13th European Conference on Applied Superconductivity (EUCAS2017), Geneva, Sep. 19, 2017

Effects of Swift-Particle Irradiations on the Critical Current Density in FeSe

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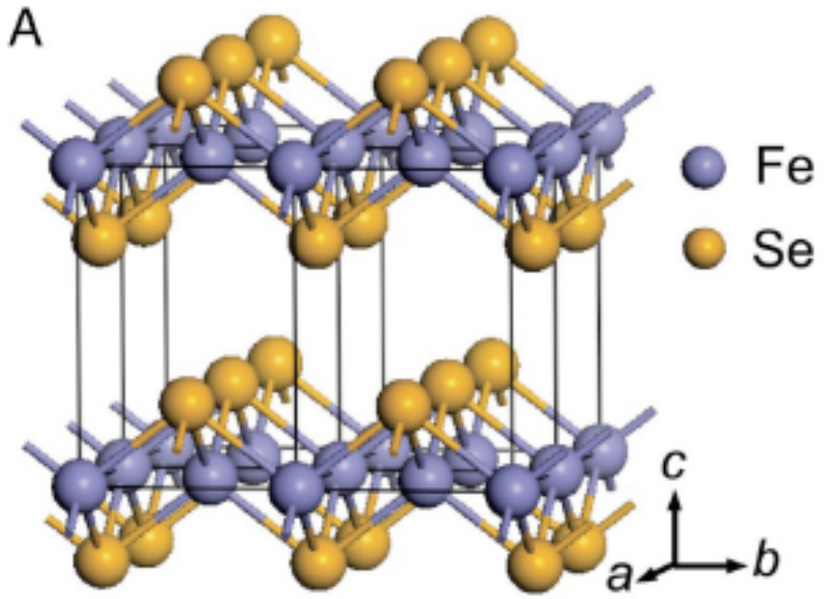
RIKEN **T. Kambara**

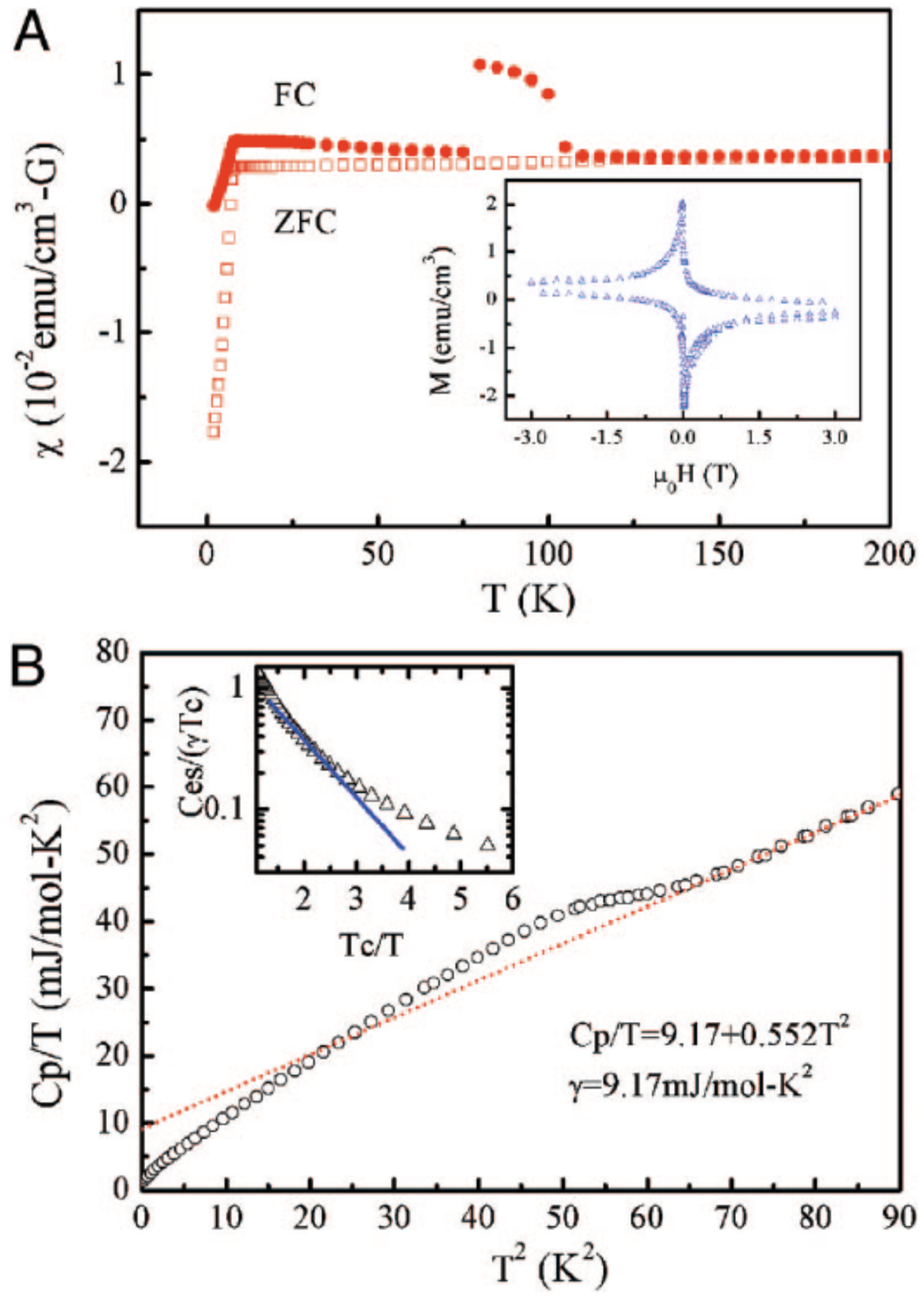
National Institute for Radiological Sciences **H. Kitamura**

