ICMAB

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Coated conductor layout overview: Pros and Cons

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eurotapes

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

Outline

- **HTS materials: power and magnet applications**
- **Why do we need the coated conductors?**
  - Physics behind the CCs
- **What are the coated conductors?**
  - Manufacturing approaches to CCs
- **Towards enhanced performances**
  - High currents
  - Vortex pinning
- **Cost and performances prospective**
- **Conclusions**

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

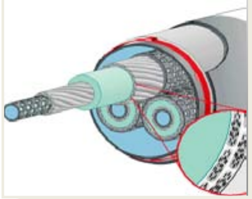
Reduced Weight/Volume ⇒ Higher Power Densities

Reduction of Losses ⇒ Better Efficiencies

Optimization of Conventional Systems

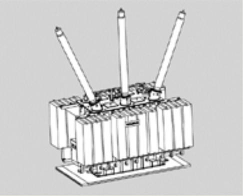
Novel Applications

Cable



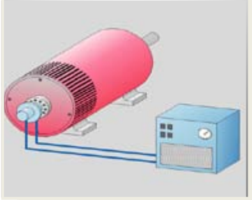
Higher Power
Density
Retrofit

Trans-former



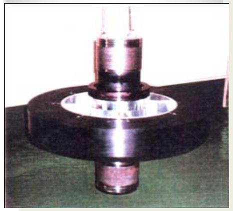
Energy Savings
Life
Safety

Motor
Generator



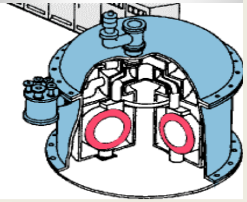
Volume, Weight
Energy Savings

Flywheel



Energy Density
Energy Savings
Safety

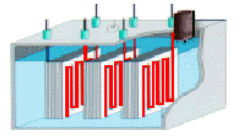
Sc. Magn.
Energy
Storage
(SMES)



Availability
Savings of
Ressources

Fault Current
Limiter

Siemens

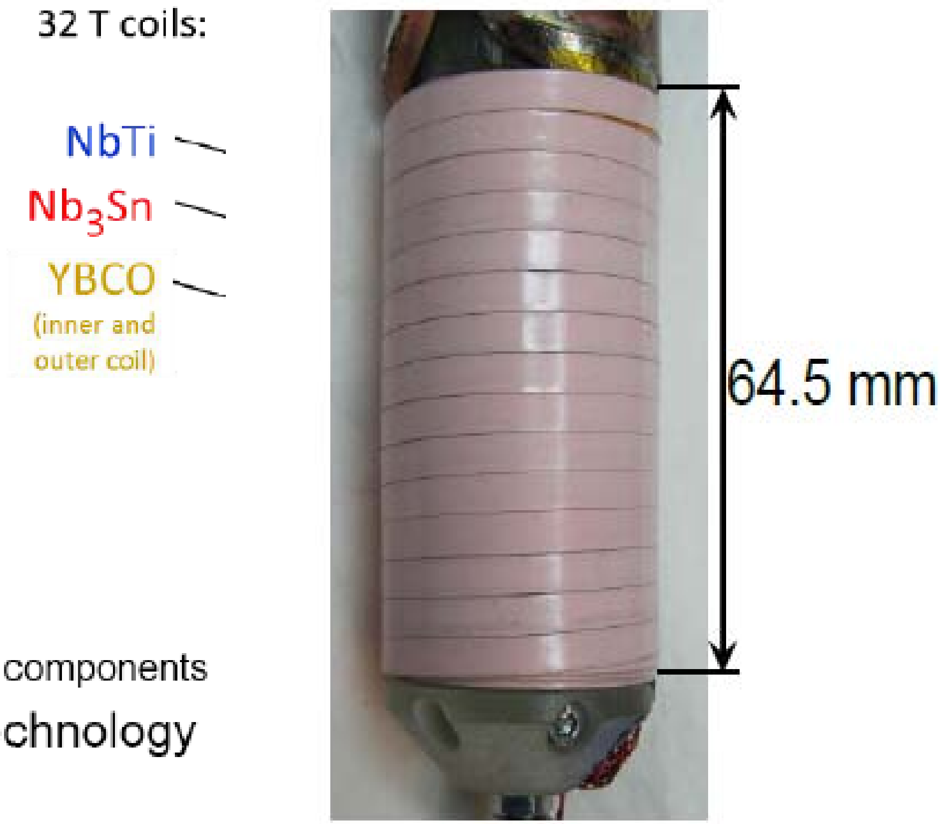


Novel Power Grids
Savings of
Ressources
Power Quality

Courtesy of H.C. Freyhardt

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

Motivation

„…there is a technology gap from 2G wire to practical applications…“

Industry needs

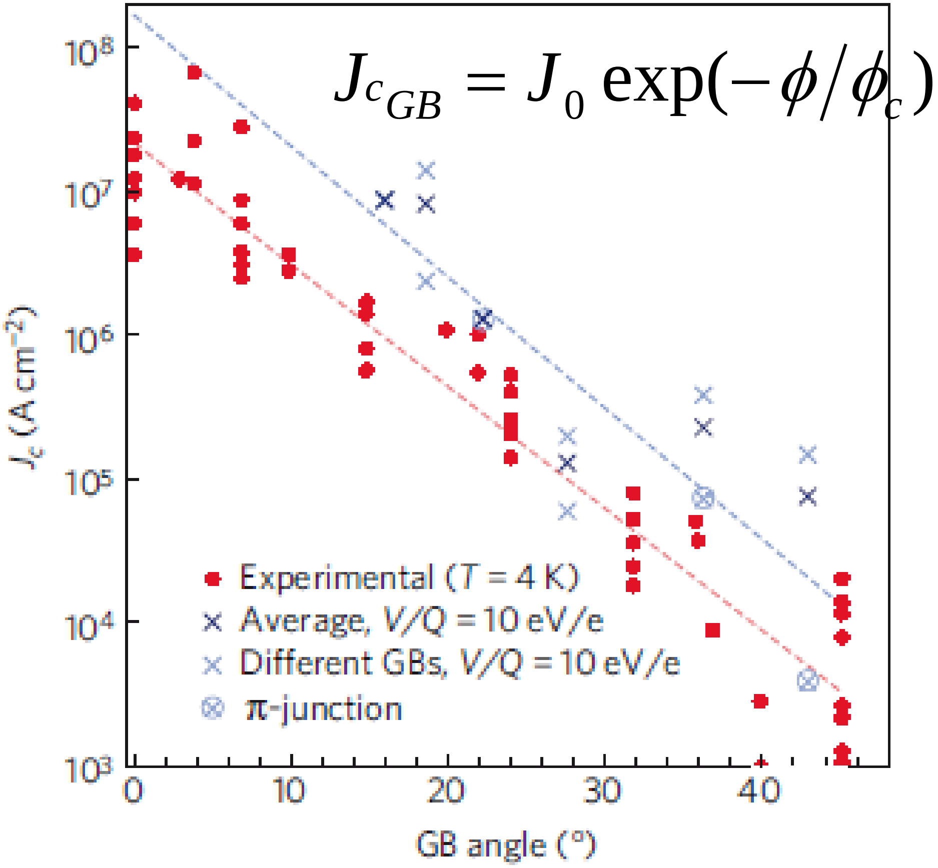
- Scalable currents and various geometries
- Reproducible quality and quantity within an acceptable time
- Mechanical and electrical stability
- Low degradation, long lifetime
- Reliable and specific electrical insulation
- Simple, low ohmic contacts and joints
- Low losses
- Competitive cost
- ….

Industry
Bruker, GE, Innopower, LS Cable, Nexans, nkt cables, Oswald Siemens, Sumitomo, Southwire, …

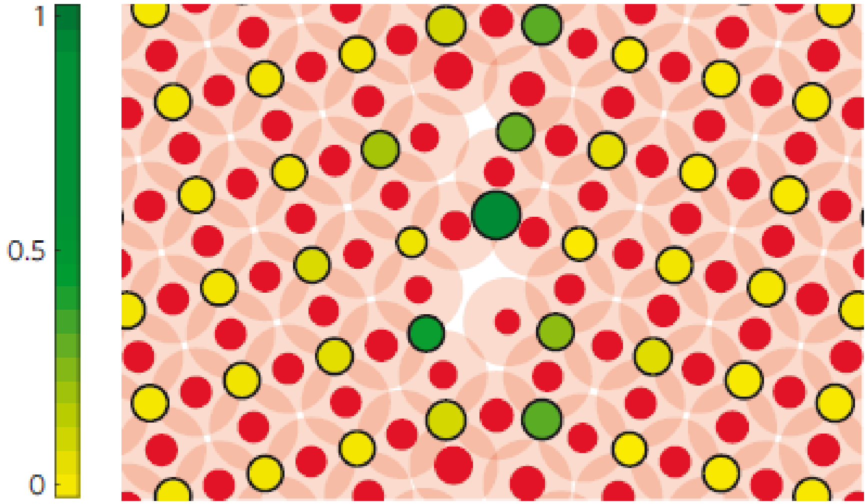
Outline

- **HTS materials: power and magnet applications**
- **What are the novel opportunities raised by coated conductors?**
    - Physics behind the CCs

HTS main issues: grain boundary problem



$$J_{c_{GB}} = J_0 \exp(-\phi/\phi_c)$$



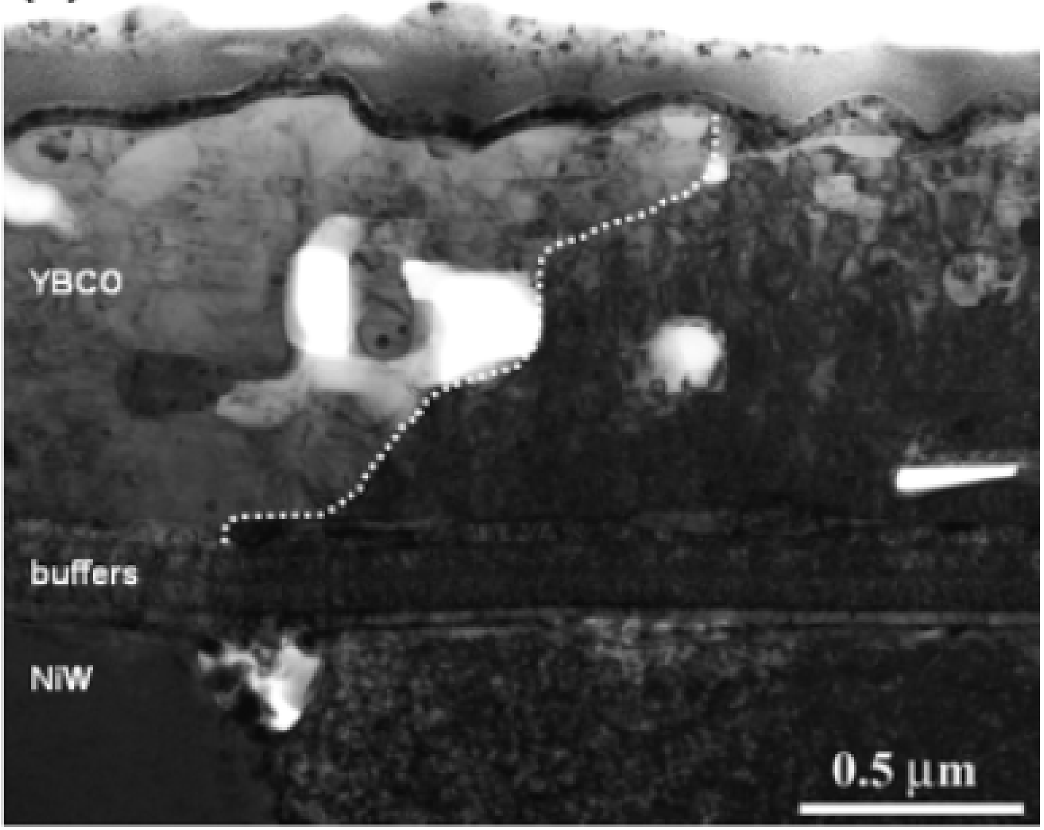
Charge imbalance at the GB depresses J_c at the interface (t – J model calculations)

- **Charging of CuO_4 squares: screening length similar to interatomic distances**
- **Supercurrents flow through regions between distorted regions**
- **Conductors rely on current percolation through grain boundaries**

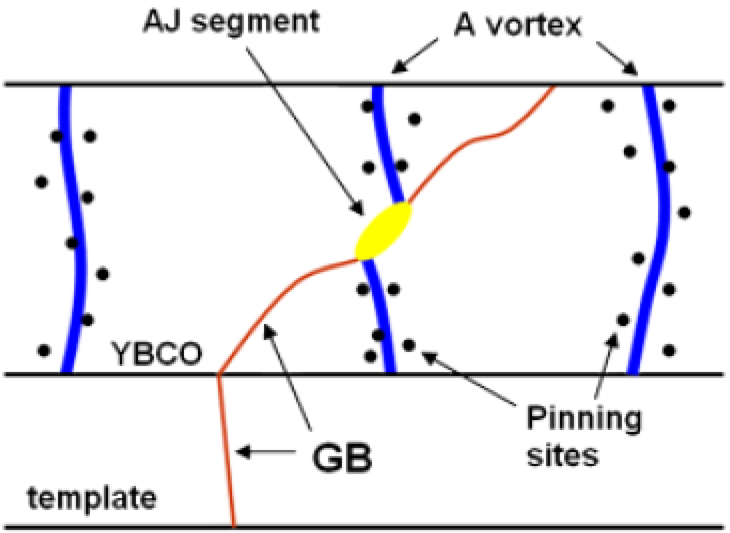
H. Hilgenkam, J. Mannhart, Rev. Mod. Phys. 74, 485 (2002)
S. Graser, P.J. Hirschfeld, et al, Nature Physics 6, 609 (2010)
F. A. Wolf et al, Phys. Rev. Lett. 108,117002(2012)

HTS main issues: grain boundary problem

(d)



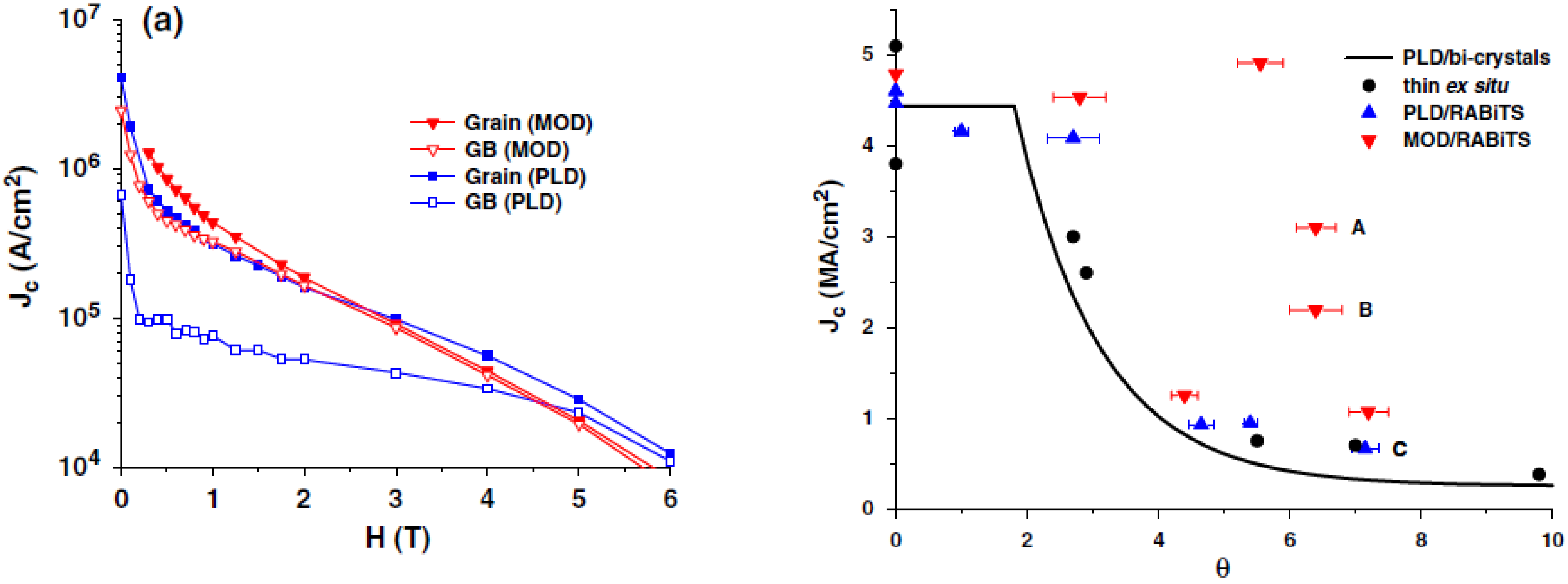
(b)



- Grain boundaries may exhibit meandering in ex-situ grown YBCO CCs
- Vortices may not lie completely in a HAGB
- A meandered HAGB exhibits a behavior similar to LAGB
- Some hope to relax the texture quality requirements?

D. M. Feldmann et al, J. Am. Ceram. Soc. 91, 1689 (2008)

HTS main issues: grain boundary problem



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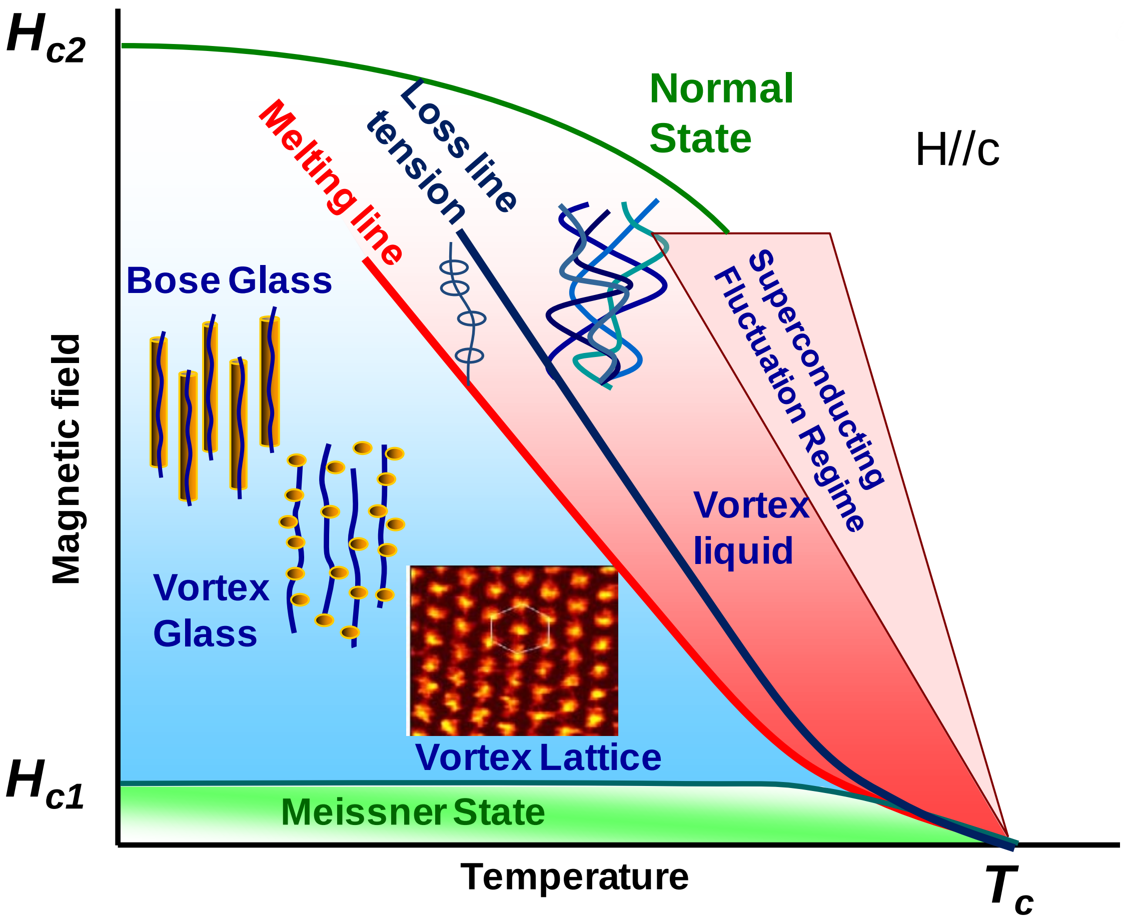
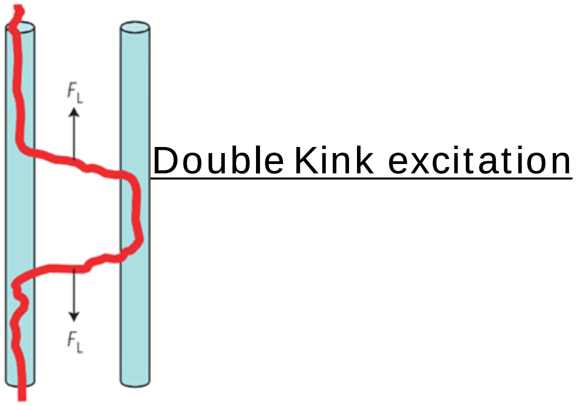
HTS main issues: vortex physics

Control of vortex motion → Nanometric defects ~ ξ (nm)

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





$$U(T,H) = A\frac{\Phi_o^2}{4\pi^2}\frac{\gamma}{\kappa}\frac{1}{\lambda_{ab}}\left(\frac{H_{c2}(T)-H}{H_{c2}(T)}\right)$$

Energy cost of deformation at different H

$$U(T,H) \approx kT$$

Maximal excitation of a bulge

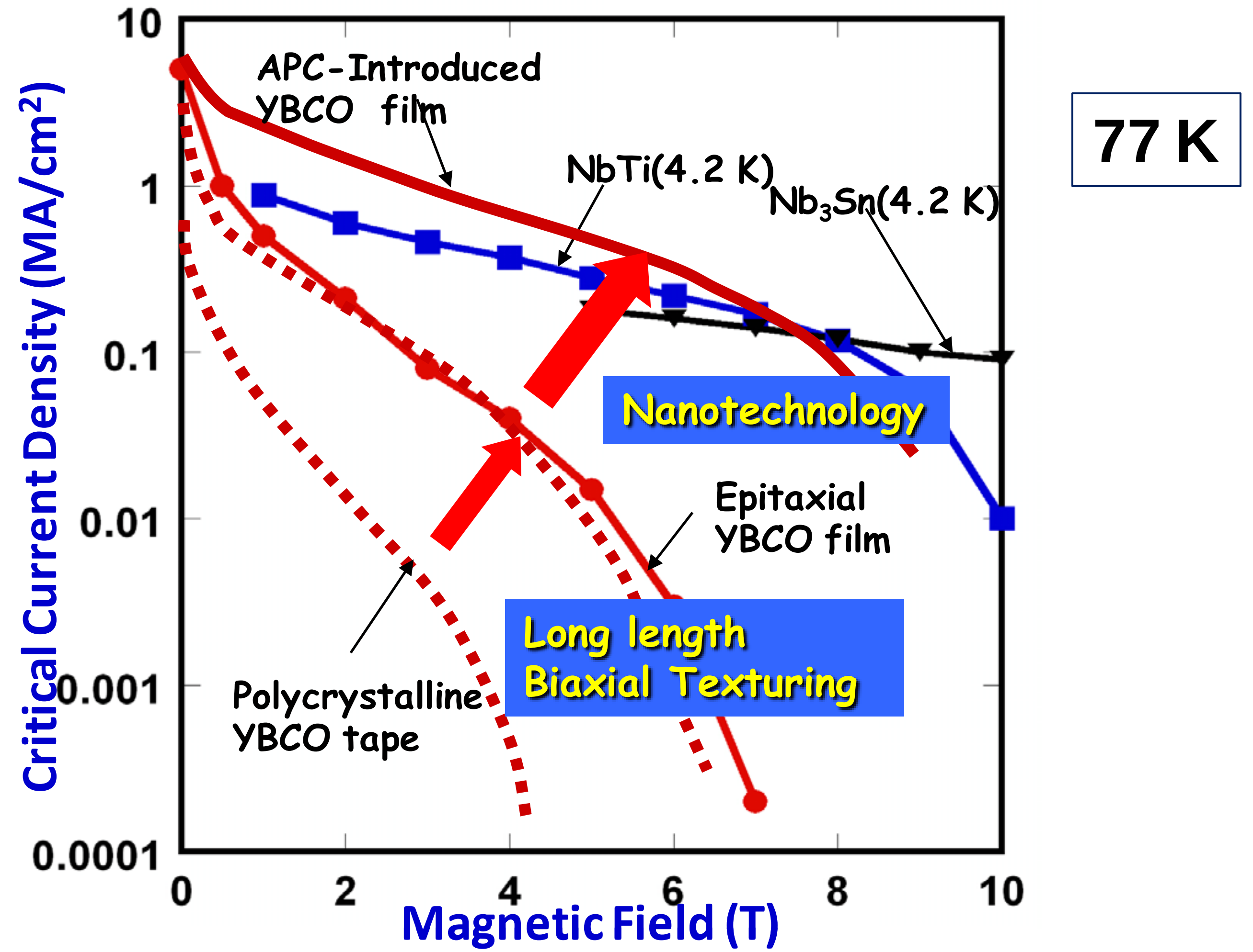
$$H_l(T) = H_{c2}(T)\left[1-(g/A)t(1-t)^{-1/2}\right]$$

YBCO: T=77K : $H_l \approx 1.5\, H_m \sim 14$ T

J. Figueras, X. Obradors et al., Nature Physics 2, 402 (2006) / A. Xu et al, APL Mat (2014)

CC’: HTS materials for power applications

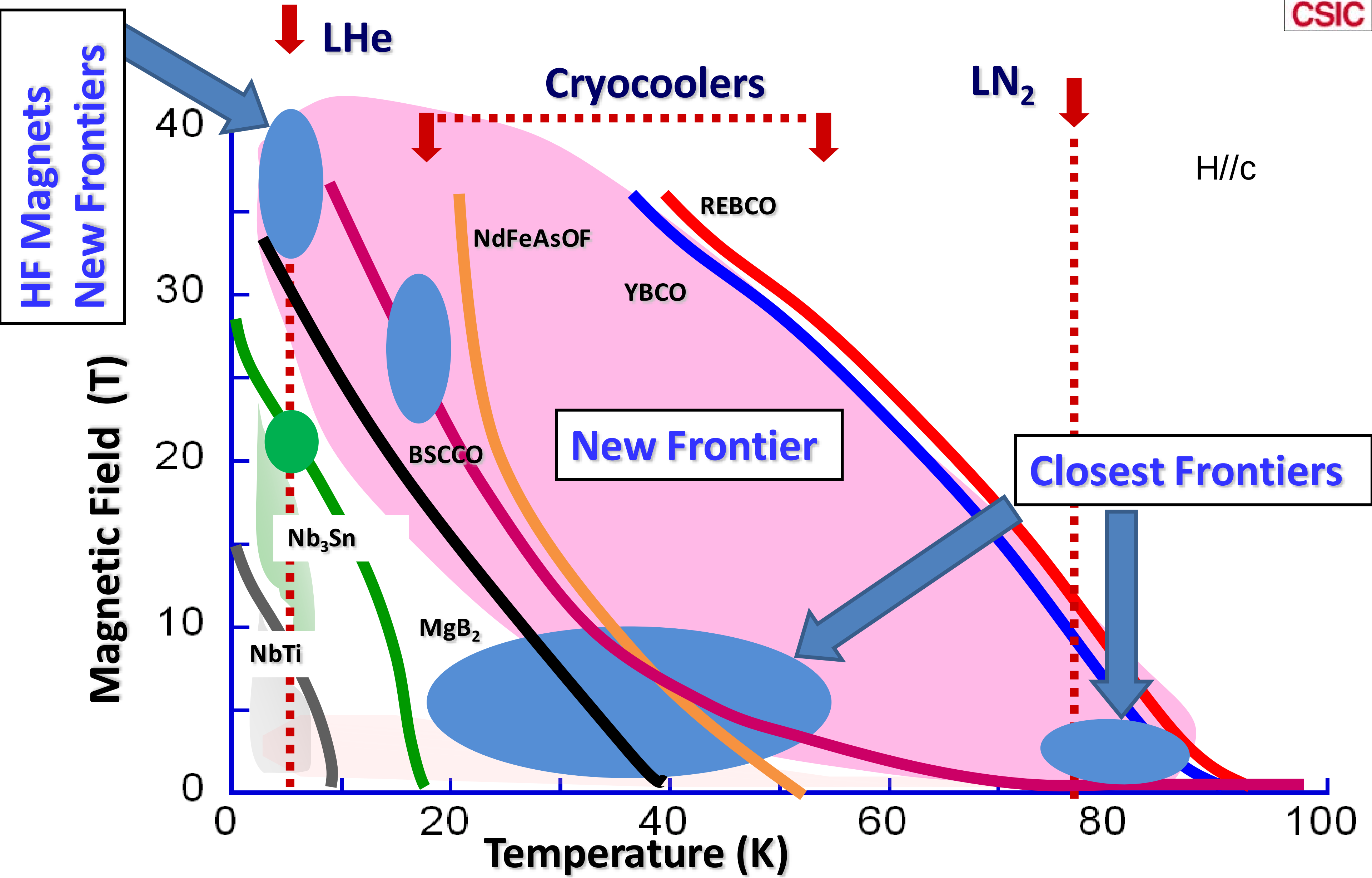
J_c breakthroughs



Courtesy M. Matsumoto

X. Obradors, T. Puig, SUST 27, 044003 (2014)

New frontiers for applications



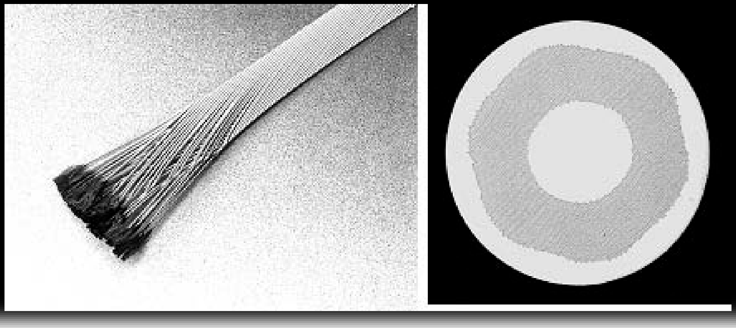
Adapted from M. Matsumoto

X. Obradors, T. Puig, SUST 27, 044003 (2014)

Superconducting Wires & Tapes

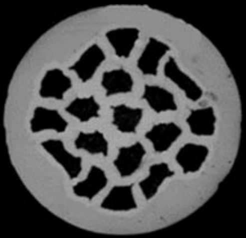
Metallic

NbTi (Nb_3Sn etc.)



Metallic

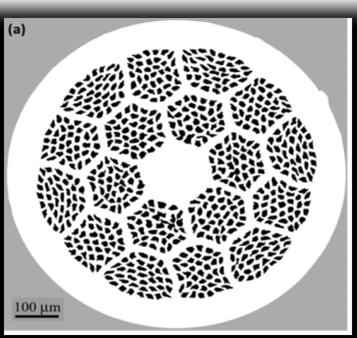
MgB_2 / Fe based

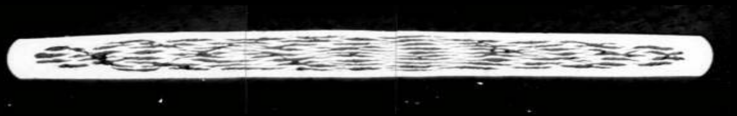


Oxide

Bi2223

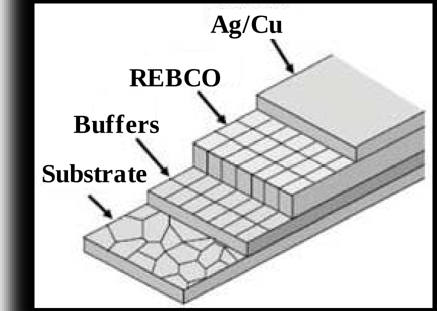
Bi2212





Oxide

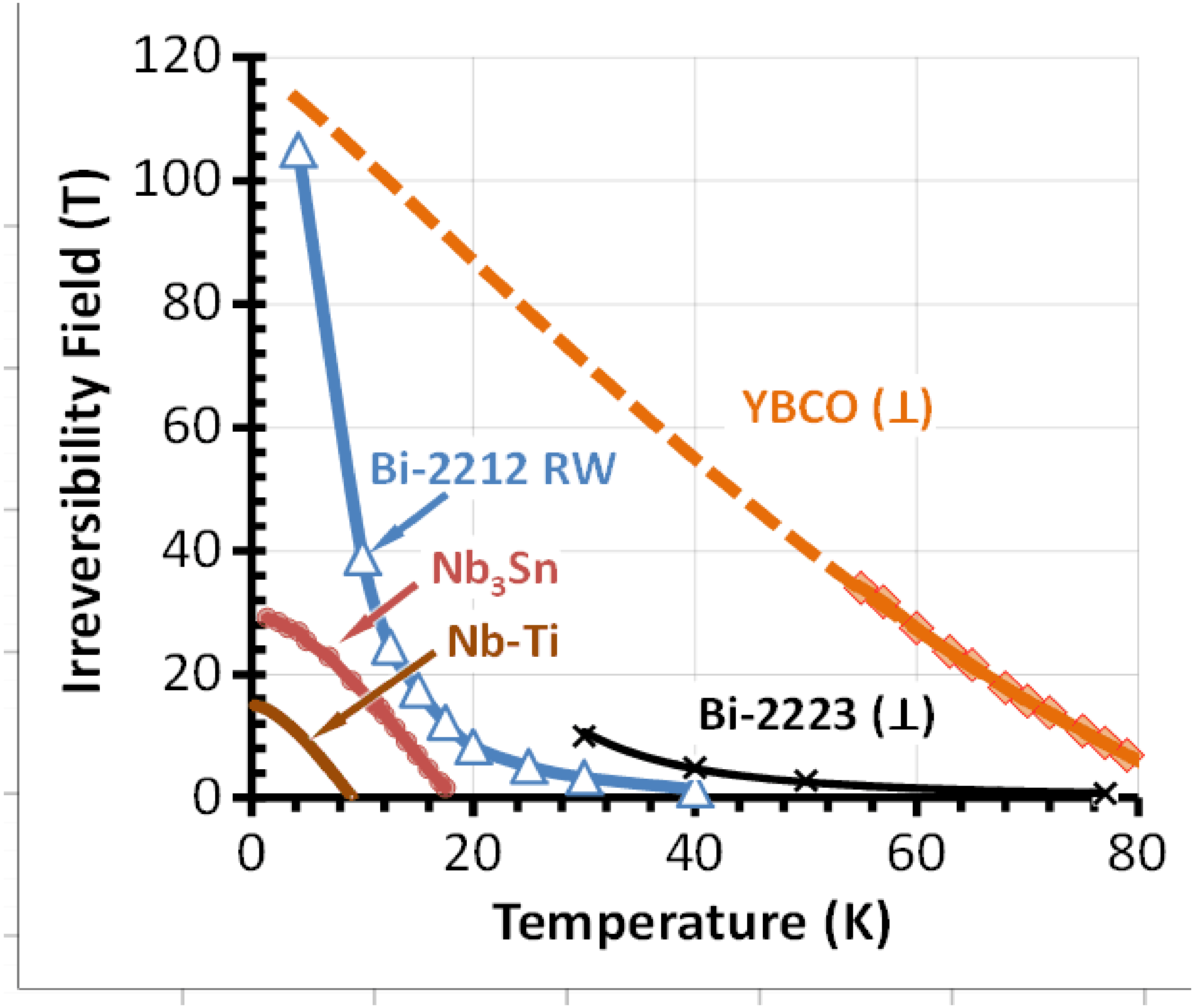
YBCO



Only a few materials allows wire manufacturing !

