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中國科學院
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Exploring the impact of irradiation fluence on shaping the superconducting performance of $EuBa_2Cu_3O_{7-\delta}$

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6/20/2025

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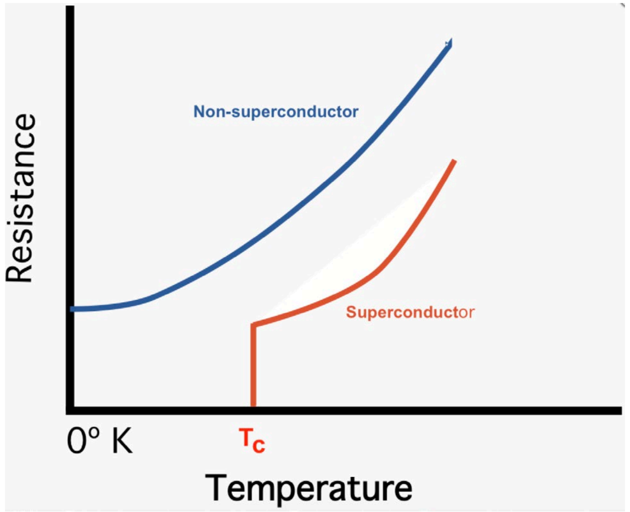
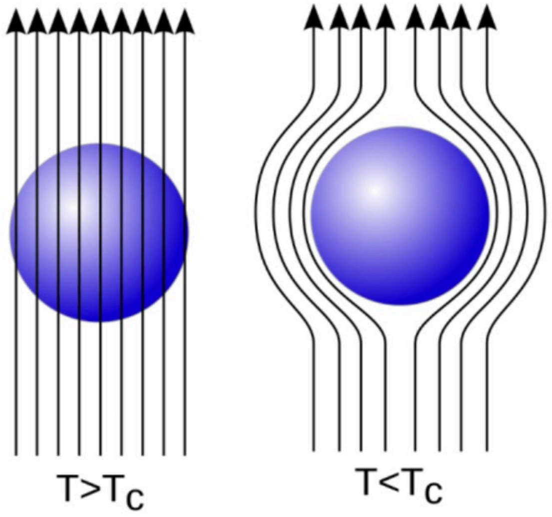
Outline

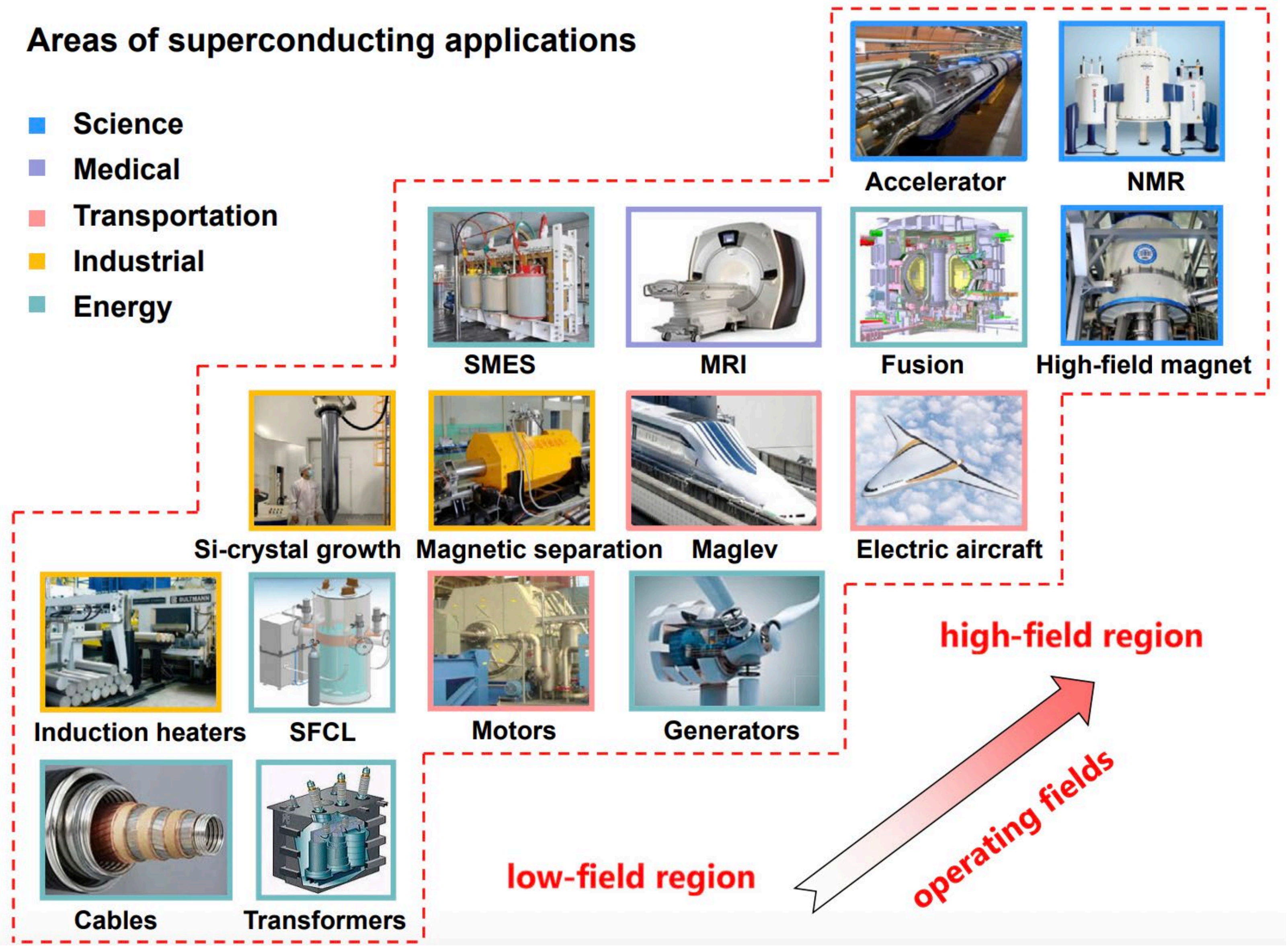
Motivations: Superconducting Properties

Zero resistance



Meissner Effect

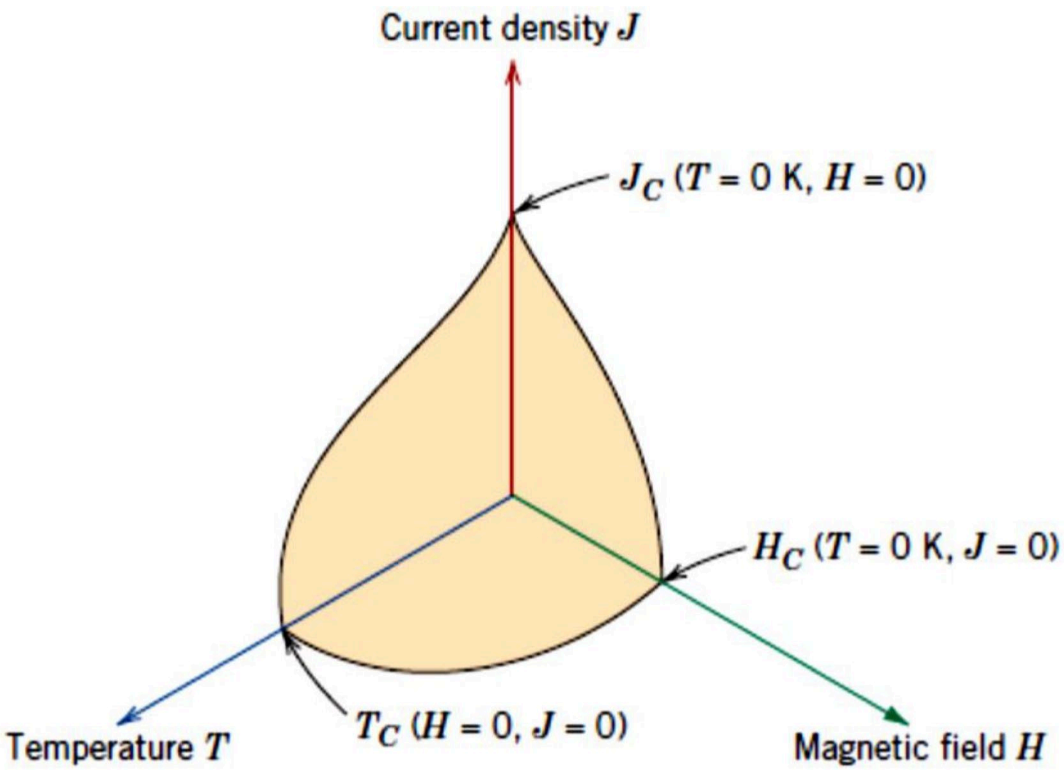


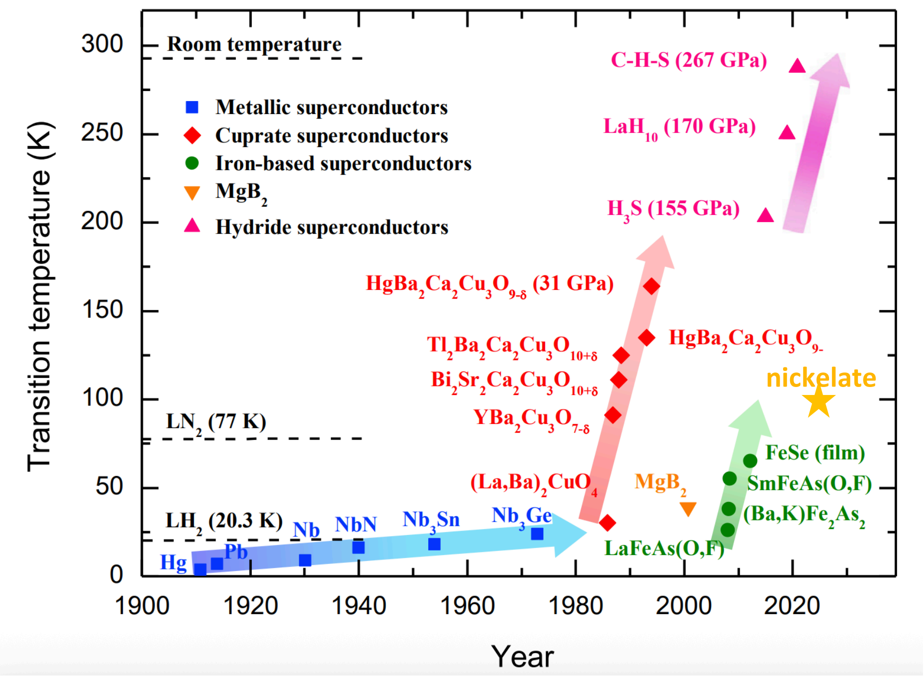


Y. Ma, iScience 24, 6, 102541, 2021

Motivations: Superconducting Properties

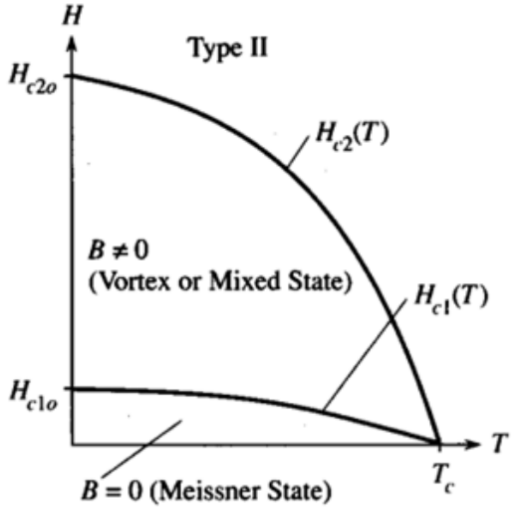
T_c : pairing mechanician, structure/symmetry, superfluid density





