High-T$_c$ superconductors for next-generation undulators

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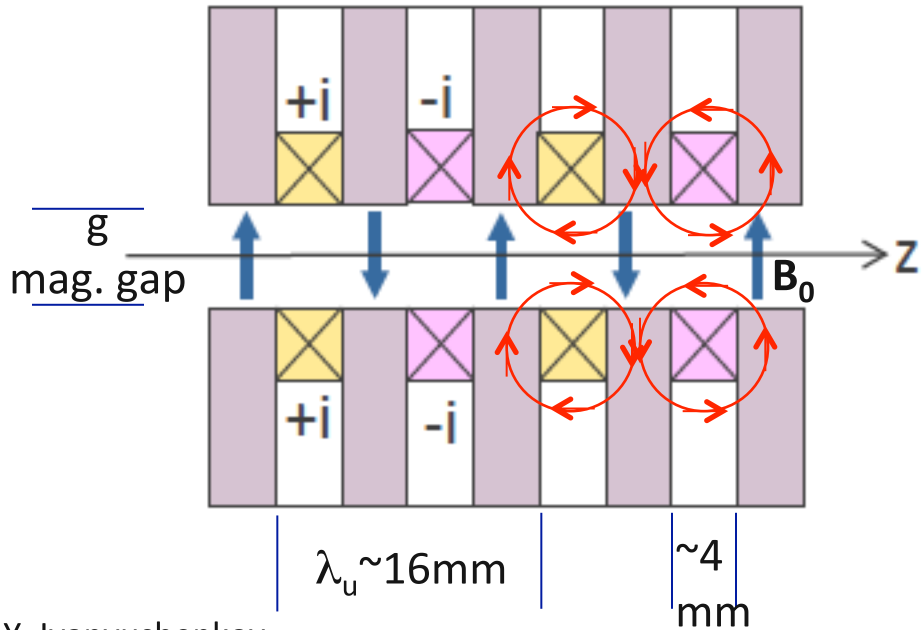
OUTLINE

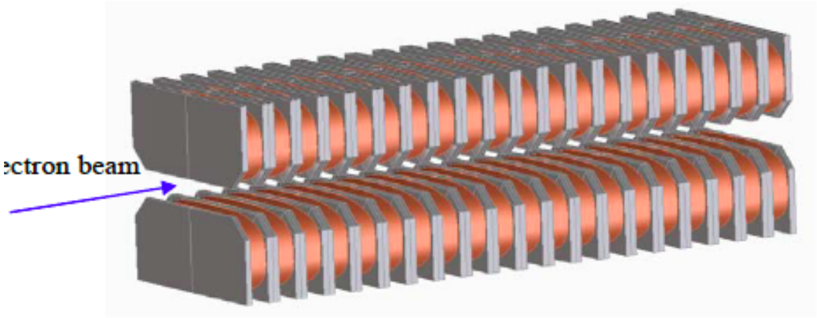
- Introduction
- YBCO-coated conductors
- Winding schemes

Introduction



Y. Ivanyushenkov

sc coils with magnetic poles



planar undulator

$$\lambda = \frac{\lambda_u}{2\gamma}\left(1+\frac{K^2}{2}\right) \qquad E(keV) = \frac{0.95E_e^2[GeV]}{\lambda_u[cm]\left(1+K^2/2\right)}$$

$$K = 0.93B_0[T]\lambda_u[cm]$$

Name of the Game:
As much current through the winding-block as possible at highest possible temperature

superconducting windings

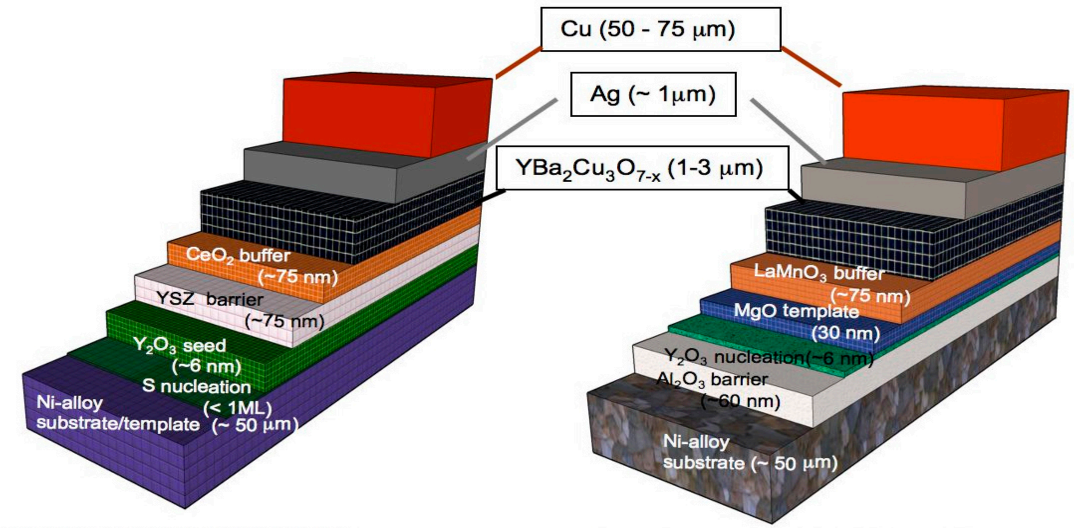
Highly non-uniform field (cf., sc solenoid, power-cables)

Field cancellations: $B_0 \sim \exp\left(-\alpha g / \lambda_u\right)$

YBaCuO Coated Conductors

Highly engineered, commercial products

(American Superconductor, SuperPower, Fujikura, Showa)



Rolling-Assisted Biaxially Textured Substrates (RABiTS)

Ion-Beam-Assisted Deposition (IBAD)

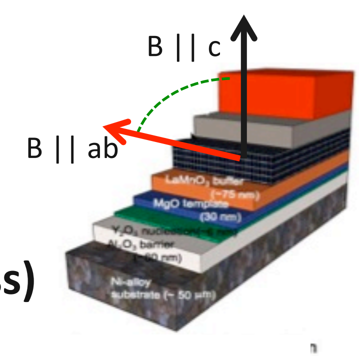
Multi-layered tapes:
avoid grain-boundaries