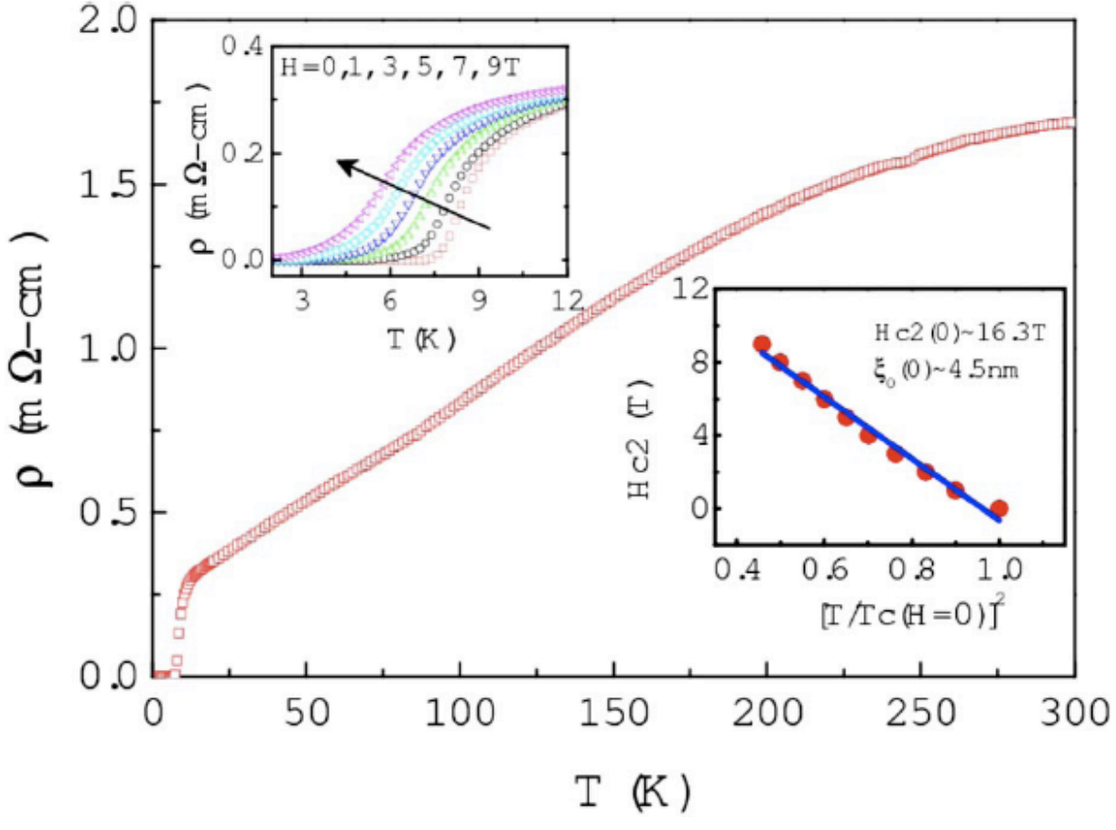
CRIEPI **A. Ichinose**

Superconductivity in FeSe



PbO-structure

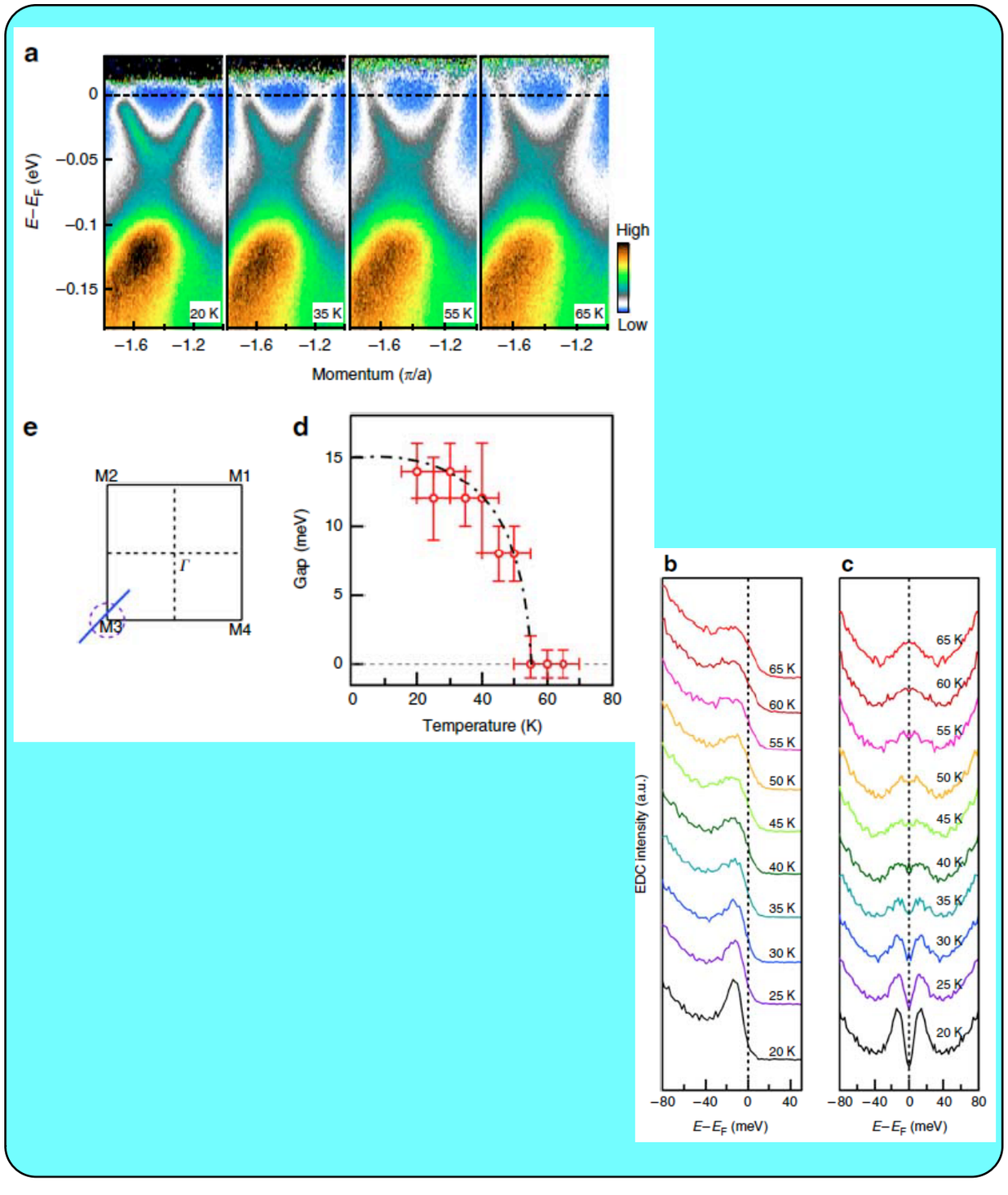