H_{c2} : coherence length

$$H_{c2} = \frac{\Phi_0}{2\pi\xi^2}$$



Three key parameters for application:
T_c , H_{c2} , J_c

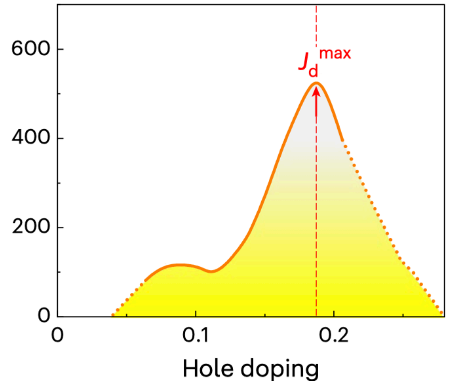
A. Gurevich, Rep. Prog. Phys. 74, 124501 (2011)

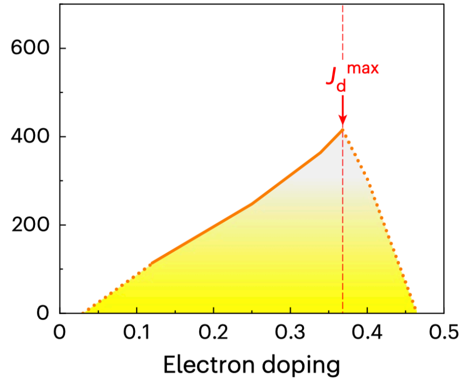
Y. Ma, iScience 24, 6, 102541, 2021

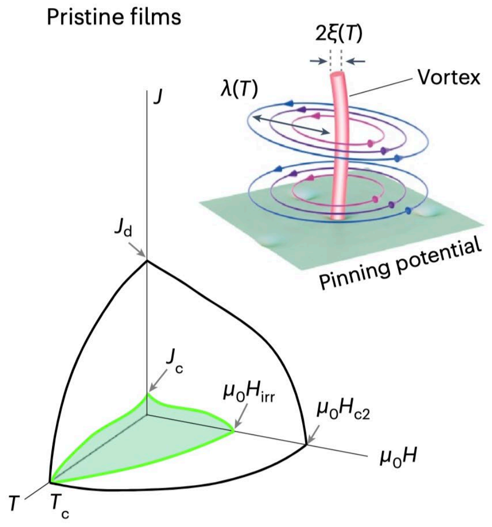
Motivations: Superconducting Properties

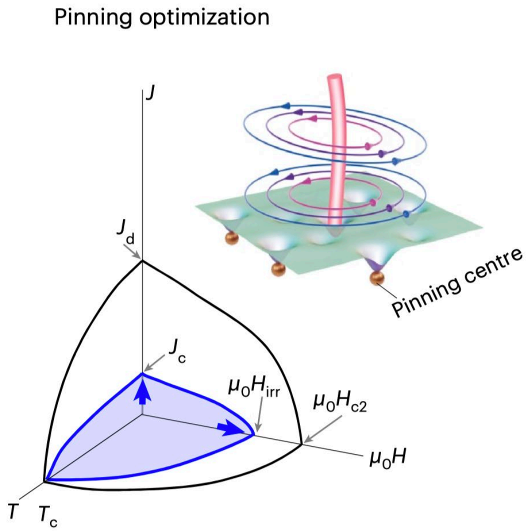
J_c : depairing current density J_d, vortex pinning

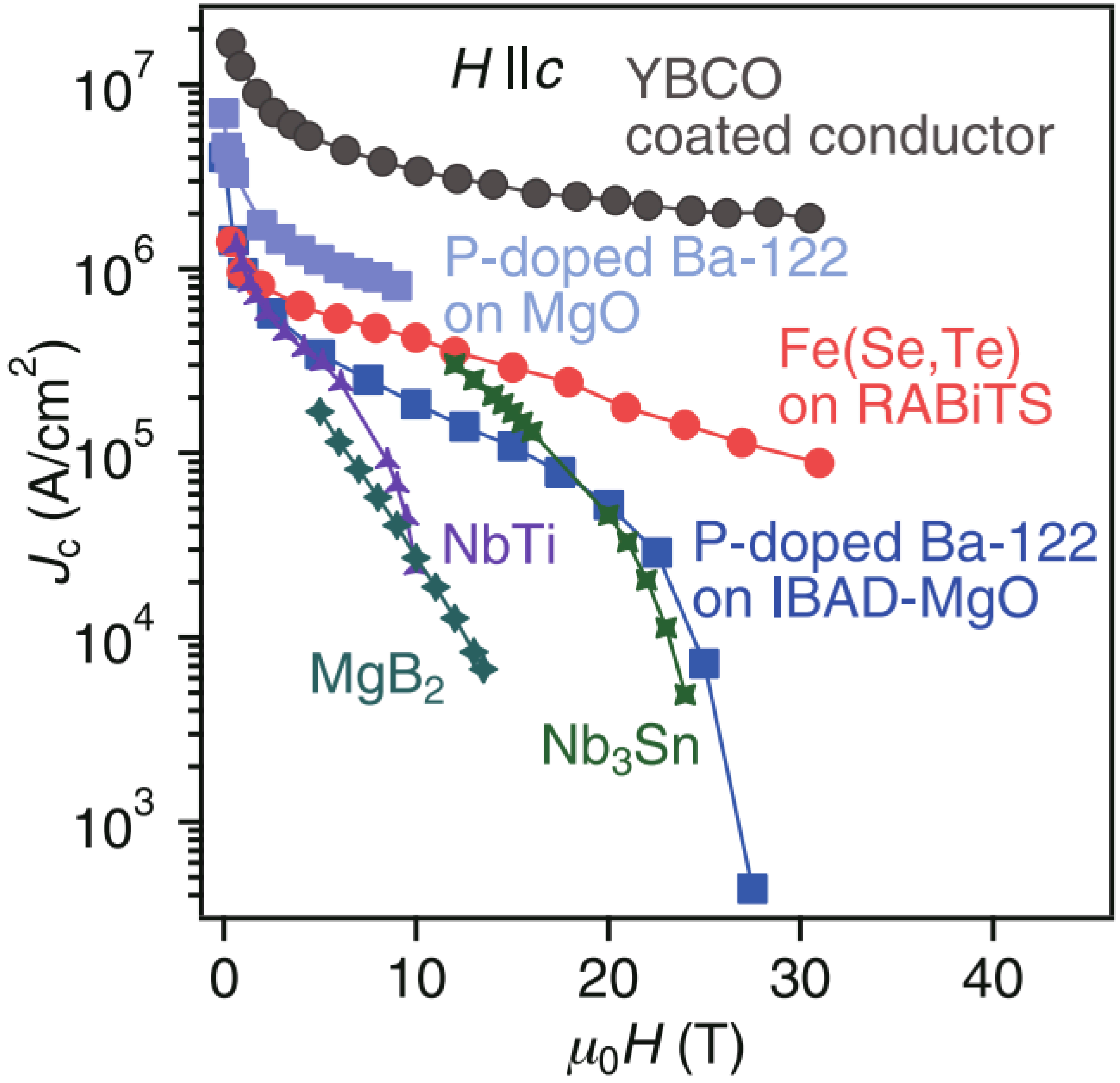
$$J_\mathrm{d}(T) = \frac{\phi_0}{3\sqrt{3}\pi\mu_0\lambda_{ab}^2(T)\xi_{ab}(T)} \qquad J_c \sim 32\%\, J_d$$





