# High current superconductors: materials challenges for large scale applications

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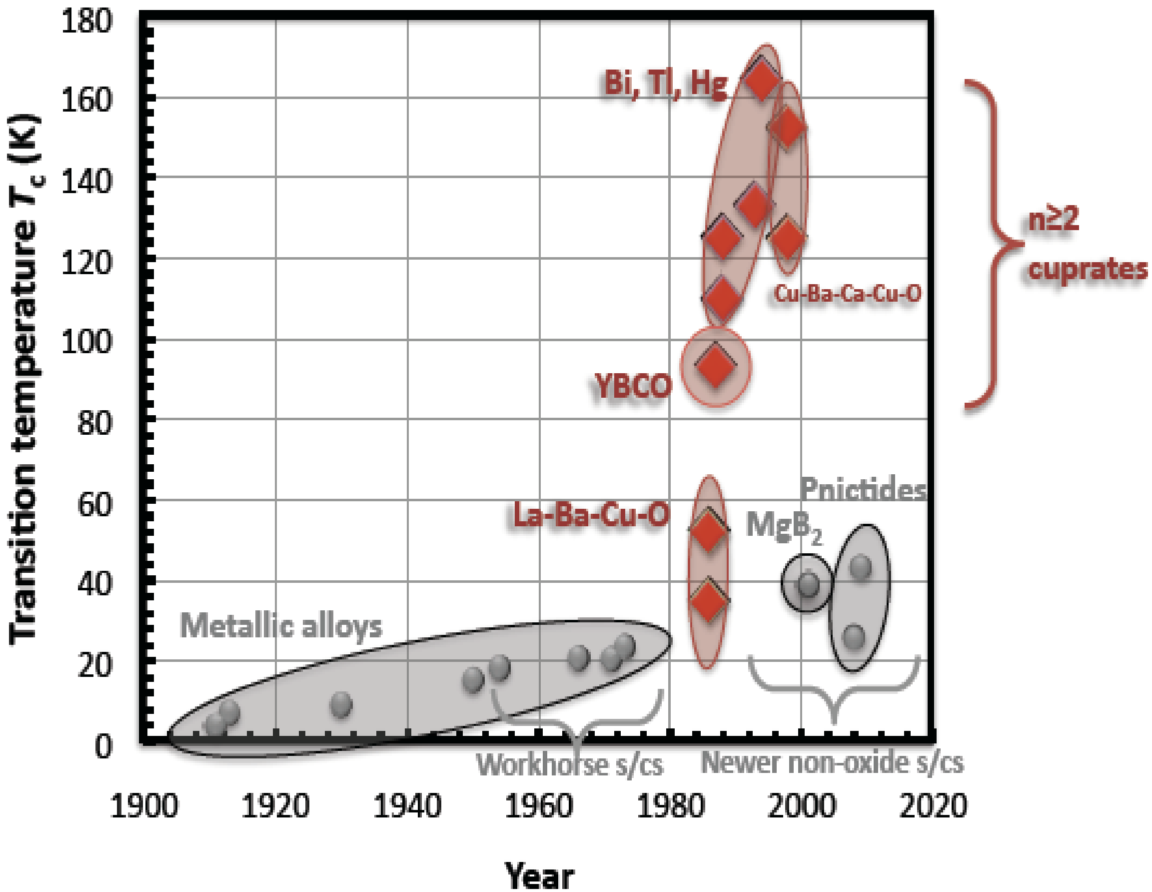
*CSIC, 08193 Bellaterra, Spain*

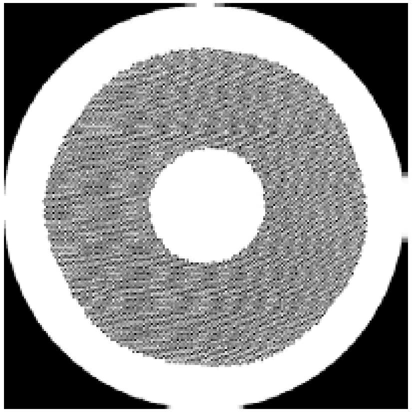
# Progress in superconducting materials

***25 years after the discovery of HTS ….***

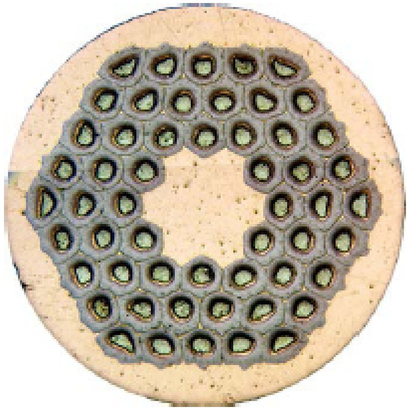



***$YBa_2Cu_3O_{7-x}$ is still the most promising material for power applications: $T_c$ is not the most relevant parameter***

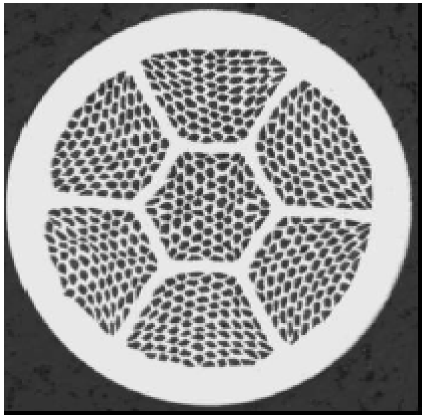
# Superconducting Wires & Tapes



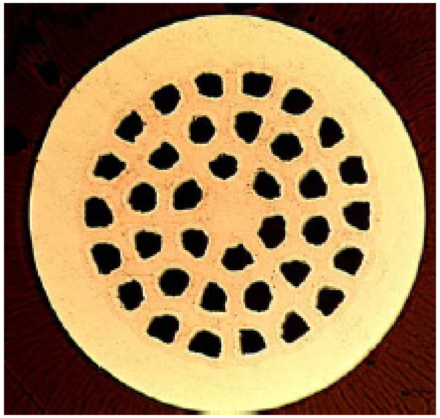
Nb-47Ti



Internal Sn $Nb_3Sn$

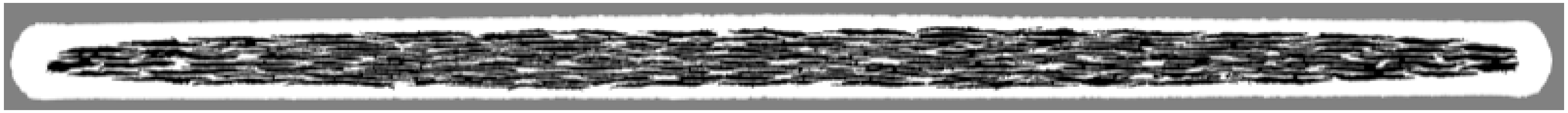


Bi-2212

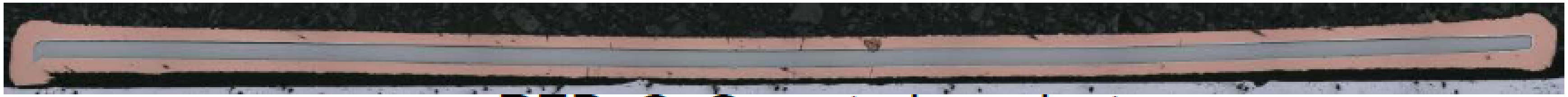


$MgB_2$

**Magnet wires should be long, strong, stable, affordable, have high critical current density, high upper critical field and preferably round**

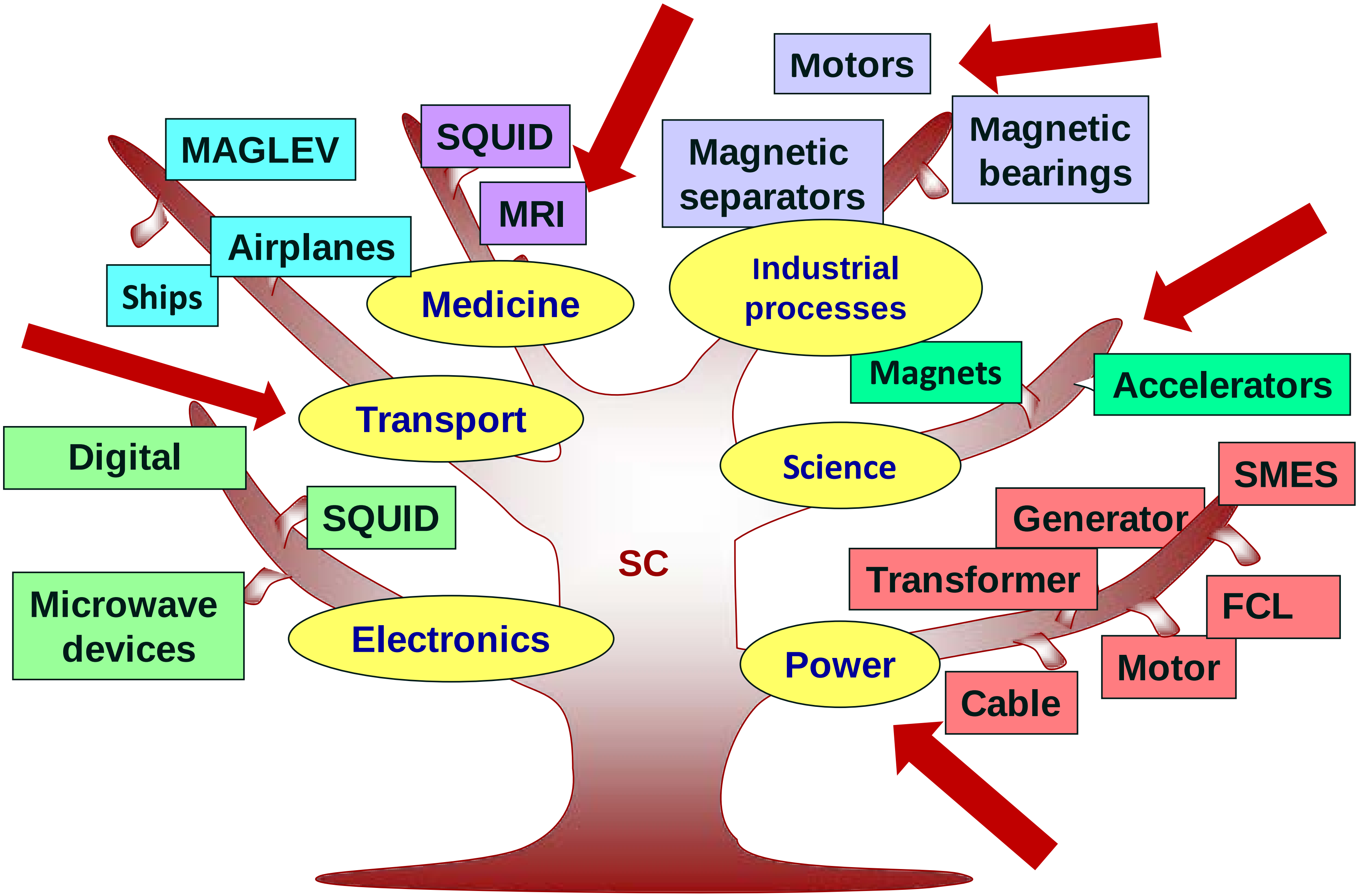


Bi-2223



REBaCuO coated conductor

# Superconductivity applications tree



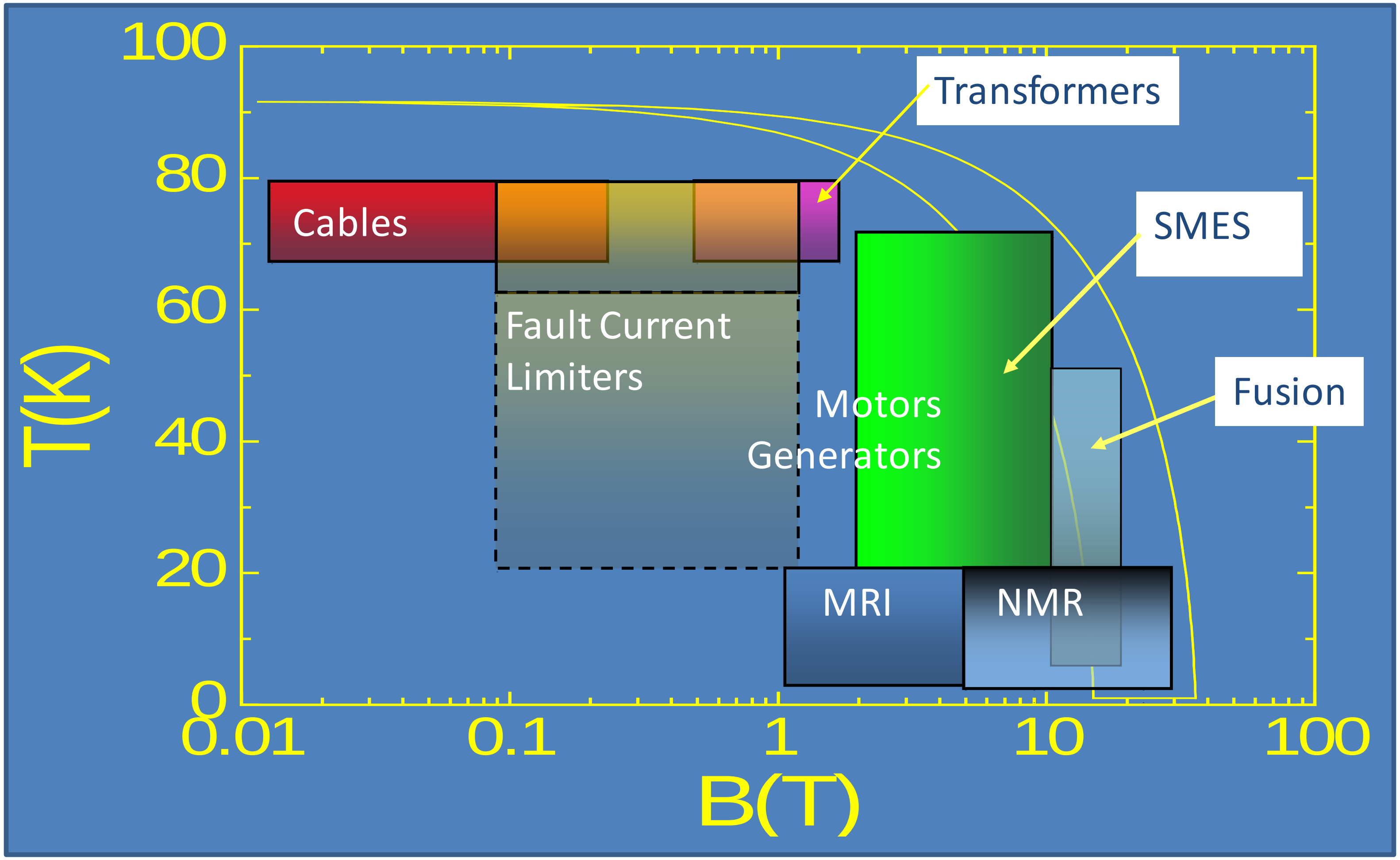
# Introduction - Contributions to Power Applications at Applied Superconductivity Conference 2012 in Portland

| | Cables | Fault Current Limiters | Rotating Machines | Trans-formers | SMES | Total |
|---|---|---|---|---|---|---|
| Korea | 14 | 42 | 10 | - | 14 | **80** |
| China | 13 | 19 | 11 | - | 13 | **56** |
| Japan | 10 | 5 | 7 | 1 | 8 | **31** |
| **Europe** | 6 | 21 | 14 | 5 | 4 | **50** |
| **US** | 7 | 4 | 5 | - | 3 | **19** |
| **Others** | 2 | 8 | 3 | 1 | 2 | **16** |
| **Total** | **52** | **99** | **50** | **7** | **44** | **252** |

Within the past decade Korea has taken a leading role in Power Applications of Superconductivity.

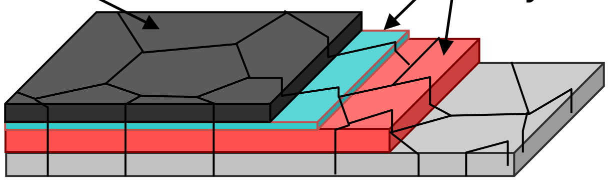
# Superconductors:
# Enabling Power Applications

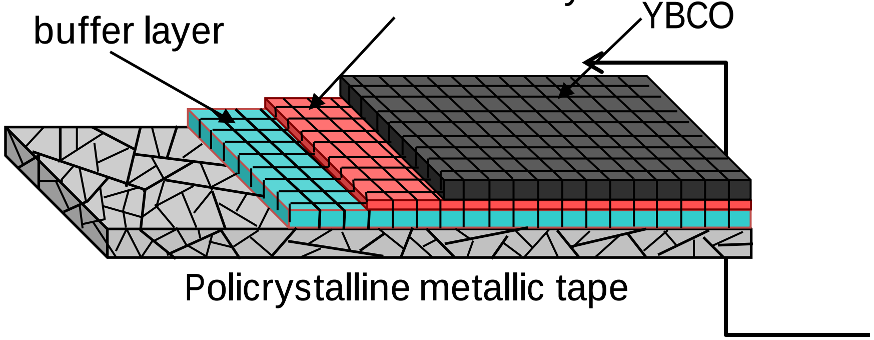
***25 years after the discovery of HTS ….***




***$YBa_2Cu_3O_{7-x}$ is the only material able to cover all the applications due to its high irreversibility line***

# YBCO COATED CONDUCTORS: EPITAXIAL ARCHITECTURE *due to its high anisotropic properties*




**Nanostructure control on km length materials: very close to real power applications**

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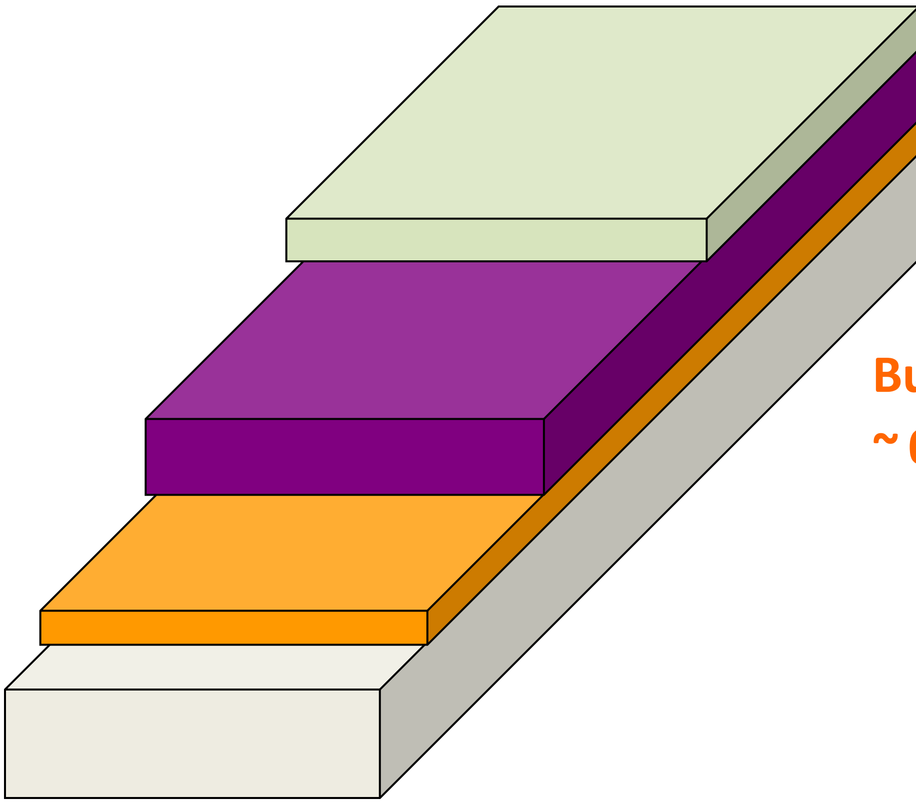


