td></td>
</tr>
<tr>
<td>Ethylhexanoate</td>
<td>Acetic acid</td>
<td></td>
</tr>
</tbody>
</table>

≈50-80% less fluorine

\[
\begin{align*}
F_3C\text{-}O^- \quad Y^{3+} \quad H_3C\text{-}O^- \quad Ba^{2+} \quad H_3C\text{-}O^- \quad Cu^{2+}
\end{align*}
\]

- 80 % F

\[J_c (77K, sf) = 3-4 \text{ MA/cm}^2\]

- More environmentally friendly (-80 % F or non-F)
- Stable solutions adapted to IJP: less sensitive to humidity (chelating agents)
- Large thickness with one coat (~1000 nm)
- Pyrolysis can be undertaken at faster ramps
- Similar growth process that TFA-based solutions
- Good progress towards F-free CC’s
CSD CC’s on ABAD-YSZ

All chemical IJP: YBCO / CeO$_2$ / ABAD-YSZ / SS

- CZO$^{\text{MOD}}$ epitaxial with good texture quality.
- Enhanced surface planarity, small grain size

$J_c(\text{s.f.,77K})=2 \text{ MA/cm}^2$  $I_c=108 \text{ A/cm-w}$

E. Bartolomé et al, SUST (in press)

- No coherence between buffer layer and YBCO grains
- Current percolation different than RABiT CC’s

Goals: Low-F - 200 A/cm-w - 1 nm/s - 10 m
Development of RABiT CC’s by ALL-CSD processes

Superconducting layer by Low F TFA process

YBCO\text{Low TFA}

Ce_{0.9}La_{0.1}O_2 Cap layer

Gd_2Zr_2O_7 barrier layer

NiW substrate

High quality buffer layer stack \cite{supercondSciTechnol25(2012)}

TEM micrograph

\text{CLO}

interface

c axis

\text{YBCO}

\text{Thickness = 200 nm}

\text{JC (77K, SF) = 2.1 MA/cm^2}

\text{A strong surface texture and a superior morphology on the cap layer ensure the high performance of the YBCO layer}
BASF GmbH owner

- CSD for all layers is considered to be the "most promising and most challenging process"
- Unique and protected CSD-multi-layer technology, IJP.
- Established industrial cooperations on metallic substrates (Thyssen Krupp), coating solutions (Honeywell) and insulation (Elektrisola)

✓ All samples continuously processed in minimum 10 m lengths
✓ $J_c (77K, sf) = 1.2 - 1.8 \text{ MA/cm}^2$ for 1 $\mu$m HTS
✓ 7mm wide slitted and stabilized sample, $I_c / \text{cm-w} > 160A$
✓ 100 m wound to coil with overall $J_c = 1.4 \text{ MAcm}^2$
Round wire objective: more compact and low cost cables

Core made of superconductive wires

Welding technology already developed by Nexans

Nexans patent
Korean approach: high growth rate CC’s

- **RCE-DR**: Reactive Co-Evaporation by Deposition & Reaction
- High rate co-evaporation to the target thickness (> 1 µm) (6 ~ 10 nm/s)
- Fast (<< 30 sec.) conversion from amorphous glassy phase to superconducting phase (∼ 100 nm/s)
- Simple, higher deposition rate & area, low system cost
- Easy to scale up: single path

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
Vortex pinning in YBCO Nanocomposites

Nanoengineering is the path towards control of vortex pinning and enhance performances

\[ F_L = J \times B \]

Anisotropic and strong defects

Isotropic and strong defects

Isotropic and weak defects

1D-APC

2D-APC

3D-APC

0D-APC

dislocation, columnar defect

grain boundary, planar defect

fine precipitate, second phase
RF antisite clusters,
isotropic nano-strain

Superconductor

Oxygen vacancies, ...

