Maximizing the critical current in YBCO superconductors[1]

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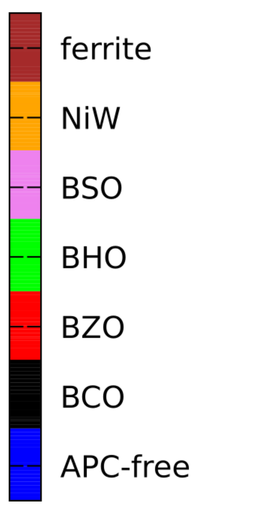
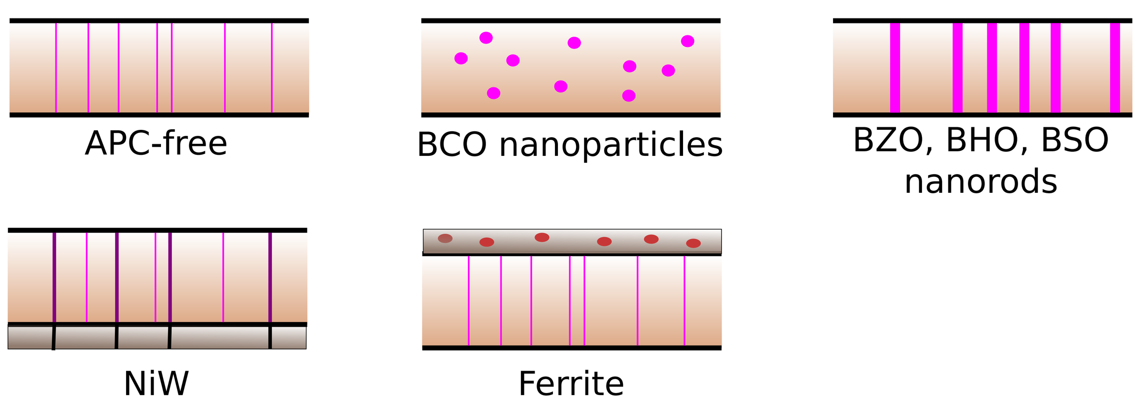
Problem & solution

- Can we still increase $J_c(B)$ in the whole range?
- What are the factors behind the different shapes of $J_c(B)$?
- Analysing data from large set of different YBCO thin films
- Finding the overall correlations between structure, J_c and T_c
- Understanding the physics behind the whole $J_c(B)$ and T_c

Samples

- ≈ 70 YBCO samples
- $SrTiO_3$, Nb-doped $SrTiO_3$, MgO, SLAO, $NdGaO_3$ and LSAT single crystals as well as buffered and textured metal substrates
- With and without $BaMO_3$ (M = Ce, Zr, Hf, Sn) artificial pinning sites





Experimental & Analysis

- PLD: λ=308 nm, E = 1.5 J/cm^2 & f = 5 Hz, $T_{\text{substrate}} = 725-800$ °C and p = 175 mTorr.
- XRD: 10–110° 2θ-ω and 2θ from (005) peaks and $2\theta-\phi$ of (122)/(212) peak sets
  → Lattice parameters, Williamson-Hall analysis (WH) oxygenation level, mean free path
- Magnetic PPMS at 10 K and in −8 – 8 T
  → T_c from $M_{ac}(T)$ and $J_c(B)$ from $J_c = \frac{3\Delta M}{a^3 d}$

Electron mean free path from XRD

- Defects disturb the periodicity of the lattice decrease ℓ and increase ρ_{normal}

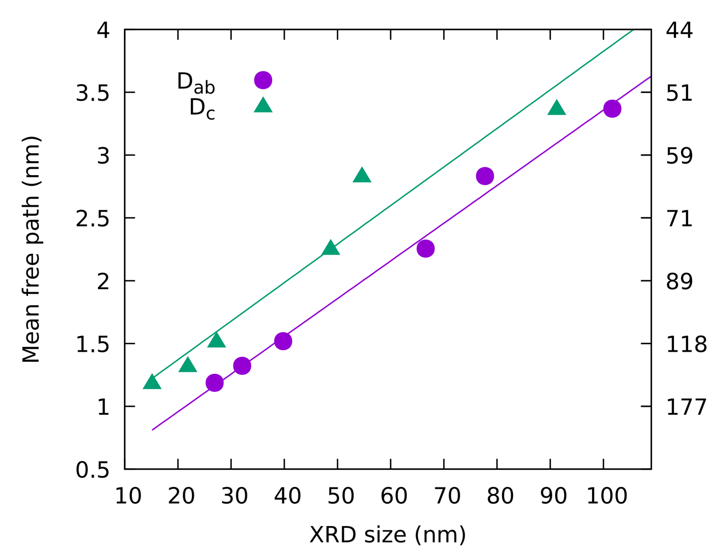
$$\ell = \frac{m v_F}{e^2 n}\frac{1}{\rho_{\text{normal}}}$$