Courtesy of T. Izumi

Conductors at ultrahigh fields and low temperatures



4.2 K

Several HTS conductors can be suitable for ultrahigh field magnets

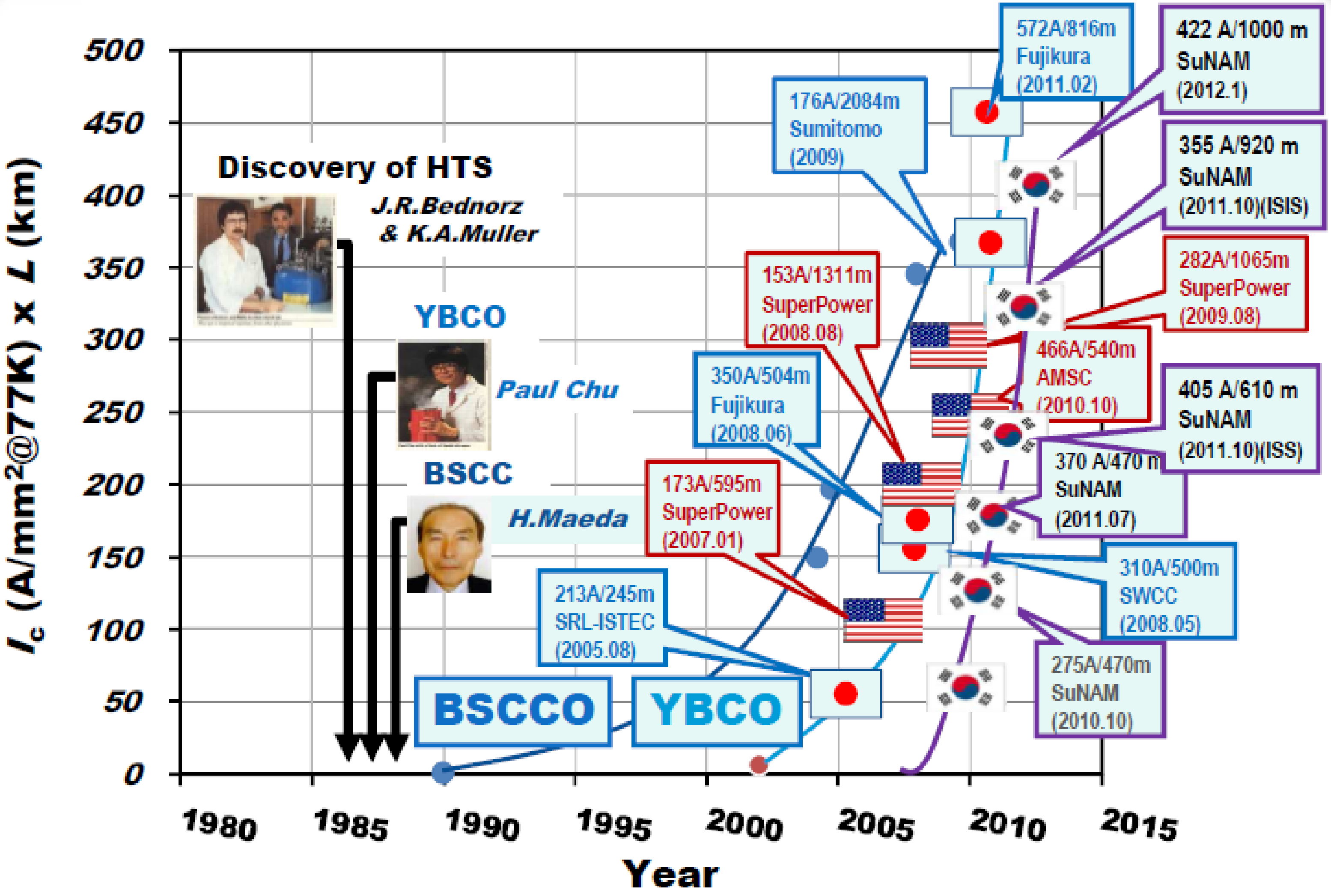
YBCO has the highest J_c

Bi2212 round wire is also very appealing

32 T magnet at Tallahassee

Courtesy of D. Larbalestier, Nature Materials (2014)

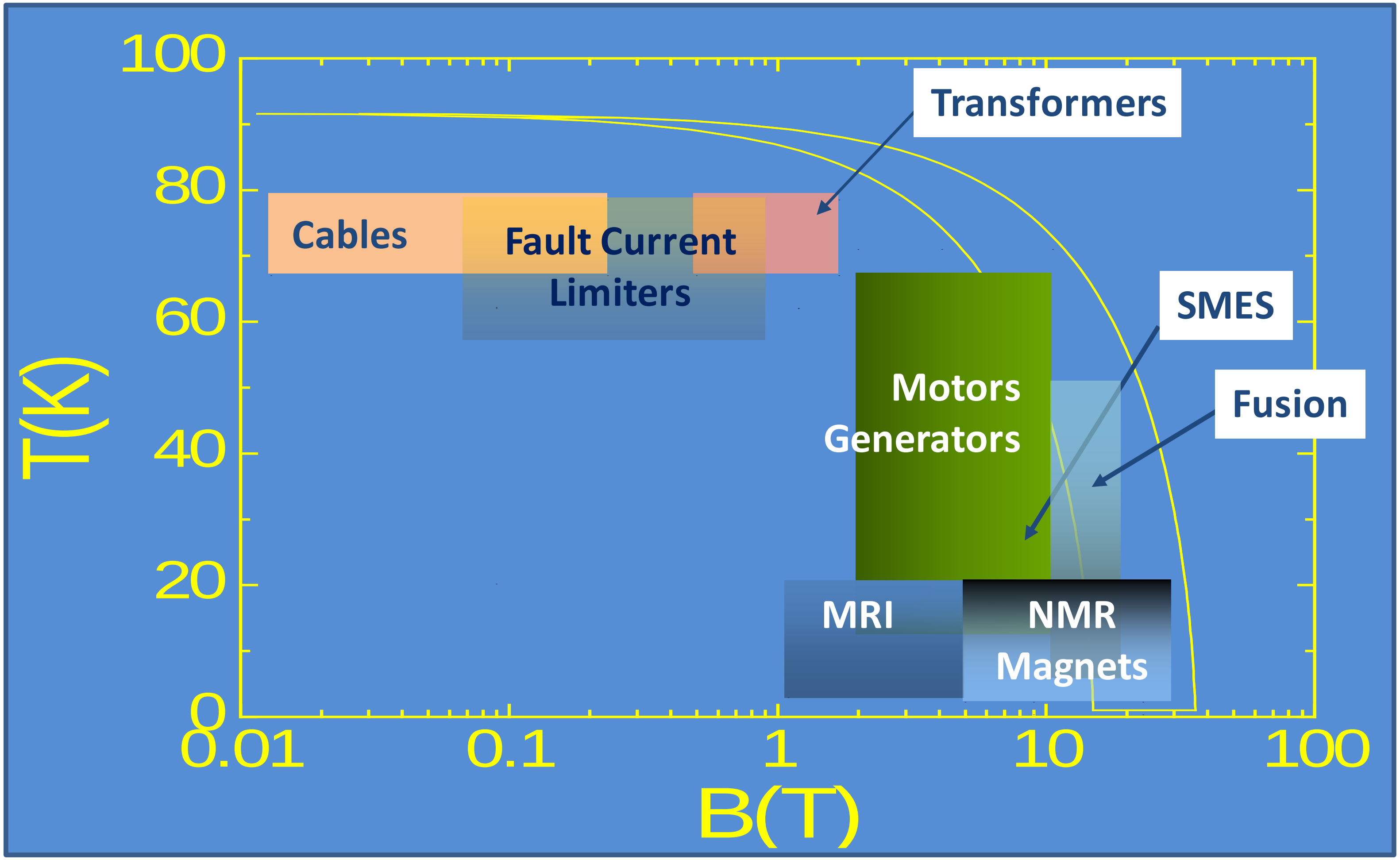
10 years of coated conductors: huge progress



Courtesy of T. Izumi

HTS: Enabling Power Applications

26 years after the discovery of HTS ….we are ready !



$YBa_2Cu_3O_{7-x}$ is able to push all the power applications up to the present limits

Lenght, allowed cost and required performances strongly differ (~1 km to 300 km)

X. Obradors, T. Puig, SUST 27, 044003 (2014)

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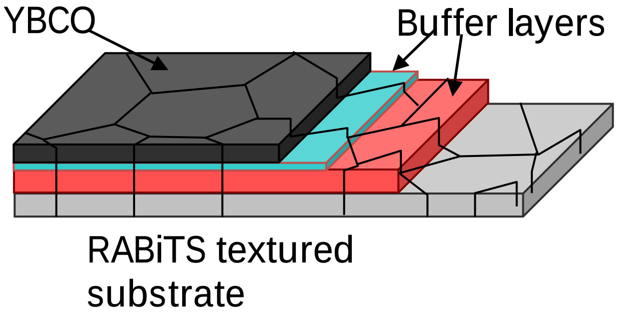
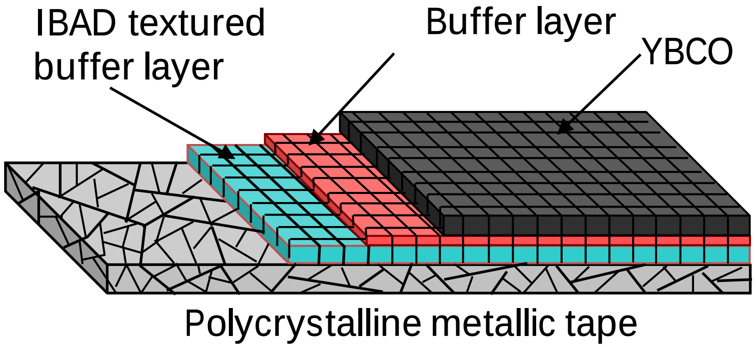
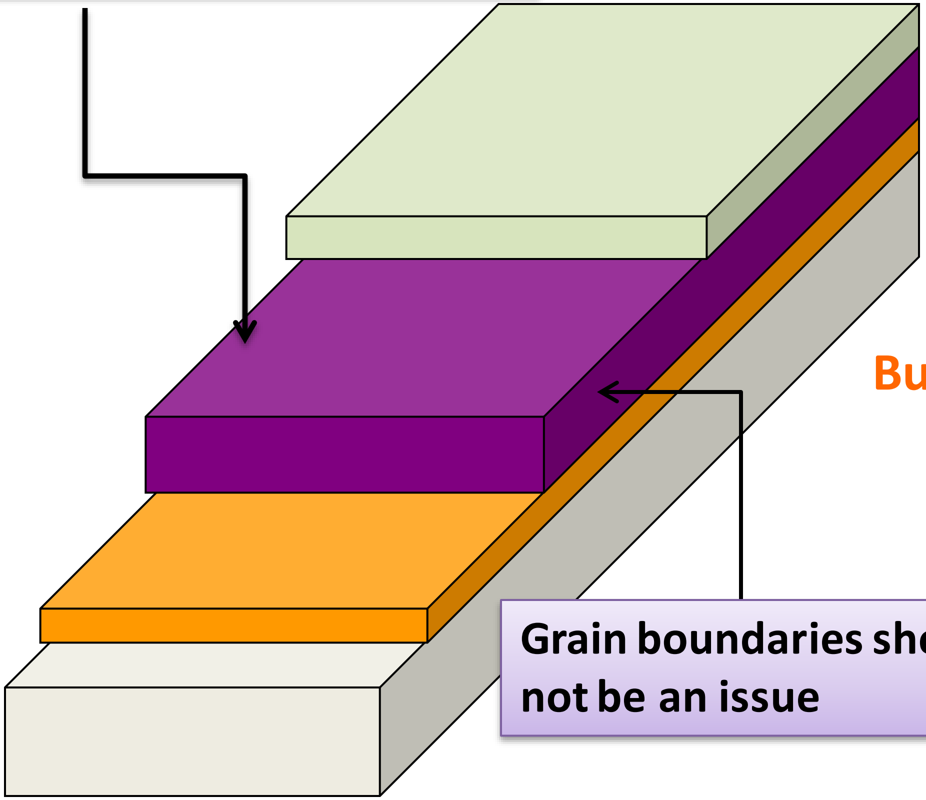
YBCO COATED CONDUCTORS: EPITAXIAL ARCHITECTURE





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

YBCO COATED CONDUCTORS: EPITAXIAL ARCHITECTURE



Nanoengineering of the vortex landscape defines the properies

Cap layer : Ag thickness ≈ 0.2 - 0.5 μm

SC layer : YBCO ~ 1.0 -2.0 μm

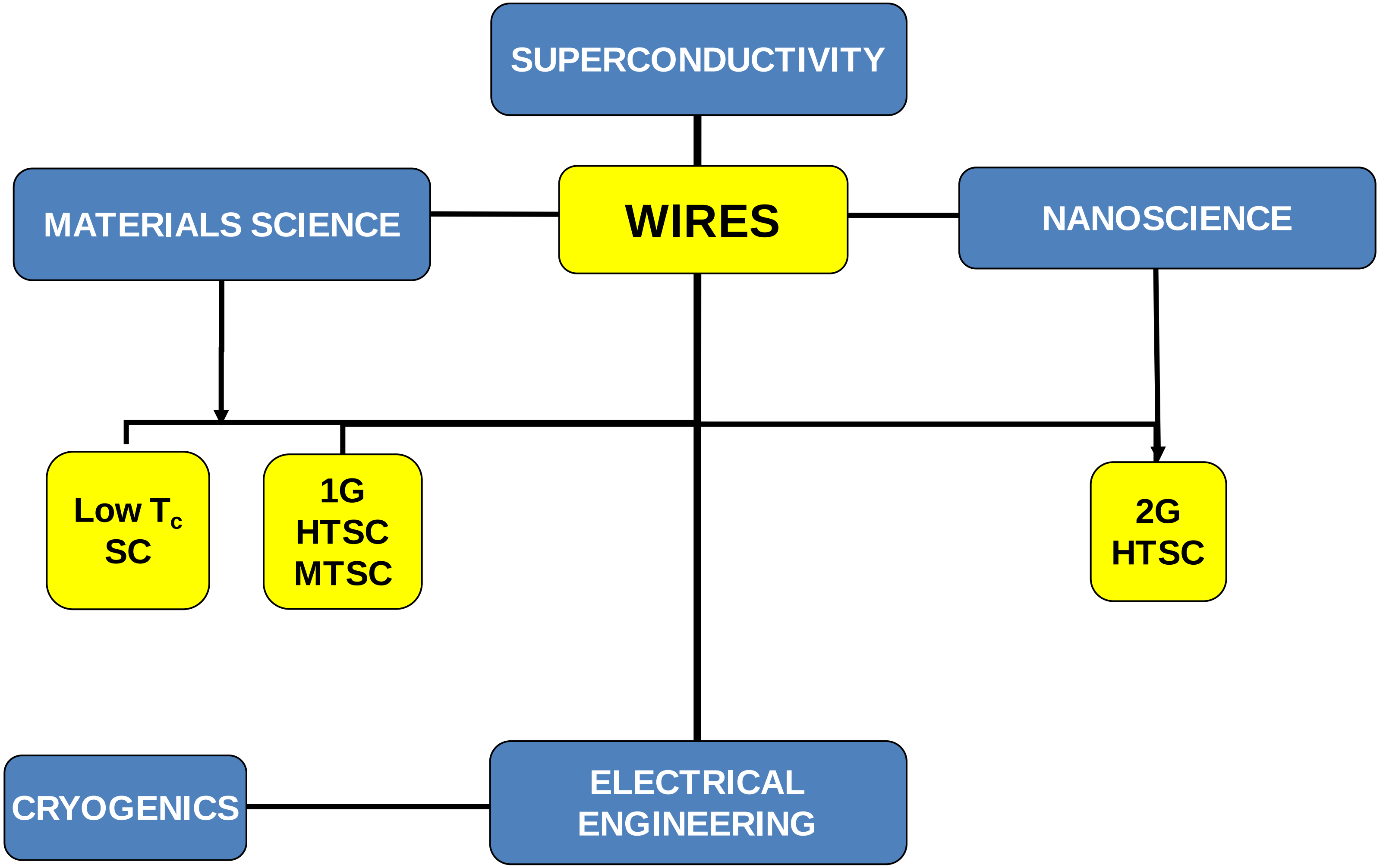
Buffer layers : **CeO$_2$, YSZ, STO,…~ 0.1 μm**

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

Grain boundaries should not be an issue

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

Science and technology of superconductor wires



SUPERCONDUCTIVITY

MATERIALS SCIENCE

WIRES

NANOSCIENCE

Low T_c SC

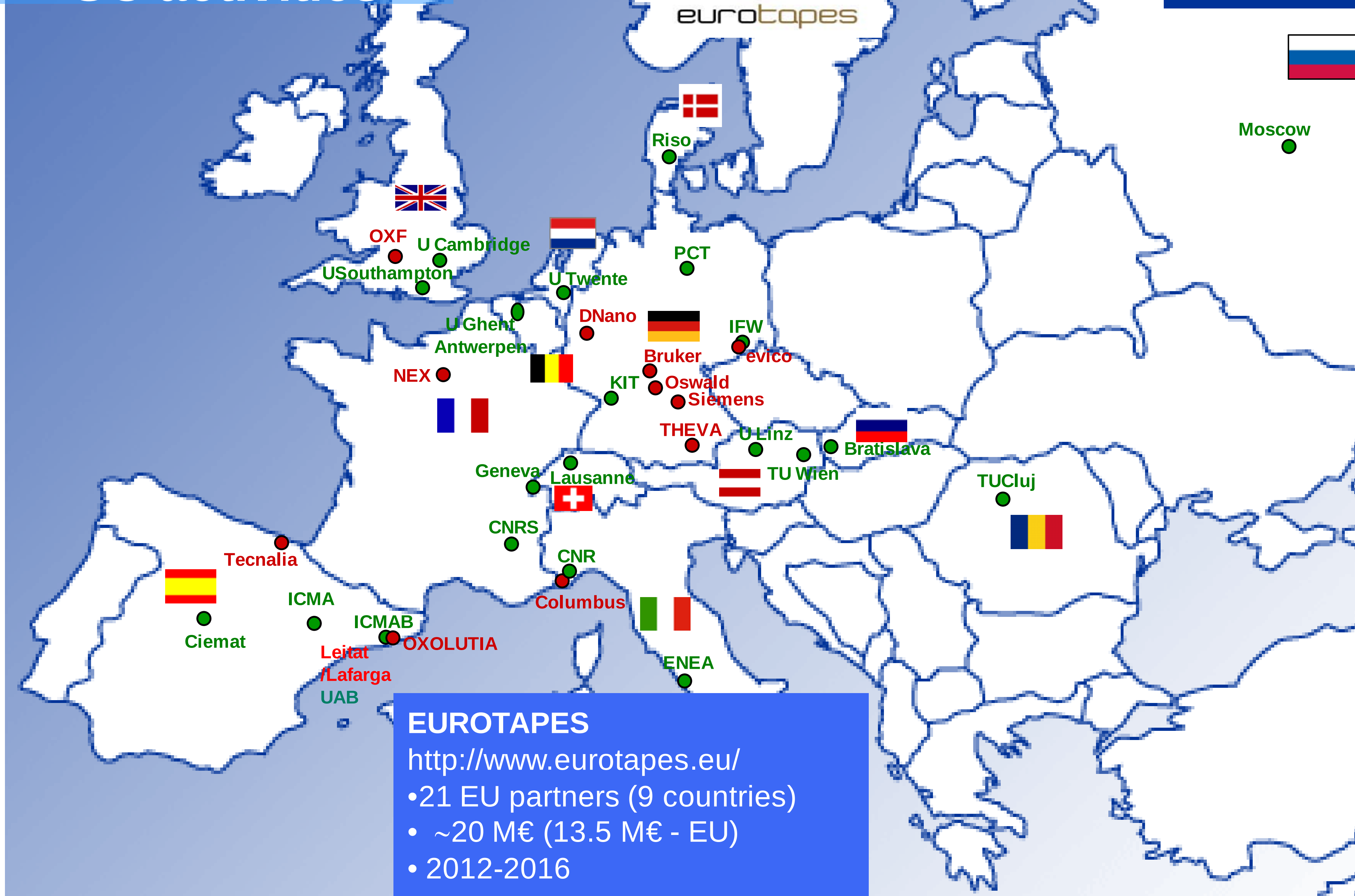
1G HTSC MTSC

2G HTSC

CRYOGENICS

ELECTRICAL ENGINEERING

European main SC activities

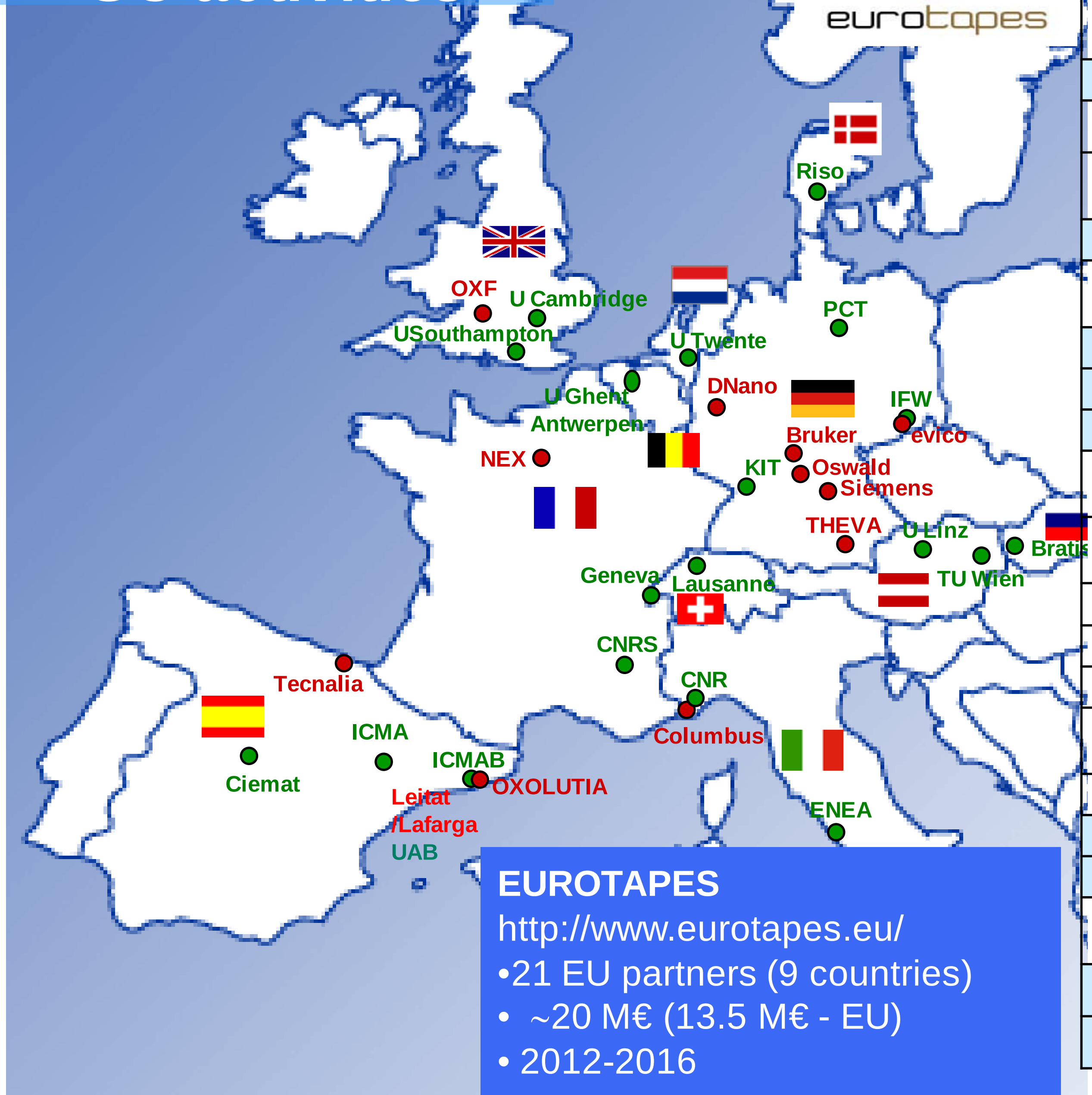


EUROTAPES

http://www.eurotapes.eu/

- 21 EU partners (9 countries)
- ~20 M€ (13.5 M€ - EU)
- 2012-2016

European main SC activities



EUROTAPES
http://www.eurotapes.eu/
- 21 EU partners (9 countries)
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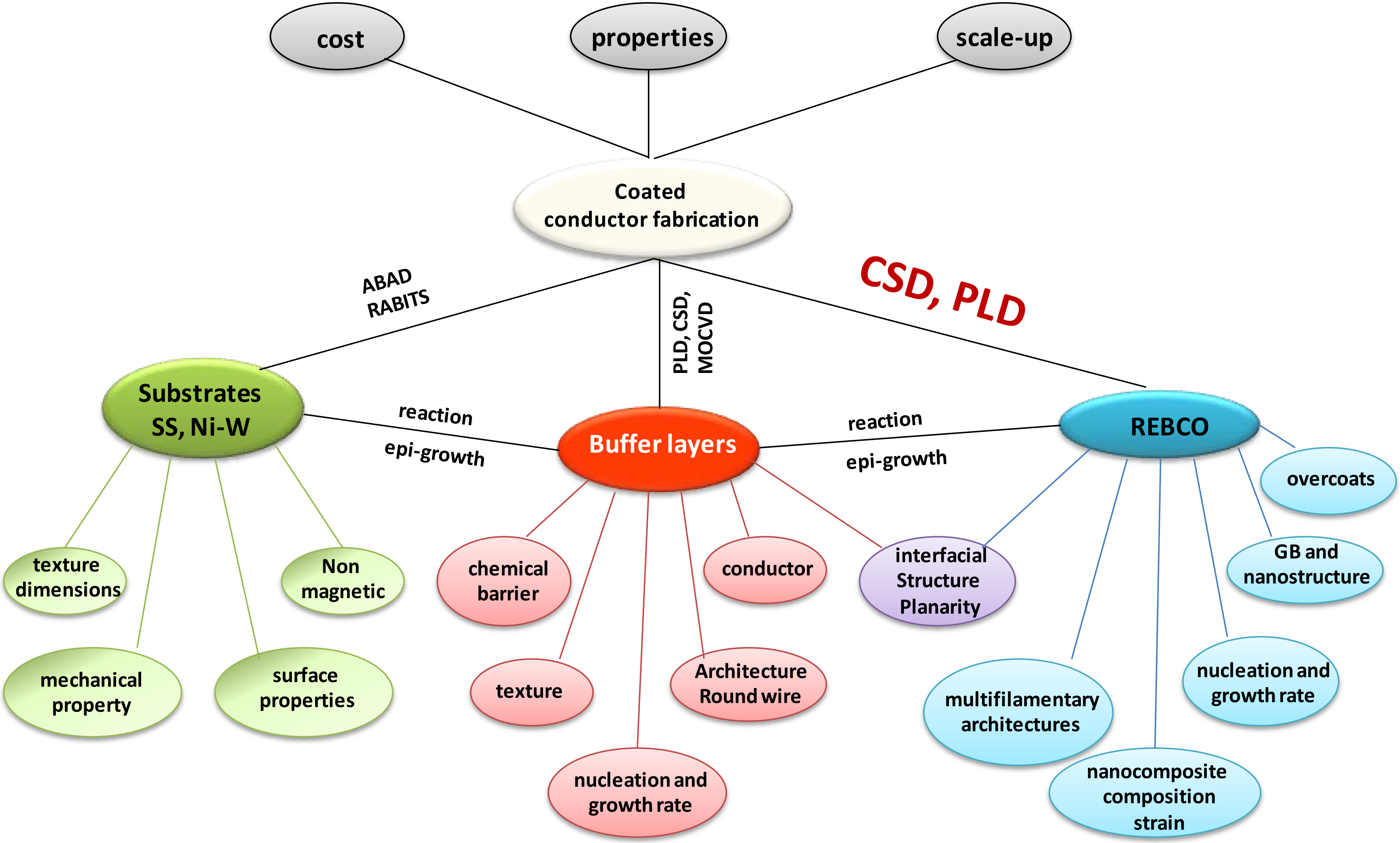
	Participant	Country
1 (Cord)	ICMAB- CSIC	ES
2	Bruker HTS GmbH	DE
3	Italian National agency ENEA	IT
4	Institute of Electrical Eng. Slovak	SK
5	La Farga la Cambra	ES
6	IFW Dresden	DE
7	Nexans SA	F R
8	Oxolutia, SL	ES
9	DNano	DE
10	Technical University of Cluj-Napoca	RO
11	Vienna University of Technology	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
21	KIT	DE

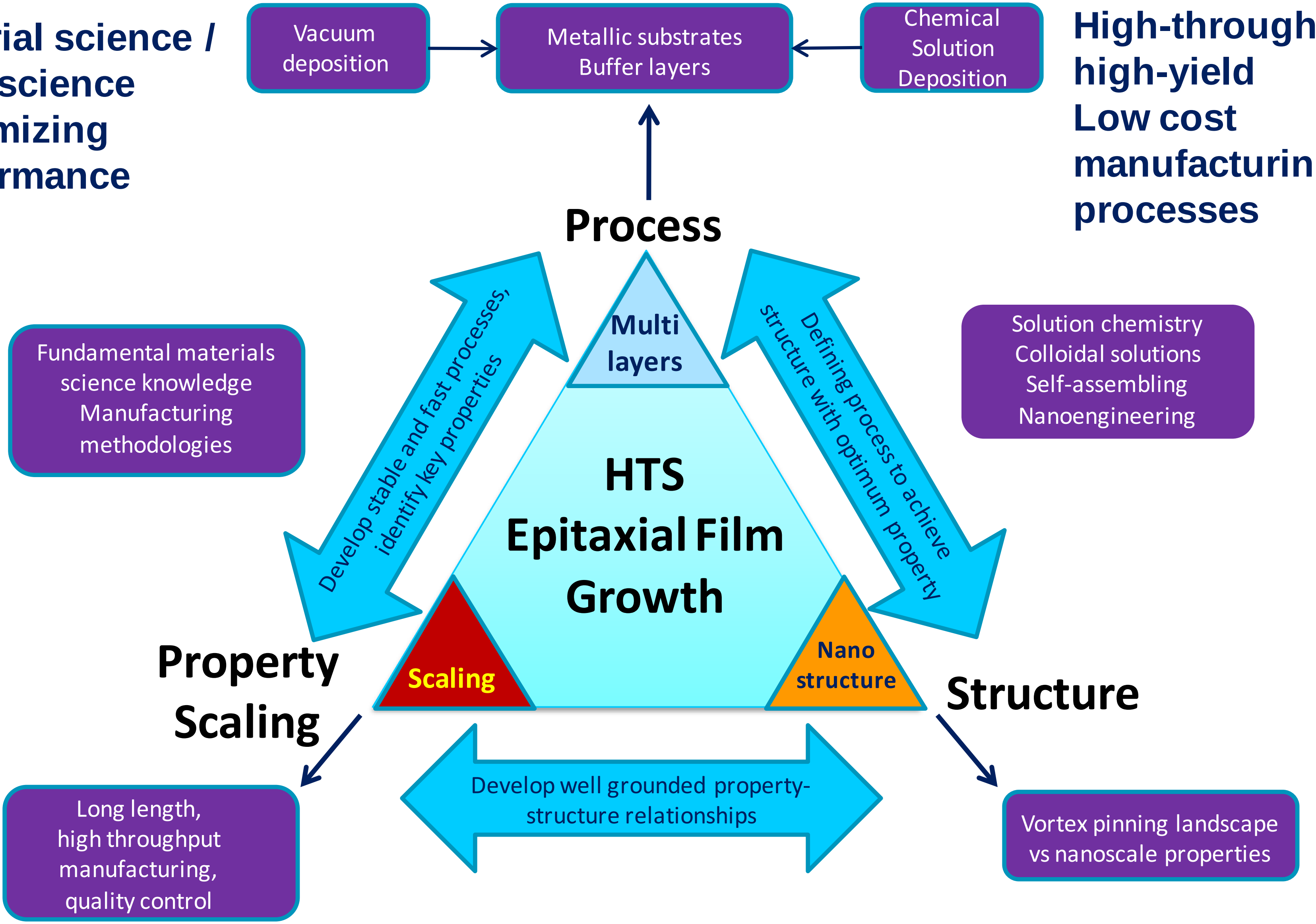
CC's: multiparameter integration



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

Material science / Nanoscience maximizing performance

High-throughput / high-yield Low cost manufacturing processes



Vacuum deposition

Metallic substrates
Buffer layers

Chemical Solution Deposition

Process

Multi layers

HTS Epitaxial Film Growth

Scaling

Nano structure

Property Scaling

Structure

Develop stable and fast processes, identify key properties

Defining process to achieve structure with optimum property

Develop well grounded property-structure relationships

Fundamental materials science knowledge
Manufacturing methodologies

Solution chemistry
Colloidal solutions
Self-assembling
Nanoengineering

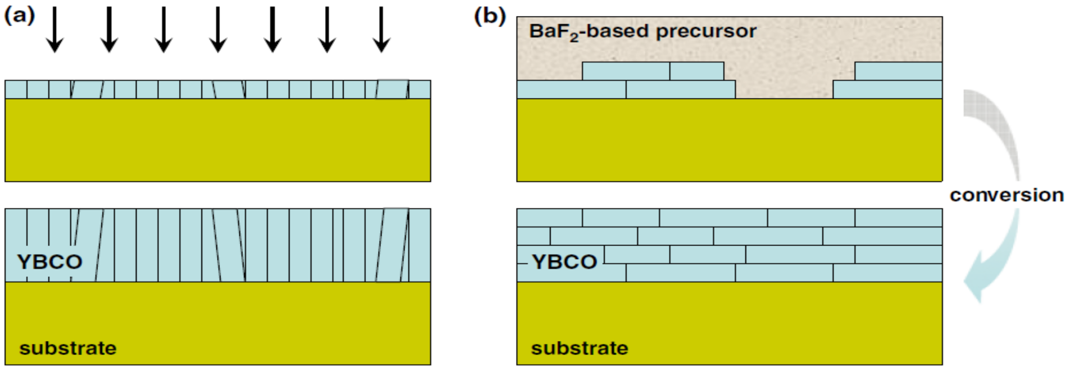
Long length,
high throughput manufacturing,
quality control

