IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, March, 2024. Invited presentation given at IREF 23, Nov. 2023, Arona, Italy

Comparative analysis of particle irradiation and second-phase additions effects on the critical current densities of $YBa_2Cu_3O_7$ single crystals, thin films, and coated conductors

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IREF23

IRradiation Effects on HTS for Fusion

12 – 16 November 2023, Arona, Italy

Research partially supported by the US DOE, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering.

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Motivation

- Radiation damage in the superconducting magnets is a concern for the fusion reactors community. However…
- …disorder (material defects) is required for vortex pinning
- *Re*BCO-based CCs have the highest J_c in any known SC ⇒ effective strong pinning defects
- Added defects in CCs (e.g. second phases) are optimized for high J_c
- Irradiation-induced defects will interact with pre-existing disorder
- Irradiation will start modifying the properties of the CC magnets in fusion reactors from day one of operation

The LANL team

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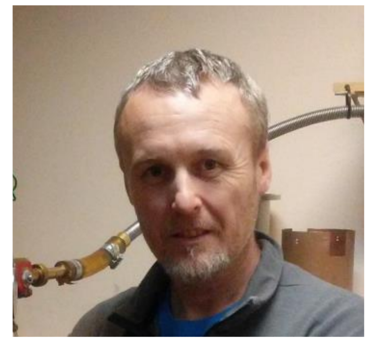

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Wai Kwok

Thanks to all the collaborators!!

Outline

- Introduction to vortex matter – defects, pinning centers and critical currents
- J_c enhancement in YBCO single crystals by particle irradiation
- YBCO films have the highest J_c of any known SC. Can it be enhanced further?
- Engineering the vortex pinning landscape in YBCO films and coated conductors:
  - ✓ Second phase additions
  - ✓ Particle irradiation: Further J_c enhancement is still possible!
- Cooperation and competition effects in mixed pinning landscapes
- Conclusions

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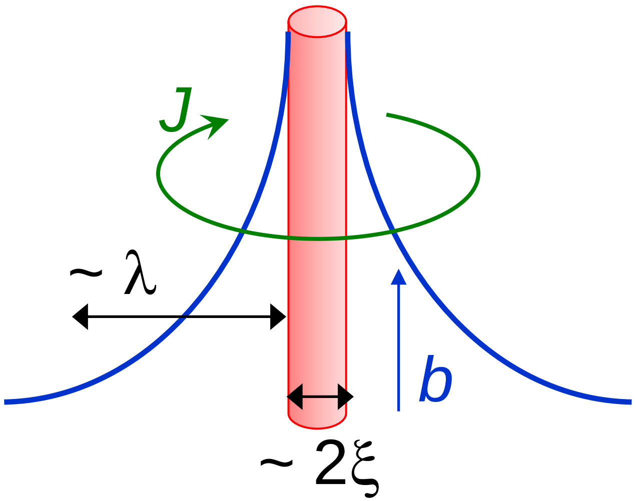
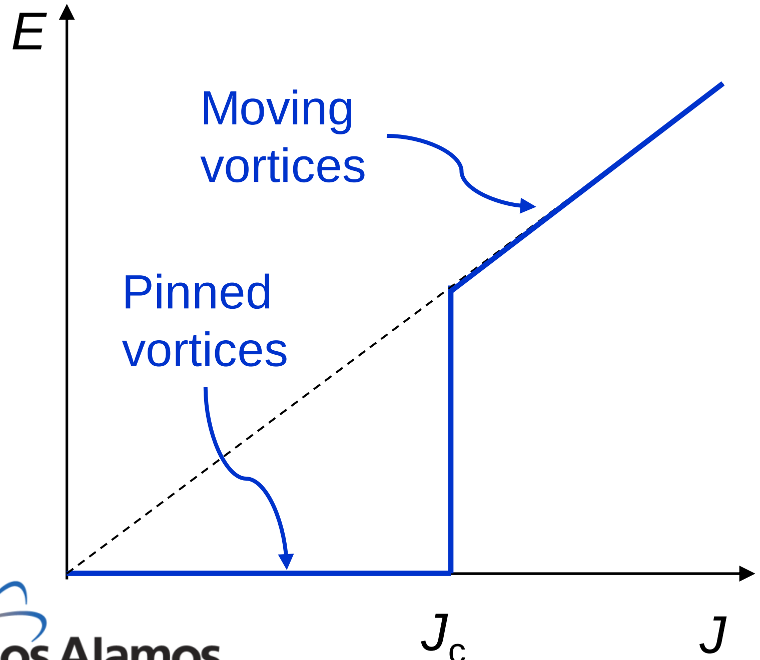
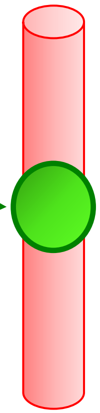
Vortices appear in the "mixed state" of type II superconductors

- Quantized "tubes" of magnetic field
  – each carries a flux quantum Φ_0
- Central filament where superconductivity is suppressed (core) surrounded by circulating currents and associated magnetic field.
- Energy: magnetic + kinetic (currents) + core





- Electric currents exert force on vortices ⇒ vortex motion is dissipative ⇒ resistance
- Motion may be precluded by material disorder (reduced core energy)
- Vortices remain pinned until J reaches the critical current density J_c



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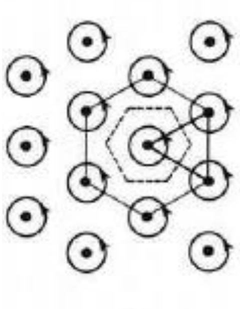
Vortex matter physics arises from the interplay of 3 energies



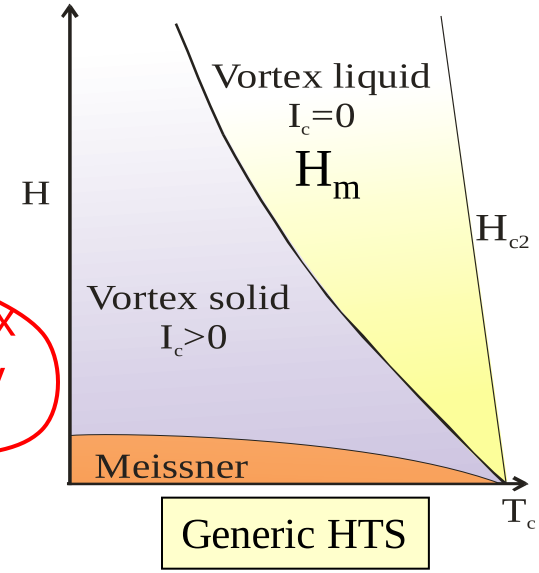
$$a = \left(\frac{4}{3}\right)^{1/4}\left(\frac{\Phi_0}{B}\right)^{1/2}$$

Gi

Thermal fluctuations

- produce flux creep & vortex liquid phases
- bad for applications

Main source of complex vortex phenomenology in HTS



Vortex-vortex interactions

controlled by "intrinsic" material properties (λ,ξ,γ)

Ordered lattice (Abrikosov) Equilibrium

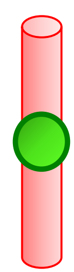
H

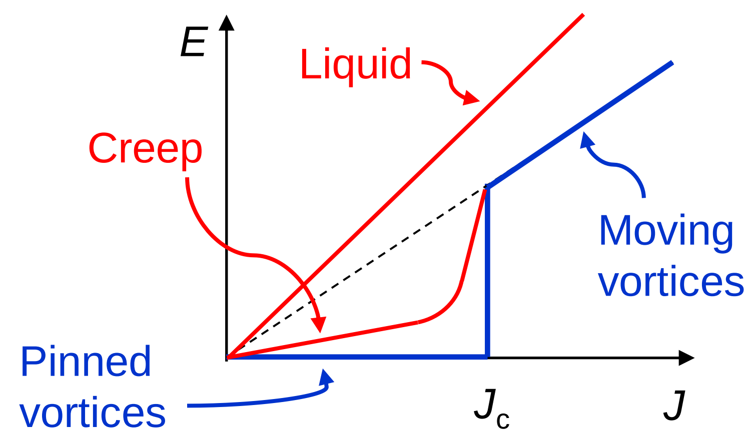
J_c/J_0

Vortex-defects interactions

- "Extrinsic" effect responsible for vortex pinning
- J_c can vary by orders of magnitude *in the same material*
- "Pinning landscape"

Disordered arrays Metastable states





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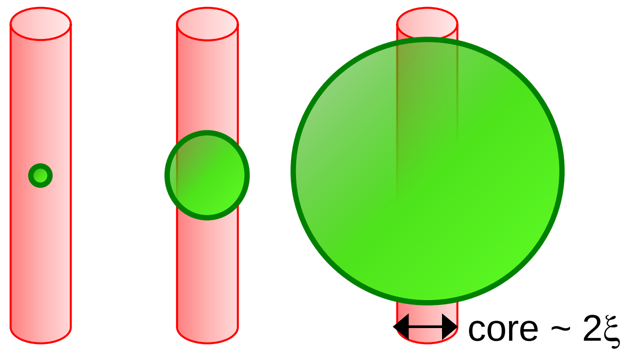
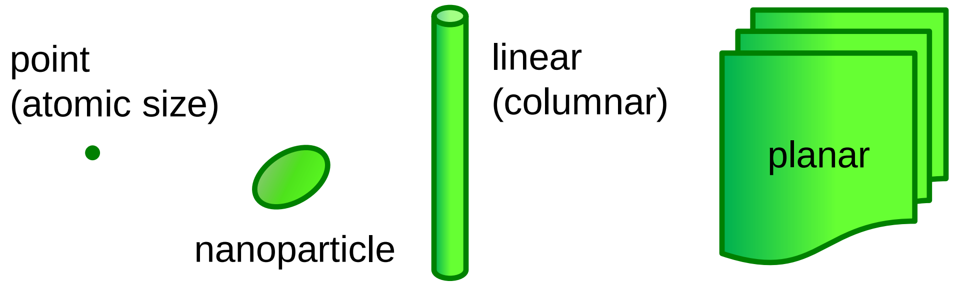
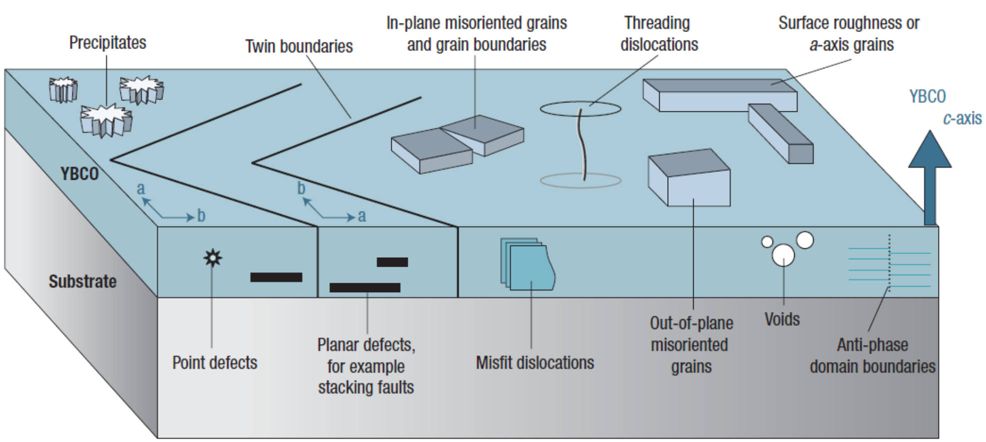
Many types of defects can act as pinning centers, some are better than others…