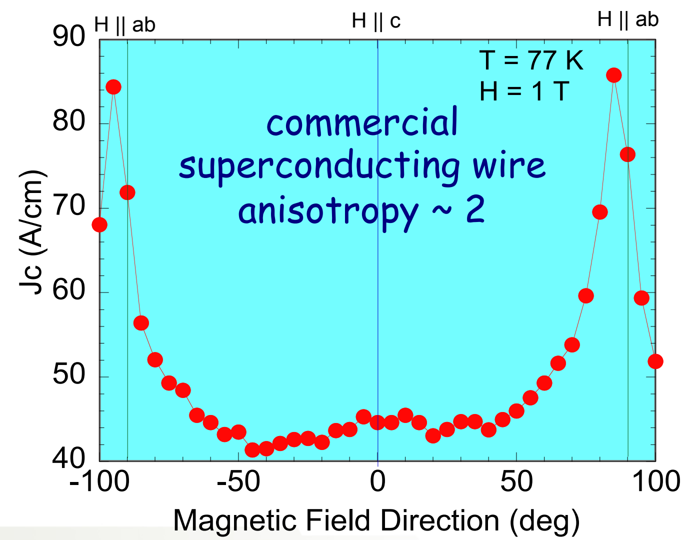
J_c (77K,sf) ~ 3-5 MA/cm^2

T_c ~ 92 K: T-margin for cryo-plant

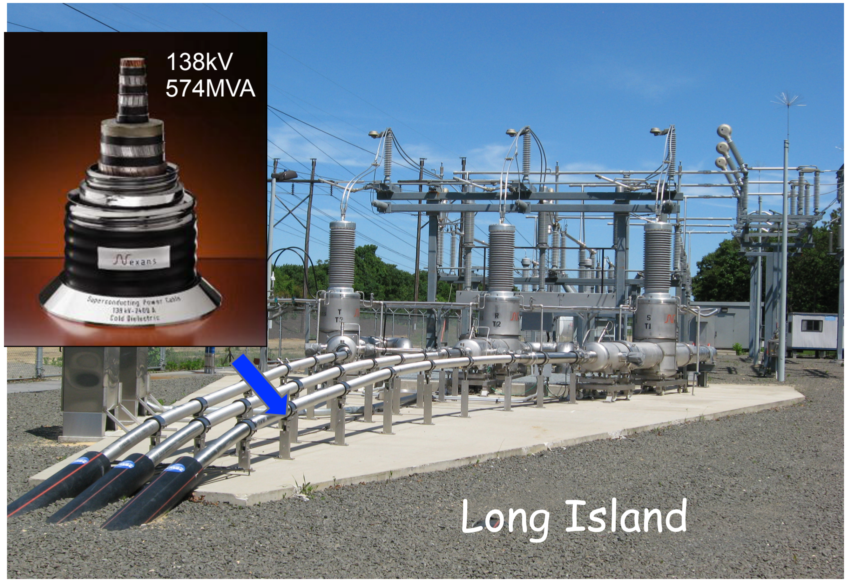
High mechanical strength

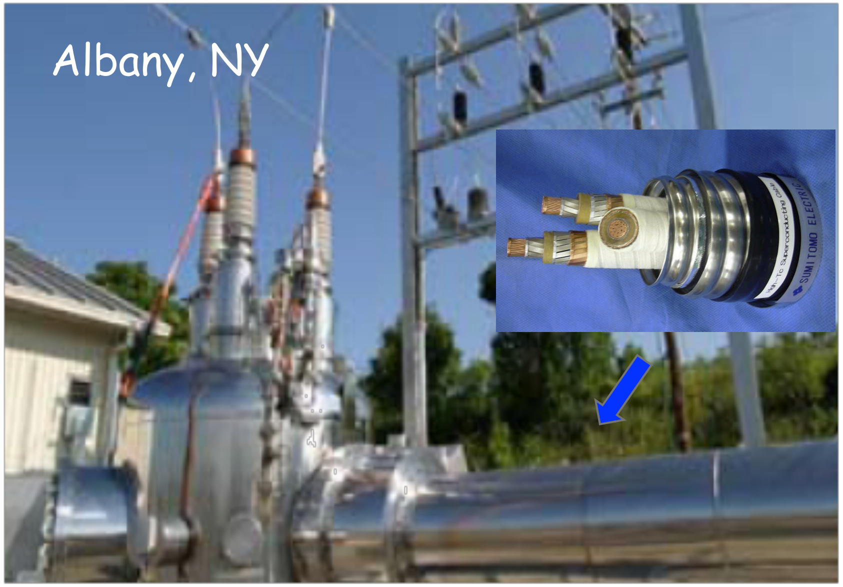
- **Anisotropy:**
  conductor shape, J_c vs field angle
- **J_c(B)**
- **J_E ~ 1-2% J_c (J_c decreases with thickness)**
- **no sc-joints**