Vortex pinning landscape vs nanoscale properties

Approaches to CC production

In – situ growth

Ex – situ growth

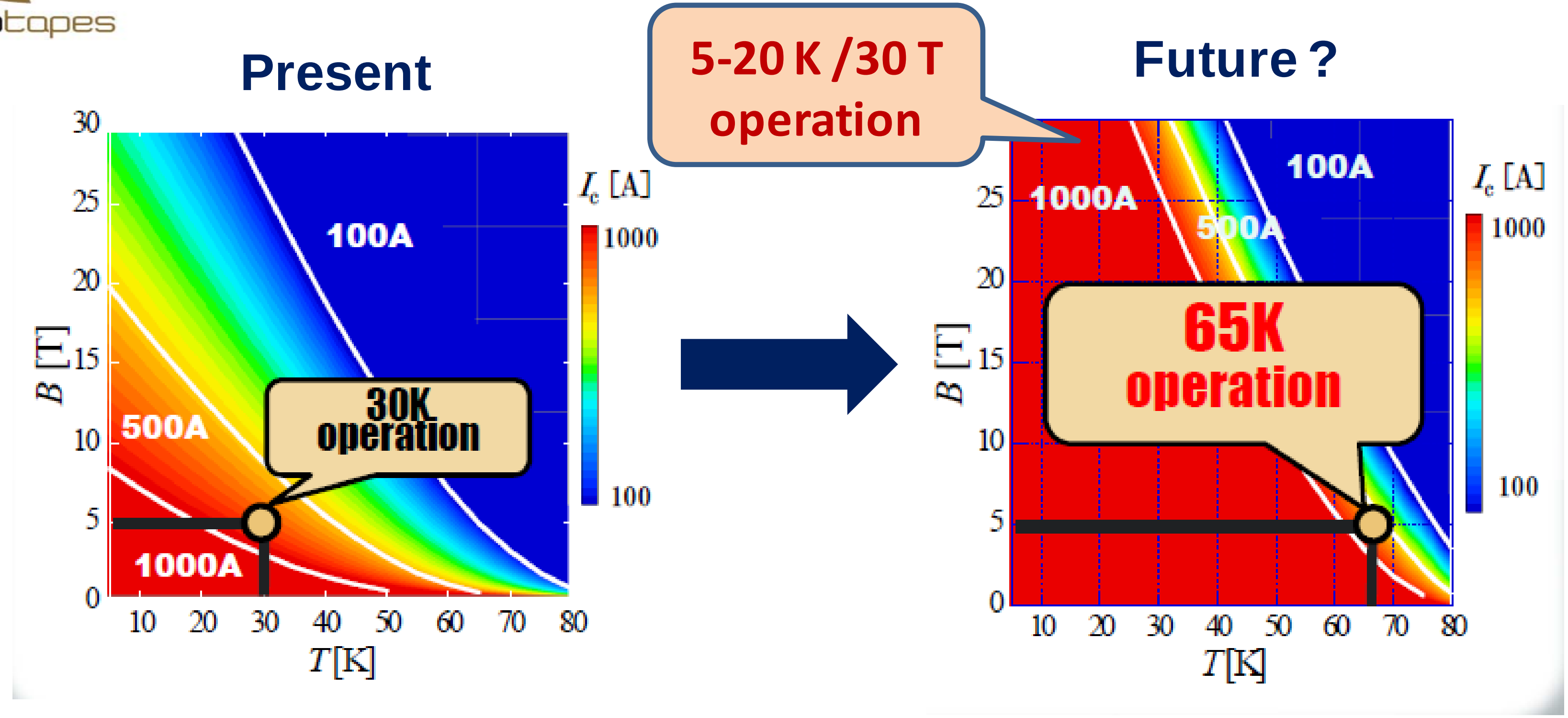


D. M. Feldmann et al, J. Am. Ceram. Soc. (2008)

Deposition Growth	PVD	Chemical
In - situ	PLD, EV, ISD	MOCVD
Ex - situ	RCE-DR	CSD

- In – situ deposition and growth techniques have been widely used in recent years and a wide knowledge and technological expertise already exists
- Ex – situ deposition and growth techniques are novel approaches with a potential for a reduced cost and a higher throughput but there exists still some lack of knowledge and some technological hurdles are being solved simultaneously to the generation of knowledge
- Knowledge on preparation of nanocomposites is more widely spread in the case of in-situ growth approaches than in ex - situ approaches

Plenty of room for improvement: I_c(T,B)



Present

Future ?

5-20 K /30 T operation

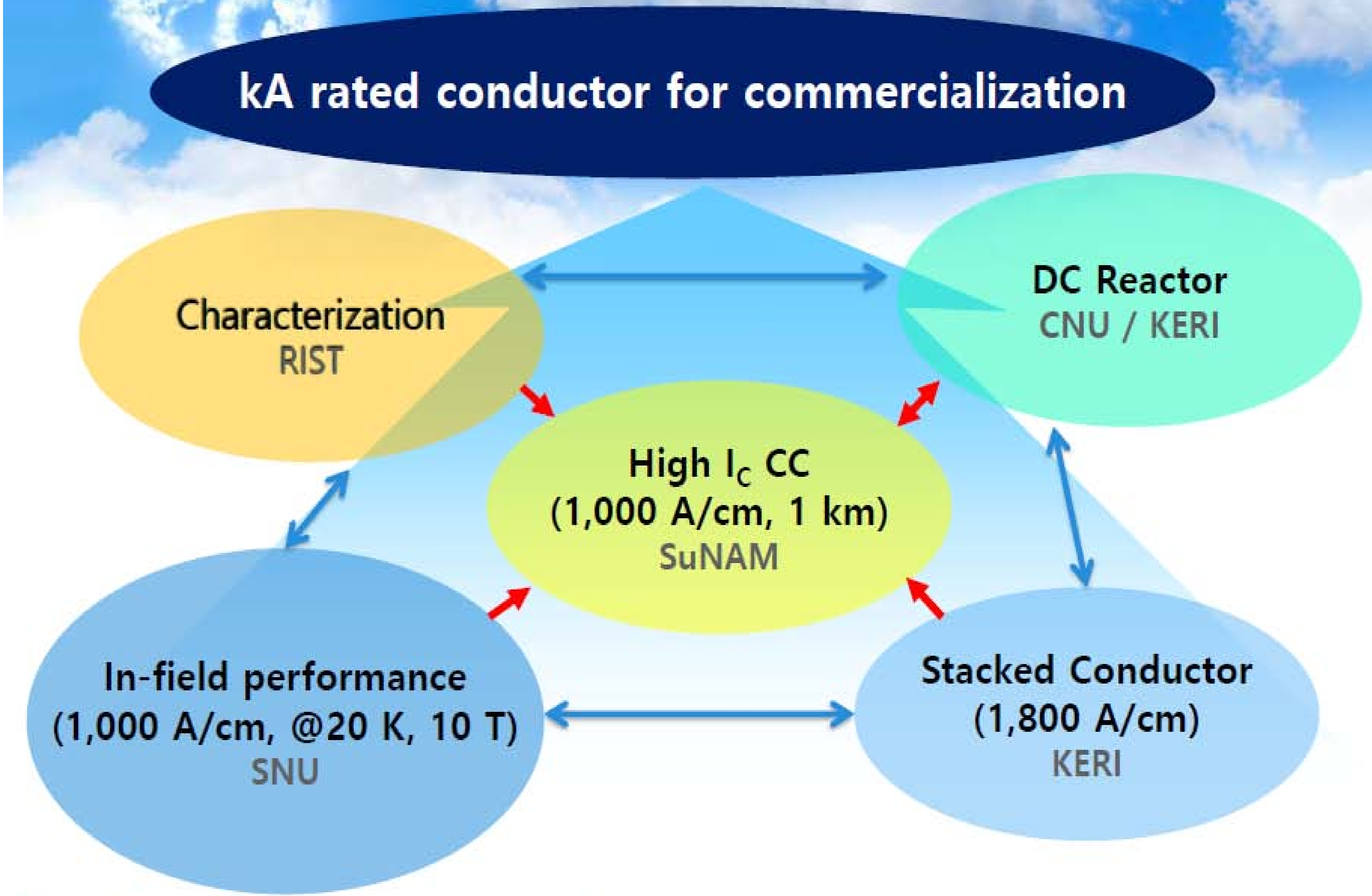
Japanese and Korean programs

- 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

Courtesy of T. Izumi

New Gov't Sponsored Coated Conductor Project

Up to 2017



kA rated conductor for commercialization

Characterization
RIST

DC Reactor
CNU / KERI

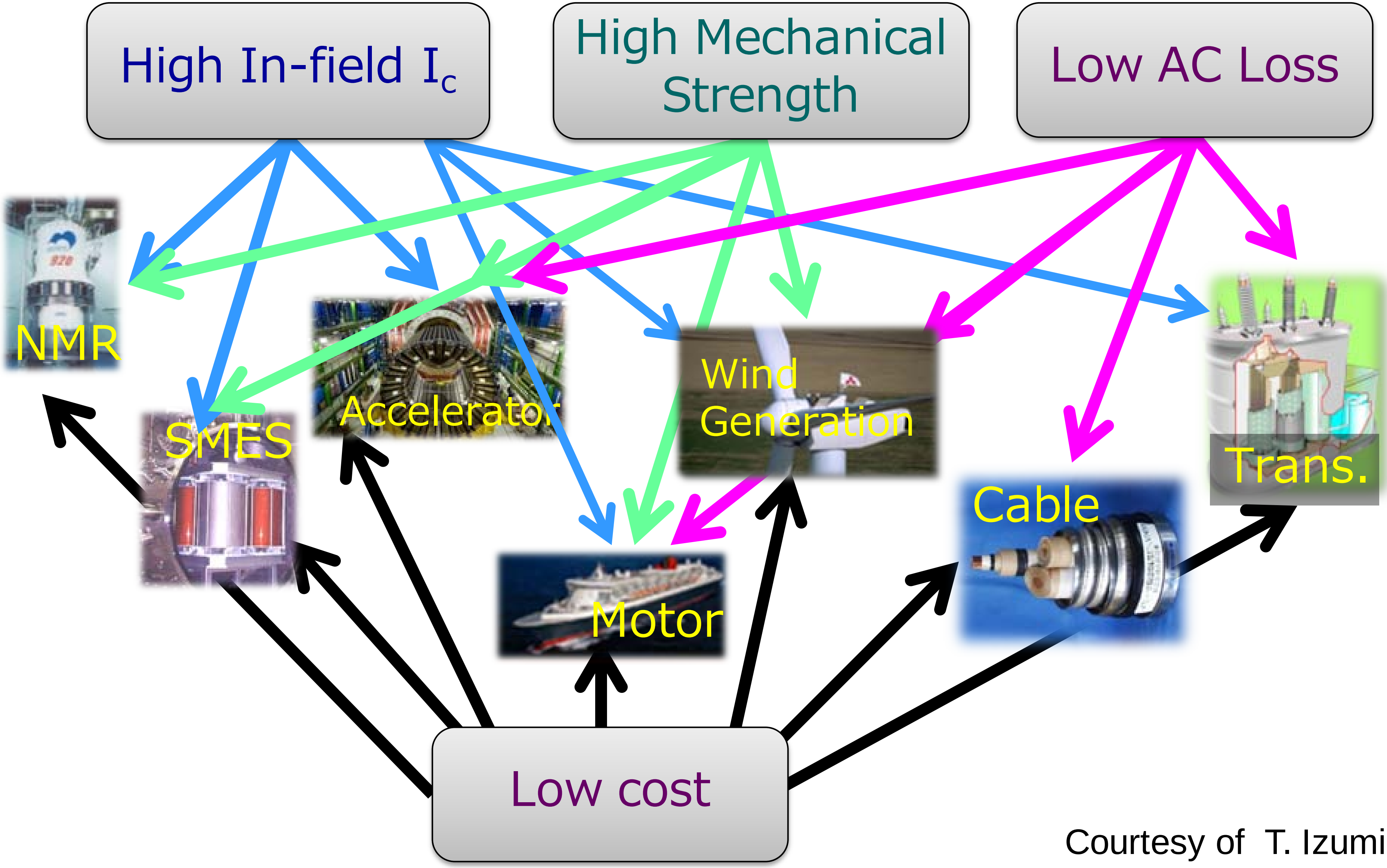
High I_C CC
(1,000 A/cm, 1 km)
SuNAM

In-field performance
(1,000 A/cm, @20 K, 10 T)
SNU

Stacked Conductor
(1,800 A/cm)
KERI

SuNAM KERI RIST

Specifications and cost for applications



High In-field I_c

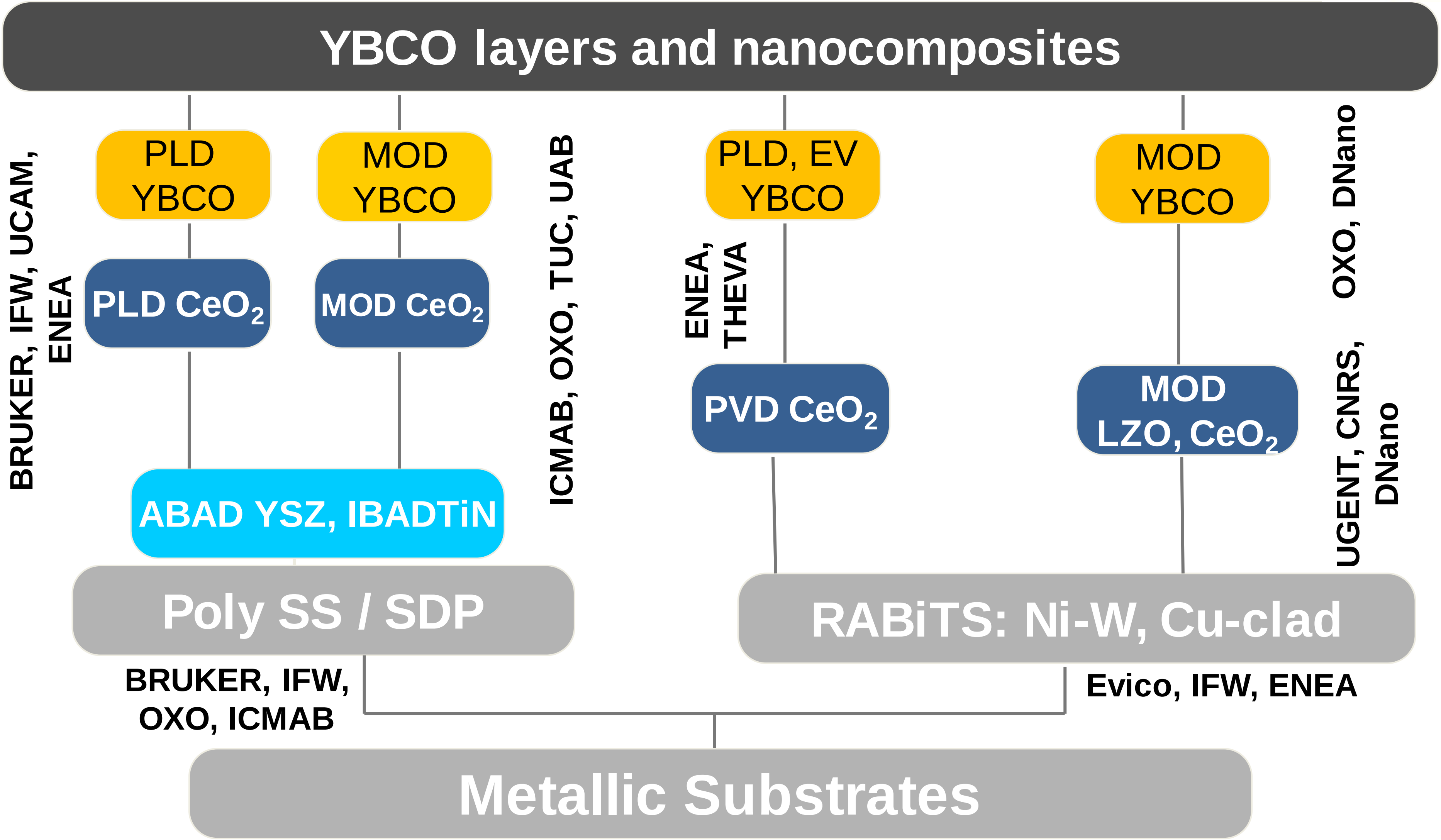
High Mechanical Strength

Low AC Loss

Low cost

Courtesy of T. Izumi

EUROTAPES project



YBCO layers and nanocomposites

BRUKER, IFW, UCAM, ENEA

PLD YBCO

PLD CeO_2

MOD YBCO

MOD CeO_2

ABAD YSZ, IBADTiN

ICMAB, OXO, TUC, UAB

Poly SS / SDP

BRUKER, IFW, OXO, ICMAB

ENEA, THEVA

PLD, EV YBCO

PVD CeO_2

MOD YBCO

MOD LZO, CeO_2

OXO, DNano

UGENT, CNRS, DNano

RABiTS: Ni-W, Cu-clad

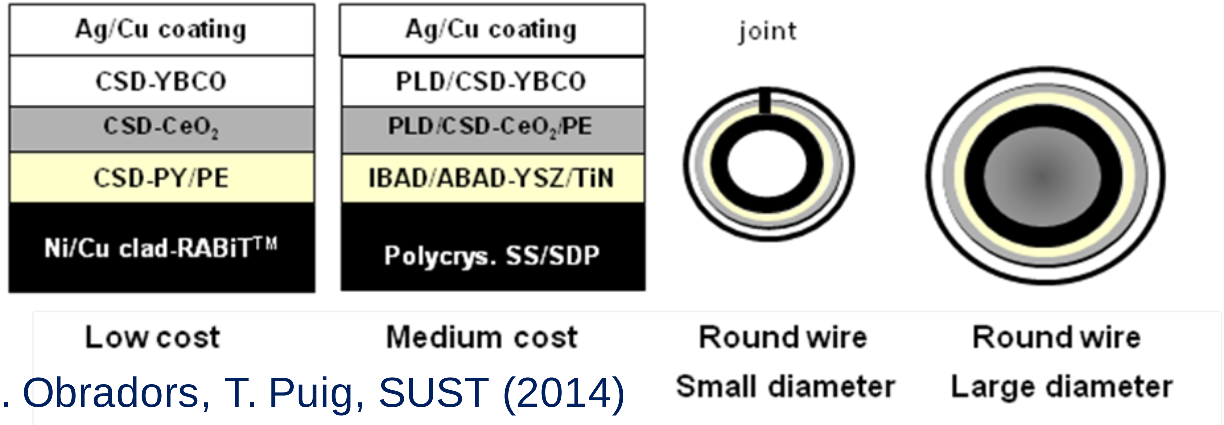
Evico, IFW, ENEA

Metallic Substrates

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



X. Obradors, T. Puig, SUST (2014)

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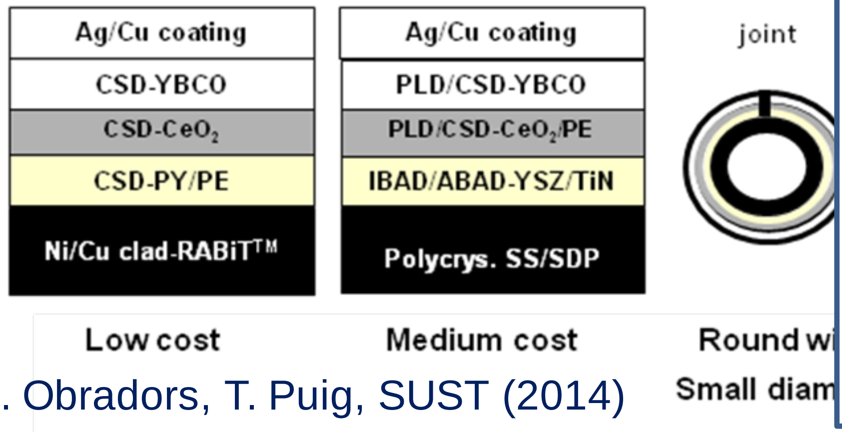

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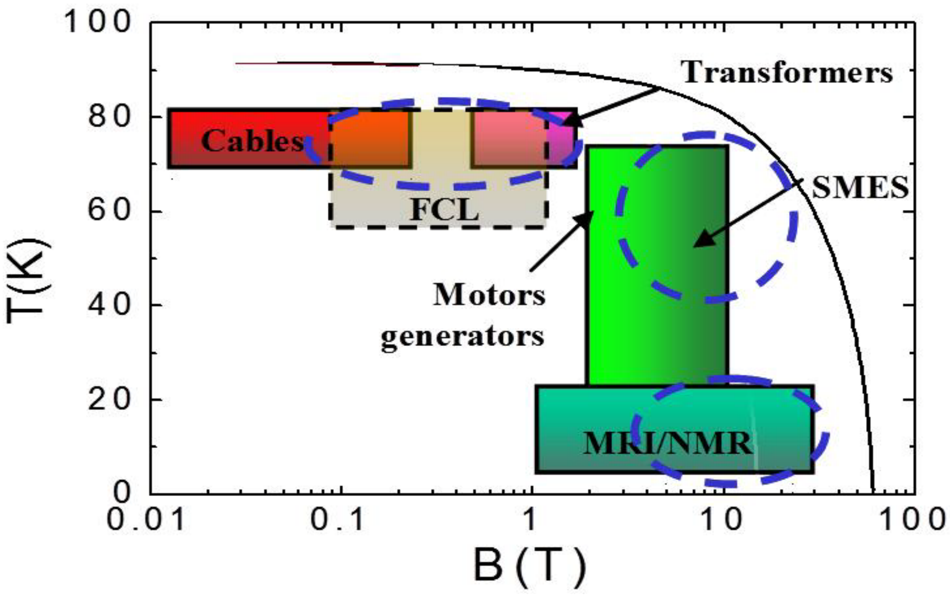


TARGETS:

- **Pre-comercial cost**: ~100 €/kAm
- **Length** :+500 m
- **Performance:**
- For low fields (B< 1 T):

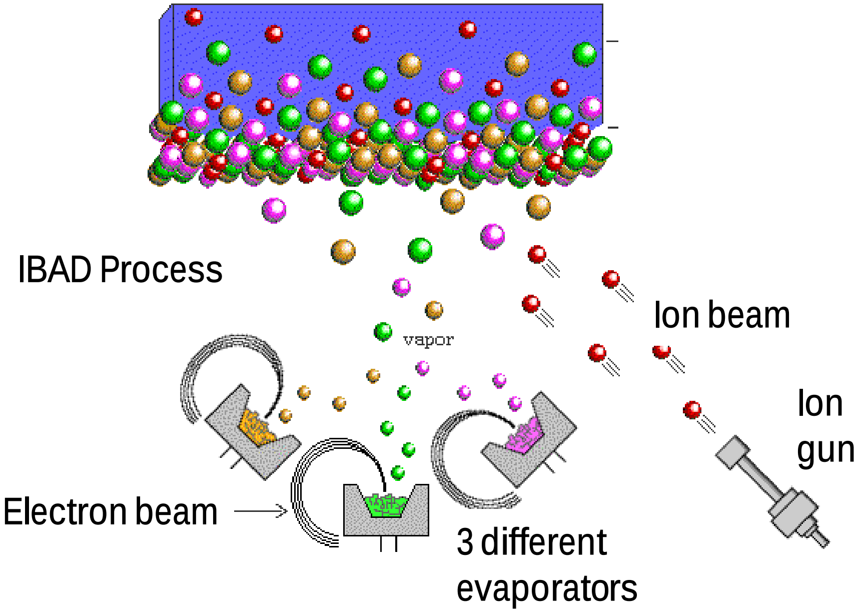
  I_c (77K, sf) > 400 A/cm-w
- For ultrahigh fields (B > 15 T):

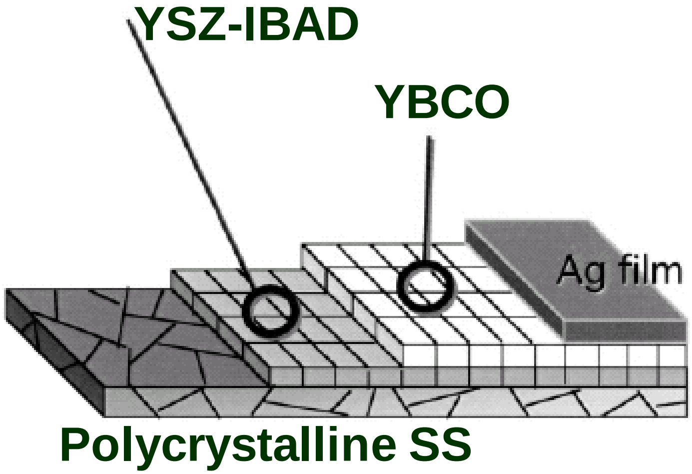
  I_c(5K, 15 T) > 1000 A/cm-w
- For high fields (B ~3-5 T):

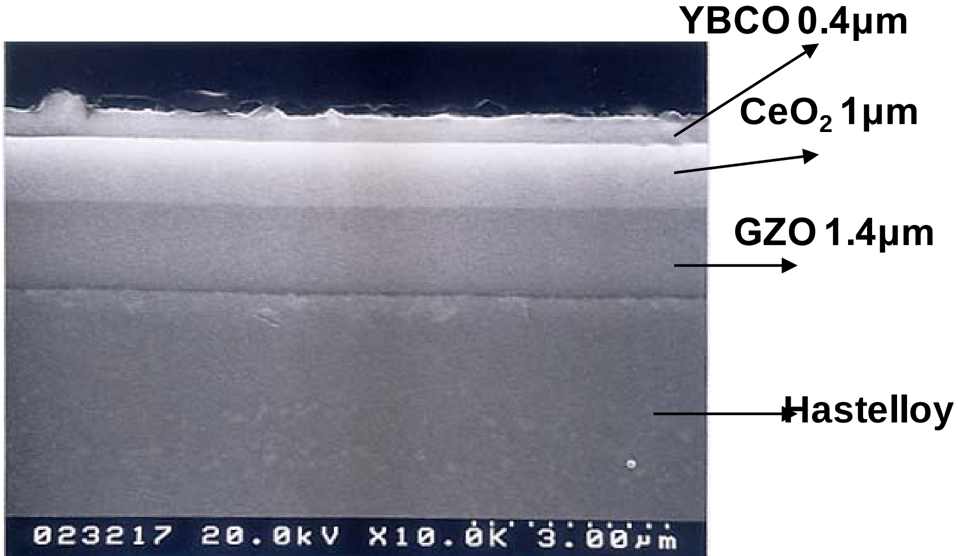
  F_p(60 K) > 100 GN/m^3

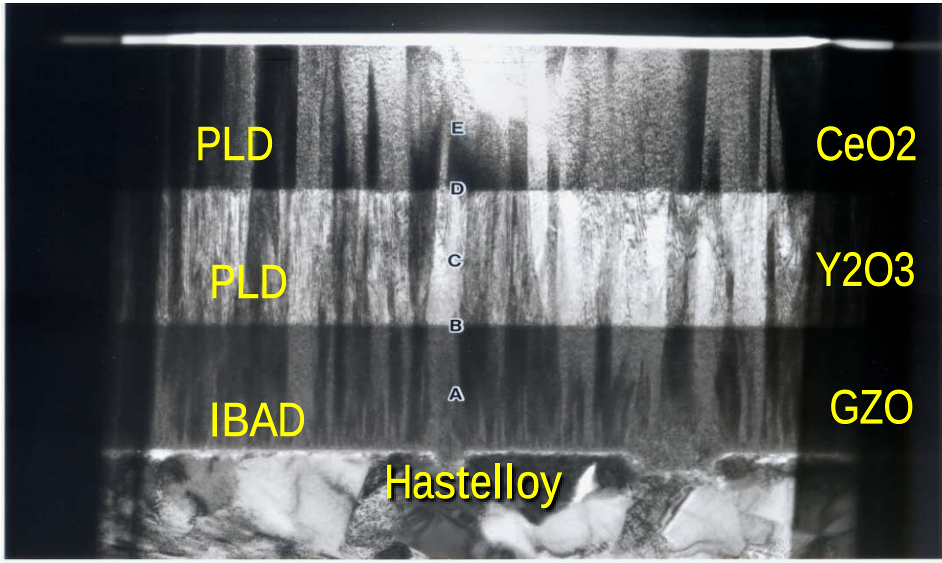
IBAD COATED CONDUCTORS

IBAD (ION BEAM ASSISTED DEPOSITION)





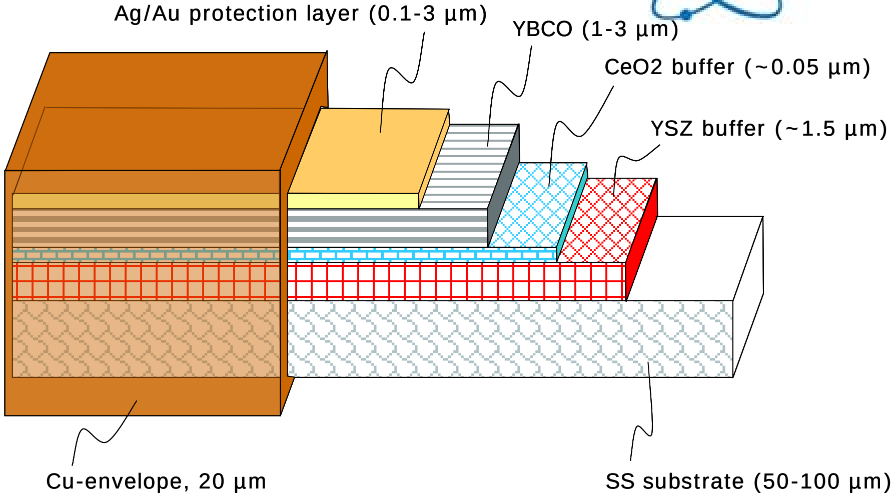




ABAD metallic substrates

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

Towards cost reduction :

Solution Deposition Planarization (SDP) process to substitute mechanical polishing

Status in substrate tape development

material / feature	Single phase ceramics (as YSZ)	Single phase metal (as Ni or Hastelloy)		Multi-phase metal (as stainless steel)
polishing	abrasive	electro	⟷✗	abrasive-chem.
I / ABAD	YSZ+	MgO	? ⟷✗	YSZ
costs	very high	high		low

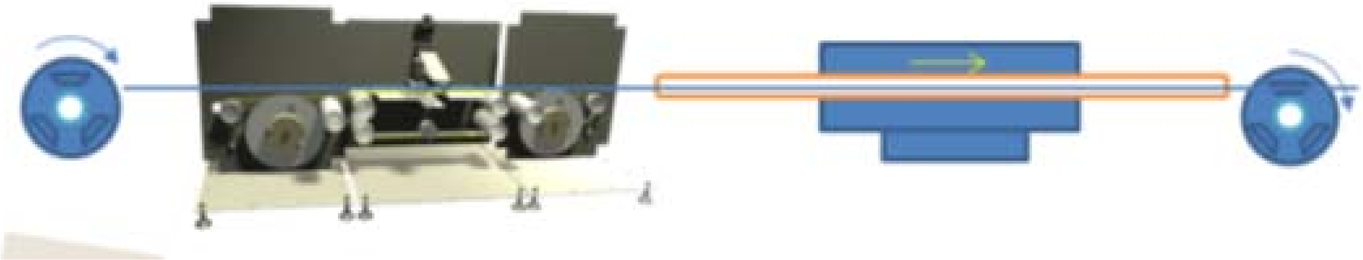
- Planarization layer is expected to be the right solution: Collaboration ICMAB - Oxolutia