F. C. Hsu *et al*., PNAS **105**, 14262 (2008).

Recent Topics in Fe(Te,Se) Superconductors

high T_c SC in single layer FeSe



D. Liu. *et al*., Nat. Commun. **3**, 931 (2012).

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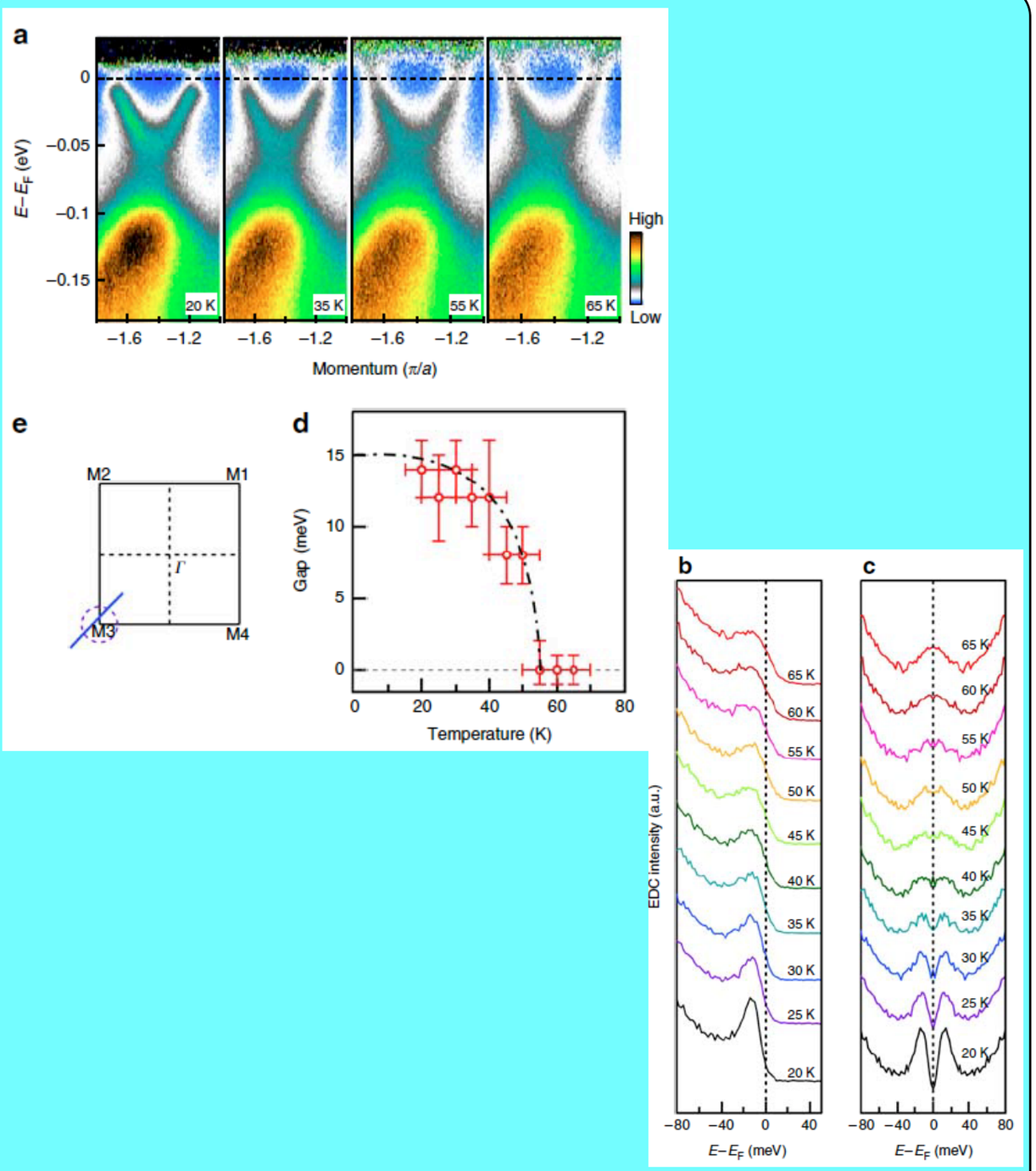
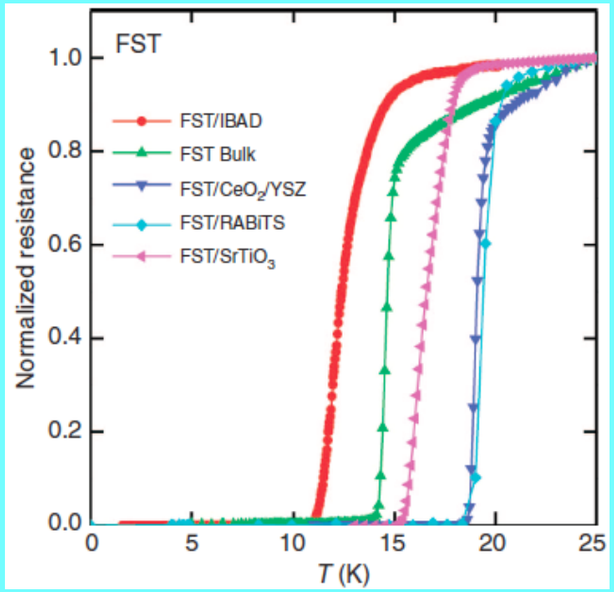
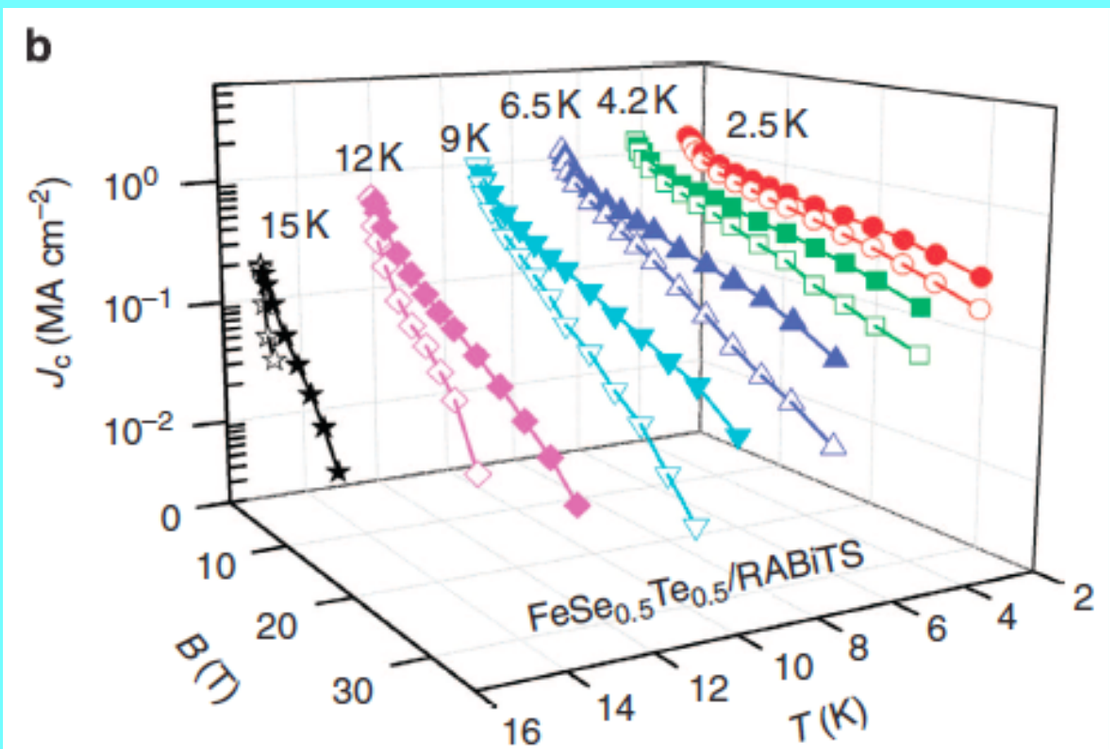