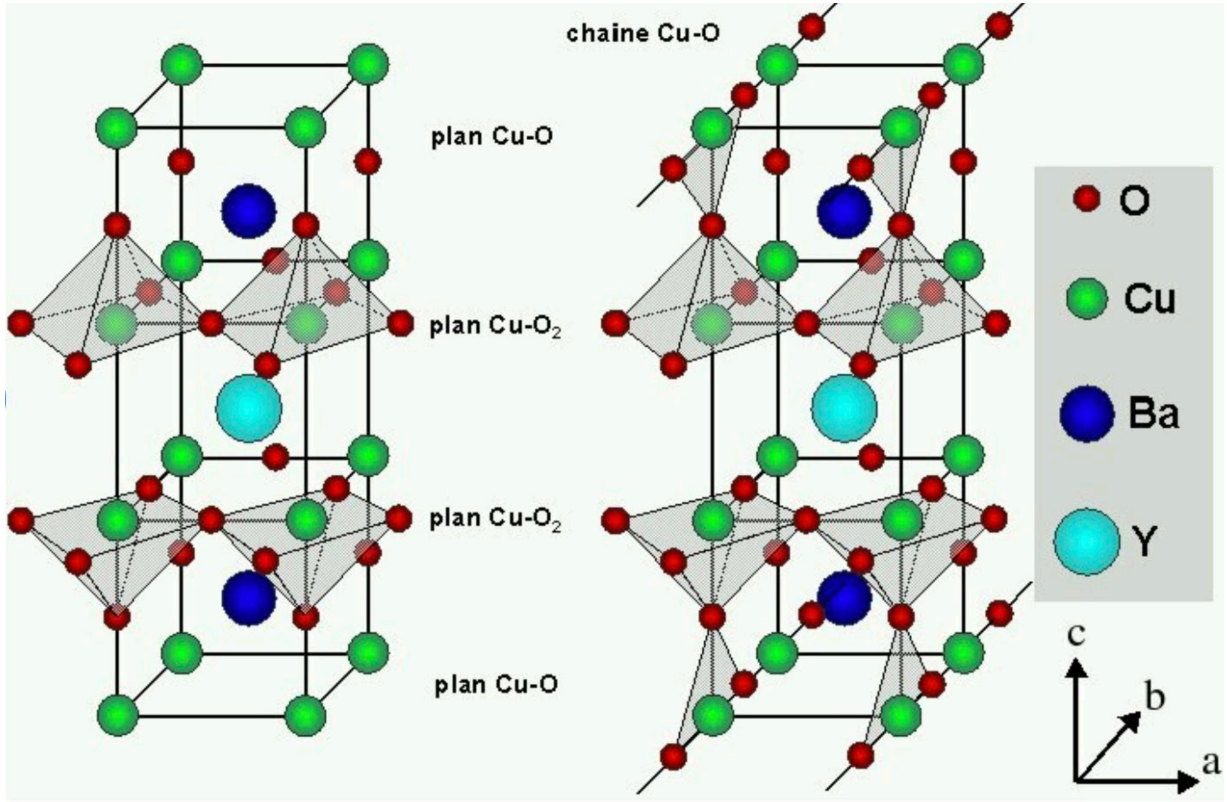






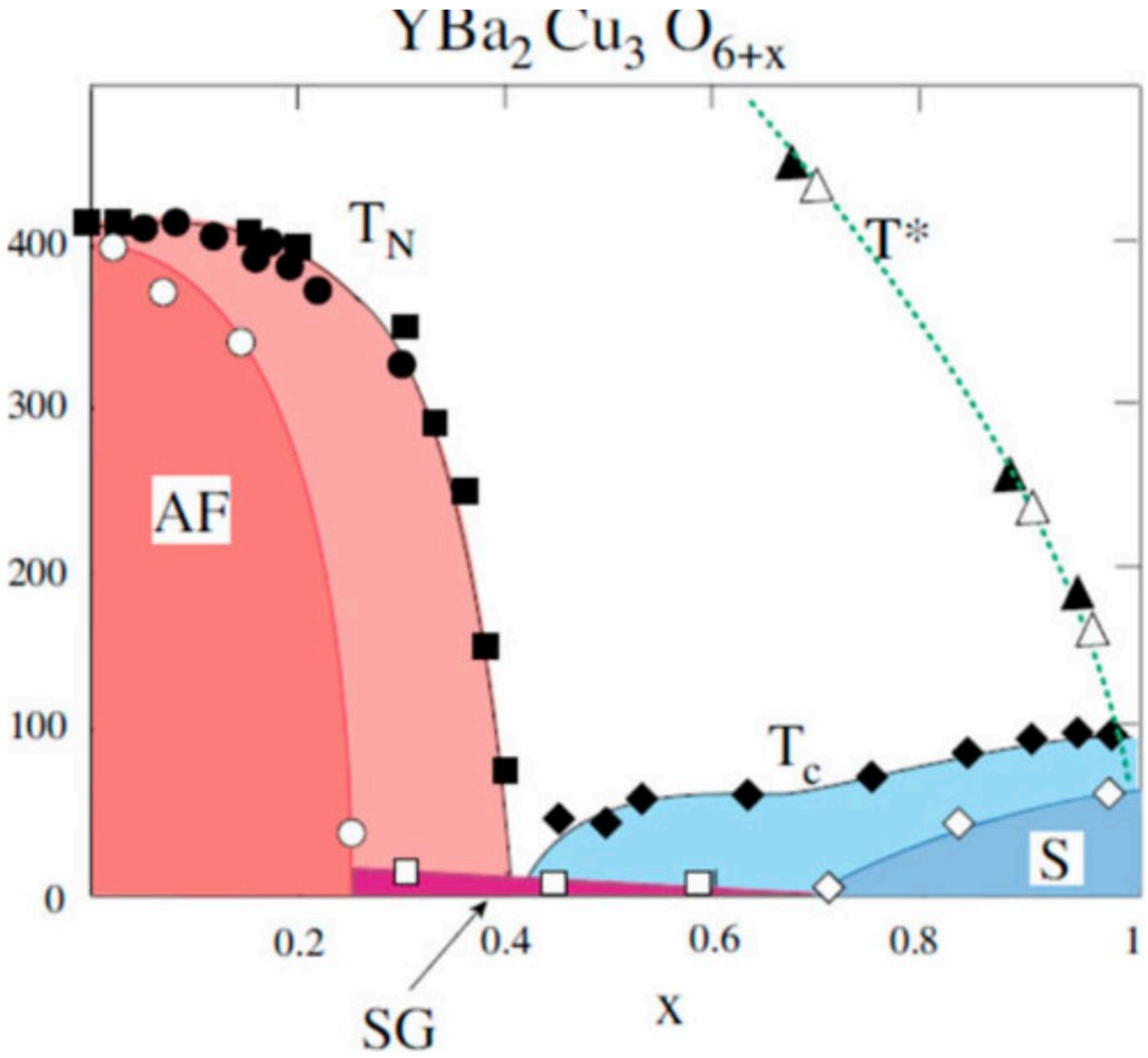
Masashi Miura et al,. Nat. Mater. 23, 1370–1378 (2024)

Motivations: Superconducting Properties



$YBa_2Cu_3O_6$ | $YBa_2Cu_3O_7$

Non superconductivity | $T_c \sim 92K$



Henri Alloul, Front. Phys., 05, 2024

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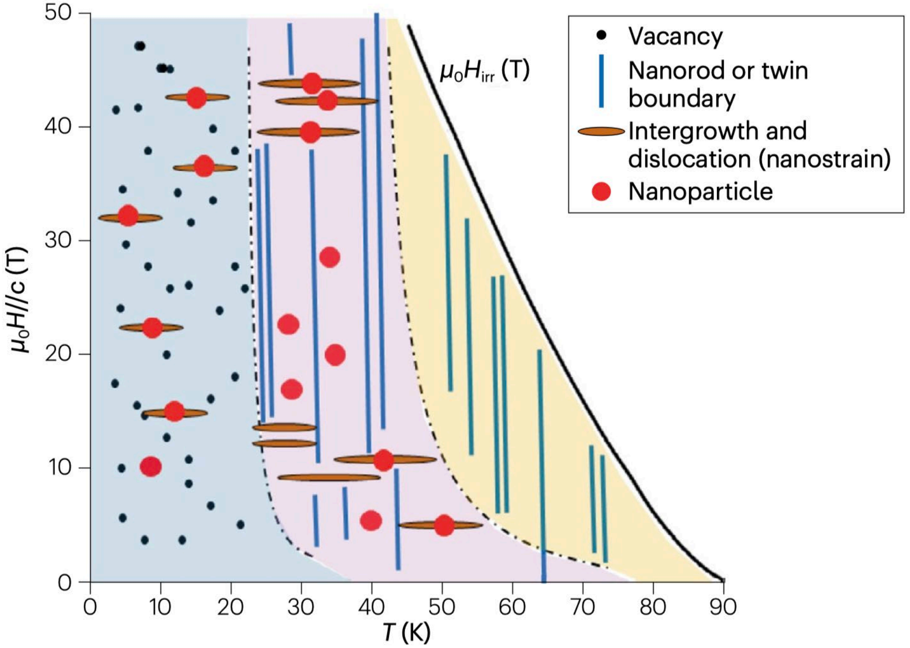
Motivations: Methods to enhance J_c

Growth-controlled defect engineering



Collective pinning energy

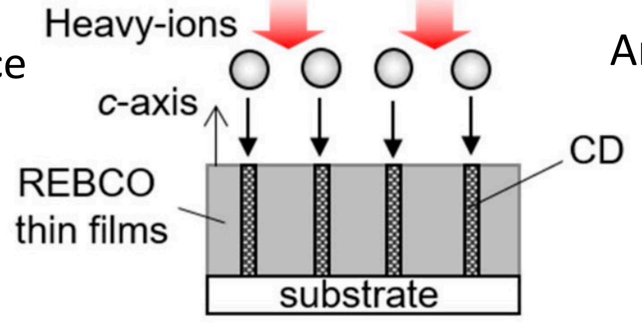
$$U_c \propto \sqrt{V_c}$$

V_c is bundle volume $V_c \simeq R_c^2 L_c^b$

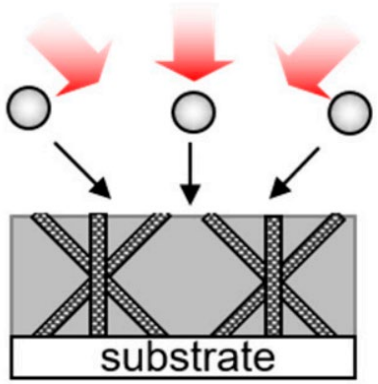
Pinning effect is most effective when the bundle volume is large.

Irradiation-induced defect engineering

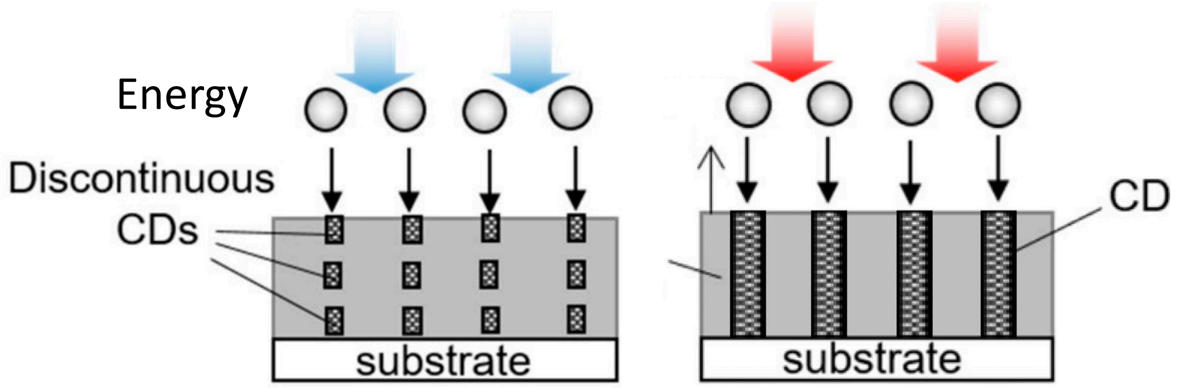
Fluence



Angle



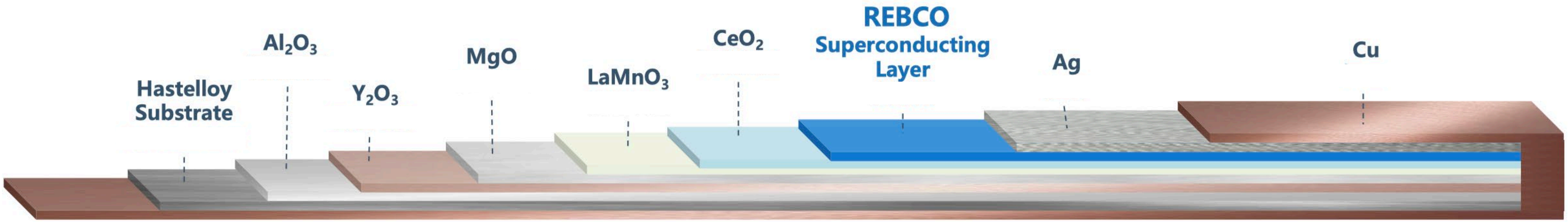
Energy



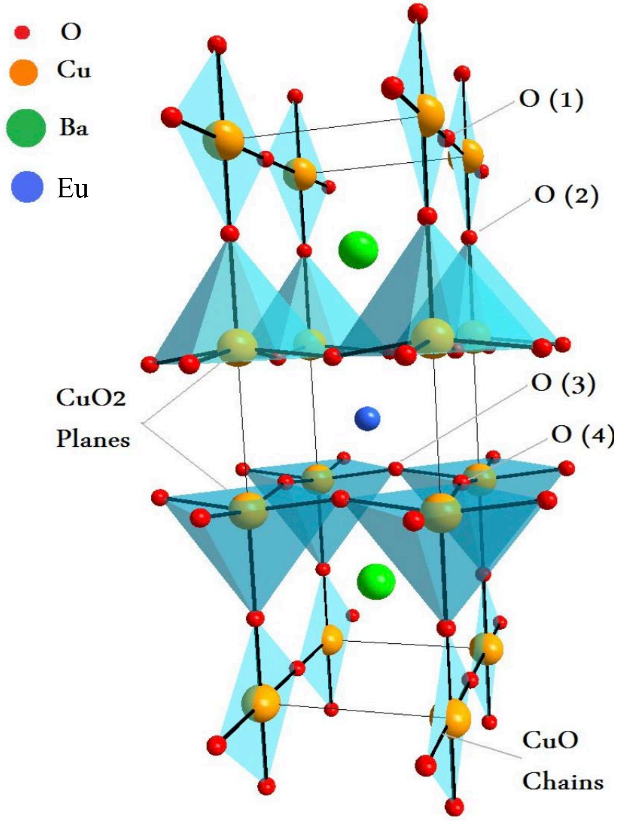
Teresa Puig et al, Nat. Rev. Phys. 6,132–148 (2024) Blatter et al., Rev. Mod. Phys. 66, 1125 (1994) Tetsuro Sueyoshi, Quantum Beam Sci. 5, 16, 2021