**Cap layer : Ag**

thickness ≈ 0.2 - 0.5 μm

**SC layer : YBCO**

**~ 1.0 -2.0 μm**

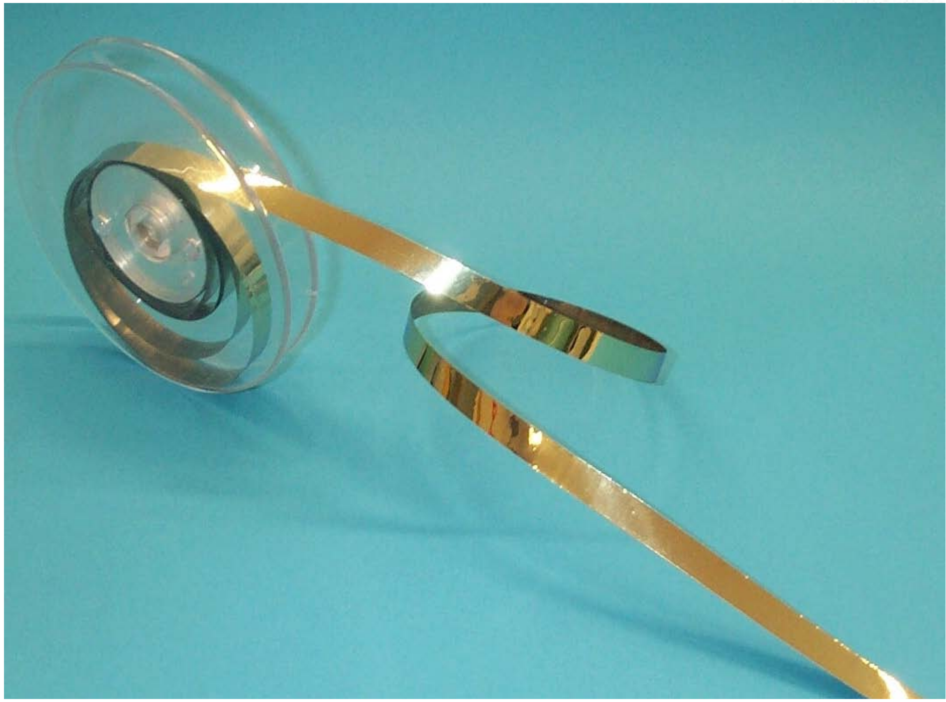
**Buffer layers : $CeO_2$ , YSZ, STO,…**

**~ 0.1 μm**

**Metallic substrate: RABiTS Ni, SS-IBAD,** thickness ~ 80 μm

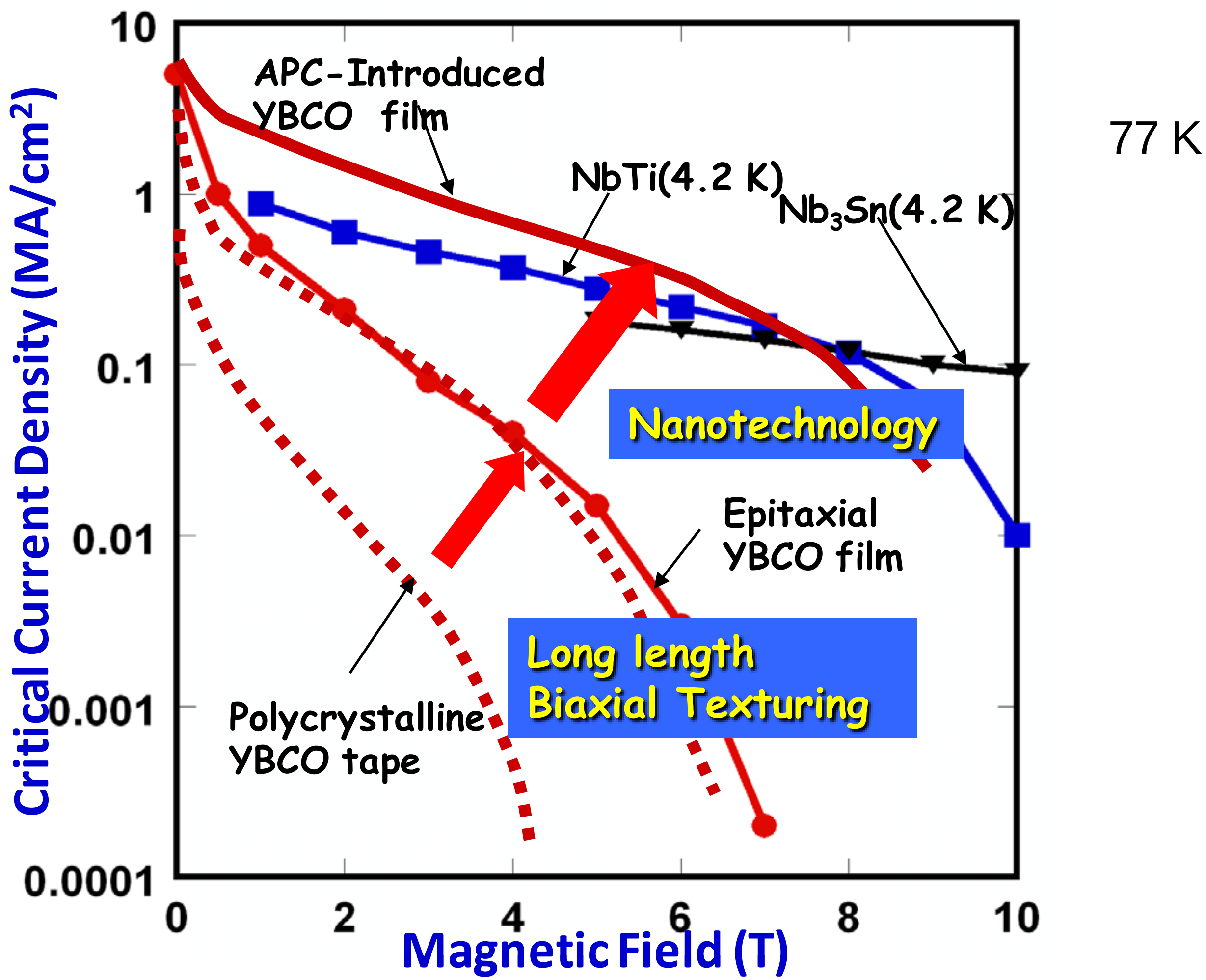
**Nanostructure control on km length materials: very close to real power applications**

# YBCO COATED CONDUCTORS: EPITAXIAL ARCHITECTURE *due to its high anisotropic properties*



**Nanostructure control on km length materials: very close to real power applications**

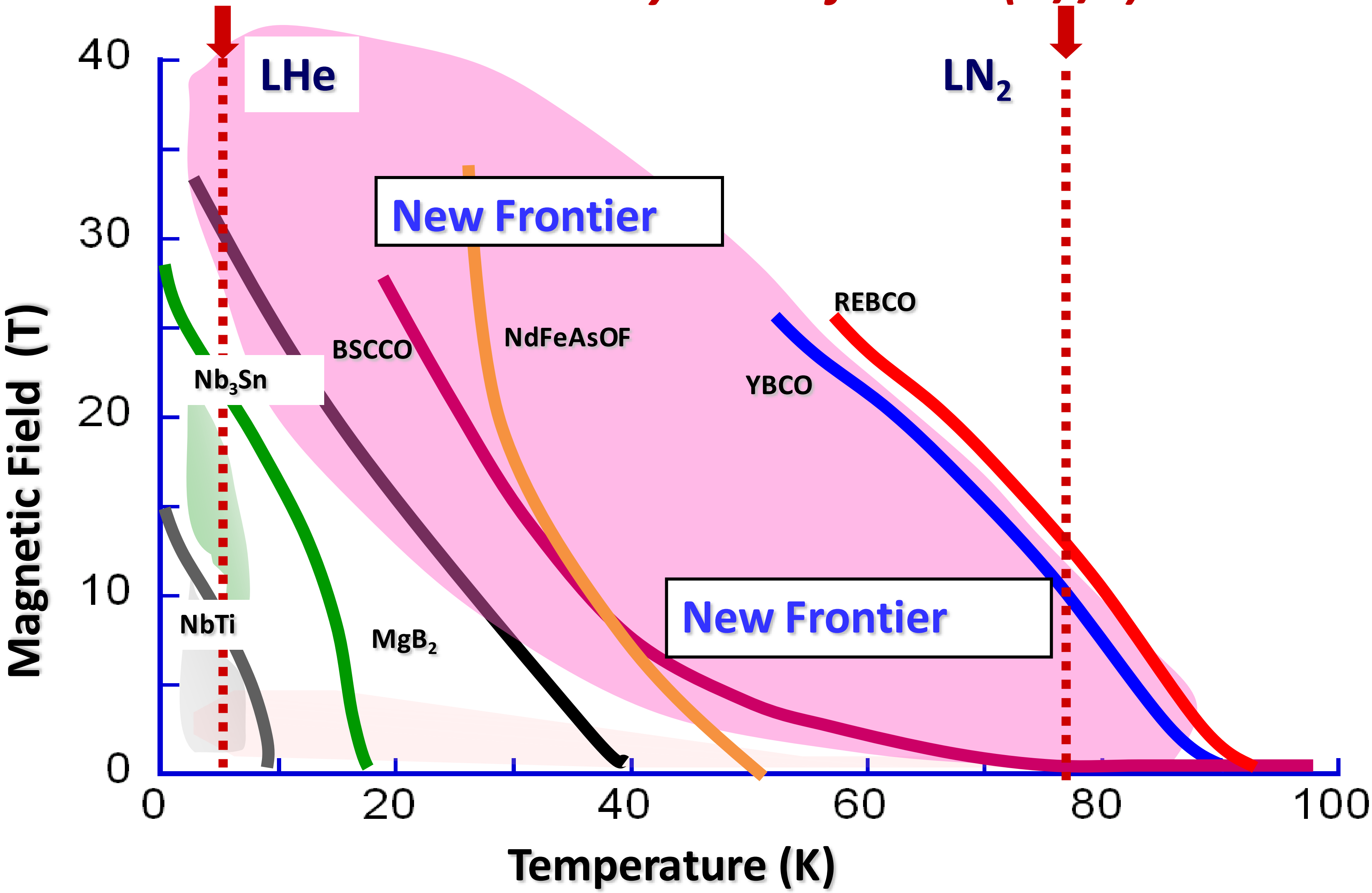
# Coated Conductors: the HTS materials for power applications. $J_c$ breakthroughs