D. Liu. *et al*., Nat. Commun. **3**, 931 (2012).

high J_c in Fe(Te,Se) coated conductor

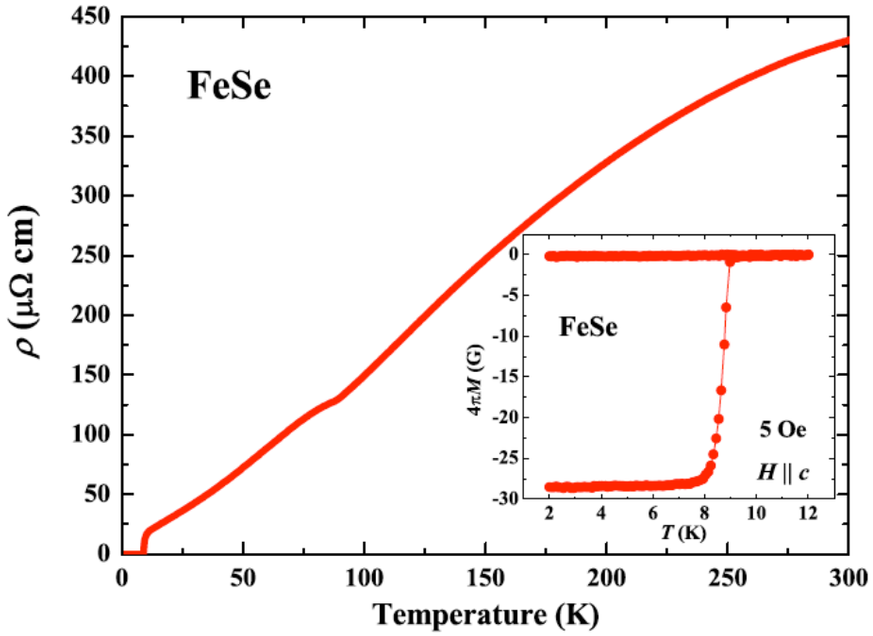




W. D. Si. *et al*., Nat. Commun. **4**, 1347 (2013).

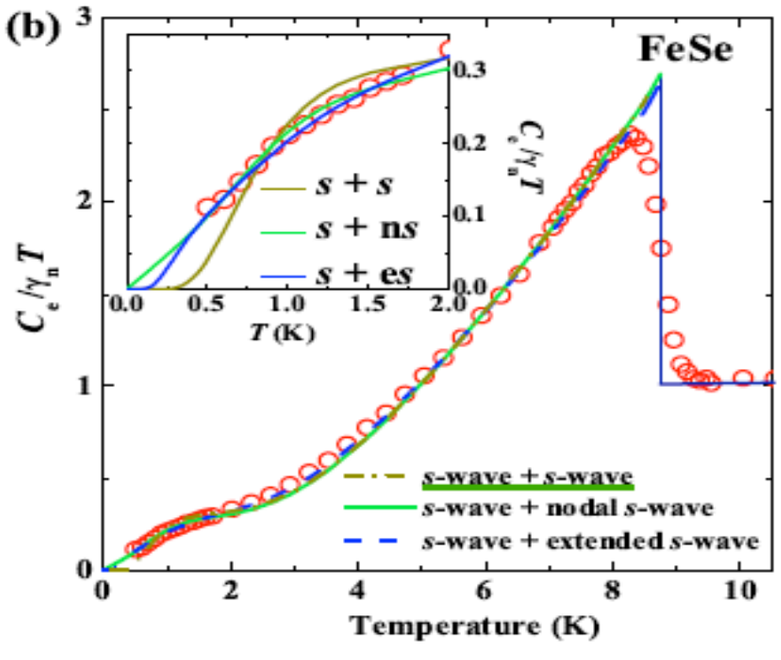
Characterizations of FeSe Crystals Grown by $KCl/AlCl_3$