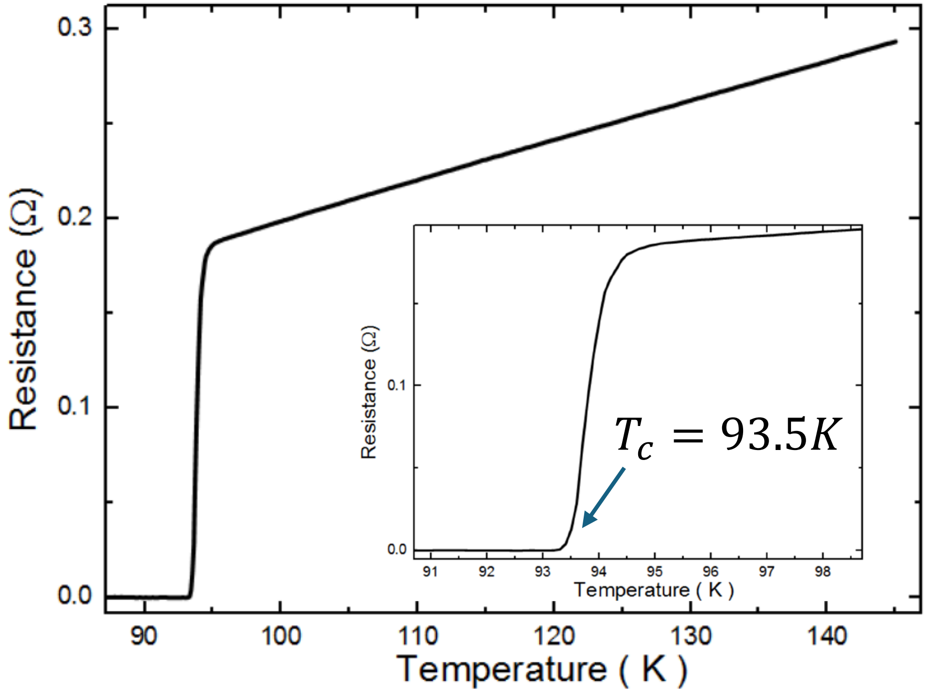
Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$

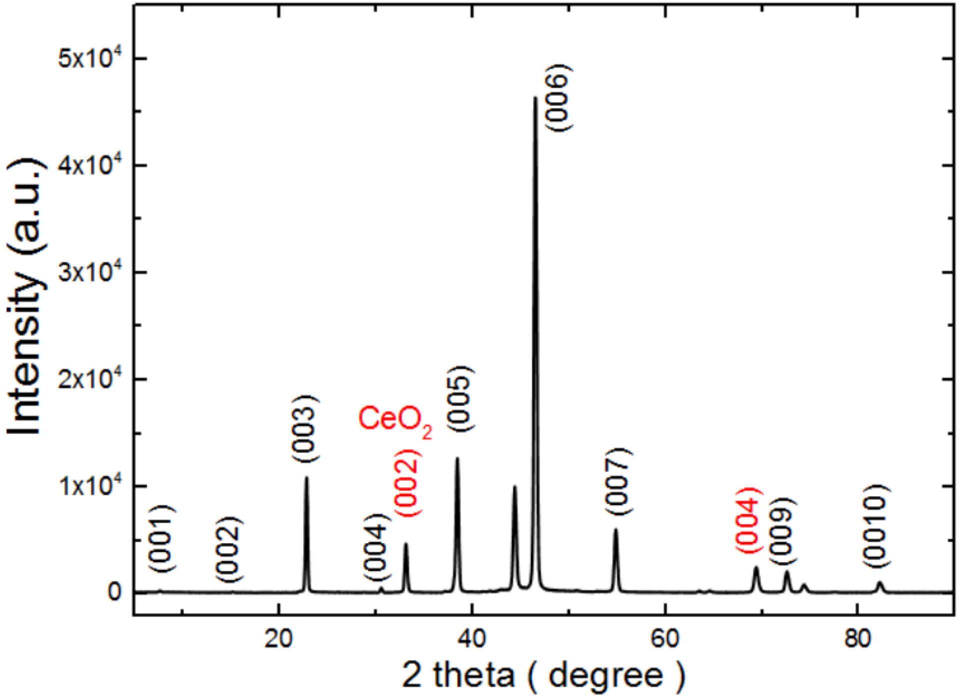
$EuBa_2Cu_3O_{7-\delta}$ + 3.5mol % $BaHfO_3$ Y → Eu $EuBa_2Cu_3O_7$ $T_c \sim 94K$



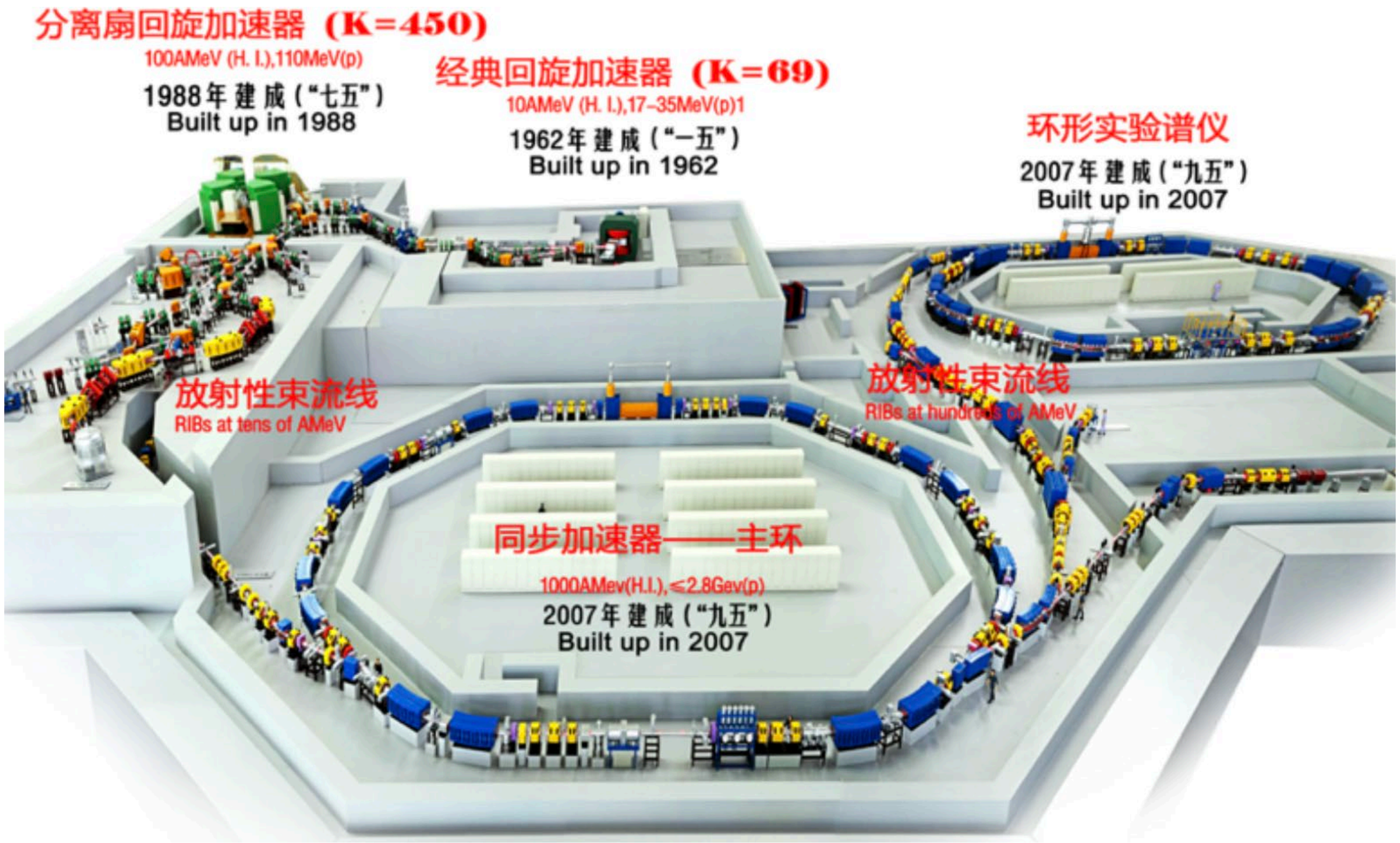
Provided by Shanghai Superconductor Technology Co.,Ltd







Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$



Heavy Ion Research Facility in Lanzhou (HIRFL) at IMP, CAS

Xe^{2+} irradiation parameters

Energy:
100 MeV, 150 MeV, 200 MeV

Fluence:
5×10^{10}, 2×10^{11}, 1×10^{12} ions/cm²

Matching field:
1T, 4T, 20T

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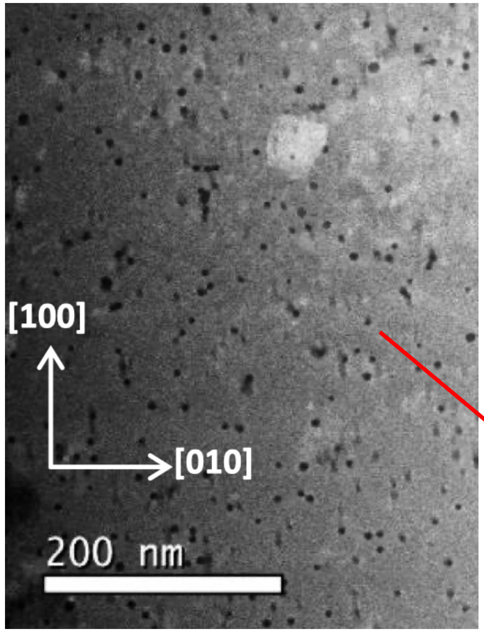
Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$

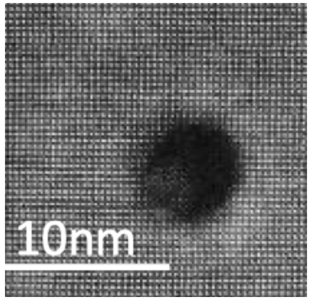
Transmission Electron Microscopy

Fluence : 2 x 10^{11} ions/cm^2

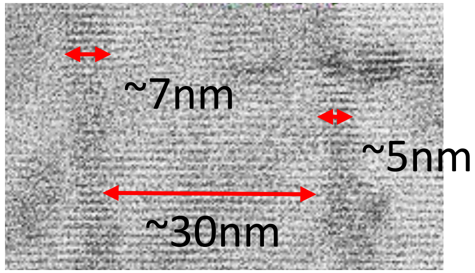


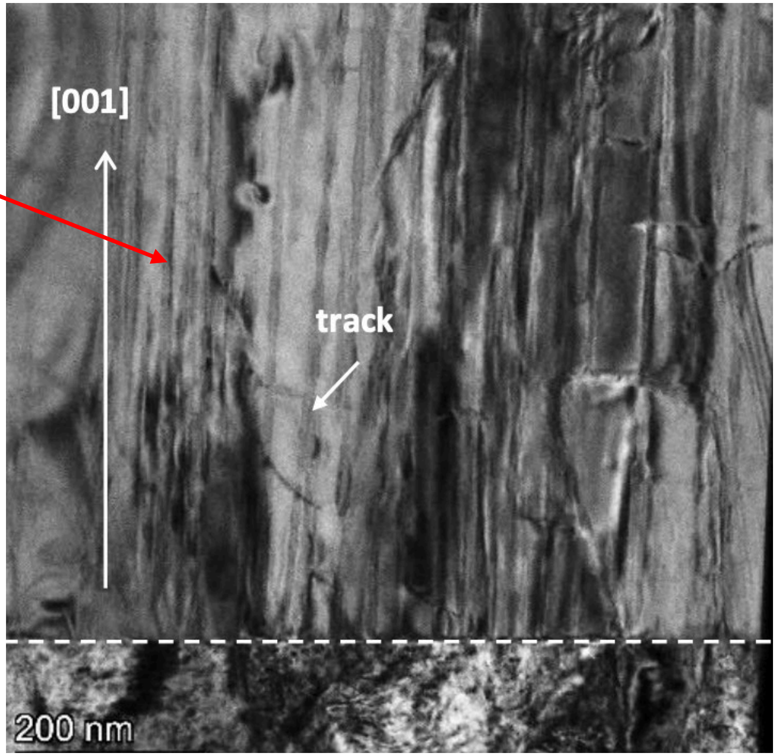
defect density n ~ 1.3 × 10^{11}

~ 65% of nominal fluence



Continuous column defects



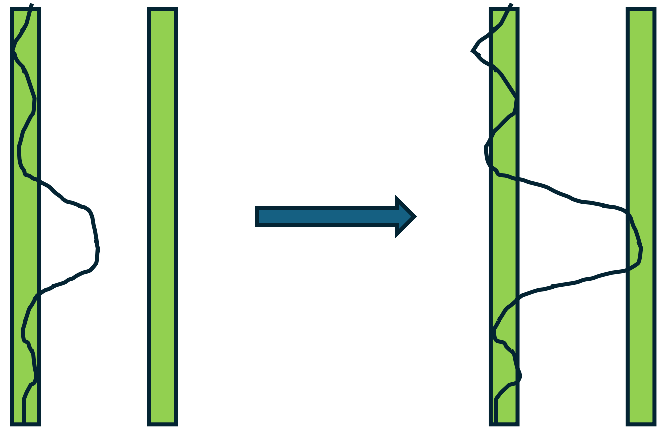


Mean distance between the defects $d = \sqrt{1/n} \approx 27nm$

Xe^{2+} irradiation induces continuous columnar defects approximately 5~7 nm in size.

Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$

simple estimation of J_c from an isolated columnar defect



$d \approx 27nm$

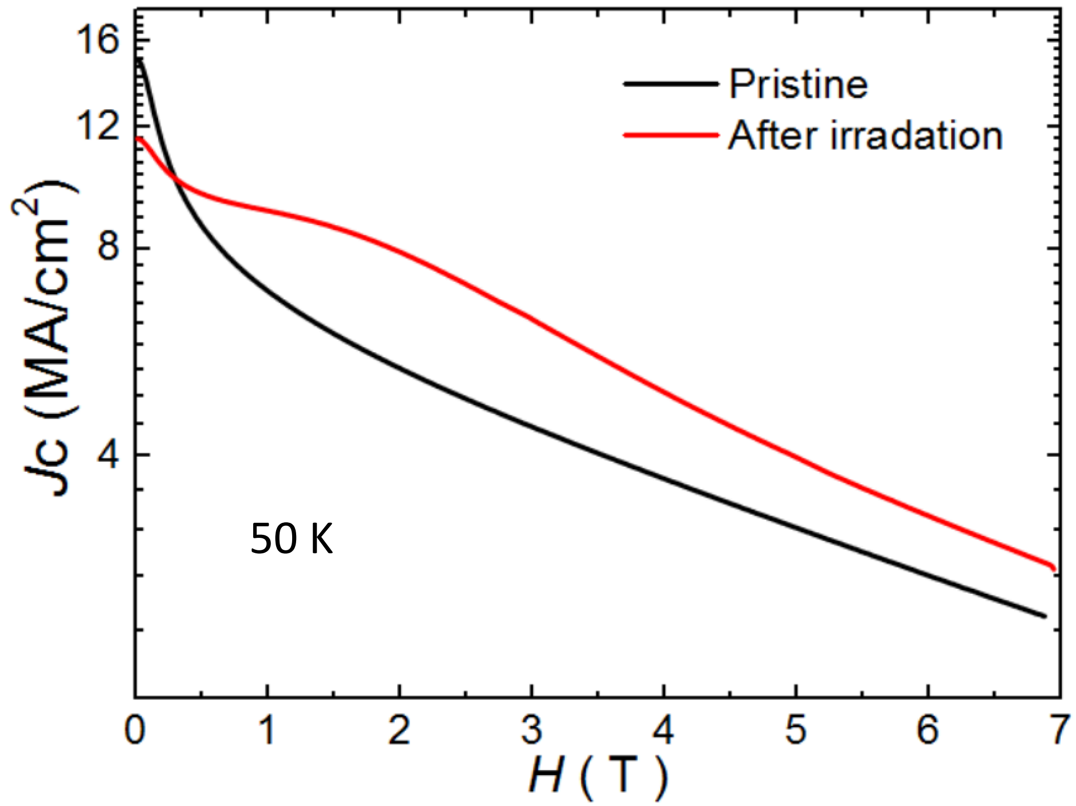
$$U_p^{max} = f_L d$$

Lorentz force $f_L = \frac{\phi_0}{c} j$ $\quad U_p = \frac{\phi_0^2}{16\pi^2\lambda^2} ln\frac{b}{\xi}$

$$J_c = \frac{c}{\phi_0} f_L = \frac{c}{\phi_0}\frac{U_p^{max}}{d} = \frac{c}{d}\frac{\phi_0}{16\pi^2\lambda^2} ln\frac{b}{\xi}$$

J_c~30 MA/cm^2

J_c from magnetization measurements



Bean model

$$J_c = \frac{20\,\Delta M}{a(1 - a/3b)}$$

J_c~10 MA/cm^2 at low field

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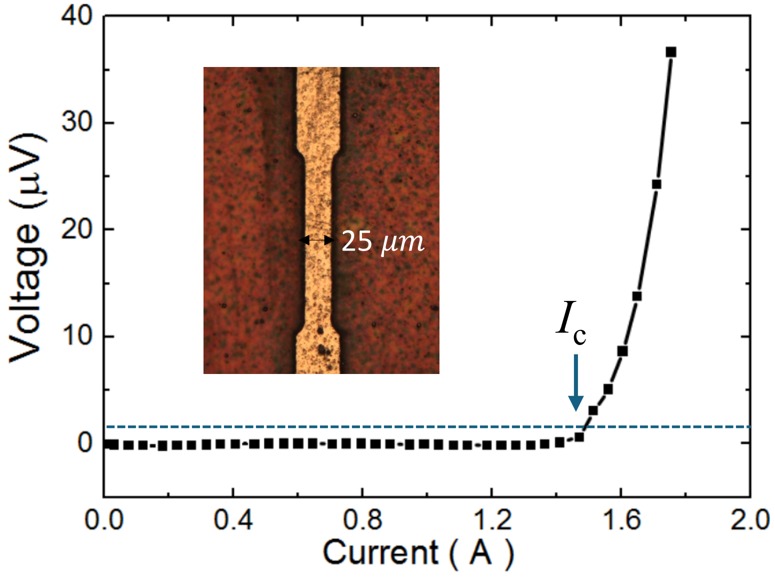
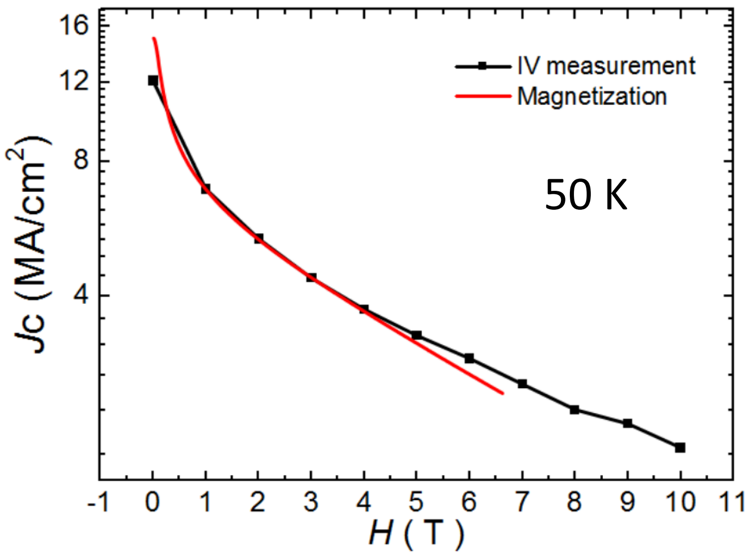
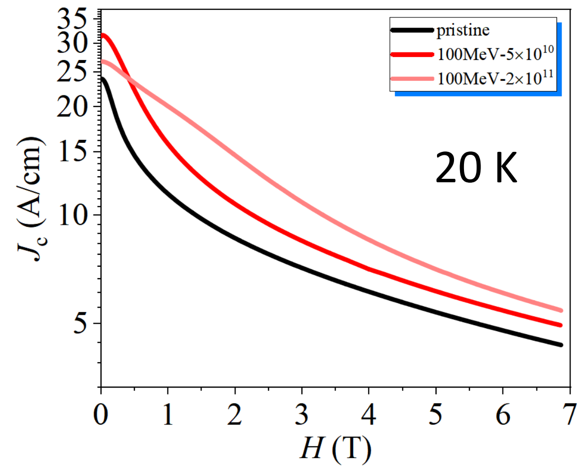
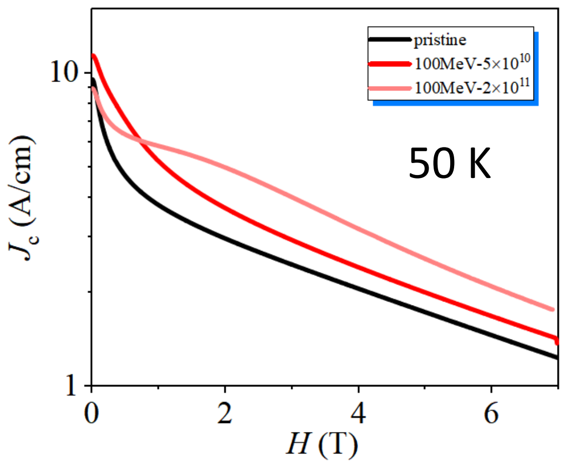
Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$

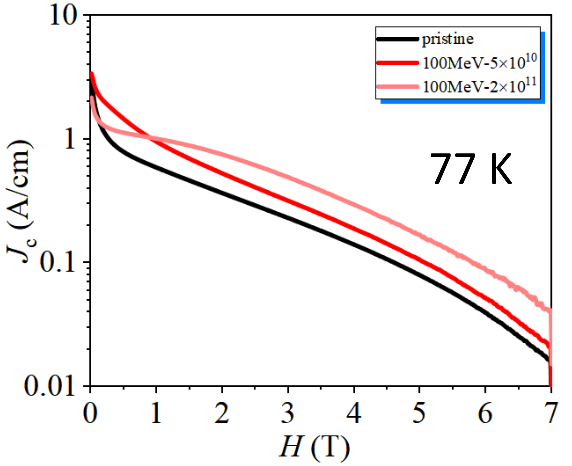
J_c from IV measurements

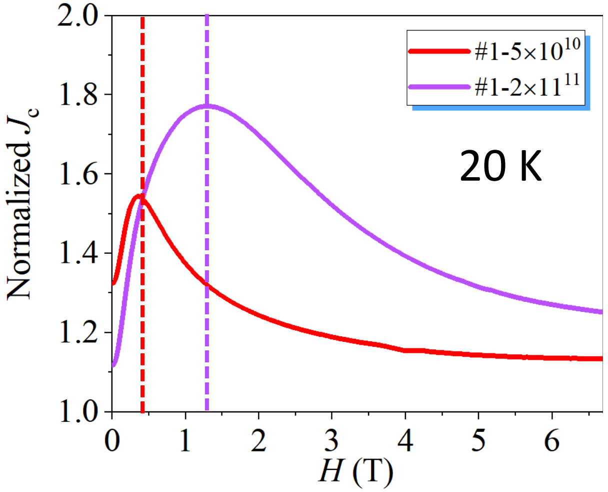


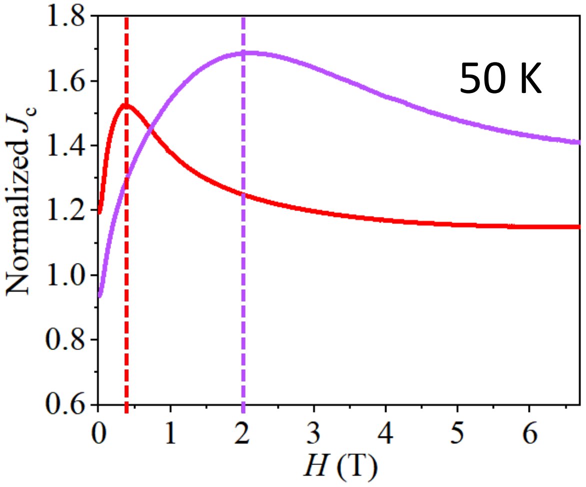


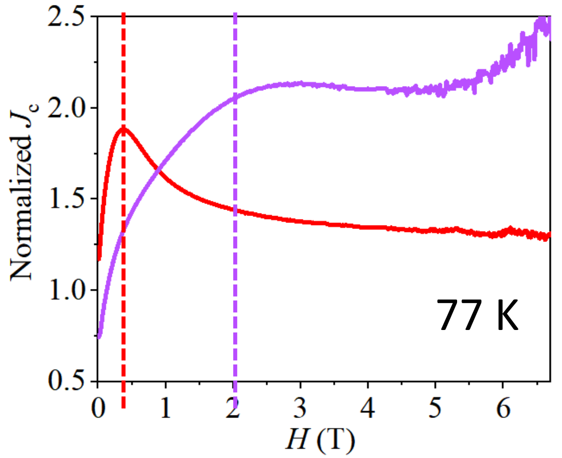












The observed peaks can be attributed to the matching field effect.