Too small good Too big

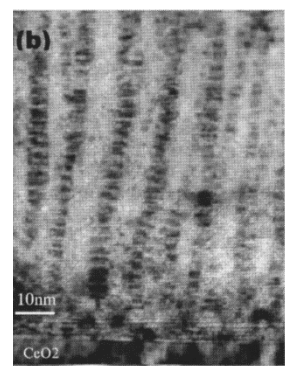


Defects formed during fabrication (e.g., in YBCO films)

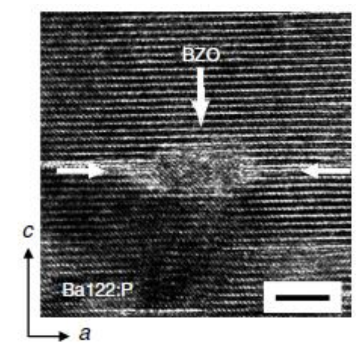


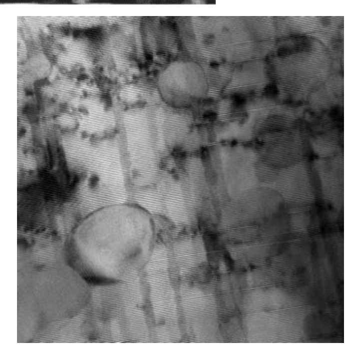
Artificially introduced defects
Popular methods in HTS:

Particle irradiation



Chemical incorporation of second phases





Combinations

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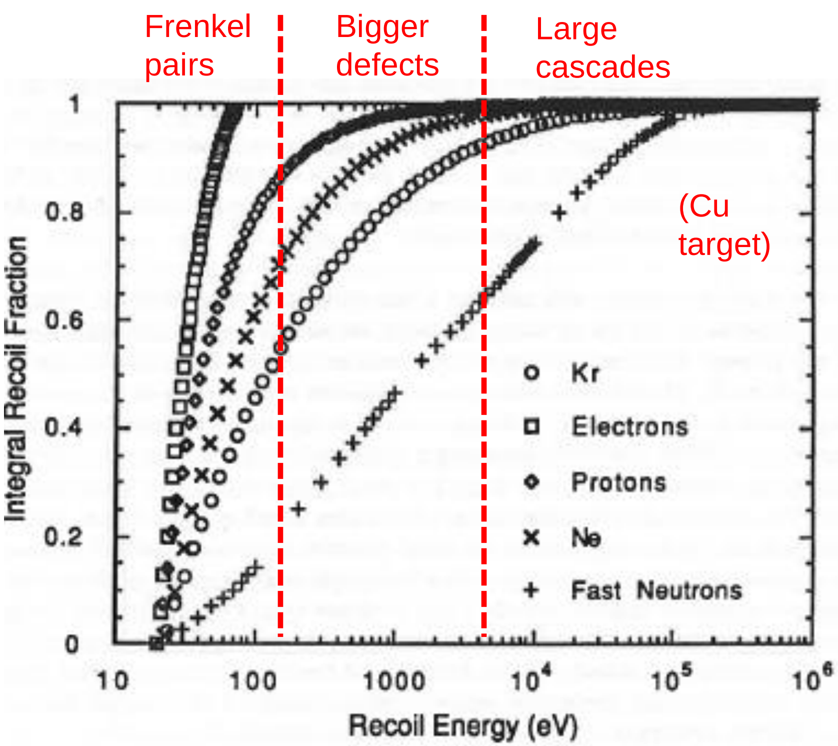
Particle irradiation of HTS was a very popular activity in the early 1990s

Incident ions transfer energy to the solid by:

Direct collisions with lattice nuclei
(nuclear or non-ionizing energy loss):
Dominant for light ions up to few MeV

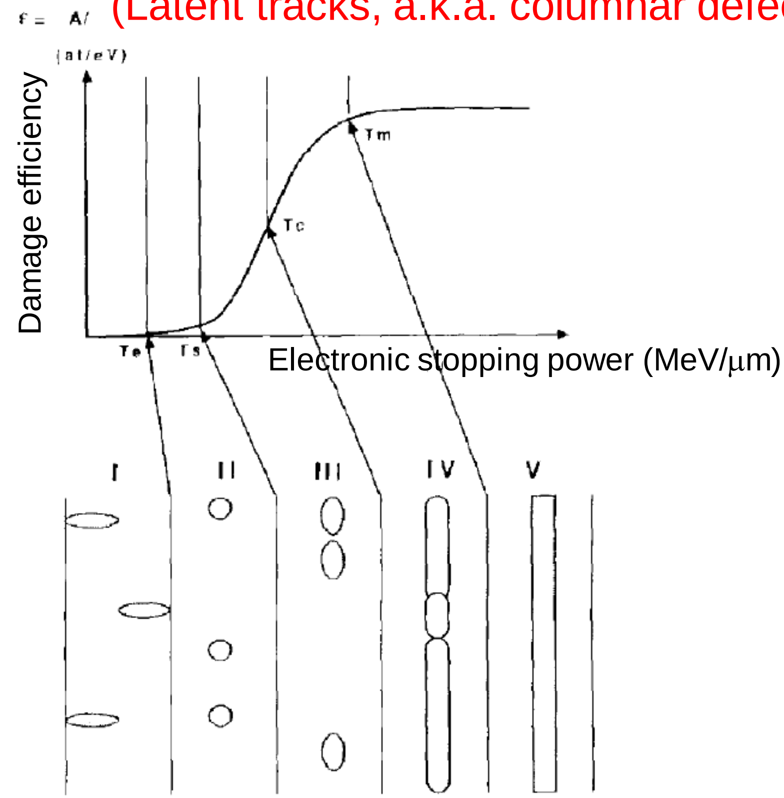
Localized uncorrelated disorder



M.A. Kirk & H.W. Weber (1992)

Ionization or electronic excitations
(electronic or ionizing energy loss):
Dominant for heavy ions 100s of MeV to GeV

Correlated disorder
(Latent tracks, a.k.a. columnar defects)



F. Studer & M. Toulemonde (1992)

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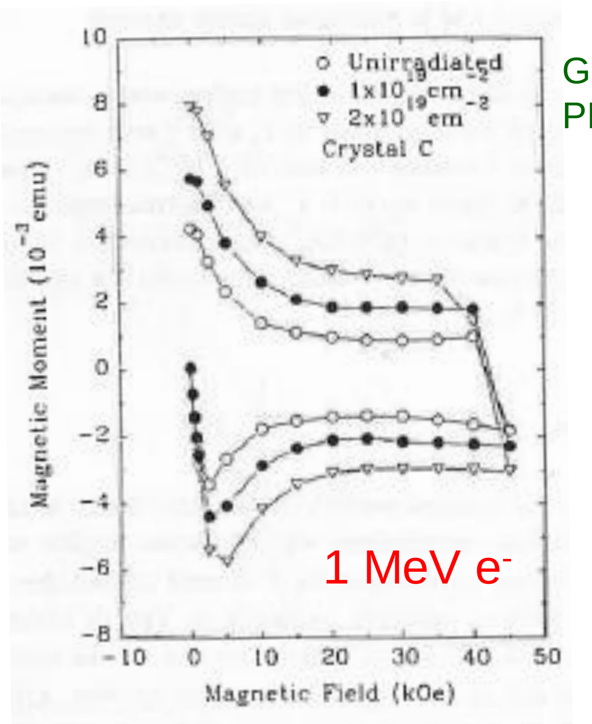
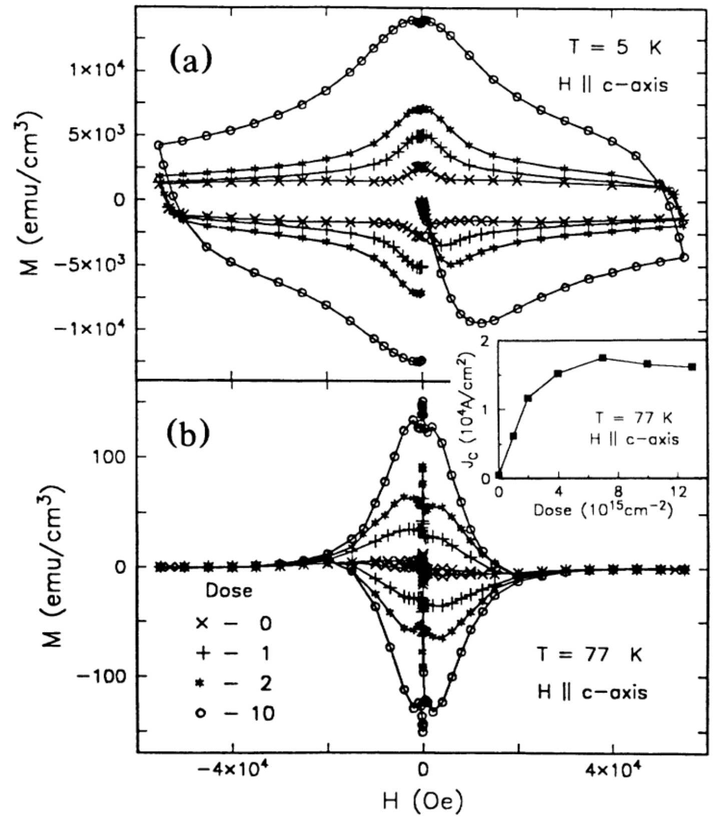
Irradiation creates effective pinning centers in clean YBCO single crystals

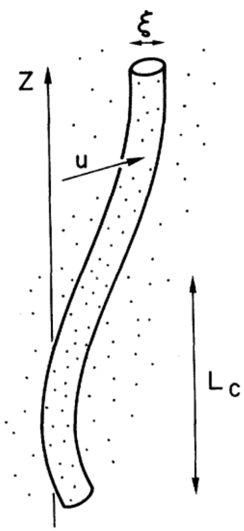


Giapintzakis *et al.*, PRB **45**, 10677 (1992)

3 MeV p$^+$



L. Civale *et al.*, PRL **65**, 1164 (1990)



Even point defects are effective in YBCO because

- ξ is small
- affects whole unit cell
- there are many (collective pinning)