- Defects also widen the XRD peaks and decrease the coherent domain size of x-rays.

→ **XRD domain size can be used as proxy for ℓ**

- Coherent domain size from WH size and width of (005) rocking curve

$$D_c = \frac{K}{\epsilon} \qquad D_{ab} = \frac{K\lambda}{\beta_\omega 2\sin\theta}$$



Acknowledgements

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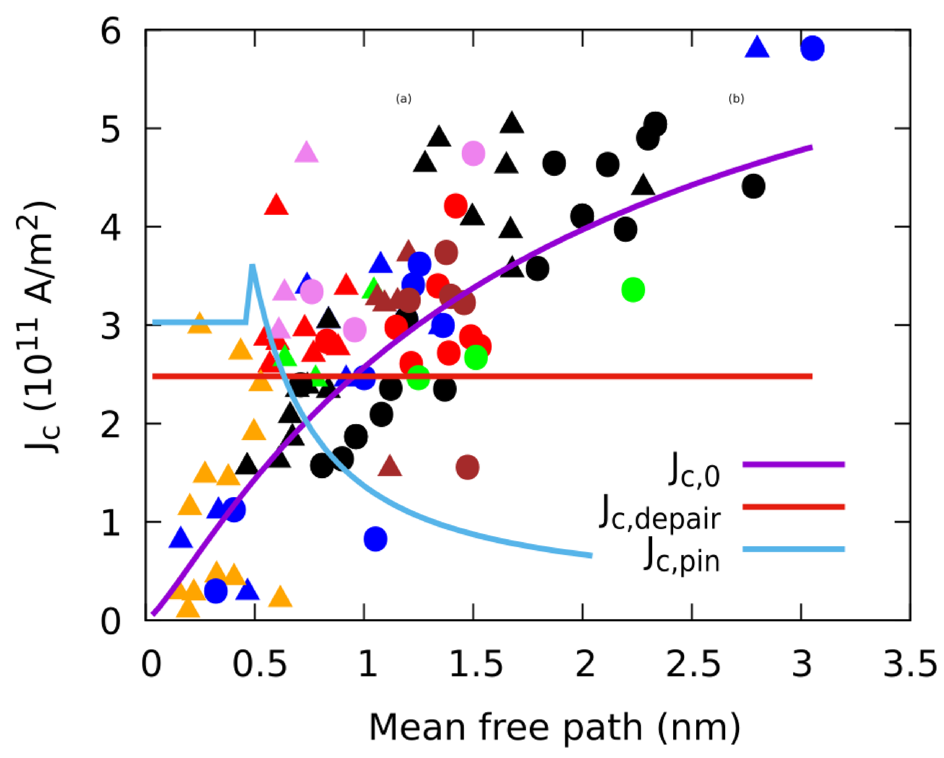
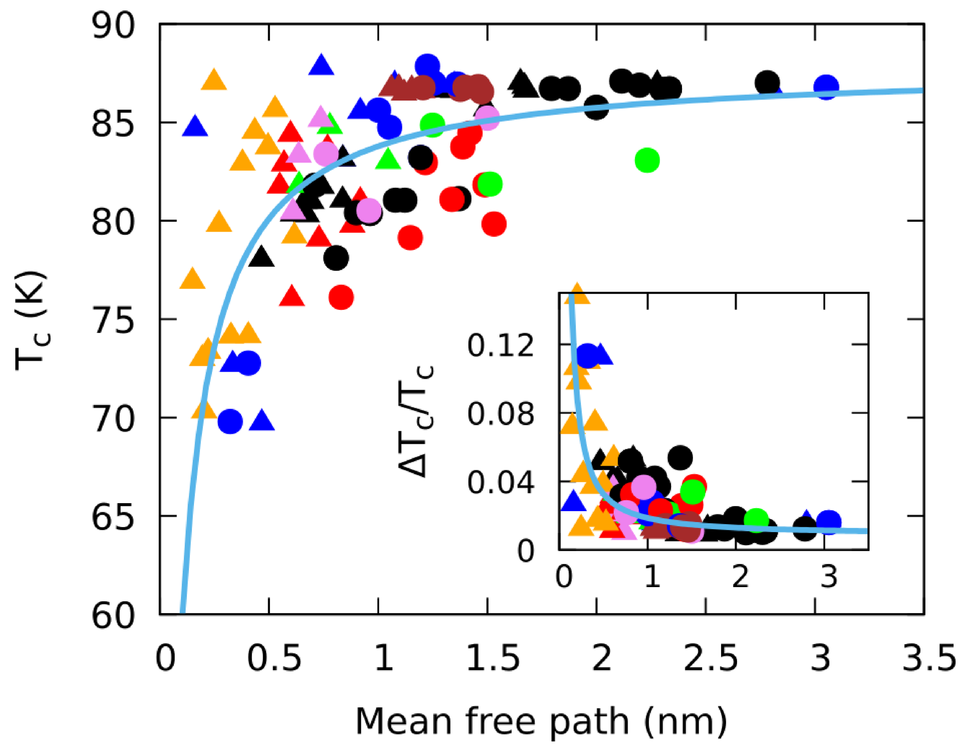
Zero field J_c, T_c and the mean free path