flux: $KCl/AlCl_3$

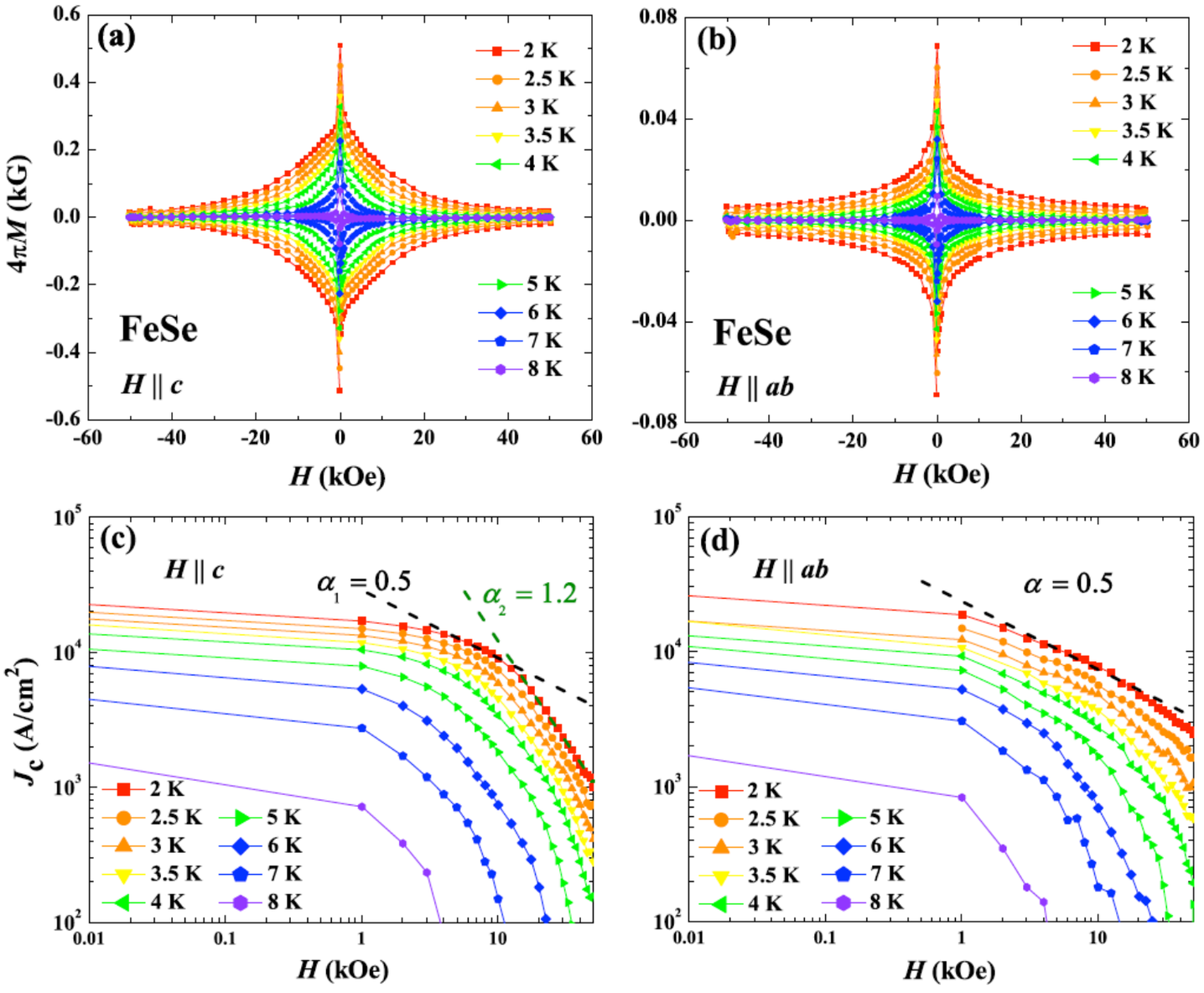


low resistivity

Y. Sun *et al.*, PRB **92**, 144509 (2015).



two-gap SC



- J_c is low, J_c ~ 4x10^4 A/cm^2

  J_c ~ 3x10^5 A/cm^2 : Fe(Te,Se)
- For *H*//*c*, $J_c \propto H^{-\alpha}$ with α=1.2