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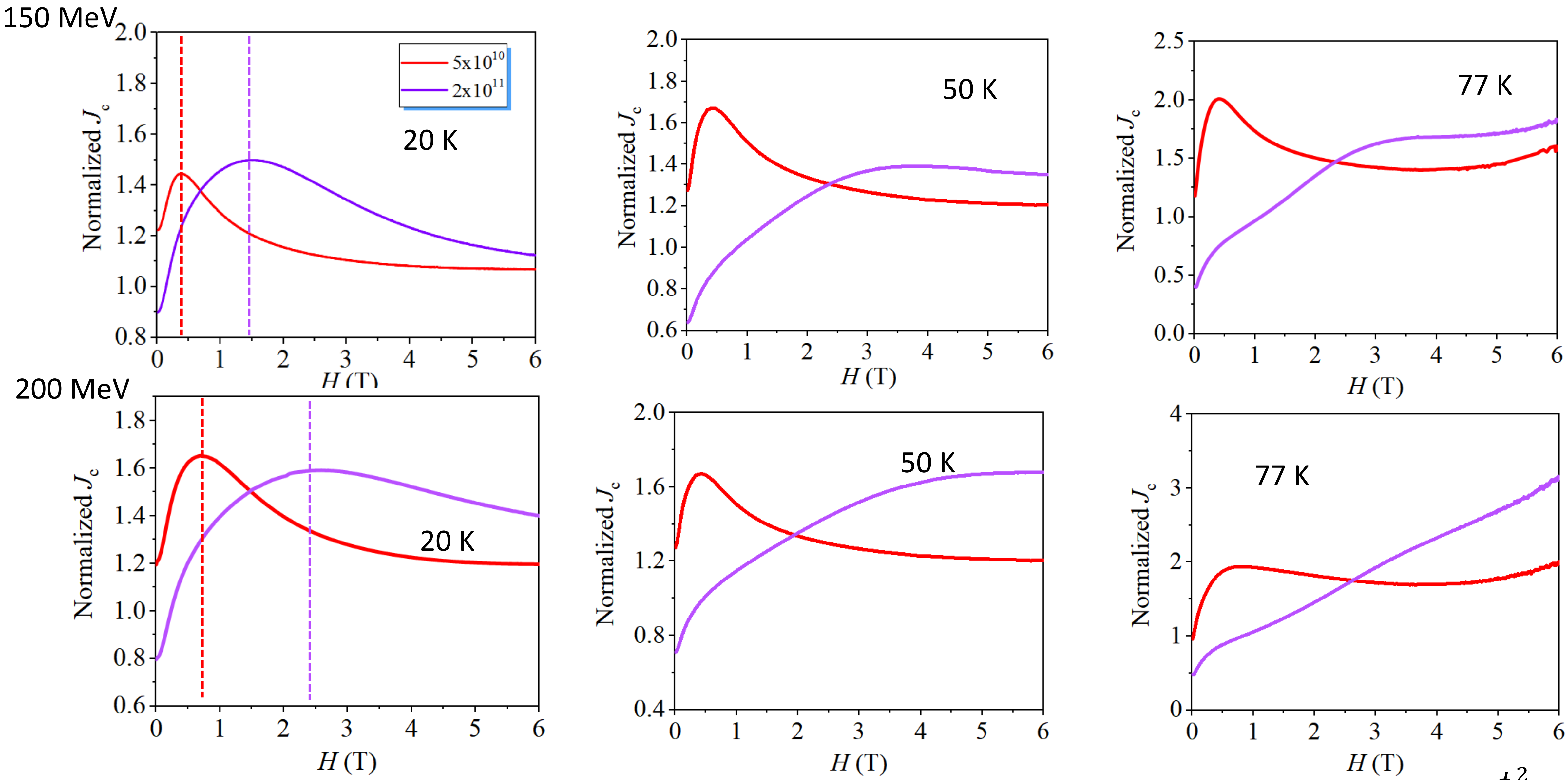
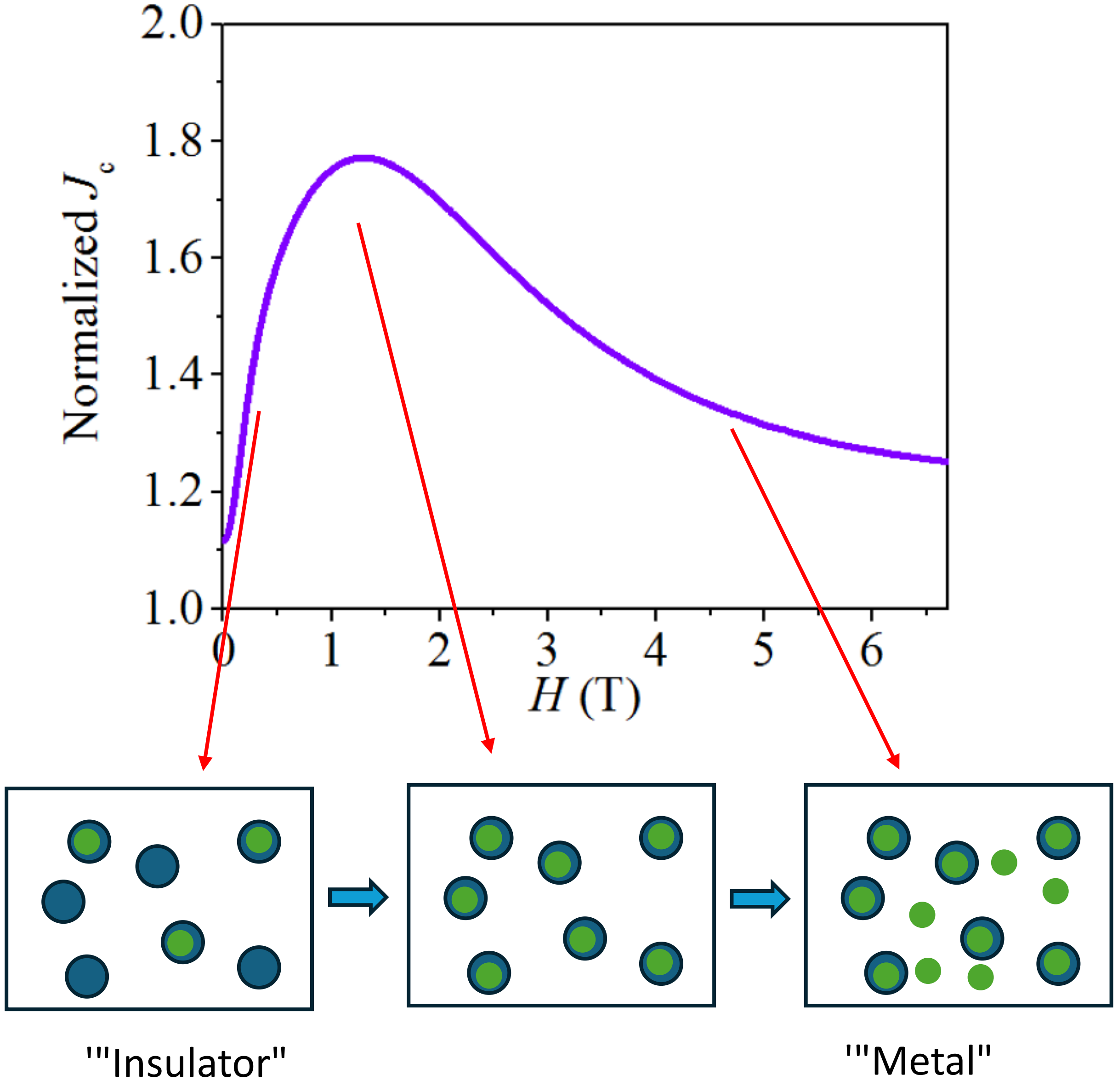


The irradiation energy can alter the size of columnar defects, thereby modifying the pinning energy.

$$U_p = \frac{\phi_0^2}{16\pi^2\lambda^2} ln \frac{b}{\xi}$$

Vortex pinning mechanisms



At low field region H<<H_m

Single vortex model

$$J_c = \frac{c}{\phi_0} f_L = \frac{c}{\phi_0}\frac{U_p^{max}}{d} = \frac{c}{d}\frac{\phi_0}{16\pi^2\lambda^2} ln\frac{b}{\xi}$$

$$d \simeq (\phi_0/B_\Phi)^{1/2} \qquad J_c \propto \sqrt{B_\phi}$$

At high field region H>>H_m

Collective pinning model

$$J_c = \frac{c}{Bl}\frac{U_p}{V_c}$$

$$U_p \simeq \eta(H_c^2/8\pi)\pi\xi_{ab}^2 L \qquad V_c \simeq d^2 L \qquad d \simeq (\phi_0/B_\Phi)^{1/2}$$

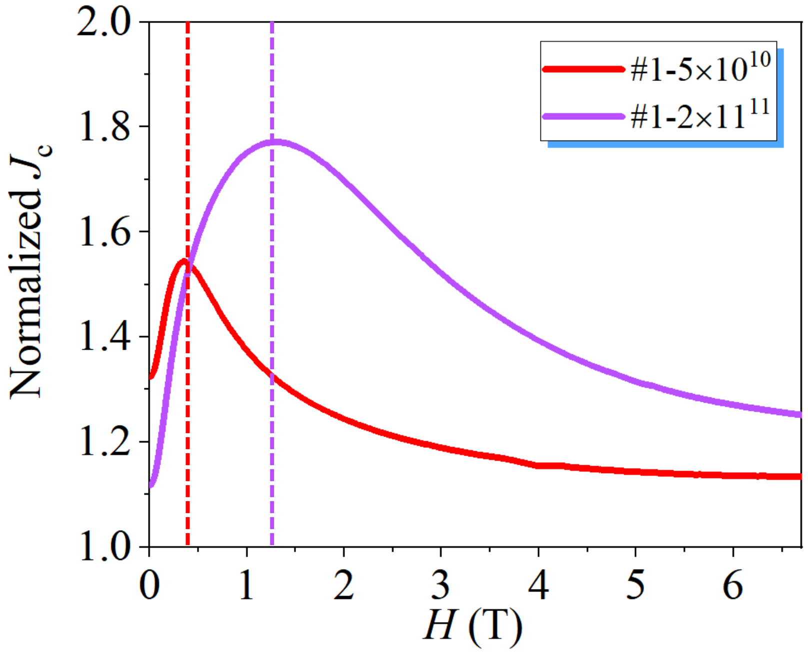
$$J_c \simeq \eta c \frac{H_c^2}{8\pi}\pi\frac{\xi_{ab}}{\phi_0}\frac{B_\Phi}{B} \qquad J_c \propto B_\phi$$