SDP/ABAD metallic substrates

- Several solution formulations have ben tested
- IJP can be used with 512 nozzle printhead

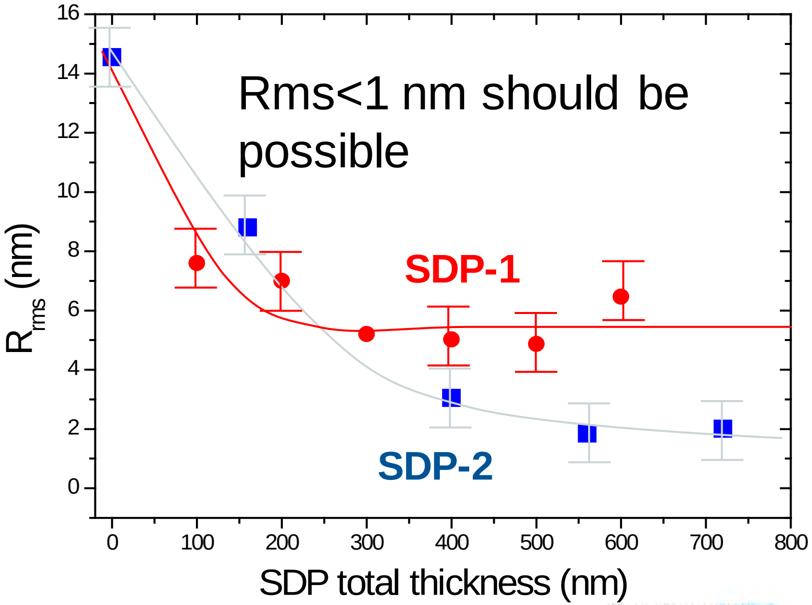
R2R inkjet printing coupled to R2R thermal treatment

0.5 to 9 m/h



Towards cost reduction :

Solution Deposition Planarization (SDP) process to substitute mechanical polishing



Rms<1 nm should be possible

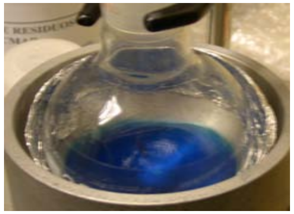
Bruker HTS

- No delamination and promising performance in terms of YSZ and YBCO texture vs thickness
- Important cost reduction is expected

TFA based CSD: Low cost YBCO and nanocomposites

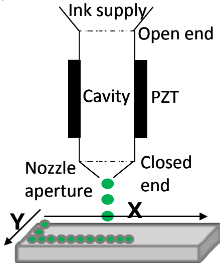
Precursor solution synthesis

Y, Ba,Cu metal-organic precursors



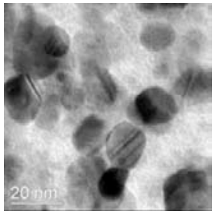
Solution deposition

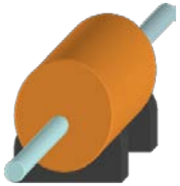
Ink-jet Printing



Pyrolysis

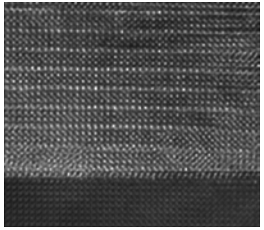
Removal organic precursors





Ex-situ Growth

Nucleation, crystallization and oxygenation



X. Obradors, et al, SUST (2012)

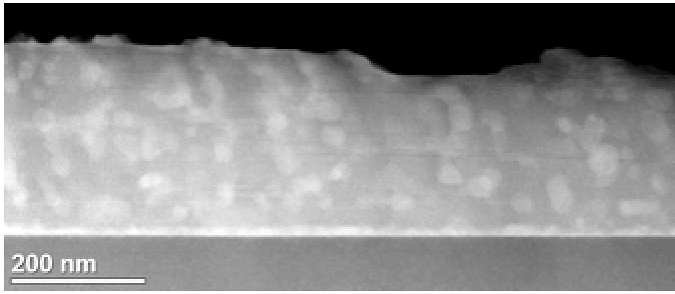
For Nanocomposites: In-situ

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, $BaCeO_3$,** …

Nature Materials (2007); Nature Materials (2012)

For Nanocomposites: Ex-situ

TFA colloidal precursor solutions: **MFe_2O_4 (M=Co, Mn), CeO_2 ($BaCeO_3$), …**

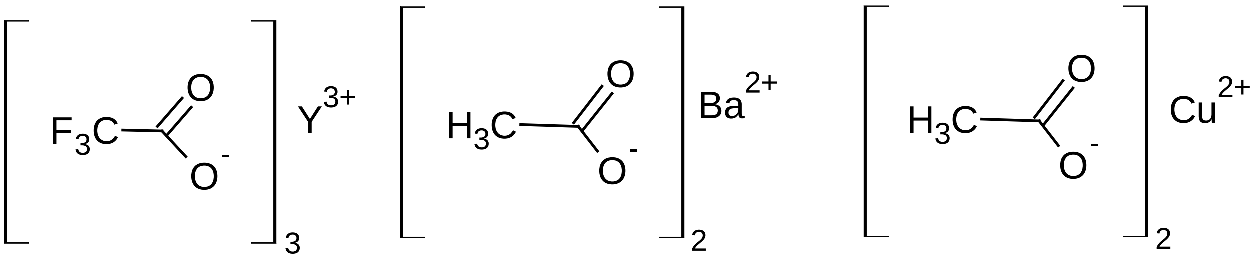


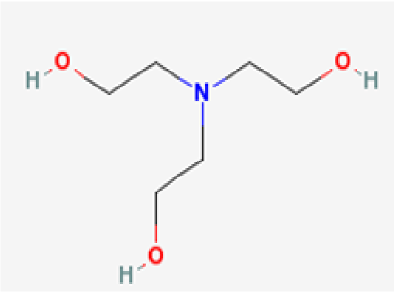
J. Nanoparticle Res. (2012); Mat. Res. Bull. (2013)

Low fluorine precursor solutions

Carboxylate salts	+Solvent	+ Chelating Agent
Acetate	Methanol, ethanol	Triethanolamine (TEA)
Propionate	Propionic acid	

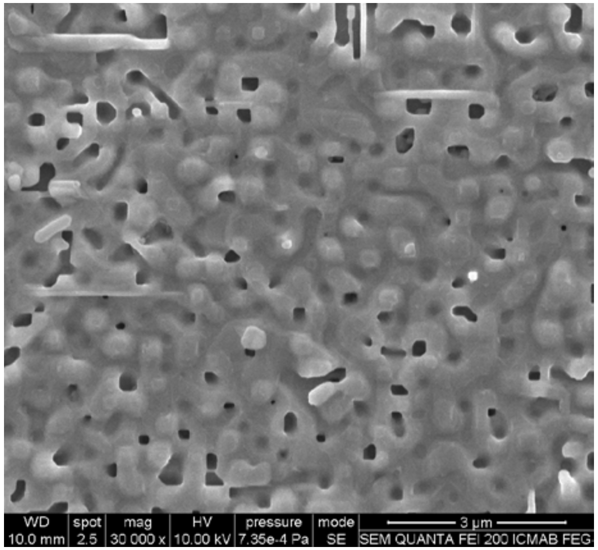
~80-90% less fluorine





J_c (77K, sf) = 3-4 MA/cm^2 ; 700-800 nm

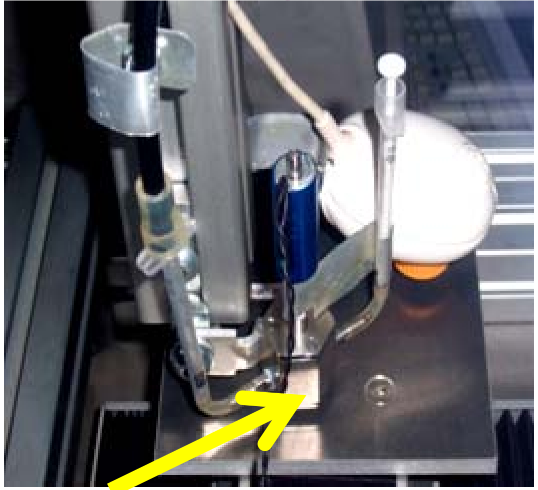
- ❖ **More environementally friendly (-80 % F)**
- ❖ **Stable solutions adapted to IJP: less sensitive to humidity (chelating agents)**
- ❖ **Large thickness with one coat (~1000 nm)**
- ❖ **Pyrolysis can be undertaken at faster ramps**
- ❖ **Similar growth process that TFA-based solutions**



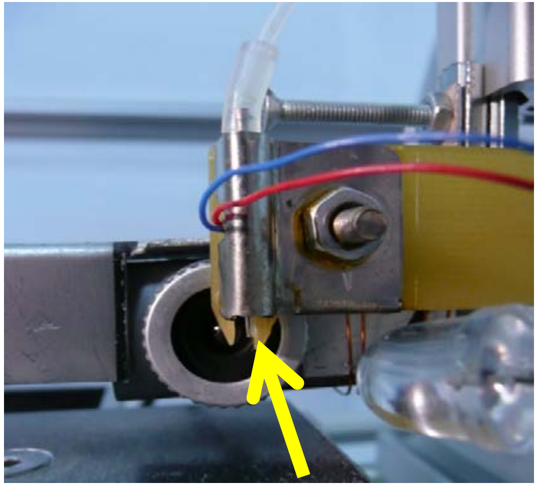
X. Palmer et al,, to be published

Inkjet printing deposition systems

Single nozzle printheads



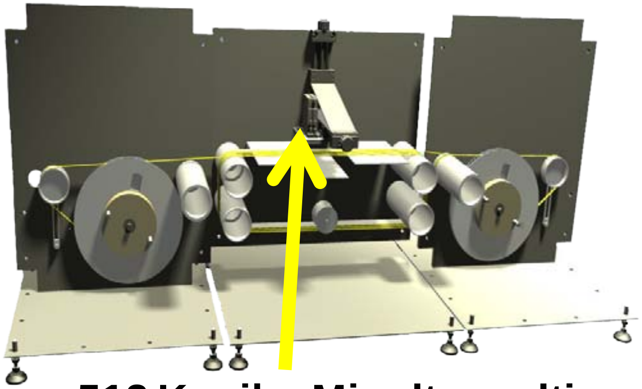
single nozzle electromagnetic valve



single nozzle piezoelectric printhead

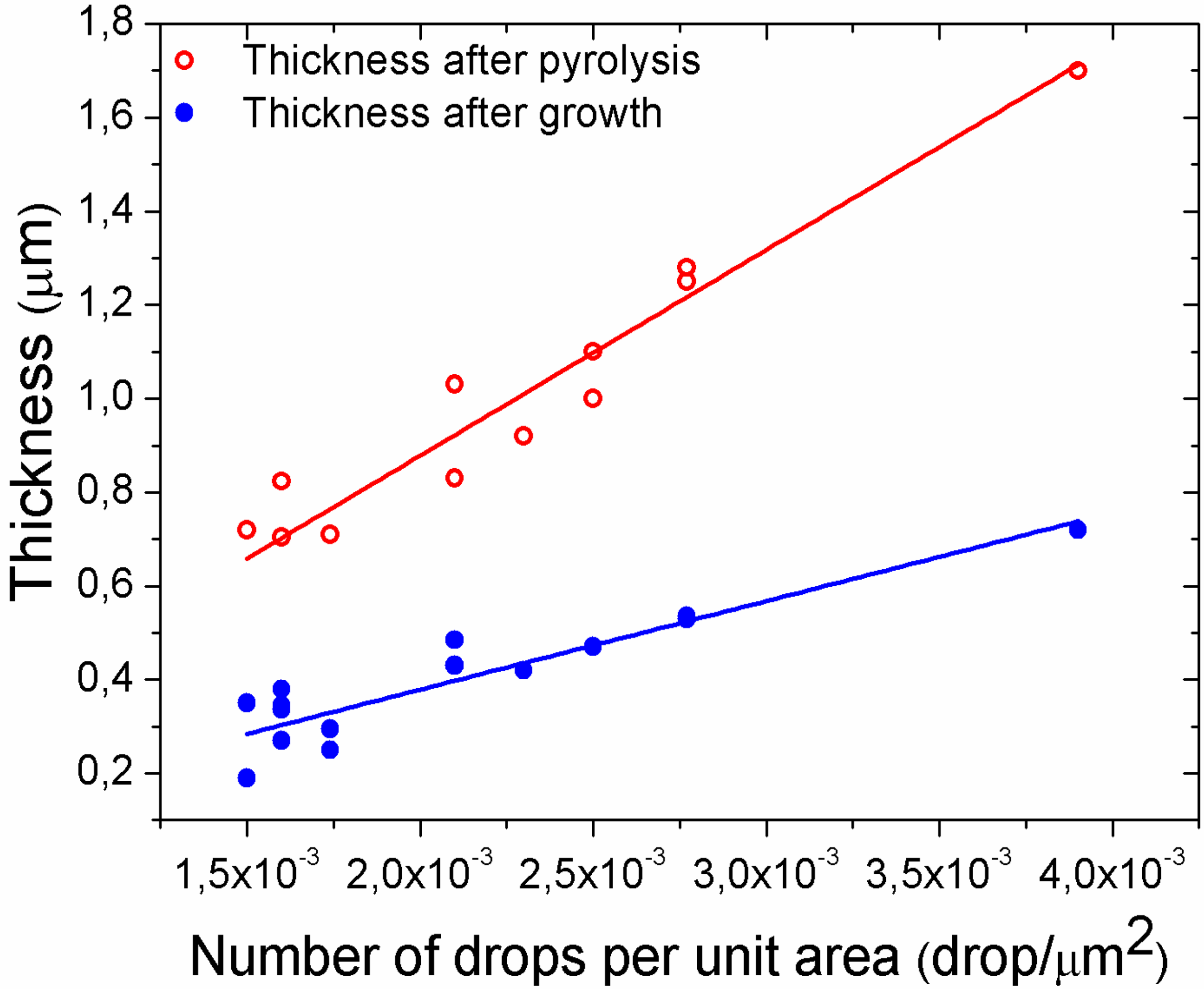
Multinozzle printheads

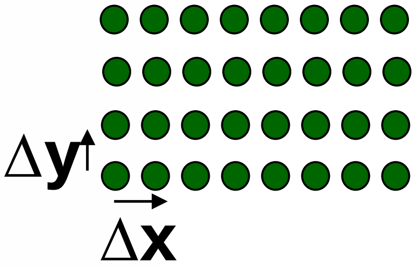
16 nozzles piezo head



512 Konika Minolta multinozzle piezohead

Film thickness tuning through drop pitch adjustment





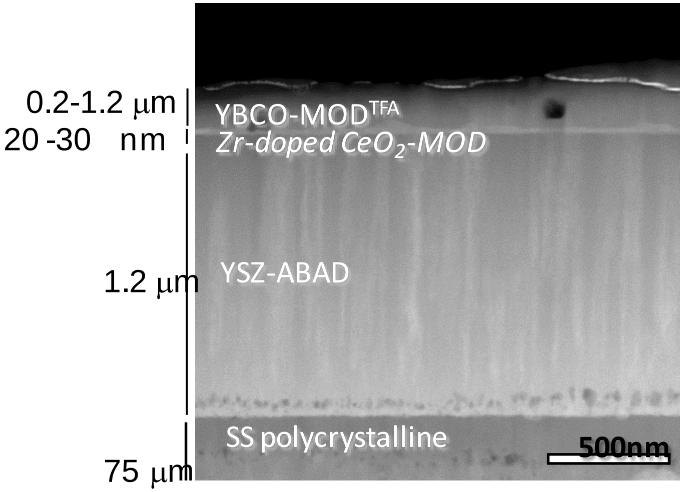
drop density (drop/µm²)

Possibility to tune film thickness by adjusting the density of drops

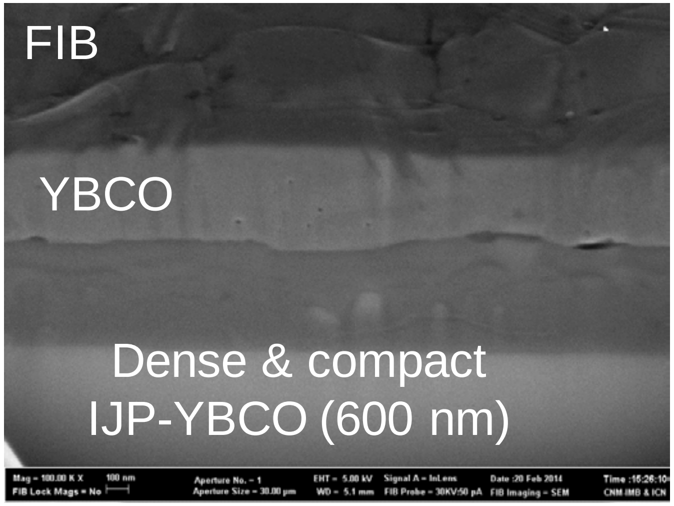
CSD CC's on ABAD-YSZ

All chemical IJP: YBCO / CeO_2 / ^{ABAD}YSZ /SS

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

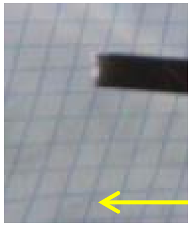


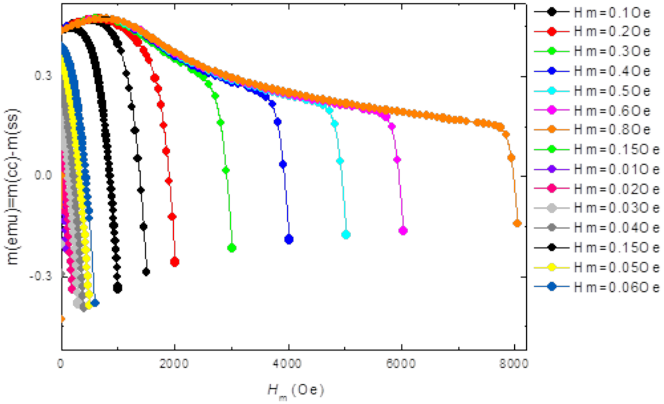
Bruker HTS GmbH

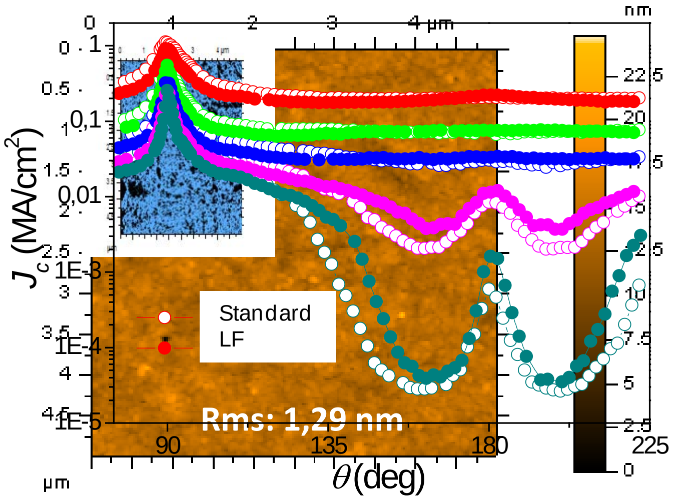


J_c(sf,77K)=2 MA/cm^2 I_c=108 A/cm-w

E. Bartolomé et al, SUST (2013)







- **No cohe**
- **Current**

BCO grains

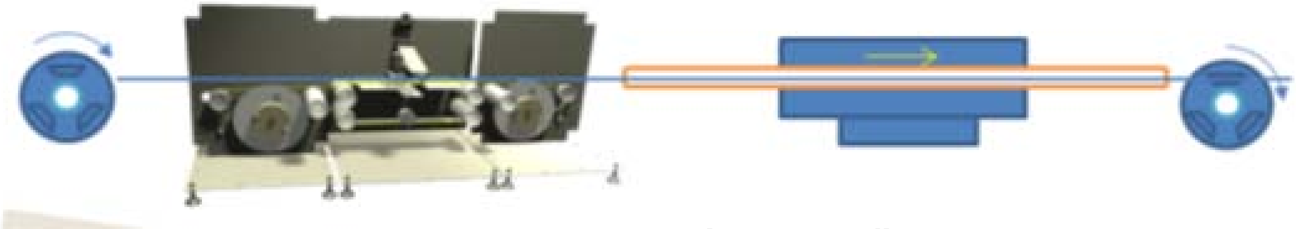
C's

Goals: J_c^G(77K)=3.3 MA/cm^2
J_c^{GB}(77K)=2 MA/cm^2 **. nm/s - 10 m**

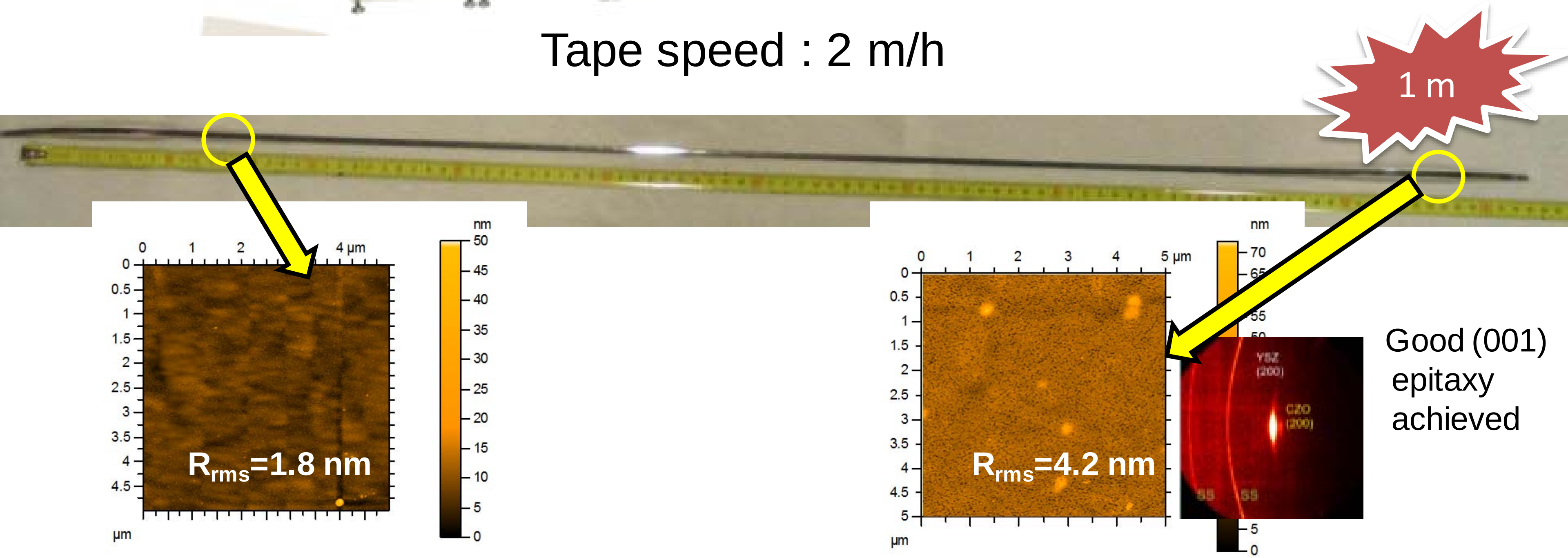
CSD CC's on ABAD-YSZ

All chemical IJP CC: ^{LF}YBCO / ^{CSD}CeO$_2$ / ^{ABAD}YSZ /SDP/SS
Good progress towards scaling up

CZO buffer layers: R2R inkjet printing coupled to R2R thermal treatment



Tape speed : 2 m/h



R_{rms}=1.8 nm

R_{rms}=4.2 nm

Good (001) epitaxy achieved

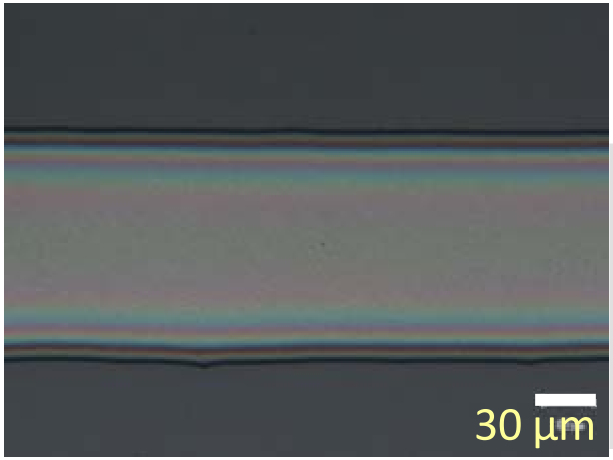
ICMAB OXOLUTIA

YBCO Patterning by inkjet printing

eurotapes

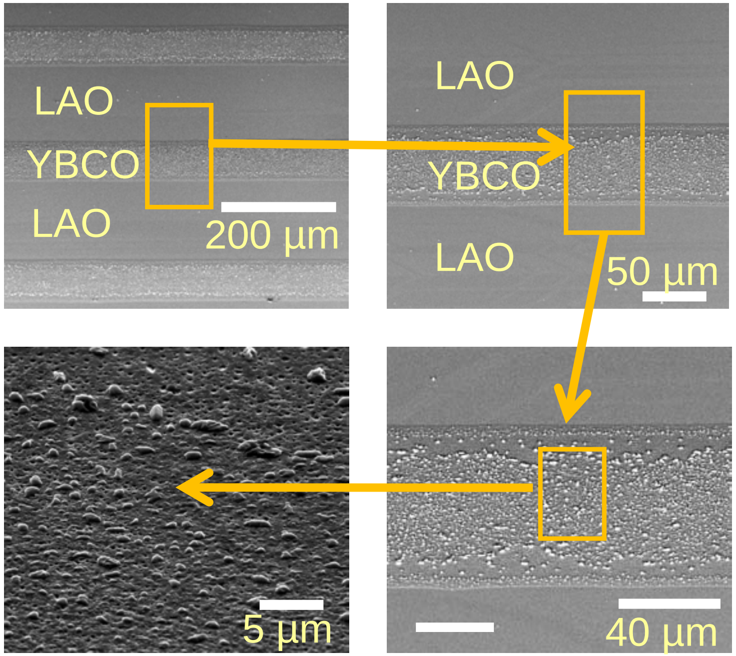
UNIVERSITY OF CAMBRIDGE

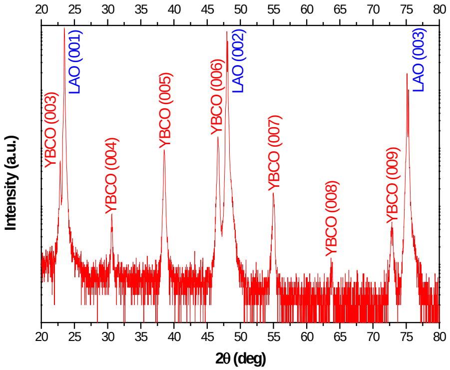
Optical microscopy after pyrolysis



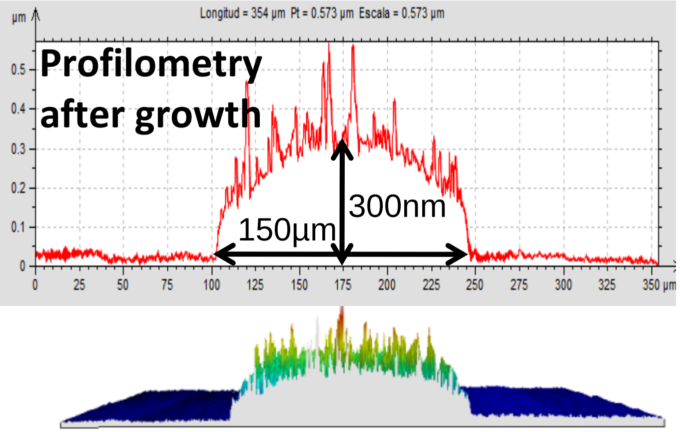
M. Vilardell et al., Inkjet printing: towards flexible manufacturing of functional coatings, Thin Solid Films (2013)

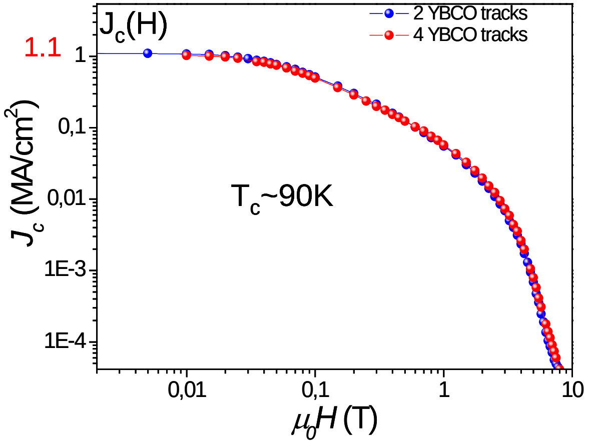
SEM after growth





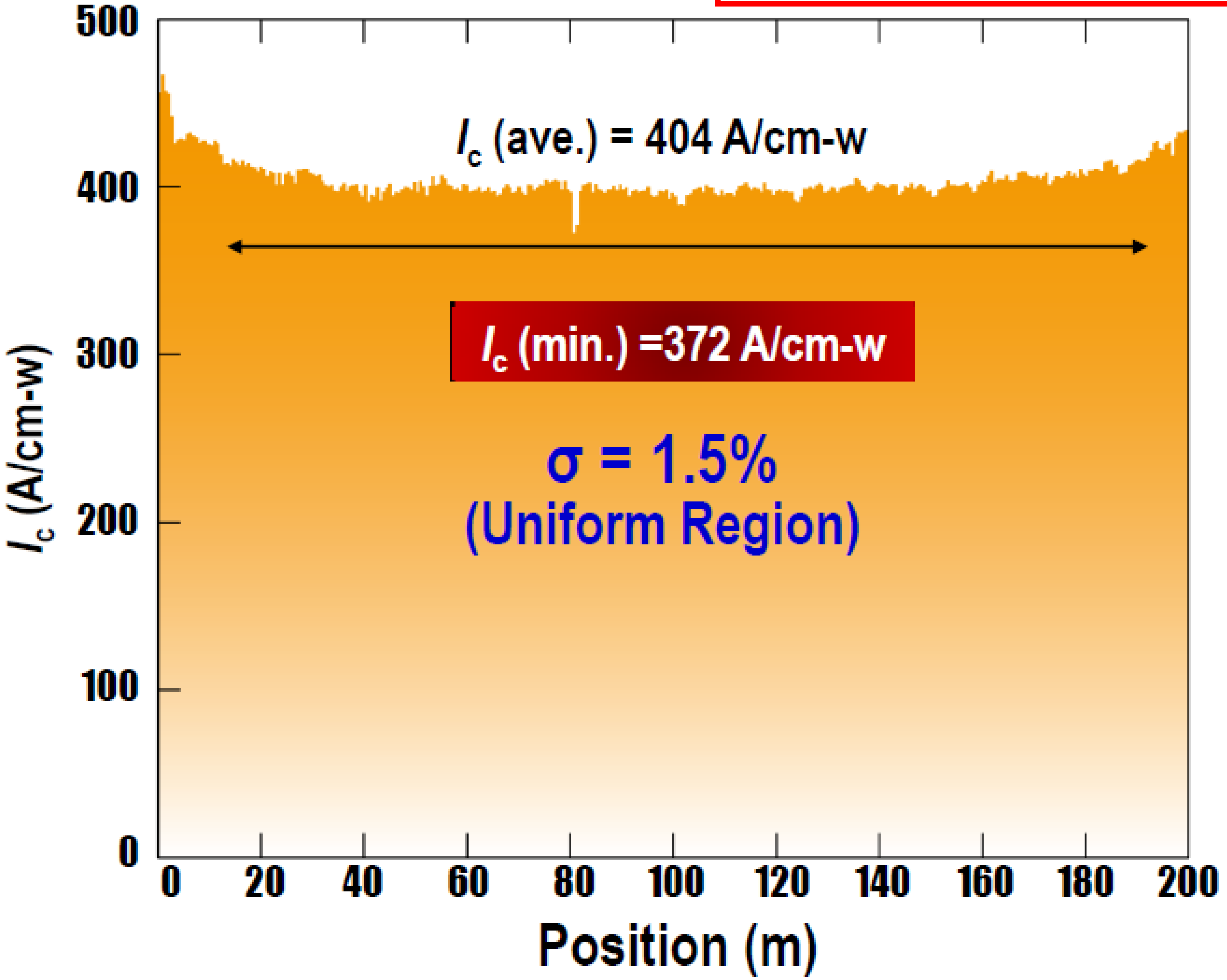
High homogeneity and uniformity along all track length.