- Superconducting parameters λ and ξ depend on electron mean free path ℓ as

$$\frac{1}{\xi} = \frac{1}{\xi_0} + \frac{1}{\ell} \qquad \lambda = \lambda_0\sqrt{1+\xi_0/\ell},$$

- Experimental value λ = 90 – 150 nm
- Depairing current $J_{c,\text{depair}} = \phi_0/4\pi\mu_0\lambda^2\xi$ is independent of ℓ and implies $\lambda \approx 770$ nm
- Pinning $J_{c,0}$ decreases with ℓ with $\lambda \approx 880$ nm

$$J_{c,\text{pin}} = \begin{cases} \frac{27\sqrt{2}}{64}\left(\frac{r_r}{2\xi}\right)^2 J_{c,\text{depair}} & r_r < \sqrt{2}\xi, \\ \frac{3\sqrt{3}}{4\sqrt{2}} J_{c,\text{depair}} & \sqrt{2}\xi < r_r < \lambda, \end{cases}$$

- Talantsev [2] model $J_{c,0}$ has the experimental dependence with $\lambda \approx 87$ nm

$$J_{c,0} = \frac{H_{c1}}{\lambda_{ab}} \times \frac{\lambda_c}{d}\tanh\frac{d}{\lambda_c}$$

- In HTS

$$T_c = \frac{T_{c0}}{1+\alpha 0.882\frac{\xi_0}{\ell}}$$

- Transition width follows

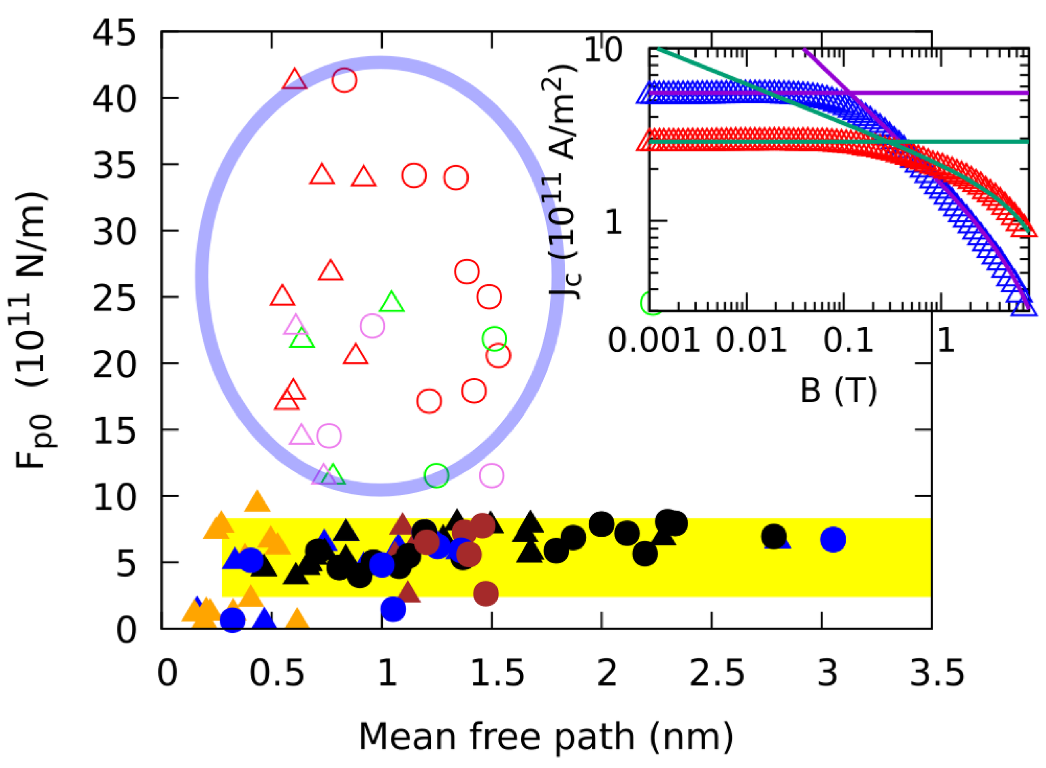
$$\frac{\Delta T_c}{T_c} = 1.11\left(\frac{k_B}{\pi c_n \xi^3}\right)^{1/2}$$