Courtesy M. Matsumoto

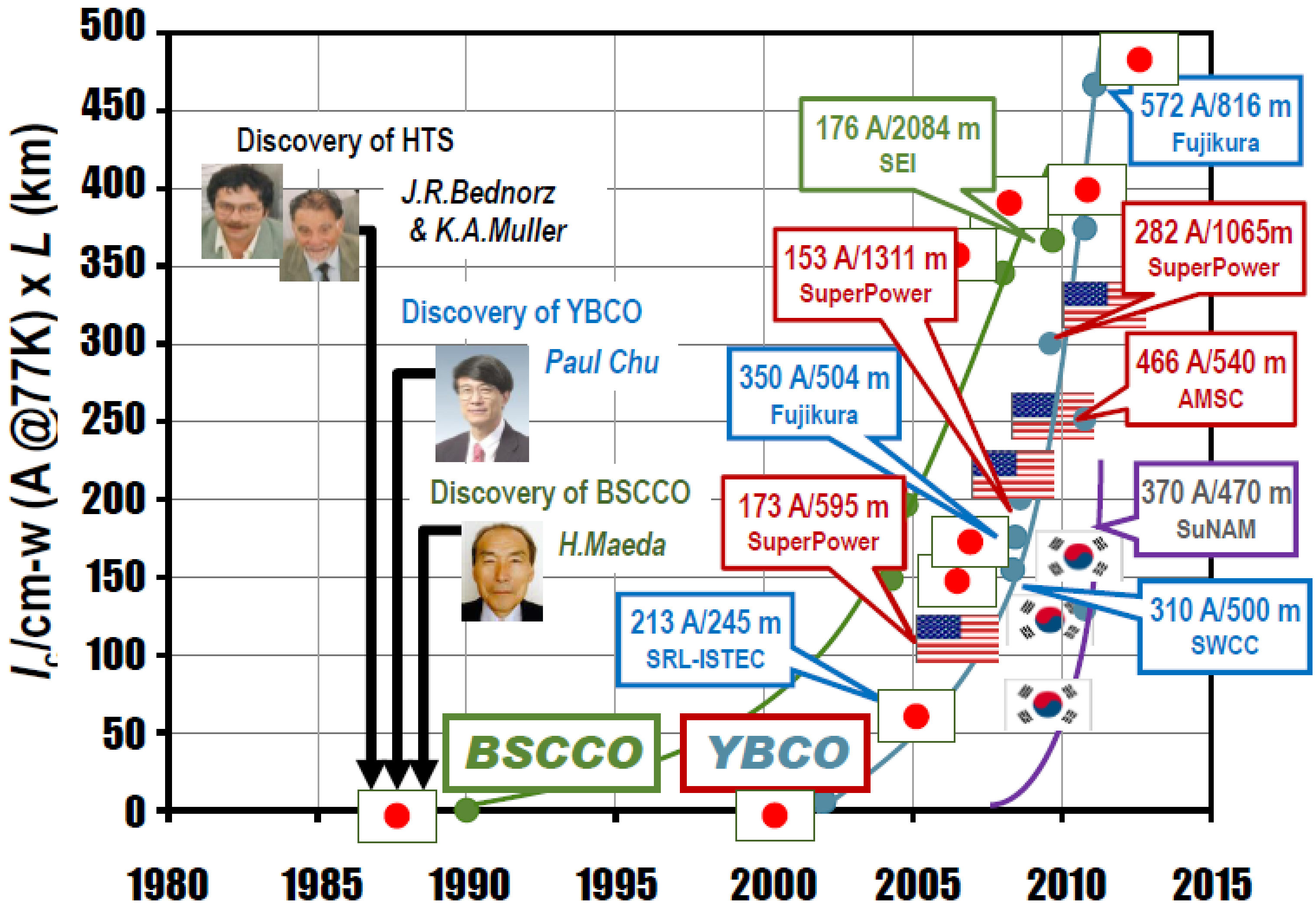
# A new frontier for applications

*Irreversibility Line of YBCO (H//c)*

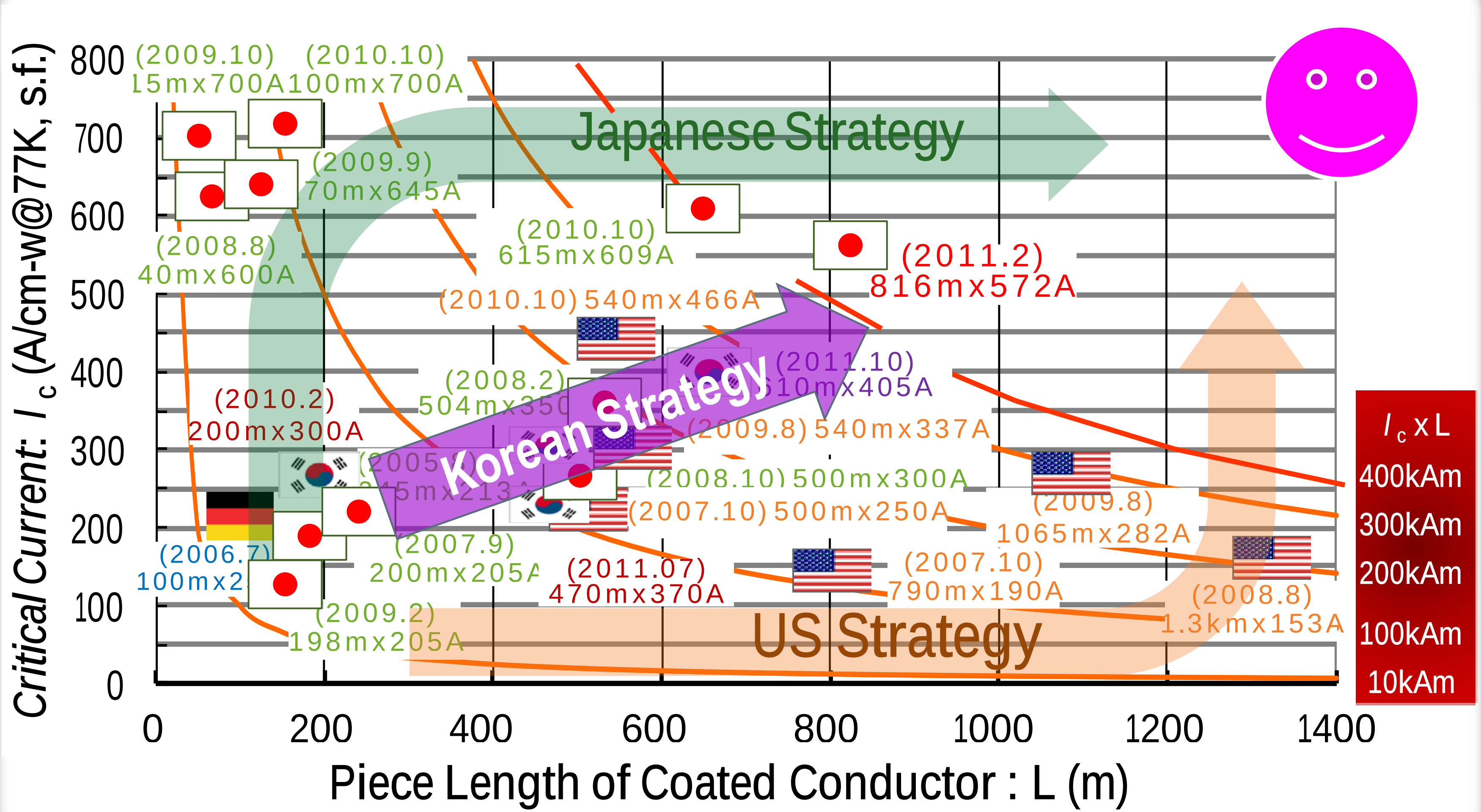



*Adapted from M. Matsumoto*

# Development of HTS conductors



# Development of Coated Conductors



# Coated Conductor research in Europe

*Xavier Obradors, Teresa Puig*

*Institut de Ciència de Materials de Barcelona*
*CSIC, 08193 Bellaterra, Spain*

**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

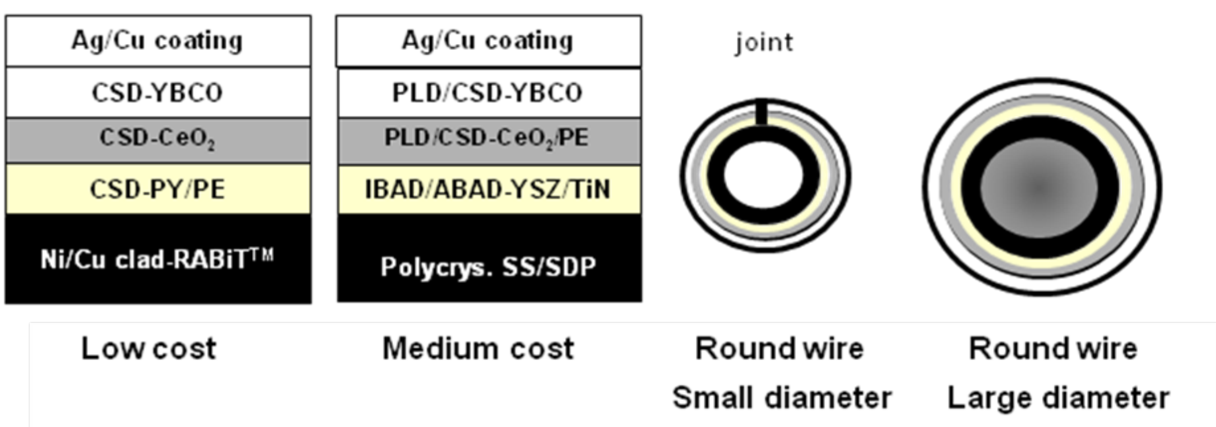
# European main SC activities

**EUROTAPES**
http://www.eurotapes.eu/
- 20 EU partners (9 countries)
- ~20 M€ (13.5 M€ - EU)
- 2012-2016


| | Participant | Country |
|---|---|---|
| 1 (Coord) | ICMAB-CSIC | ES |
| 2 | Bruker HTS GmbH | DE |
| 3 | Italian National agency ENEA | IT |
| 4 | Institute of Electrical Eng. Slovak | SK |
| 5 | La Farga la Cambra | ES |
| 6 | IFW Dresden | DE |
| 7 | Nexans SA | FR |
| 8 | Oxolutia, SL | ES |
| 9 | PerCoTech AG | DE |
| 10 | Technical University of Cluj-Napoca | RO |
| 11 | Vienna University of Technology | AT |
| 12 | Institute Neel | FR |
| 13 | University of Antwerp | BE |
| 14 | University of Cambridge | UK |
| 15 | University Autonoma de Barcelona | ES |
| 16 | University of Ghent | BE |
| 17 | Evico | DE |
| 18 | Nexans GmbH | DE |
| 19 | Leitat Technological Center | ES |
| 20 | Theva | DE |

# EUROTAPES objectives

- New metallic substrates with reduced ac –losses (non-magneitc RABiT) and lower cost ABAD templates (SDP process)
- 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
- Medium term decision



# EUROTAPES objectives

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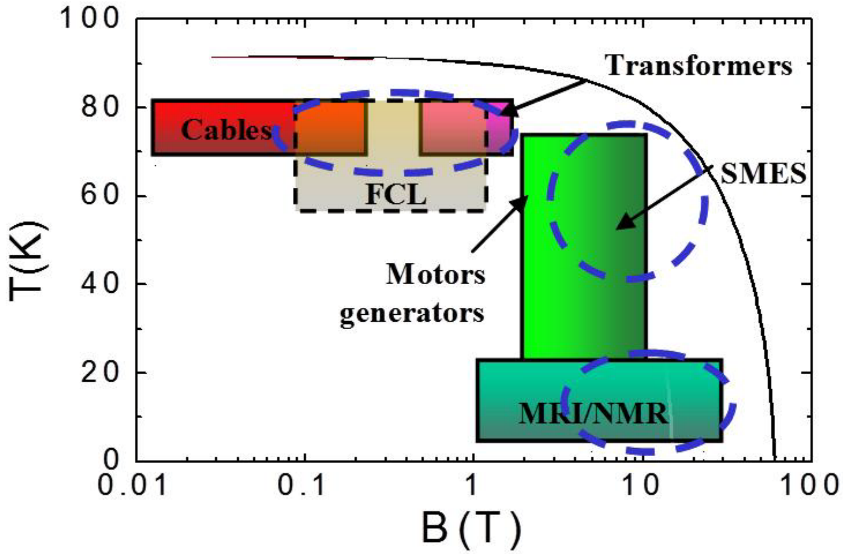
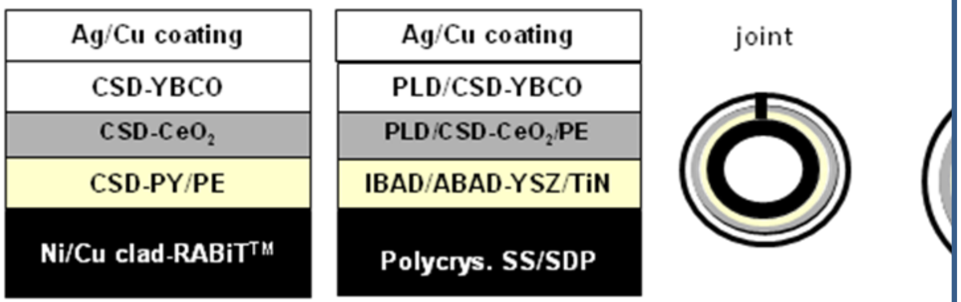



**TARGETS:**

- **Pre-comercial cost**: 100 €/kAm
- **Length** :+500 m
- **Performance:**
- For low fields (B< 1 T):
  $I_c$ (77K, sf) > 400 A/cm-w
- For ultrahigh fields ( B > 15 T):
  $I_c$(5K, 15 T ) > 1000 A/cm-w
- For high fields (B ~3-5 T):
  $F_p$( 60 K) > 100 GN/m$^3$




Low cost

Medium cost

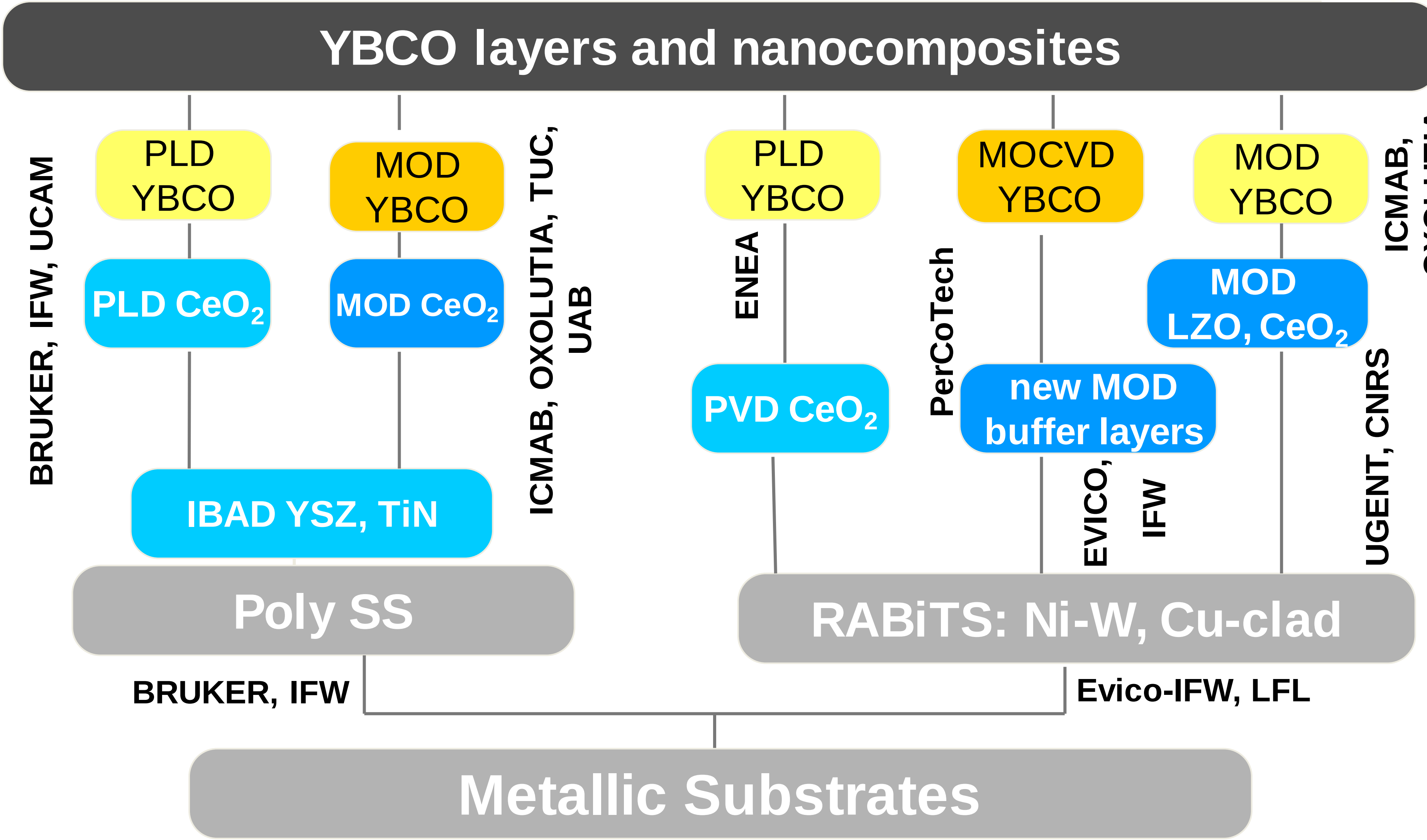
Round wire
Small diameter

# Power applications: operating conditions, required lengths and fraction cost of CC

| Application | Operating magnetic field (T) | Operating Temperature (K) | $I_c$ x L (kA-m, per cm width) |
|---|---|---|---|
| Cables | 0.01 – 0.1 | 70 – 77 | 40,000 to 2,500,000 |
| Transformers | 0.1 | 65 – 77 | 2,000 – 3,000 |
| FCL | 0.1 | 65 – 77 | 1,000 – 10,000 |
| Generators | 1 – 3 | 30 – 65 | 2,000 – 60,000 |
| Motors | 2 – 5 | 30 – 65 | 1,000 – 25,000 |
| SMES/magnets | 2 – 20 | 4 – 50 | 2,000 – 30,000 |

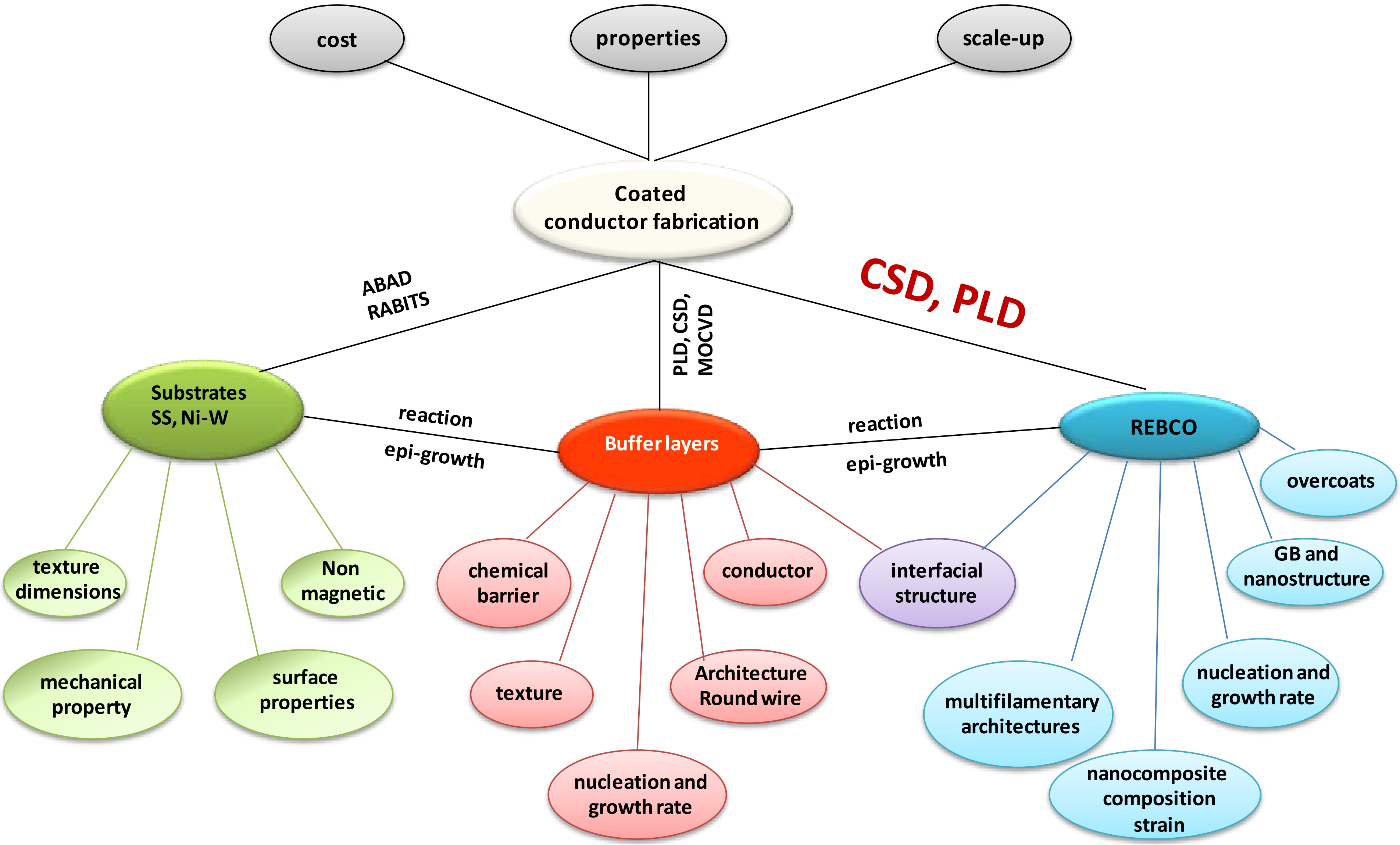
| Application | Example | Fraction of HTS wire on total system costs |
|---|---|---|
| Magnet | NMR, MRI, Induction heater Fault current limiter | 5-15 % |
| Rotating machines | Ship motor, Wind power generator, Hydro generator | 10-30 % |
| Transmission/ Distribution | Cable (AC / DC), FCL (resistive / inductive type), Transformer | 20-25 % |

# EUROTAPES EU project



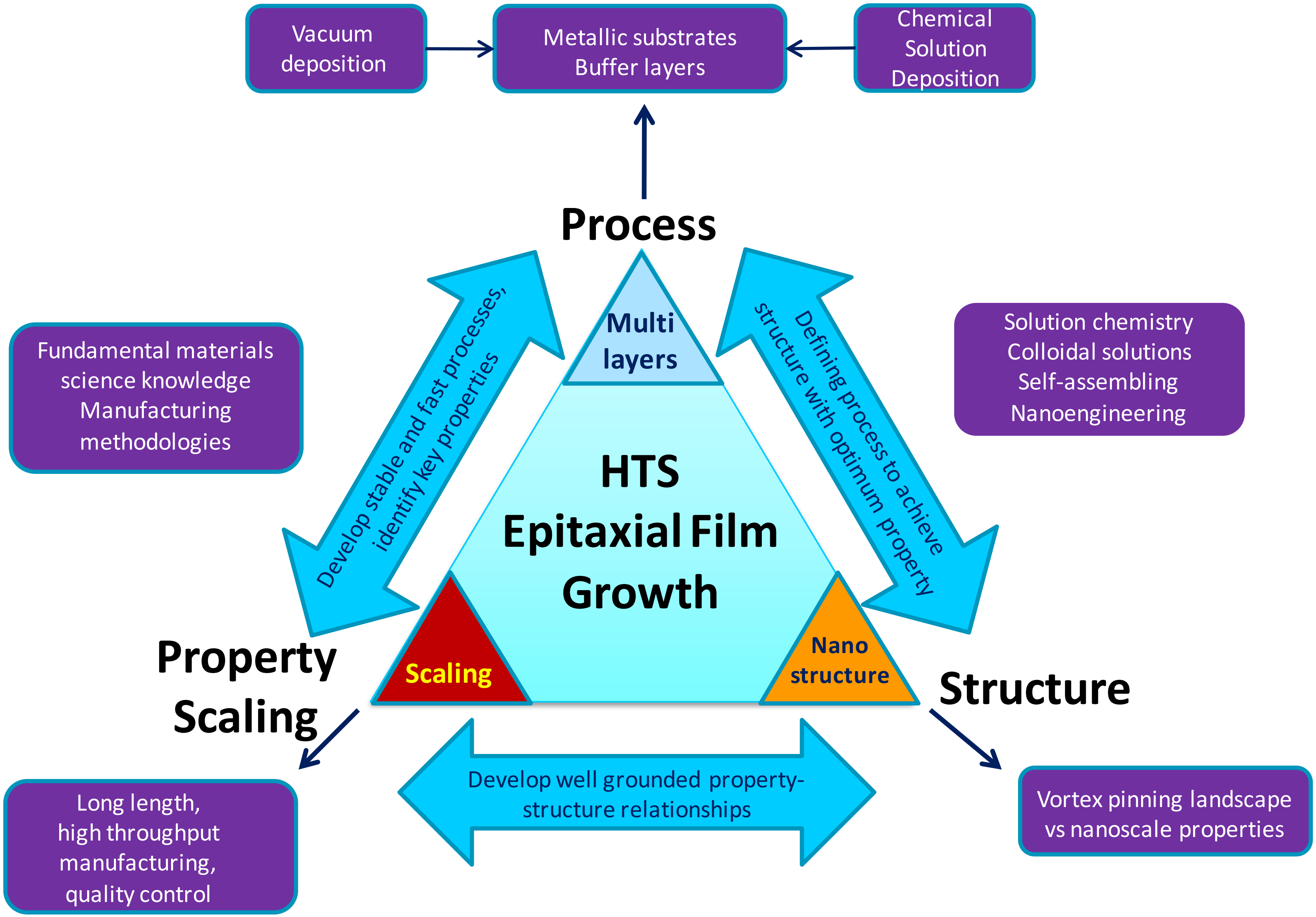

Advanced characterization and in-situ monitoring: TUWien, UAntwerpen, THEVA
Striations, ac losses, round wire : UCAM, Bratislava, NEXANS