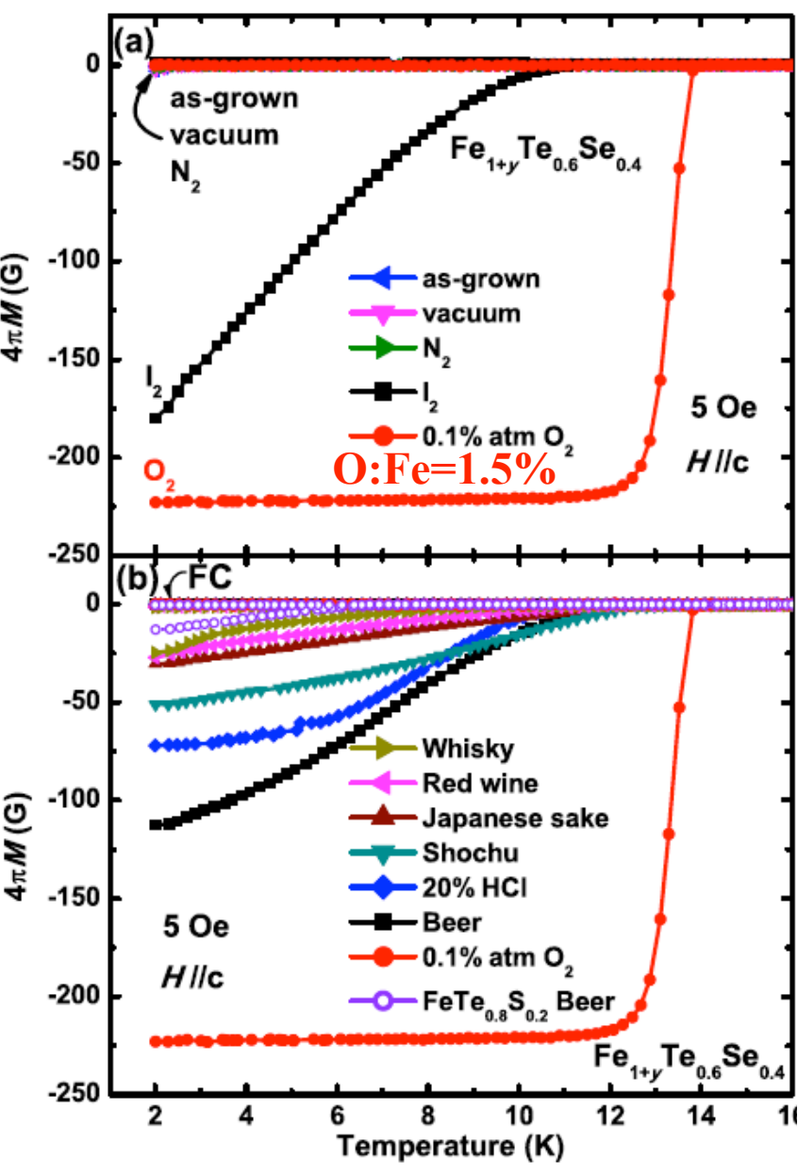
  α~1/2 : $(Ba,K)Fe_2As_2$, $Ba(Fe,Co)_2As_2$

