IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
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TECHNISCHE UNIVERSITÄT WIEN

ATOMINSTITUT

HTS versus LTS:
physics, technology, and application prospects

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EUCAS 2017

Acknowledgments

- Teresa PUIG (ICMAB), Amalia Ballarino (CERN), Staf Van Tendeloo (UA), Wilfried Goldacker (KIT), Jianyi Jiang (NHFML), Walter Fietz (KIT), Mark Stemmle (Nexans), X. Xu (FNAL), Tabea Arndt (Siemens)
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Motivation

Hundreds of superconducting elements and compounds are known…

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

Nb, NbN (electronics)

NbTi, Nb_3Sn (wires, magnets)

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Motivation

However, there are many promising candidates…

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

- Cuprates
- Iron-based compounds
- MgB_2
- …

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Motivation

What are the hurdles....

...for becoming an ”important” superconductor?

Outline

- Comparison of the superconducting properties of the materials most promising for or used in applications
- Prediction of the critical current densities after optimization
- State-of-the-art performance
- Current activities and issues
- Application prospects

Requirements

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

Alternative solutions: cost!

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

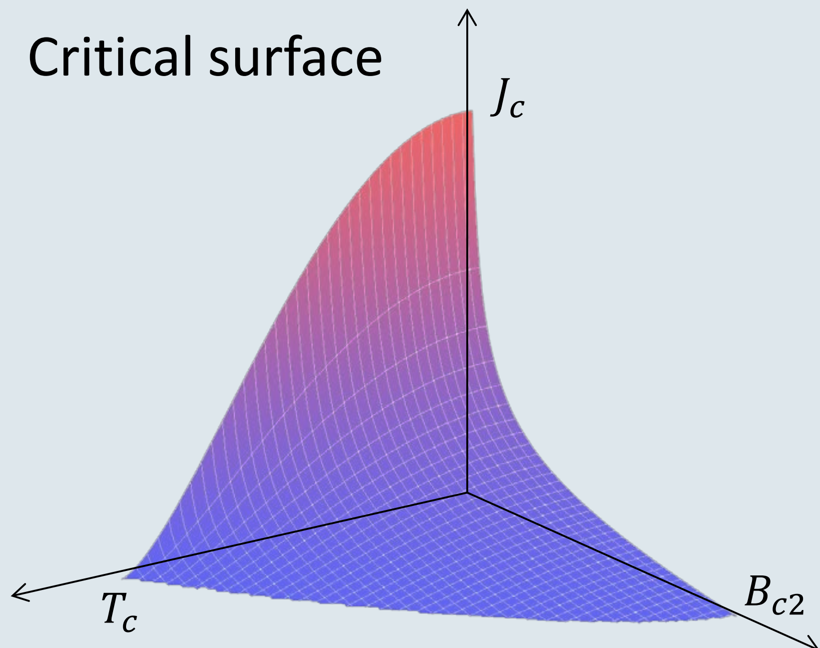
Processing: long length, cost effective, high yield…

Basic superconducting properties

Superconductors

Basic superconducting properties

Critical surface



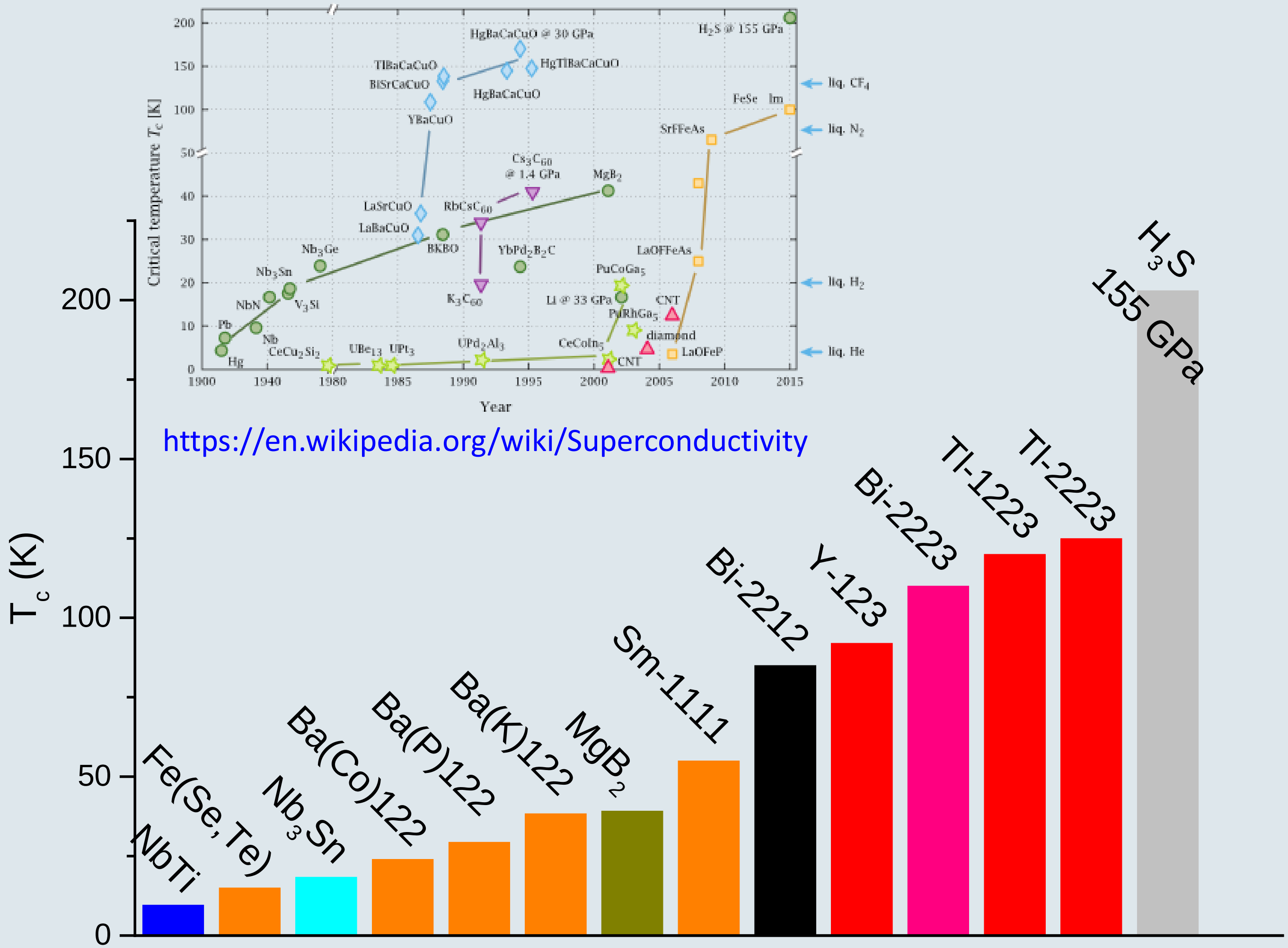
Three basic parameters:

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

Spoilsports:

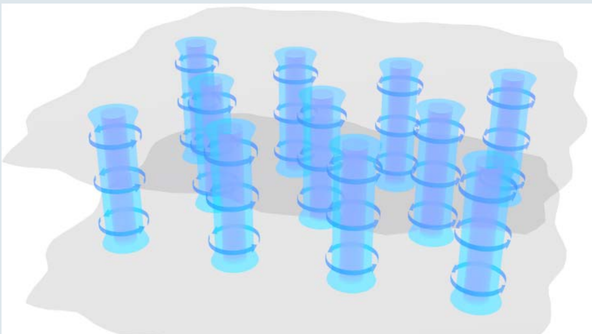
- Inter-grain connectivity
- Anisotropy

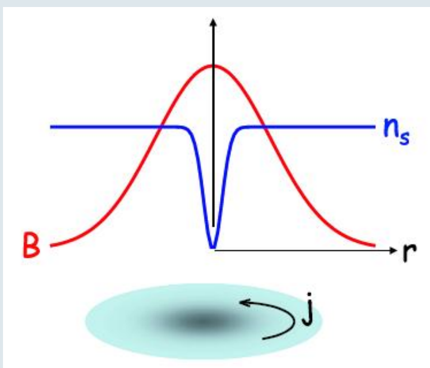
Critical temperature

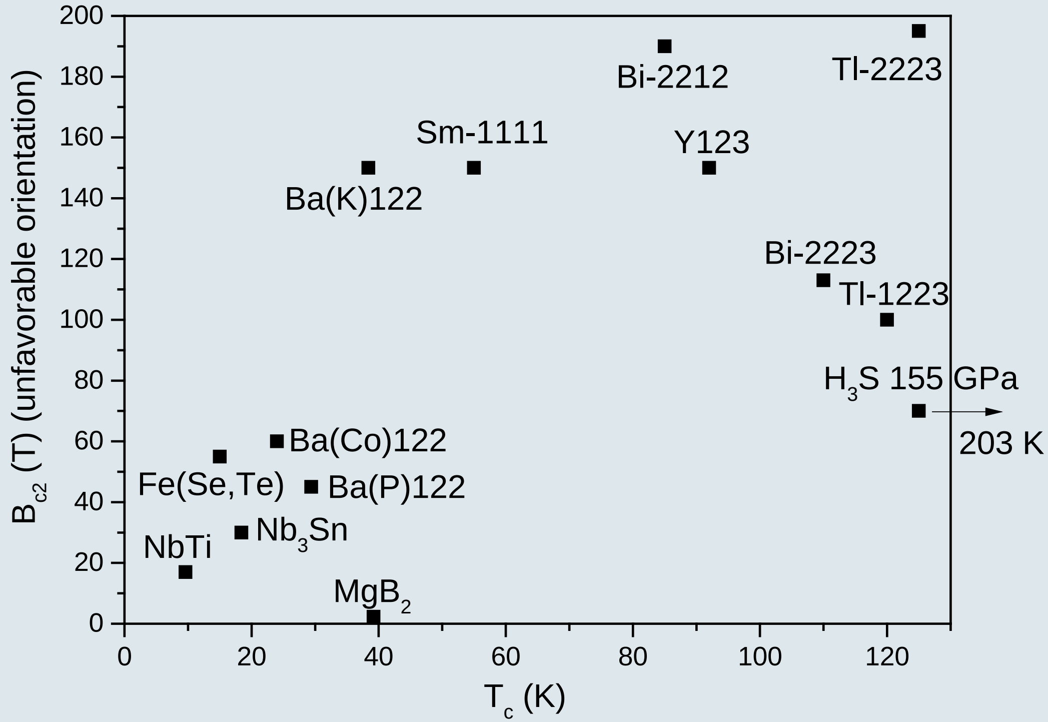


- T_c defines the maximum operation temperature
- Robustness of superconducting state against thermal energy

Upper critical field







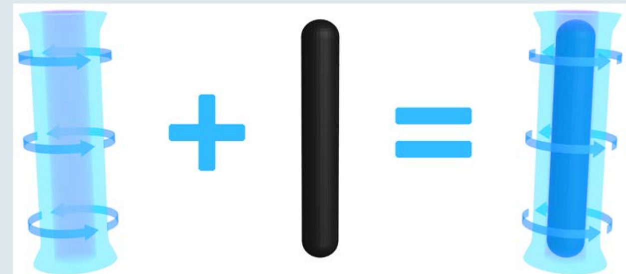
http://www.oettinger-physics.de/vortex.html

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

☺ Cuprates, some iron based compounds

☹ MgB_2, NbTi, (Nb_3Sn)

Critical current density: flux pinning



- Thermodynamic limit: depairing current density

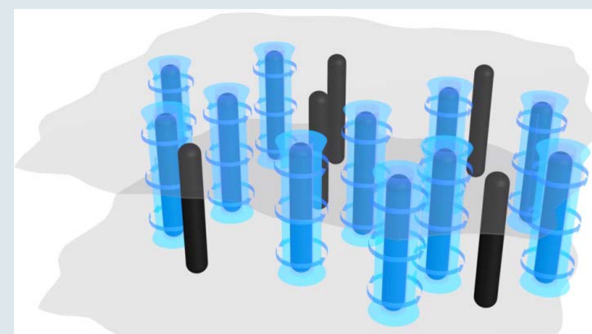
$$J_\mathrm{d} = \frac{\phi_0}{3\pi\sqrt{3}\mu_0\lambda^2\xi}$$

- Energy of vortex core per meter: $E_\mathrm{core} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2}$

$$f_p^\mathrm{max} = \frac{E_\mathrm{core}}{\xi} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2\xi}$$

- Critical state: $F_p = F_L = |J_c \times B\,|$
- Highest possible pinning force per vortex and unit length: cylindrical defect with $r_D \geq \xi$
- Force balance for one vortex ($B \perp J_c$): $f_L = f_p$

$$f_L = \iint F_L \mathrm{d}A = \iint J_c \times B \mathrm{d}A = J_c\phi_0 \leq f_p^\mathrm{max} = \frac{\phi_0^2}{16\pi\mu_0\lambda^2\xi}$$

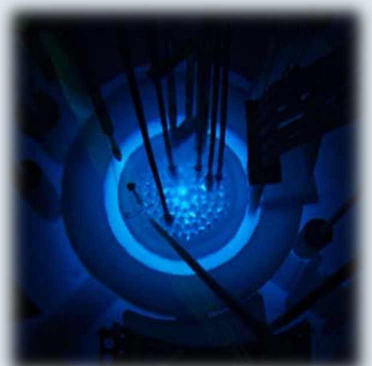


- $J_c^{max} = \frac{f_p^{max}}{\phi_0} = \frac{\phi_0}{16\pi\mu_0\lambda^2\xi} = \frac{3\sqrt{3}}{16} J_d \approx 0.32 J_d$
- $\eta = \frac{J_c}{J_d}$ … pinning efficiency
- $\eta_{max} \approx 32\%$

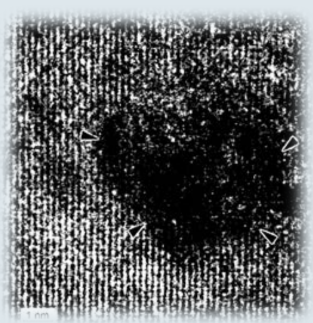
J_d sets the scale for the achievable critical current density!