# Fully integrated coated conductors



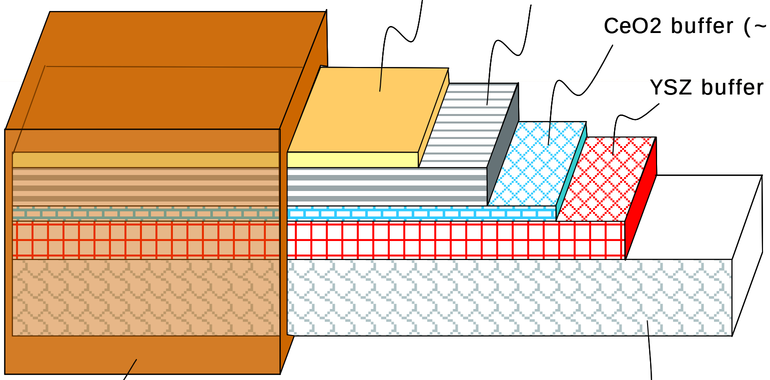
# COATED CONDUCTORS ISSUES

## Material science - maximizing performance – Nanoscience
## high-throughput / high-yield / Low cost manufacturing processes



# ABAD metallic substrates

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



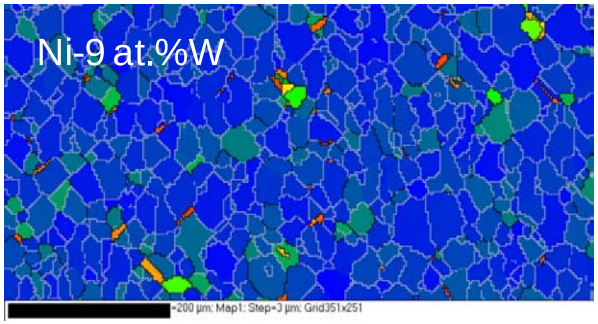

*Targets:*

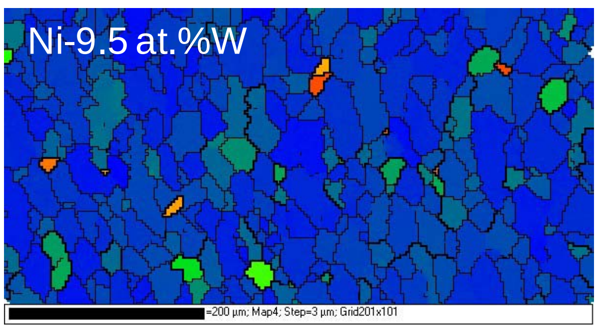
| | |
|---|---|
| Substrate polishing | 8 => 150 m/hour |
| ABAD | 4 => 35 m/hour |
| width | 12 => 40 mm |
| length | 100 => 500 m |

**To be investigated** (within EUROTAPES) for cost reduction **:**
Solution Deposition Planarization (SDP) process to substitute mechanical polishing

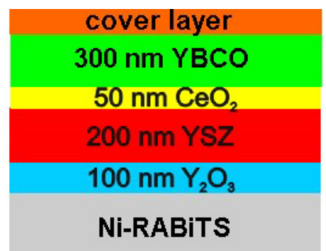
# Higher alloyed Ni-W tapes

## *Development of highly textured non-magnetic RABiTS tapes*



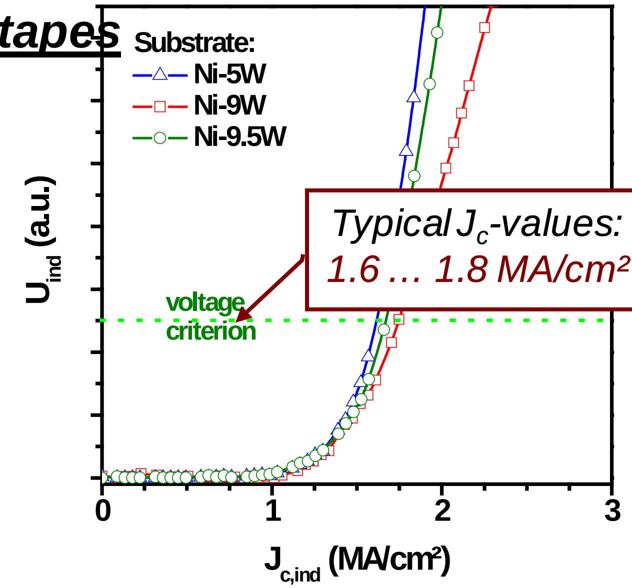




YBCO coated conductor architecture grown by pulsed laser deposition on small samples (1 x 1 $cm^2$)

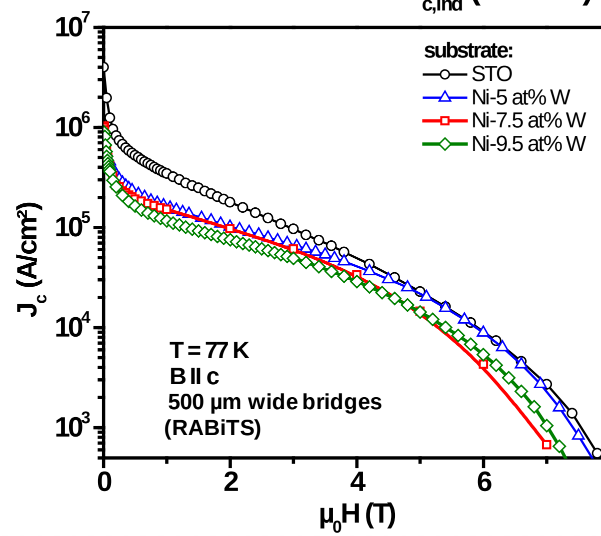



Fraction of cube texture: >95%

*Deviation from (001)[100] cube texture:*


*Typical $J_c$-values:* *1.6 … 1.8 MA/cm²*

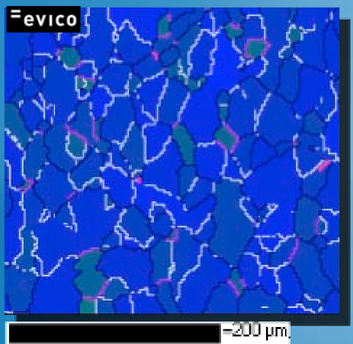



*R. Hühne et al., Supercond. Sci. Technol. 23 (2010) 034015*

## The leading manufacturer of Ni-based highly cube textured substrates in Europe

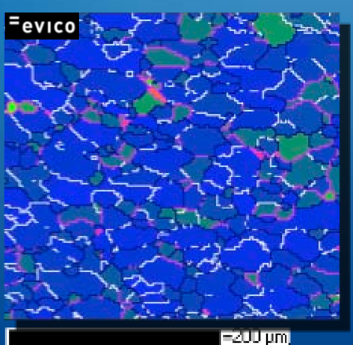

### Available products:

**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

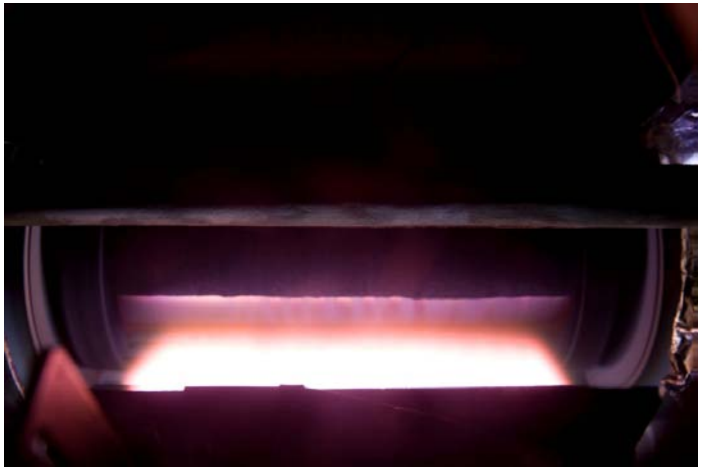
- **customized dimensions on request**
- **Ni9at%W - Research**
  not available yet
  > 94 % cube texture fraction
  Status: transfer to production soon

eurotopes

**Spin-off from IFW- Dresden (founded in 2004)**
**9 employees**

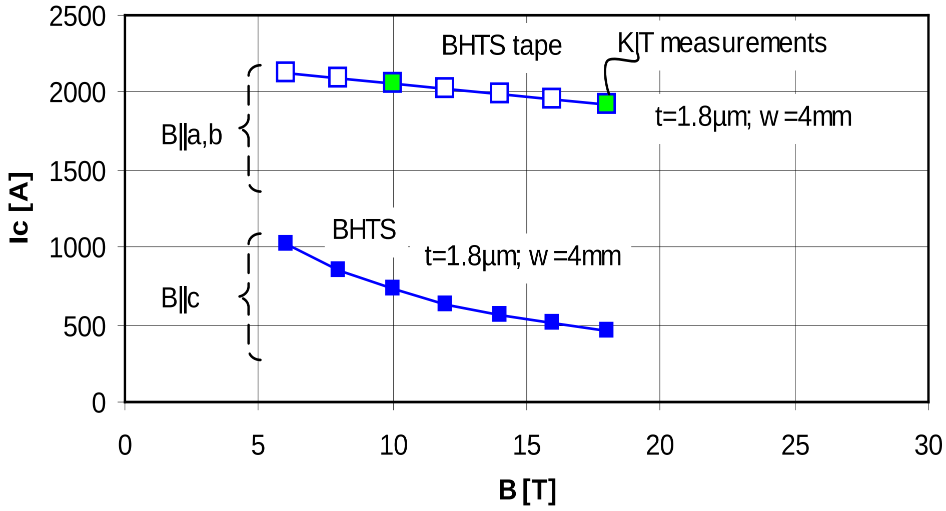
evico

# Multi plume HR-PLD for Large area HTS coated conductors



45m long, 4mm wide tape

- 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

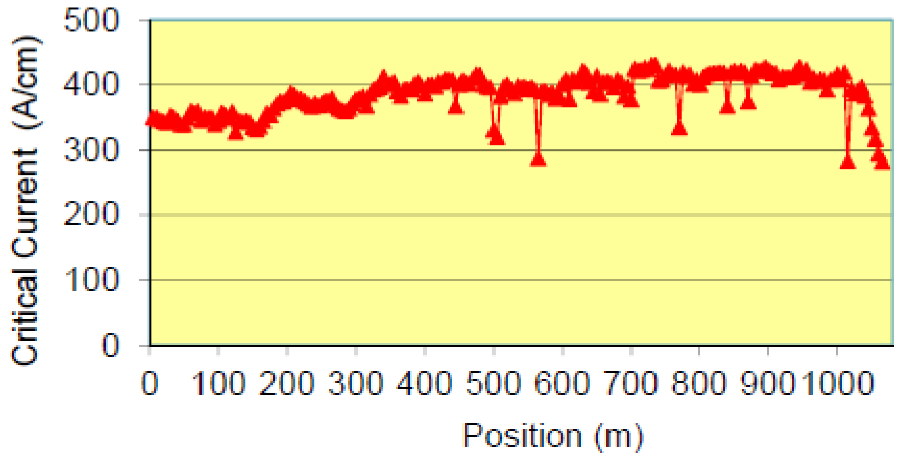



**Highest $I_c$ achieved in 6m long tape: 500 A/cm-w at 77K, SF**

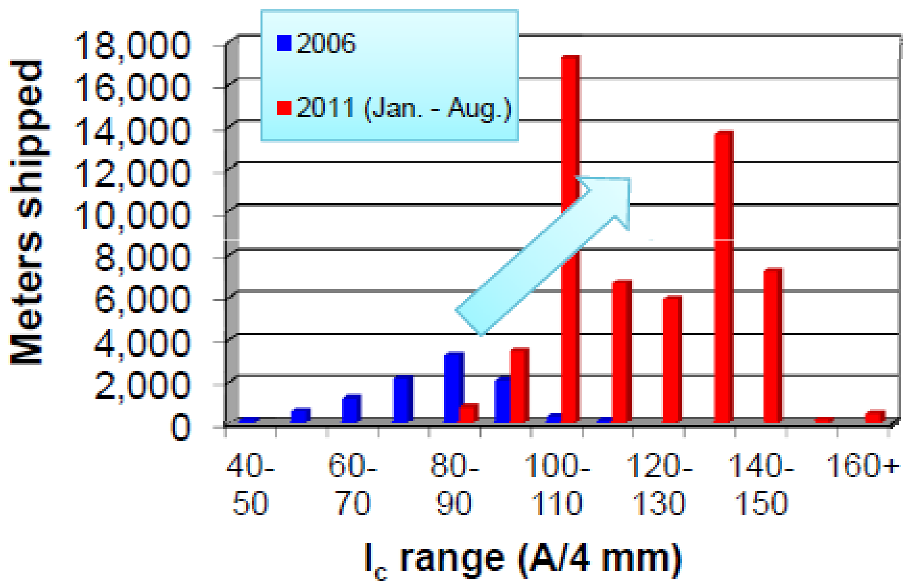
**Well-reproducible $I_c$: 250 A/cm-w at 77K, SF**

# Successful scale up of IBAD-MOCVD based 2G HTS wires

- 1,000 m 2G HTS wire first demonstrated in July 2008 1,400 m lengths are now routinely produced.
- High throughput processing (>> 100 m/h* in IBAD & buffer processes, > 100 m/h* in other processes)




| Metric | 2006 | 2011 |
|---|---|---|
| Total wire shipped (meters) | **10,000** | **150,000** (projected for the year) |
| Average $I_c$ (A/4 mm) | **80** | **122** |
| $I_c$ range (A/4 mm) | **40 – 118** | **80 - 165** |

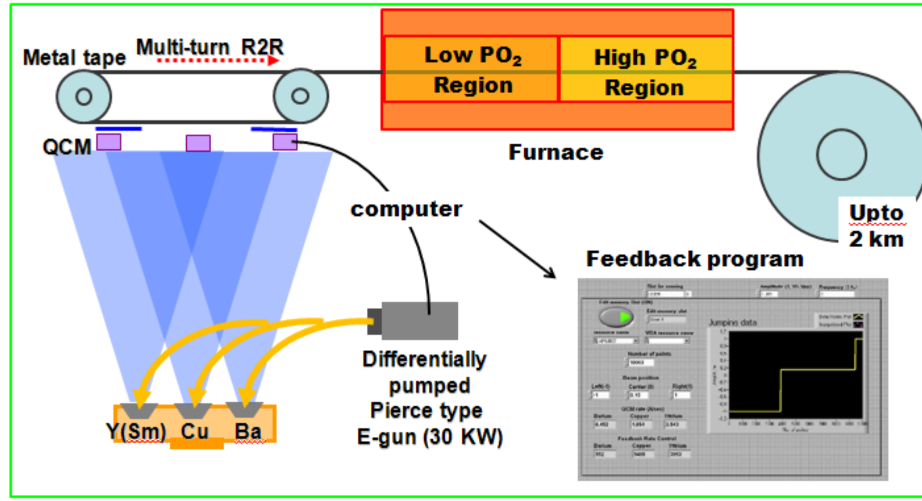


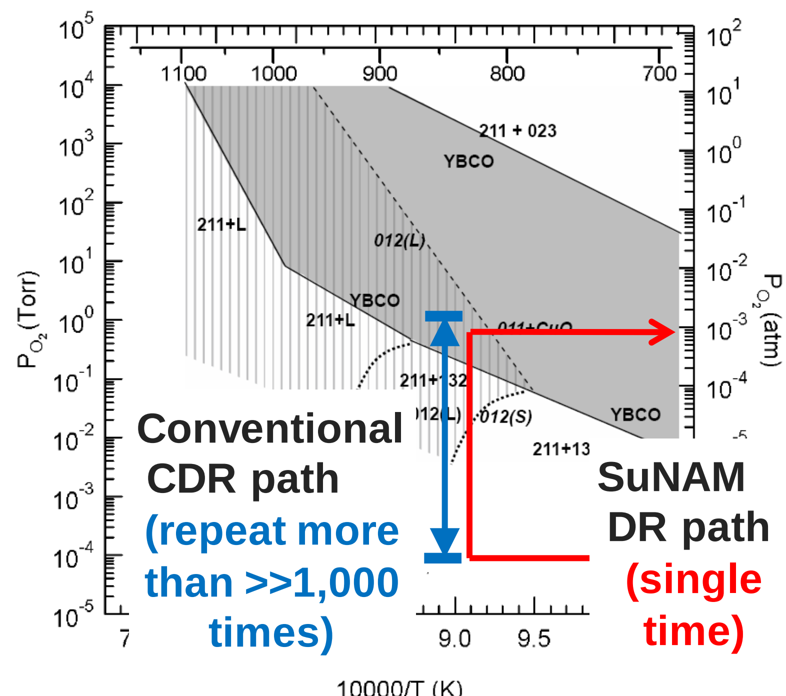

TcSUH

*4 mm wide equivalent

# New SuNAM RCE-DR process

- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R)
- High rate co-evaporation at low temperature & pressure to the target thickness(> 1 μm) at once in deposition zone (6 ~ 10nm/s)
- <u>Fast (<< 30 sec. ) conversion</u> from **amorphous glassy phase to superconducting phase** at high temperature and oxygen pressure in reaction zone
- **Simple, higher deposition rate & area, low system cost**
- <u>Easy to scale up :single path</u>



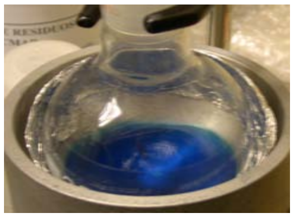

SuNAM

# CSD: YBCO and nanocomposites

*… a versatile, scalable and low cost methodology for growing nanostructured epitaxial films*

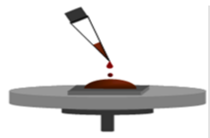
**Precursor solution synthesis**

Y, Ba,Cu metal-organic precursors



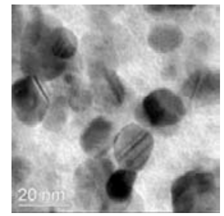
**Solution deposition**

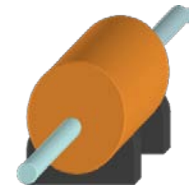
Ink-jet Printing



**Pyrolysis**

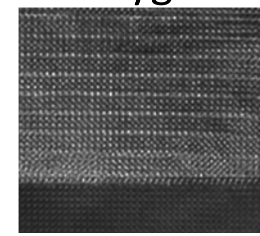
Removal organic precursors



**Ex-situ Growth**

Nucleation, crystallization and oxygenation



It is an ex-situ solution based growth method

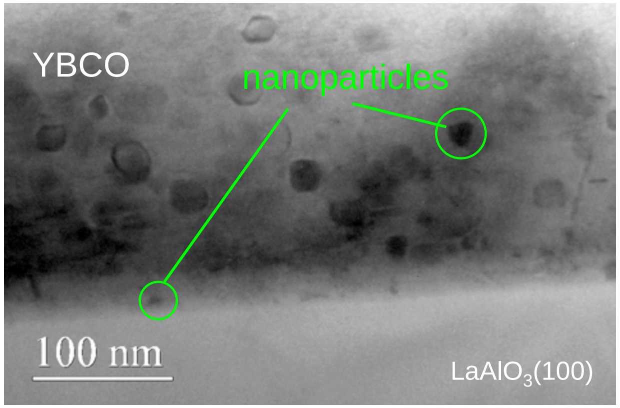
*X. Obradors, T. Puig et al, SUST (2012)*