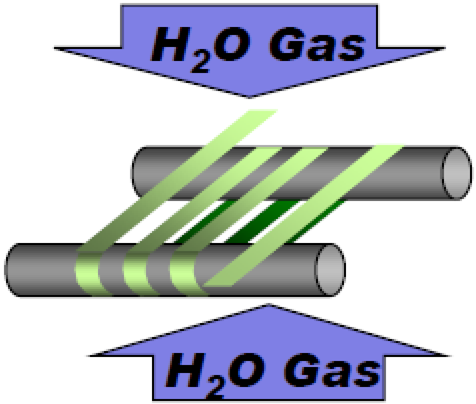




Lower Cost C.C. Fabrication by TFA-MOD

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



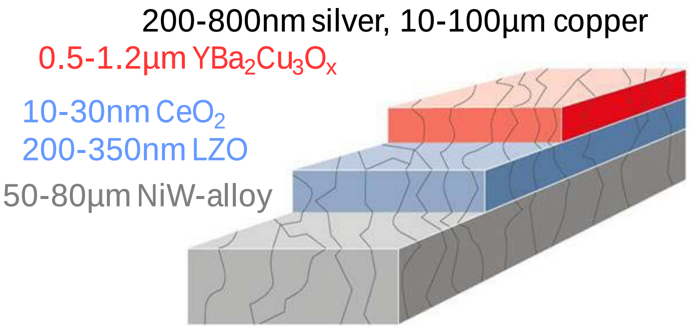


ISTEC SWCC

Ink-Jet Printed RABiT CC's

deutsche nanoschicht

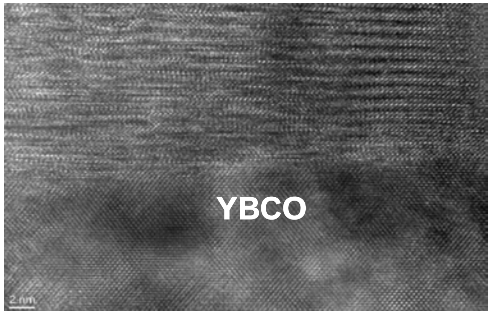
BASF GmbH owner



Ink-jet printing in continuous processing

- **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)**

universitätbonn



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

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

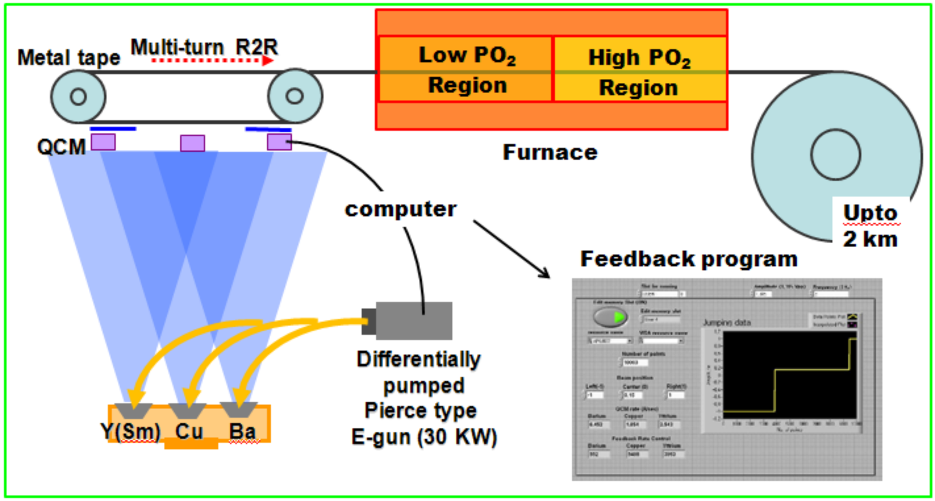
✓ 7mm wide slitted and stabilized sample, I_c/cm-w > 160A

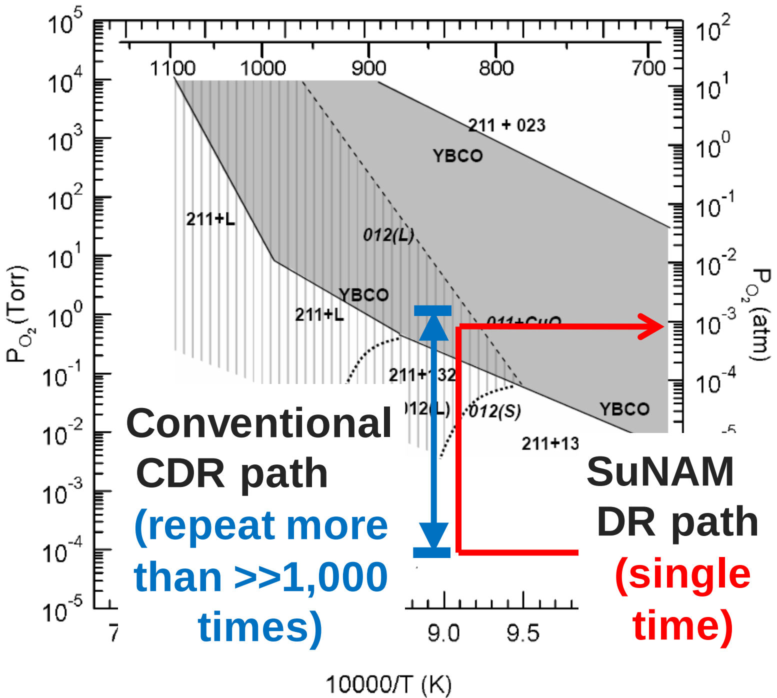
✓ 100 m wound to coil with overall J_c =1.4 MAcm^2

UNIVERSITY OF CAMBRIDGE

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 ~ 10nm/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

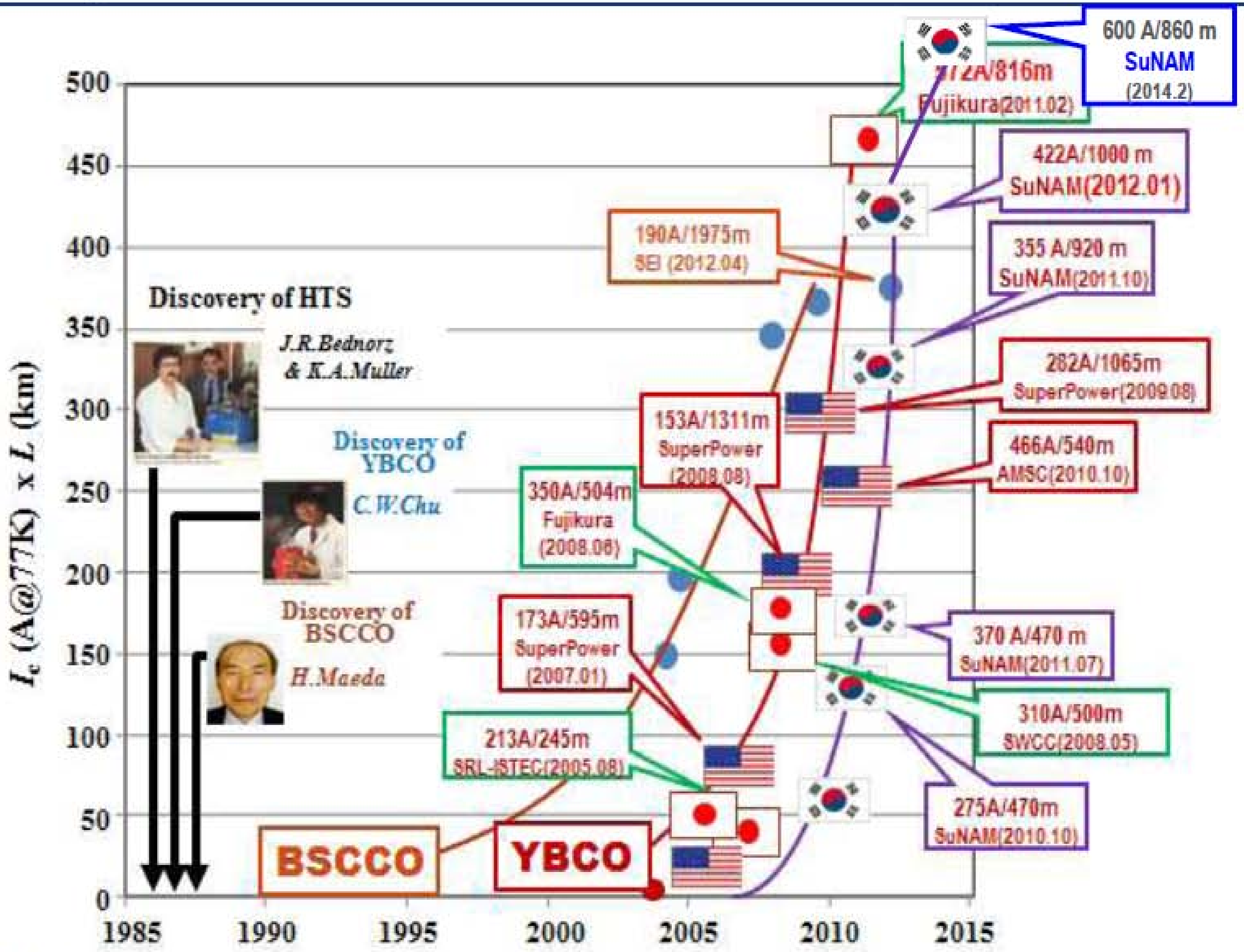




Conventional CDR path (repeat more than >>1,000 times)

SuNAM DR path (single time)

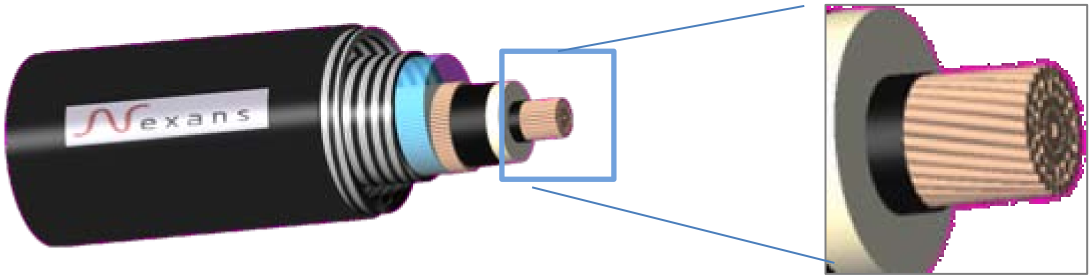
Development of HTS 2G Wire



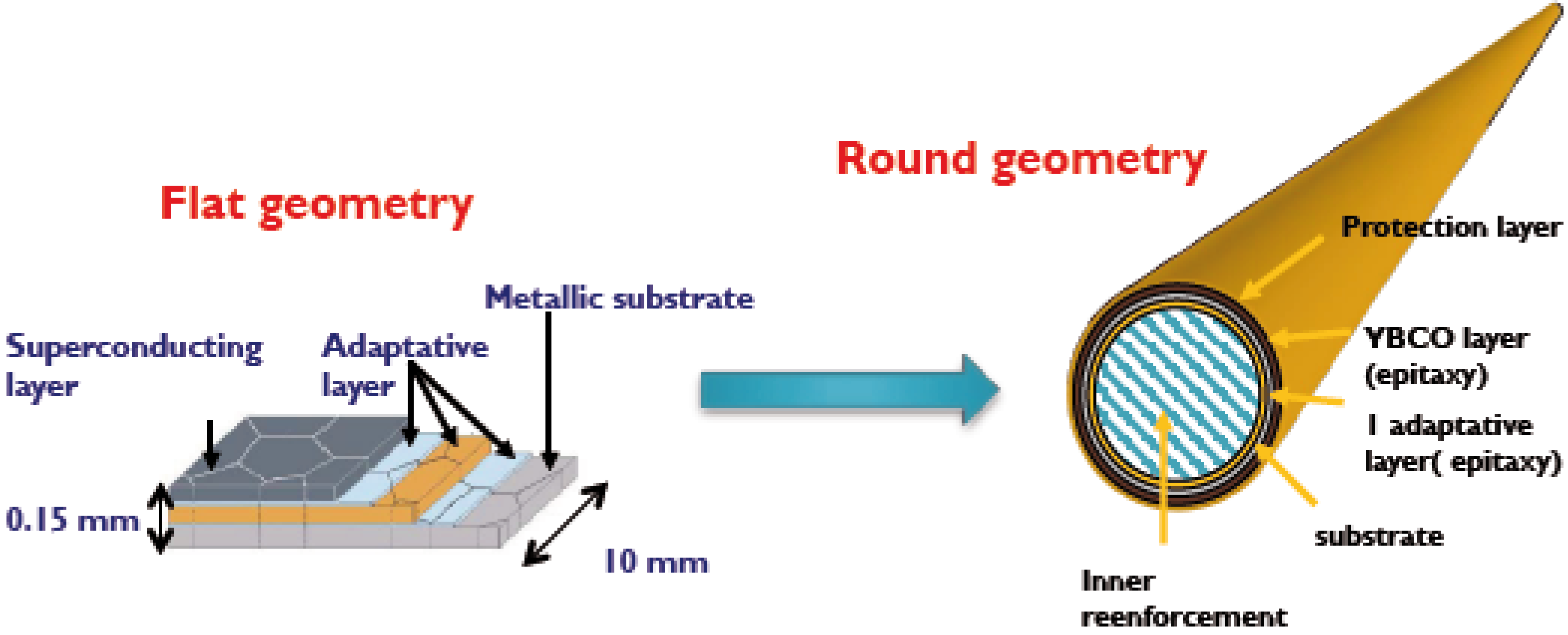
SuNAM

Courtesy of T. Izumi and S.H. Moon

Round wire objective: more compact and low cost cables



Core made of superconductive wires



Welding technology already developed by Nexans

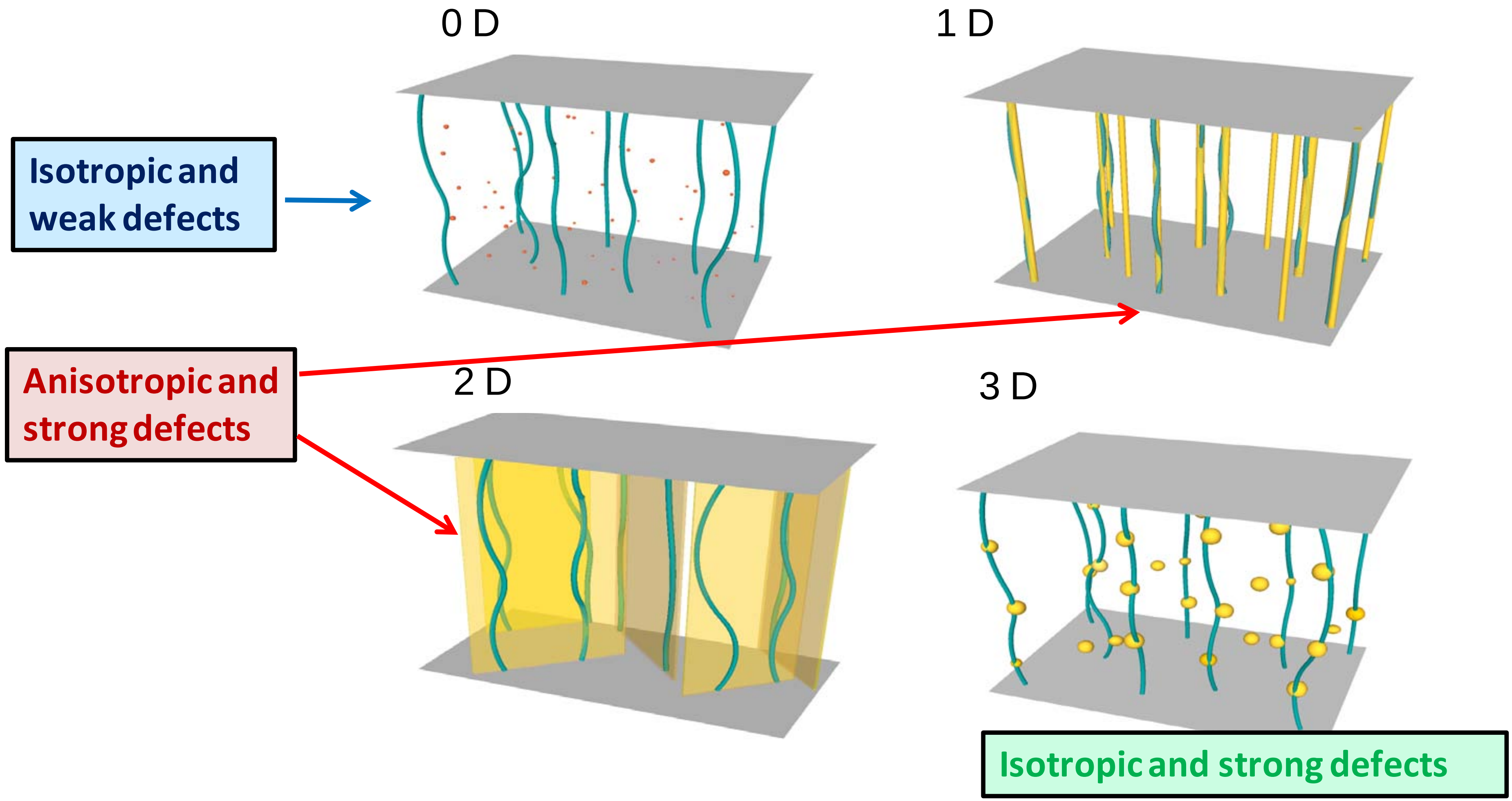
Nexans patent

Outline

- **HTS materials: power and magnet applications**
- **What are the novel opportunities raised by coated conductors?**
  - Physics behind the CCs
- **What are the coated conductors?**
  - Manufacturing approaches to CCs
- **Towards enhanced performances**
  - High currents
  - Vortex pinning

Vortex pinning in YBCO Nanocomposites

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



Isotropic and weak defects

Anisotropic and strong defects

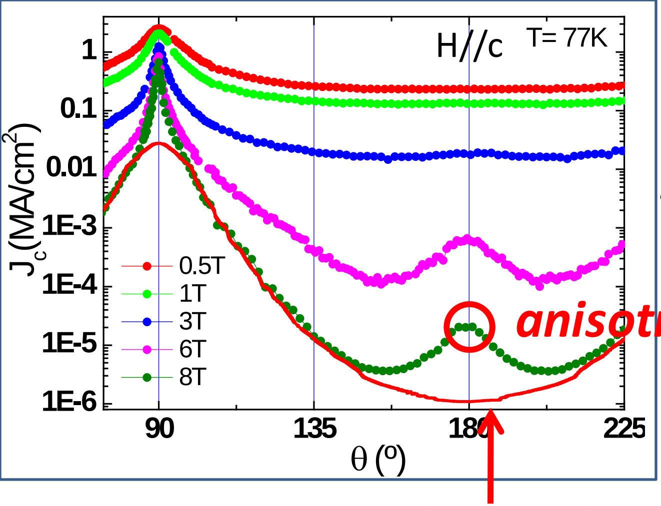
Isotropic and strong defects

The role of interfaces in nanocomposites are the key issue

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

Pinning strength diagrams

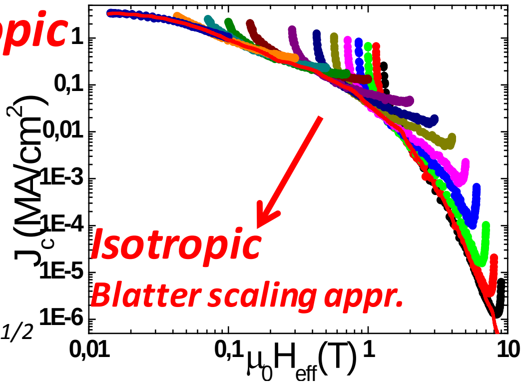
… from $J_c(H,T,\theta)$ we separate the different components



anisotropic

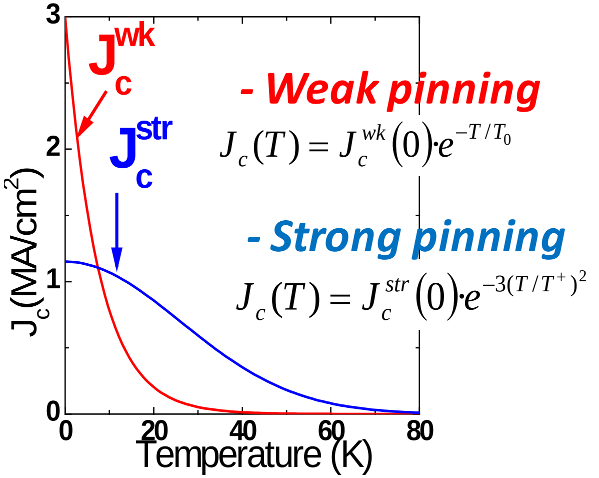
isotropic

$H_{eff}=H(\cos^2\theta+\gamma_{eff}^{-2}\sin^2\theta)^{1/2}$



Isotropic

Blatter scaling appr.

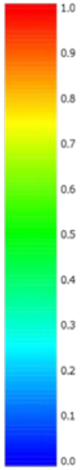


- Weak pinning

$$J_c(T)=J_c^{wk}(0)\cdot e^{-T/T_0}$$

- Strong pinning

$$J_c(T)=J_c^{str}(0)\cdot e^{-3(T/T^+)^2}$$

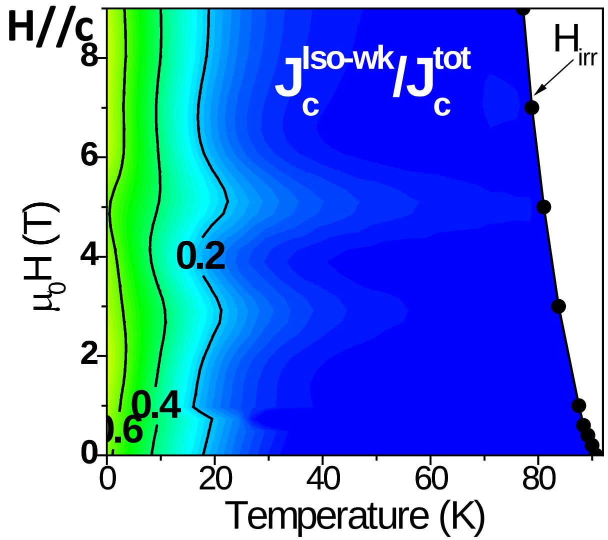


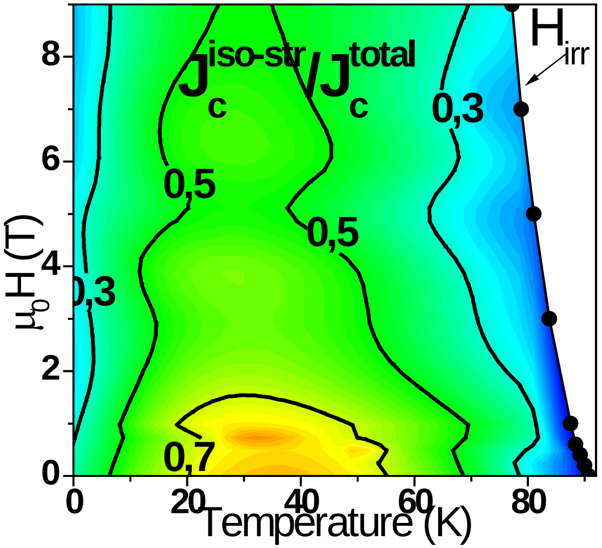
Isotropic-weak contr.

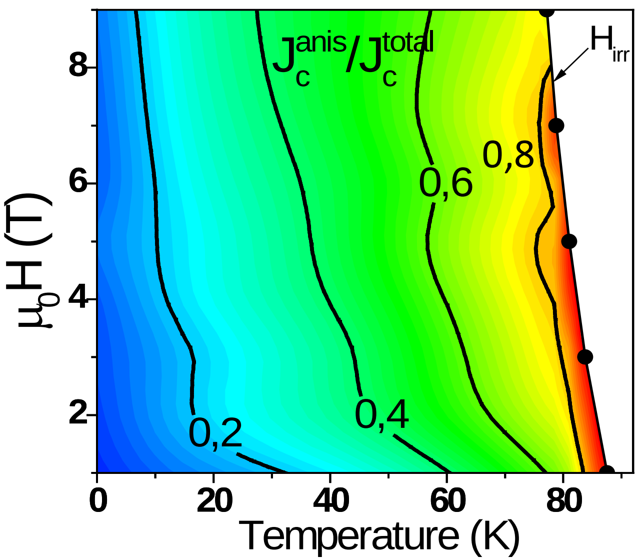
Isotropic-strong contr.

Anisotropic-strong contr.

H//c







275 nm YBCO-TFA films

*T.Puig et al., SUST **21,** 034008 (2008); J. Plain et al, PRB 65, 104526 (2002); J.Gutierrez et al., Appl. Phys. Lett. 90 (2007)*

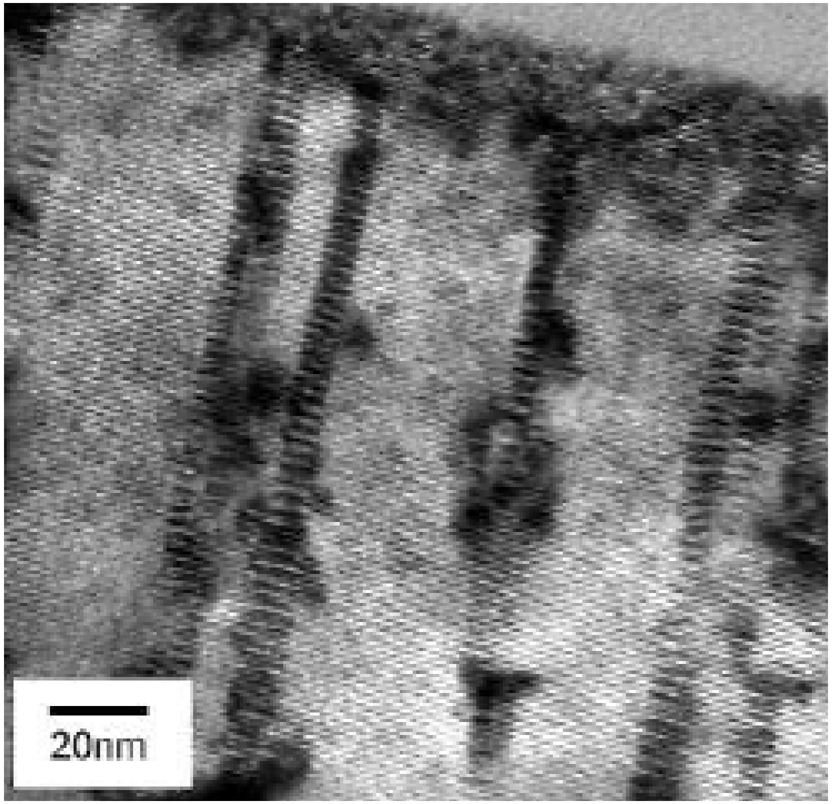
PLD YBCO nanocomposites

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

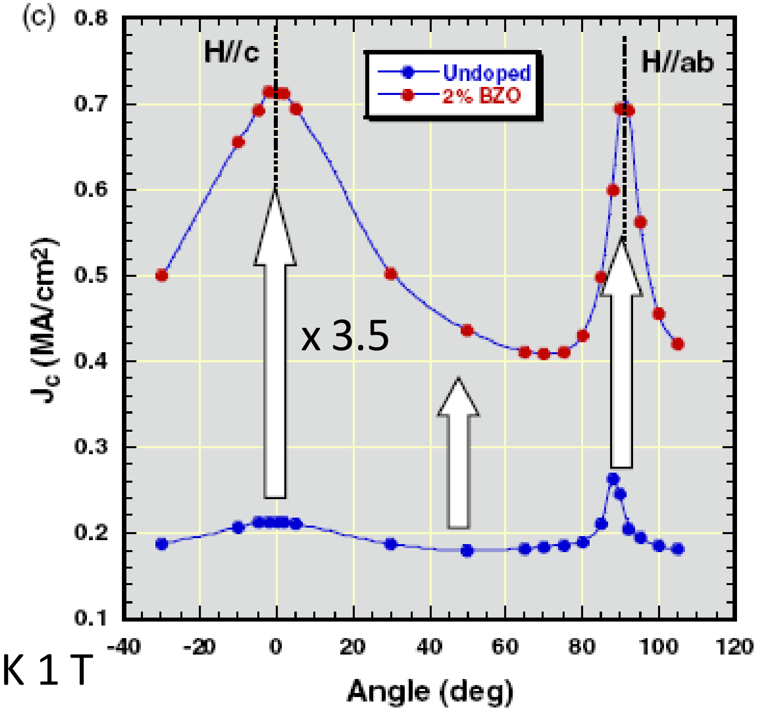
$YBa_2Cu_3O_{7-x}$ – $BaZrO_3$ nanocomposite by PLD/MOCVD (in-situ growth)

Epitaxial YBCO-BZO interfaces

Self-organized $BaZrO_3$ nanorods



J. McManus-Driscoll, Nat. Mat. 3, 439(2004)



77 K 1 T

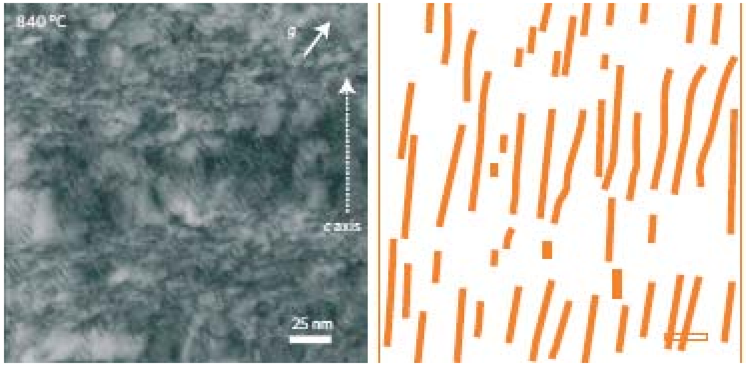
Anisotropic increase of performances

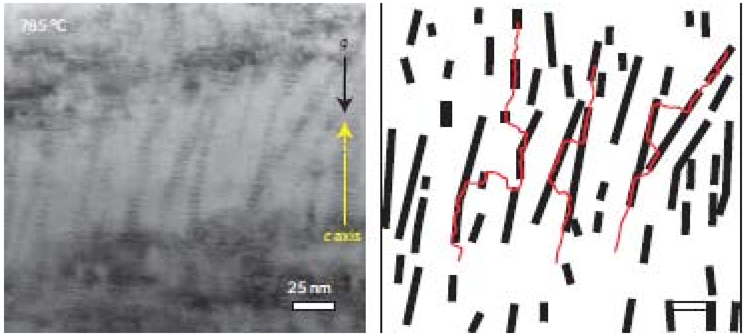
Y. Yamada, APL 87(2005) *B. Maiorov, Nat Mat 8 (2009)*

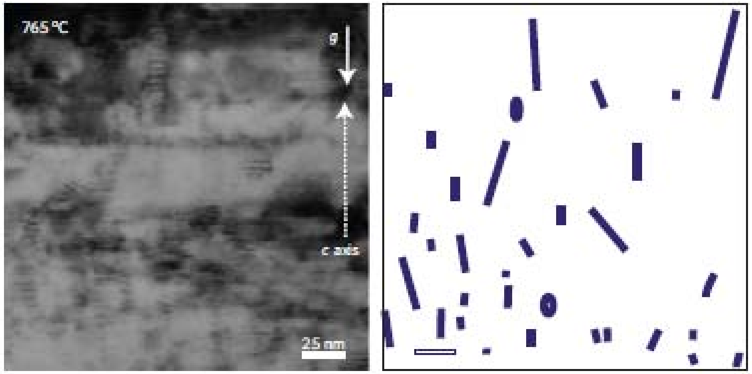
S. Kang, Science 311 (2006)

Tuning self assembling in films grown by PLD

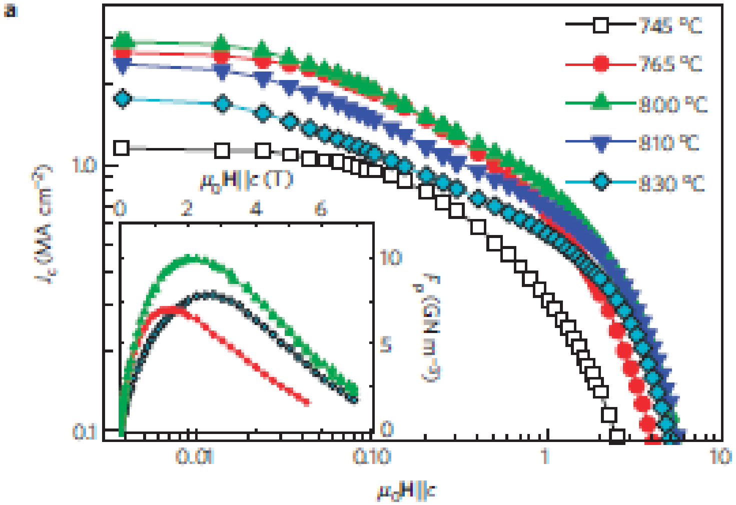
Tuning the temperature and growth rate during PLD deposition of BZO doped YBCO → nanoparticles or self-assembled columnar defects