Critical current density: neutron irradiation

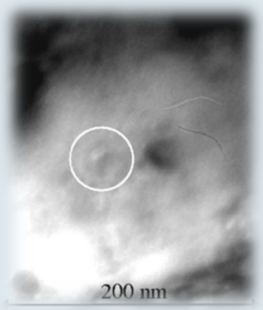
TRIGA reactor



YBCO



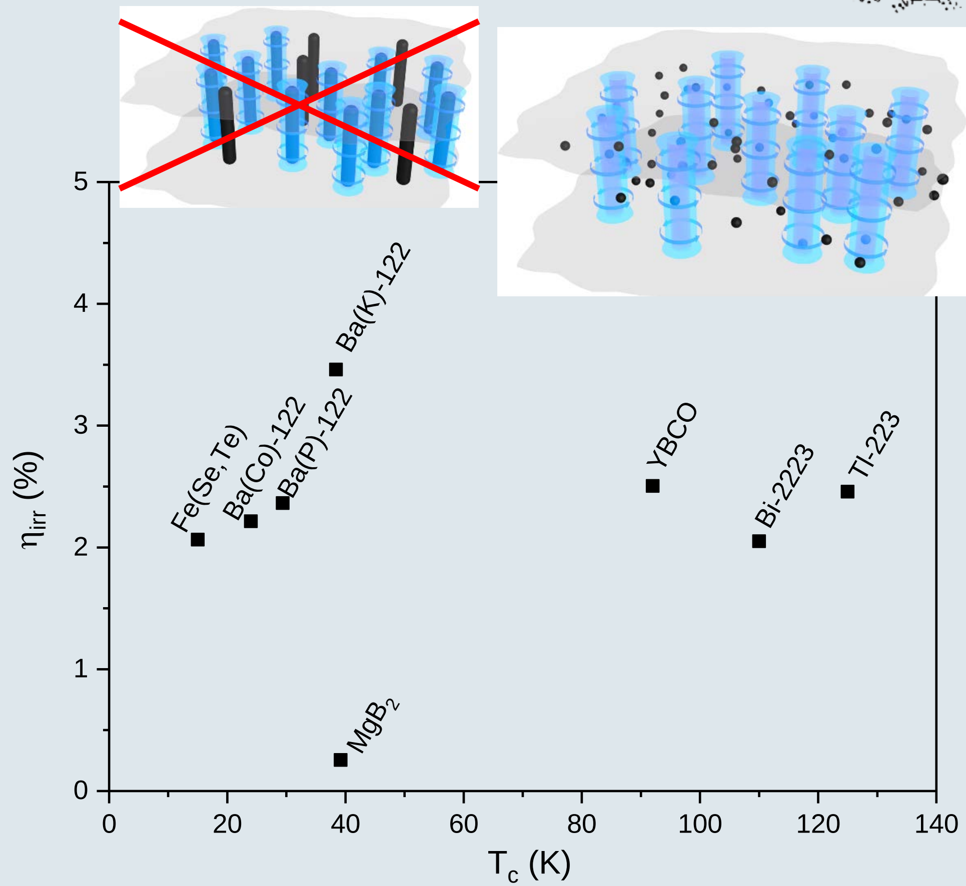
MgB_2



$r_D \approx$ 2-3 nm

M. C. Frischherz et al., Physica C **232** (1994) 309

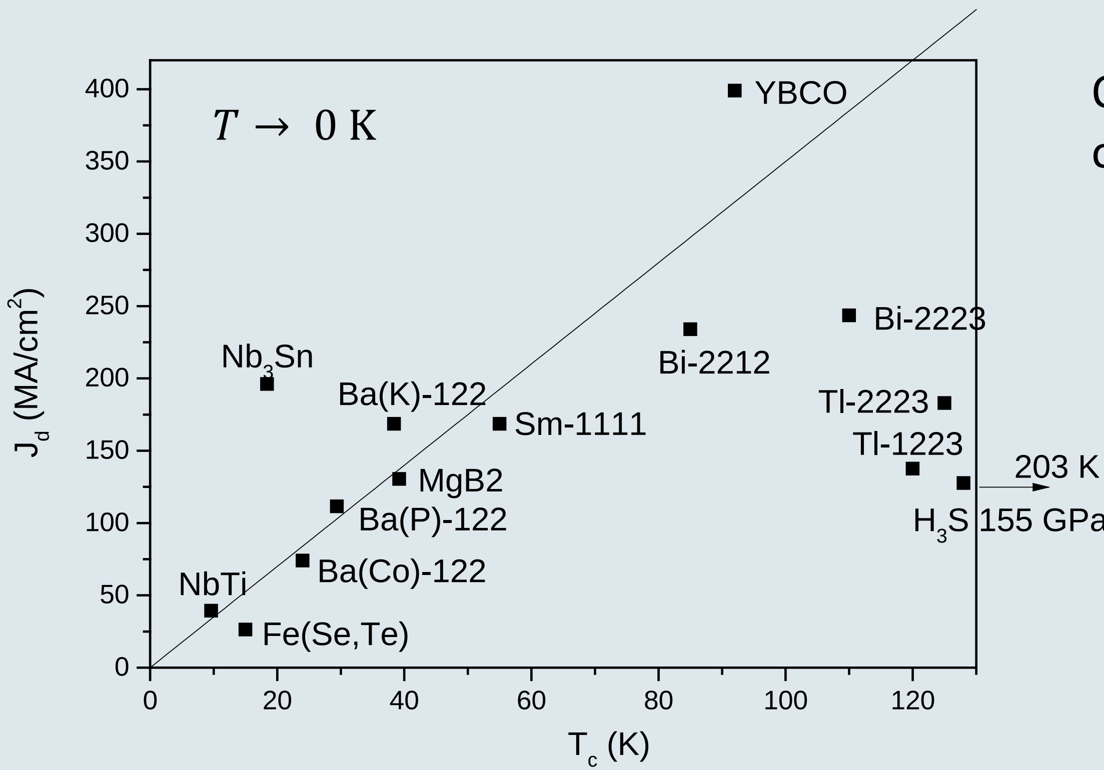
M. Zehetmayer et al., PRB **69** (2004) 054510



MgB_2: $r_D \ll \xi \approx 10$ nm → Pinning efficiency reduced by $\left(\frac{r_D}{\xi}\right)^2 \approx \left(\frac{2.5}{10}\right)^2 \approx 0.06$

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

Depairing current density



Quantitative determination of λ is difficult.

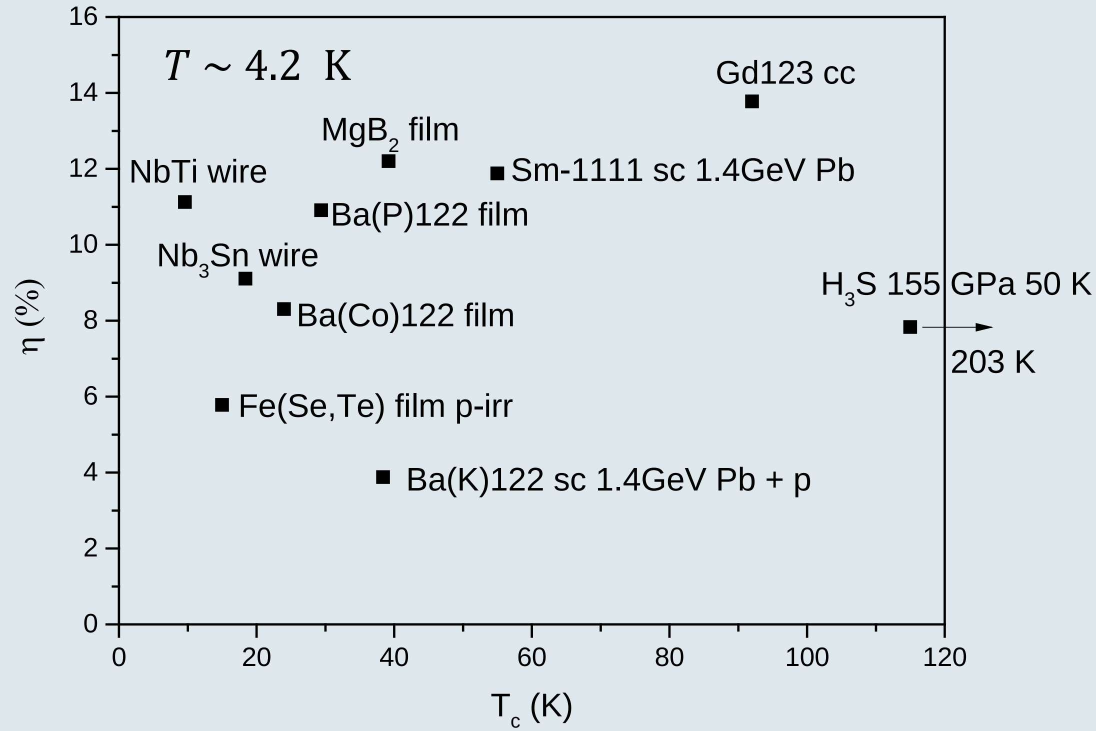
$$J_\mathrm{d} = \frac{\phi_0}{3\pi\sqrt{3}\mu_0\lambda^2\xi}$$

🙂 YBCO, Nb_3Sn

🙁 NbTi, Fe(Se,Te)

Pinning efficiency: highest(?) reported values

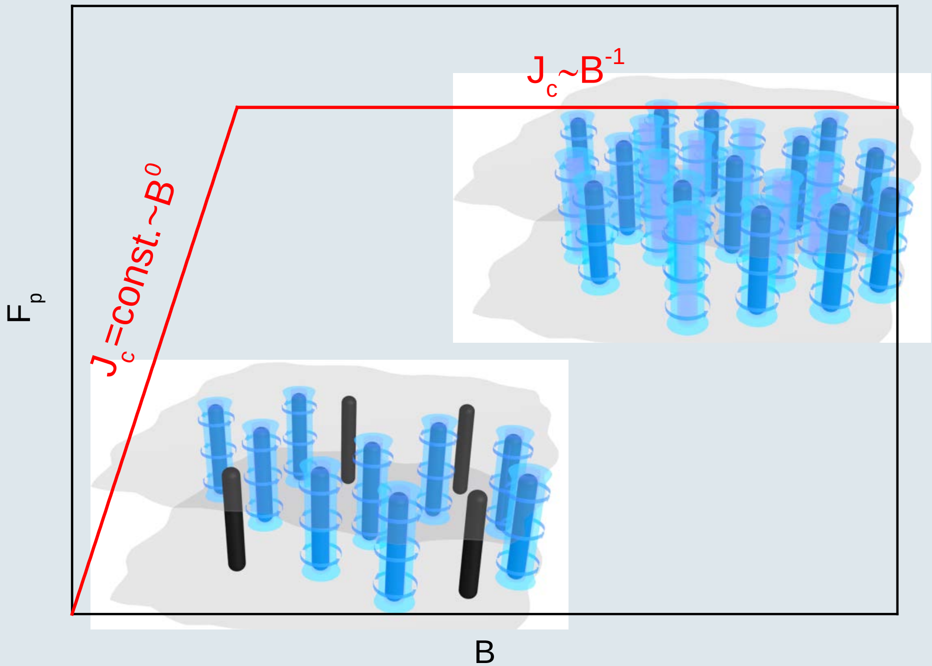
J_c^{sf}/J_d at low temperatures

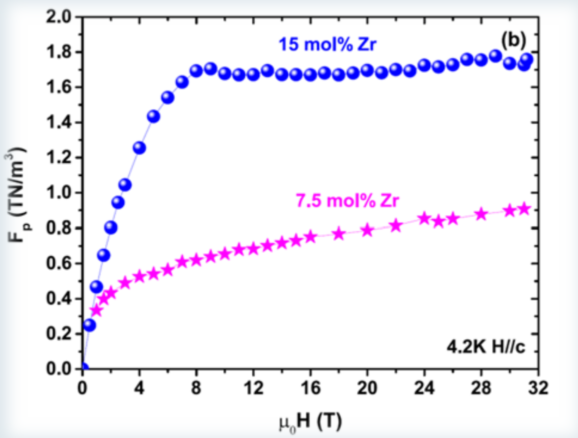


$J_c = 0.15 J_d$ ($\eta = 15$ %) can be achieved realistically at low fields.

Achievable in-field performance

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





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

Achievable in-field performance

- Assumption: $J_c^{sf} = 0.15 J_d$
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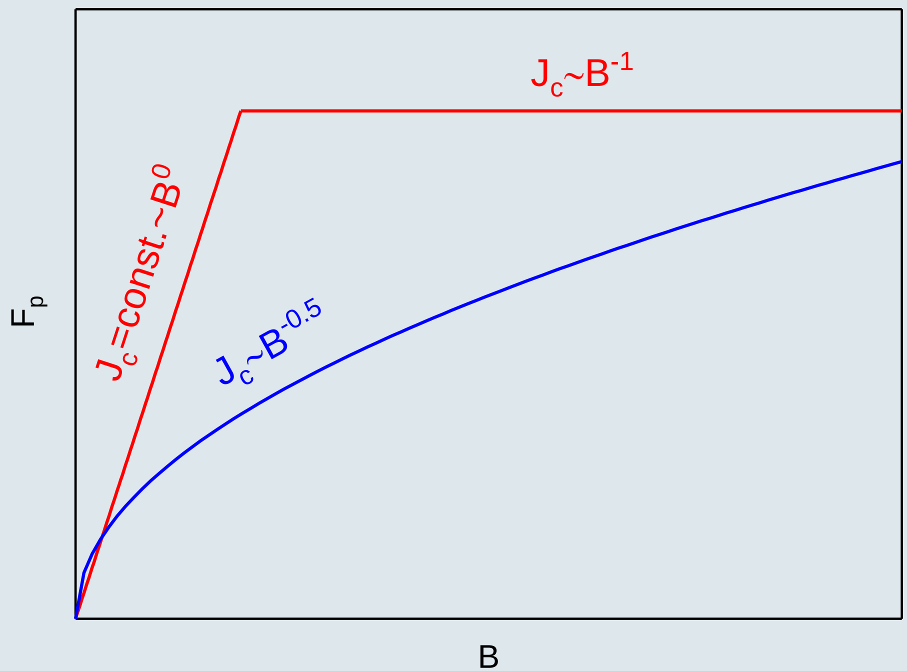
- $J_c \propto B^{-\alpha}$, $\alpha = 0.5$



Achievable in-field performance

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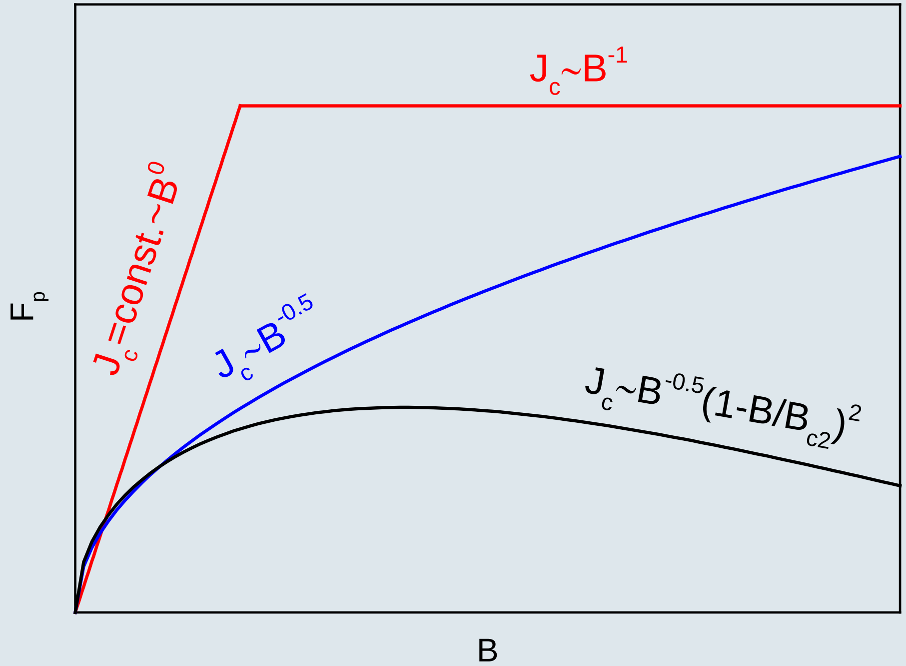
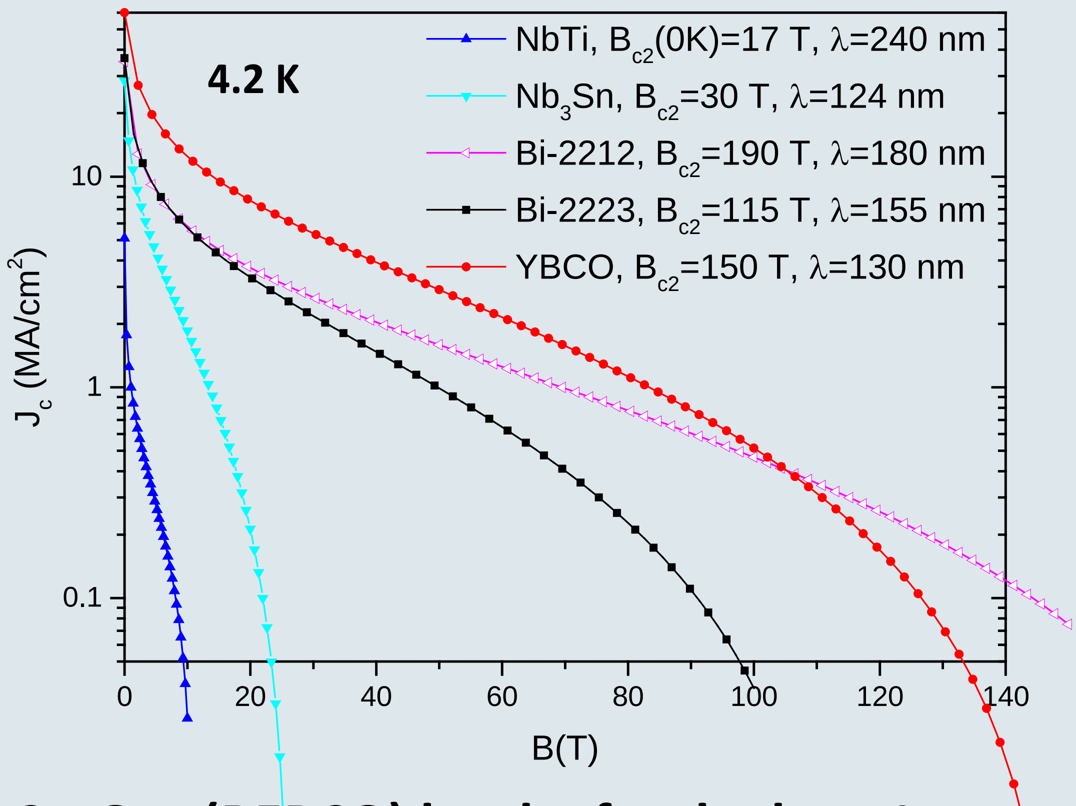
- Critical state: $F_p = F_L = |J_c \times B|$
- Maximum Lorentz force configuration: $J_c = \frac{F_p}{B}$
- $J_c \propto B^{-\alpha}(1 - B/B_{c2})^2, \alpha = 0.5$



Decrease of condensation energy, overlapping vortices

Optimum performance of various superconductors

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



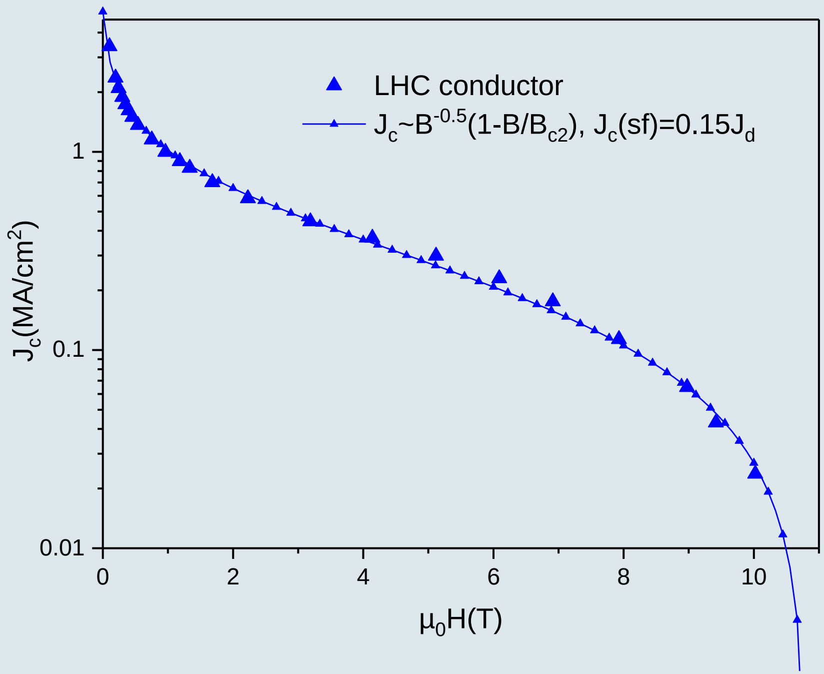
$\mathit{RE}Ba_2Cu_3O_{7-\delta}$ (REBCO) has by far the best J_c-properties.