## For Nanocomposites:

**Addition of metal-organic salts (Zr, Ce, Ta, …) in the TFA precursor solution :** Spontaneous Np segregation within the epitaxial $YBa_2Cu_3O_7$ matrix : **$Y_2O_3$, $BaZrO_3$, $Ba_2YTaO_6$, $BaCeO_3$**, … ($\varepsilon$ = -2.7%, +8.5%, +8.7%, +12.1% )

***Key control of Nanoparticles size, shape, concentration, orientation and strain …***

***Interfaces are the key issue for the performances achieved***

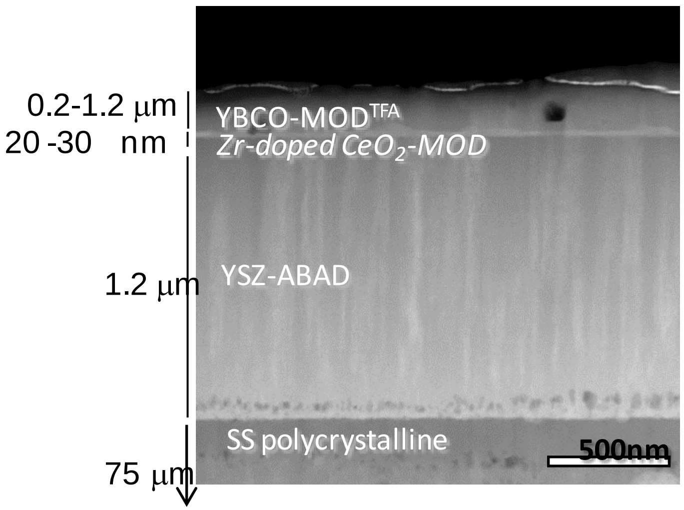


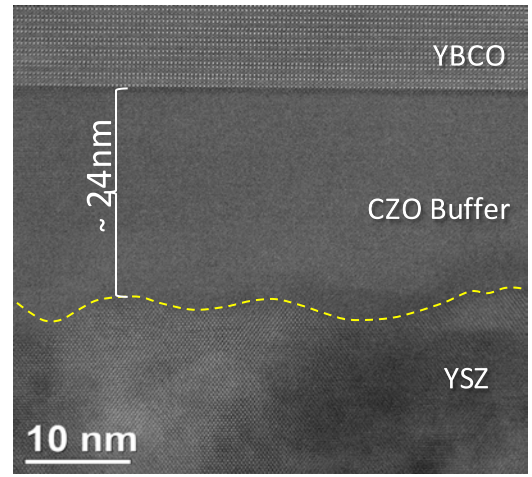

*Nature Materials (2007); Nature Materials (2012)* www.oxolutia.com

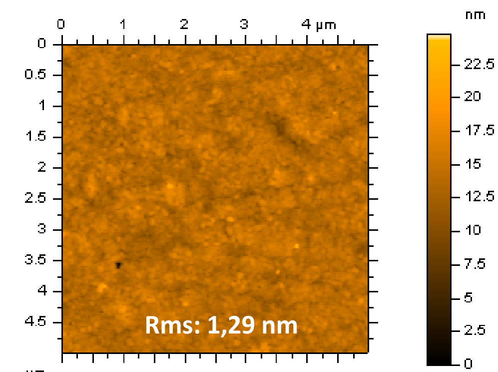
*Technology-based spin-off company created from ICMAB-CSIC currently committed to scale-up* ***2G superconductor tapes by metalorganic decomposition (MOD).***

***5 employees***

5 patents licenced by CSIC




Buffer target 2013:

Establish Zr-doped $CeO_2$ Ink Jet Deposition for continuous mode in 10 m pieces

New buffer process 8x time reduction with 70% surface planarity in tapes

# InkJet printed MOD YBCO layers

OXOLUTIA

ICMAB CSIC eurotapes

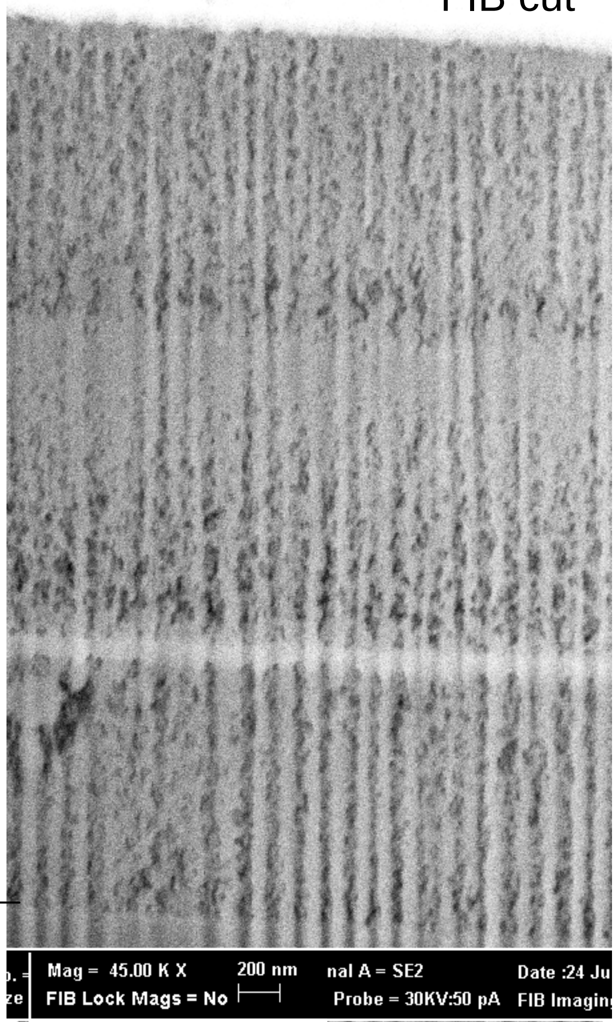
Ag layer

3 layers

FIB cut

Pyrolyzed precursor

3.5 µm



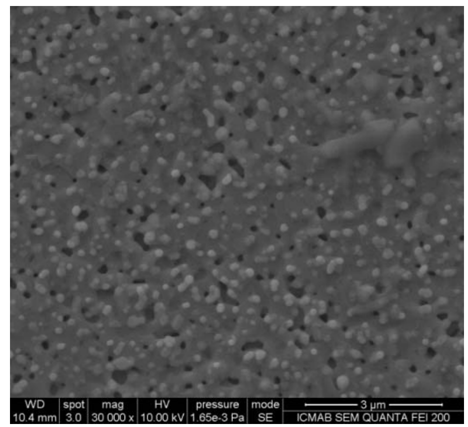

YBCO/LAO

$J_c$ = 2.4 MA/cm$^2$ (800 nm), $I_c$ = 192 A/cm-w

$J_c$ = 1.2 MA/cm$^2$ (1.2 µm), $I_c$ = 144 A/cm-w

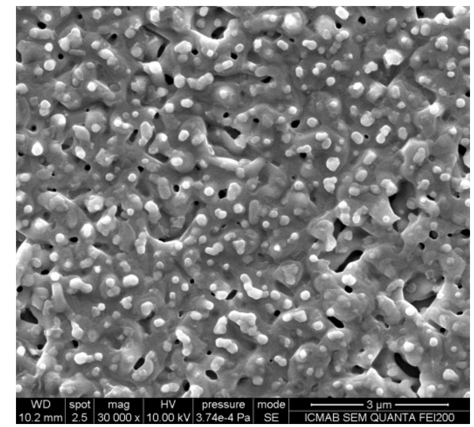
**YBCO / $CeO_2$ / $^{ABAD}$YSZ /SS**

**1 layers ( 300 nm)**




$J_c$(sf,77K)=2 MA/cm$^2$

**3 layers (900 nm)**




$J_c$(sf,77K)=1.2 MA/cm$^2$

$I_c$=108 A/cm-w

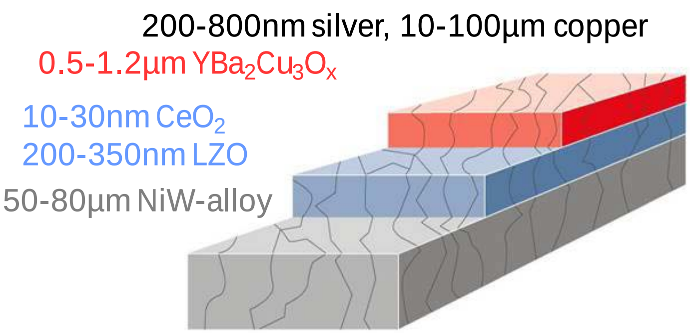
**Target for high $I_c$ (2013):**

- Thickness (IJP) ~ 1.2 µm ( two coats)
- $J_c$ (77K, sf) ~ 2 MA/cm$^2$
- Growth rate > 1 nm/s (two module process)
- In continuous mode

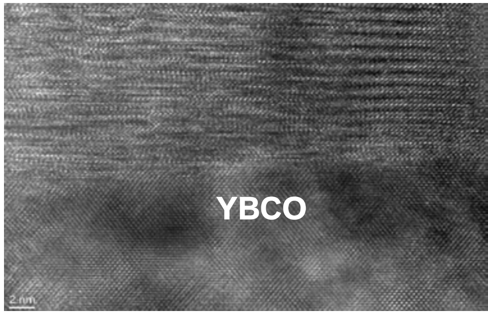
# Ink-Jet Printed RABiT CC's

*23 employees, BASF GmbH involved as cooperation partner*

- 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)




Ink-jet printing in continuous processing




✓ **All samples continuously processed in minimum 10 m lengths**

✓ $J_c$ (77K, sf) = 1.2 -1.8 MA/cm$^2$ for 1 µm HTS

✓ 7mm wide slitted and stabilized sample, $I_c$ /cm-w > 160A

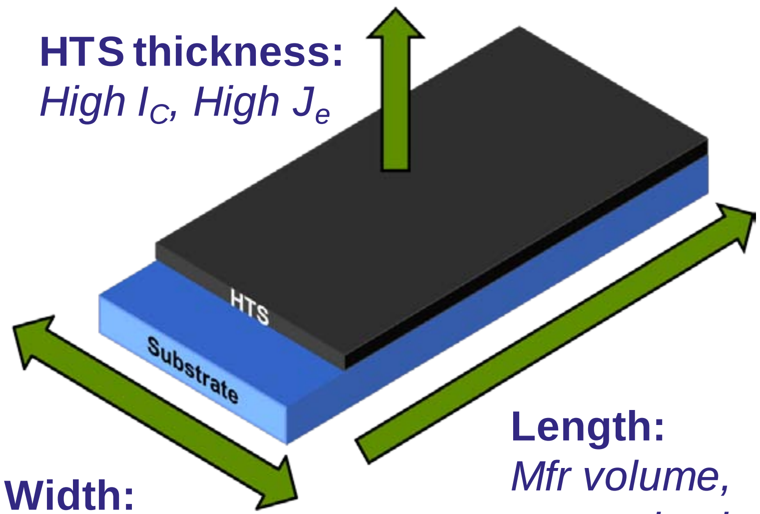
✓ 100 m wound to coil with overall Jc =1.4 MAcm$^2$

American Superconductor®

# MOD/RABiTS™ HTS Wire Manufacturing Flexibility

### *HTS Strip: Scalable in 3 Dimensions*

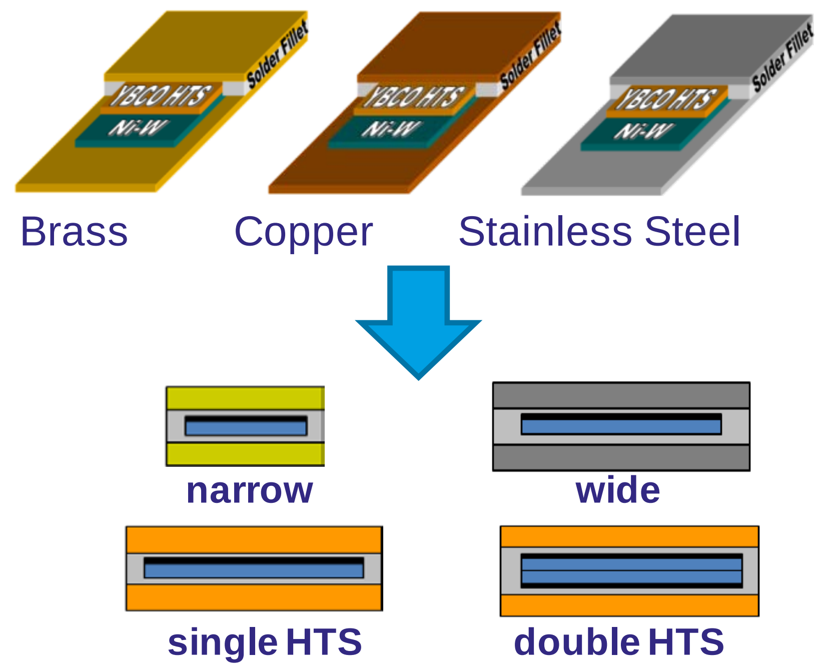
**HTS thickness:**
*High $I_C$, High $J_e$*




**Width:**
*Mfr volume, cost reduction, wire design flexibility*

**Length:**
*Mfr volume, cost reduction*

### *Application-Specific Lamination*




#### ***MOD RABiTS HTS Strip***

- Highly scalable process technology
- High $I_C$ uniformity
- Able to slit to any width

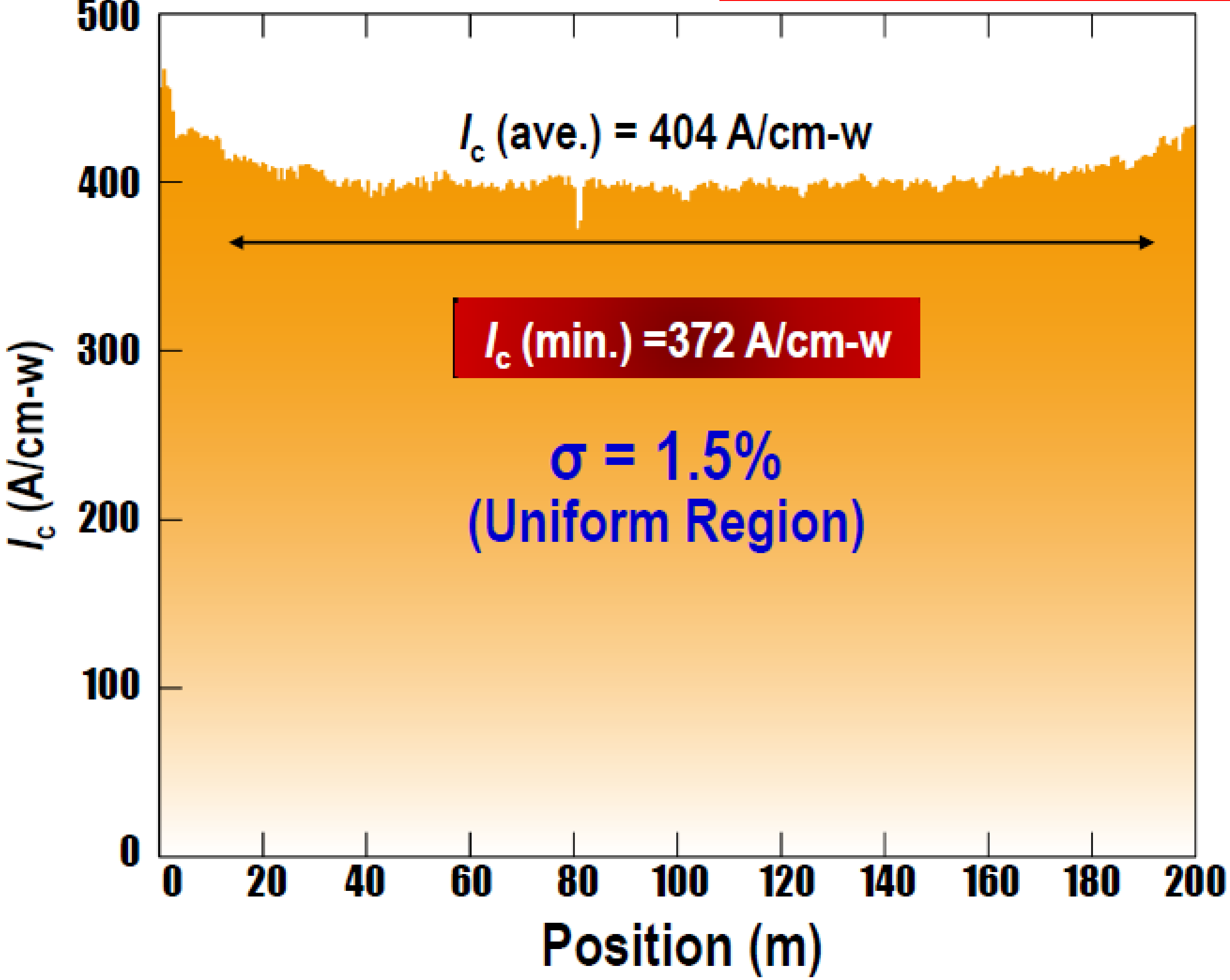
#### ***Finished HTS Wire***

- Tailored mechanical properties:
- Tailored normal electrical properties
- Multiple architecture options

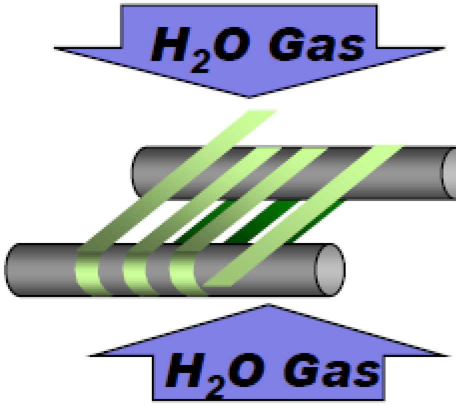
***Low cost, high performance HTS wire optimized to meet application requirements***

# Lower Cost C.C. Fabrication by TFA-MOD

$Y_2O_3 + CuO + BaF_2 + H_2O\downarrow \Rightarrow YBa_2Cu_3O_{6+\delta} + HF\uparrow$