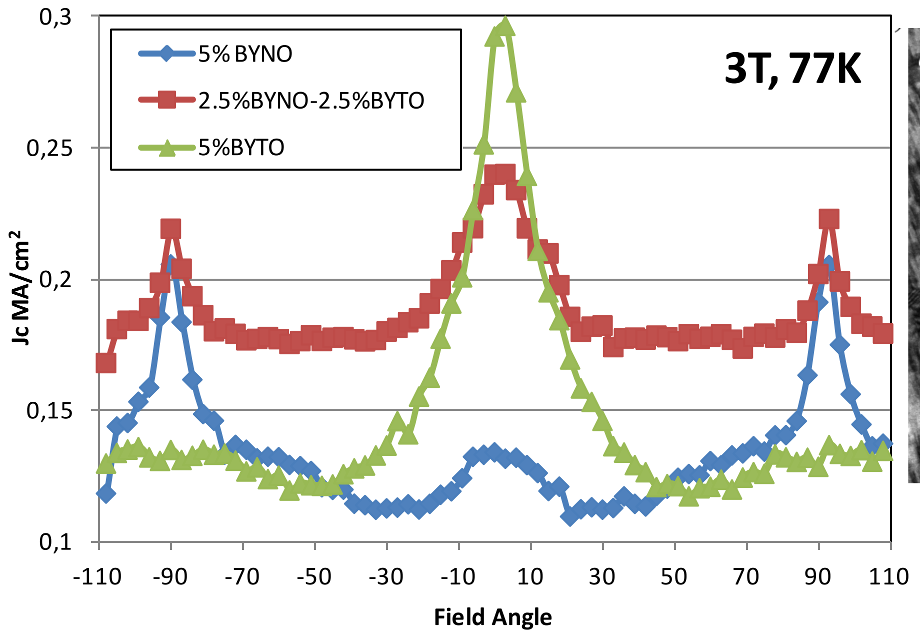


Synergetic combination of different types of defect to optimize pinning landscape

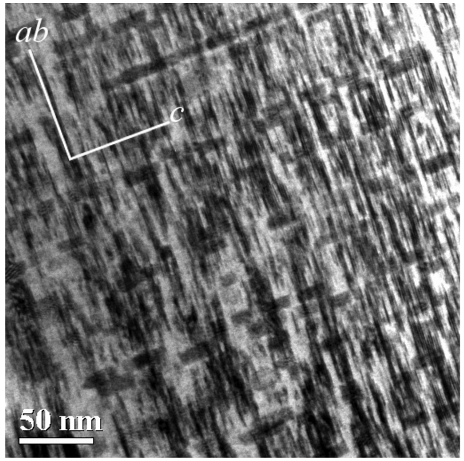


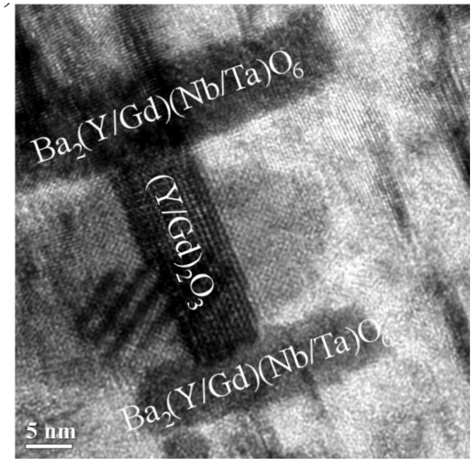
Maiorov et al. Nature Mat. 8(2009)

PLD: YBCO co-doping with Nb and Ta

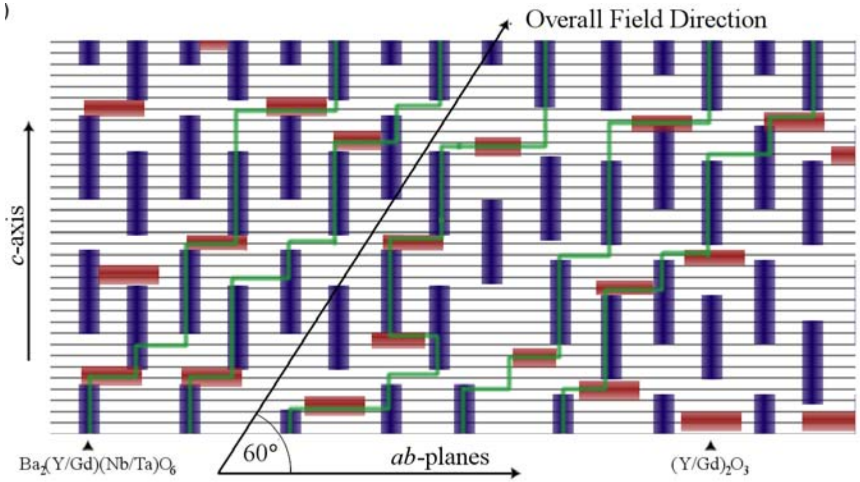


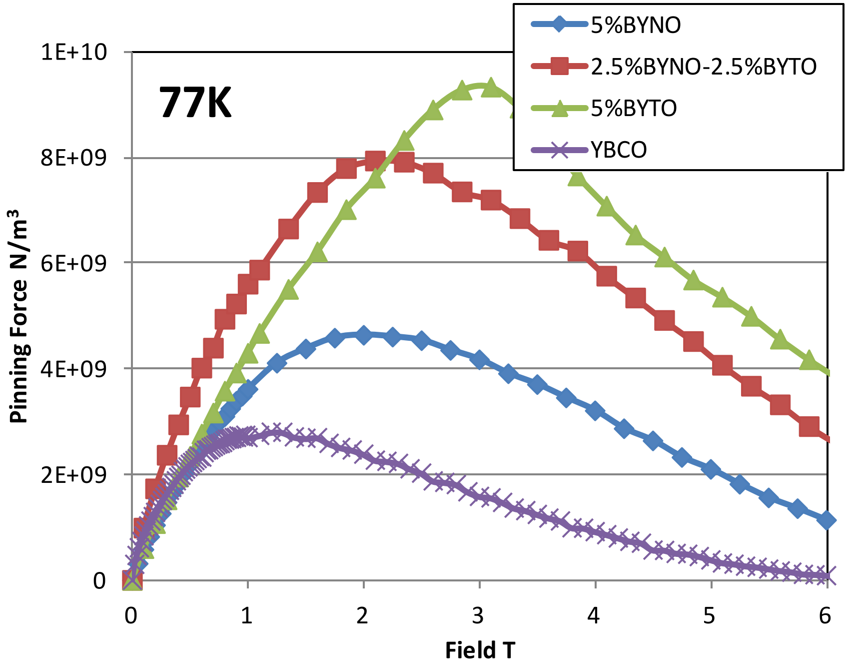
Nanorods / nanoplatelets





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

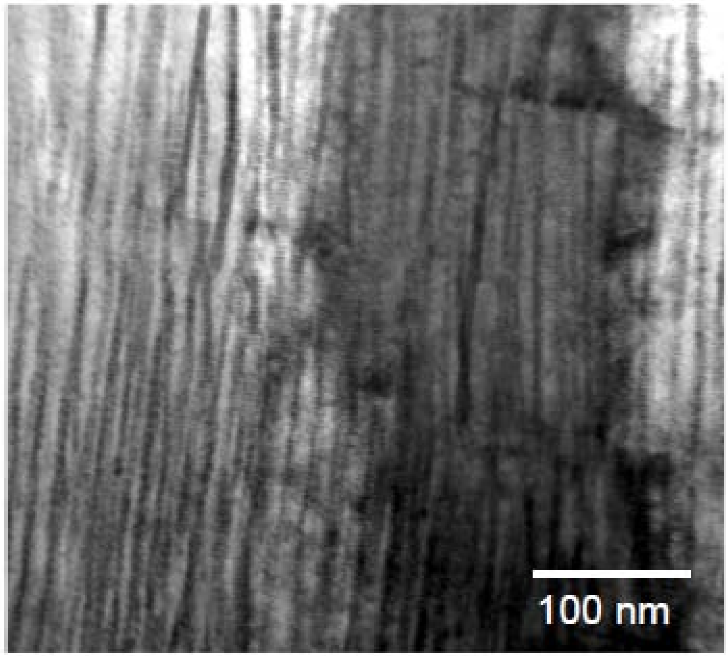




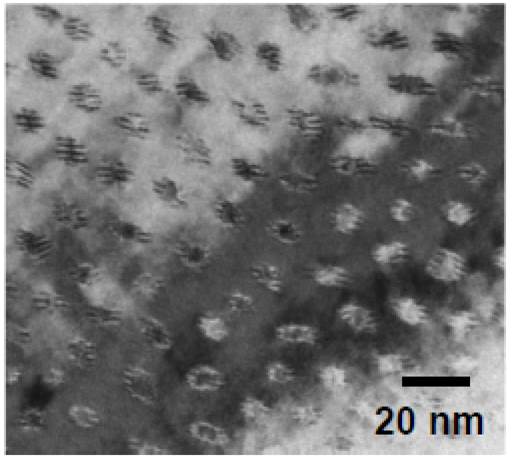
M.Bianchetti, G.Ercolano, A.Kursumovic , J.L. Macmanus-Driscoll (unpublished)

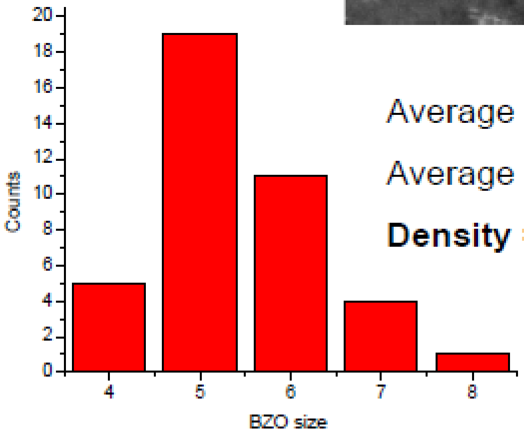
B. Maiorov, Nat Mat 8 (2009)

Very high density of columnar defects in 15%-25%ZrO_2-added YBCO



Very few interruptions to BZO growth along the c-axis





Average BZO size 5.5 nm

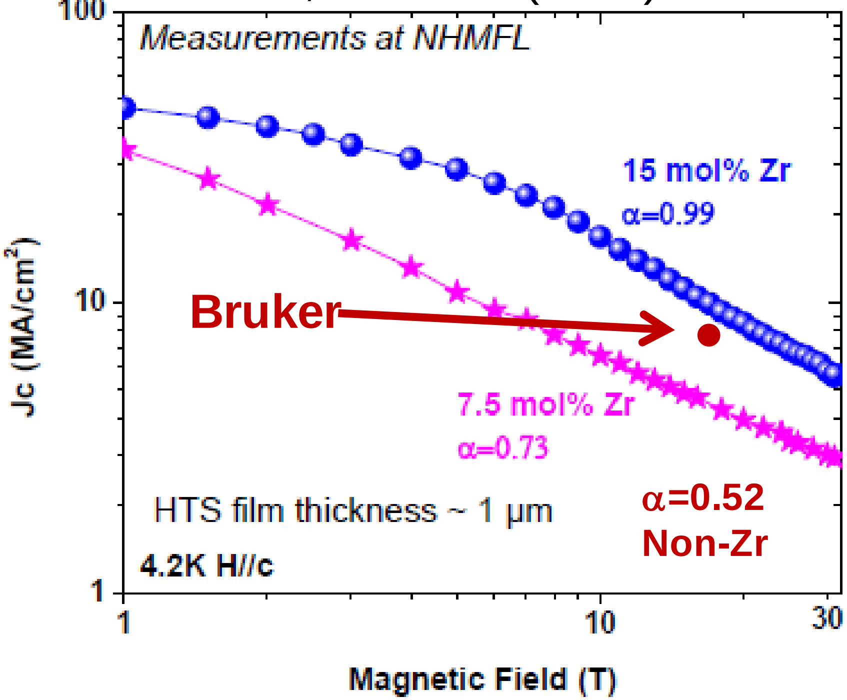
Average spacing ~ 12 nm

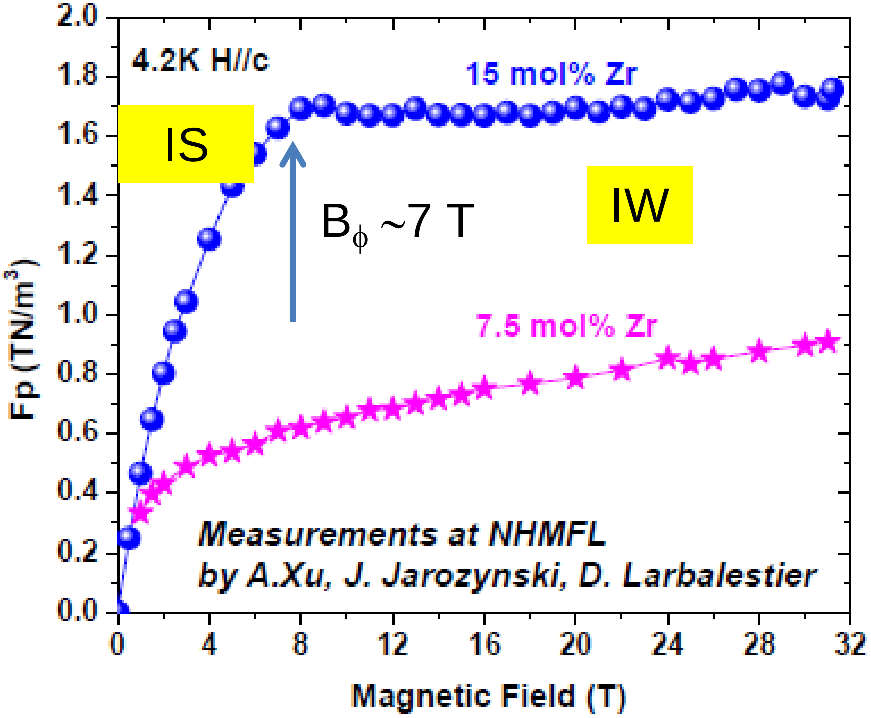
Density = 6.9×10^{11} cm^{-2}!

Modified processing: no texture degradation and T_c remains constant

Far superior pinning in 15%Zr tape at 4.2K compared to the best 7.5%Zr tape to date

A. Xu et al, APL Mat (2014)



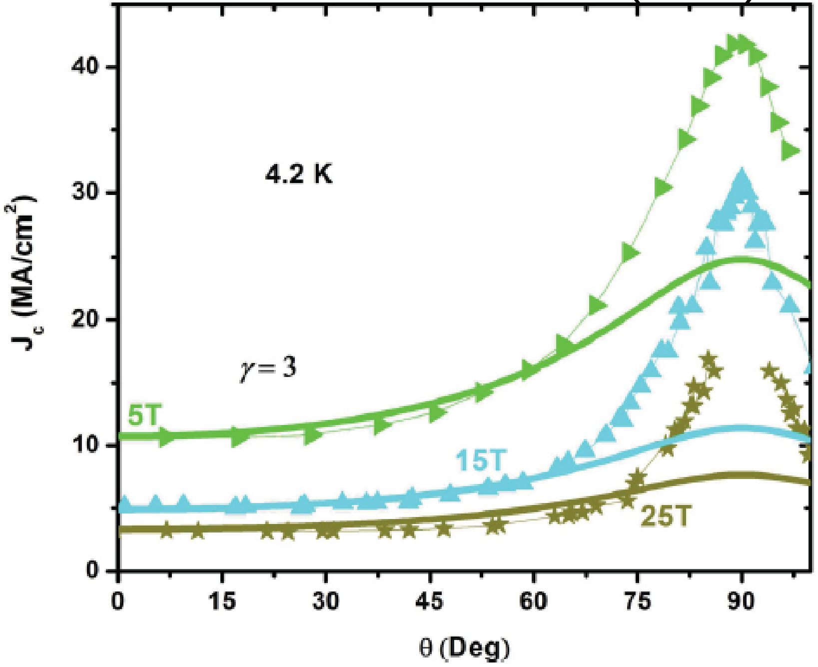


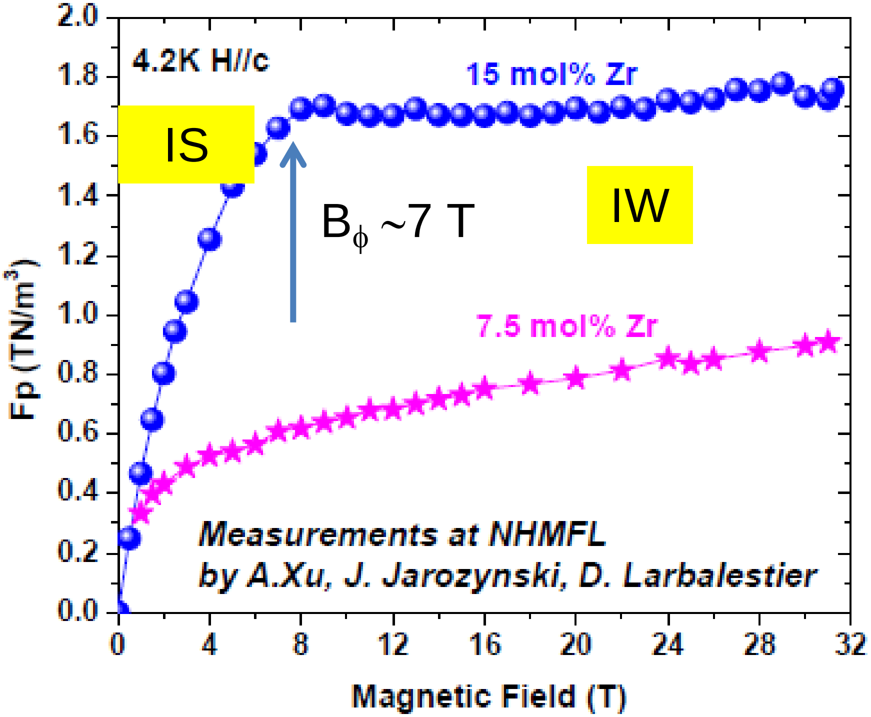
- *2.5X higher Jc in 15%Zr at 4.2 K, 10 T and 2.1X higher Jc in 15%Zr at 4.2 K, 20T*
- *The max pinning force increases from 0.9 TN/m³ in 7.5%Zr to 1.7 TN/m³ in 15%Zr*
- *Pinning force in 15%Zr nearly constant 1.7TN/m³ from 8 to 31 T*
- *α = 0.99 indicate huge weak pinning in 15%Zr at 4 K (in addition to pinning by nanocolumns)*

Very likely at 4.2 K: Isotropic/strong B<7 T and Isotropic weak B>7 T

Far superior pinning in 15%Zr tape at 4.2K compared to the best 7.5%Zr tape to date

A. Xu et al, PRB86, 115416 (2012)





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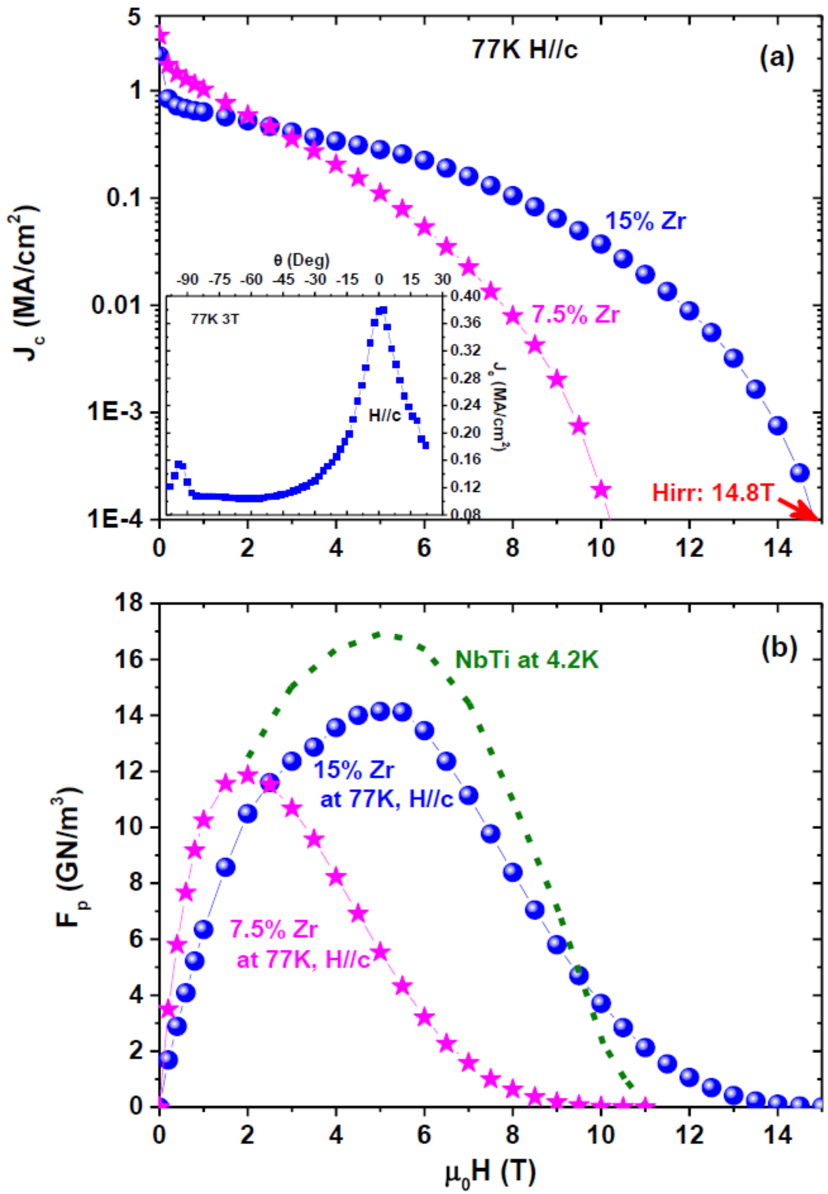


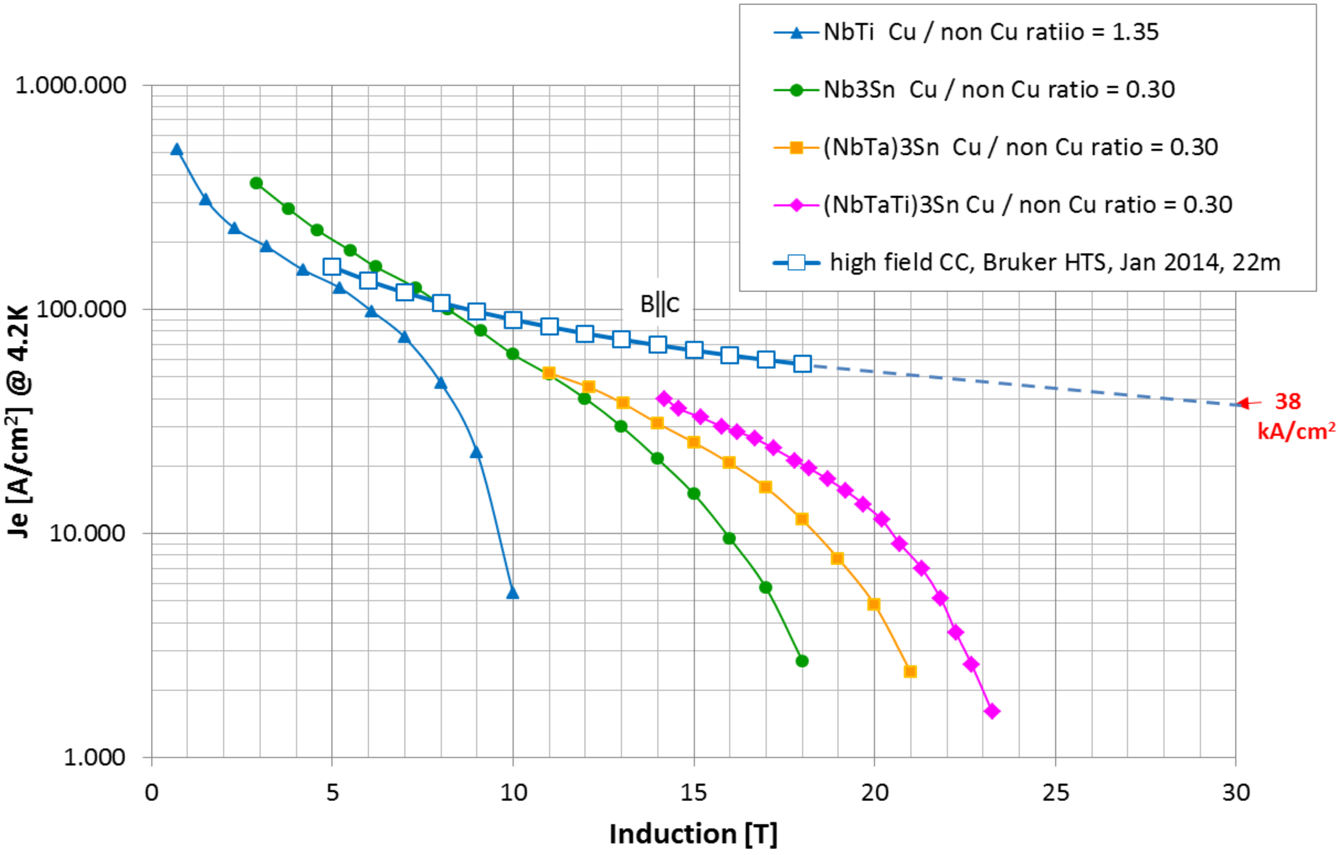
- Performances at 77 K are also strongly improved

- Highest IL reported so far. Reaching the predicted limit considering thermodynamic fluctuations

- Anisotropic strong pinning by columnar defects is the dominant term

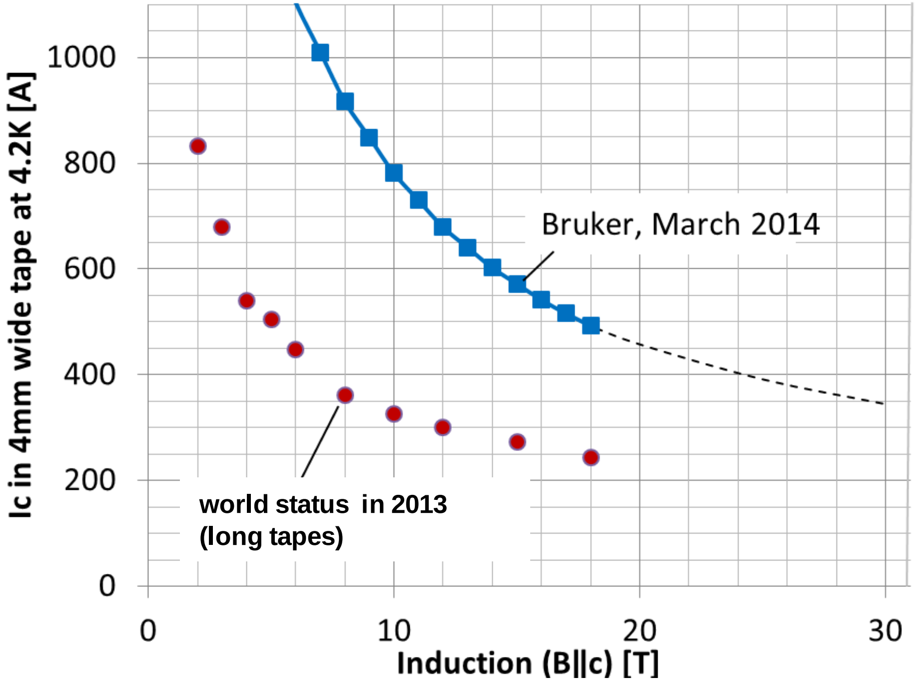
A. Xu et al, APL Mat (2014)

ReBCO self-doped tapes in high fields



- in magnetic field B||c 18T: I_c=495A at 4.2K
- measured in short piece of recently PLD2-fabricated 22m long, 4mm wide HTS tape

ReBCO self-doped tapes in high fields



Tape lengths:
up to 200 m

I_c homogeneity: 2-5 %

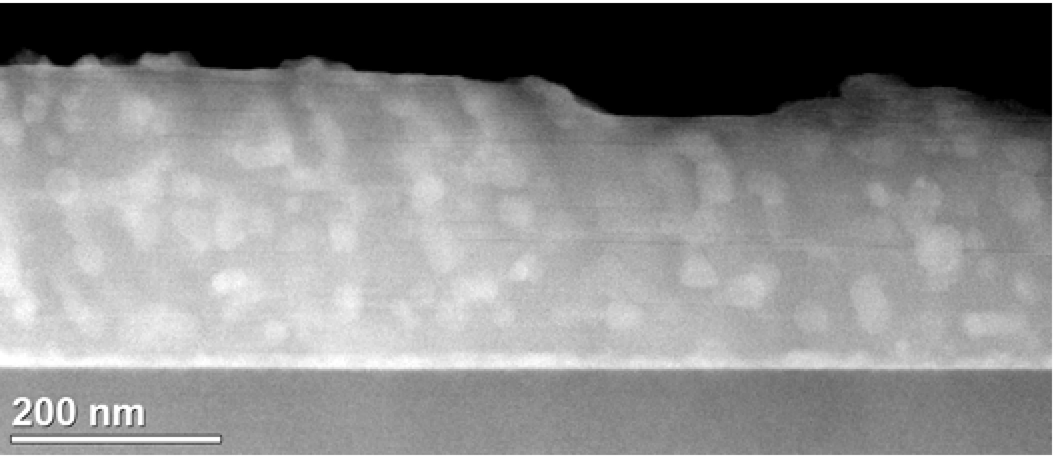
I_c at 77K, SF:
250-550 A/cm-width

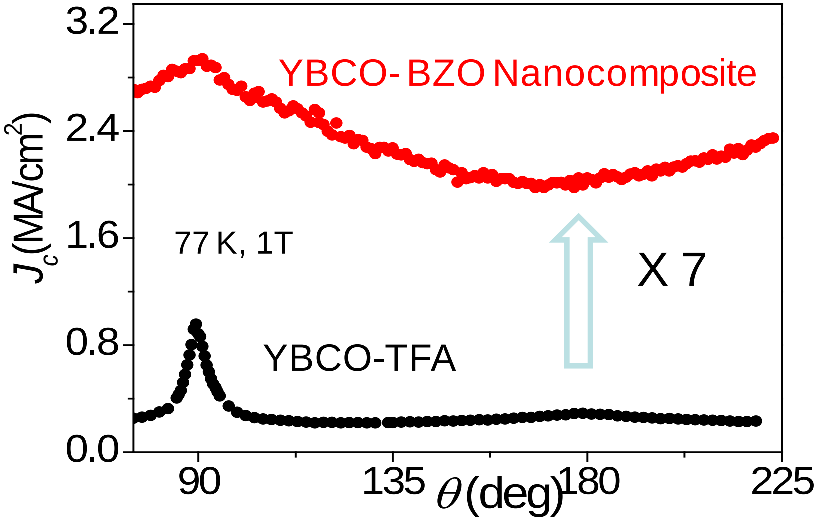
I_c at 4.2K, 18T, B||c:
up to 1230 A/cm-width

- **in magnetic field B||c 18T: I_c=495 A at 4.2 K**
- **measured in short piece of recently PLD2-fabricated 22m long, 4mm wide HTS tape**

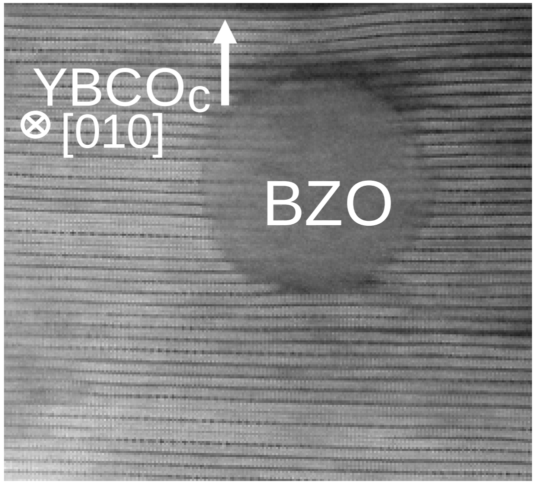
Solution derived- YBCO nanocomposites

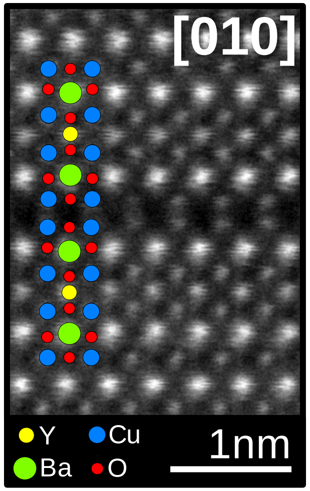
Addition of metal-organic salts in the TFA precursor solution : Spontaneous nanoparticle segregation within $YBa_2Cu_3O_7$ matrix : $BaZrO_3$, Ba_2YTaO_6, $BaCeO_3$, Y_2O_3

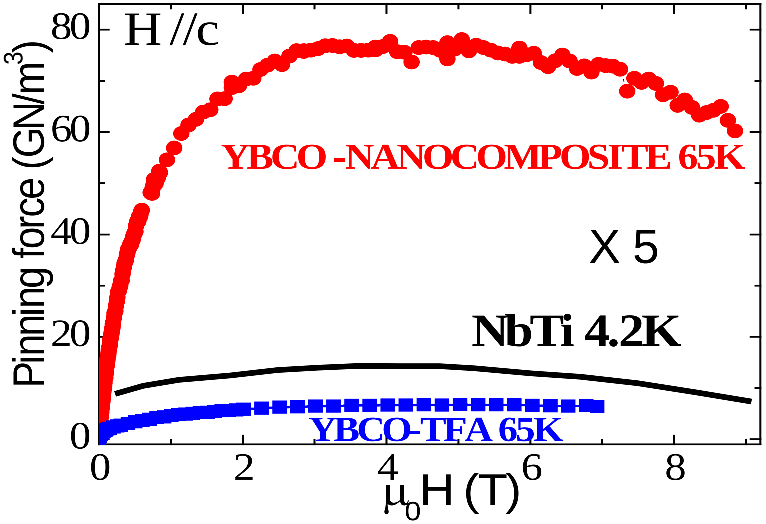




Incoherent YBCO-BZO interfaces give rise to high density of Y248 intergrowths





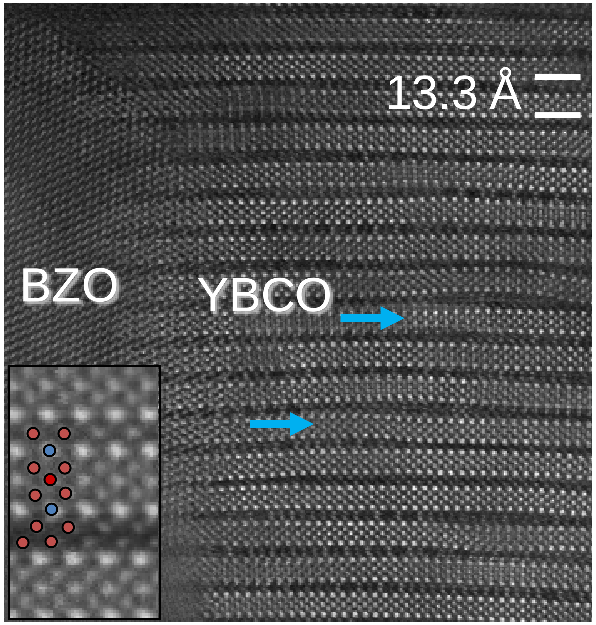


The highest isotropic performance ever found in any superconducting material

A. Llordés, et al. Nat. Mater , 11, 329 (2012)
J. Gutierrez et al, Nat. Mater. 6, 367 (2007)

New vortex pinning mechanims in CSD YBCO nanocomp.

