Comparative analysis of particle irradiation and second-phase additions effects on the critical current densities of $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals, thin films, and coated conductors

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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

- ReBCO-based CCs have the highest $J_c$ in any known SC $\Rightarrow$ 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

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Thanks to all the collaborators!!
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
Vortices appear in the “mixed state” of type II superconductors

- Quantized “tubes” of magnetic field – each carries a flux quantum $\Phi_0$
- 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 $\Rightarrow$ vortex motion is dissipative $\Rightarrow$ resistance
- Motion may be precluded by material disorder (reduced core energy)
- Vortices remain pinned until $J$ reaches the critical current density $J_c$
Vortex matter physics arises from the interplay of 3 energies

Vortex-vortex interactions controlled by “intrinsic” material properties ($\lambda, \xi, \gamma$)

Ordered lattice (Abrikosov) Equilibrium

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

$J_c / J_0$

$G_i$

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

Main source of complex vortex phenomenology in HTS

Vortex liquid $I_c = 0$
- $H_m$

Vortex solid $I_c > 0$

Meissner

Generic HTS

$\Phi_0$

$B$

$\Phi_0 / B$

$a = (4/3)^{1/4} \left( \frac{\Phi_0}{B} \right)^{1/2}$
Many types of defects can act as pinning centers, some are better than others...

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

Artificially introduced defects
Popular methods in HTS:

- Particle irradiation
- Chemical incorporation of second phases

Combinations

Too small  good  Too big
point (atomic size)
nanoparticle
linear (columnar)
planar

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

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

**Localized uncorrelated disorder**
- Frenkel pairs
- Bigger defects
- Large cascades (Cu target)

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

![Graph showing damage efficiency and electronic stopping power](image)


F. Studer & M. Toulemonde (1992)
Irradiation creates effective pinning centers in clean YBCO single crystals

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

3 MeV p⁺

Even point defects are effective in YBCO because
- $\xi$ is small
- affects whole unit cell
- there are many (collective pinning)

L. Civale et al., PRL 65, 1164 (1990)
Orders of magnitude increases in $J_c$ in clean YBCO single crystals

Thermal neutrons
U-doped YBCO
R.L. Fleischer et al.,
PRB 40, 2163 (1989)

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

3 MeV p$^+$
$\vec{H} \parallel c$ axis
$H = 1$ T

J.R. Thompson et al.,
PRB 47, 14440 (1993)
High energy heavy ion irradiation creates aligned columnar defects

Directional pinning

CDs are the most effective pinning centers for \( H \parallel \text{defects} \) and below matching field \( B_\phi \)

However....

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

$J_c \sim 100\ \text{MA/cm}^2$

$J_c/J_0 \sim 0.3$

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
$J_c$ 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 $H//c$, $\Rightarrow$ 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


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

B. Maiorov et al., Nat. Mat. 8, 398 (2009)
Same BZO additions in films grown by different methods (MOD) or under different conditions may produce strong pinning by random nanoparticles.

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

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

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

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

No changes in $H_{c2}$ and $\gamma$ (because $\xi_{50}$ 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

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$_2$Cu$_3$O$_7$ 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.

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

Irradiation introduces clusters and point defects
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 $\Rightarrow$ Evidence for competing effects
- Annealing (removing point defects) increases $J_c$!!


Collaboration with ANL (EFRC Center for Emergent Superconductivity)
Confirmation of the benefits of mixed pinning landscapes by combined 4MeV p$^+$ and 250 MeV Au irradiations

Pristine Protons

Mixed landscape benefit

Combined irradiations
Concluding considerations

- Disorder (material defects) is required for vortex pinning
- ReBCO-based CCs have the highest $J_c$ in any known SC ⇒ 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 $(H, \Theta)$ condition (not just an overall factor) ⇒ the location of the limiting position in the magnet will change.

Thank you for your attention!