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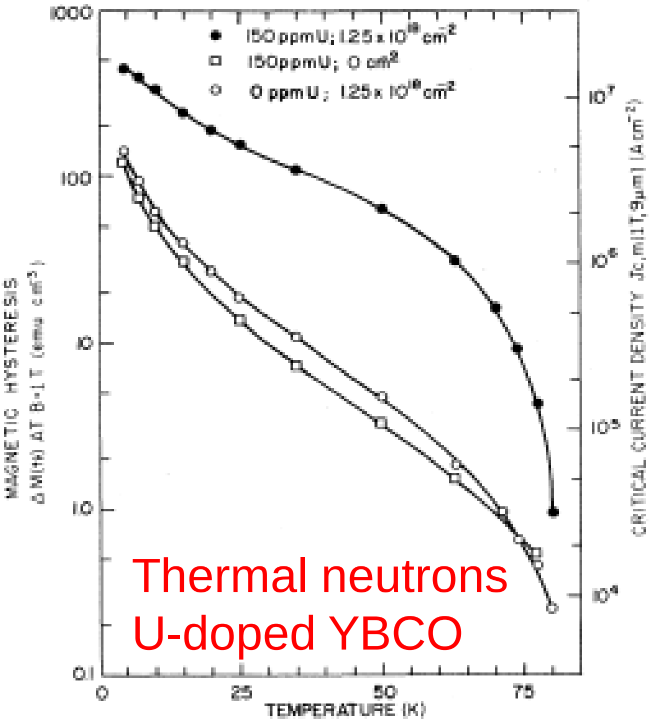
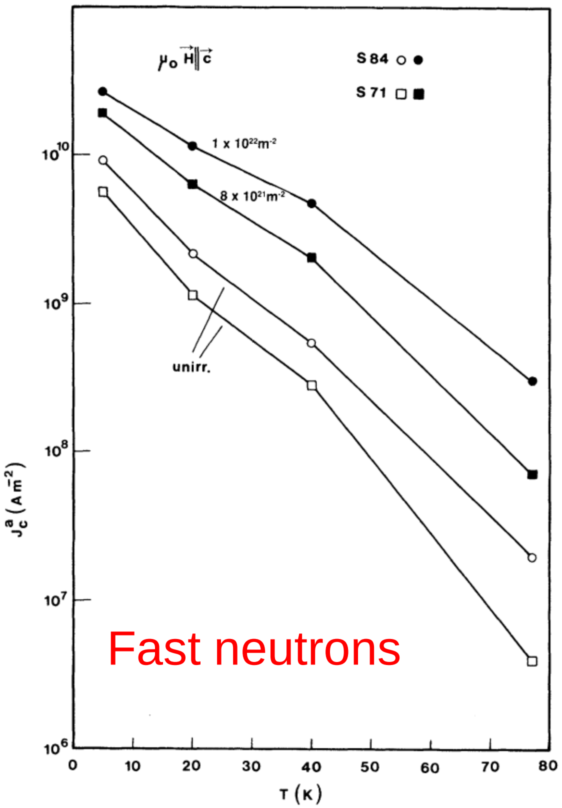
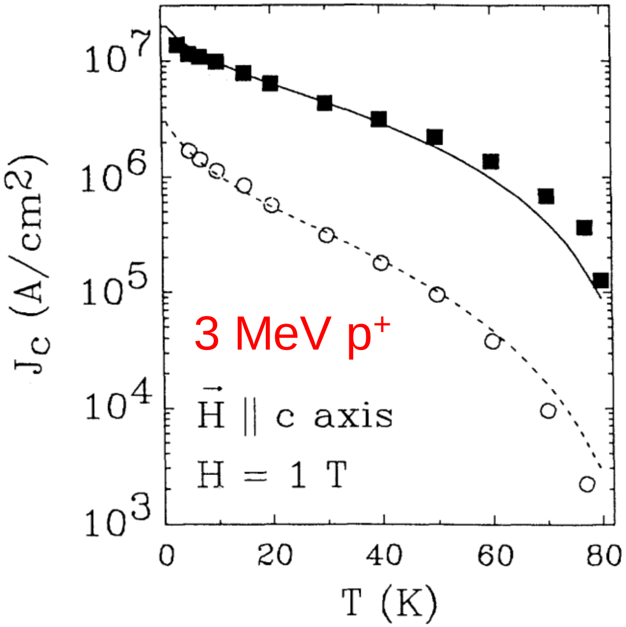
Orders of magnitude increases in J_c in clean YBCO single crystals



R.L. Fleischer *et al.*,
PRB **40**, 2163 (1989)



F.M. Sauerzopf *et al.*,
PRB **43**, 3091 (1991)



J.R. Thompson *et al.*,
PRB **47**, 14440 (1993)

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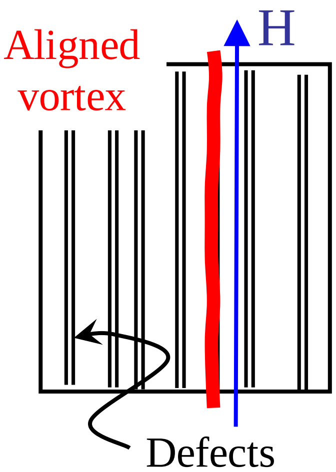
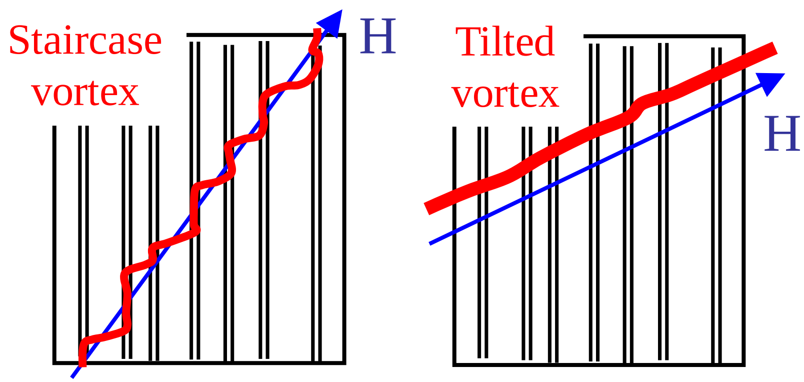
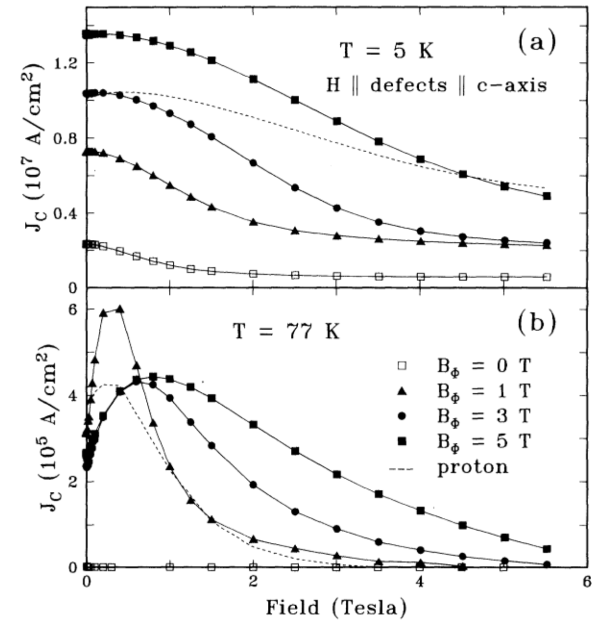
High energy heavy ion irradiation creates aligned columnar defects

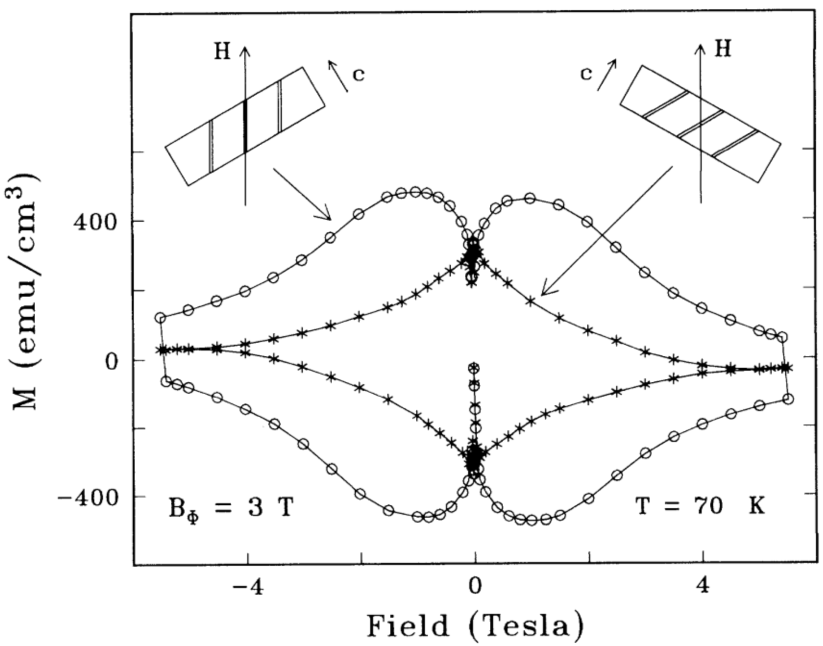
Directional pinning

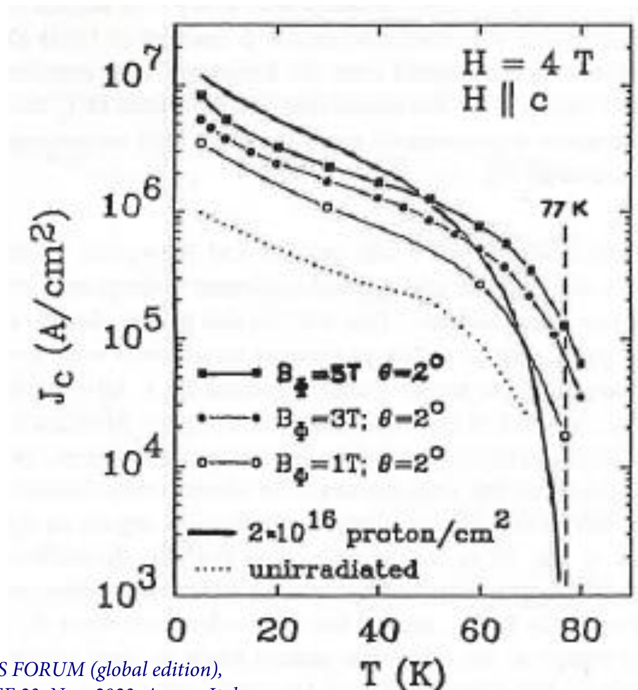




L. Civale *et al*., PRL **67**, 648 (1991)







CDs are the most effective pinning centers for **H**||defects and below matching field B_Φ

However….