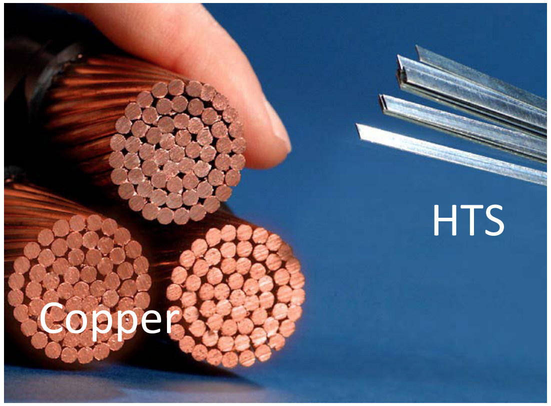




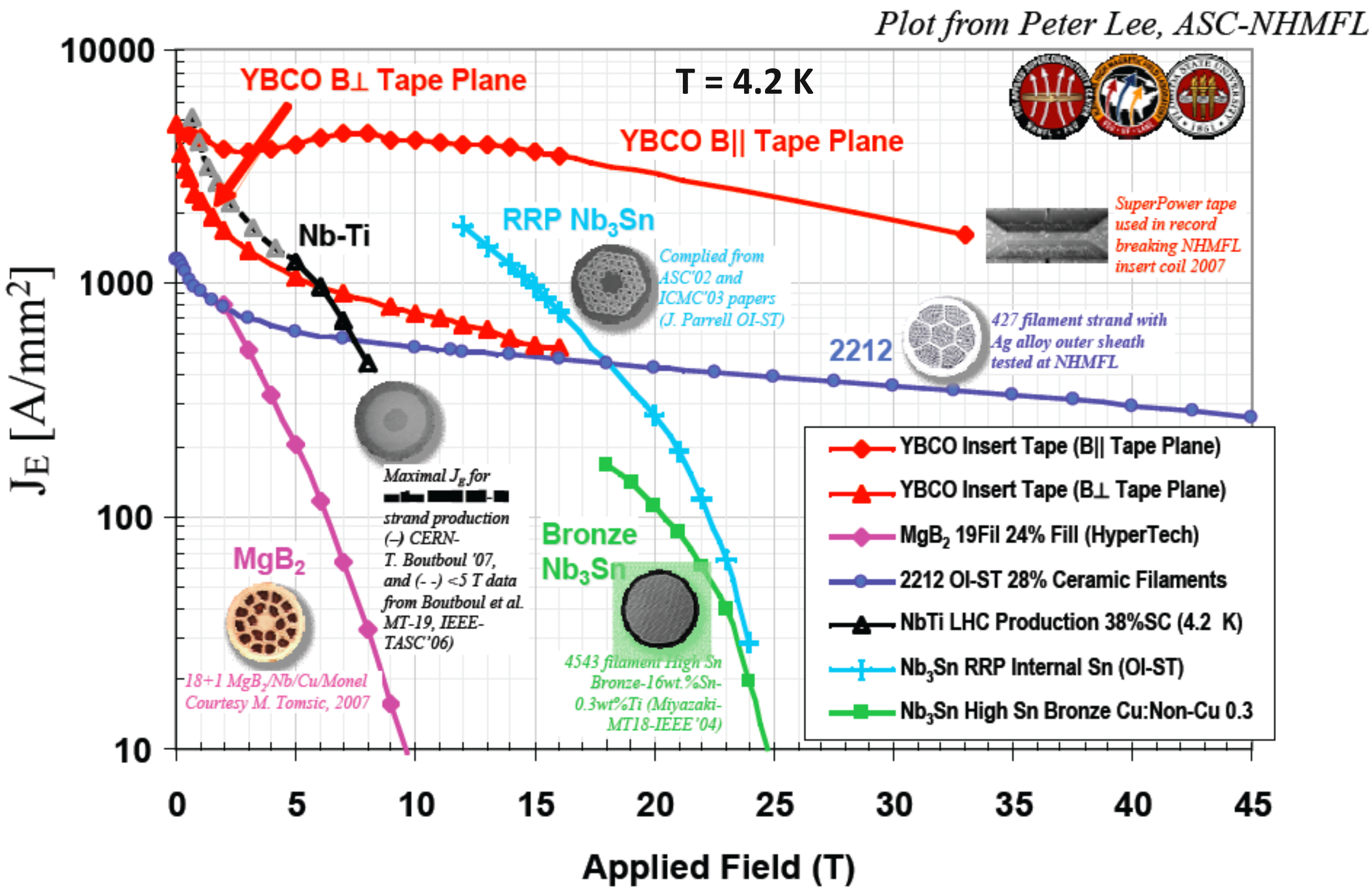
impacting the grid today …



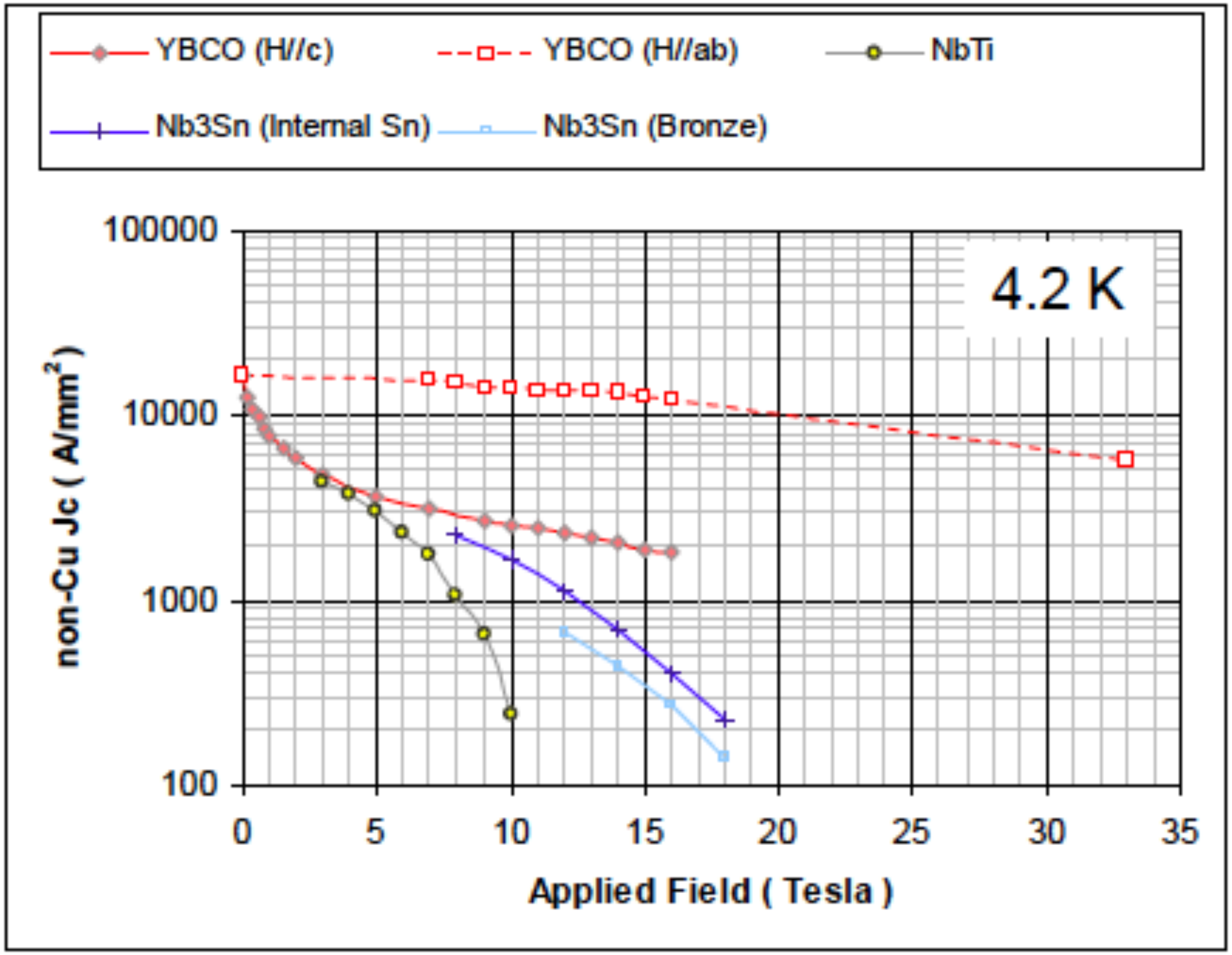




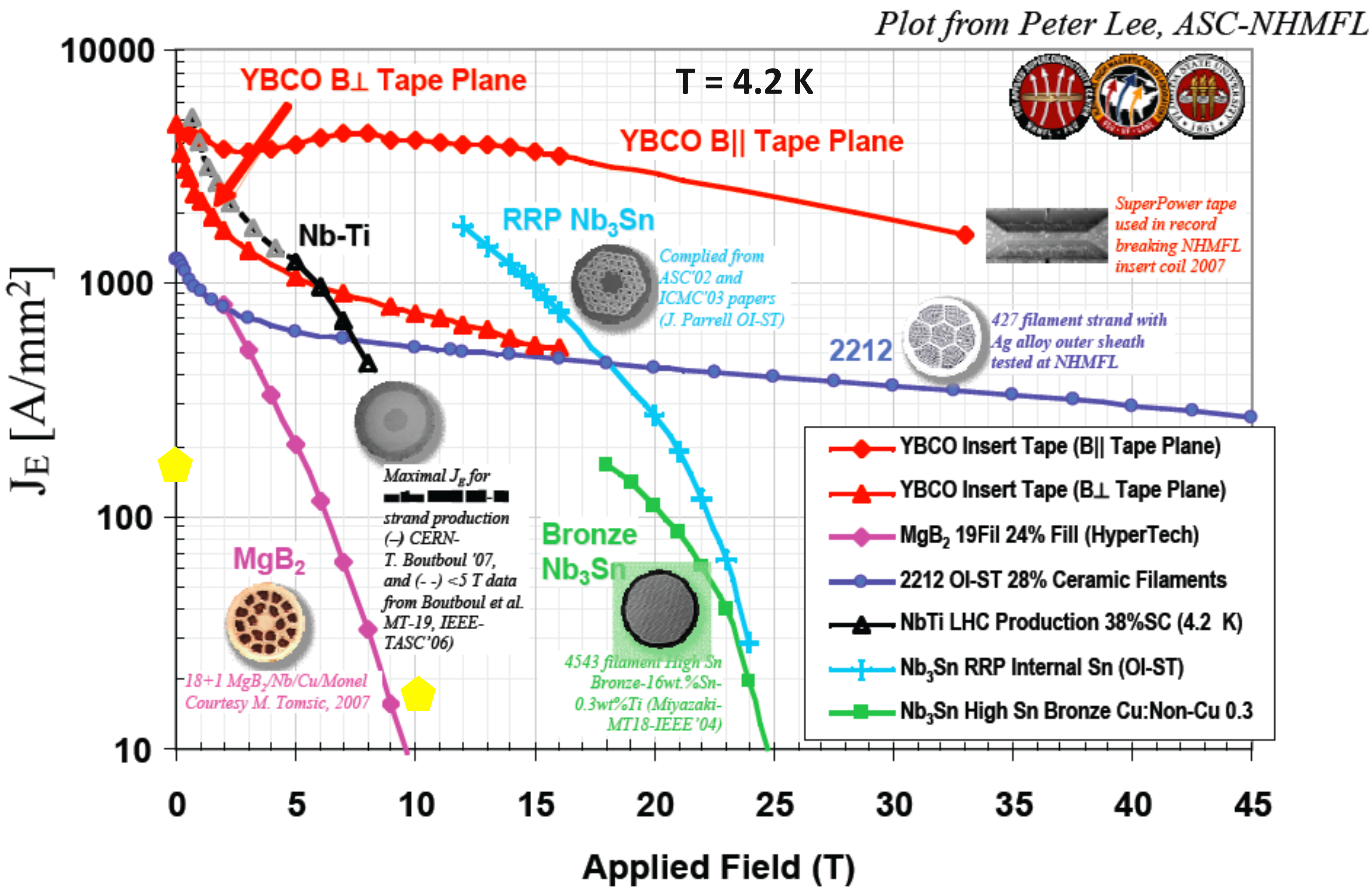
5x power capacity of copper in same cross-sectional area



Plot from Peter Lee, ASC-NHMFL
T = 4.2 K
YBCO B⊥ Tape Plane
YBCO B|| Tape Plane
Nb-Ti
RRP Nb_3Sn
Complied from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
SuperPower tape used in record breaking NHMFL insert coil 2007
2212
427 filament strand with Ag alloy outer sheath tested at NHMFL
Maximal J_E for [redacted] strand production (–) CERN-T. Boutboul '07, and (- -) <5 T data from Boutboul et al. MT-19, IEEE-TASC'06)
MgB_2
18+1 MgB_2/Nb/Cu/Monel Courtesy M. Tomsic, 2007
Bronze Nb_3Sn
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
YBCO Insert Tape (B|| Tape Plane)
YBCO Insert Tape (B⊥ Tape Plane)
MgB_2 19Fil 24% Fill (HyperTech)
2212 OI-ST 28% Ceramic Filaments
NbTi LHC Production 38%SC (4.2 K)
Nb_3Sn RRP Internal Sn (OI-ST)
Nb_3Sn High Sn Bronze Cu:Non-Cu 0.3
J_E [A/mm²]
10000
1000
100
10
0
5
10
15
20
25
30
35
40
45
Applied Field (T)