At high field region, the larger B_ϕ or irradiation fluence leads to an enhanced J_c

M. Baert et al., Phys. Rev. Lett. 74.3269 (1995)

L. Civale et al., Phys. Rev. Lett. 67.648 (1991)

Vortex pinning mechanisms



At low field region H<<H_m

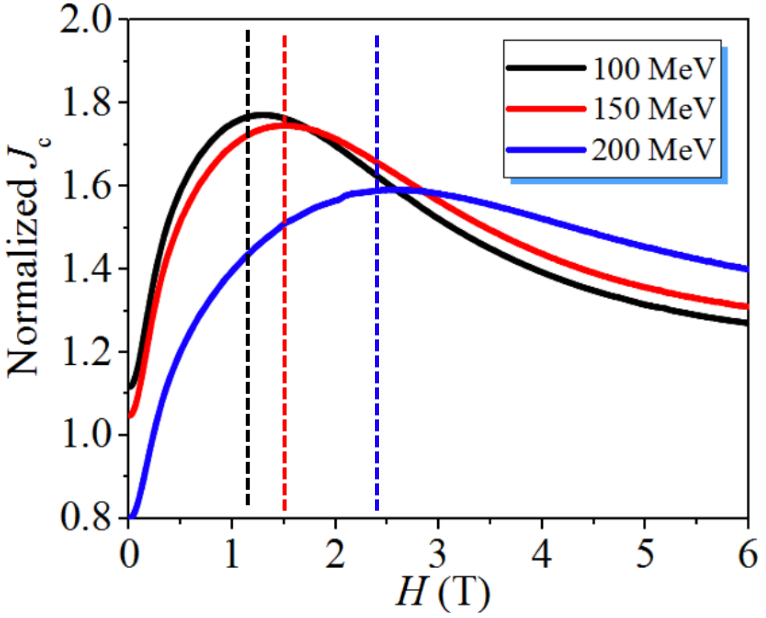
$$J_c \propto \sqrt{B_\phi}$$

Single vortex model X

At high field region H>>H_m

$$J_c \propto B_\phi$$

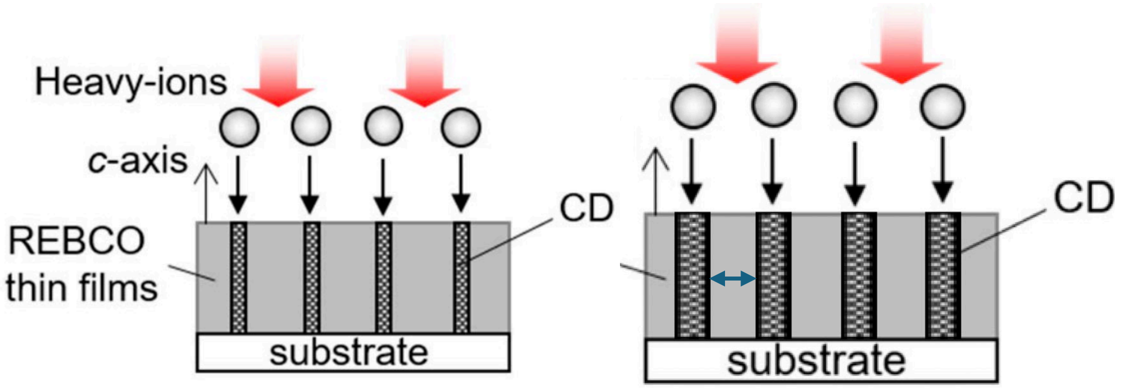
In the low-field region, the reduction in J_d and superconducting volume caused by irradiation may lead to the breakdown of the single-vortex pinning model.



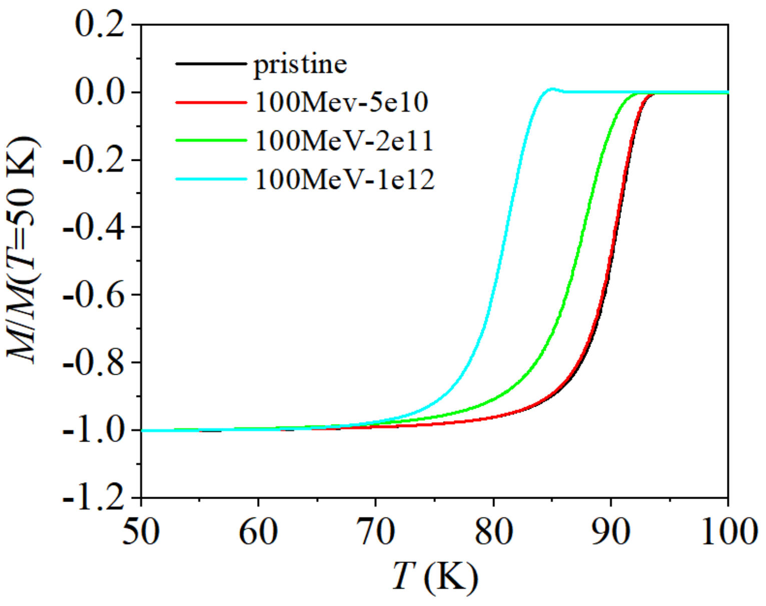
$$d \simeq (\phi_0/B_\Phi)^{1/2}$$

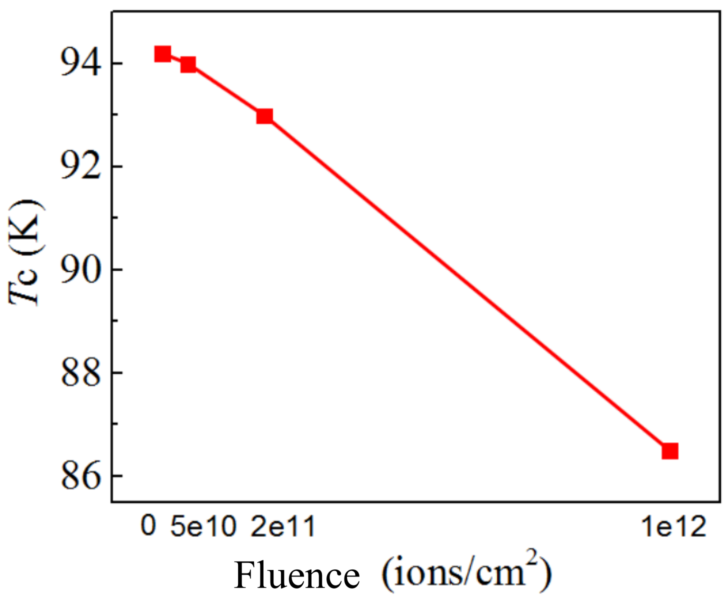
$$B_\phi \approx \phi_0/d^2$$

d is the distance between defects

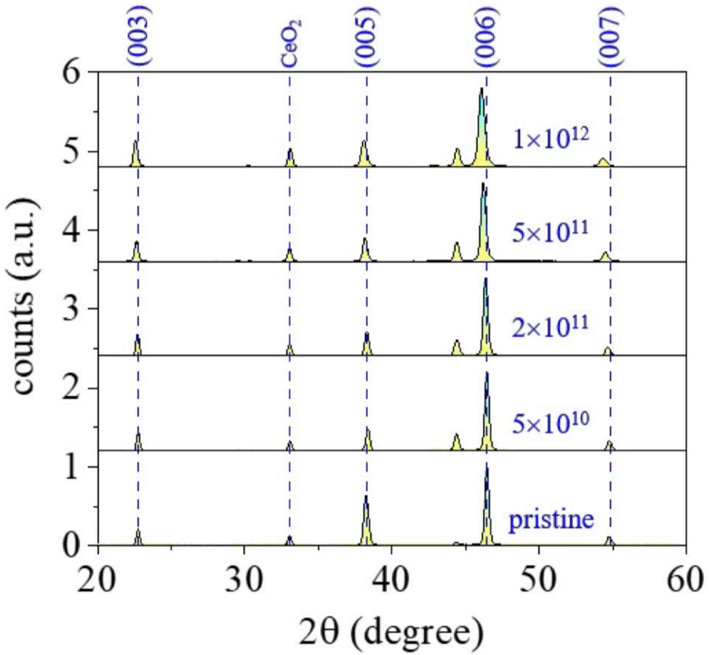


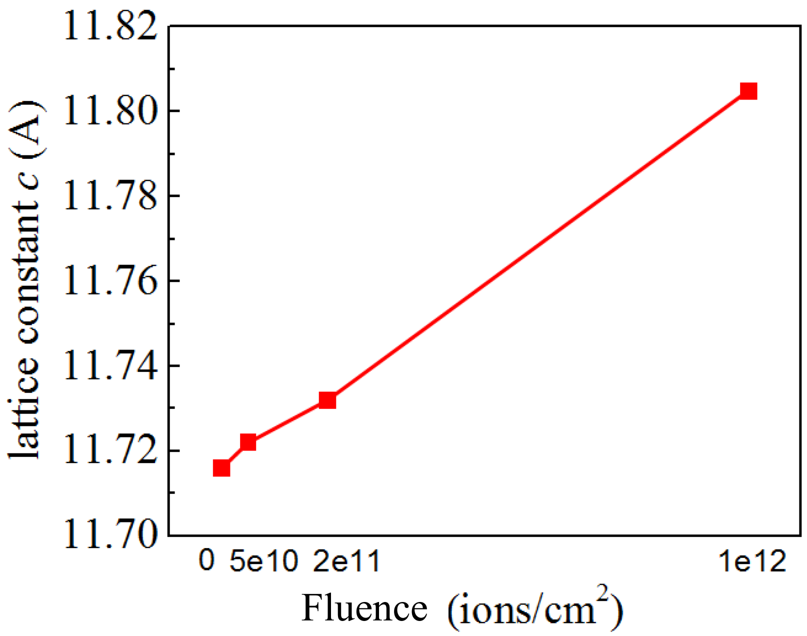
Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$





Further increasing the irradiation fluence significantly suppresses Tc.