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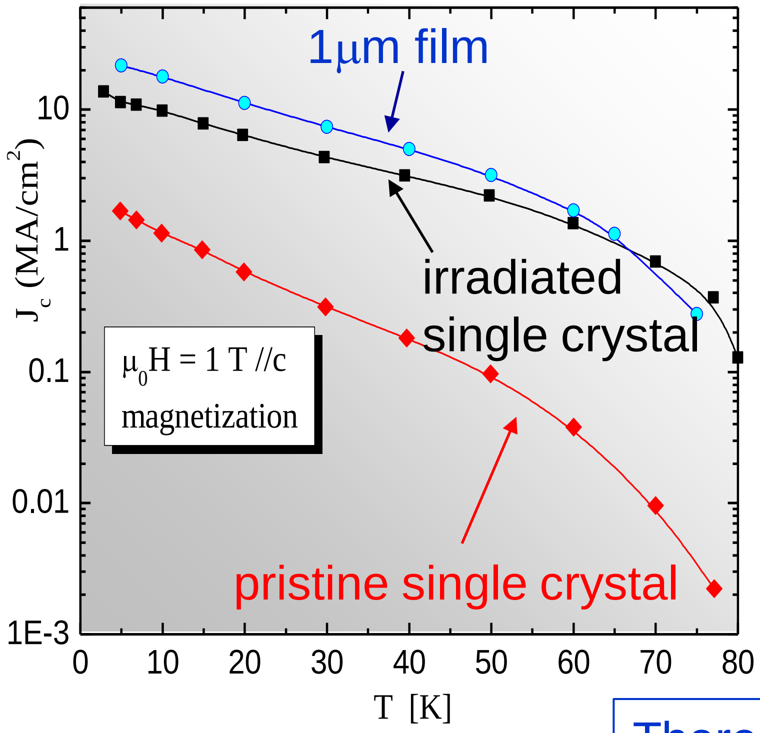
However, J_c in "standard" YBCO films is higher than the best that could be achieved in irradiated single crystals



The maximum possible J_c is the depairing current density

$$J_0(T) = \frac{cH_c(T)}{3\sqrt{6}\pi\lambda(T)}$$

YBCO films have the highest

$J_c \sim 100$ MA/cm^2

$J_c/J_0 \sim 0.3$

of any known superconductor

There are two reasons to study YBCO films:

- Technological applications (obvious)
- Basic science: they are an "extreme case"

Why is the J_c of YBCO films so high?
This was a big mystery for the CC community in the early 2000s

A successful approach: pinning landscape engineering

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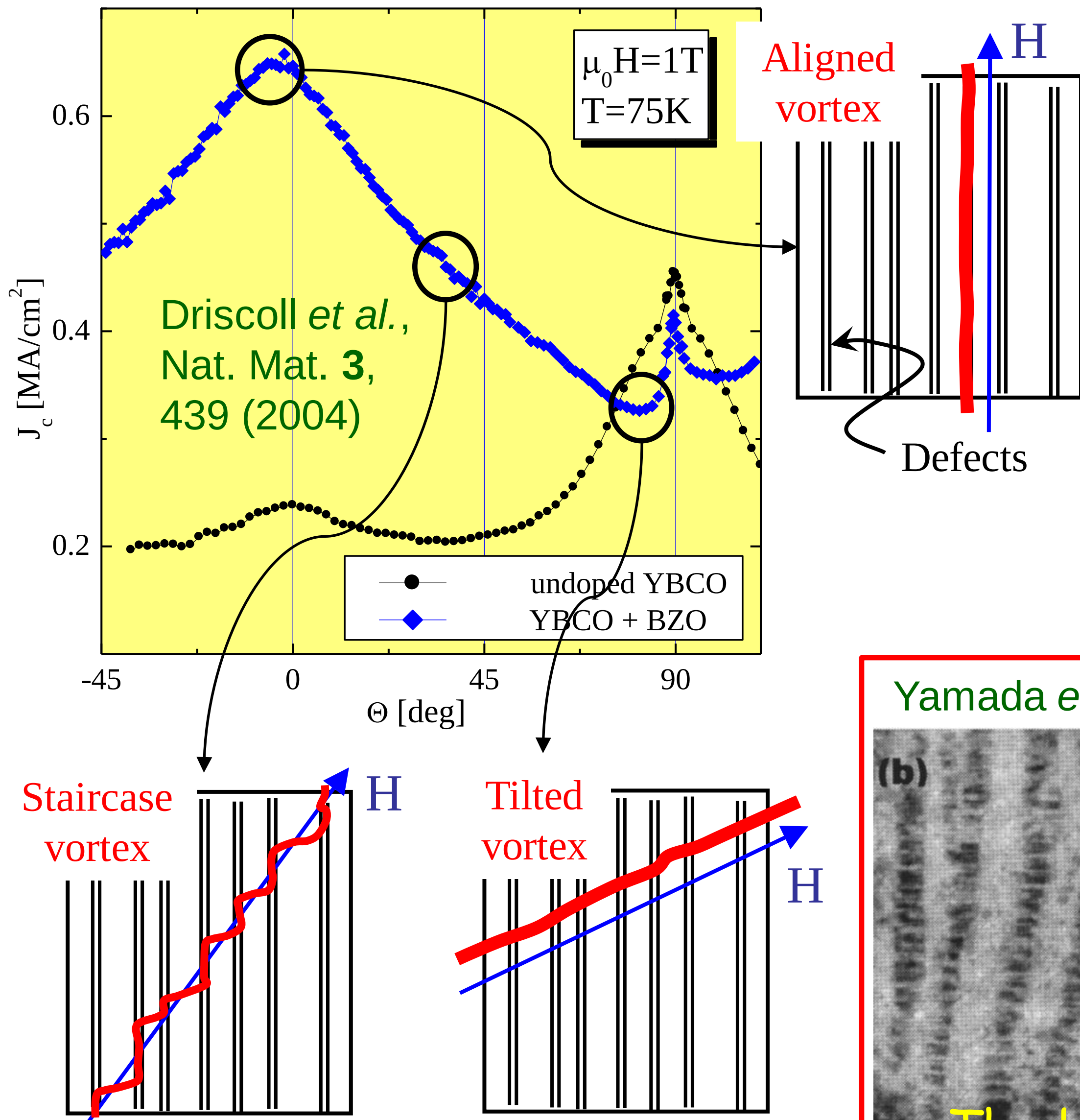
J_c in YBCO films can be increased by chemical introduction of defects

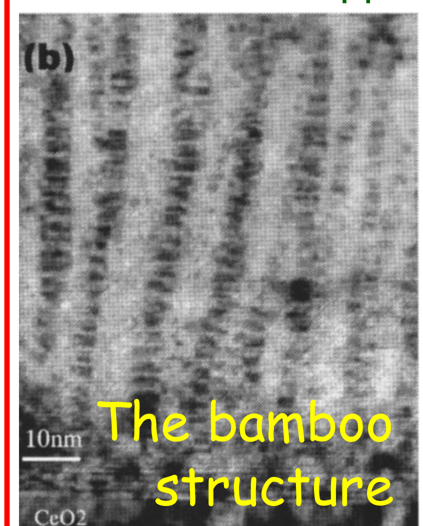


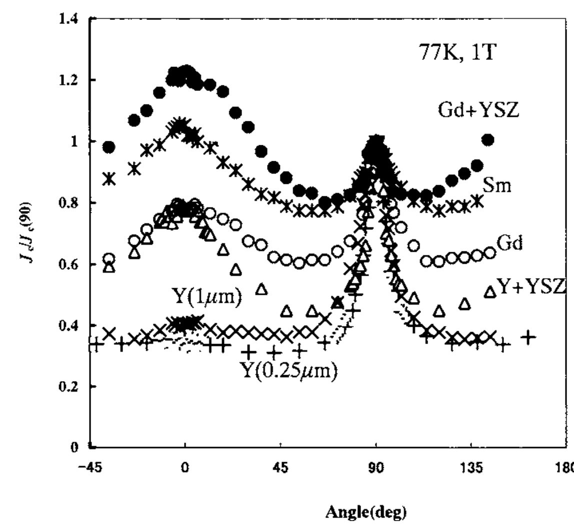
We produced large J_c increases in PLD YBCO films by adding $BaZrO_3$ second phases

Angular dependence of J_c:
large peak for H//c, ⇒ correlated pinning by self-assembled nanorods (columnar defects).

The BZO doping did not increase the ***self-field*** J_c, but produced a much improved in-field performance

Yamada *et al.* Appl. Phys. Lett. **87**, 132502, 2005





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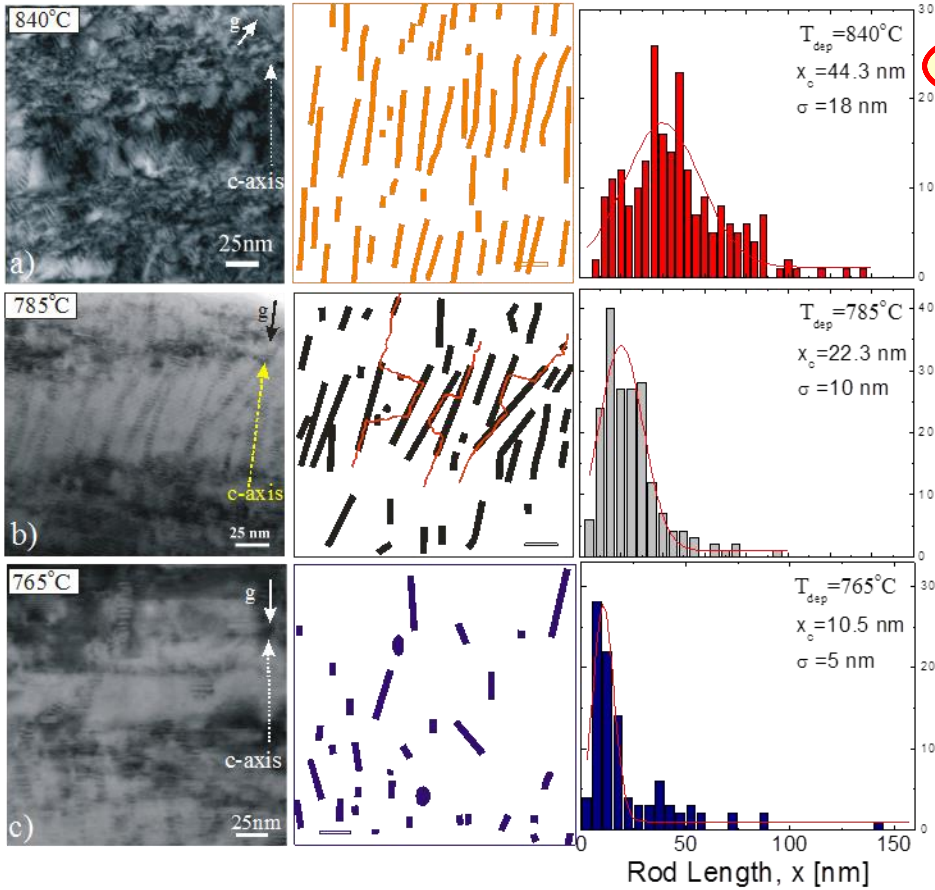
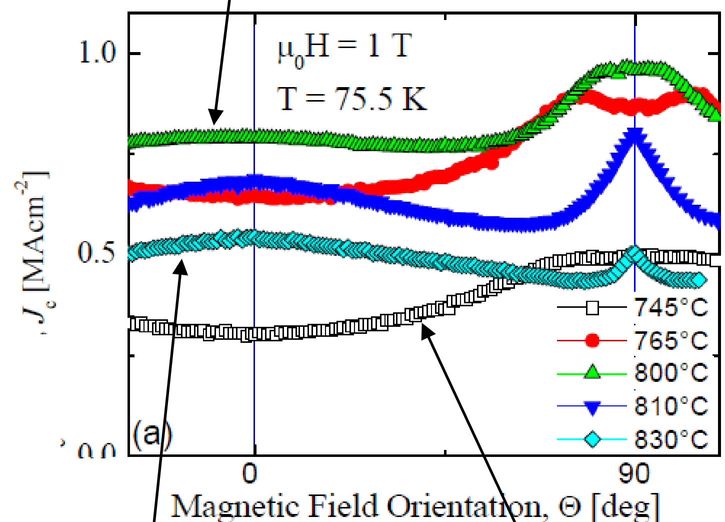
We learned to nanoengineer the pinning landscape by tuning the growth conditions in PLD YBCO+BZO