The role of interfaces in nanocomposites are the key issue

... but there always exits superposition of different contributions in a single material
PLD YBCO nanocomposites

Interfaces and associated strains, defects, ... can be tuned and maximized and vortex pinning properties enhanced

$YBa_2Cu_3O_{7-x} - BaZrO_3$ nanocomposite by PLD/MOCVD

Epitaxial YBCO-BZO interfaces  
Self-organized BaZrO$_3$ nanorods

Anisotropic increase of performances

77 K 4 T

$J_c(MA/cm^2)$

$H//c$ $H//ab$

$2%$ BZO

$x 3.5$

$Y. Yamada, APL 87 (2005)$
$B. Maiorov, Nat Mat 8 (2009)$

PLD: YBCO co-doping with Nb and Ta

- Superior, but complex, angular properties
- Excellent and easy tunability

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2013
Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
Solution derived- YBCO nanocomposites

Addition of metal-organic salts in the TFA precursor solution: Spontaneous nanoparticle segregation within YBa$_2$Cu$_3$O$_7$ matrix: BaZrO$_3$, Ba$_2$YTaO$_6$, BaCeO$_3$, Y$_2$O$_3$

Incoherent YBCO-BZO interfaces give rise to high density of Y248 intergrowths

The highest isotropic performance ever found in any superconducting material
New vortex pinning mechanisms in CSD YBCO nanocomp.

Addition of metal-organic salts for TFA nanocomposites with Y$_2$O$_3$, BaZrO$_3$, Ba$_2$YTaO$_6$, BaCeO$_3$ nanoparticles

Nanostrain is the key issue for the performances achieved

- Local lattice strains generated by CuO intergrowth
- XRD: nanostrain determination

J. Gutierrez et al, Nat. Mater. 6, 367 (2007)
M. Coll et al., SUST 26, 015001 (2013)
YBCO CSD nanocomposites: isotropic pinning landscape

**Isotropic $J_c(H)$**

![Graph showing isotropic pinning landscape for YBCO CSD nanocomposites](image)

**Anisotropic $J_c(H)$**

![Graph showing anisotropic pinning landscape for YBCO CSD nanocomposites](image)

**YBCO - BZO nanocomposite**

![Graph showing $J_c(H)$ for YBCO - BZO nanocomposite](image)

References:

New vortex pinning proposal: Bond contraction pairing model

Coupling lattice strains with Cooper pair suppression

**Pair breaking energy:**

\[
2\Delta = 4 \left( \frac{t_{CuO}}{U} \right)^2 - 8t_0
\]

- \( \Delta \): pseudogap
- \( t_{CuO} \): transfer integral between Cu \( d \) and O \( p \) orbitals
- \( U \): on-site Coulomb repulsion
- \( t_0 \): half bandwidth

**In plane—dislocation**

**Strained regions**

**vortex**

**In-plane partial dislocation**

Huge dislocation density \( \sim \) 1–5 \( \times 10^{12} \) cm\(^{-2} \)

---

Can we further improve $J_c^{sf}$ and $F_p$?

$J_c^{sf}$: Blocking effects of nanodots on percolating current should be reduced.

$J_c(H)$: Enhanced nanostrain avoiding np coalescence.

See M. Coll 4M-MA2-11.
CSD: novel vortex pinning approach

Superconducting nanocomposites

Composition Processing → Randomly oriented nanoparticles → Incoherent interface Intergrowth generation → Intergrowth lateral size Dislocation density → Nanostrain → Vortex pinning: APC is within the matrix

Nanoparticle size Coalescence → Processing

Cooper pair breaking

Quasi-isotropic nanostrain distribution

Quasi-isotropic pinning landscape: all B – T range

See M. Coll 4M-MA2-11
Vortex pinning issues in YBCO nanocomposites

APC generation nanocomposites

Simultaneous YBCO/NP growth (PLD, MOCVD)

Self-assemble
Superposition anisotropic defects
(nanorods, nanoplatelets)

Complex combination of defects to smooth \(J_c(\theta)\)

Complex vortex behavior

Fast implementation in CC’s

Sequential NP/YBCO growth: Ex-situ (CSD)

Random nanoparticles induce isotropic nanostrain

Natural generation of quasi-isotropic \(J_c(\theta)\)

Need atomic scale understanding Cooper pair breaking

New vortex pinning mechanism: nanostrain?