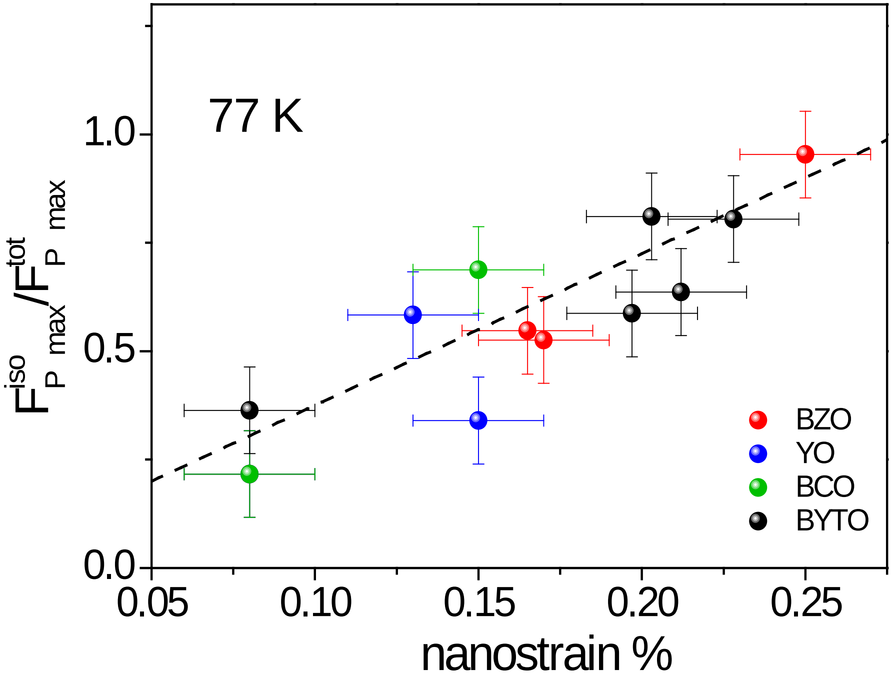
Addition of metal-organic salts for TFA nanocomposites with Y_2O_3, $BaZrO_3$, Ba_2YTaO_6, $BaCeO_3$ nanoparticles

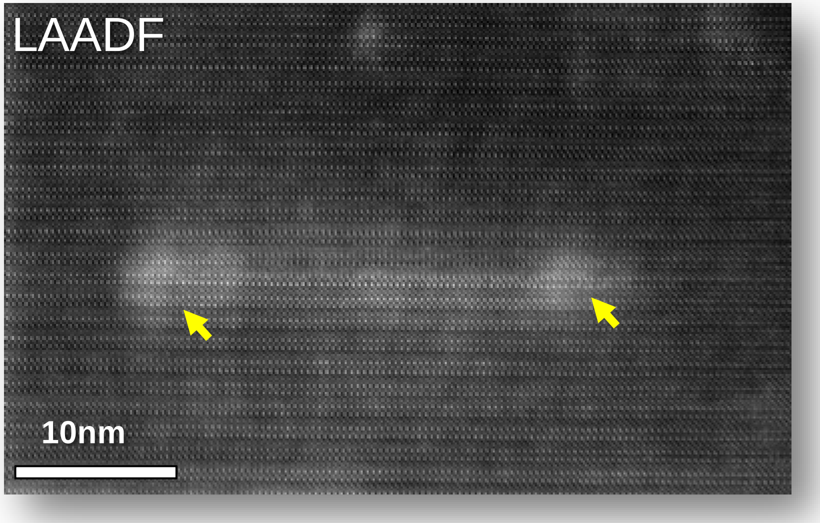


- *Local lattice strains generated by CuO intergrowth*
- *XRD: nanostrain determination*

Nanostrain is the key issue for the performances achieved

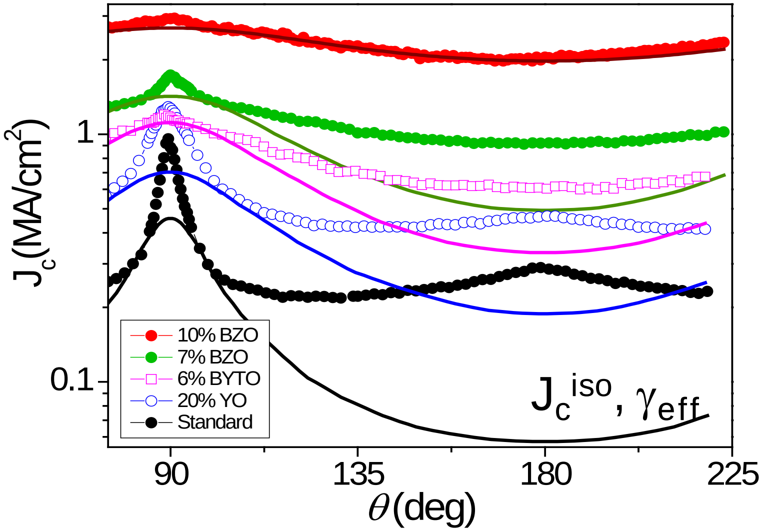
A. Llordés, et al. Nat. Mater , 11, 329 (2012)
J. Gutierrez et al, Nat. Mater. 6, 367 (2007)
M. Coll et al., SUST 26, 015001 (2013)

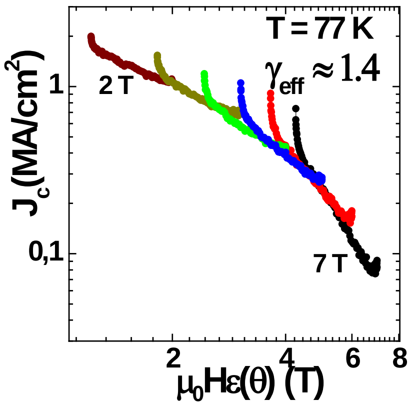


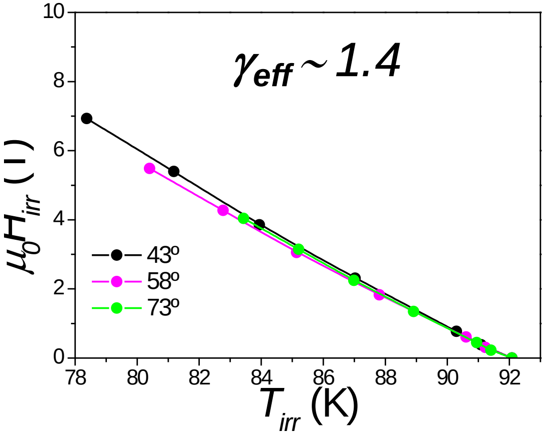


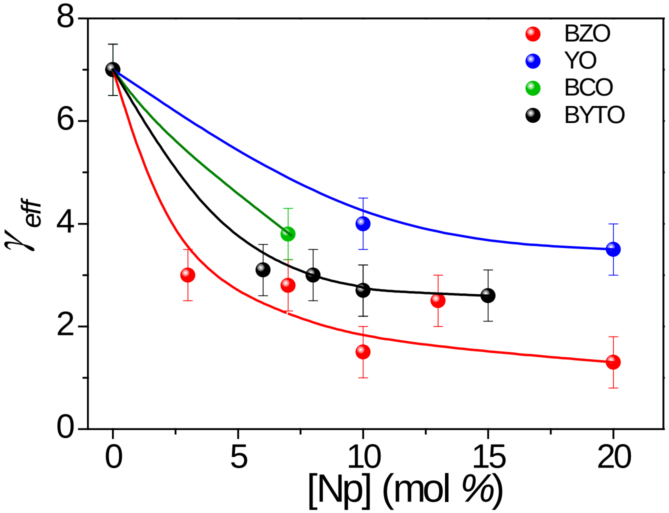
Effective pinning anisotropy

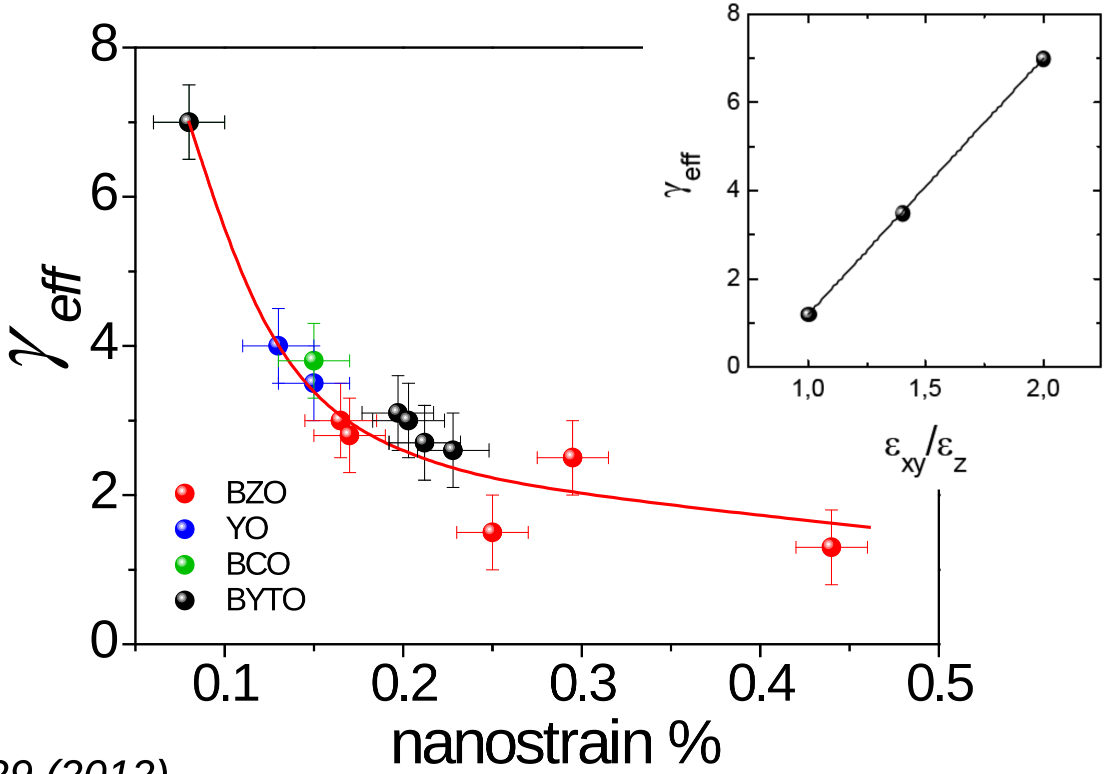
Blatter appr. from IL(θ) down to $J_c(\theta)$ $\mathbf{H_{eff}}=H(\cos^2\theta+\gamma_{eff}^{-2}\sin^2\theta)^{1/2}$









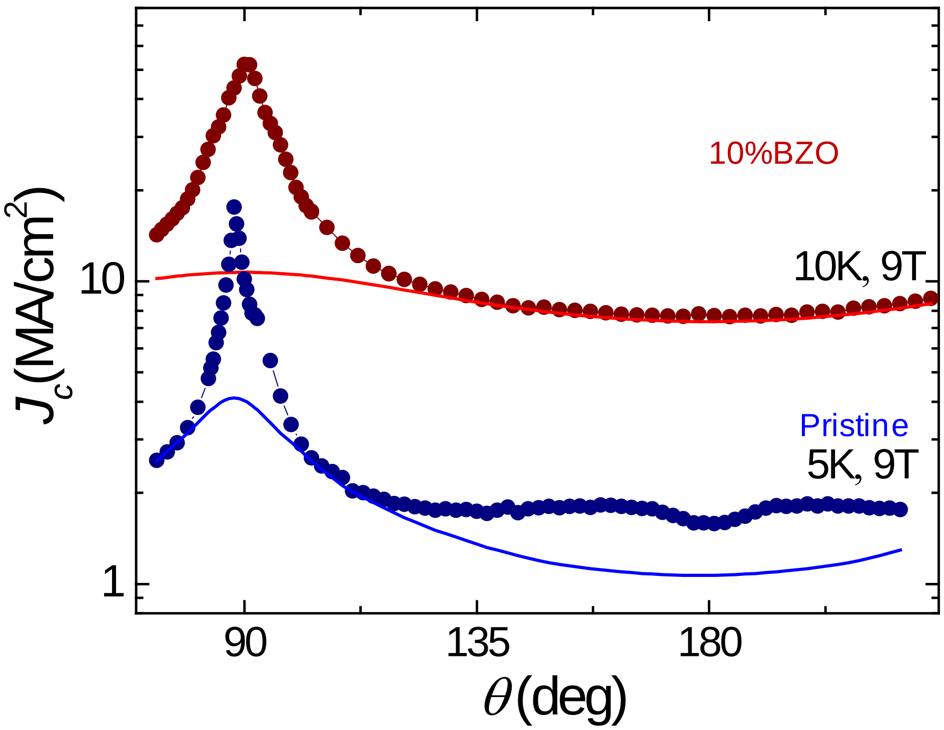


Nanostrain and nanostrain-anisotropy correlate with γ_{eff}

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

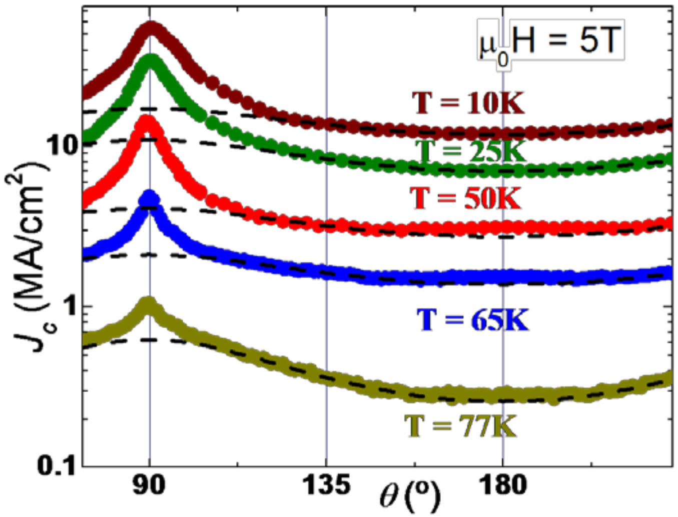
YBCO CSD nanocomposites
isotropic pinning landscape and in-plane pinning

Strong pinning contribution at H//ab: intrinsic pinning and planar defects



CSD - YBCO

YBCO – BZO nanocomposite



MOCVD - YBCO

Ex – situ and in-situ grown films seem to have similar pinning landscapes at low temperatures

YBCO CSD nanocomposites
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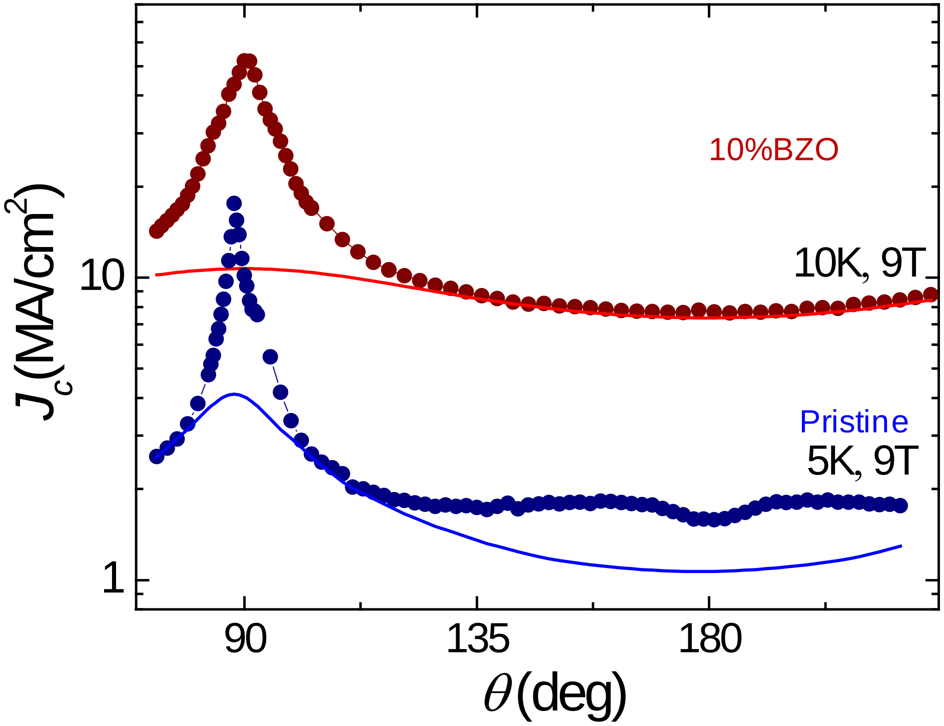
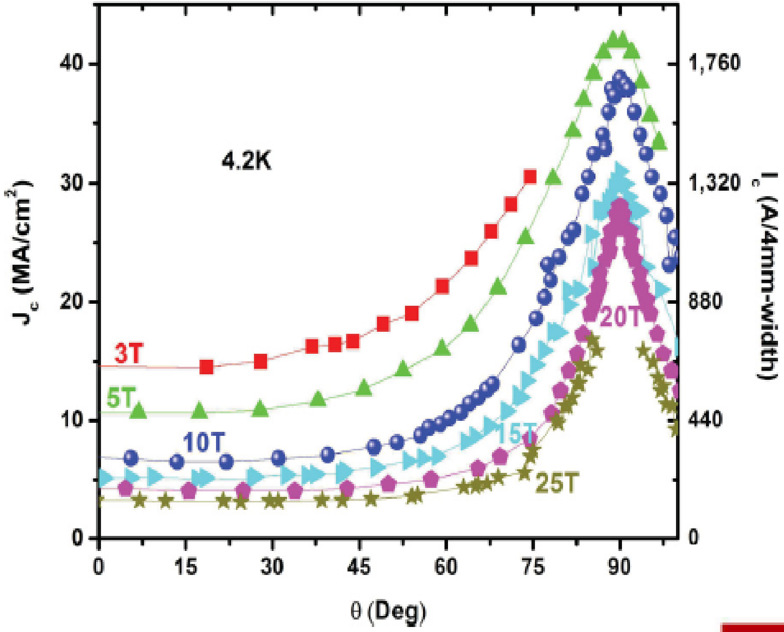


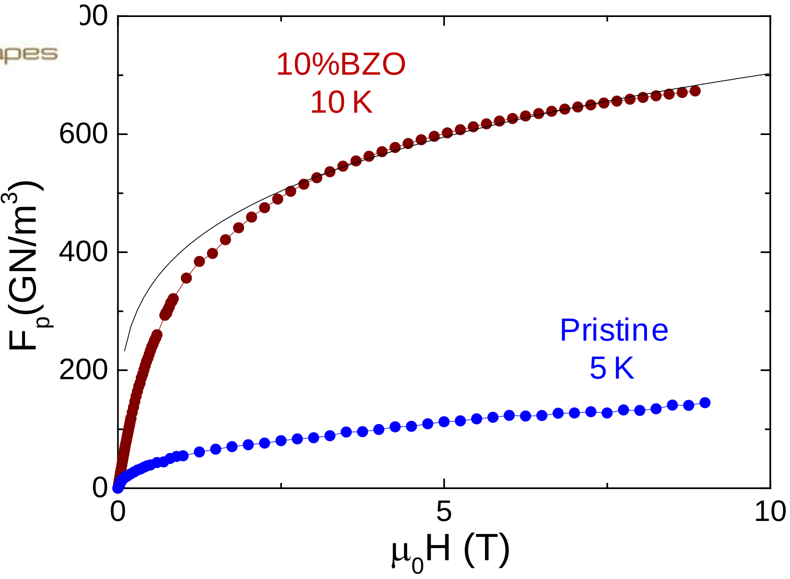
CSD - YBCO

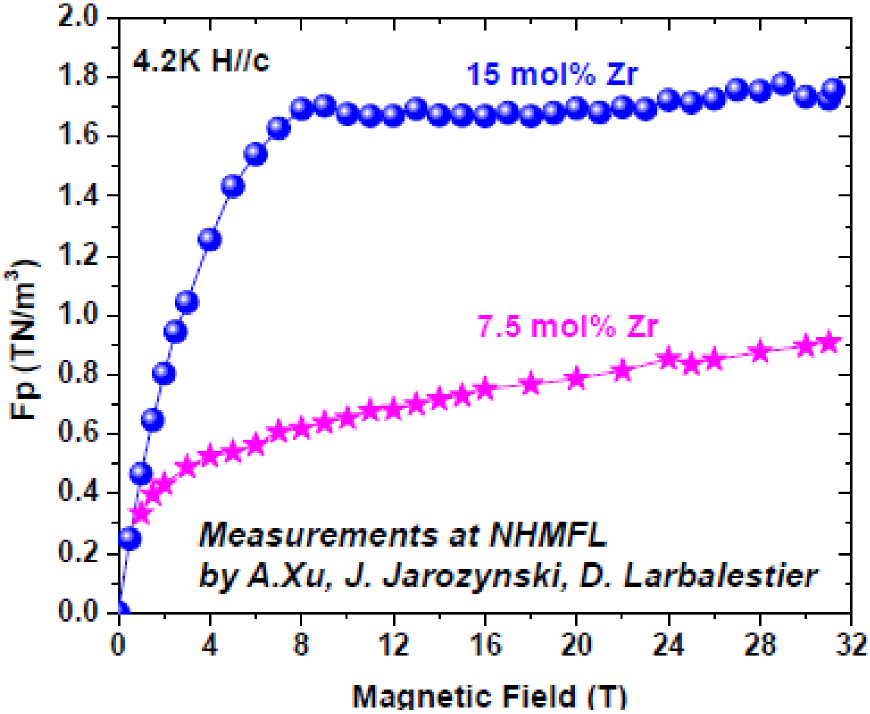


MOCVD - YBCO

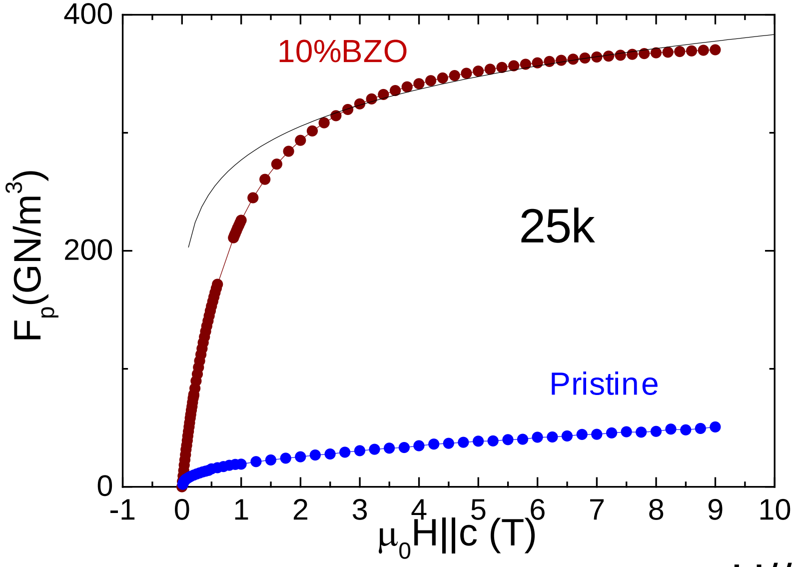
Ex – situ and in-situ grown films seem to have similar pinning landscapes at low temperatures

Pinning properties of the CSD-YBCO nanocomposites (H//c)





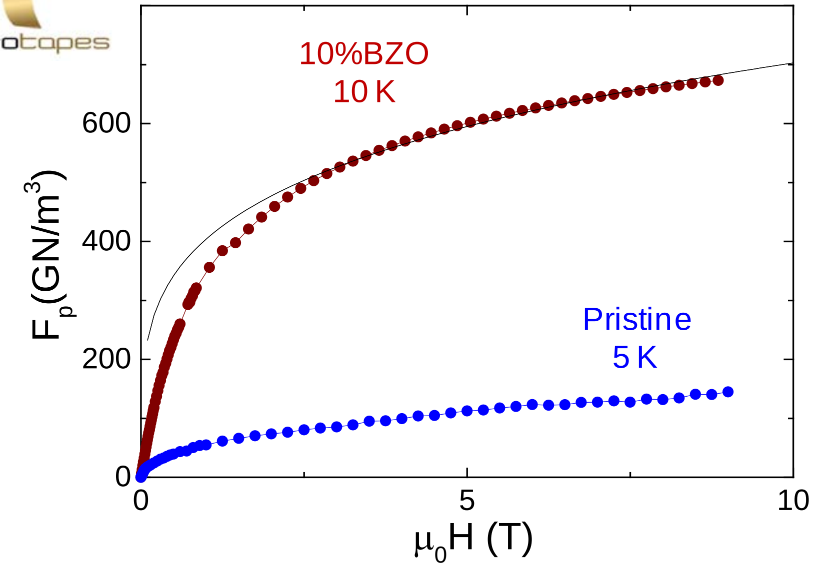
MOCVD CCs from Superpower
APL Materials (2014)

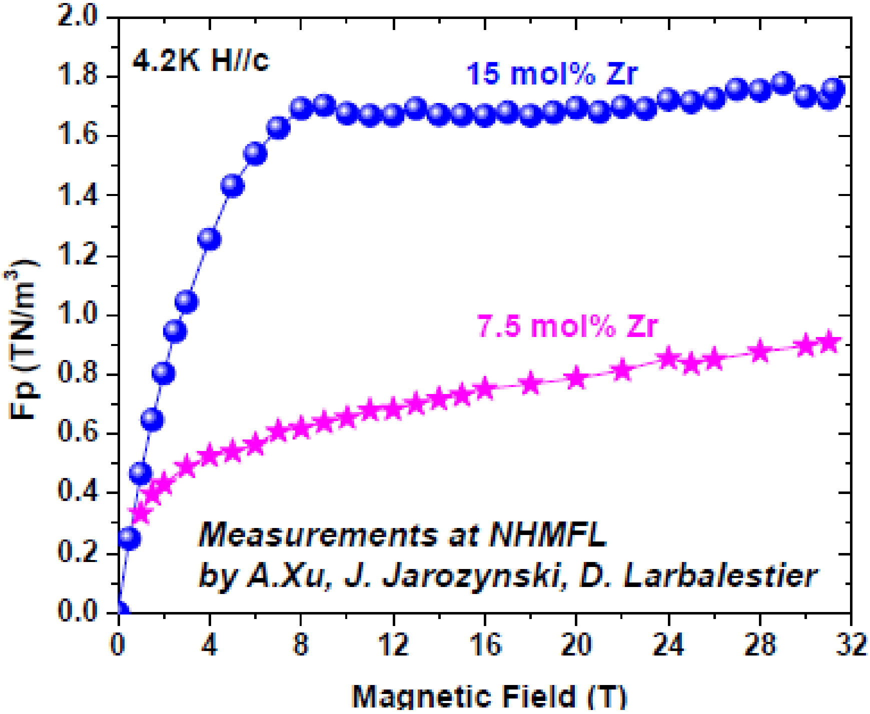


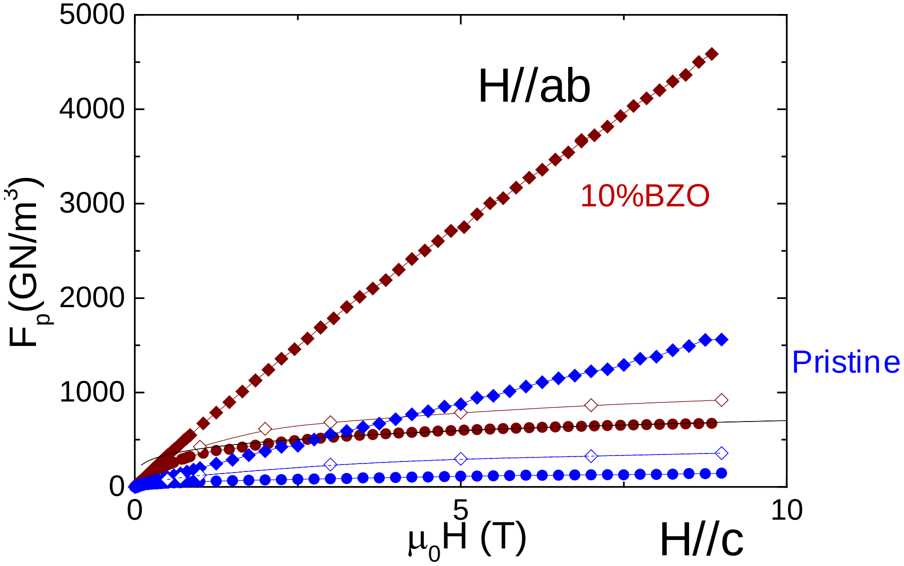
H//c

- **Very high pinning forces can be achieved in both cases with different pinning landscapes**
- **The 5K -20 K temperature range appears very attractive to use CCs for HFM**
- **Huge pinning forces for H//ab**

Pinning properties of the CSD-YBCO nanocomposites (H//c)







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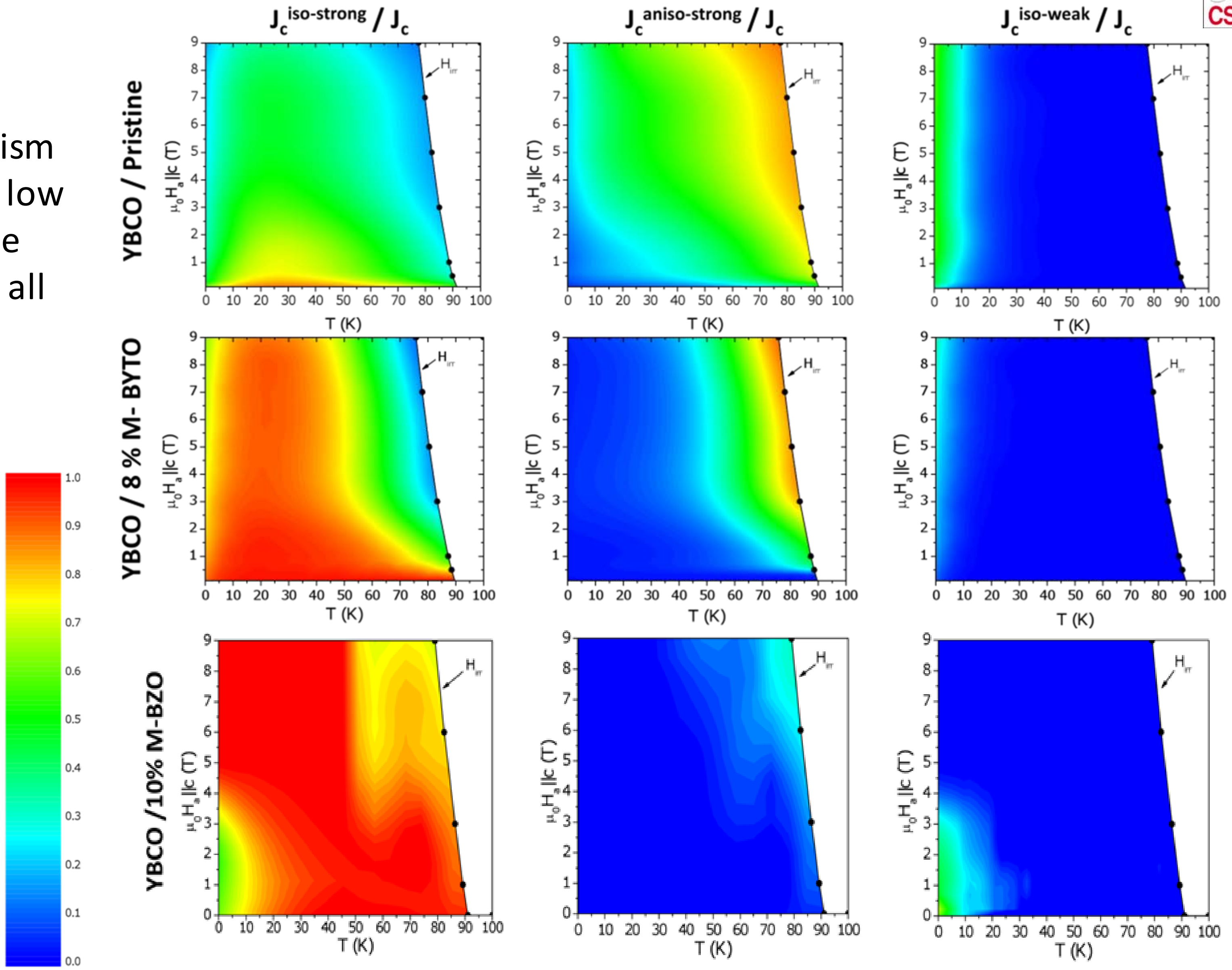
- **The 5K -20 K temperature range appears very attractive to use CCs for HFM**
- **Huge pinning forces for H//ab**