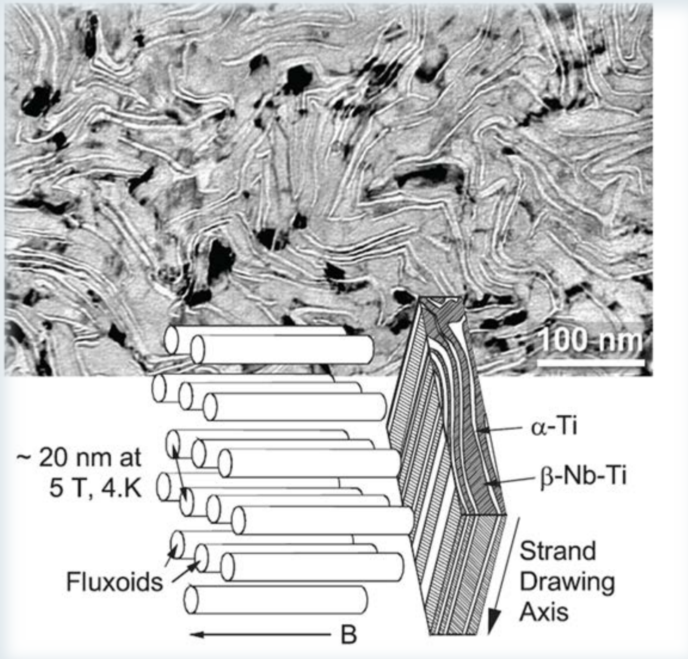
(Nevertheless, NbTi is used by far most frequently)

State-of-the-art

MATERIAL PROPERTIES: LTS

NbTi





P.J. Lee and D.C. Larbalestier, Presentation at Interwire (Atlanta, GA, 2001)

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

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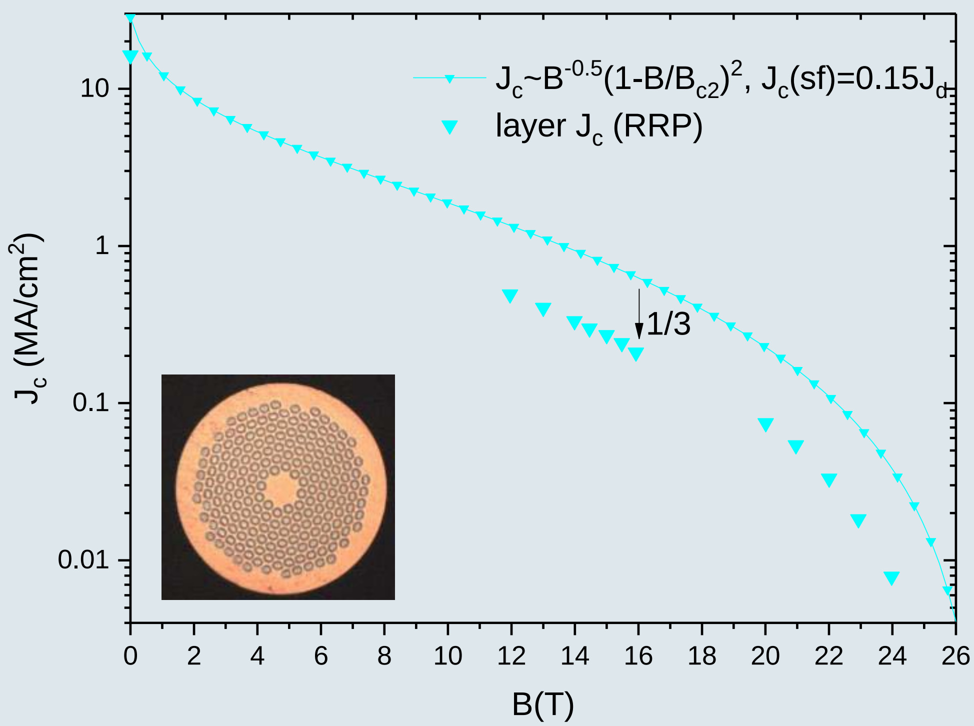
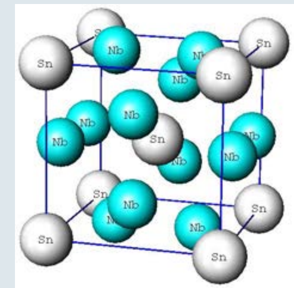
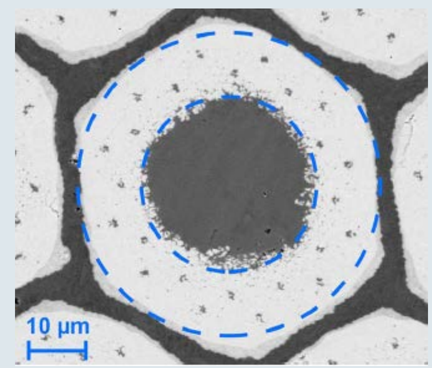
Nb_3Sn



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



www.geocities.jp

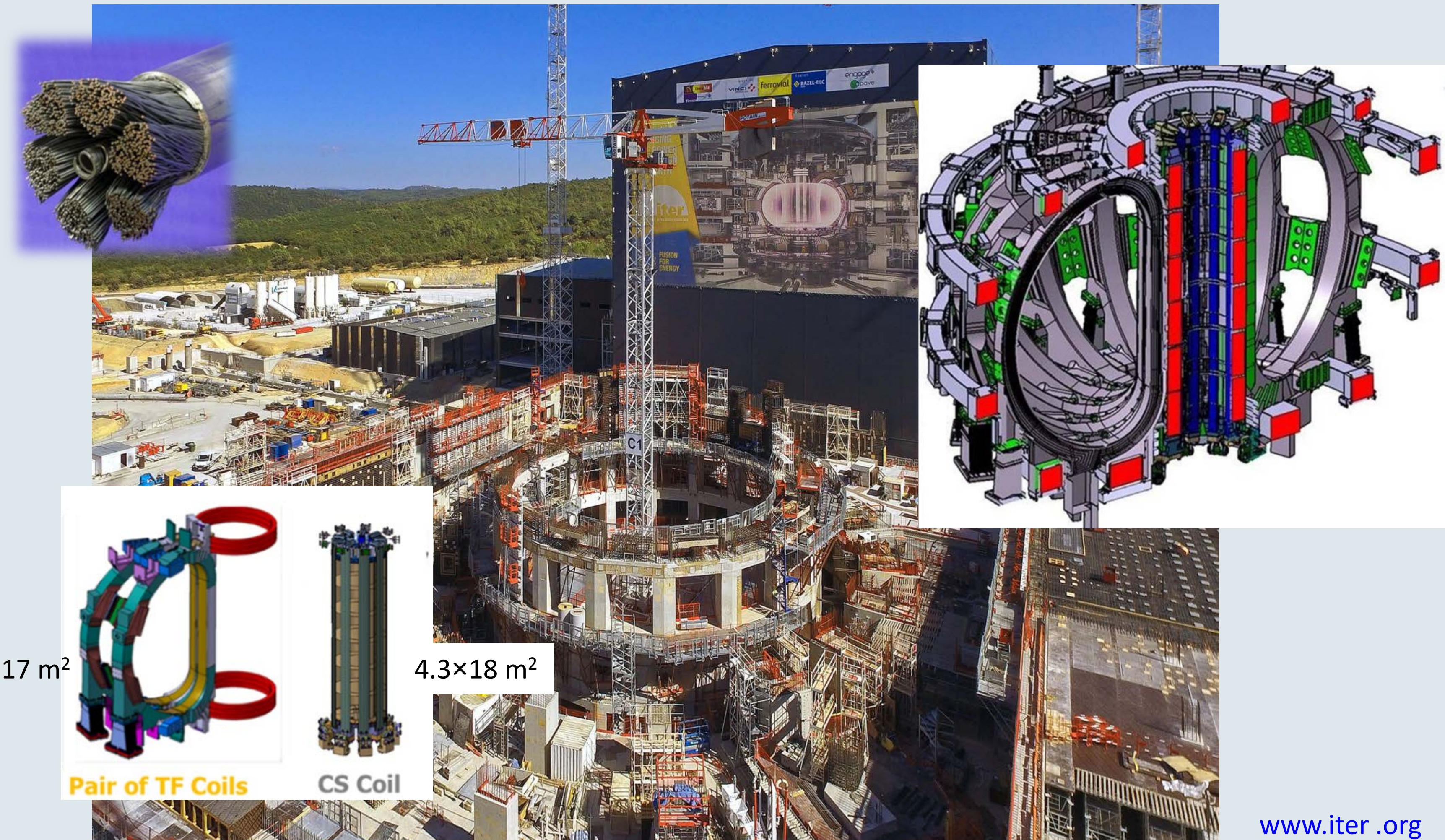


- High field magnets (10-23 T)
- Brittle material (wind & react)
- Grain boundary pinning
- Room for optimization

Actual challenges

Fusion magnets (ITER/DEMO)

- Thermomechanical properties (500 tons Nb_3Sn)
- Technological issues



9×17 m^2

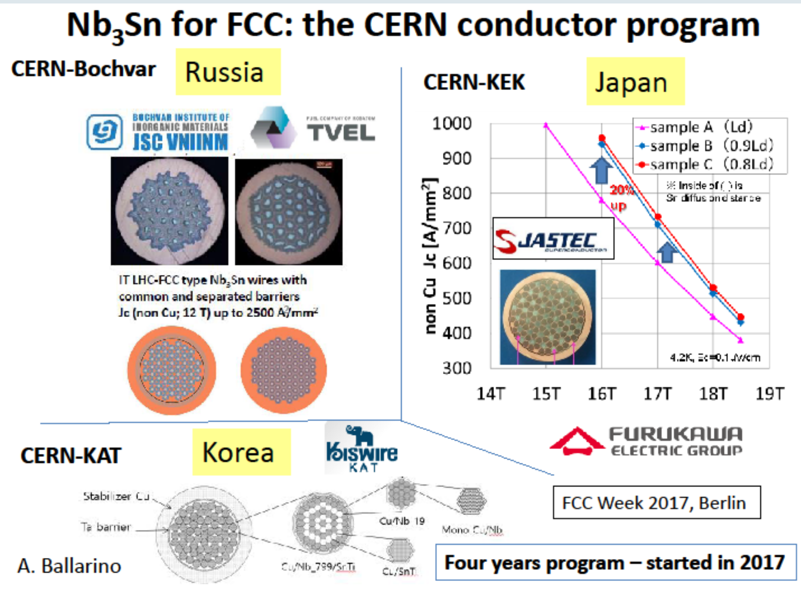
4.3×18 m^2

www.iter .org

Actual challenges

Future Circular Collider (FCC-hh)

- Demanding superconducting properties and production costs



Superconductor for FCC (100 km, 100 TeV)

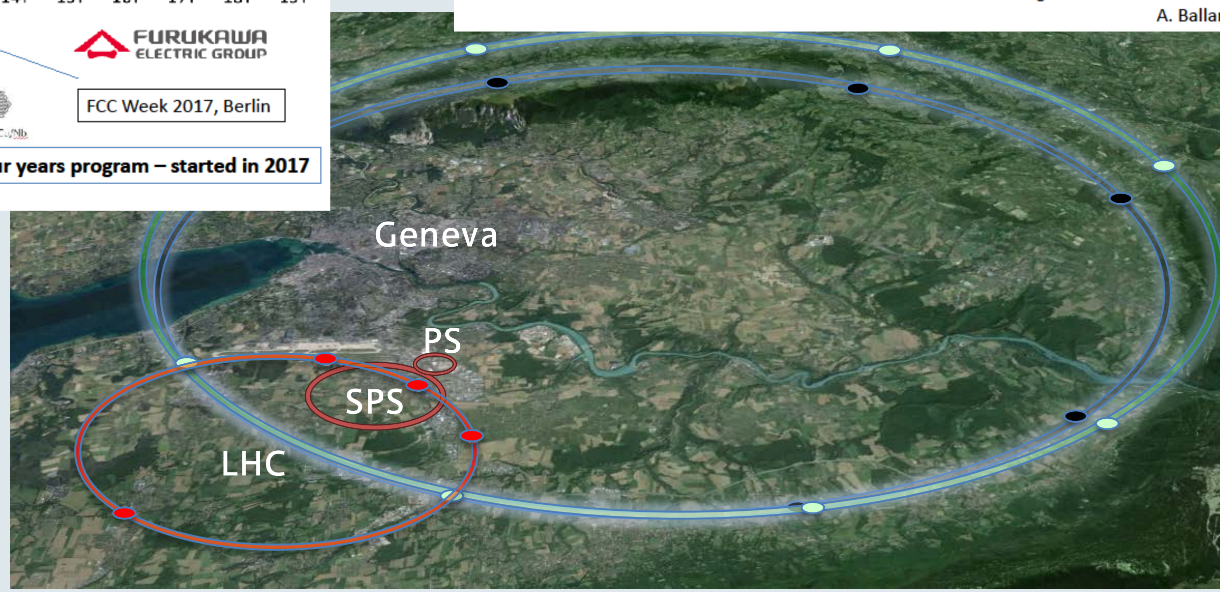
Nb_3Sn Wire Specification

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

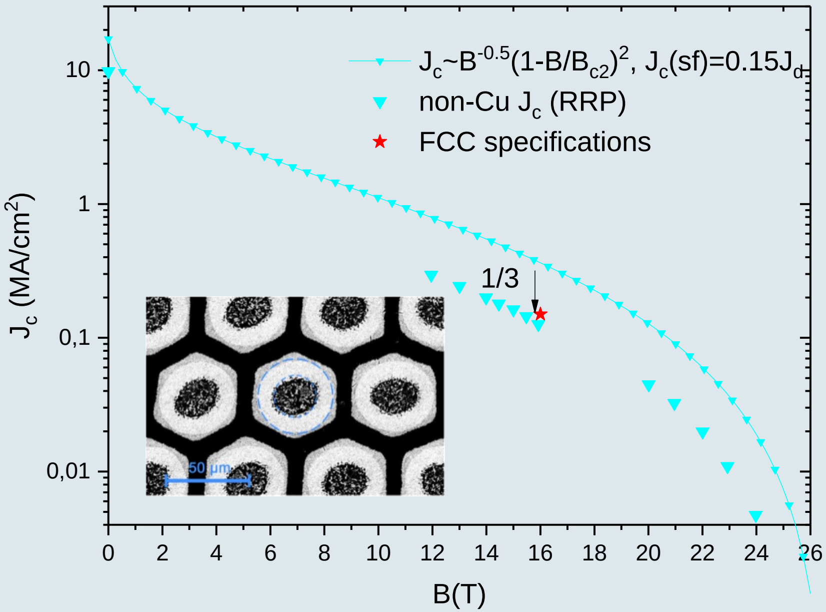
Total quantity required: ~ **8000 tons**

(~1200 tons of Nb-Ti in LHC, ~500 tons of Nb_3Sn in ITER)

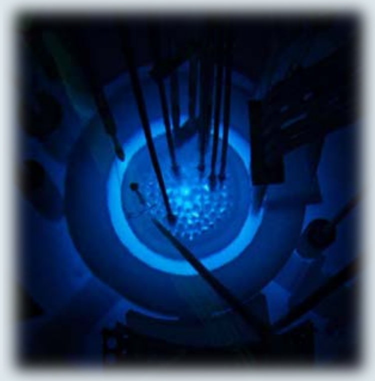
A. Ballarino



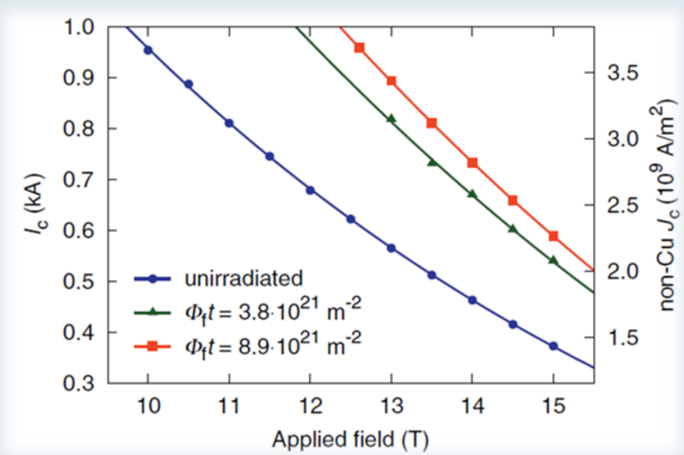
Nb_3Sn optimization: flux pinning

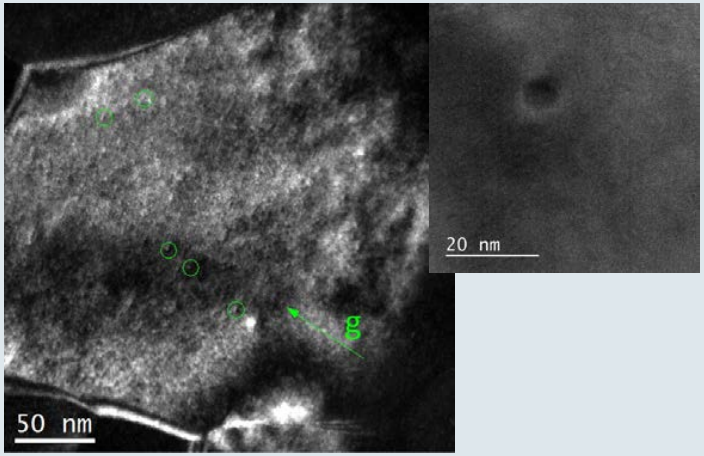


Fast neutron irradiation



Introduced defects (?)