Low growth temperature or High rate = random nanoparticles
High growth temperature or Low rate = self-assembled nanorods



Mixed pinning landscape (splayed nanorods + nanoparticles): best J_c



Columnar defects: large c-axis peak

Random nanoparticles: no c-axis peak

Processing → properties correlations: The columnar growth of Pulsed Laser Deposition (PLD) films promotes the self-assembly of BZO nanorods

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B. Maiorov *et al.*, Nat. Mat. **8**, 398 (2009)

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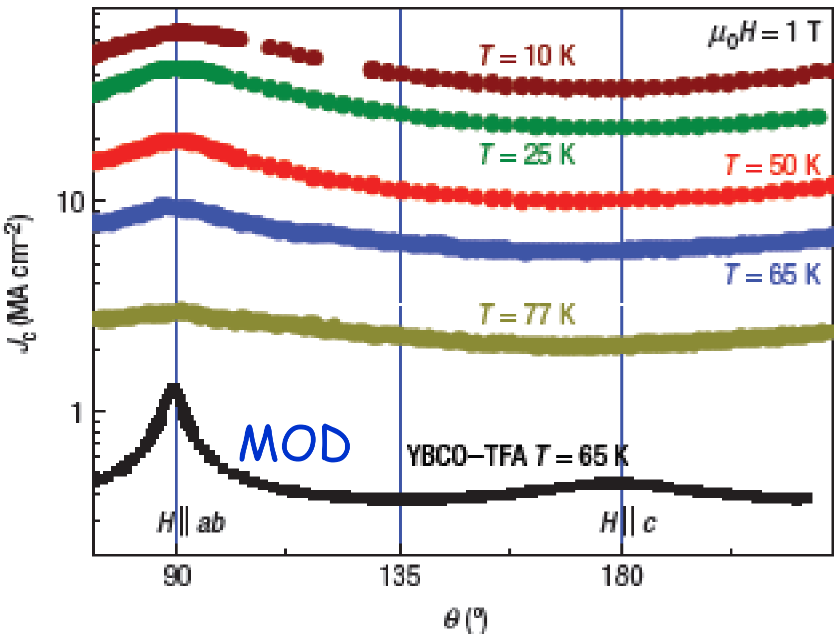
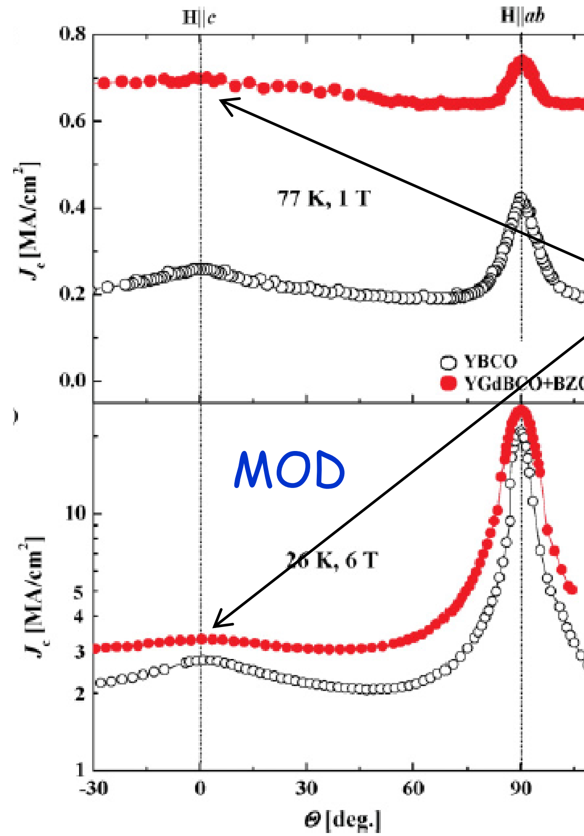
Same BZO additions in films grown by different methods (MOD) or under different conditions may produce strong pinning by random nanoparticles

J. Gutierrez *et al.*, Nat Mat. **6**, 367 (2007)

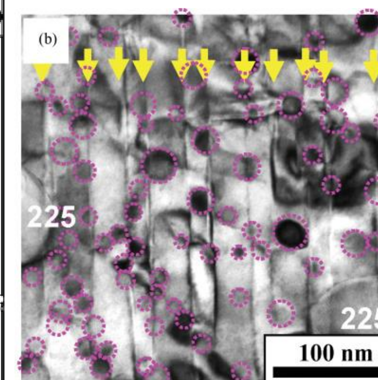


Very strong pinning by nanoparticles and no evidence of c-axis correlated disorder

M. Miura *et al.*, PRB **83**, 184519 (2011)



c-axis peak: pinning by twin boundaries



Correlated pinning from twin boundaries is present, but at high T pinning is dominated by the random nanoparticles

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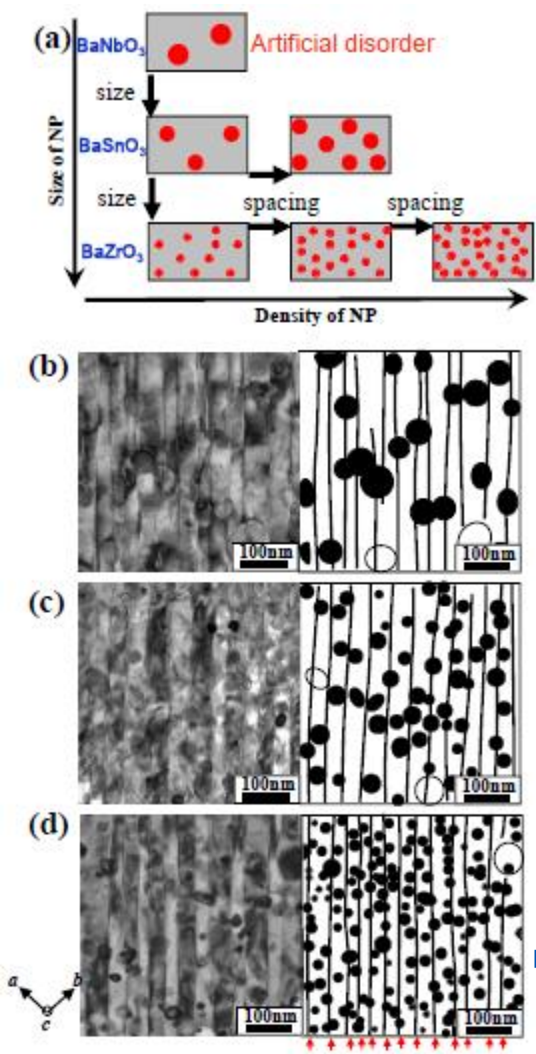
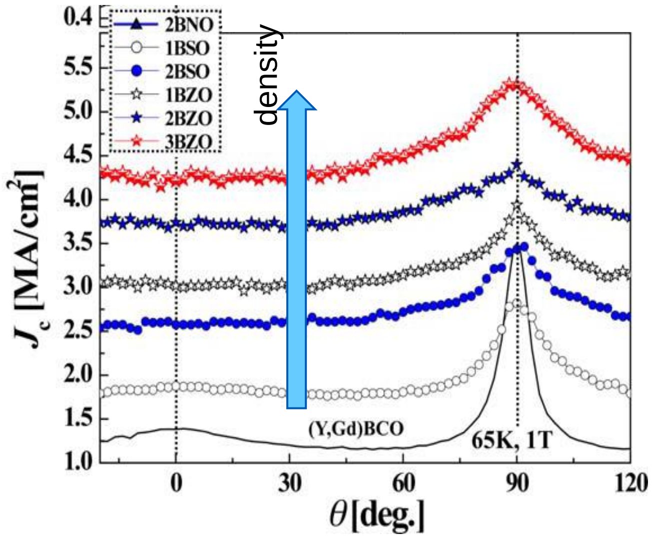
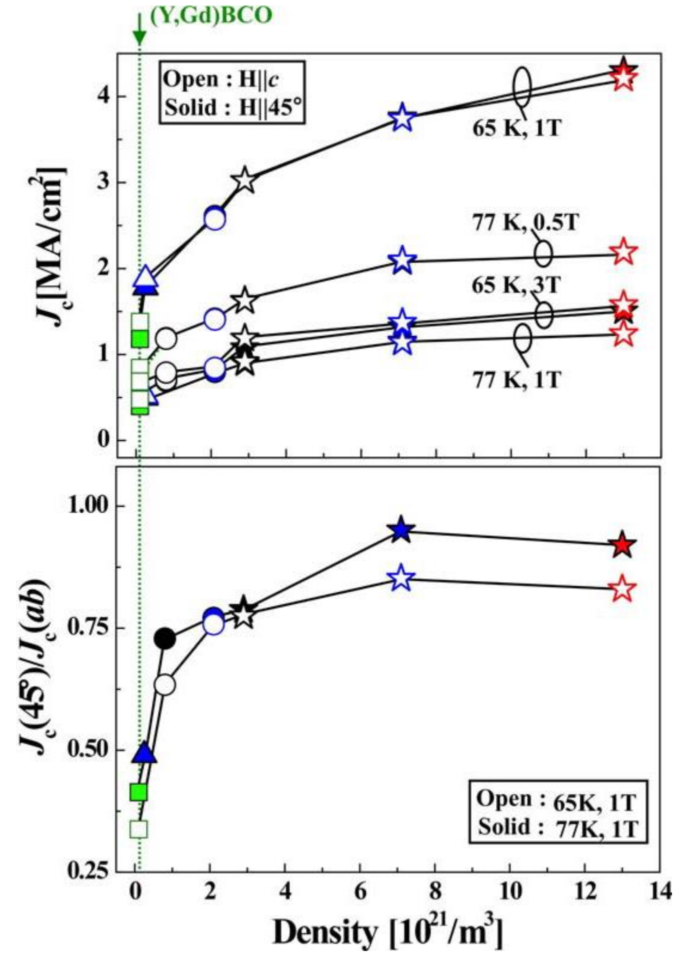
Influence of the density and size of added random nanoparticles on vortex behavior in YBCO-based CC grown by MOD