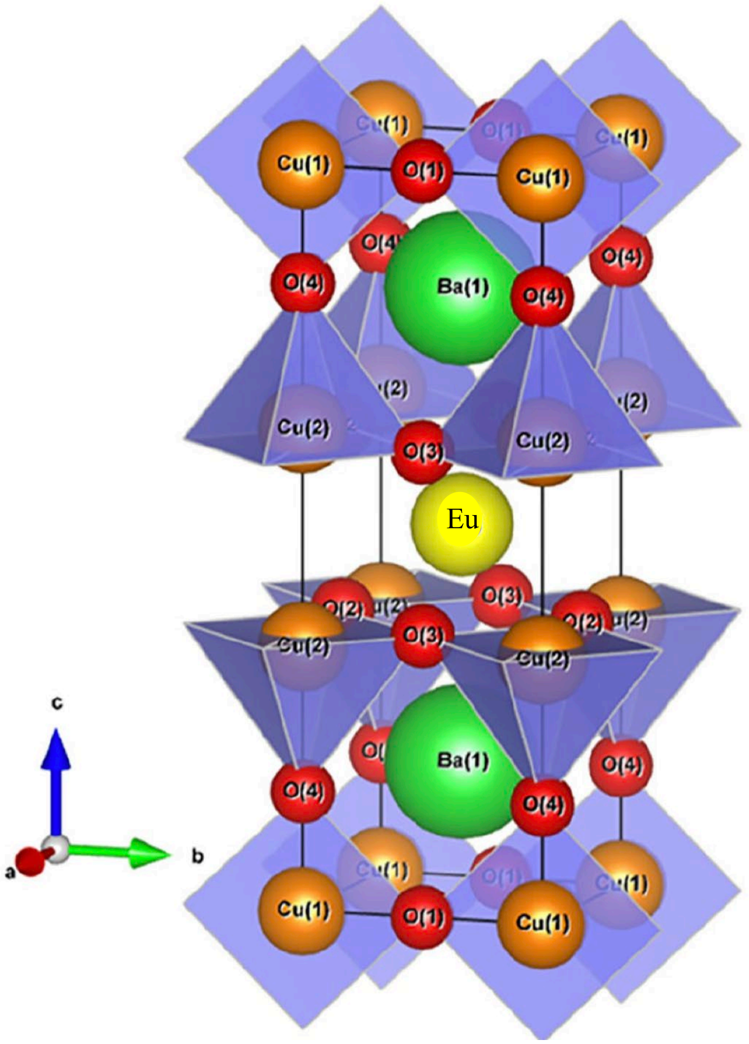


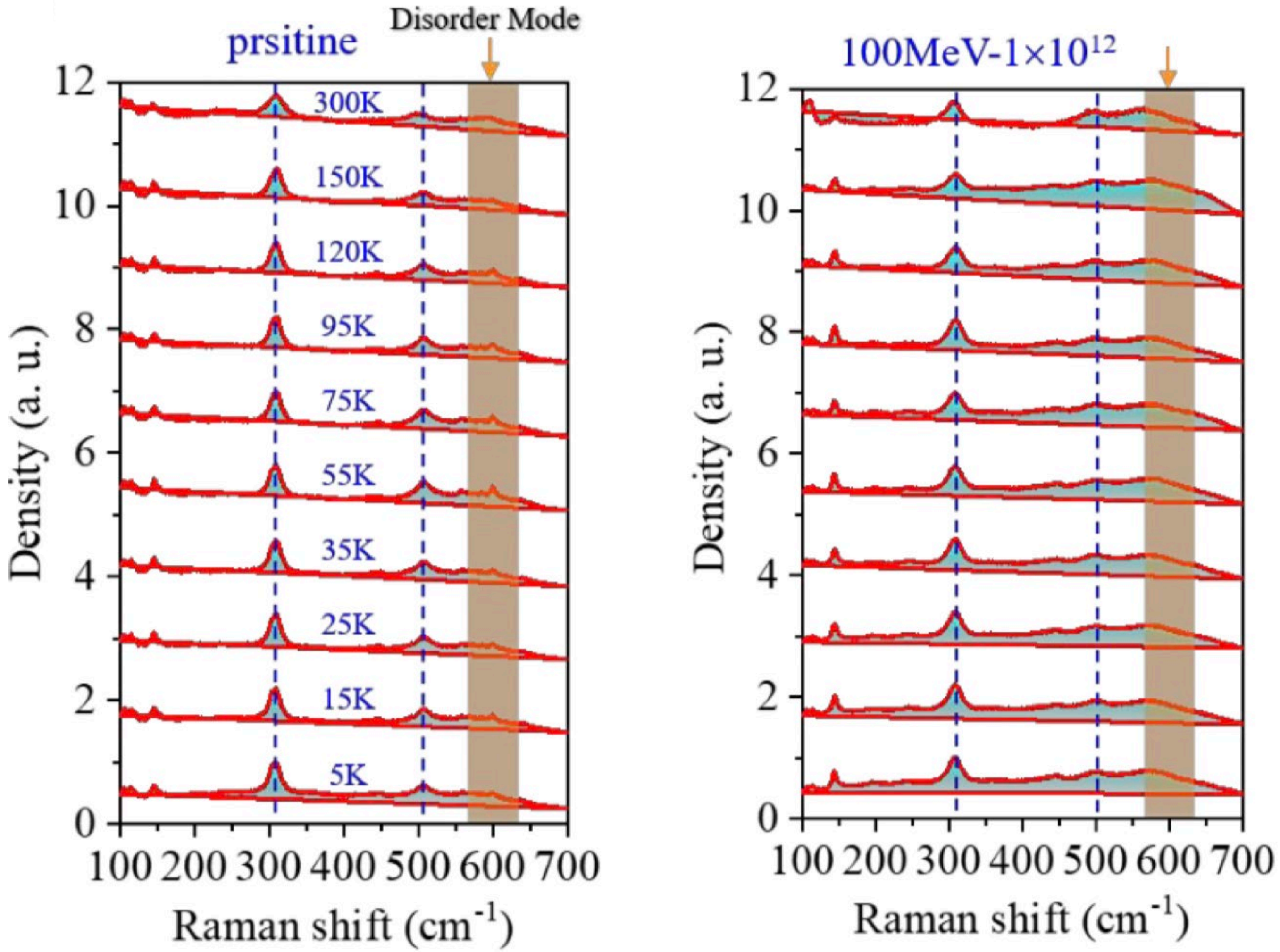


Further increasing the irradiation fluence leads to an expansion of the lattice constant c.

Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$

Raman Spectroscopy Measurements



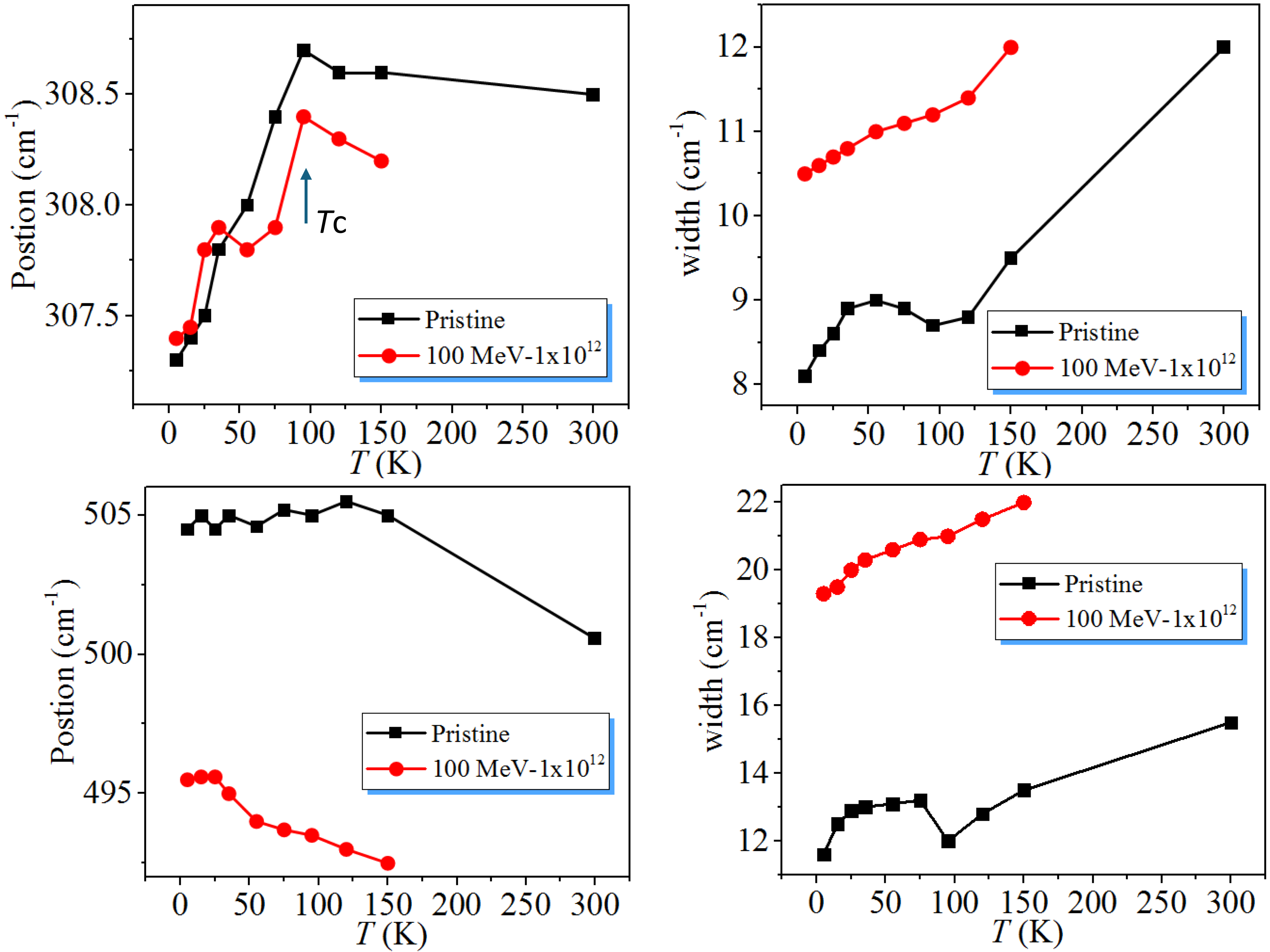


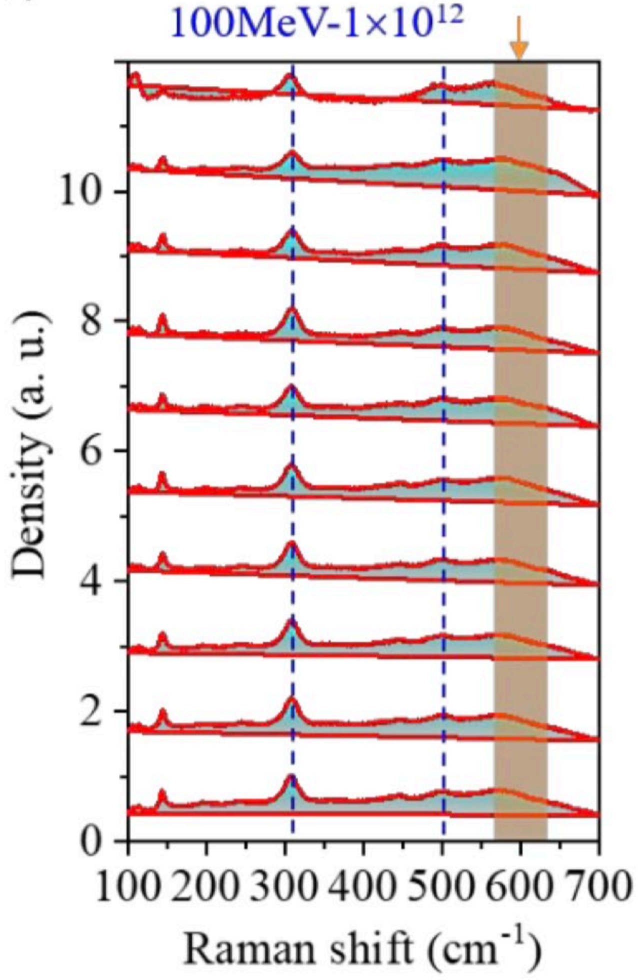
Cu–O_2 plane Vibrational Modes ~ 300 cm^{-1} hole density

Cu–O(4) chain Vibrational Modes ~ 500 cm^{-1} charge transfer

M. Bennár et al., J Mater Sci: Mater Electron 35:1472 (2024)

Characteristics of Irradiated $EuBa_2Cu_3O_{7-\delta}$





High irradiation fluence introduces disorder in the CuO chains and leads to the suppression of superconductivity

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Conclusions

- Xe^{2+} irradiation serves as an effective method to tailor superconducting performance across a broad range by systematically varying the fluence.

- The enhanced mechanism can be well understood in terms of the matching field effect, although in the low-field region, the single-vortex model fails to accurately describe the behavior, likely due to irradiation-induced reductions in the depairing current density (Jd) and the effective superconducting volume.

- Further increasing the irradiation fluence to 10^{12} ions/cm^2 results in a marked suppression of superconductivity, which is mainly attributed to oxygen disordering within the CuO chains.

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Jianqi Li

Thank you for your attention!