Adapting optimal implementation to CC’s

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
What's next?: engineered nanocomposites from colloidal solutions

**Thermal (2h) and MW (10 min) synthesis**

Highly dispersed and crystalline nanoparticles (∼90 mM)

- **MFe₂O₄ NPs** (M = Mn, Fe, Co, Ni and Zn)
- **CeO₂, YSZ, Ru, ...**


- **Stable solutions in alcoholic media**
- **TFA colloidal solutions are stable!**

NPs precursor

**Triethylene glycol (TREG)**

Np size: 5 ± 2 nm

MnFe₂O₄

A. Garzón et al., (to be published)
Growth of nanocomposites: YBa$_2$Cu$_3$O$_7$ + NP

CeO$_2$ NP size: 2-4 nm

Challenges
- Keep nanoscale dispersion of NP’s
- Control chemical reactivity NP’s with YBCO precursors
- Avoid coarsening of NP’s
- Minimize impurity diffusion into YBCO (keep high $T_c$)

$T_c=85.6$ K

CeO$_2$ NPs react with Ba: BaCeO$_3$ NP’s are formed
Some NP coarsening occurs (∼20 nm)
$T_c$ ∼ 90 K, $J_c$ = 3-3.5 MA/cm$^2$

Concentrations of spinel NPs in YBCO: ∼ 10 % mole
Some decrease in $T_c$: Fe diffusion into YBCO lattice
Laser structuring of CC (IR Pico-second laser) at KIT

- KIT Picosc pulse-laser generates nearly no heat
- negligible melting effects at the edges of the groves

![Achieved DC Currents in striated CC](image)

- **Green curve**: expected $I_c$ due to loss of superconducting material in the groove
- **Red curve**: measured $I_c$ additional degradation occurs from statistically distributed inhomogeneities

**Up to 120 filaments shown**

- (100 / cm-w.)

- Filament width
  - H 80 µm

**See: EUCAS 3P-WTR-12**

- Width 20 micron

**120 filaments**

**Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).**
YBCO pattern after a 5 x fold printing sequence, without an intermediate drying step.

The homogeneous lines with average thickness of 200 nm at a width of 200 µm.

High homogeneity and uniformity along all track length. Tracks are **150 µm x 300 nm**. Similar $J_c$ in all filaments.
Low Temperature performance of KIT Roebel cables

- > 5 m long produced at KIT
- 2 m tested at CERN (FRESCA) at 4.2 K and B < 10 T (sample B, C)
  - $I_c = 1100 \text{ A} @ 77 \text{ K}$ s.f.
  - $I_c = 14000 \text{ A} @ 4.2 \text{ K}$ s.f.
- Modified cable design will allow > 5 x current enhancement for Fusion magnets, LHC dipoles

KIT cable 10 strands, 12 mm width (B, C)

**Electrical characterization of REBCO Roebel cables**

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Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
Rutherford Cable with CC Roebel strands

Concept for >20 kA for HTS Fusion Magnets (12T, 50K) and large Power Generators

Several strands investigated on the RF-former

The edge bending was too strong for crack-free Roebel strand application

Longer transposition needed

The flat cable concept

The new and alternative round concept

Roebel strands
Coated conductors for fusion magnets

Neutron irradiation changes $J_c$-anisotropy:

Damage in fusion reactor can be simulated by irradiation in the TRIGA MARK II Reactor and stress sensitivity:

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
Lower cost and higher performance of conductors is key for propagation!

Propagatio

Marketable

Applicable

Capable

Courtesy of T. Izumi
CC’s: expected market growth and cost decrease

Throughput and performance are key to reduce cost/kAm: capital investment, depreciation and total current

Estimated world market evolution of SC systems

~ 6.5 bn € by 2030 (1.3 bn € in wires)
~ 1.500.000 km/year by 2030 (x 1000 present production)
Contributions to Power Applications at Applied Superconductivity Conference 2012 in Portland

<table>
<thead>
<tr>
<th>Country</th>
<th>Cables</th>
<th>Fault Current Limiters</th>
<th>Rotating Machines</th>
<th>Transformers</th>
<th>SMES</th>
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**Percentage contributions**
- 66% Asia
- 20% Europe
- 7% USA