M. Miura *et al.*, SuST **26**, 035008 (2013)







As the NP density increases:

- J_c increases
- The J_c anisotropy decreases

We need: smaller NPs, higher density

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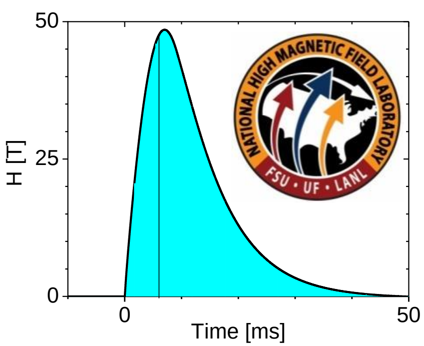
Influence of the density and size of added random nanoparticles in YBCO-based CC grown by MOD at very high fields

Angular dependent resistivity measurements in pulsed magnetic fields



First measurement of a CC in pulsed fields

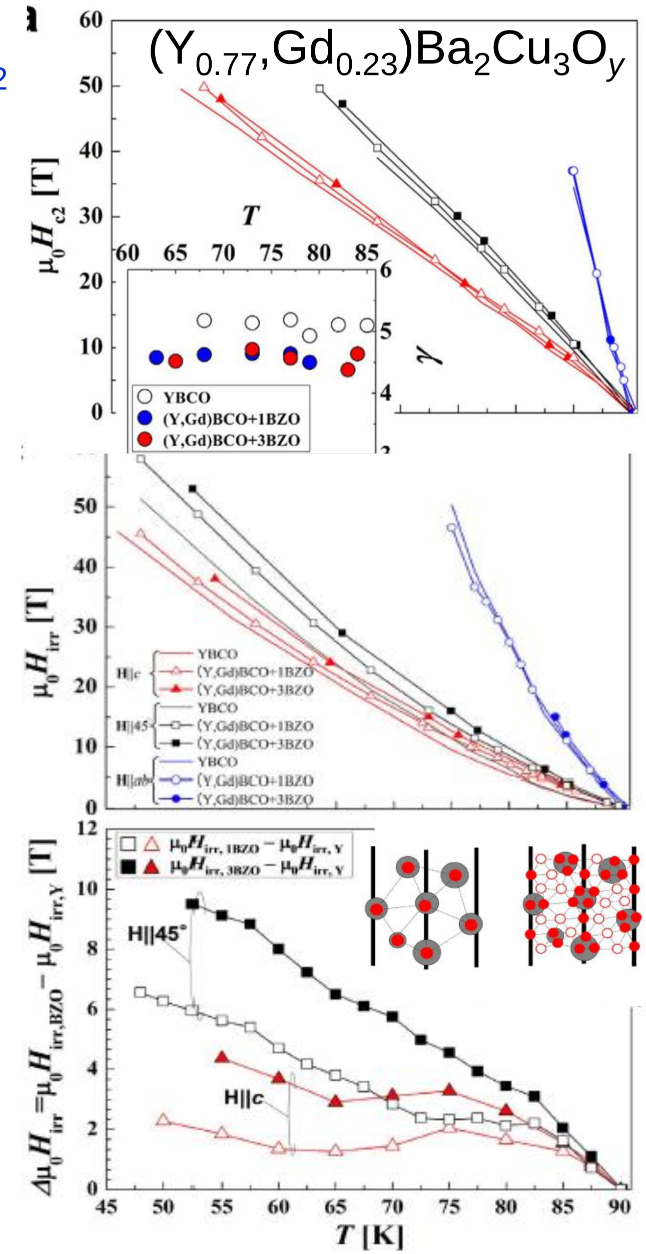
M. Miura *et al*., Appl. Phys. Lett. **96**, 072506 (2010)

No changes in H_{c2} and γ (because ξ_0 is very small)

H_{irr} (melting line) still increases for fields as high as 60T ! Largest increase at intermediate angles

Record high H_{irr} no saturation with NP density: further increases possible

M. Miura *et al.*, *Sci. Rep.* **6**, 20436 (2015)



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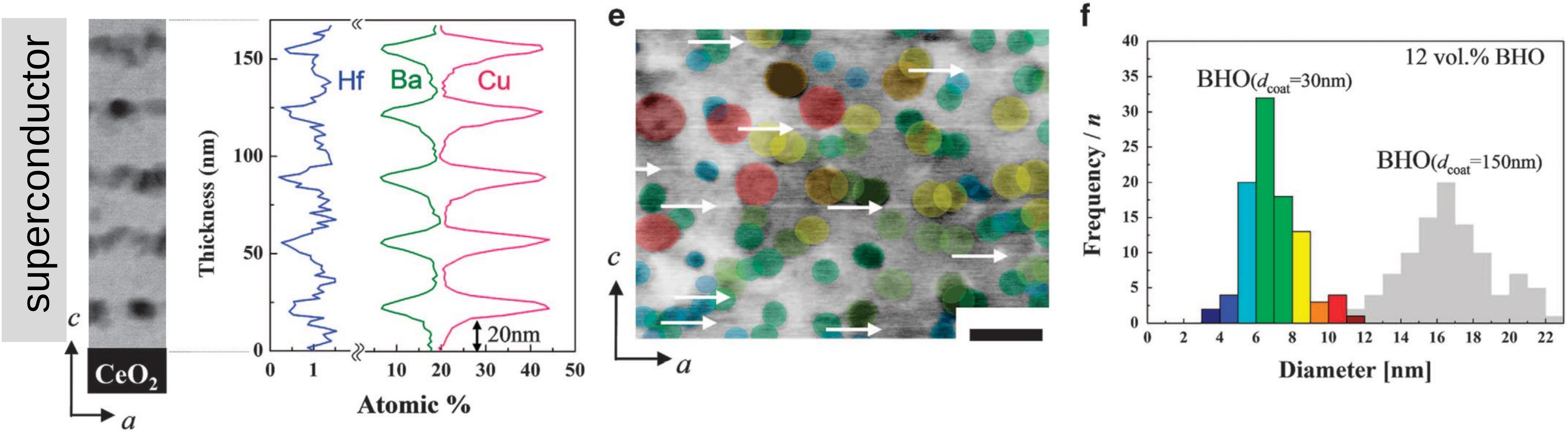
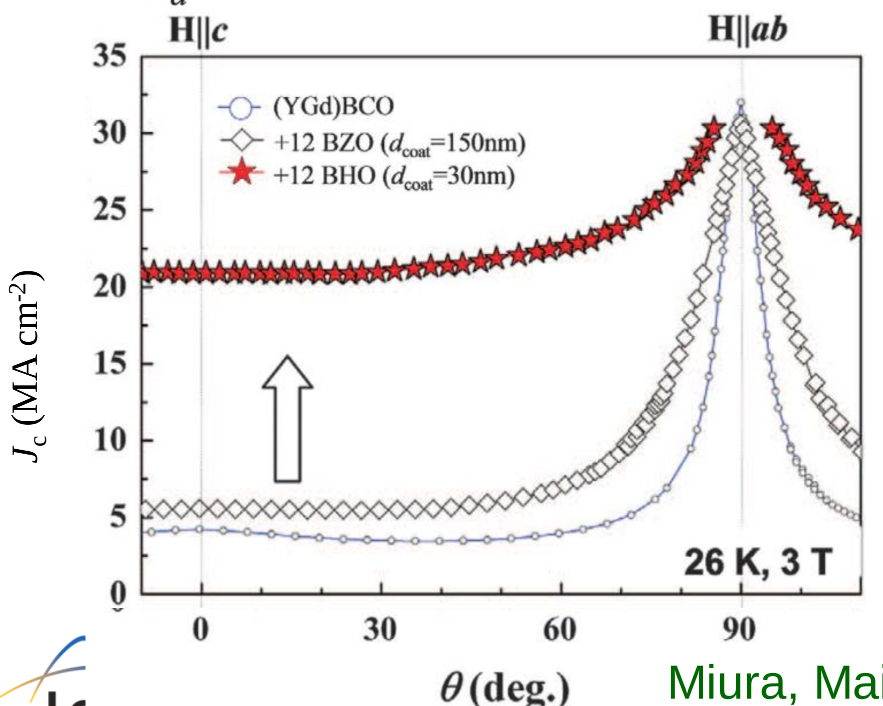
We developed a multilayer deposition method enables introduction of even smaller random nanoparticles in YBCO-based CC grown by MOD

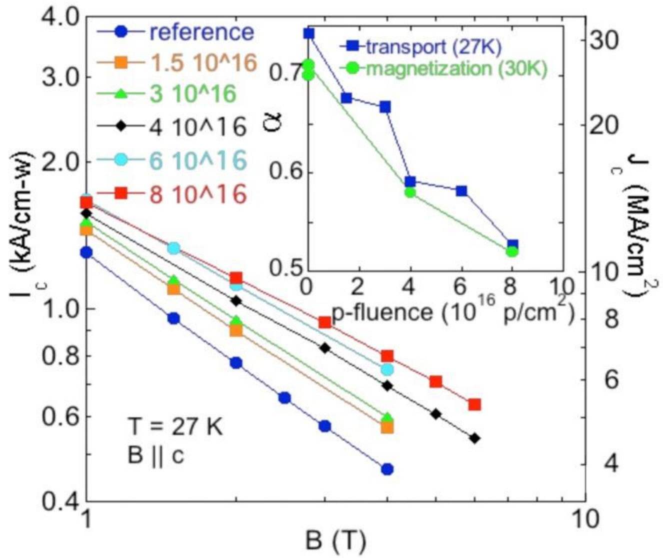


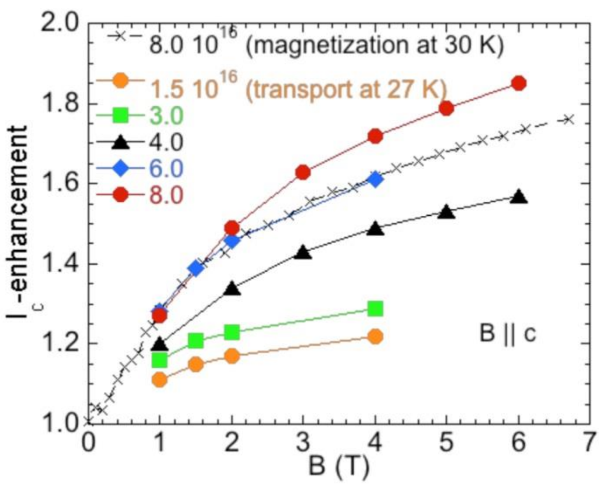


- Matching size of nanoparticle to vortex size is essential for effective pinning
- In previous studies nanoparticles in MOD were much larger than needed at low *T*
- Multilayer deposition creates Ba-poor regions that stop the growth of $BaHfO_3$ NPs
- Particle size reduced x5
- Pinning at low *T* is increased dramatically

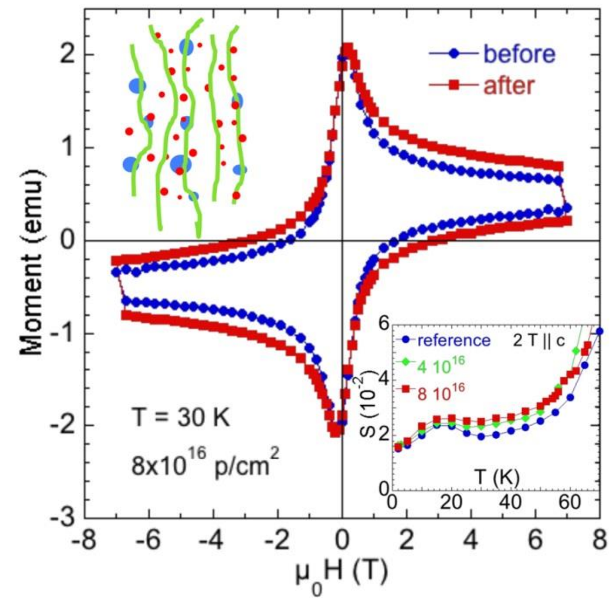
Miura, Maiorov, *et al*
NPG Asia Materials **9**, e447 (2017)

Pinning in commercial $YBa_2Cu_3O_7$ coated conductors can still be substantially enhanced by irradiation with 4 MeV protons.