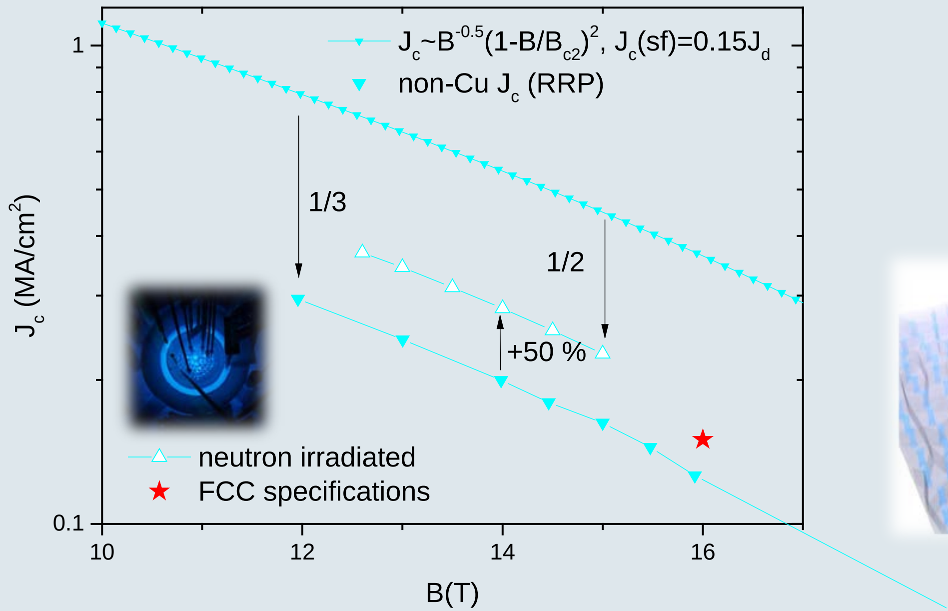




T. Baumgartner et al., Sci. Rep **6** (2015) 10236

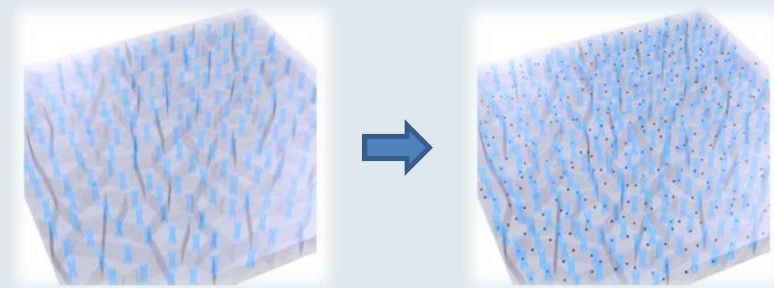
USTEM, TU Wien; S. Pfeiffer et al., 1MP4-01

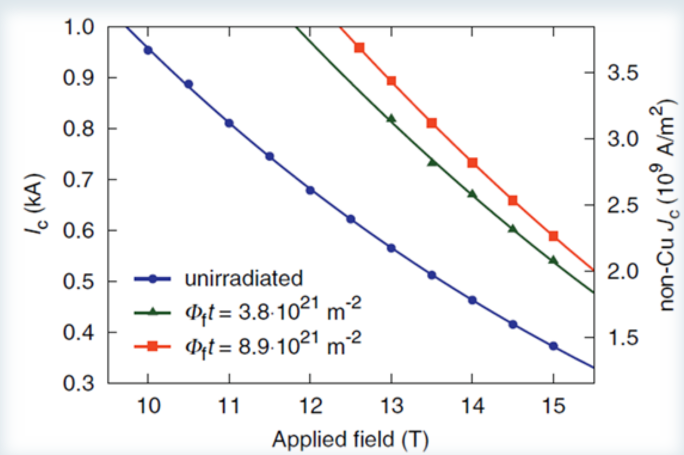
Nb_3Sn optimization: flux pinning

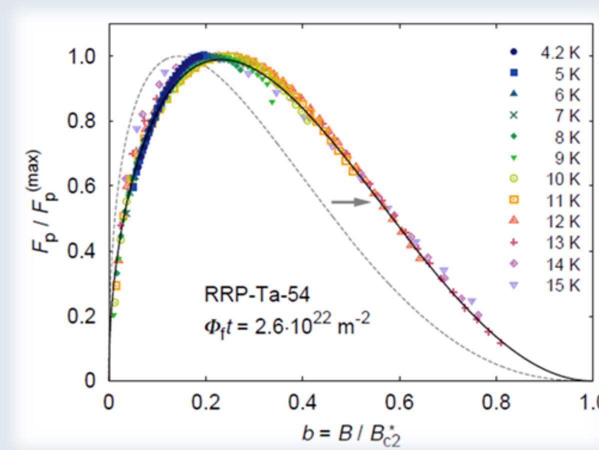


Fast neutron irradiation

- Introduction of small defects
- Point pinning contribution



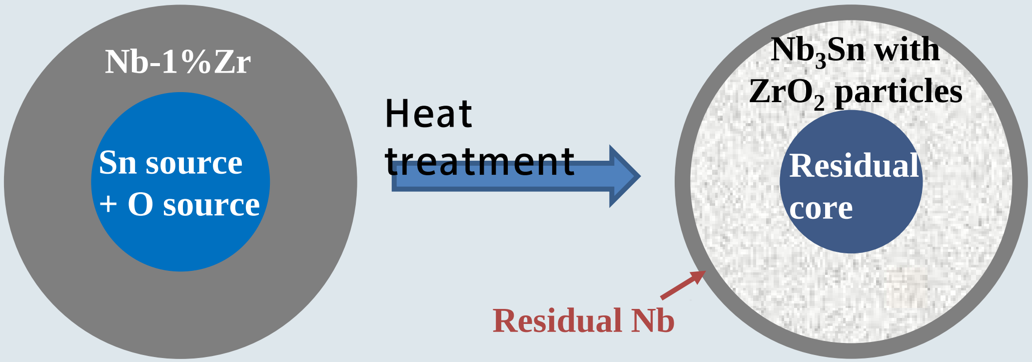


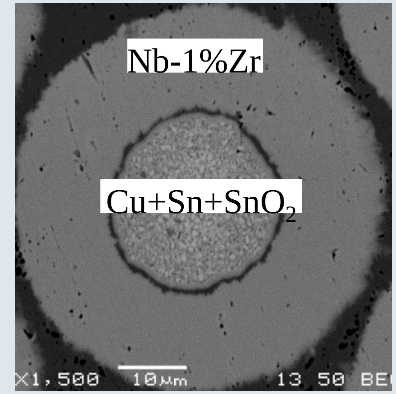


T. Baumgartner et al., SUST **27** (2014) 015005; 1MP1-09

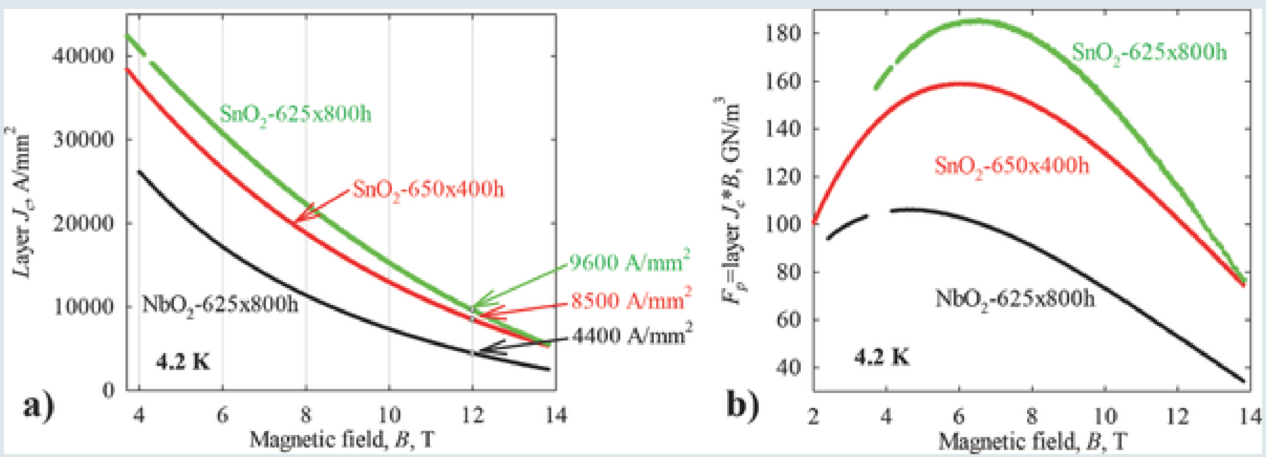
APC: flux pinning/grain refinement

Internal oxidation method





Courtesy of X. Xu, FNAL

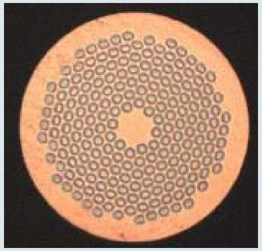


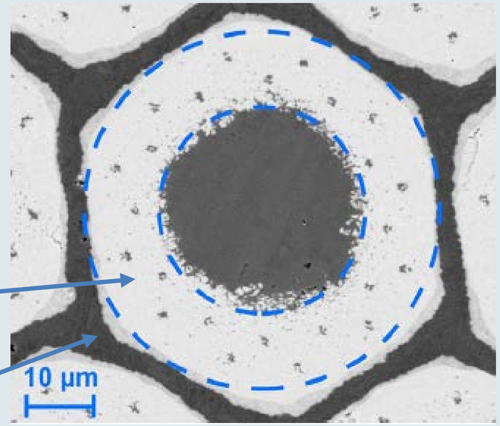
Nb_3Sn grain size:
100-150 → 35-50 nm

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

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

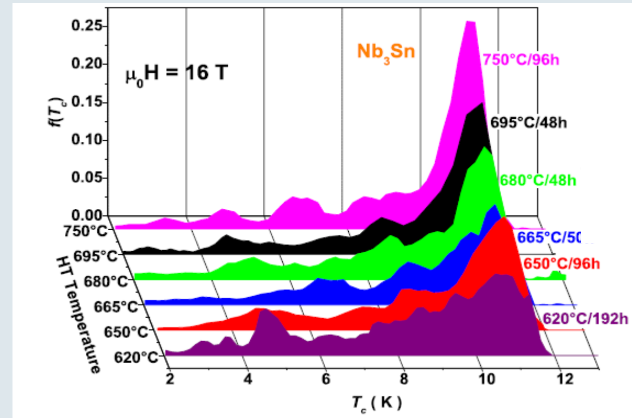
Nb_3Sn optimization





Useful Nb_3Sn layer
40-60% of subelement

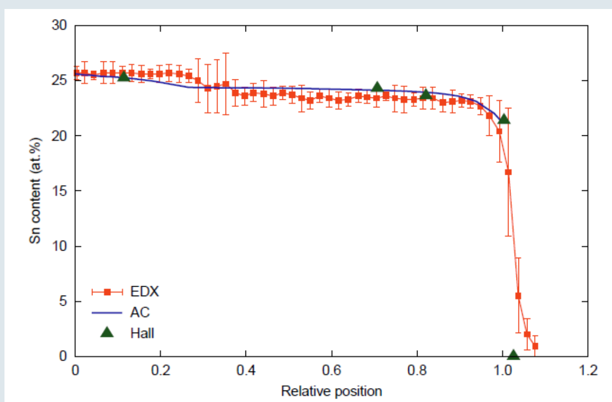
Unreacted Nb



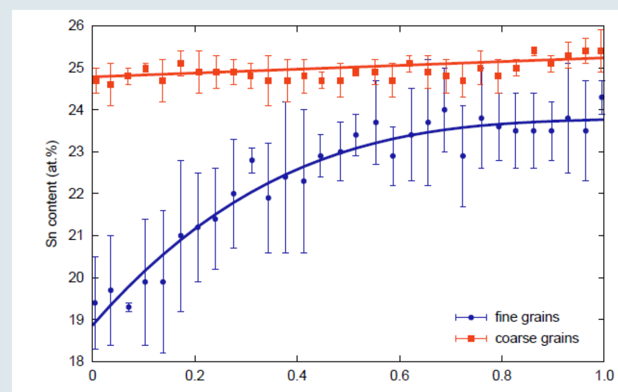
Tarantini et al., SUST **27** (2014) 065013

Sn-gradients:

In sub-elements



Inside grains

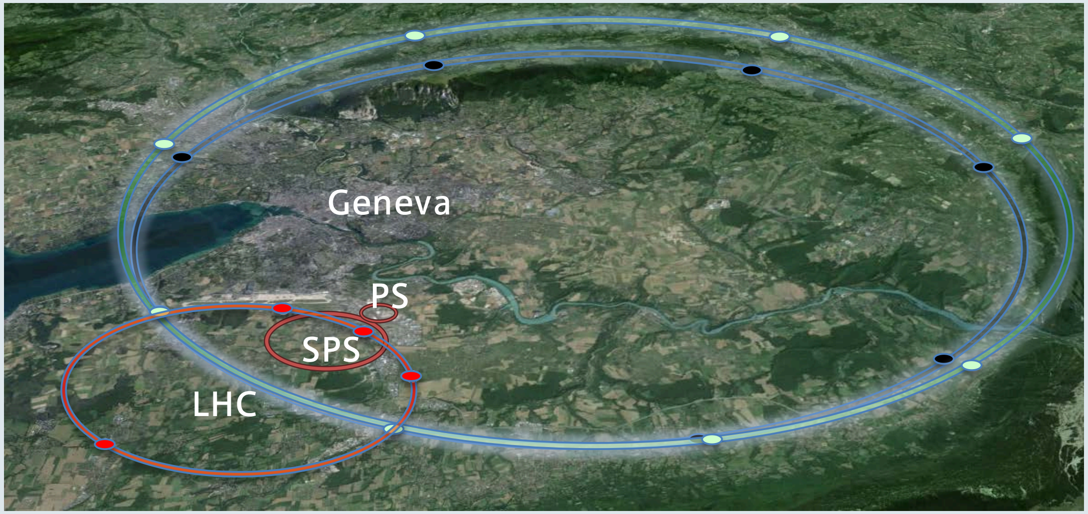


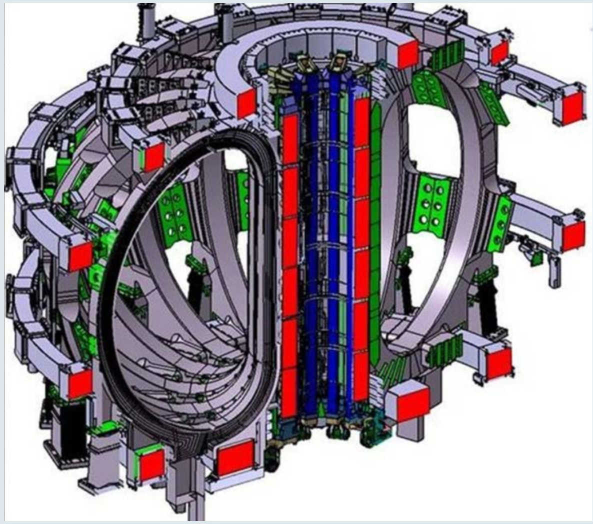
- Increasing fraction of current carrying layer (e.g. heat treatment)
- Improving stoichiometry (e.g. heat treatment)
- Quaternary wires (Ti, Ta)