Asia is taken a leading role in Power Applications of Superconductivity
Significant effort EU and USA. Leadership towards a new electrical paradigm?
Superconducting Cables

10 kV, 40 MVA, 1 km HTS cable plus FCL in the German City of Essen

HTS Cable and resistive type FCL will be installed by end of 2013

Source: M. Stemme et al. "40 MVA HTS Cable and Fault Current Limiter Installation", ASC Conference 2012, Portland USA

Paper based on this presentation was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044003 (2014).
EU FP7 ECCOFLOW Superconducting FCL

Resistive FCL 1 kA, 24kV, YBCO

2010-2014

One resistive SCFCL design fits two different applications

Busbar Coupling

Transformer Feeder

Endesa Grid in Mallorca, Spain (6 months 2013)

Slovakia, permanent installation

Other FCL:

Bruker (10 kV, 800 A inductive), Italy (9 kV, 3.4 MVA Resistive), Russia (3.5 kV, 650 A Resistive)
Rotating Machines: Synchronous Machines at Siemens

4 MW HTS II – Long term field test at Siemens motor factory in Nuremberg

Test results:
- Loss reduced by 50%
- Full capacitive power
- High overload stability
- Low voltage drop
- Low total harmonic distortion
- More than 7500 operating hours
- Safe operation

None of the shutdowns caused by HTS winding or cooling!
All operating states and shutdowns tolerated by the system!

Source: Tabea Arndt. „Experience, status and prospects of HTS rotating machines with 1G and 2G HTS at Siemens“, ASC Conference 2012, Portland USA

Other Rotating Machines: Wind generator projects (USA, Korea, Japan)
Russia (Synchronous generator, 10 MVA), Oswald (Torque motor 26000 Nm, 156 kW, 57 rpm)
HTS SMES
(Superconducting Magnetic Energy Storage)

USA
25 T, 20 kW, 3 MJ HTS prototype
HTS - SMES for integrating renewables

JAPAN
10 m
2 GJ, 100 MW for load compensation

GRIDS SMES SYSTEM
Power Converter
ABB
SMES
Brookhaven National Lab
2G HTS Wire
SuperPower/University of Houston

High power density and low discharge time
energy storage for smart grids
New National Projects in JAPAN

"Development of HTS Coiling Technology"
(2013~2017 $9M/year) Awarded!
Realization of He-less Medical Magnet

1. **HTS Coils for MRI**
   - 10ppm in 40cmΦ
   - with 1 ppm/h @ 3, 10T

2. **HTS Coils for Medical Accelerator**
   - 100ppm in 10cmΦ
   - under Pattern Excitation to 3T

3. **Common Technologies for HTS Coils**
   - "Coil operated in Liq. N₂" and "Low Loss Coil"
   - "Long CC with High Ic(P)" and "Ultra-low loss CC"
Conclusions

- After 100 years of superconductivity, materials are ready to transform electrical engineering: contribution to a new energy paradigm

- The input of nanoscience has been essential to meet the challenges faced for high performance coated conductors

- Progress in “all chemical conductors”: very promising low cost approach. It requires a solid understanding and control of the whole growth process. Cost reduction is progressing in all CC’s.

- Nanocomposites very useful to enhance vortex pinning in HTS. Further understanding of nanostructure versus pinning required: room for improvement

- Power systems based on HTS are being spread all around the world
Acknowledgements

- Eurotapes partners, Europe
- ICMAB staff and students, Barcelona
- M. Noe, W. Goldacker, KIT
- M. Baecker, Deutsche Nanoschicht
- J. C. Grivel, T U Copenhagen, Denmark
- T. Arndt, Siemens
- H.C. Freyhardt, Univ. Gottingen
- V. Selvamanickham, Univ. Houston - Superpower
- D. Larbalestier, High Field Lab., Tallahassee
- T. Izumi, ISTEC, Japan
- K. Matsumoto, Kyushu Inst. Tech., Japan
- S. H. Moon, SUNAM, Korea
- M. Rupich, American Superconductor
- Sergey Samoilenkov, SUPEROX, Russia
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