V. Selvamanickam et al., EUCAS 2011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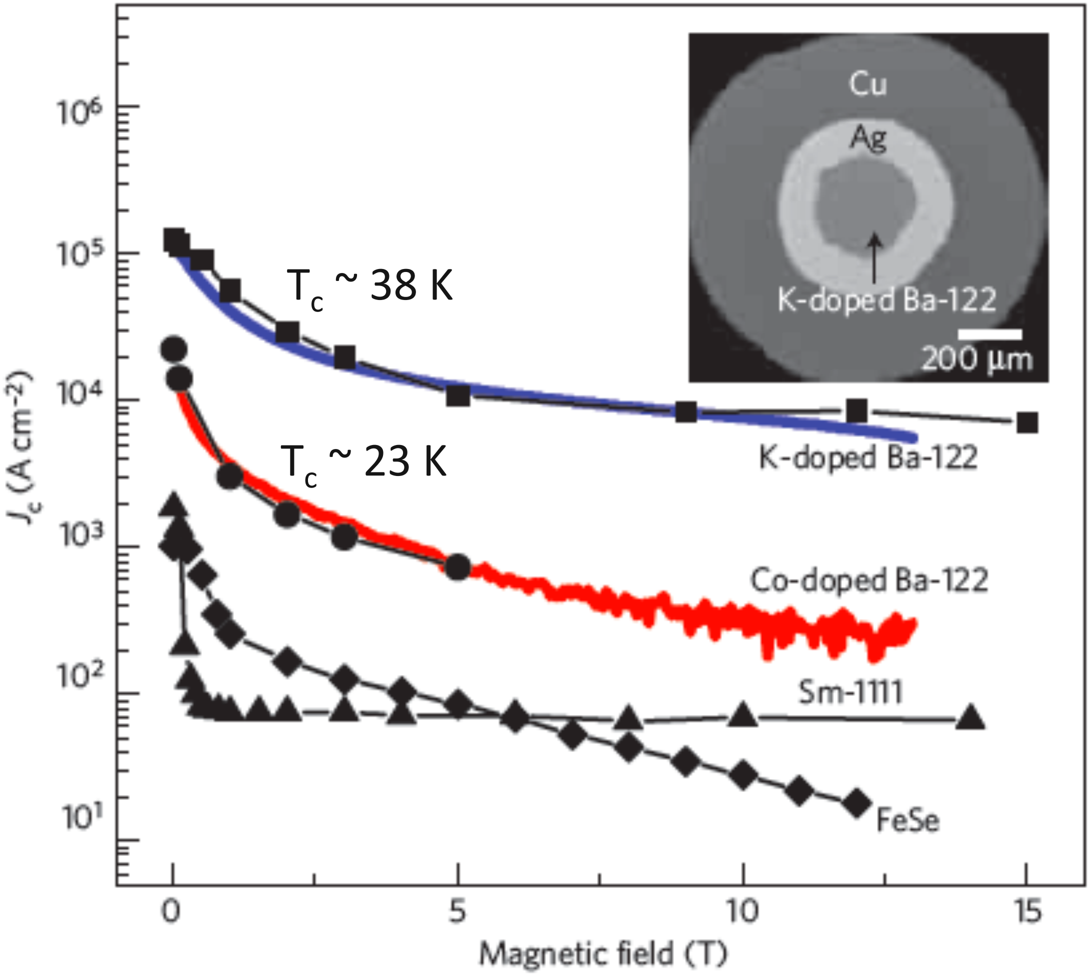
Nb_3Sn RRP Internal Sn (OI-ST)
Nb_3Sn High Sn Bronze Cu:Non-Cu 0.3
J_E [A/mm^2]
10000
1000
100
10
0
5
10
15
20
25
30
35
40
45
Applied Field (T)

FeAs-superconductors

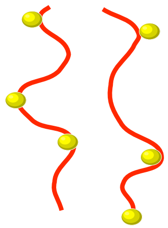


J_E ~ 7% J_c

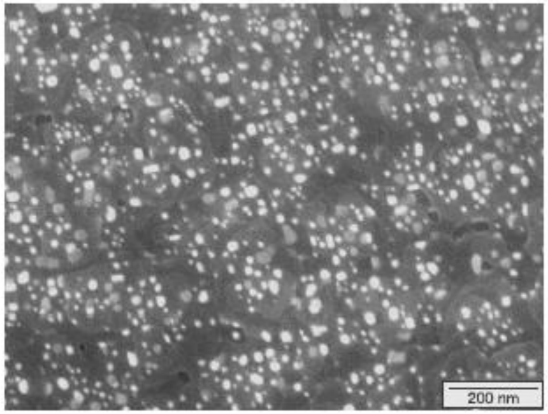
J. D. Weiss et al., Nat. Mat. **11**, 682 (2012)

Natural and Engineered Defects for Vortex Pinning

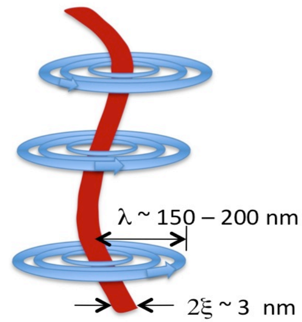
14 nm YBa_2CuO_5 nano-particles (211) in YBCO films



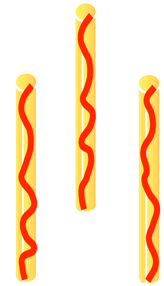
Collective pinning



T. Haugan, et al. Nature 430, 867 (2004)

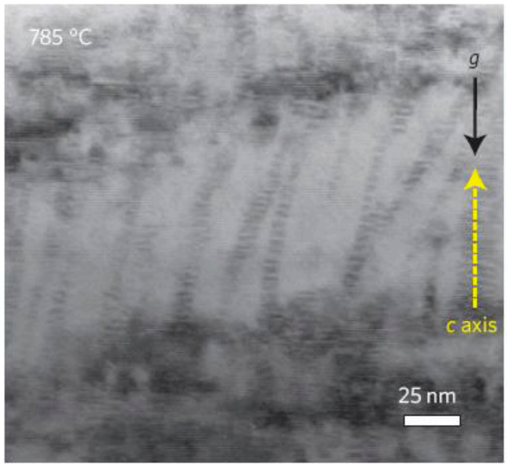


Normal core with circulating supercurrents



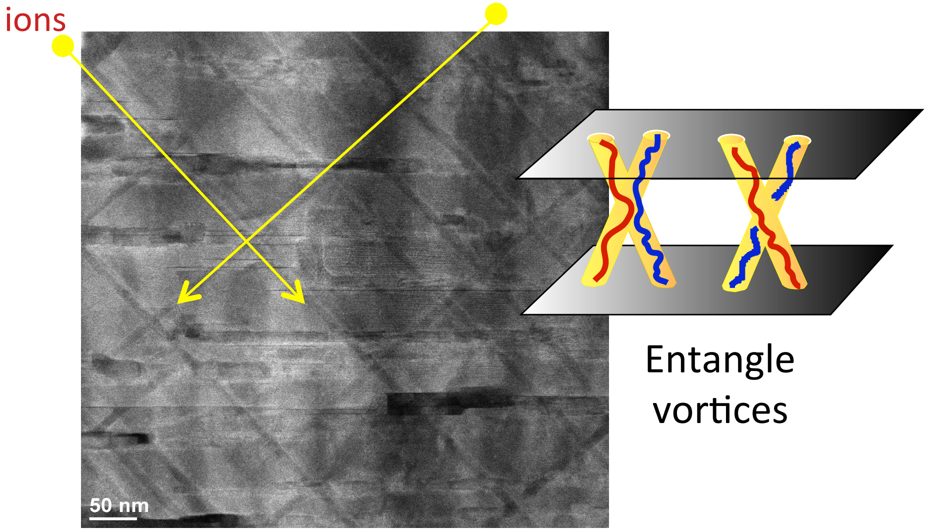
Pin entire vortex length

Self-organized BaZrO columnar defects in YBCO films



B. Maiorov et al, Nature Materials 8, 398 (2009)

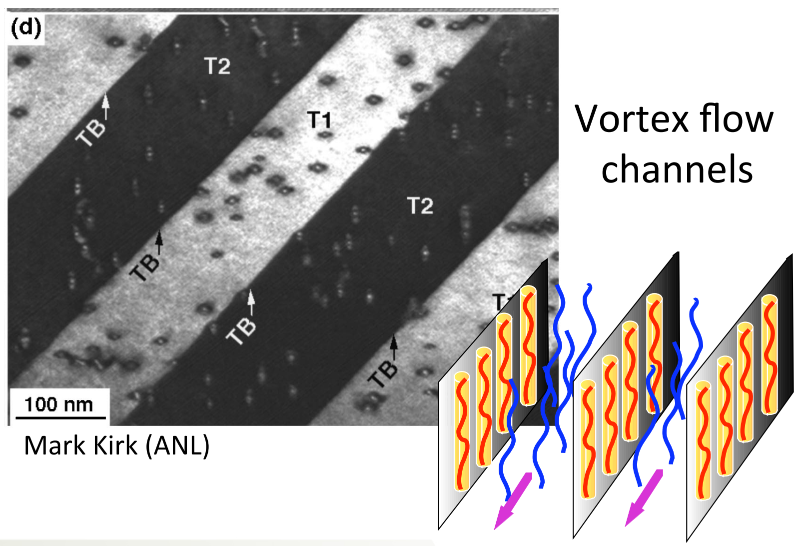
Splayed amorphous tracks in YBCO films created by heavy ion irradiation