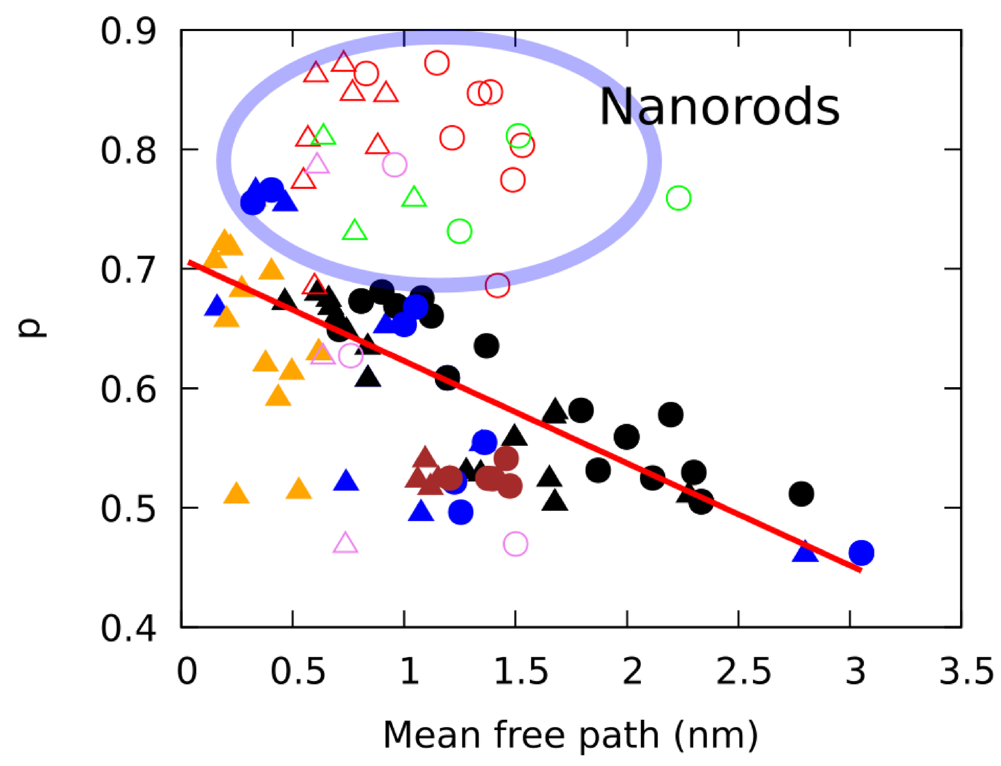
Field dependence of J_c

- Pinning force analysis with Dew-Hughes

$$F_p(B) = F_{p0}\left(\frac{B}{B_{\text{irr}}}\right)^p\left(1-\frac{B}{B_{\text{irr}}}\right)^q$$