- CC from AMSC
- Irradiation: 4 MeV protons, fluence 8x10^{16} p/cm^2
- Study lead by ANL - creep studies at LANL



- Near doubling of J_c in fields ~ 6T at ~ 27 K
- A mixed pinning landscape of preexisting precipitates and twin boundaries and small, finely dispersed irradiation induced defects.
- No significant changes in creep rates.

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Y. Jia *et al*., Appl. Phys. Lett. **103**, 122601 (2013).

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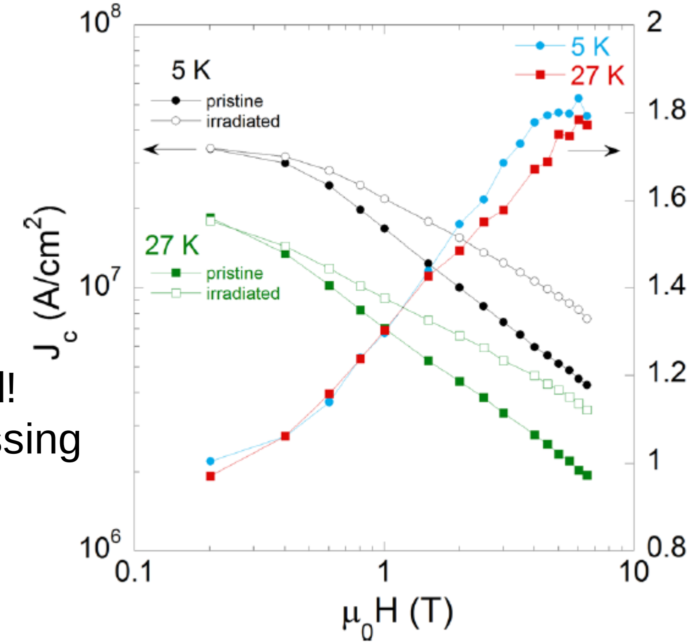
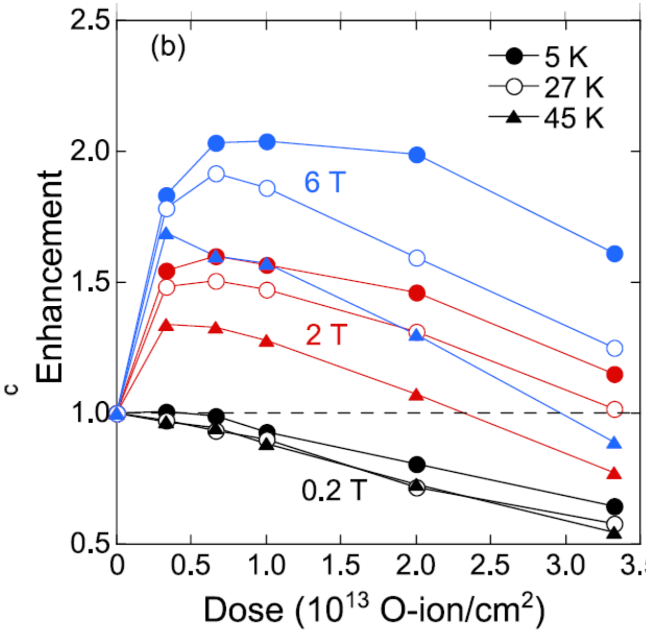
The same J_c enhancements (in the same coated conductors) can be obtained by oxygen irradiation, but with 1000 times smaller doses!

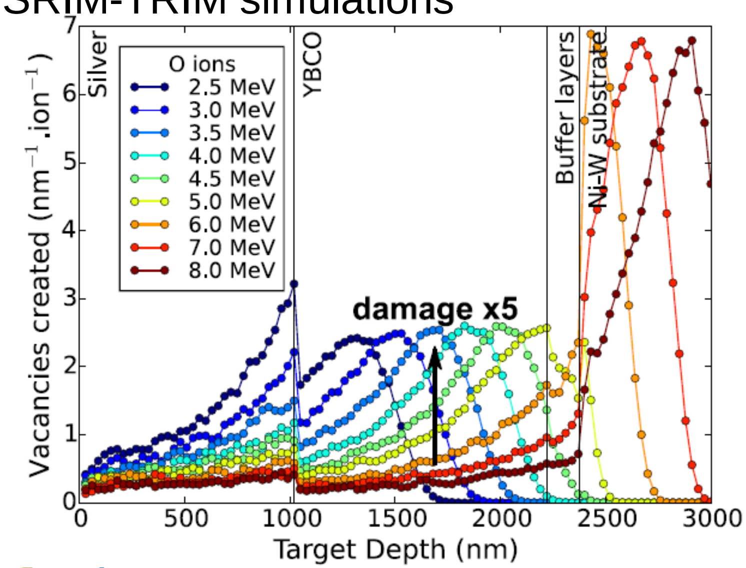
M. Leroux *et al.*,
APL **107**, 192601 (2015)



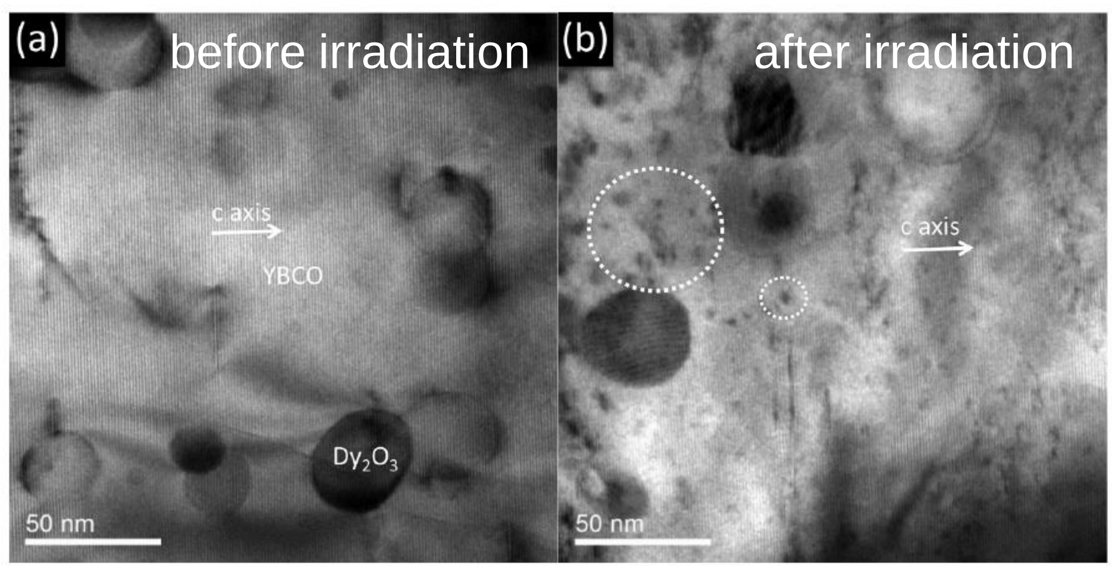


Irradiation done in 1 second!
Enables commercial processing

SRIM-TRIM simulations



Irradiation introduces clusters and point defects



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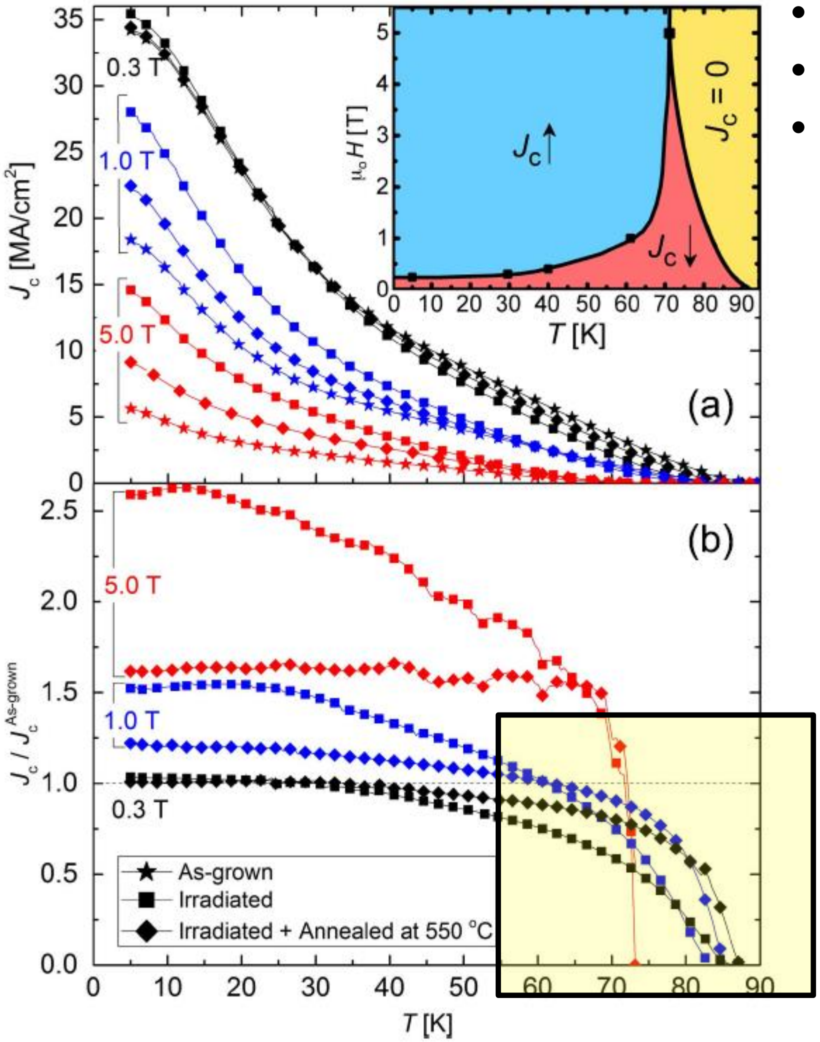
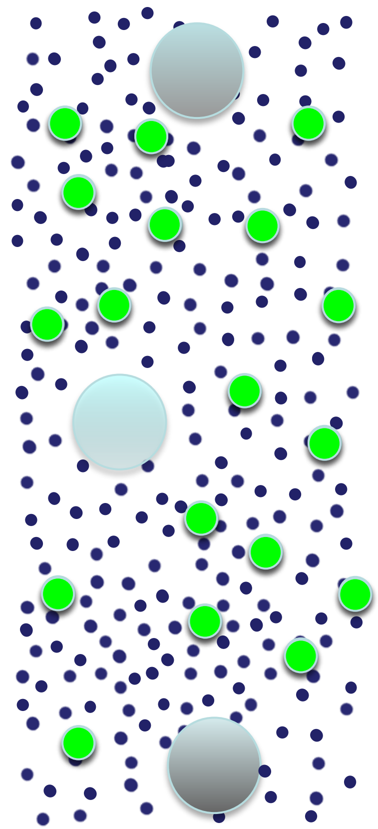
Oxygen irradiation improves J_c over most of the H-T phase diagram, but…