Entangle vortices

Jim Zuo (UIUC)

Twin boundaries in YBCO with columnar defects



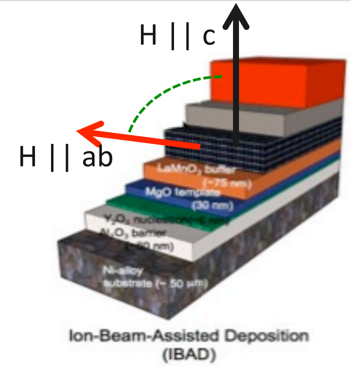
Mark Kirk (ANL)

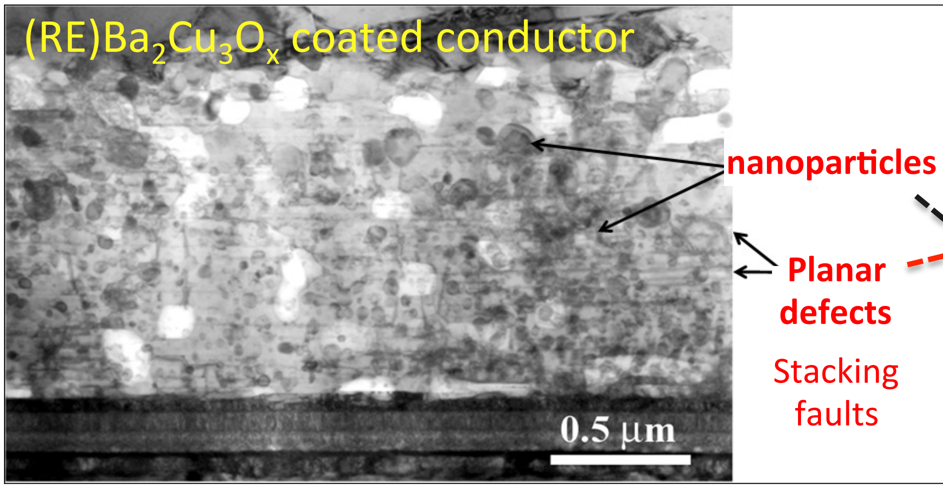
Vortex flow channels

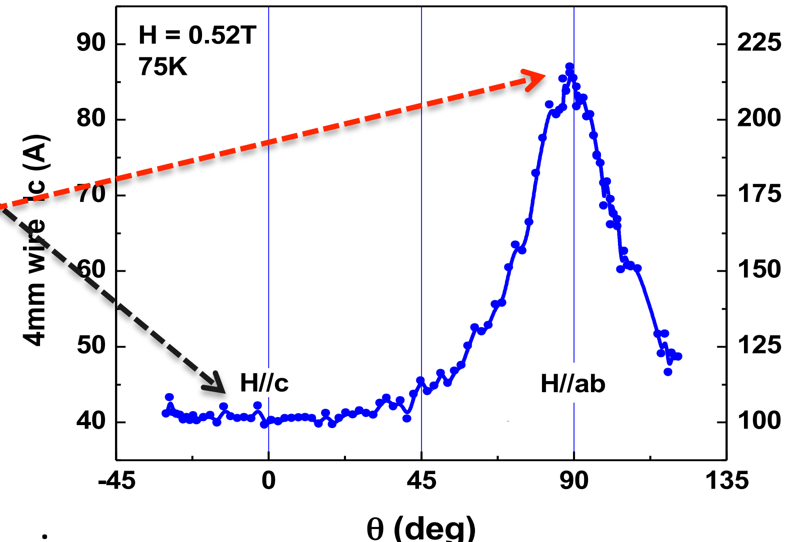
Engineering Vortex Pinning Landscapes

Motors and Generators ~850 A/cm-w at design point

- 30 K, 1.5T field oriented along *c-axis*
- 30K, 2.5T field oriented at 10° off *ab-plane*
- *Anisotropy of Ic for H||ab / H||c ~ 1.5 to 2*







(RE=Dy, Ho, etc)$_2$O$_3$ nanoparticles 20 – 30nm :

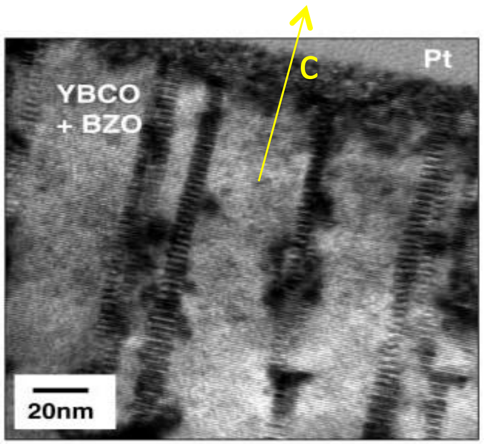
- large particles associated with twins
- vortex pinning due to strain fields around nanoparticles and twins

Stacking faults due to formation of (RE)$_2$Ba$_4$Cu$_7$:

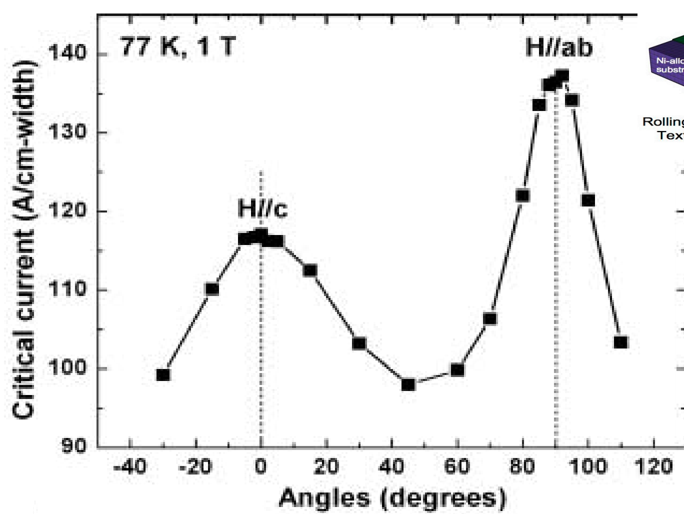
- density controlled by excess (RE) and oxygenation temperature
- effective vortex pinning at T > 50K
- intrinsic pinning mechanism due to inherent layered structure effective below 30K

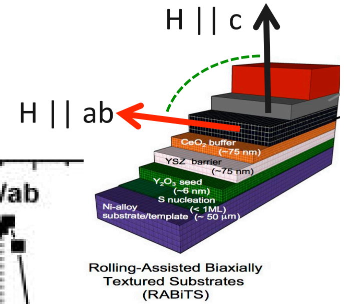
Engineering Vortex Pinning Landscapes

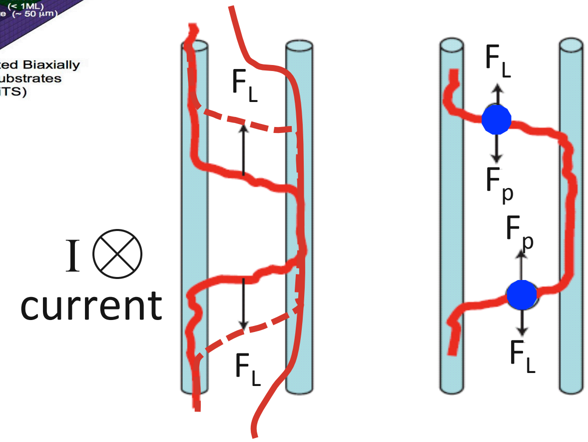
Self-assembled BaZrO nanoparticles



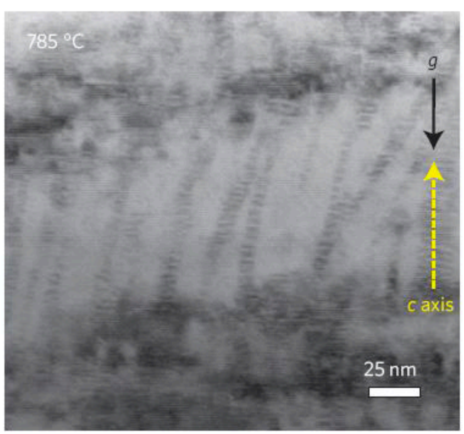
S. Kang et al., Science 311, 1911 (2006)