Pinning properties of the CSD-YBCO nanocomposites: H,T pinning strength diagrams (H//c)

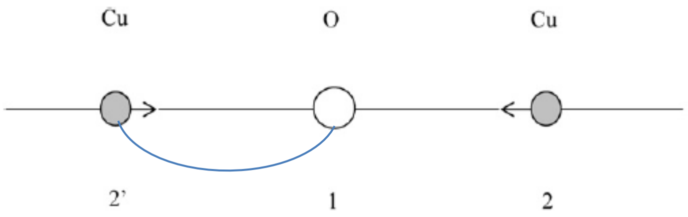
Isotropic strong pinning mechanism is dominating at low and intermediate temperatures at all magnetic fields



New vortex pinning proposal: Bond contraction pairing model

Coupling lattice strains with Cooper pair supression

BCP :

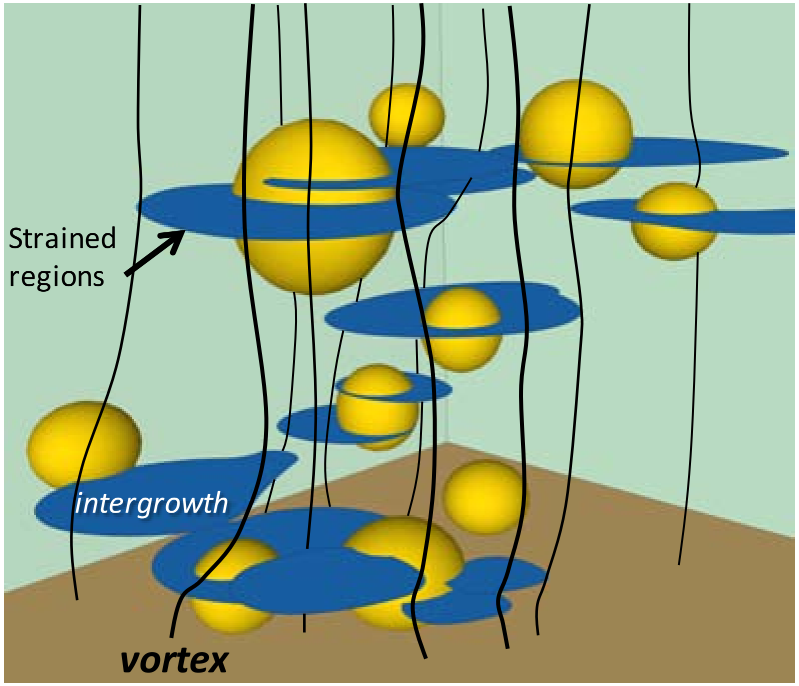


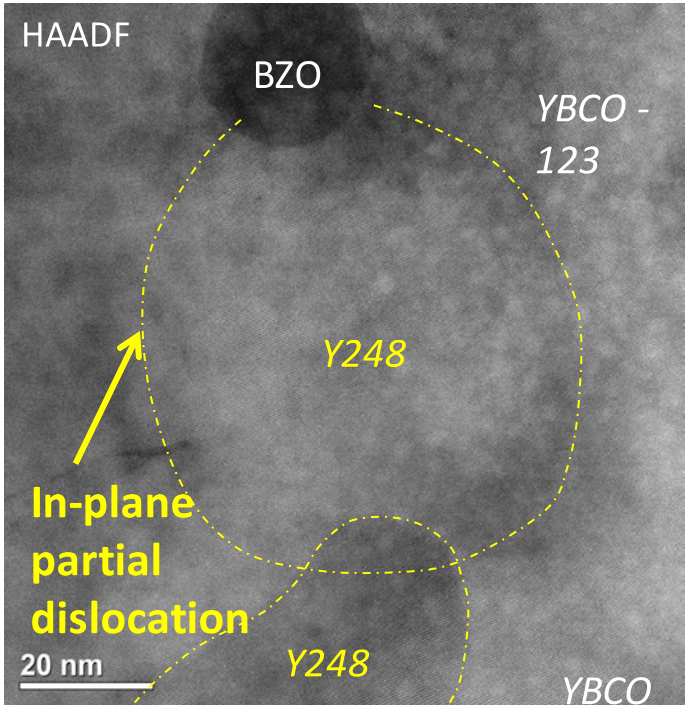
Pair breaking energy:

$$2\Delta = 4\frac{(t_{CuO})^2}{U} - 8t_0$$

t_{CuO} ($\propto 1/d_{CuO}^5$)

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





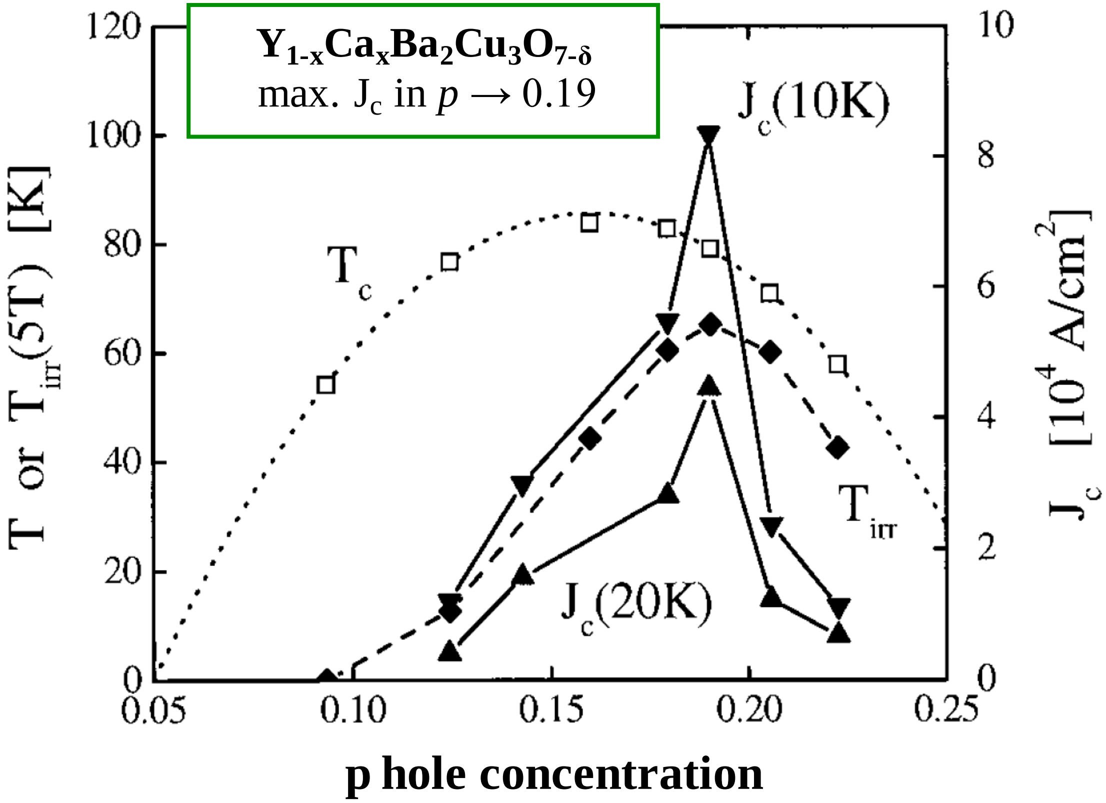
See G. Deutscher

Huge dislocation density ~1–5 x10^{12} cm^{-2}

G. Deutscher, P.G. de Gennes, CRAS (2007) / G. Deutscher, APL (2010); / A. Llordes et al., Nat. Mater (2012)

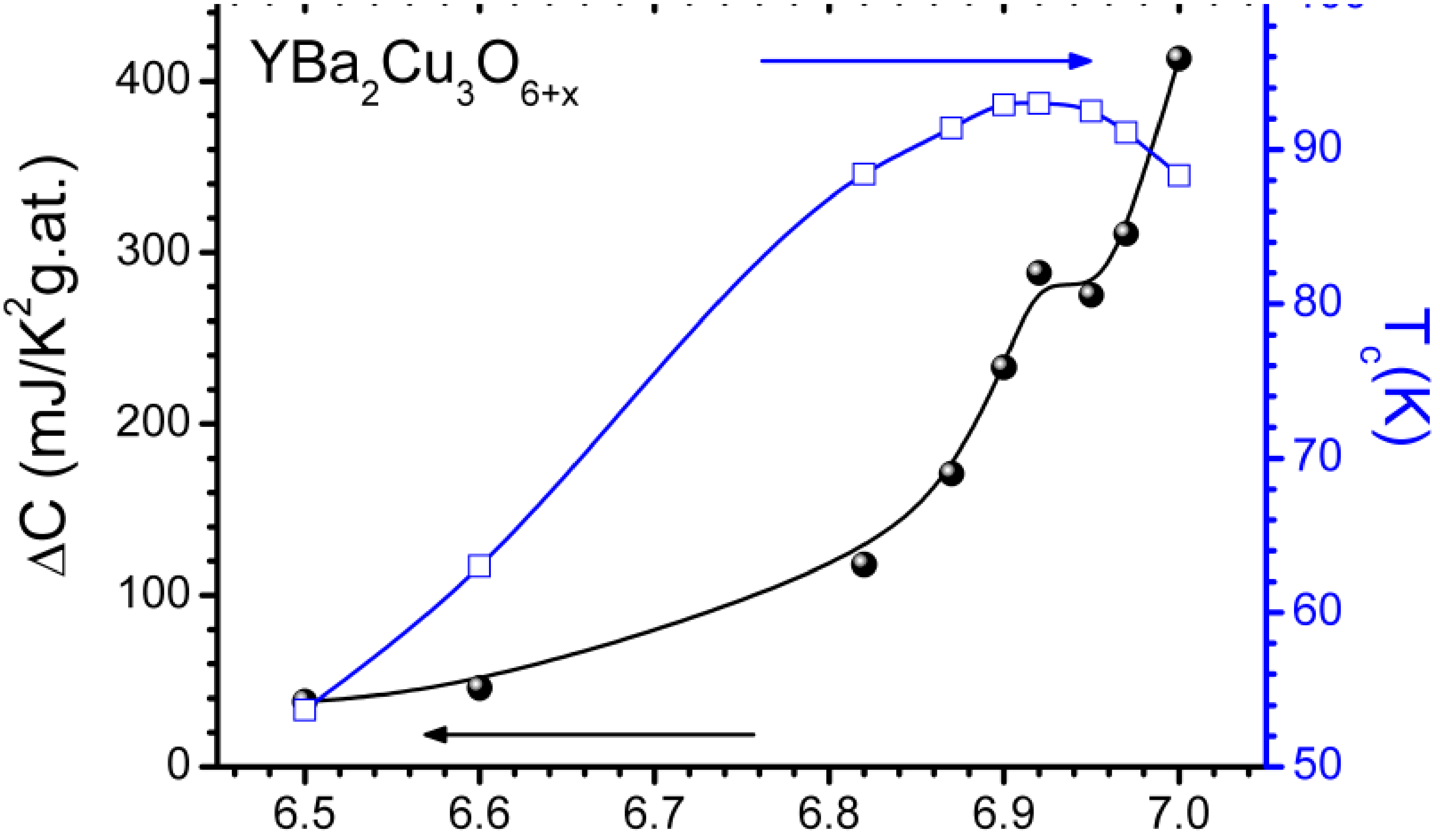
Optimal hole doping in CuO_2 planes

- Optimal doping (YBCO): max. T_c ($7-\delta = 6.95$) ~ 92.5 K.
- Universal curve Tc vs p : $T_c/T_{c,máx} = 1 - 82.6\times(p - 0.16)^2$
- Maximum in J_c is at maximum in U_{CP} $\sim(H_c^2/8\pi)(\pi\,\xi^2)$ (p ~0.19)



J.L.Tallon, Phys. Stat. Sol. (b) 215, 531 (1999).

U is strongly doping dependent



G.Deutscher, *New Superconductors: from granular to Hgh Tc, World Scientific*

There is room for improvement !

Vortex pinning issues in YBCO nanocomposites

APC nanocomposites

In-situ

- Simultaneous YBCO/NP growth (PLD, MOCVD)
- Self-asssembly Superposition anisotropic nanophases (nanorods,nanoplatelets)
- Complex combination of defects to smooth $J_c(\theta)$
- APC are the nanophases

Ex-situ

- Sequential NP/YBCO growth (CSD)
- Random nanoparticles induce isotropic nanostrain
- Natural generation of quasi - isotropic $J_c(\theta)$
- New vortex pinning mechanism: nanostrain vs Cooper pair breaking
- APC are embeded in YBCO lattice

APC characteristics in CCs

Issue Growth	Technique	Np orientation	Order of nps	REBCO matrix effects	Pinning strenght and type
In - situ	PLD, EV, MOCVD	Epitaxial	1D self-assembled nanocolumns	Local nstrain	AS IW IS
Ex - situ	CSD RCE - DR	Random + epitaxial	3D random	Long range nstrain	IS AS IW

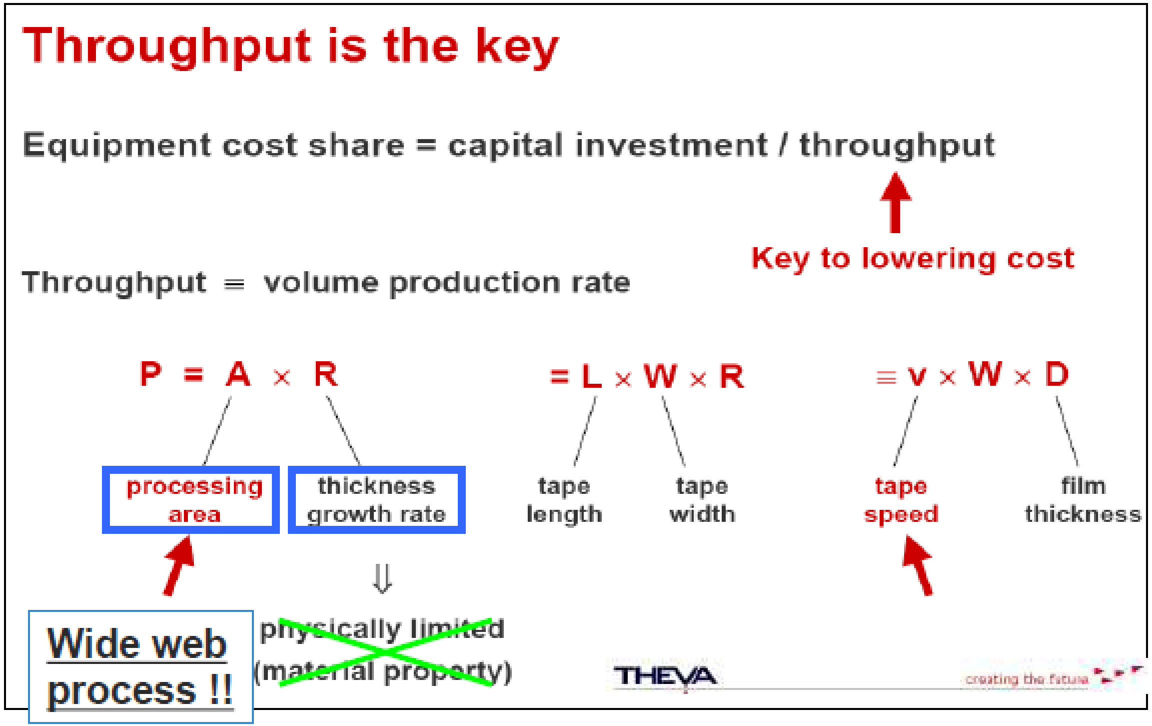
- Two very different vortex pinning landscapes appear
- Core pinning mechanism requires identification of the relevant defects and its complex interaction
- Anisotropic – strong pinning centers are usually well identified
- Isotropic strong pinning has been correlated to nanostrain in CSD, not yet in other techniques
- The real origin of isotropic weak pinning centers is unknown in all cases
- IW pinning seems to be relevant only in in-situ CCs at very high magnetic fields and low temperatures

Outline

- **HTS materials: power and magnet applications**
- **What are the novel opportunities raised by coated conductors?**
  - Physics behind the CCs
- **What are the coated conductors?**
  - Manufacturing approaches to CCs
- **Towards enhanced performances**
  - High currents
  - Vortex pinning
- **Cost and performances prospective**
- **Conclusions**

How can we realize practical HTS 2G wire? (II)

- Throughput : Important for availability & cost!!



Throughput is the key

Equipment cost share = capital investment / throughput

Key to lowering cost

Throughput ≡ volume production rate

$P = A \times R \quad = L \times W \times R \quad \equiv v \times W \times D$

Wide web process !!

RCE-DR (melt growth)

- RCE DR : ~ 100 nm/sec or faster (SuNAM)
- PLD, MOCVD ~ 10 nm/sec, MOD ~ 1 nm/sec

- **RCE-DR process : easy to scale-up to wide strip.**

Cost Analysis : what's the limiting factor?

- Assume 500 A/cm-width CC & 4 mm width equivalent wire.
- Assume throughput/single line & 100 % yield.

Through - put (m/hr)	Run time/week (hrs)	Annual Production (km)	Equipment depreciation/ yr (M$)	Labor cost (M$)	(Depreciation + labor)/length		Methods
					($/m)	($/kA-m)	
50	**60**	**150**	**1.5**	**1.5**	**20**	**100**	**PLD**
100	**100**	**500**	**2**	**2**	**8**	**40**	**MOD, MOCVD**
500	**60**	**1,500**	**2**	**2**	**2.7**	**13.3**	**MOD(100 mm)** **RCE-DR**
3,000	**100**	**15,000**	**4**	**4**	**0.53**	**2.7**	**RCE-120 mm**

- Considering yield, minimum cost increases much higher value.
- In large volume case, material cost & yield is much more important.

Direction of Technology Development in the Future

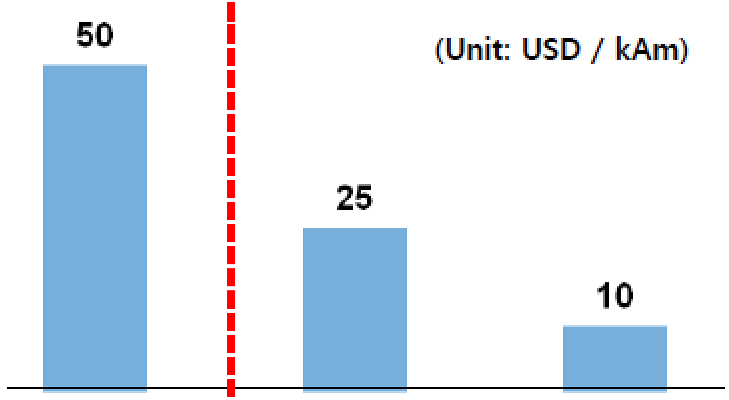
"Increasing Demand for HTS 2G wire has surpassed the supply"

"For market entrance $ 50 / kAm is the threshold "

"Price Reduction will ignite an exponential growth of demand for HTS 2G wire"

"High throughput, low material cost, High yield is 3 Critical Success Factor"

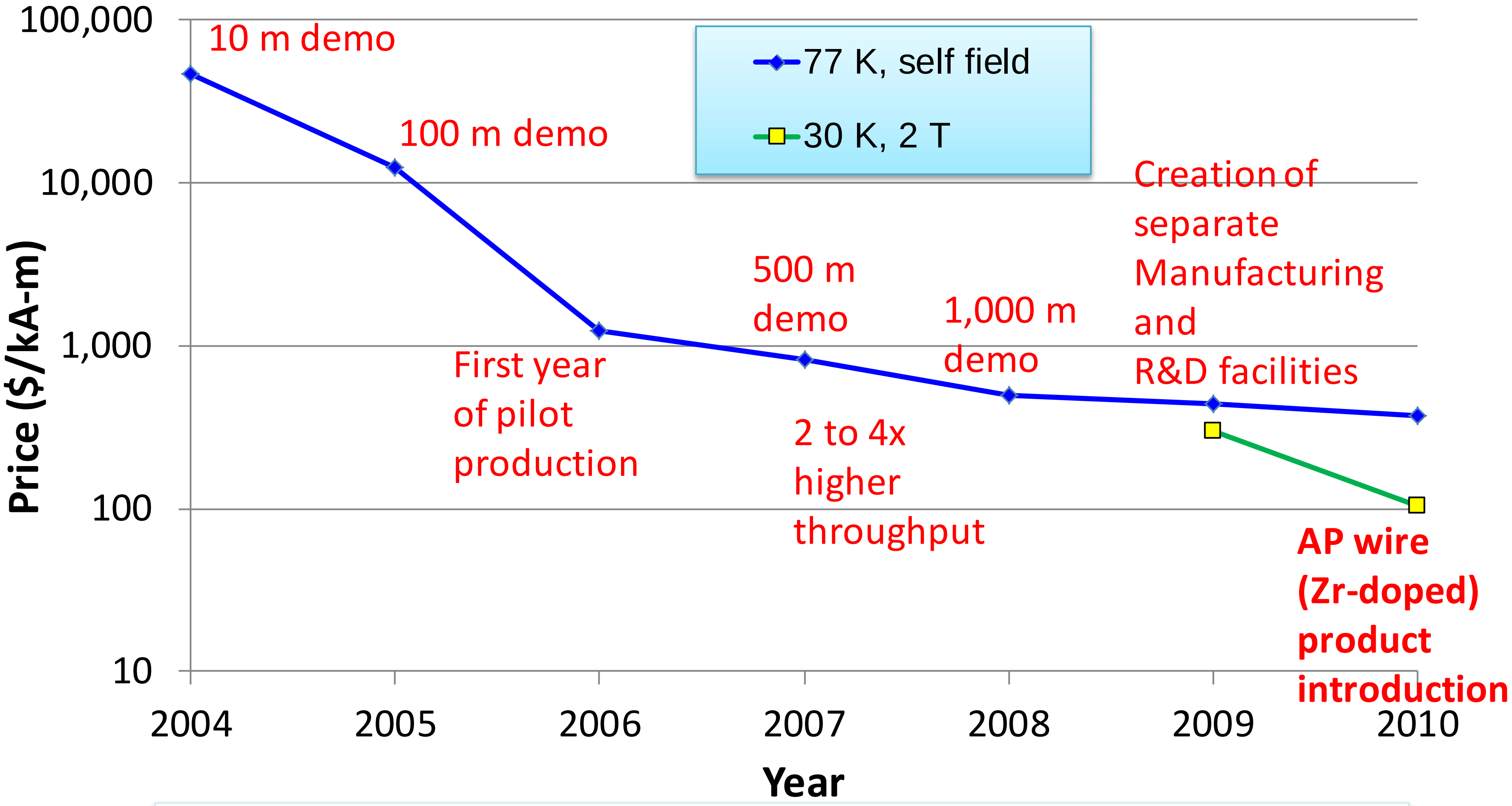
Price Reduction



Width :	12 mm	120 mm	360 mm
Capacity :	1,000 km/y	15,000 km/y	75,000 km/y
Max Revenue :	$ 20 Mil.	$ 75 Mil.	$ 150 Mil.
CAPEX* :	$ 7 Mil.	$ 20 Mil.	$ 30 Mil.
	Achievable with Existing Line of SuNAM		

* Capital Expense : Required Investment in Production Line

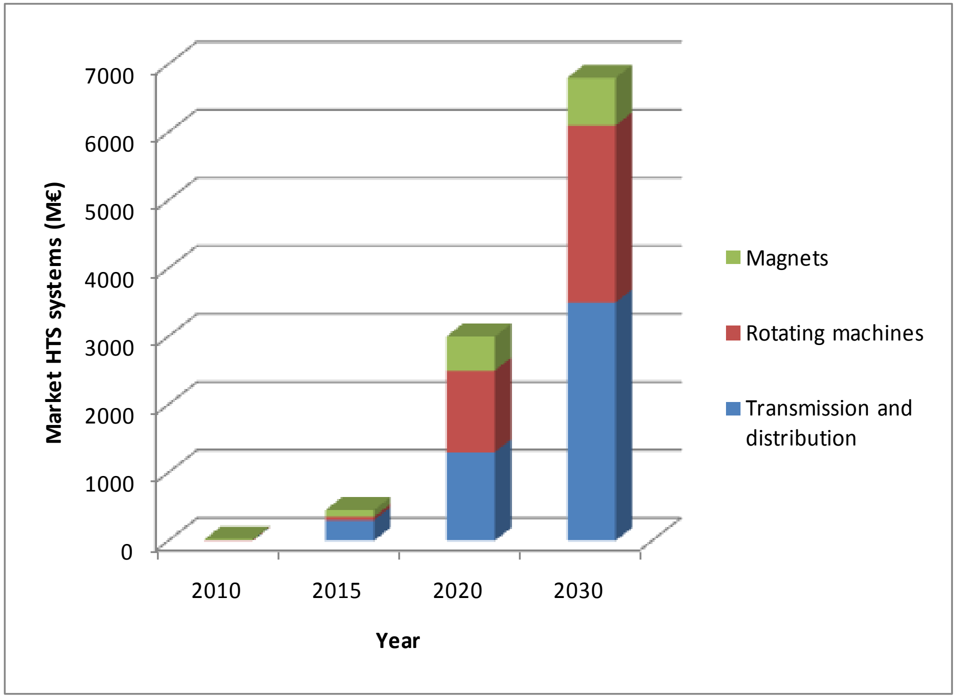
Rapidly decreasing price of 2G HTS wire through technology advancements



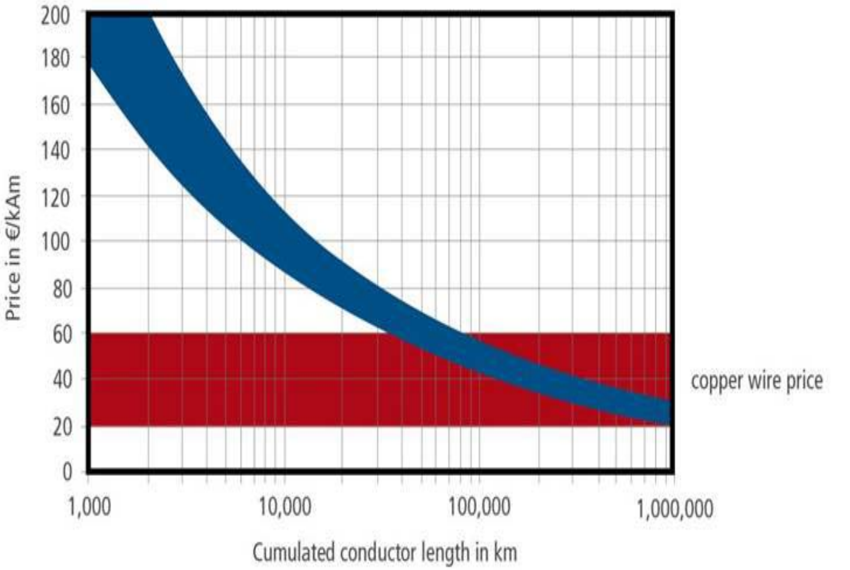
Wire price-performance improved by ~ 200% to ~ $ 100/kA-m for 30 K, 2 T applications

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



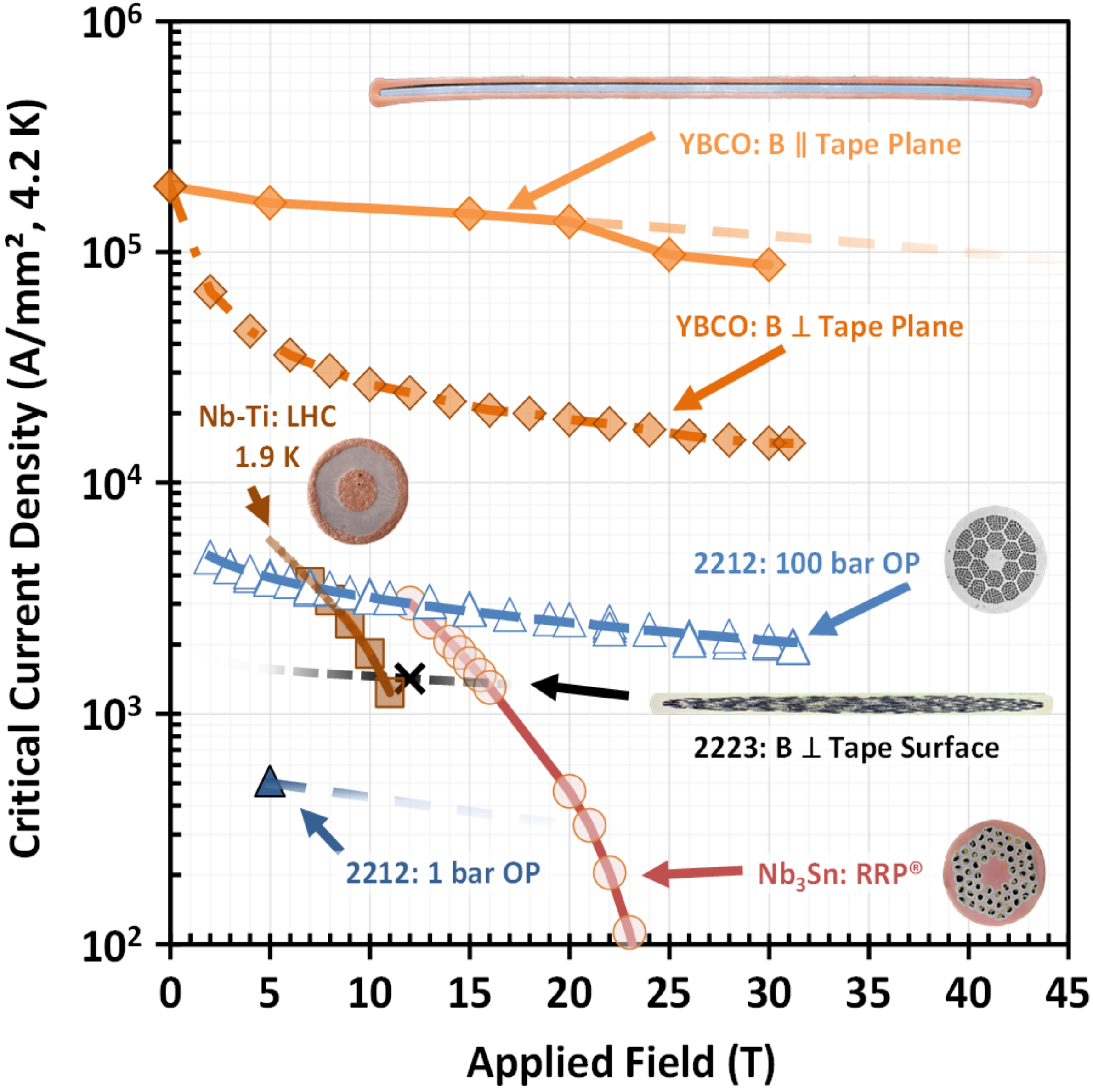
Estimated cost decrease of CC's with cumulated production: operating condition is the real metric

~ 6.5 bn € by 2030 (1.3 bn € in wires)
~ 1.500.000 km/year by 2030 (x 1000 present production)

Prospectives for CC production: a personal view !

Technology	Investement cost	Running cost	Throughput	Performances (I_c, F_p, anisotropy)
PLD	High	High	Medium	~ + -
MOCVD	Medium	High	Medium	~ + -
CSD-TFA	Low	Low	Medium	- + +
RCE-DR	Medium	Medium	High	+ - -
EV	Medium	Low	Medium	+ - -
CSD – Liquid Assisted	Low	Low	High	+ + +

Conductors at low temperatures



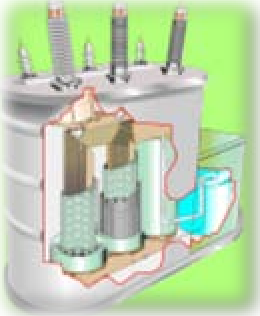
4.2 K

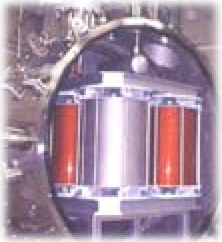
- **Several HTS conductors are suitable for ultrahigh field magnets**
- **Detailed studies of the engineering magnet characteristics and how they fit into the envisaged accelerator requirements will be necessary**

Courtesy of D. Larbalestier, Nature Materials (2014)

Road for Superconducting World by CC

Propagation





Marketable

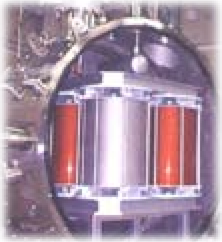
Applicable

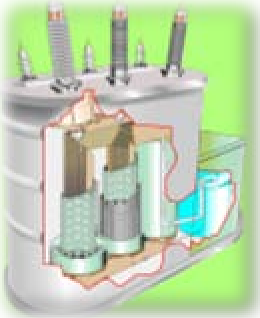
Capable

Courtesy of T. Izumi

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

Propagation





Marketable

Applicable

Capable

Courtesy of T. Izumi

Conclusions

- Carefully consider the potential of CCs to go well beyond any other superconducting materials ! Use at best the CCs capabilities !
  - HTS magnets at 30 T may become soon a reality (no physics limitations)
- Performance of CCs in the range 5 K – 20 K are very similar up to ultra-high magnetic fields. Closely scrutinize the possible advantages in terms of thermal stability and cooling expenditure
- Performance optimization at low temperatures and ultra-high fields requires further R&D effort. High T applications were a priority up to now. There is plenty of room for improvement, more knowledge needs to be generated
- Don't look at the present cost/performance ratio as a crucial parameter to envisage HFM design and projects decisions
  - A strong and fast decrease of the figure of merit €/kA m is being registered at all working conditions. Many industrial partners have plans to extend manufacturing capabilities and cost decrease
- Synergetic effects are expected between accelerators and other market demands

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