USTEM, TU Wien
S. Pfeiffer et al., 1MP4-01

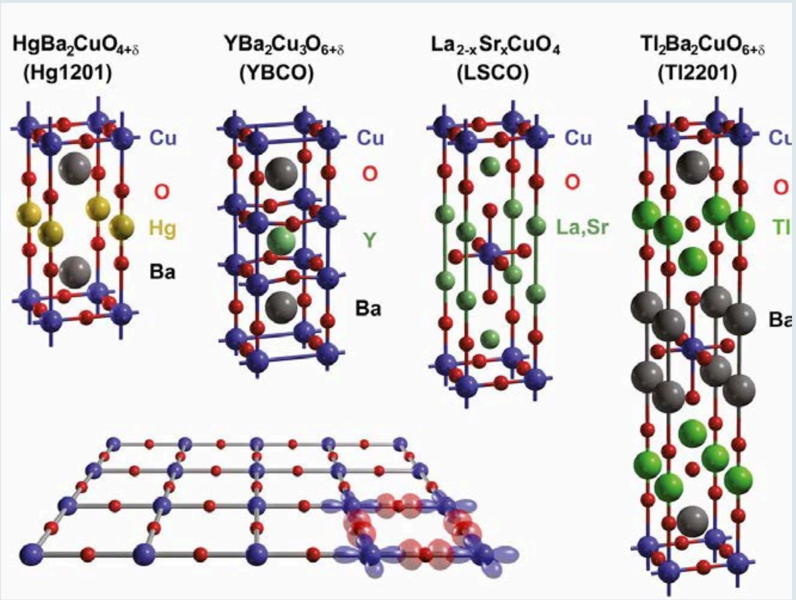
Nb_3Sn: Summary

- Nb_3Sn is the favorite conductor for high field magnets (10-23 T).
- Brittle material, demanding wind and react technology
- Performance push by accelerator project (High Luminosity LHC, FCC)
- Demanding ITER magnet technology



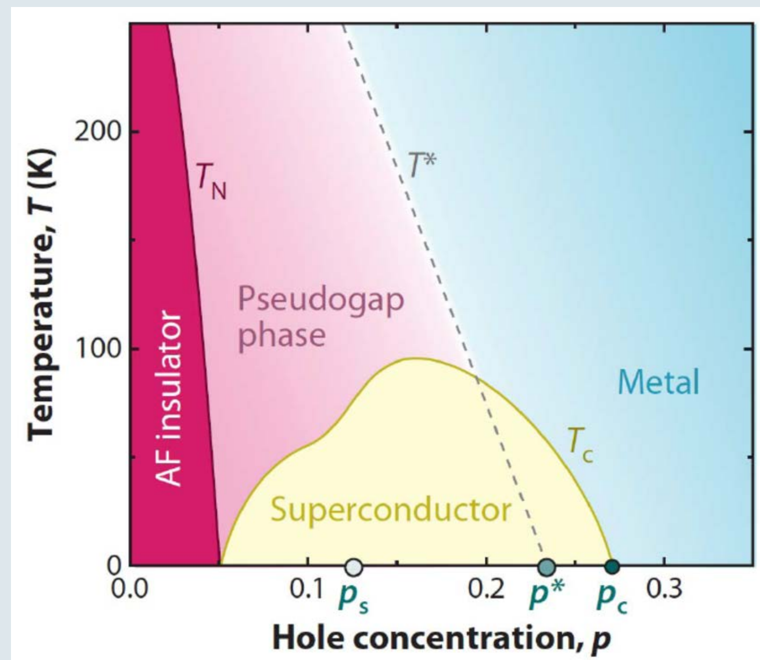


Cuprate Superconductors (HTS)



N. Barišić et al., PNAS **110** (2013) 12235

- Layered structure
- CuO_2-planes (1-3 per unit cell)

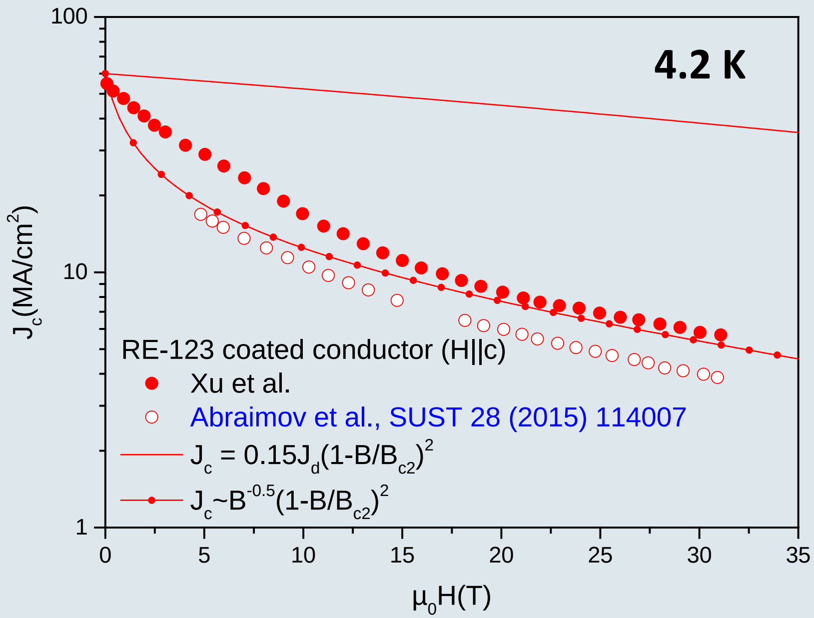


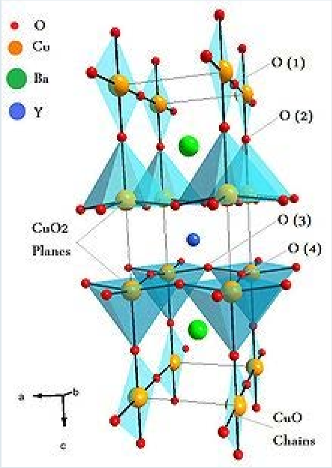
L. Taillefer, Annu. Rev. Condens. Matter Phys. **1** (2010) 51

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

Superconducting condensate essentially behaves as in conventional superconductors.

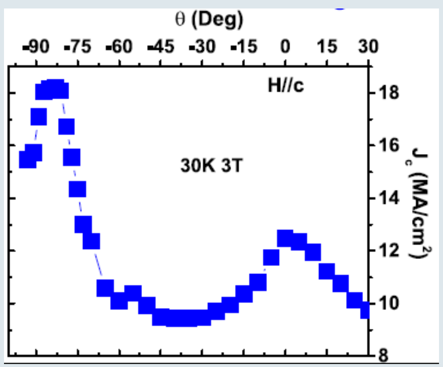
RE-123 coated conductors





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

$$J_c(B||c) > \min_{\theta} J_c?$$

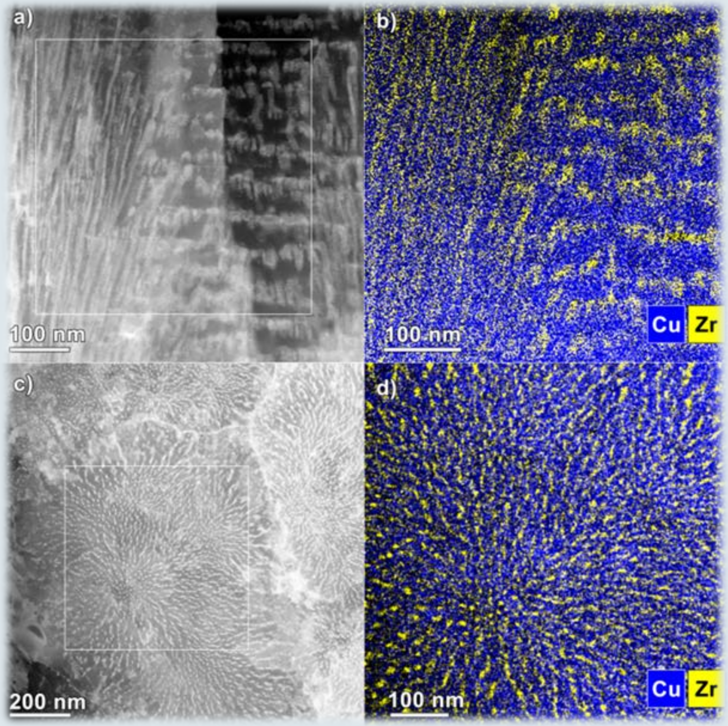


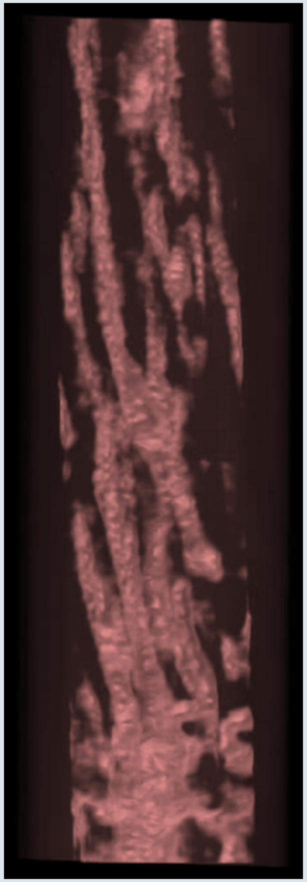
Actual status of conductor development: B. Holzapfel 2MO1

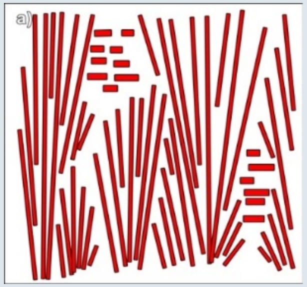
A. Xu et al., APL Materials **2** (2014) 046111

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

Microstructure



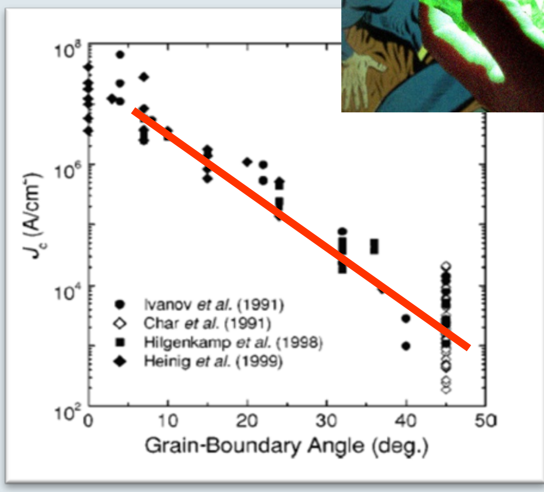




- Firework-shape defect structure (BZO)
- CuO-chain intergrowths

Courtesy of G. Van Tendeloo et al.
University of Antwerp

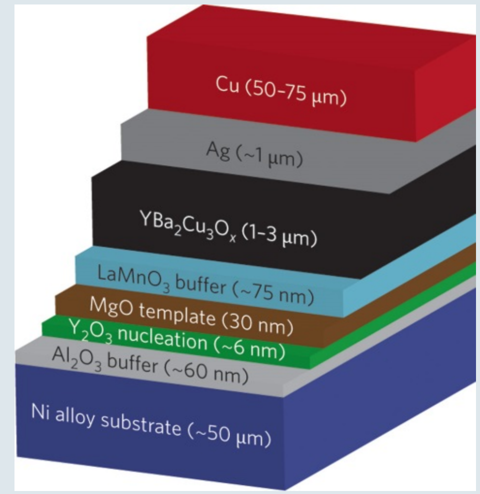
RE-123: Granularity



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

Coated conductor technology

→



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

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

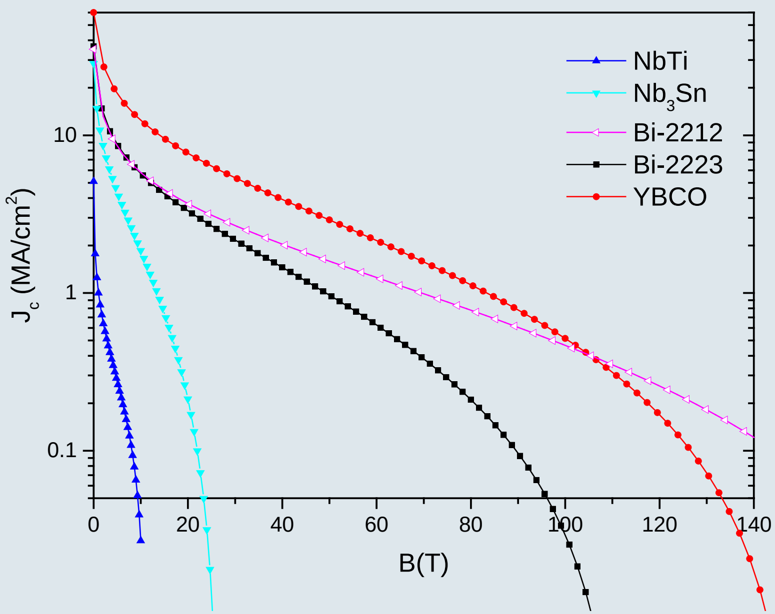
TU WIEN

Engineering current density

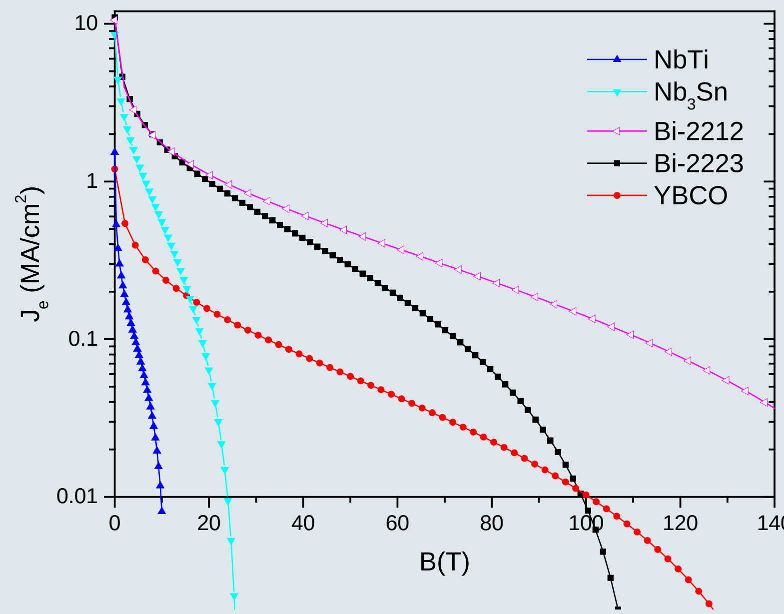
Superconducting volume fraction: wires 30 %, coated conductors 2%

Ideal performance

Critical Current Density



Engineering Current Density

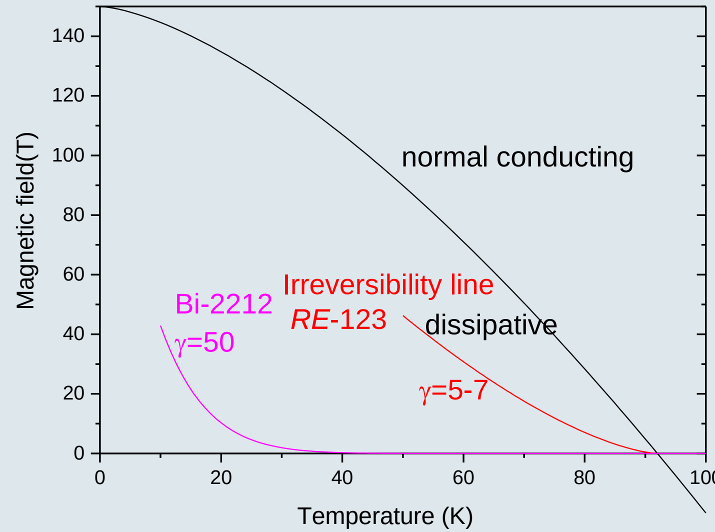


- Single filament: ac losses, no current sharing between the filaments within one strand (high current densities, large temperature margin, small quench propagation velocity → high risk of damage)

Cuprates: anisotropy

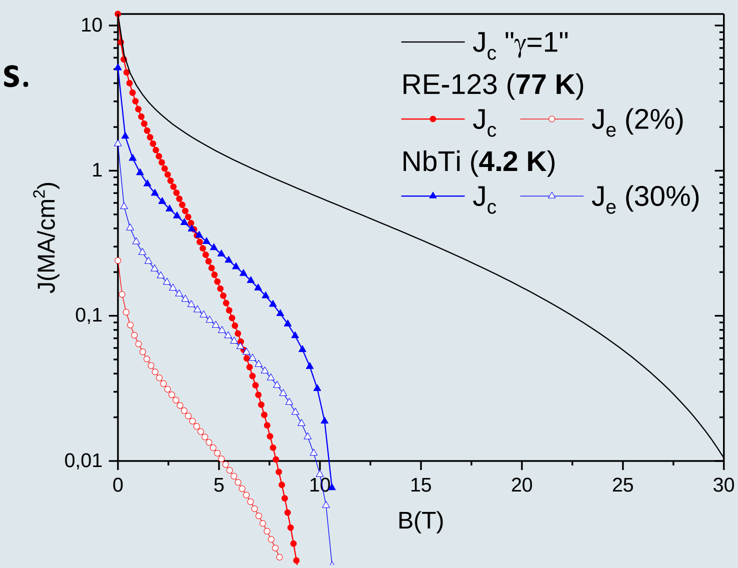
Anisotropy of the upper critical field:

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



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

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

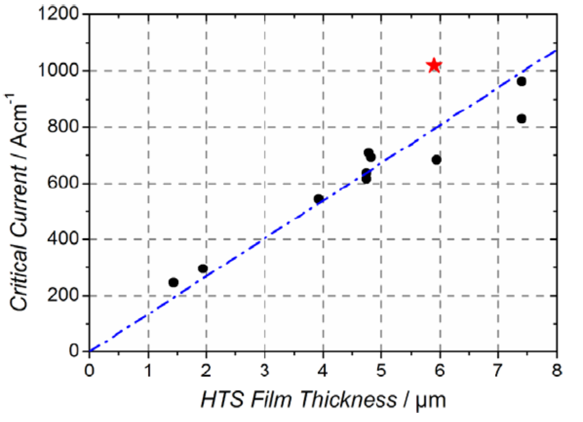


High operation temperatures:

- The maximum operation field is reduced
- The field dependence of J_c increases
- Low superconducting volume fraction of coated conductors becomes problematic at high temperatures

RE-123: current efforts

- Optimization of **pinning** for the respective operational conditions
  - Nano-precipitates: $BaZrO_3$ (BZO), $BaHfO_3$(BHO), $Ba_2YNb_{0.5}Ta_{0.5}O_6$ etc.
- Increasing RE-123 layer **thickness**

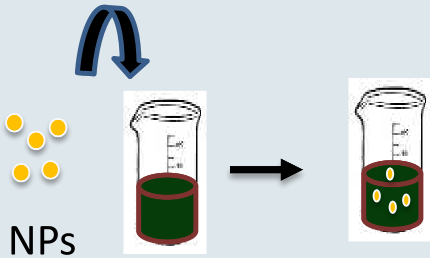


M. Dürrschnabel et al., Supercond. Sci. Technol **25** (2012) 105007

- Lowering production **cost** (upscaling, higher yield)
  - Chemical solution deposition, CSD

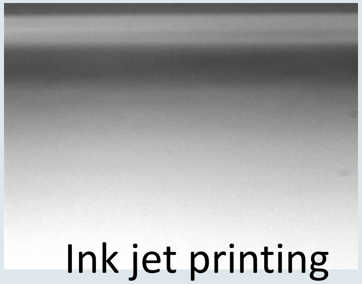
ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA · EXCELENCIA SEVERO OCHOA · CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS · eurotapes

Efforts at ICMAB-Barcelona for improving pinning in scalable, low cost CSD-CC

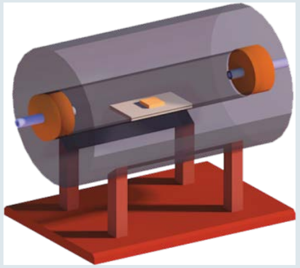


NPs

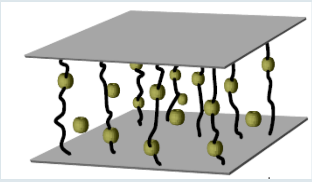
YBCO precursors



Ink jet printing solution deposition

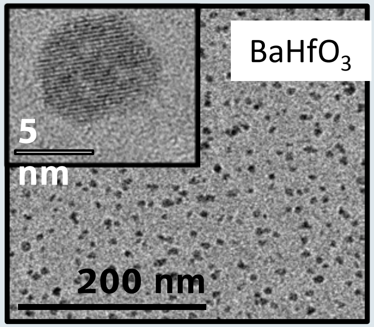


Growth process

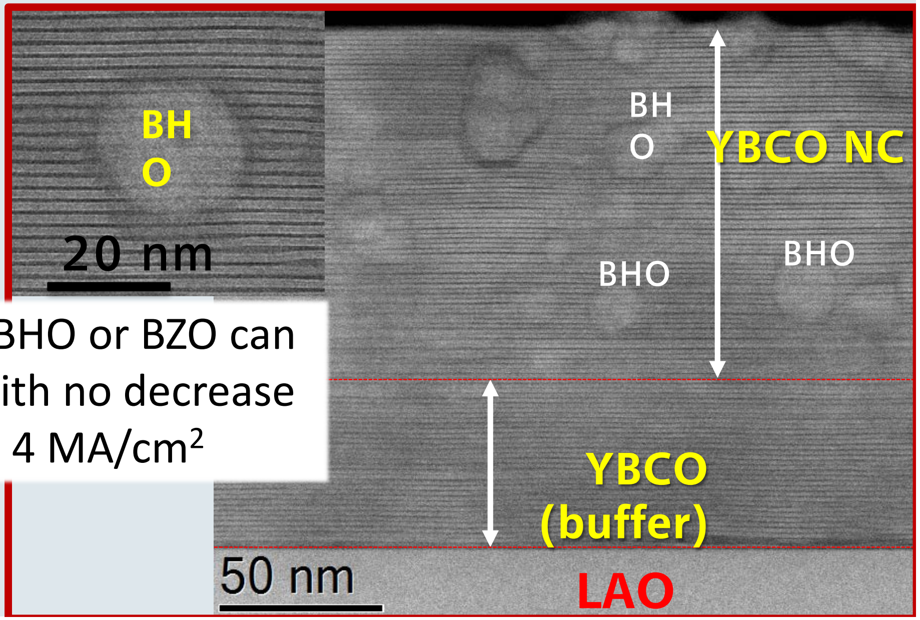


Nanocomposite with artificial pinning centers

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



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



Up to 20%M BHO or BZO can be reached with no decrease on T_c and J_c^{sf}= 4 MA/cm^2

to be published

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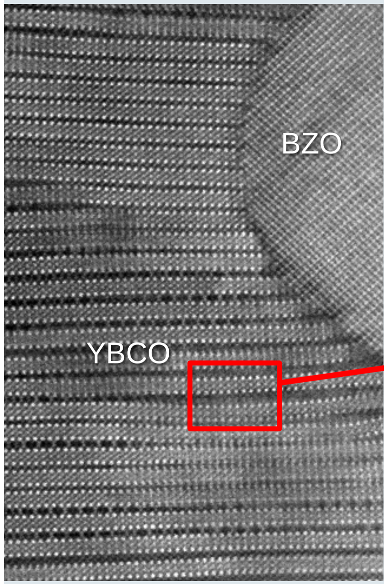
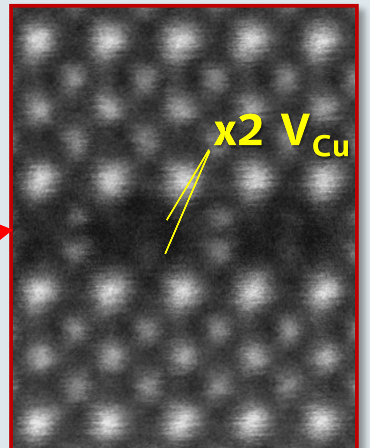
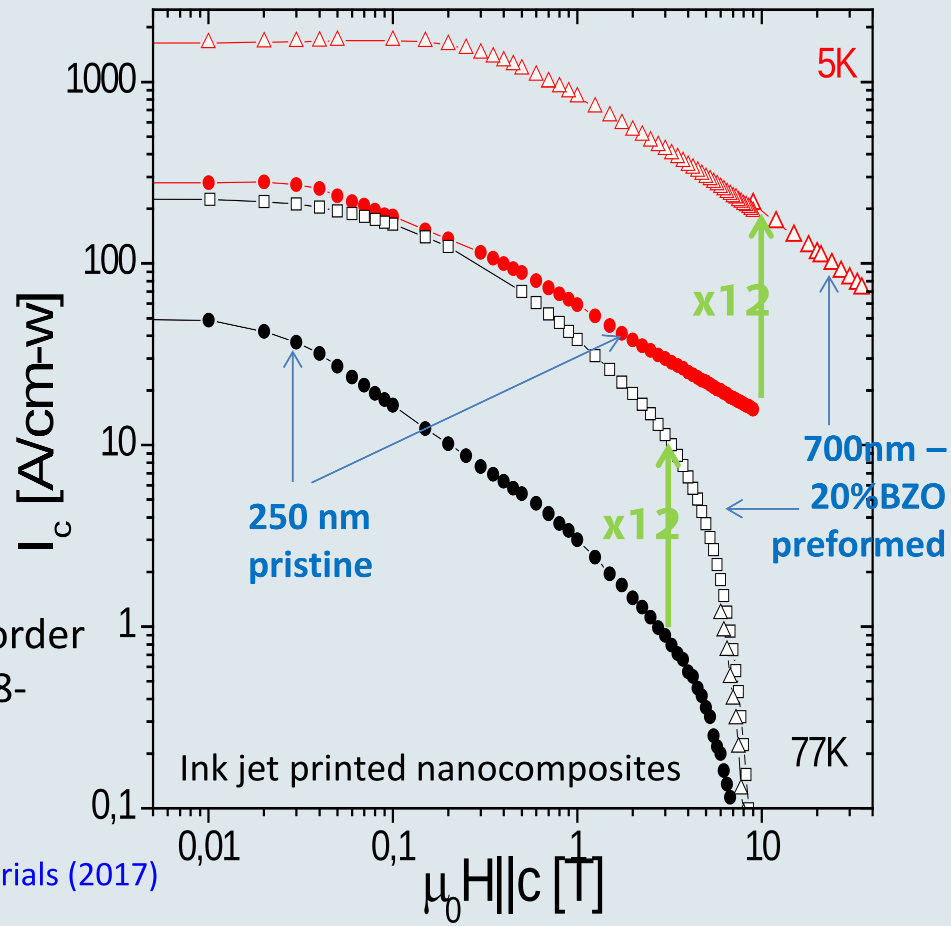
Outstanding properties of CSD nano-composites with rich pinning landscapes



HR-STEM images





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

Adv. Science **3** (2016), PRMaterials (2017)

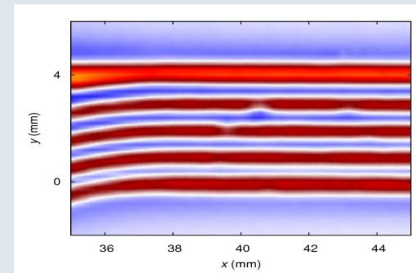
erc European Research Council Executive Agency

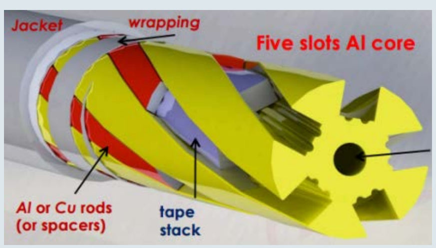
Latest approach is investigating liquid assisted growth of CSD (pre-formed) nanocomposites with 100 x faster growth rates

RE-123: current efforts

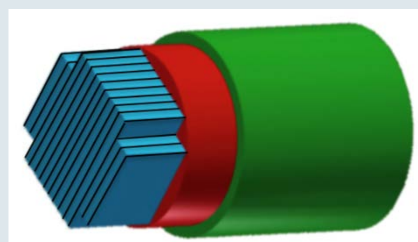
- Optimization of pinning for the respective operational conditions
  - Nano-precipitates: $BaZrO_3$ (BZO), $BaHfO_3$(BHO), $Ba_2YNb_{0.5}Ta_{0.5}O_6$ etc.
- Increasing RE-123 layer thickness
- Lowering production cost (upscaling, higher yield)
  - Chemical solution deposition, CSD
- Development of (superconducting) joints
- Quench detection/protection
- Filamentation (ac losses, field quality)
- Mechanical properties (delamination)
- High current wires/cables

Current distribution in filamented conductor





TRATOS - ENEA



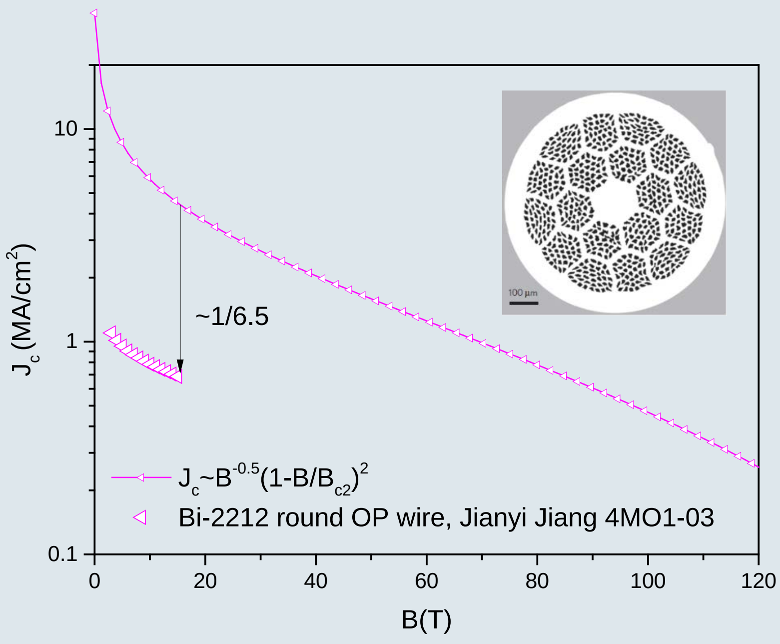
CroCo - KIT

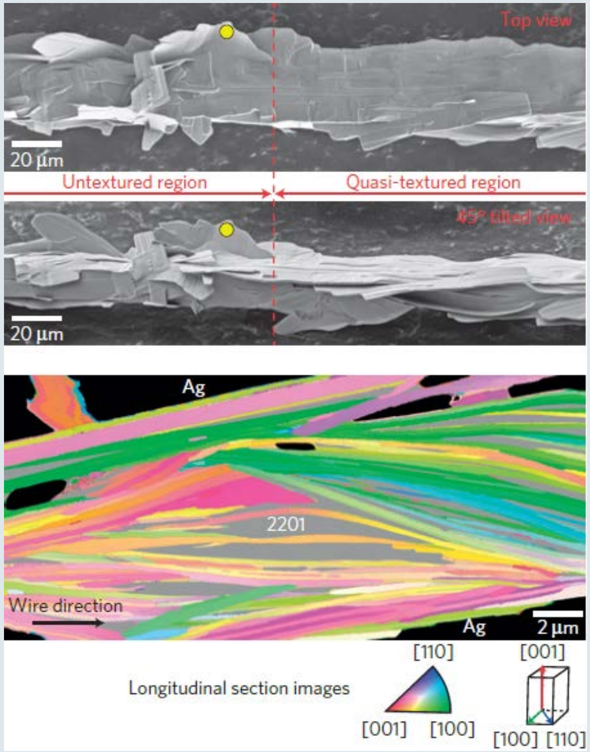
Fusion cable - EPFL

RACC - KIT

CORC® - Advanced Conductor Technologies LCC

Bi-2212





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

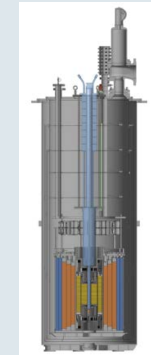
D. C. Larbalestier
Nature Mat. **13** (2014) 375

HTS Applications: High Field Magnets

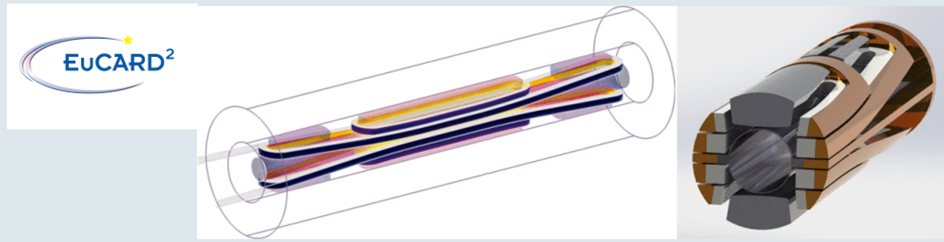
- 24.6 T cryogen free S. Awaji , 1P2

S. Awaji et al., SUST **30** (2017) 065001

- 32 T at Tallahassee (NbTi, Nb_3Sn, RE-123) Huub Weijers - 3P1

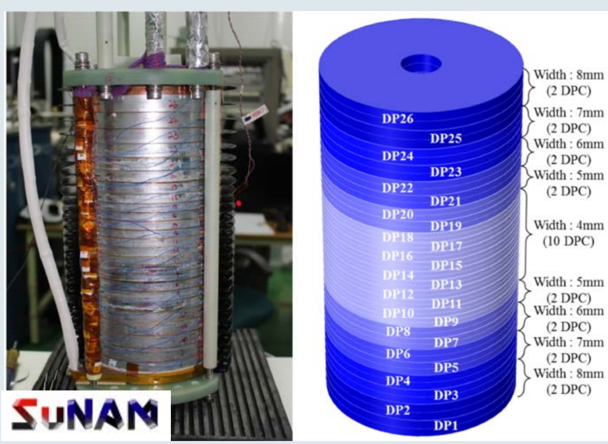


- Accelerator magnets



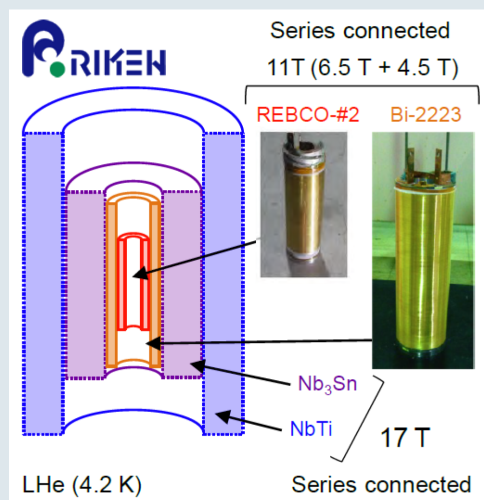
L. Rossi et al., IEEE TAS **25** (2015) 4001007, A. Kario 4LP4, P. Fazileau 3LP3