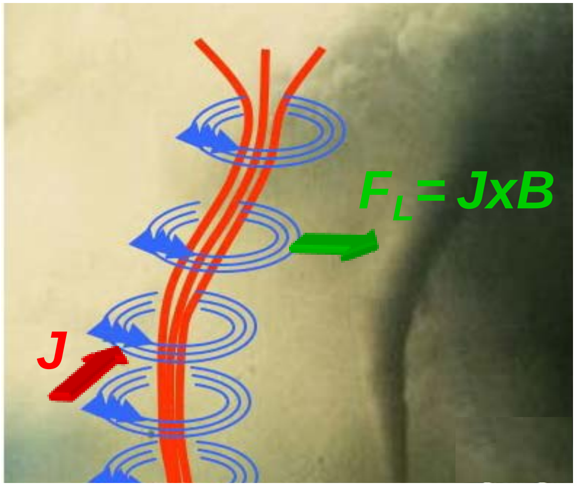





ISTEC SWCC

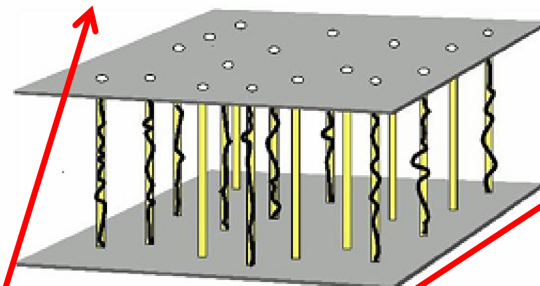
# Vortex pinning in YBCO Nanocomposites

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

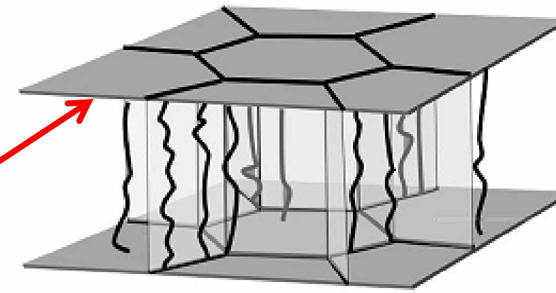



*Vortices need to be pinned in non-SC nano-regions*

✔ 1D-APC dislocation, columnar defect

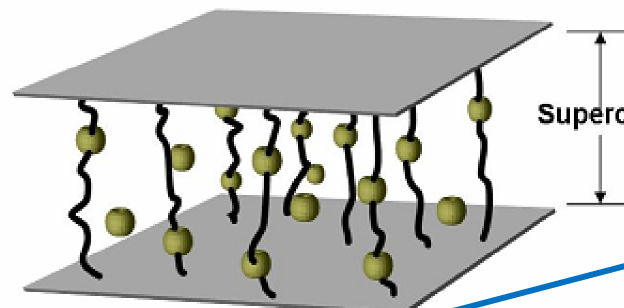


✔ 2D-APC grain boundary, planar defect



✔ 3D-APC

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




✓ 0D-APC
Oxygen vacancies, …

*Courtesy M. Matsumoto (adapted)*

**Anisotropic and strong defects**

**Isotropic and strong defects**

**Isotropic and weak defects**

*The role of interfaces in nanocomposites are the key issue*

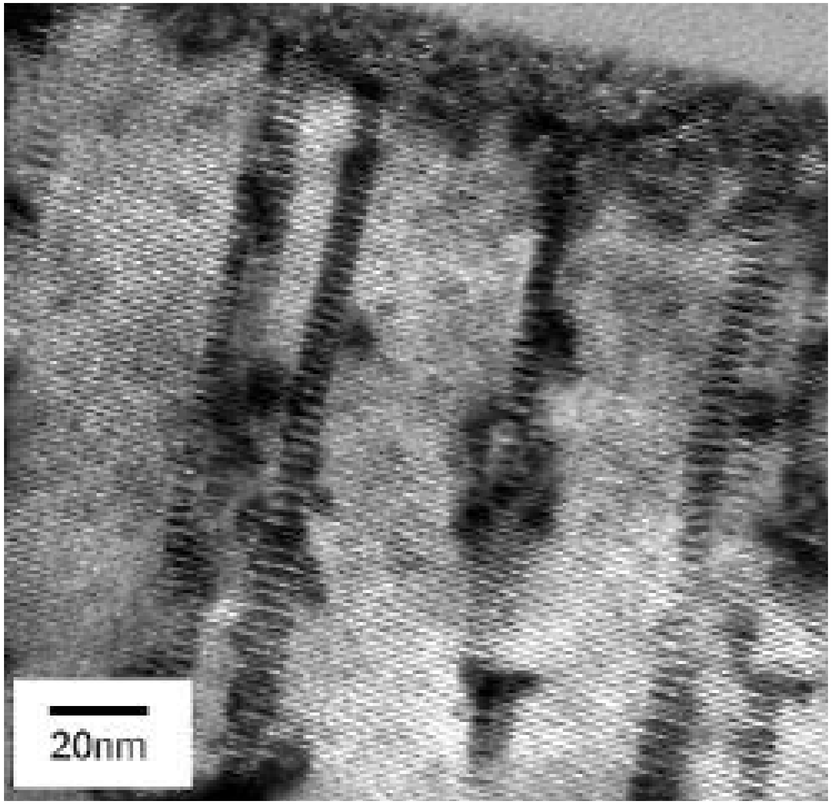
… but there always exits superposition of different contributions in a single material