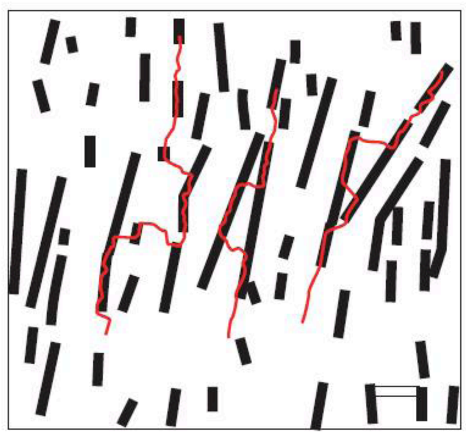






Combination of BaZrO nano-rods & particles





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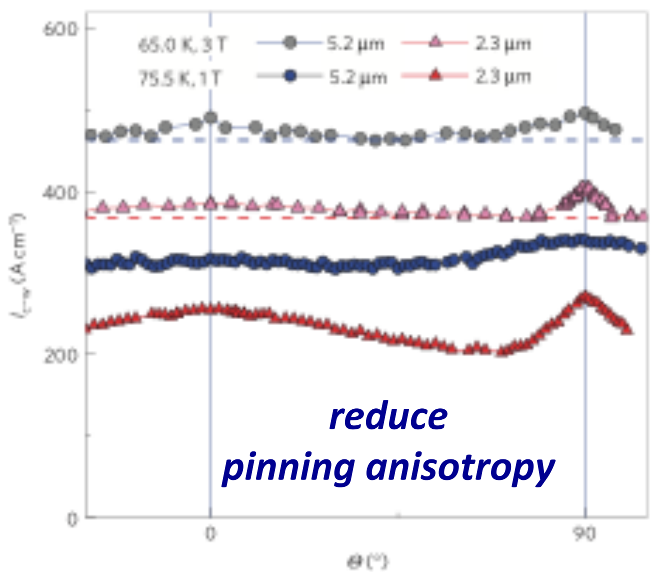
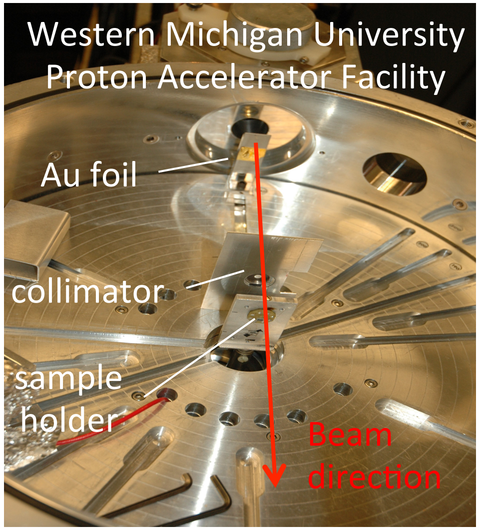


reduce pinning anisotropy

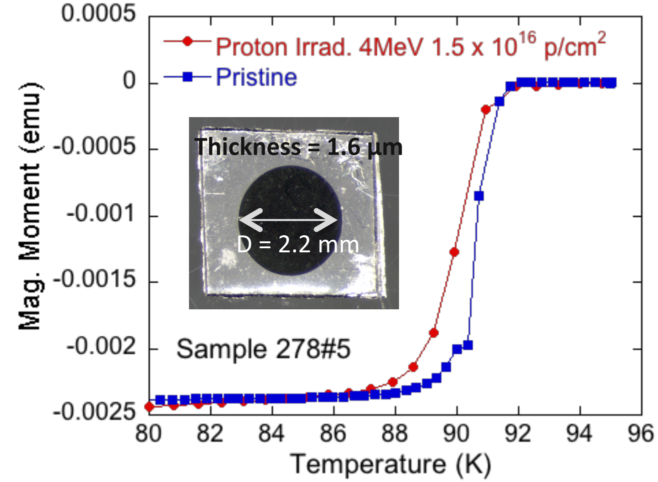
Proton Irradiation – doubling the critical current!

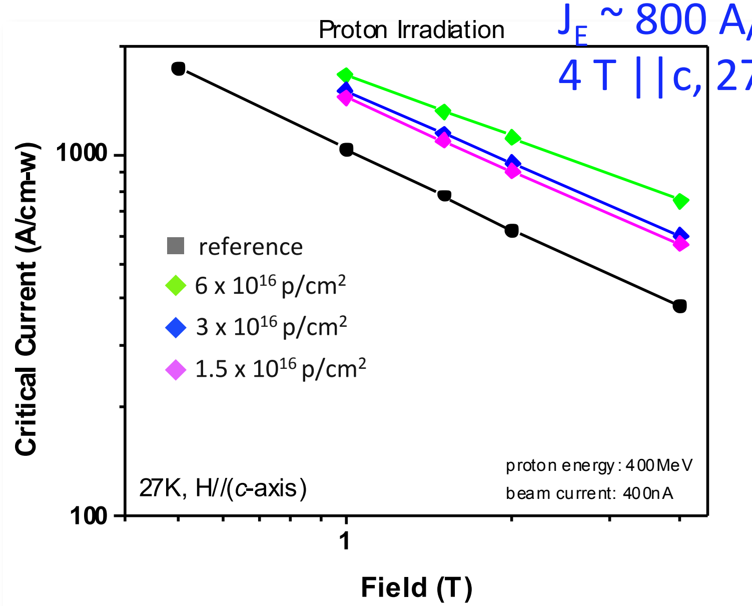


4 MeV Proton irradiation

Two types of defects: (10^{15} p/cm^2)

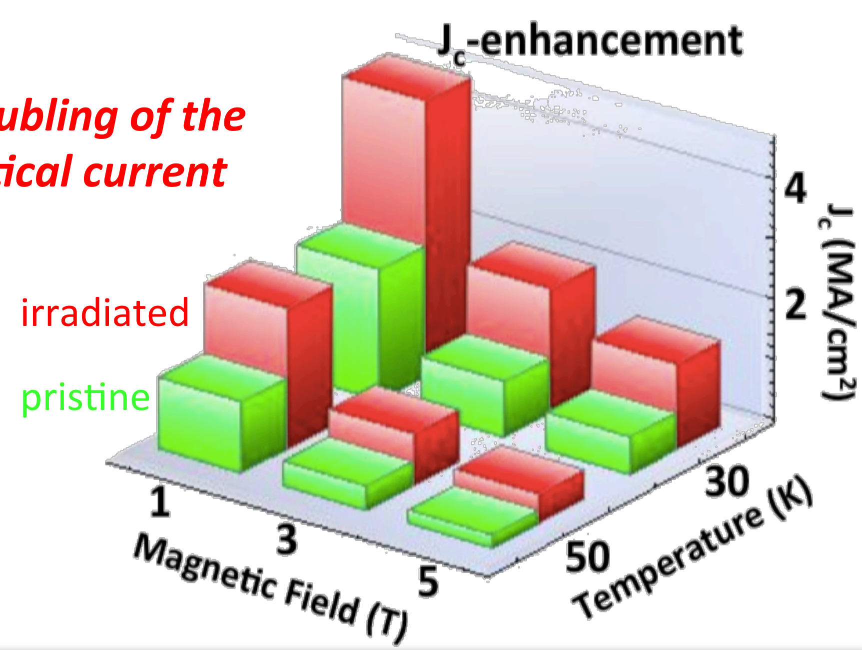
- weak random point defects
  - defect separation ~ 170 to 85Å
- cluster defects (~3nm)
- on existing wires,
  scale-up to production level