- 26.7 T, all RE-123
  no insulation coils
  (radial current sharing)



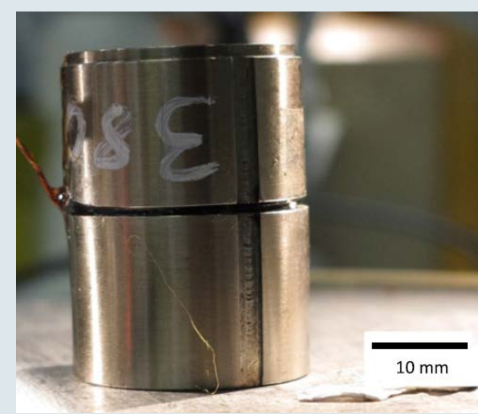
S. Yoon et al., SUST **29** (2016) 04LT04

- 27.6 T demonstrator for 1.3 GHz (30.5T) NMR project



Y. Yanagisawa et al., SNF, STH42

- 17.6 T @ 26 K
  $\emptyset = 2.5$ cm



J.H. Durrell et al.,
SUST **27** (2014) 082001

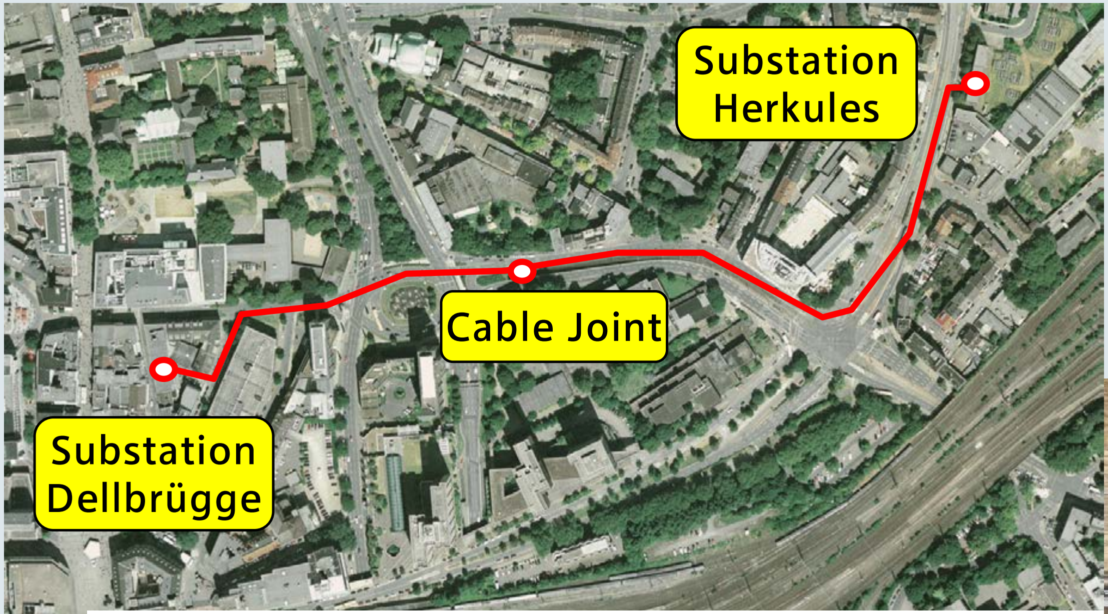
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Plenary presentation 2P1-01 given at EUCAS, 17-21 September 2017, Geneva, Switzerland.

(Possible) HTS applications

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

3.6 MW wind turbine, 128 m rotor diameter

https://ecoswing.eu/project



Luftbild: "Darstellung aus HK Luftbilder / Karten Lizenz Nr. 197 / 2012 mit Genehmigung vom Amt für Geoinformation, Vermessung und Kataster der Stadt Essen vom 13.02.2012"

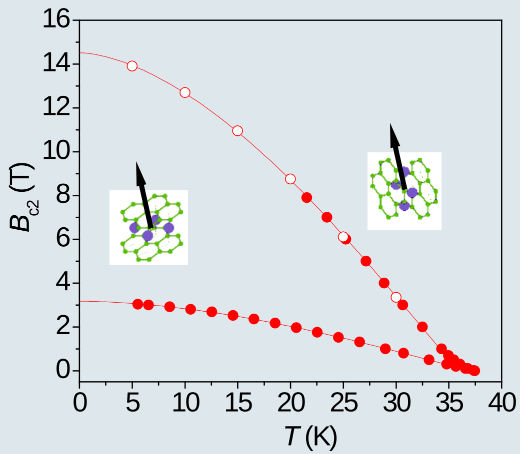
M. Stemmle et al., talk at CIRED 2015

Medium Temperature Superconductors

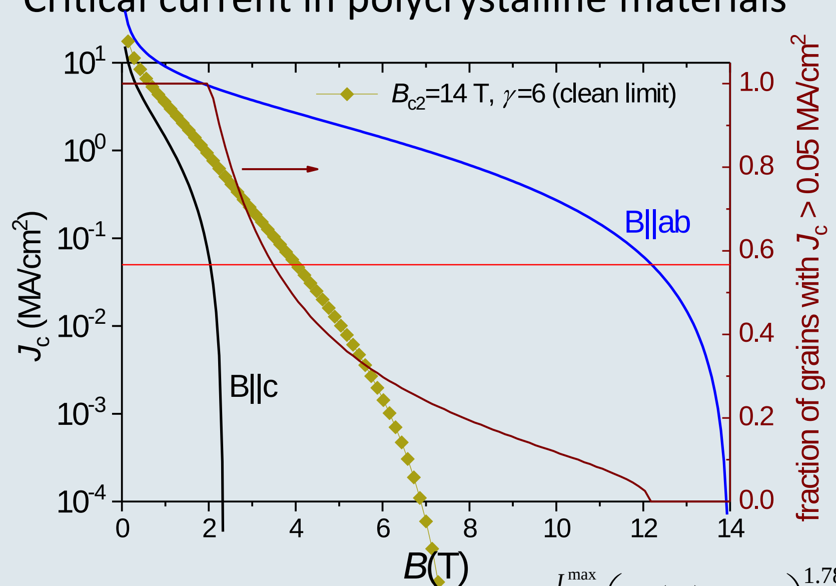
ALTERNATIVE MATERIALS

MgB_2

Upper critical field anisotropy: 5-6



Critical current in polycrystalline materials

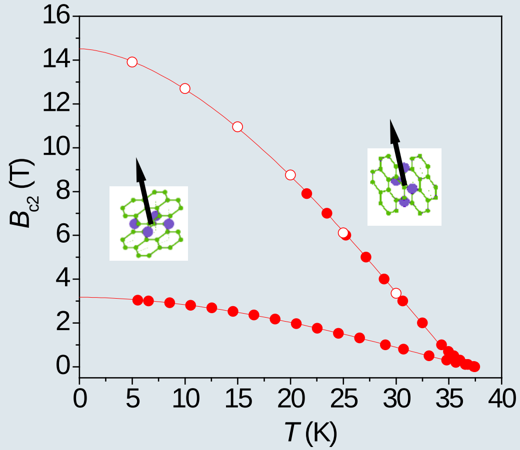


Calculated by a percolation model $J_c = \int_0^{J_c^{\max}} \left(\frac{p(J) - p_c}{1 - p_c} \right)^{1.78} dJ$

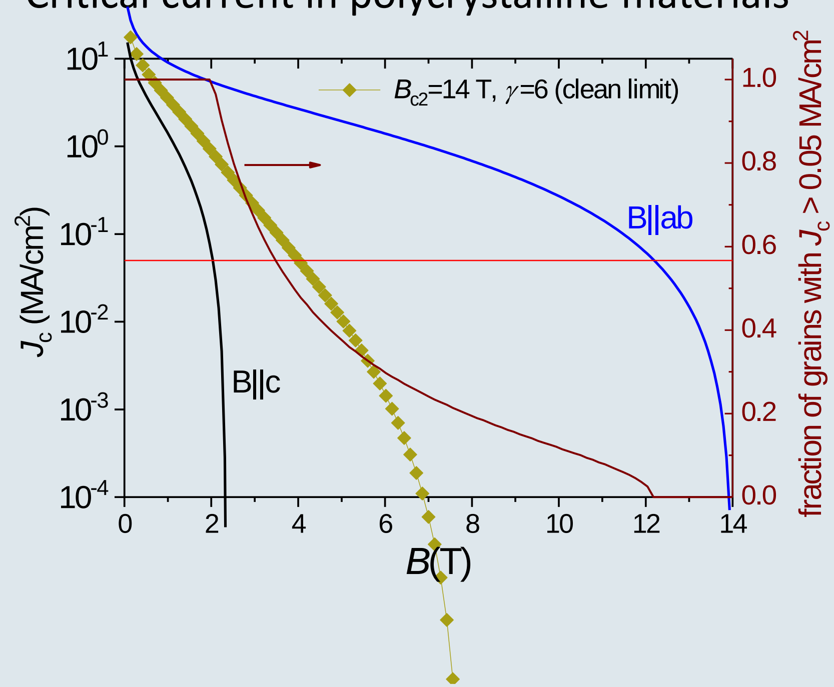
M. Eisterer et al., PRL **90** (2003) 247002

MgB_2

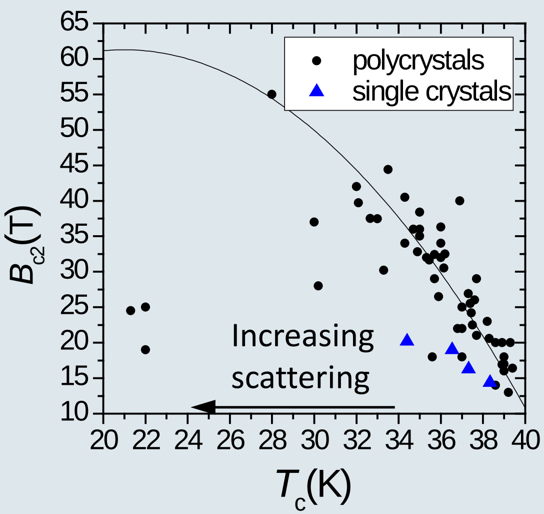
Upper critical field anisotropy: 5-6



Critical current in polycrystalline materials



Impurity scattering enhances B_{c2}



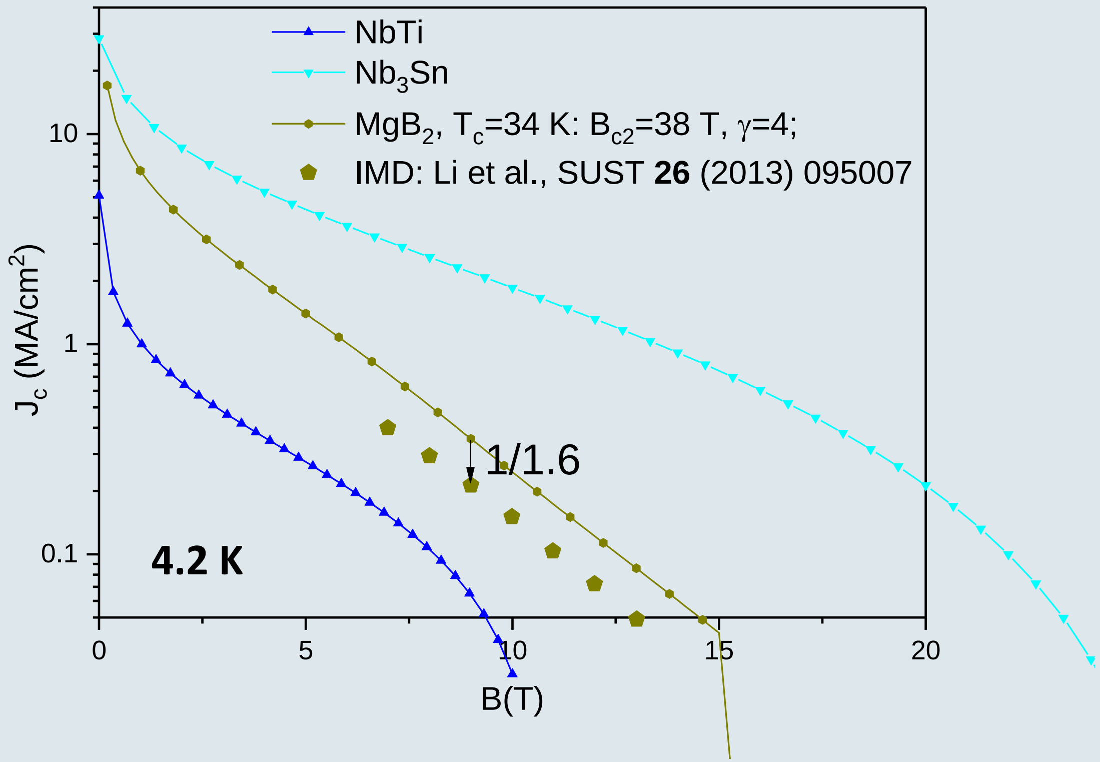
- Thin films: max. B_{c2}(H||ab)~70 T, B_{c2}(H||c)~40 T
- Bulk materials: max. B_{c2}(H||ab)<40 T, B_{c2}(H||c)~10 T
- Difference is not yet understood.

M. Eisterer, SUST **20** (2007) R 47

MgB_2

- Current issues
  - Low inter-grain connectivity (ex-situ & in-situ PIT)
  - Low mass density (in-situ PIT)
  - Small volume fraction (~10 % IMD)
- Significant potential for improvements
  - Conservative estimation: connectivity, volume fraction
  - Pinning: higher borides, Mg-B-O