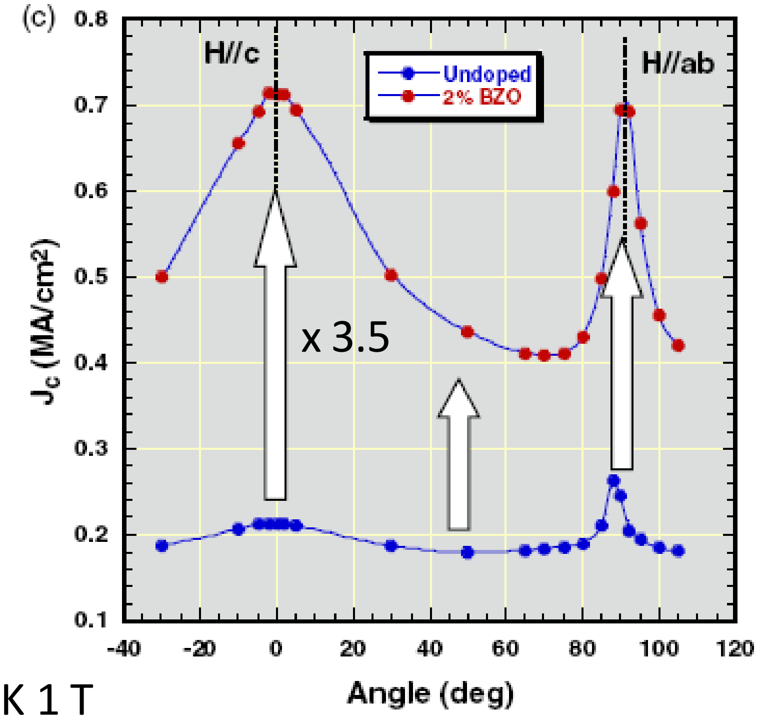
# Superconducting Nanocomposites

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

$YBa_2Cu_3O_{7-x}$ – $BaZrO_3$ nancomposite by PLD

Epitaxial YBCO-BZO interfaces



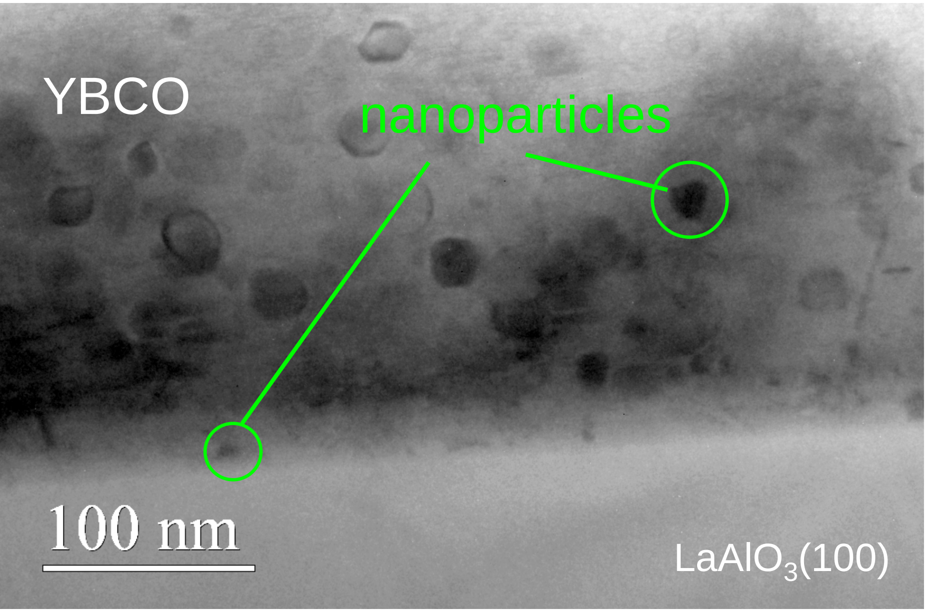



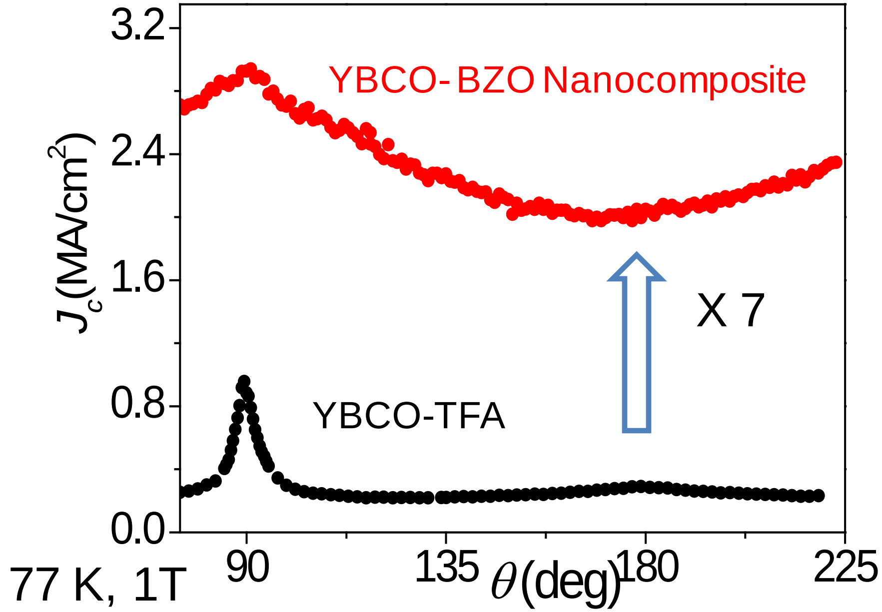

77 K 1 T

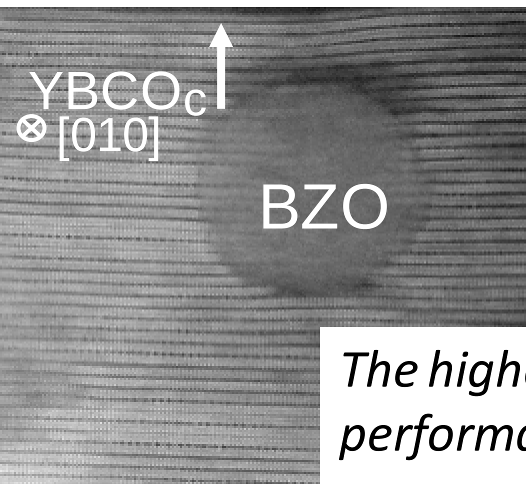
*S. Kang, Science 311 (2006)*

Huge increase of performances is achieved

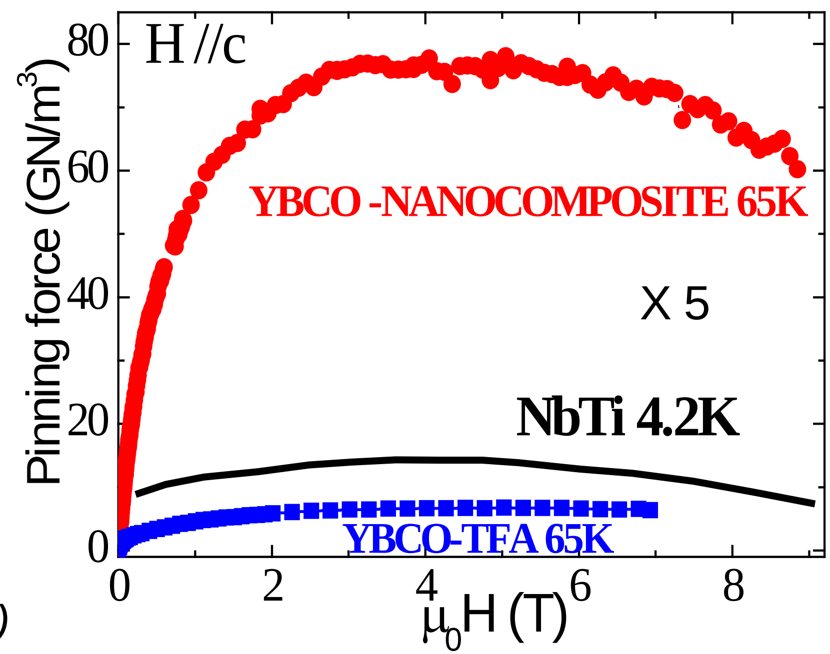
# Chemical solution HTS Nanocomposites




Incoherent YBCO-BZO interfaces

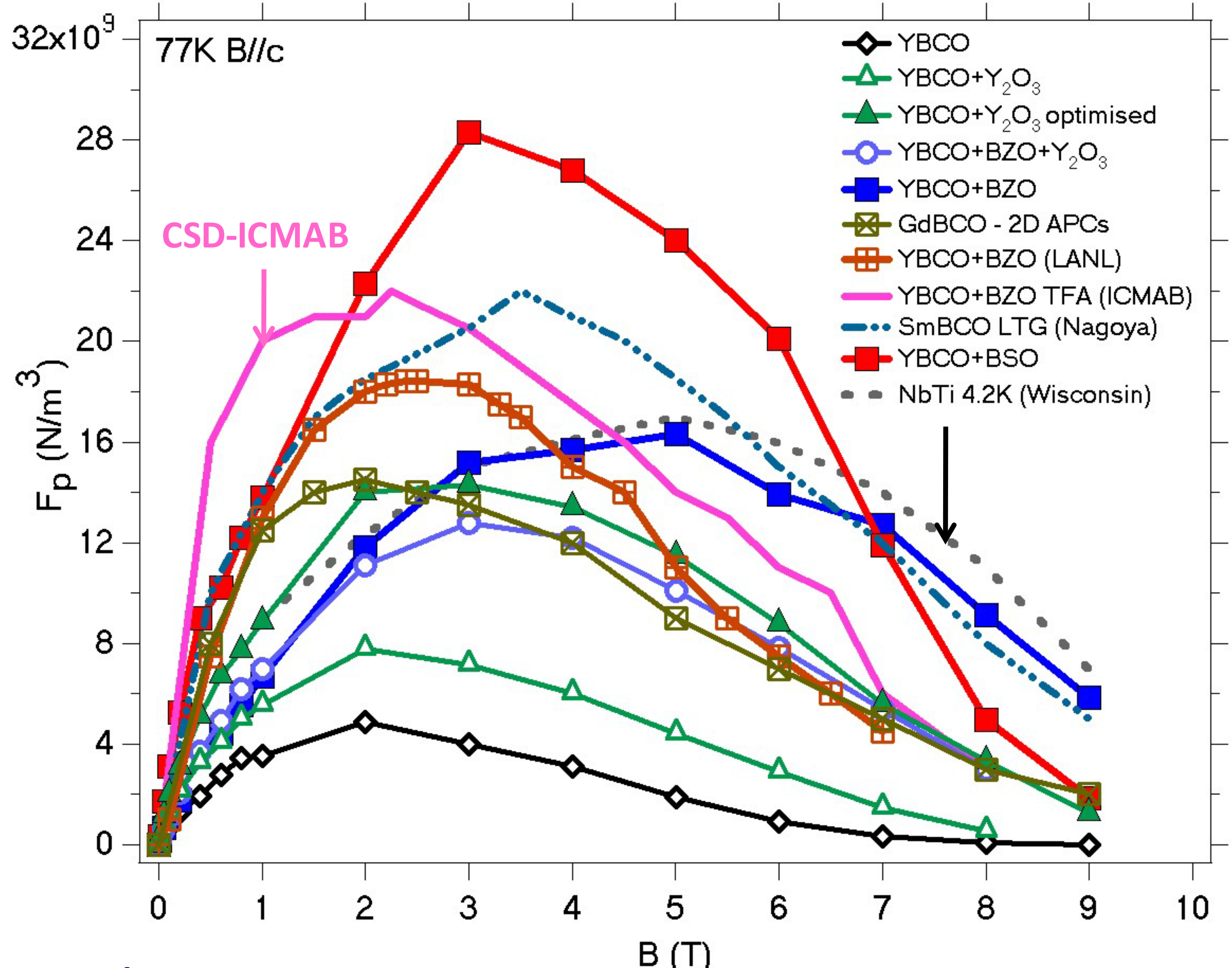



*The highest isotropic performance ever found in any superconducting material*

*J. Gutiérrez ... T.Puig., Nature Materials (2007)*

*A. Llordés ... T Puig., Nature Materials, 11, 329 (2012)*

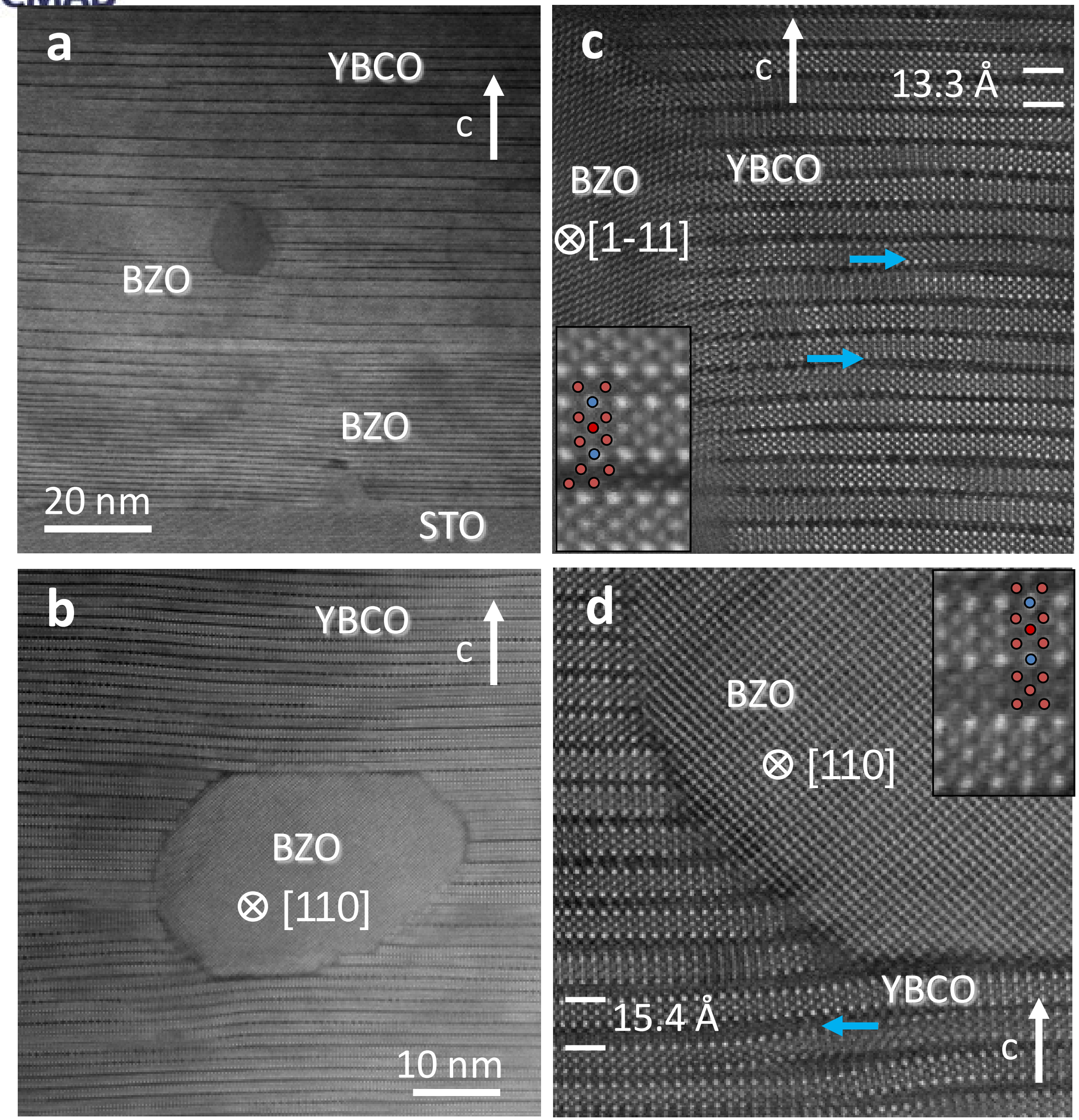
# Pinning forces in YBCO Nanocomposites




**Performances at $lN_2$ temperature overcomes for the first time low T SC at T =5 K**

*J. Gutiérrez ... T.Puig., Nature Materials (2007)*

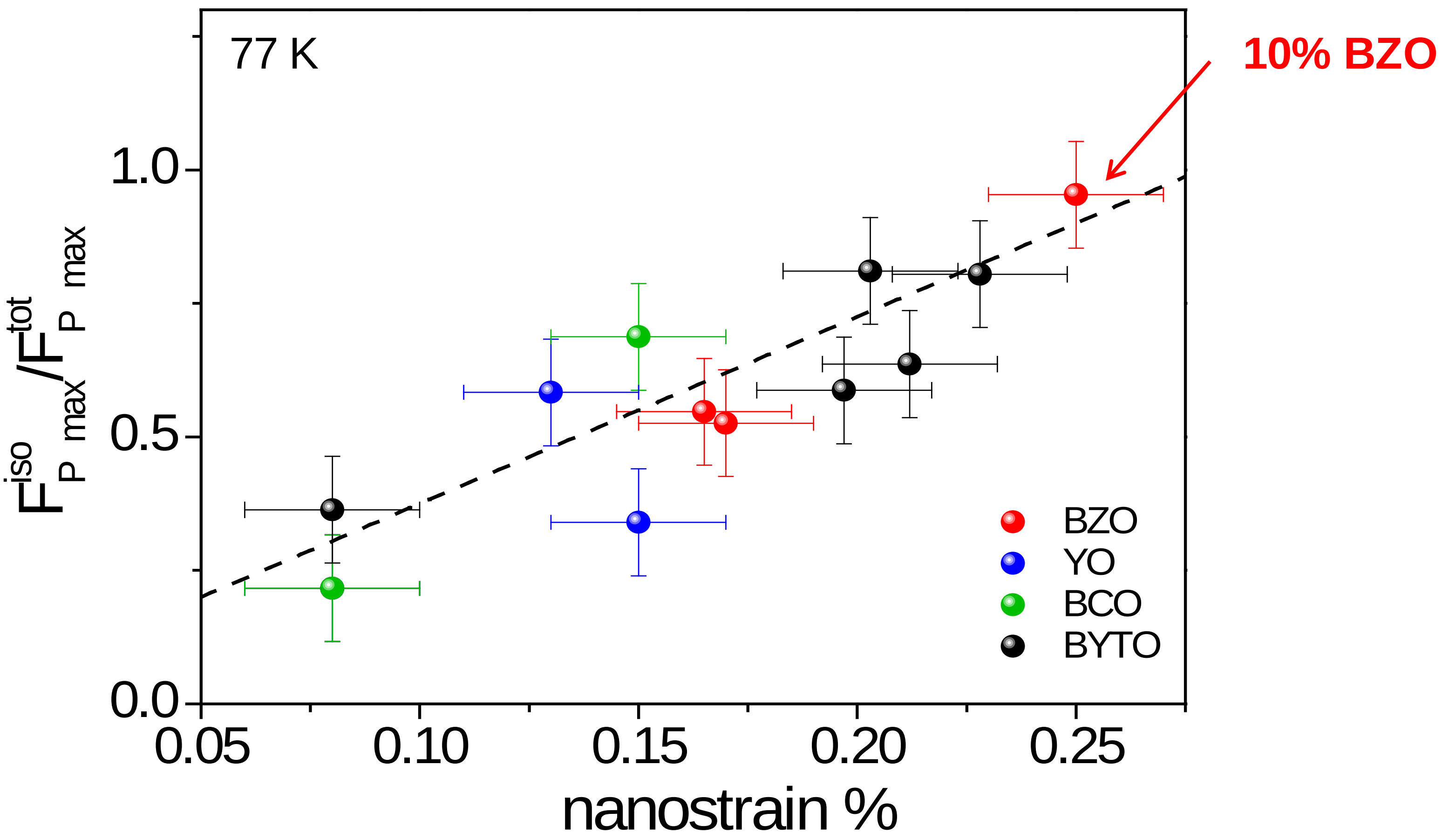
# STEM-HAADF of YBCO-BZO nanocomposites




- High density of intergrowth layers: Double (Y248) and triple (Y125) chain intergrowths
- Highly misfit orientations (>15%) also induce high density of intergrowths
- Facetted BZO nanoparticles induce a strong bending of $CuO_2$ planes
- Double chain intergrowths extend tens to hundreds of nm. Triple chains are much shorter (few nm)
- Strong strains should be appearing due to the intercalation of intergrowths

*A. Llordés ... T Puig., Nat Mat, 11, 329 (2012)*

# Isotropic Pinning Force and Nanostrain



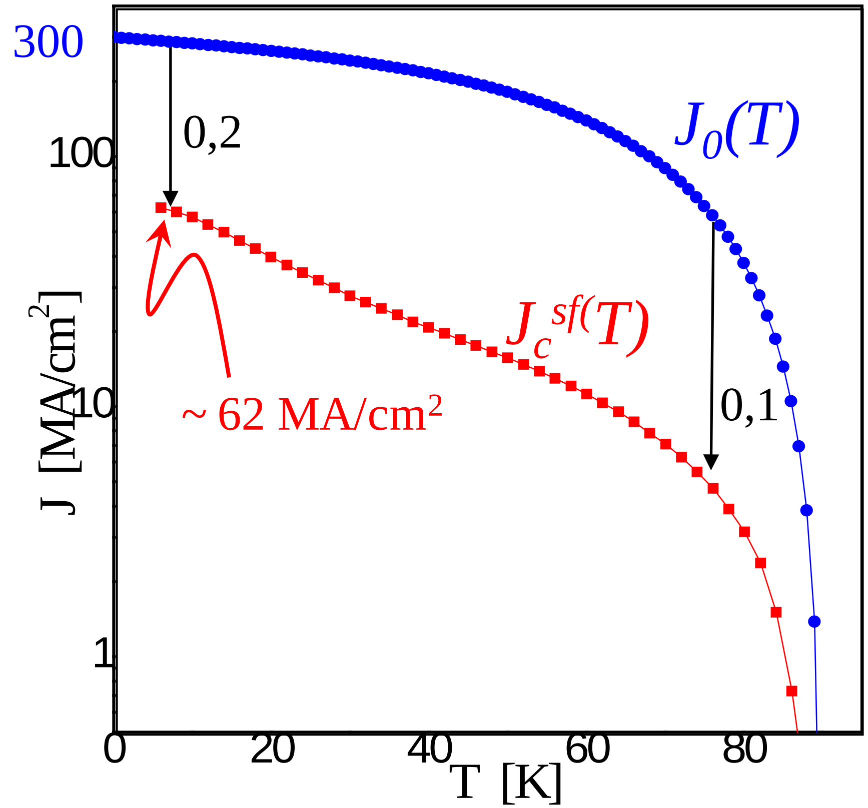

**Local lattice strain controls the isotropic contribution to the pinning force responsible for the huge increase in superconducting performance of CSD-YBCO nanocomposites**

*A. Llordés ... T Puig., Nat Mat, 11, 329 (2012)*

# Plenty of room for improvement for REBCO

For $T \rightarrow 0$, $J_c^{sf}/J_0 \sim 0.2$
At 77 K, $J_c^{sf}/J_0 \sim 0.1$

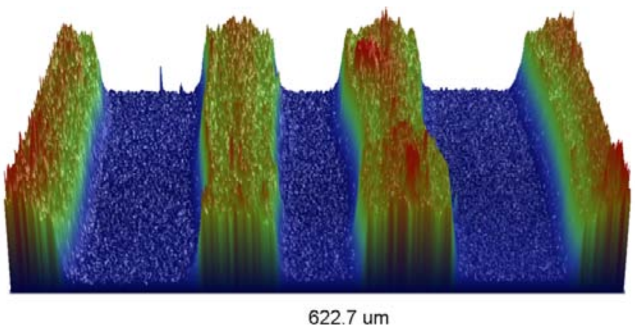
$J_c^{sf}(77K) < 6\text{-}7\ MA/cm^2$
$J_o(77K) \sim 70\ MA/cm^2$

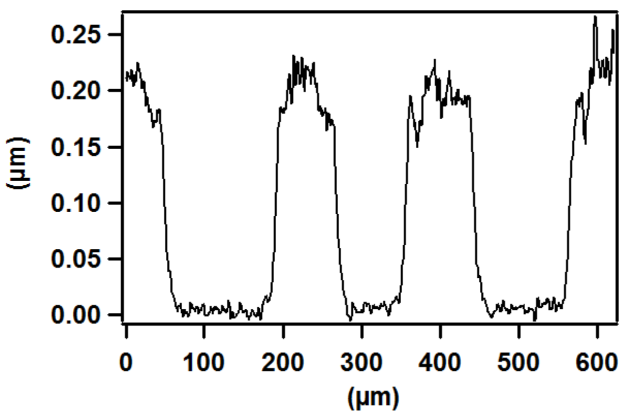



- Theoretical limit: depairing $J_c$ for YBCO
- Practical processes to achieve these performances are required

# YBCO Patterning by inkjet printing

## Water based solutions

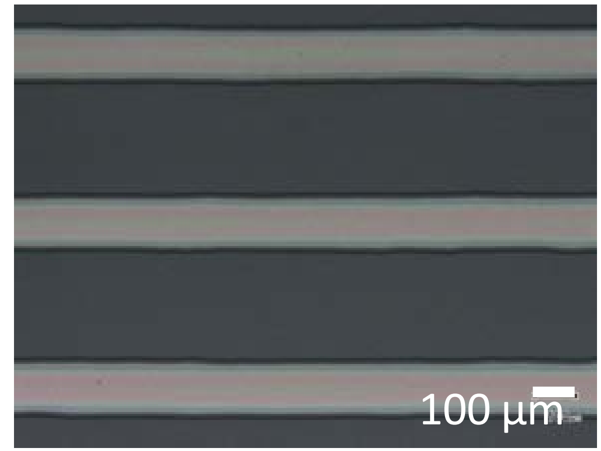


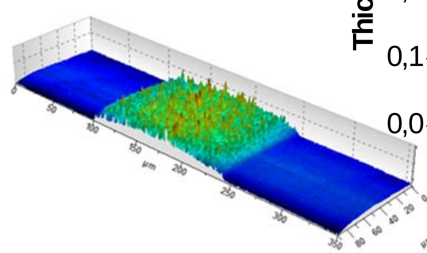



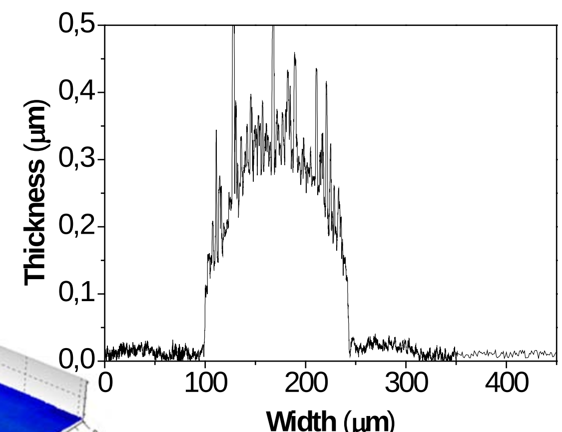

**YBCO pattern** after a 5 x fold printing sequence, without an intermediate drying step.

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

## MOD based solutions



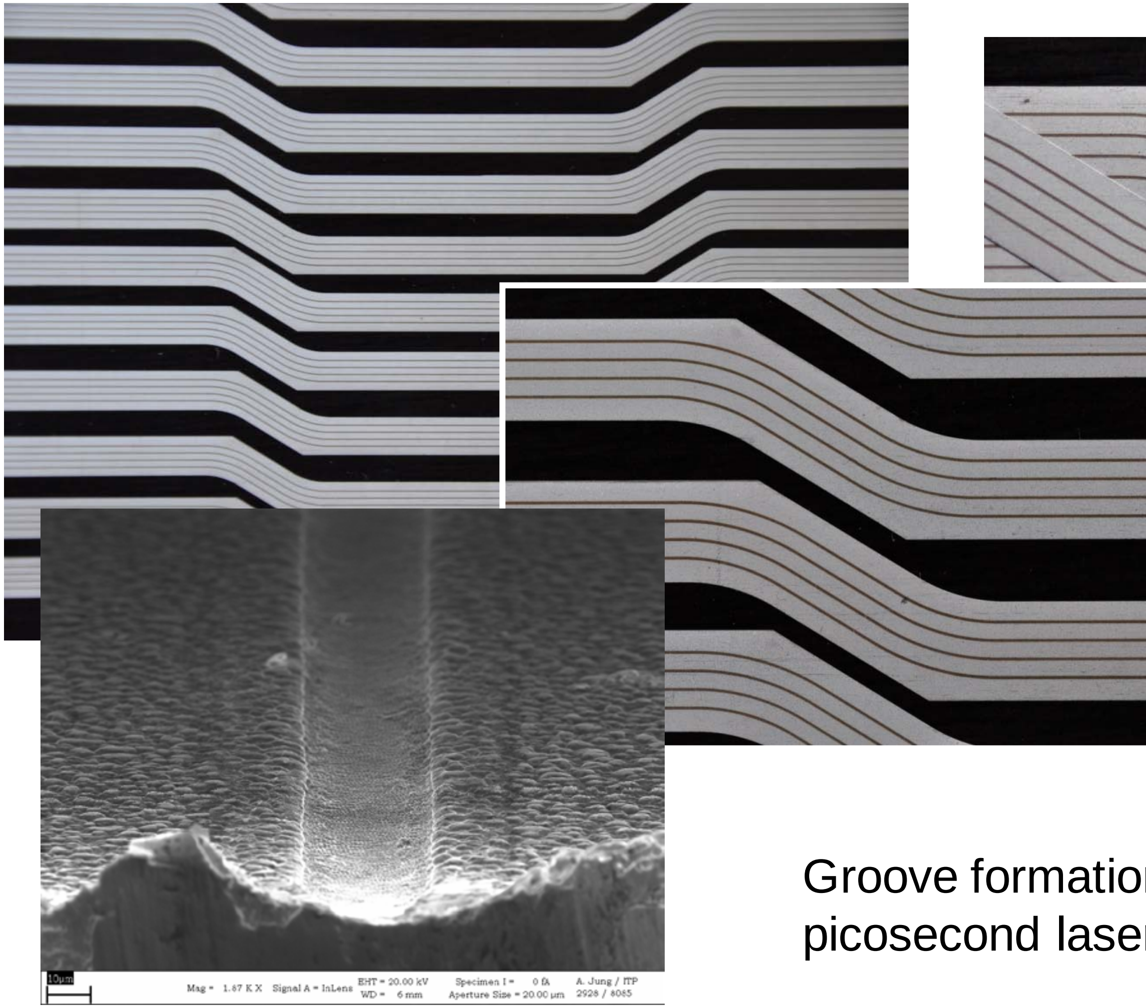



High homogeneity and uniformity along all track length. Tracks are **150 µm x 300 nm**. Similar $J_c$ in all filaments

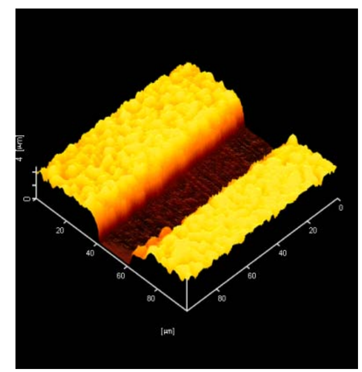
# Striated strands in Roebel bars realized by laser grooving