- Clear differences between samples with and without nanorods
- F_{p0} is independent of ℓ as expected, F_{p0} is determined by the pinning site size
- p depends on ℓ : increasing crystal lattice disorder breaks the vortex lattice and increases p
- The lower of $J_{c,0}$ and $J_{c,\text{pin}}$ defines $J_c(B)$
- Crossing of mechanism at the end of the plateau





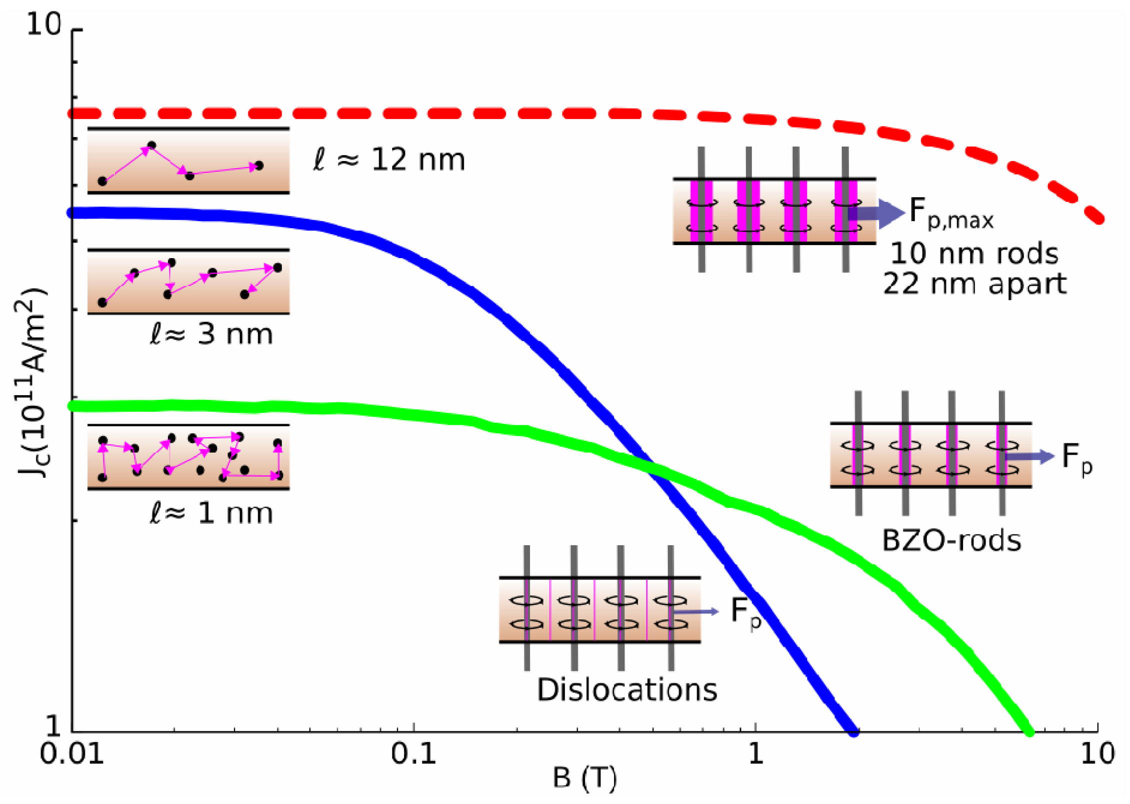
Maximal J_c

Therefore,

1. The zero and low field J_c is determined by the coherence length and penetration depth of the superconductor. These depend on the electron mean free path, ℓ, in the superconductor.
2. The critical temperature, T_c and the width of the transition are also determined by the mean free path.
3. The critical current at high fields is mainly determined by the flux pinning sites of the sample and can therefore be increased by adding non-superconducting APCs.
4. With increasing magnetic field, the transition from mostly mean free path limited $J_{c,0}$ to pinning limited J_c takes place at the crossover field B^+. When $B > B^+$, $J_{c,\text{pin}} < J_{c,0}$.

Maximal J_c in single layer can be reached by

- $J_{c,0}$: Maximize the electron mean free path, i.e. improve the crystal structure
- $J_c(B)$: Add about 50 vol-% of nanorods, the optimal size and density depends on the field, in 5 T 10 nm rods 20 nm apart



References

[1] P. Paturi and H. Huhtinen, Supercond. Sci. Tech. **35**, 065007 (2022)

[2] E. F. Talantsev and J. L. Tallon, Nat. Commun. **6**, 7820 (2015)

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