… reduces J_c at low H, high T



- Irradiation introduces clusters and point defects
- J_c reduction ⇒ Evidence for competing effects
- Annealing (removing point defects) <u>increases</u> J_c !!



Mixed pinning landscapes exhibit complex cooperation and competition effects among different types of disorder

S. Eley, *et al.*, SuST **30**, 015010 (2017)
Collaboration with ANL (EFRC Center for Emergent Superconductivity)

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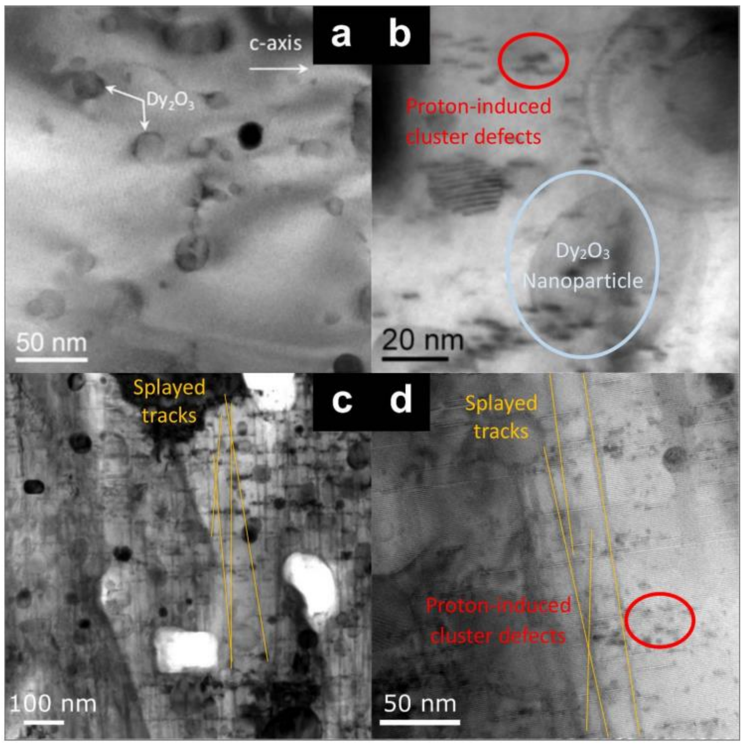
Office of Science U.S. DEPARTMENT OF ENERGY

Confirmation of the benefits of mixed pinning landscapes by combined 4MeV p^+ and 250 MeV Au irradiations

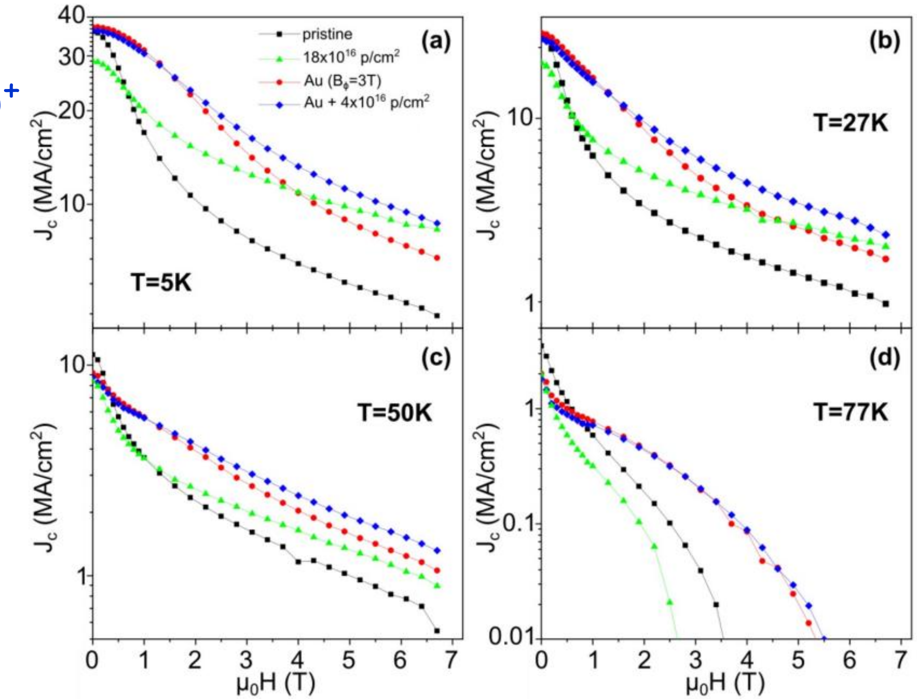
K J Kihlstrom[1,7], L Civale[2], S Eley[2,8], D J Miller[1], U Welp[1], W K Kwok[1], P Niraula[3], A Kayani[3], G Ghigo[4,5], F Laviano[4,5], S Fleshler[6], M Rupich[6] and M Leroux[1,2,9]

Supercond. Sci. Technol. **34** (2021) 015011 (13pp)

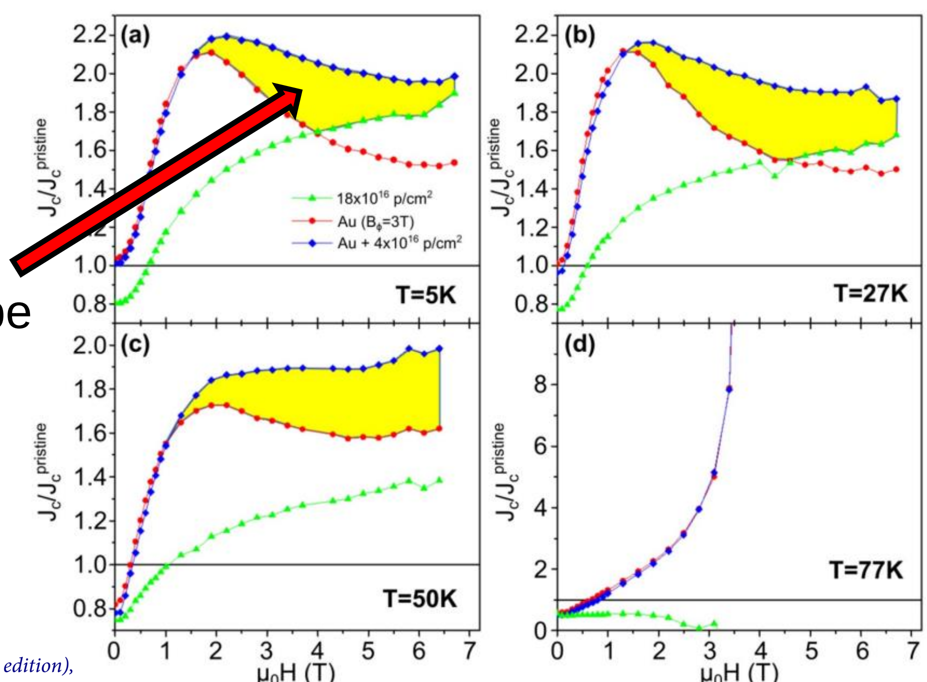
Pristine Protons



Combined irradiations



mixed landscape benefit



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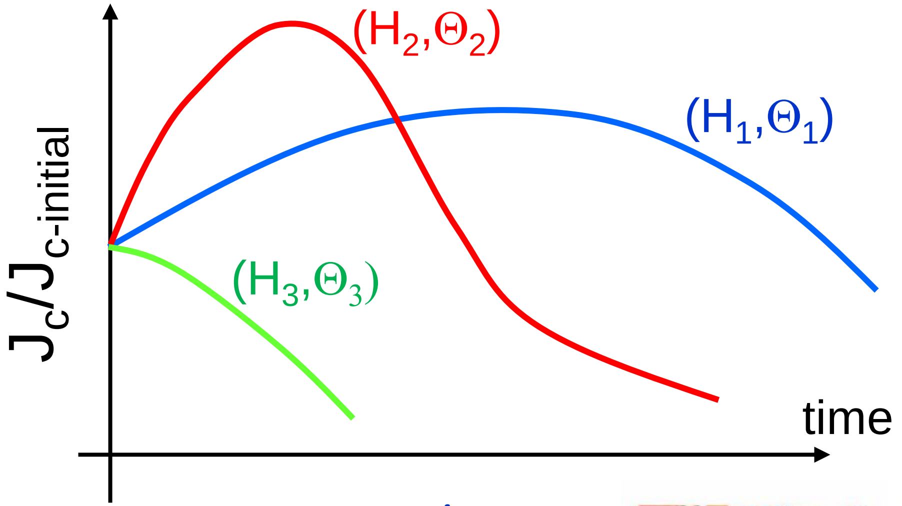
Concluding considerations

- Disorder (material defects) is required for vortex pinning
- *Re*BCO-based CCs have the highest J_c in any known SC $\Rightarrow$ many effective strong pinning defects
- Added defects in CCs (e.g. second phases) are wisely optimized for high J_c – typically “mixed pinning landscapes”
- Irradiation-induced defects will interact with pre-existing disorder. There will be cooperation and competition effects, different for each CC (“initial conditions”)
- Irradiation will start modifying the properties of the CC magnets in fusion reactors from day one of operation - The initial effect on J_c may be *mostly* positive…
- …but J_c will evolve differently for each (H,Θ) condition (not just an overall factor) $\Rightarrow$
  the location of the limiting position in the magnet will change.



Thank you for your attention!