## picosec YAG-IR laser

**Effect on AC loss reduction seen, some interfilamentary coupling remaining**

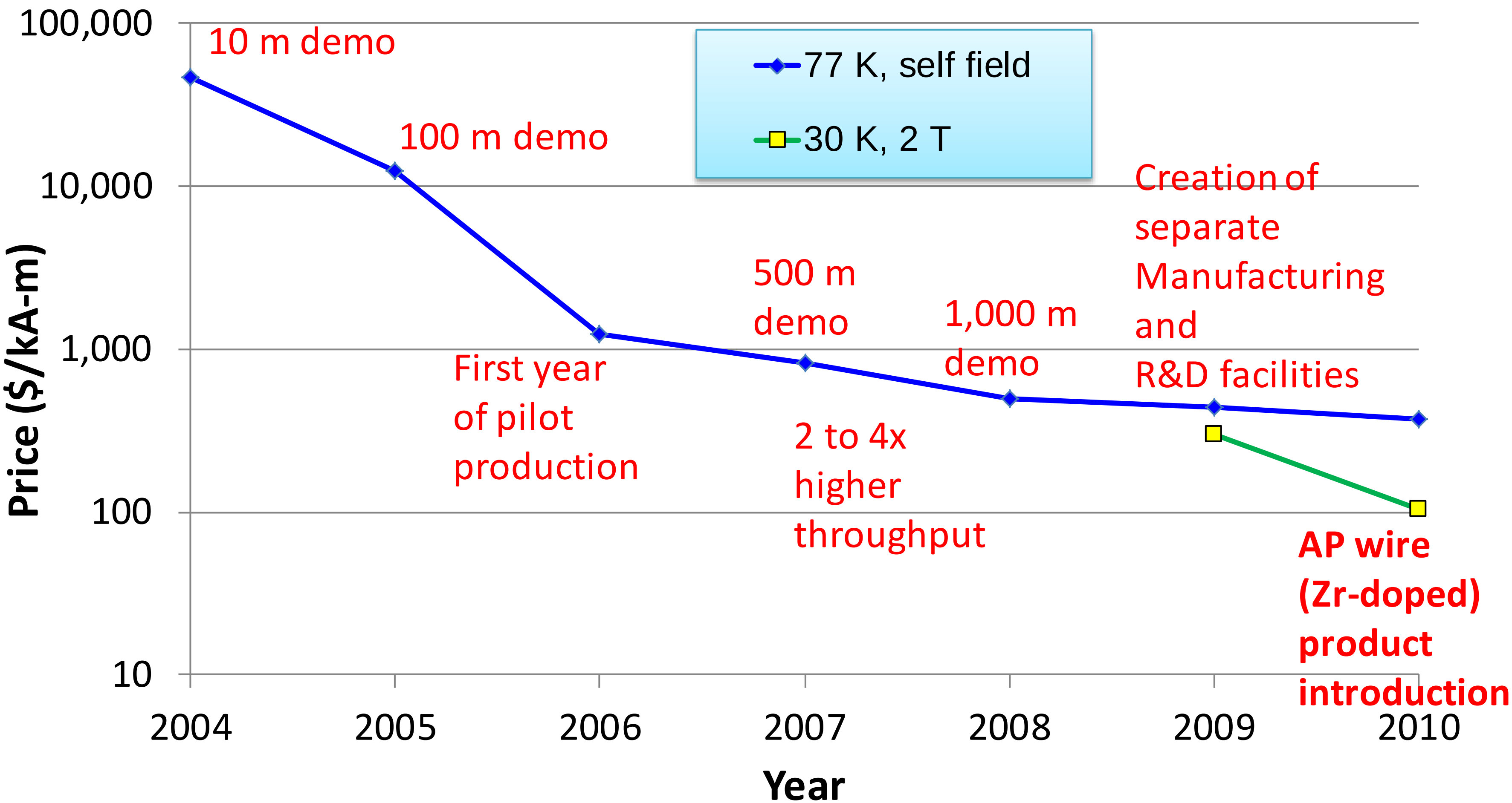


**12 mm width, 5 fil., 25 micron groves**



Groove formation very reliable applying IR picosecond laser laser grooving

# Rapidly decreasing price of 2G HTS wire through technology advancements




Wire price-performance improved by ~ 200% to ~ $ 100/kA-m for 30 K, 2 T applications

# Roadmap to driving down price

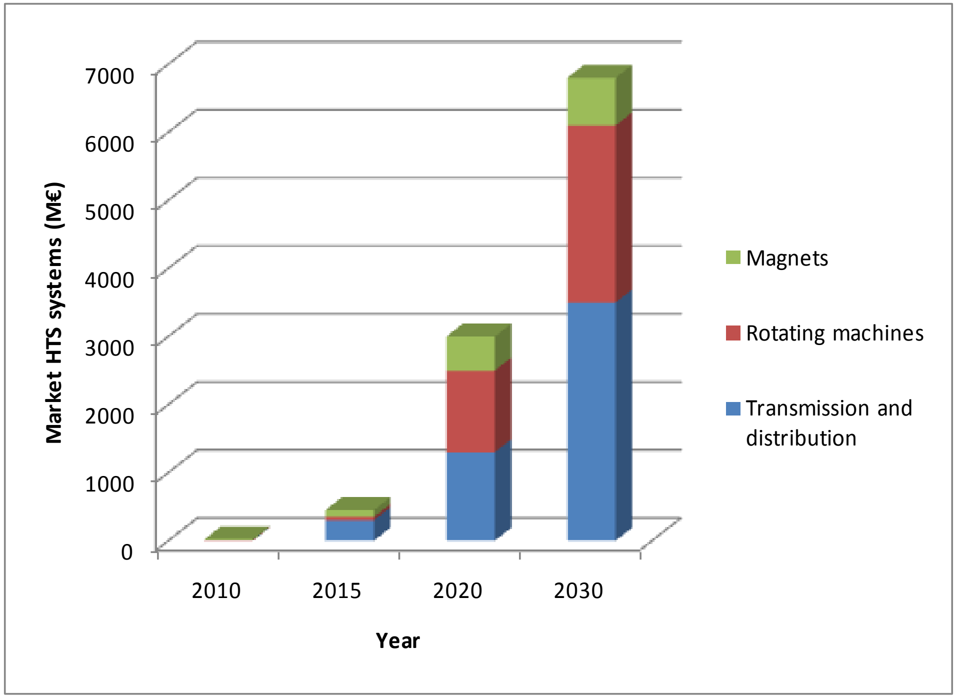
Improving manufacturing process and increasing in-field performance

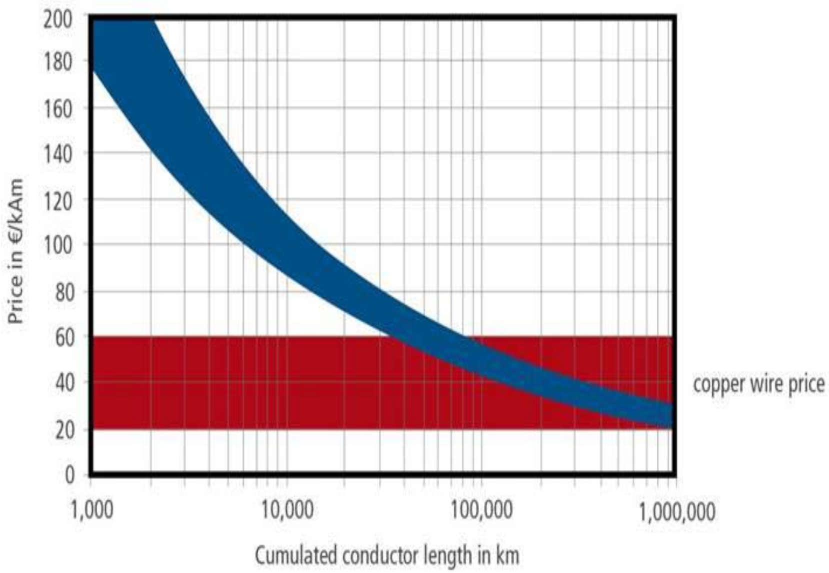
| Time | Performance at 77 K, zero field* | Lift Factor at device operating condition (30K, 2T) | Performance at device operating condition | Wire price ($/m) | Wire price ($/kA-m) at device operating condition |
|---|---|---|---|---|---|
| Now | 100 A | 2 | 200 A | $ 45 | $225 |
| 2 years** | 150 A | 4 | 600 A | $ 40 | $ 67 |
| 4 years** | 200 A | 6 | 1200 A | $ 35 | $ 30 |

* Based 4mm width ** Projections

*Improving wire performance is key to success*

# Power applications and CC's: expected market growth and cost decrease




**Estimated world market evolution of SC systems**

**Estimated cost decrease of CC's with cumulated production**

**~ 6.5 bn € by 2030 (1.3 bn € in wires)**

**~ 1.500.000 km/year by 2030 (x 1000 present production)**

# Propagation of R&D Results in M-PACC Project

**HTS - CC Technology**

- REBCO , C.C. Fabrication
- Stacked Conductor for Large Current
- Low AC Loss
- Winding Tech.
- High Field Magnet
- Electric Power Grid (System)
- Cryogenics

**2013 ~ 2015 ~ 2020~**

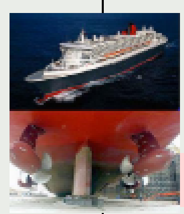
**Industry**

- Level Magnetic Field (Steel Making)
- SMES for Voltage Dip Compensation
- Magnetic Separation
- Industrial DC magnet
- NMR, MRI
- Fault Current Limiter
- >MW Class Wind Generator
- Current Lead
- Transformer (Industry, Large Build.)
- Heavy Ion Medical Accelerator



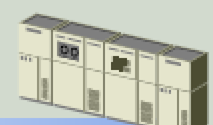

**Trans - portation**

- Ship Propulsion & Industrial Motor
- MAGLEV
- DC Feeder (Train)
- Transformer (Train & Ship)




**Others**

- YBCO C.C. Industry Market penetration stage (several tens~several hundreds km/year)
- Ultra long length DC Transmission Cable
- Indoor Distribution Line
- YBCO C.C. Industry Enterprising stage (~several thousands km/year)

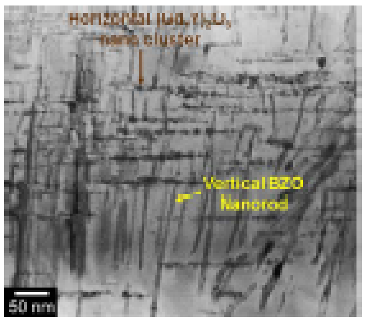


UNIVERSITY of HOUSTON

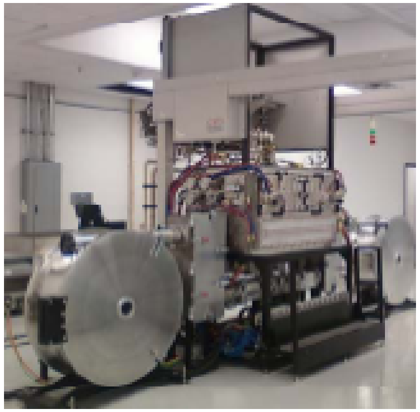
SuperPower Inc.

# 4X HTS conductor performance improvements targeted for high power wind generators

- Improved approaches to engineer nanoscale defects in coated conductors in ARPA-E funded program.
- New pilot MOCVD system set up in UH Energy Research Park to rapidly scale up new technology advances to long-length manufacturing.




*Engineered nanoscale defects*



*4x improved wire manufacturing*

*High-power, Efficient Wind Turbines*

- *Quadrupling superconductor Performance at 30 K, 2.5 T for commercialization of 10 MW wind generators*
- *Advances will also lead to high-performance HTS conductors for other high-field applications*

TcSUH

UNIVERSITY of HOUSTON SuperPower

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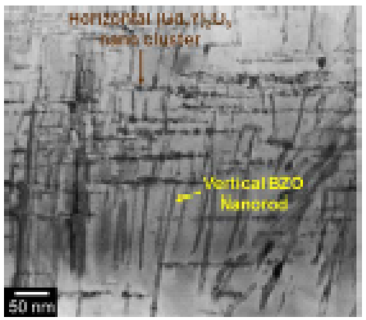
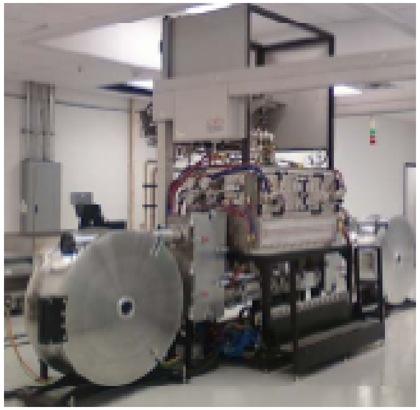



*Engineered nanoscale defects*

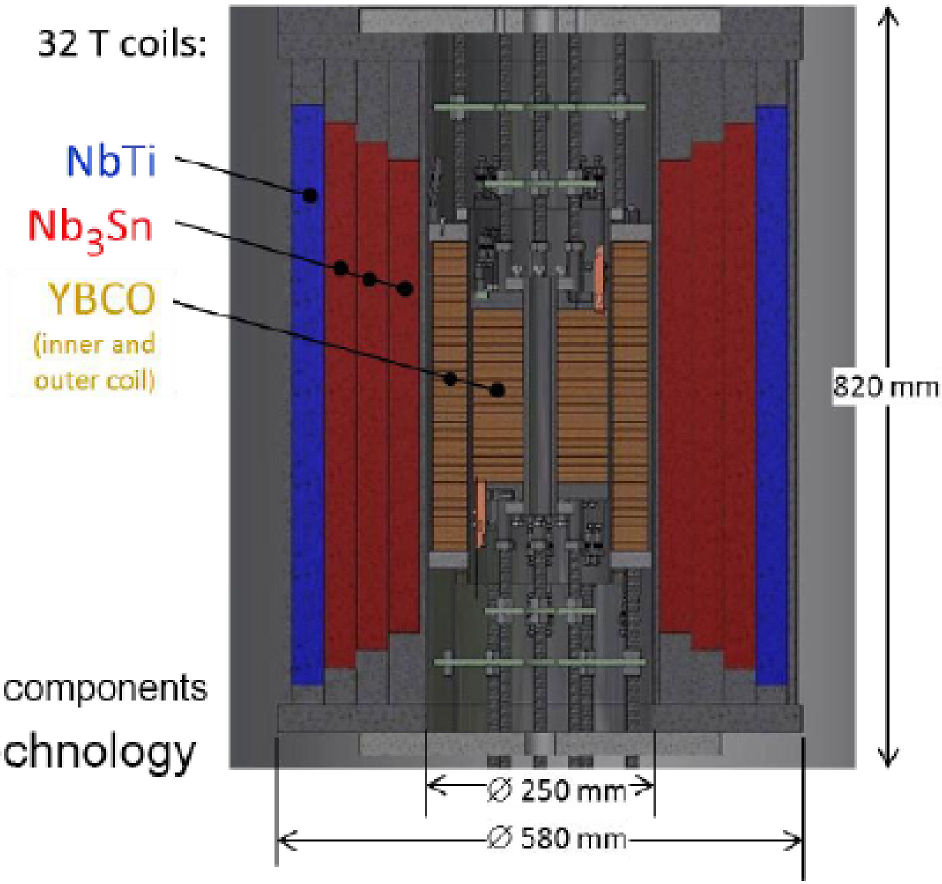


*High-power, Efficient*

| Metric | Now | End of project |
|---|---|---|
| Critical current at 30 K, 2.5 T (A/12 mm) (device operating condition) | 750 | ~3000 |
| Wire price at device operating condition ($/kA-m) | 144 | 36 |
| Estimated HTS wire required for a 10 MW generator (m) | 65,000 | 16,250 |
| Estimated HTS wire cost for a 10 MW generator $ (,000) | 7,020 | 1,755 |

# 32 T User magnet

- Goal:
  - 32 T, 4.2 K, 32 mm cold bore
  - 500 ppm in 10 mm DSV
  - 1 hour to full field
  - dilution refrigerator <20 mK
  - 20 years of operation at NHMFL
- Funding:
  - $2M grant from NSF
    - for LTS coils, cryostat, YBCO tape & other components
  - Core grant for development of new technology
    - Cover grant shortfall
    - ~ $8M total expected, ~ $4M to date
- Key Personnel
  - Huub Weijers, NHMFL: Project lead
  - Denis Markiewicz, NHMFL: Magnet Design
  - David Larbalestier, NHMFL: co-PI, SC Materials
  - Stephen Julian, Univ. of Toronto: co-PI, Science, potentially the first user




~600 H, 9 MJ

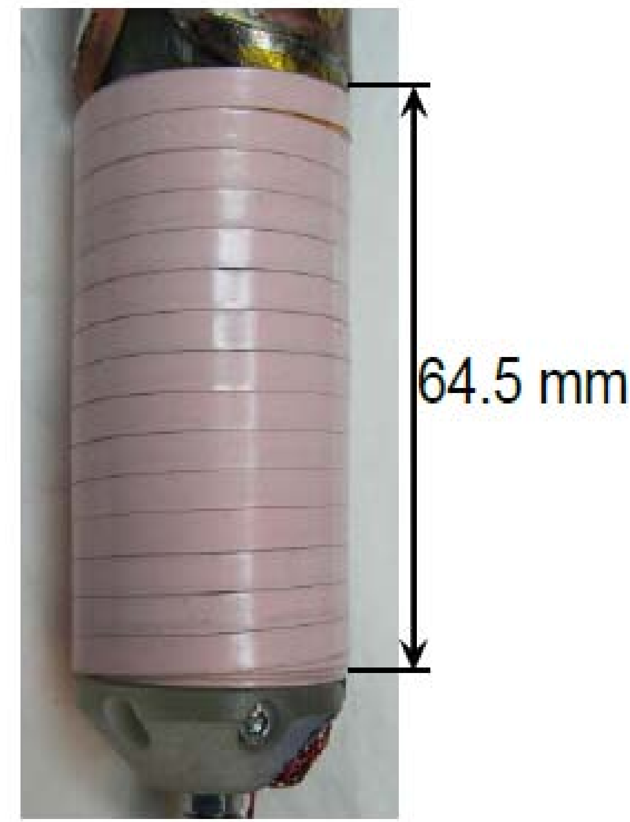
# 32 T User magnet

32 T coils:

NbTi

$Nb_3Sn$

YBCO
(inner and
outer coil)

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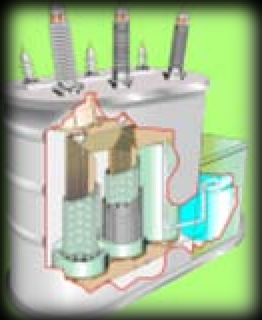
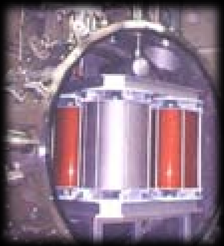
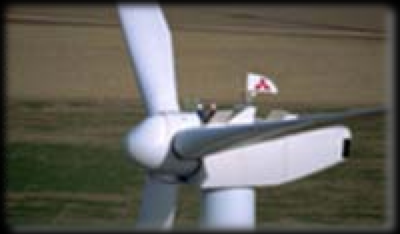
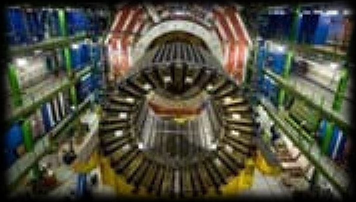
# Road for Superconducting World by CC





**Marketable**



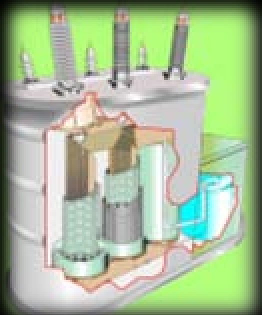


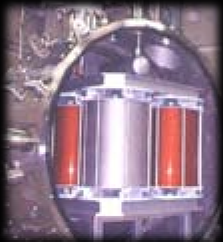
**Applicable**

**Capable**

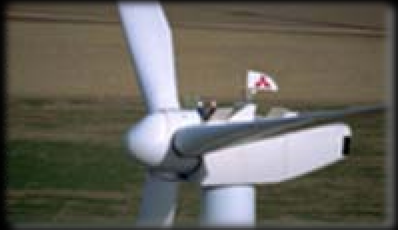
**Lower cost and higher performance of conductors is key for propagation!**

# Propagation





## Marketable



## Applicable

### Capable