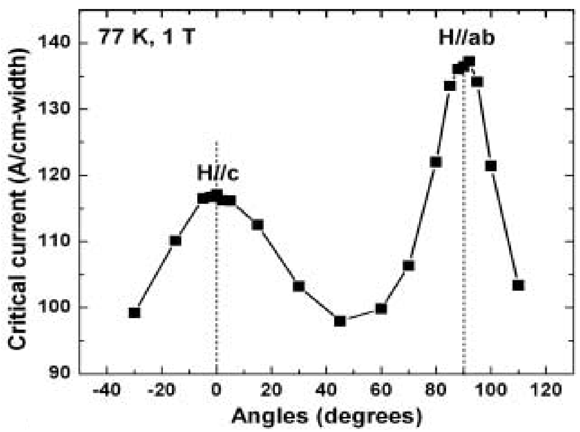


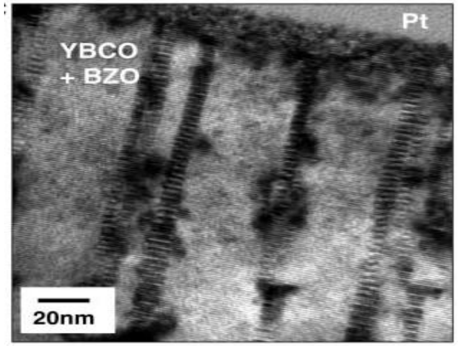
J_E ~ 800 A/mm^2
4 T ||c, 27 K

Doubling of the critical current



Tuning Anisotropy with Heavy-ion Irradiation





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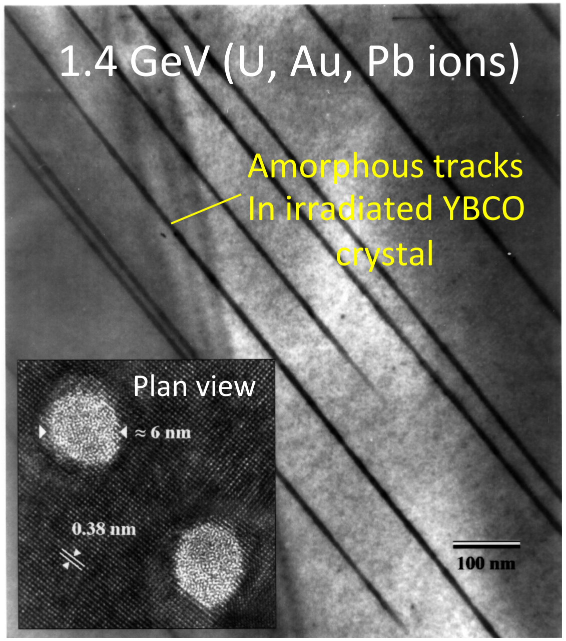
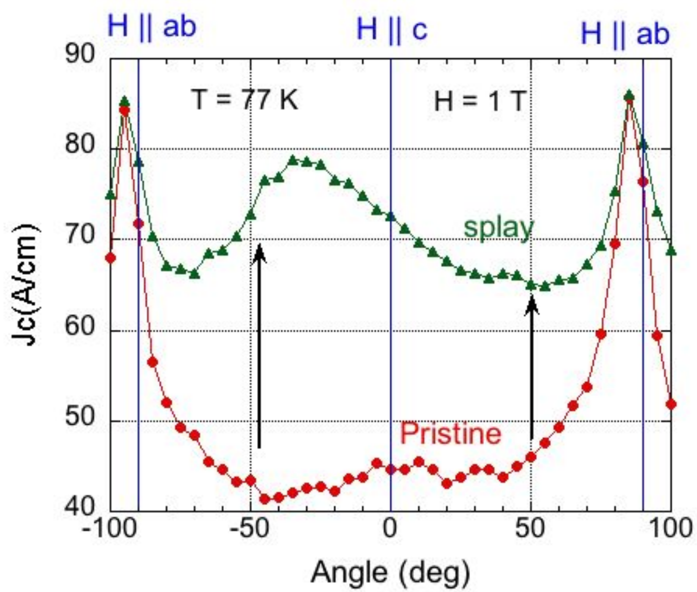
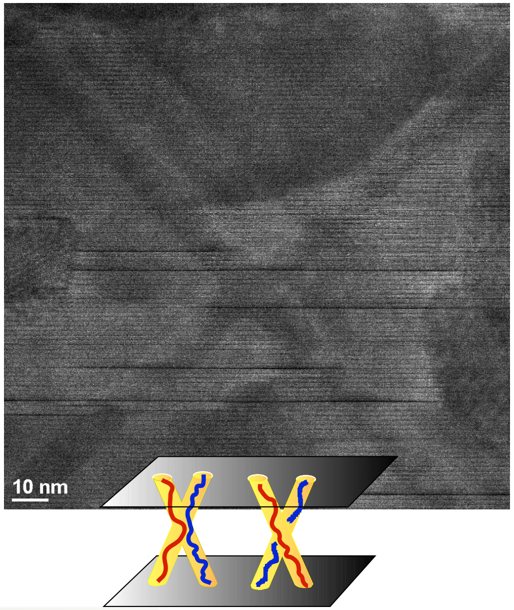


Heavy ion irradaiton
can control:

defect orientation (angle)
defect number (dose)
defect size (ion size)
defect shape:
(ion size & energy)

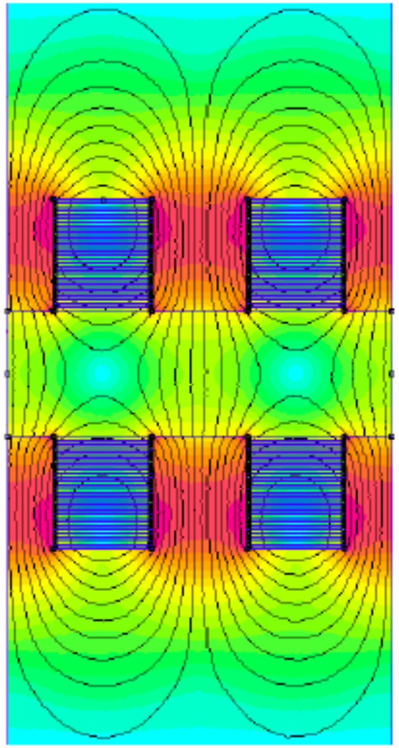




YBCO-coated conductor demo-undulator

C. Boffo et al., Babcock-Noell, KIT (ASC 2010)

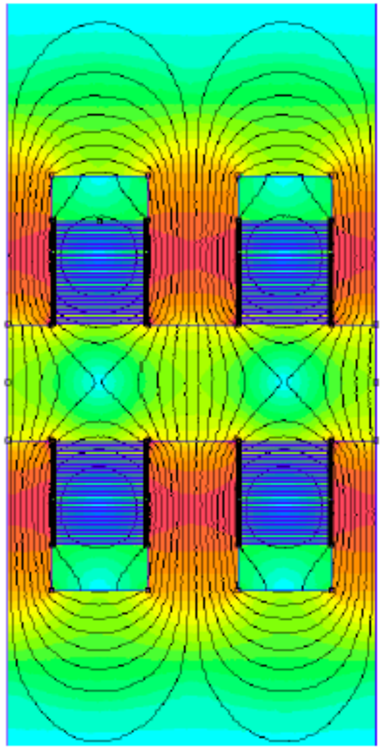
5 mm gap, 1.4T on axis, 16 mm period



Standard Design:

- 4 mm groove
- 30 layers HTS
- Interlayer insulation 50 µm
- Side insulation 50 µm

- Operating current 500A
- Field on axis 1.45 T
- Max field in conductor 2.59T
- Max ortho. Field in conductor **2.25T**

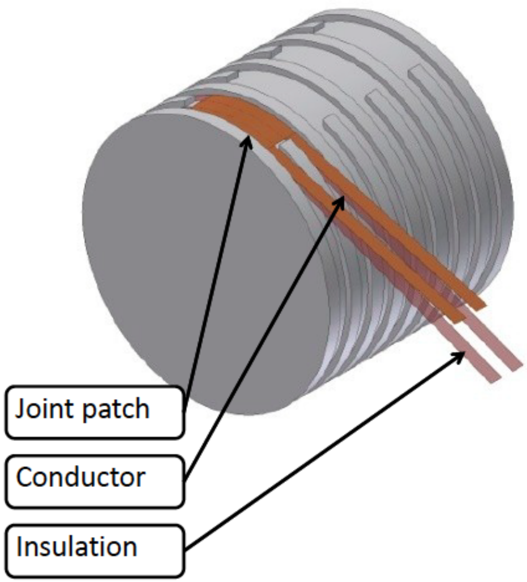


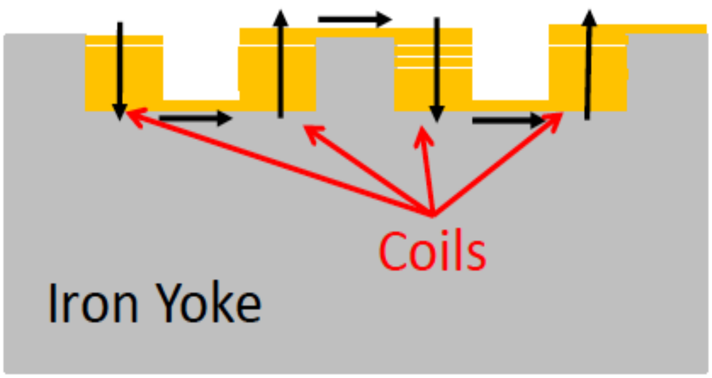
Improved Design:

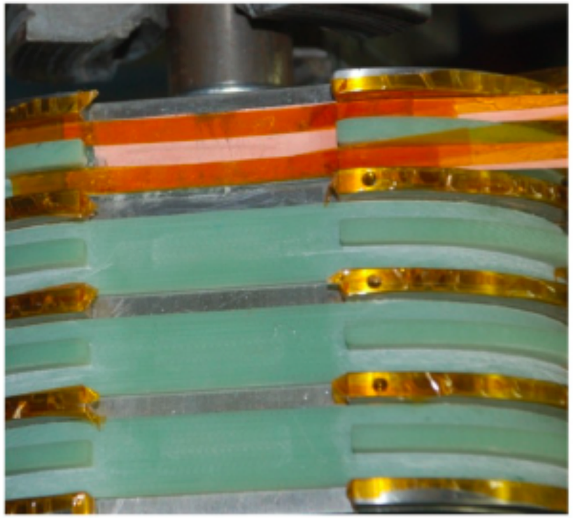
- 4 mm groove
- 30 layers HTS
- Interlayer insulation 50 µm
- Side insulation 50 µm
- **2 mm non-magnetic bottom layer**

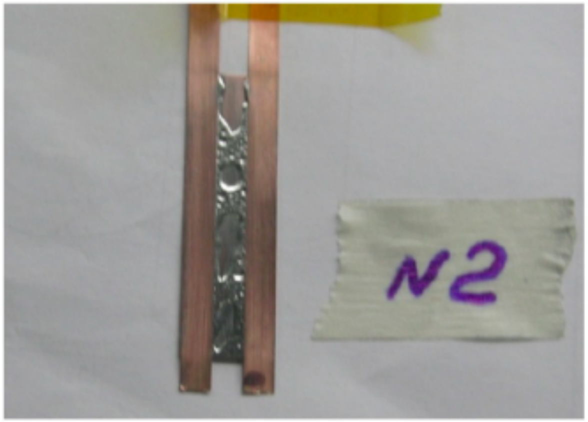
- Operating current 500A
- Field on axis 1.41 T
- Max field in conductor 2.37T
- Max ortho. Field in conductor **1.38 T**

Winding tapes









All coils wound in same direction

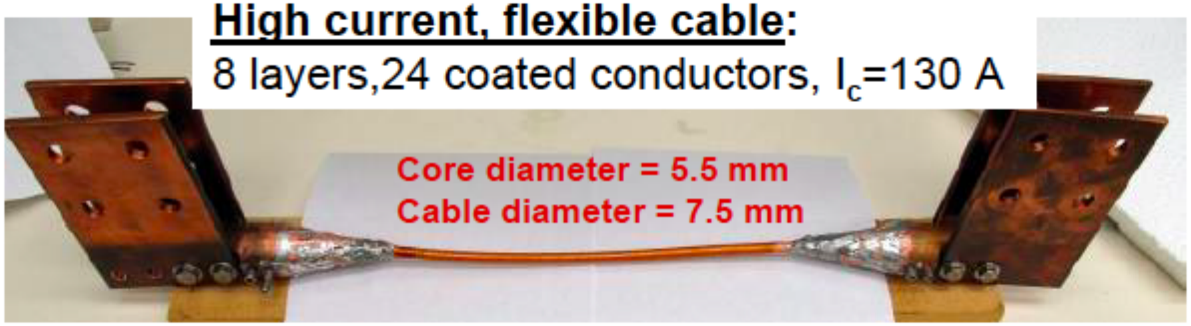
50-µm Kapton insulation

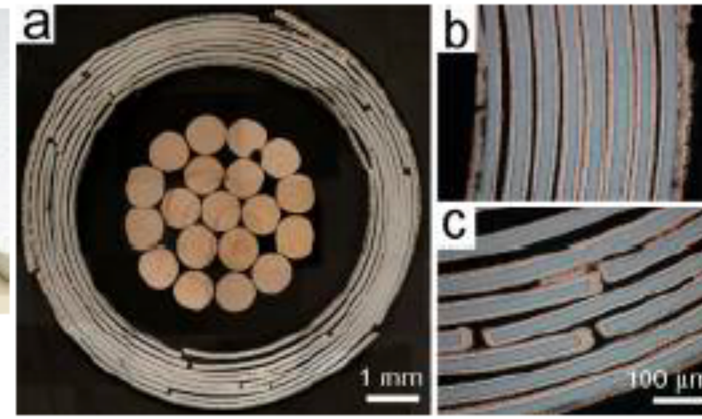
Solder joints

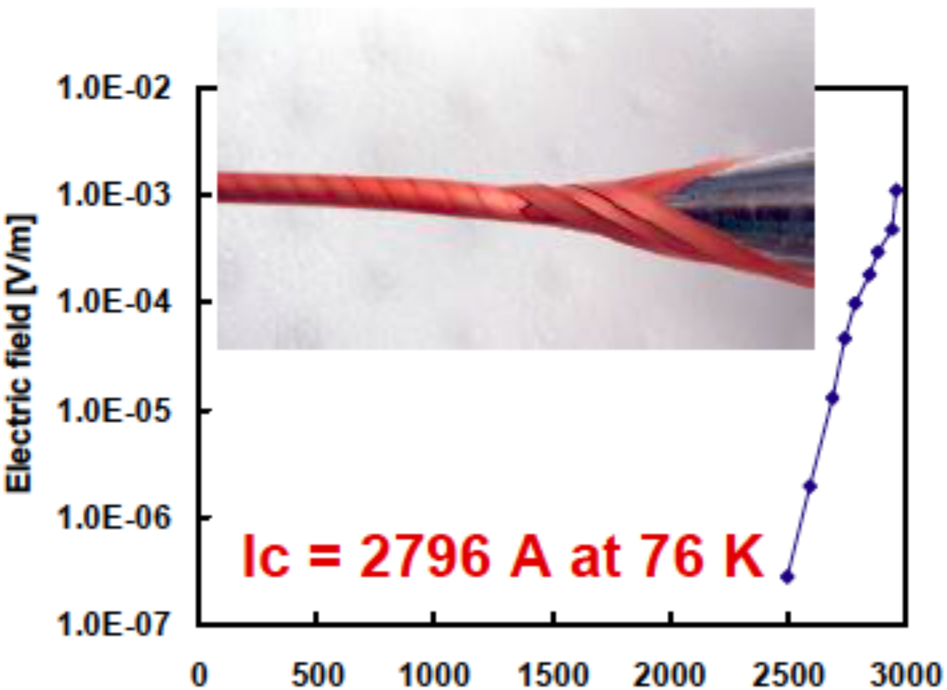
640 A

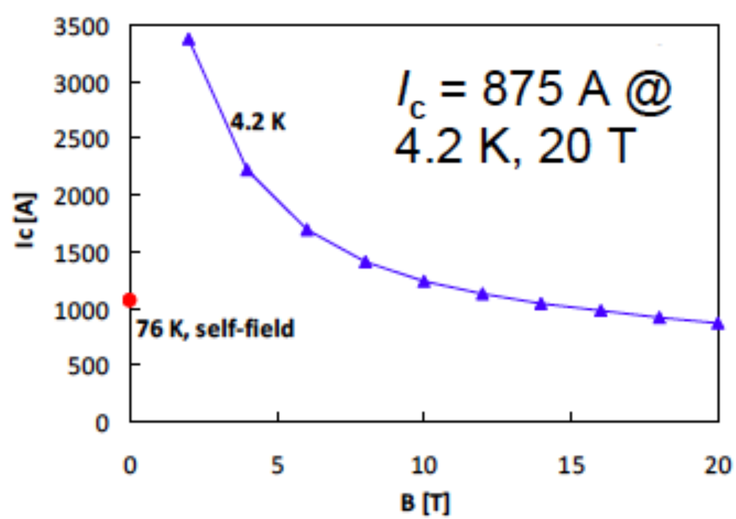
Alternative schemes: miniature helical power-cable

V. Selvamanickam et al., U of Houston, SuperPower (EUCAS 2011)









Conclusions

- Commercial state-of-the-art SC wires are continuously improving in performance, meet demands for SC undulator
- Engineered defects such as nano-particles, self-assembled columnar defects, stacking faults and combinations thereof are effective in raising J_c and lowering pinning anisotropy
- 4 MeV Proton irradiation induced defects can double the critical current at high fields and low temperatures
- Novel winding-schemes for undulator applications

Collaborators

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BROOKHAVEN NATIONAL LABORATORY

Center for Emergent Superconductivity

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