T. Prikhna 4MP2



MgB_2

- Current issues
  - Low inter-grain connectivity (ex-situ & in-situ PIT)
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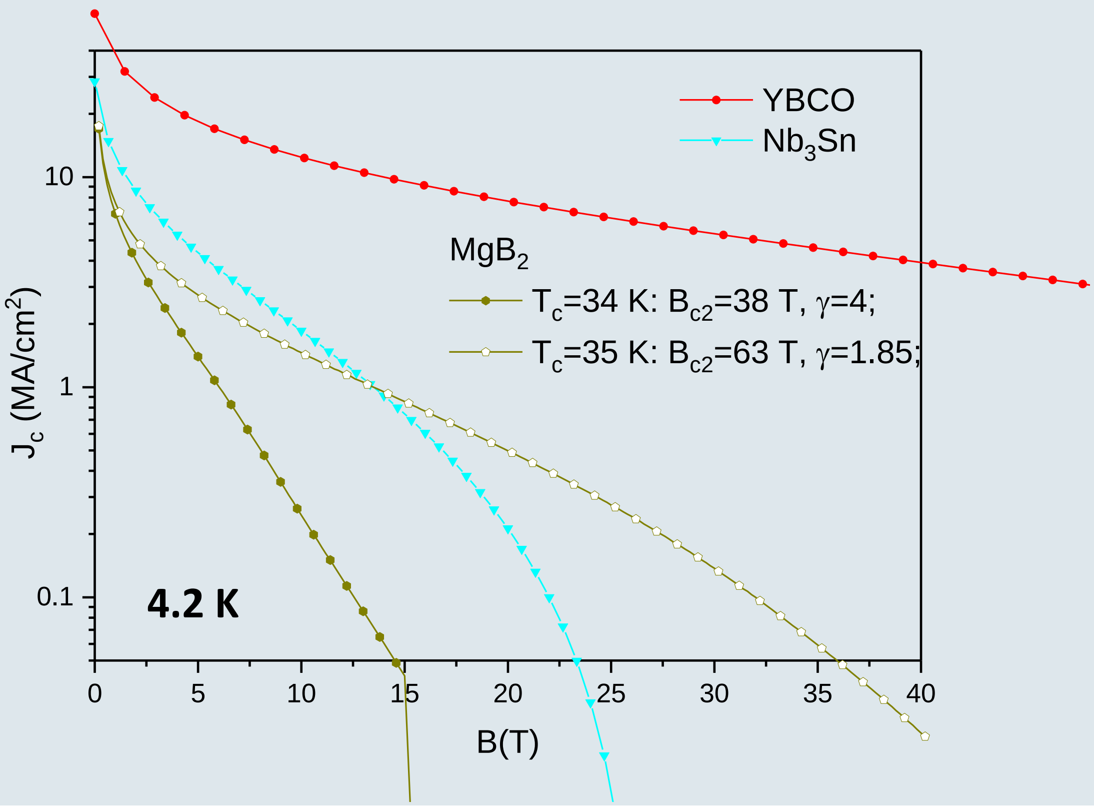
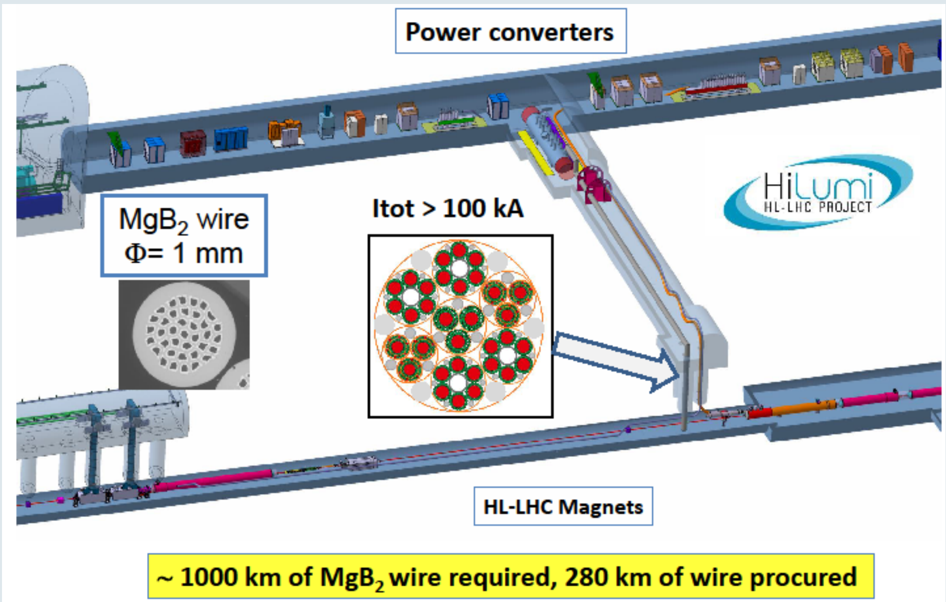
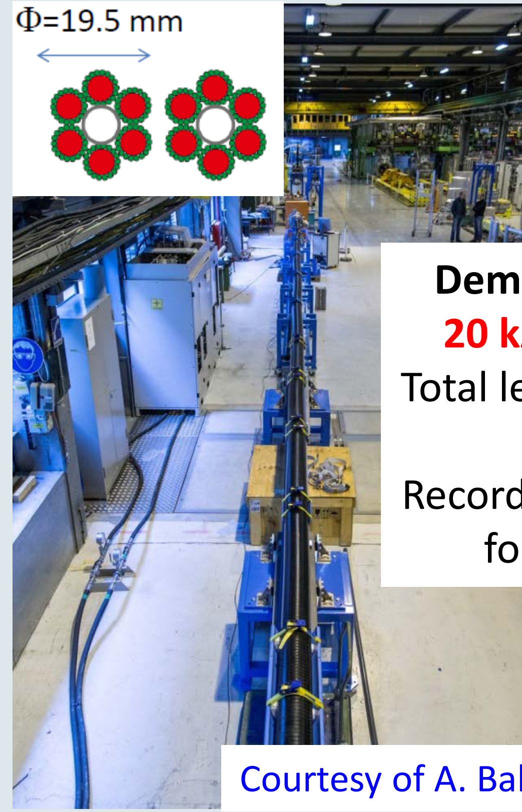
  - Small volume fraction (~10 % IMD)
- Significant potential for improvements
  - Conservative approach: connectivity, volume fraction Pinning: higher borides, Mg-B-O
    T. Prikhna 4MP2
  - **Thin film performance (B_{c2}, γ, T_c)**



MgB_2: Applications

- Power transmission
  - Superconducting cables for the HiLumi LHC



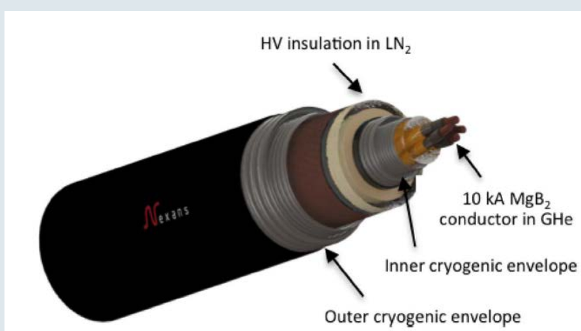


Demonstrator
20 kA at 25 K
Total length: 40 m

Record in current for MgB_2

Courtesy of A. Ballarino (CERN)

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



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

Best Paths
TRANSMISSION FOR SUSTAINABILITY

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

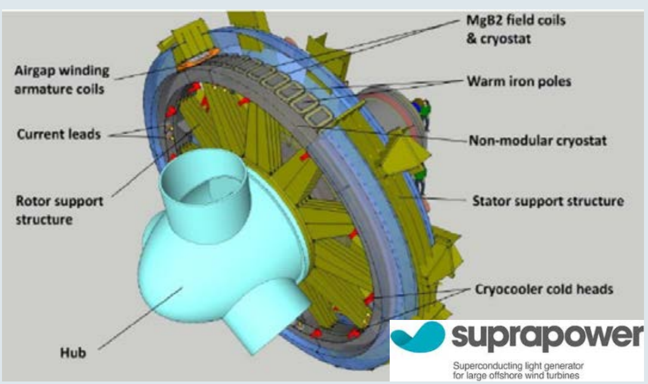
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Plenary presentation 2P1-01 given at EUCAS, 17-21 September 2017, Geneva, Switzerland.

MgB_2: Applications

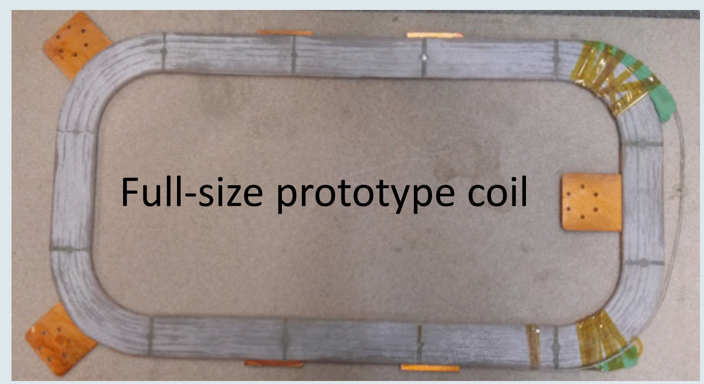
- Magnetic Resonance Imaging (MRI)
  - Commercial System
    - 0.5 T at 20 K
    - Cryocoolers

www-paramed.it

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



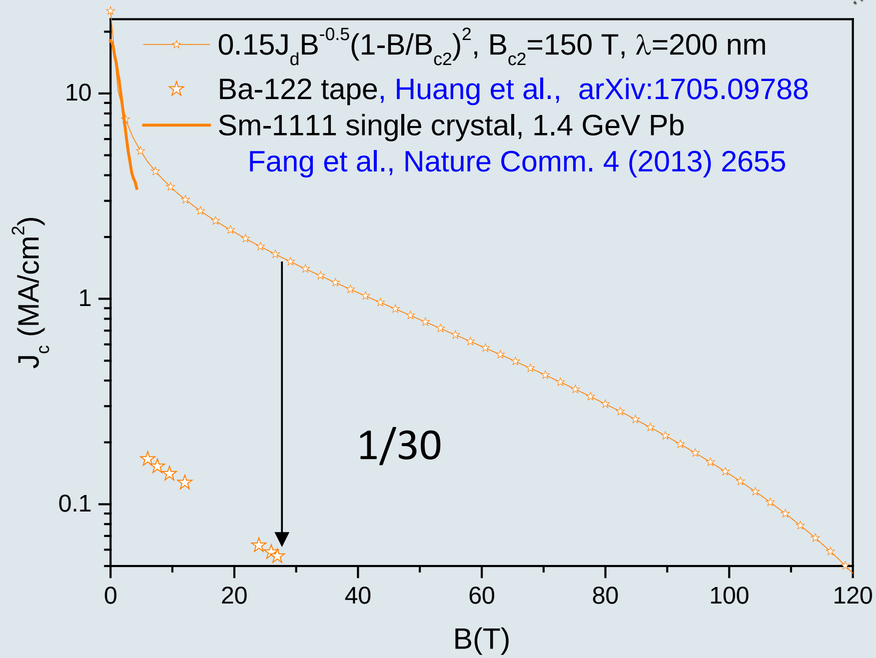
J. Sun et al., IOPCS MSE **101** (2015) 012088



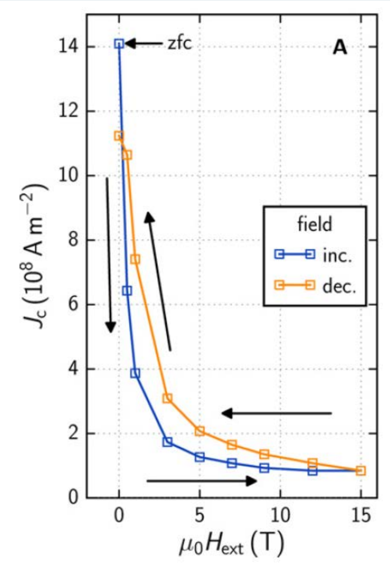
G. Sarmiento et al., IEEE TAS **26** (2016) 5203006

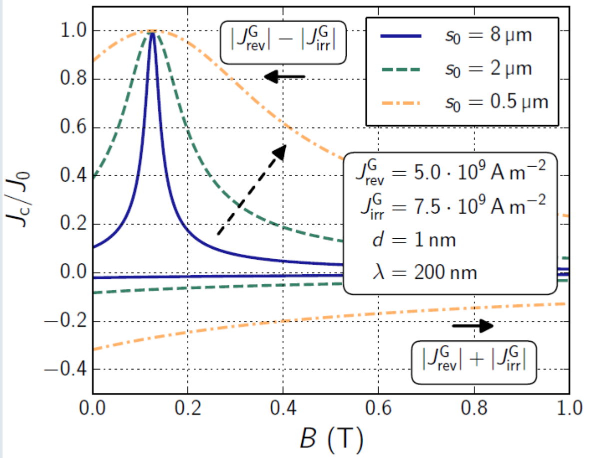
$BaFe_2As_2$

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



Polycrystalline materials:
Josephson coupled grains



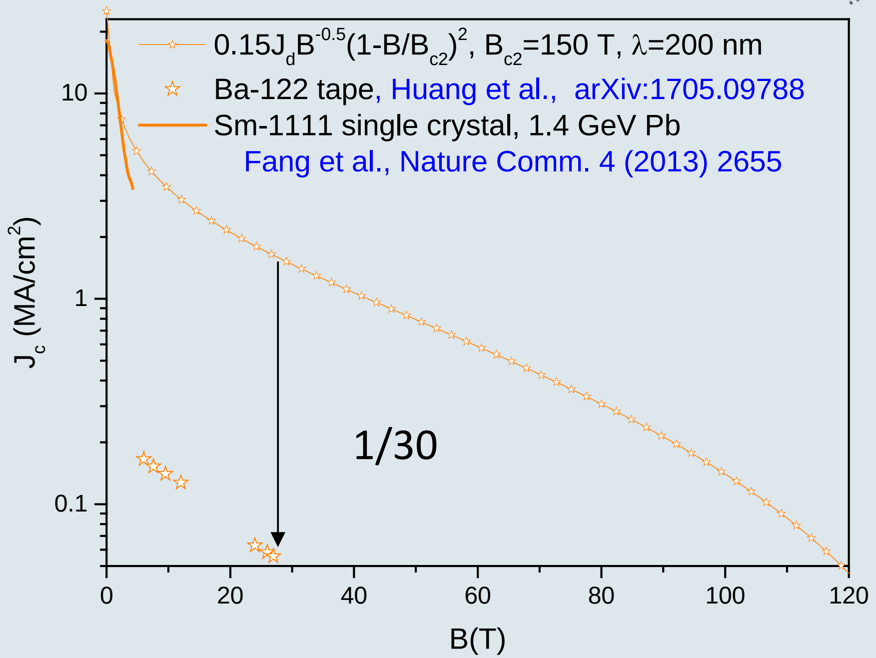


- J_c increases with decreasing grain size.
- Strong pinning within the grains reduces global J_c (increasing fields).

J. Hecher et al., SUST **29** (2016) 025004

$BaFe_2As_2$

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

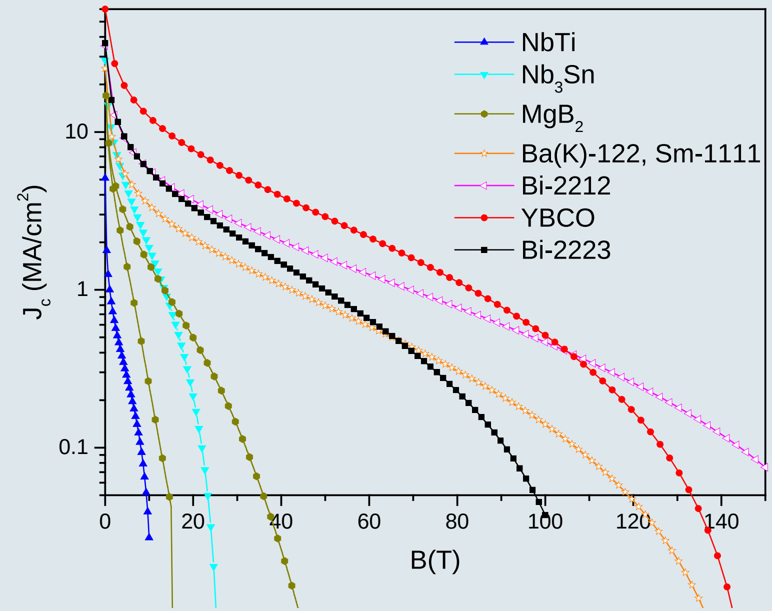


Strategies for J_c improvement (inter-grain connectivity):

- Extrinsic limitations
  - Reduction of secondary phases and cracks at the grain boundaries
- Intrinsic limitation (grain boundary angle):
  - Reduction of grain size
  - (Partial) texture

Conclusions

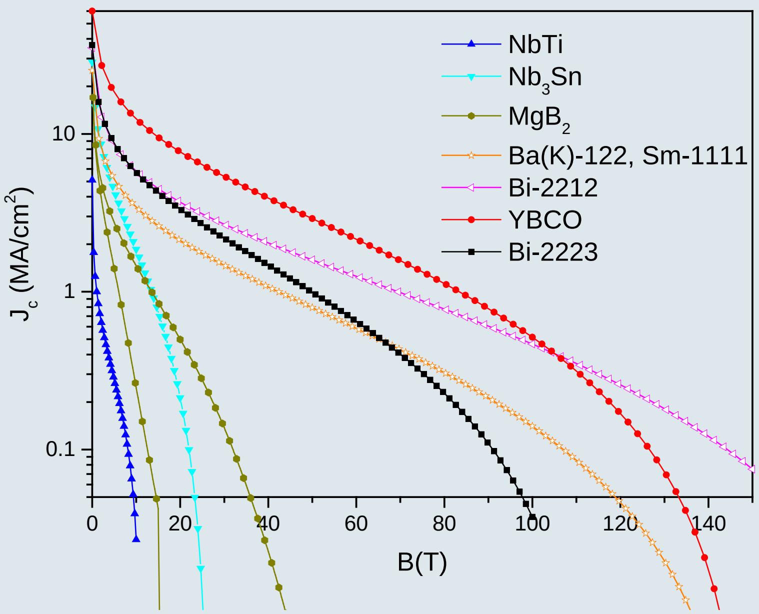
- RE-123 compounds have the most favorable superconducting properties. Pinning is highly optimized in coated conductors.
- The sc properties have to fulfill only the minimum requirements of the respective application. The cheapest solution (conductor, required technologies) is usually chosen.



- The outstanding performance of CC is mandatory so far only for high field magnets, with Bi-2212 being an interesting competitor.
- Despite the many interesting activities, a sufficiently large market for CCs is still missing. If it cannot be established, we risk to lose this option for future applications, where the performance of established superconductors is insufficient.

Conclusions

- MgB_2 is an interesting alternative for low field applications, since it can be operated without liquid helium. The in-field properties of wires are poor. It is unclear how to achieve the high critical field demonstrated in thin films.
- The iron-based superconductors promise excellent high field properties. The central issue is currently the inter-grain connectivity.



Conclusions

- MgB_2 is an interesting alternative for low field applications, since it can be operated without liquid helium. The in-field properties of wires are poor. It is unclear how to achieve the high critical field demonstrated in thin films.
- The iron-based superconductors promise excellent high field properties. The central issue is currently the inter-grain connectivity.

Thank you for your attention!