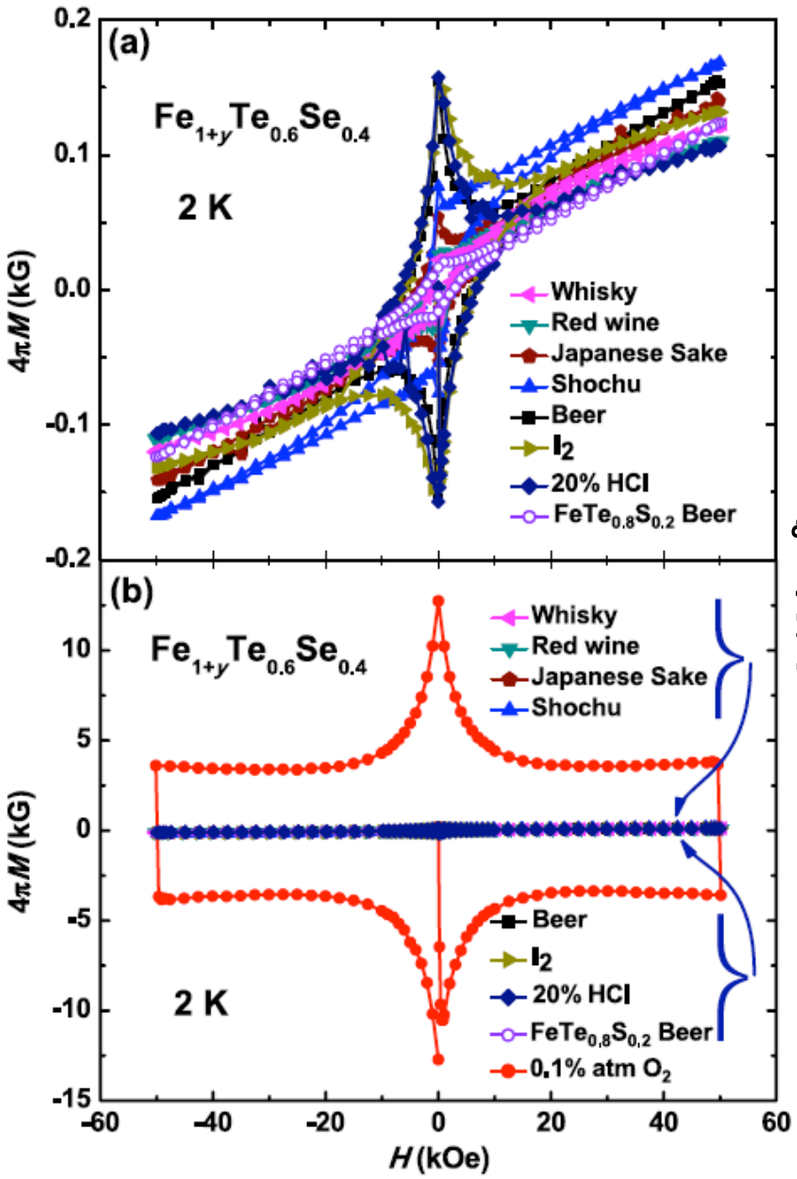
  α=5/8 : strong pinning

  α=1 : correlated pinning

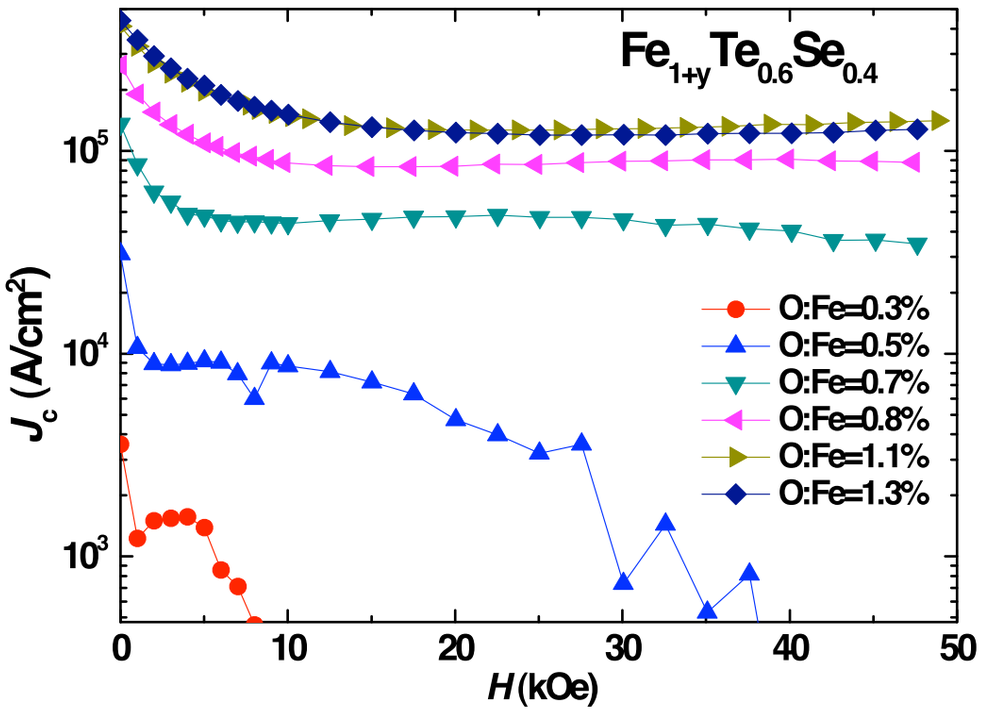
Superconducting Properties of Post-Processed Fe(Te,Se)

$FeTe_{0.6}Se_{0.4}$





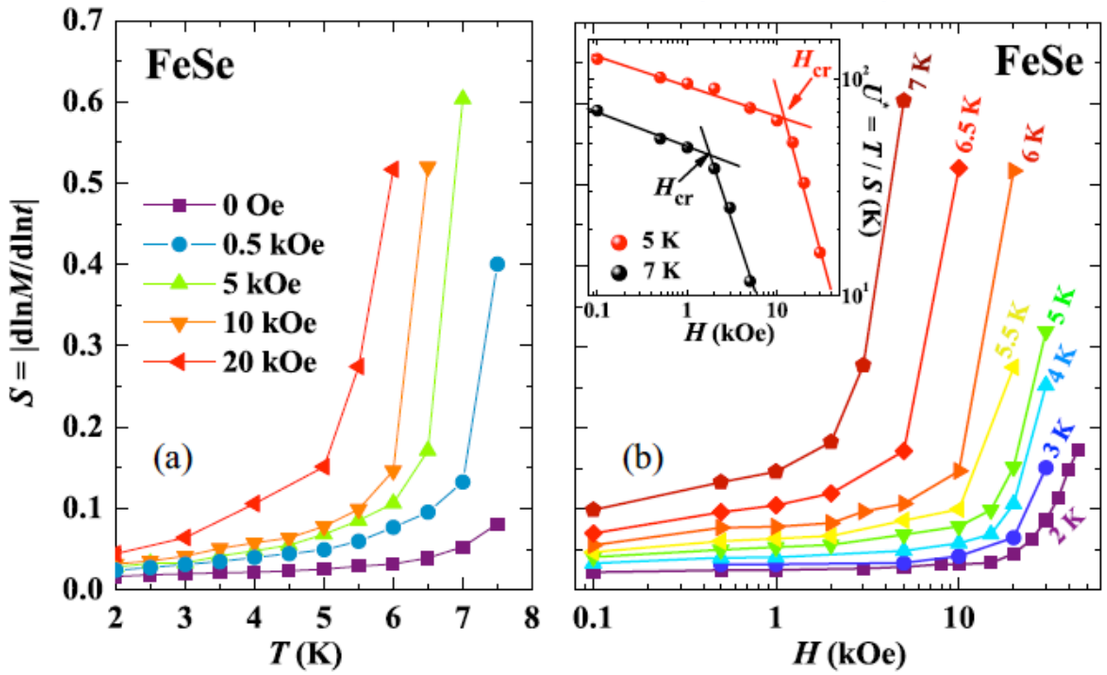
$J_c \sim 5 \times 10^5$ A/cm^2 (2 K, sf)

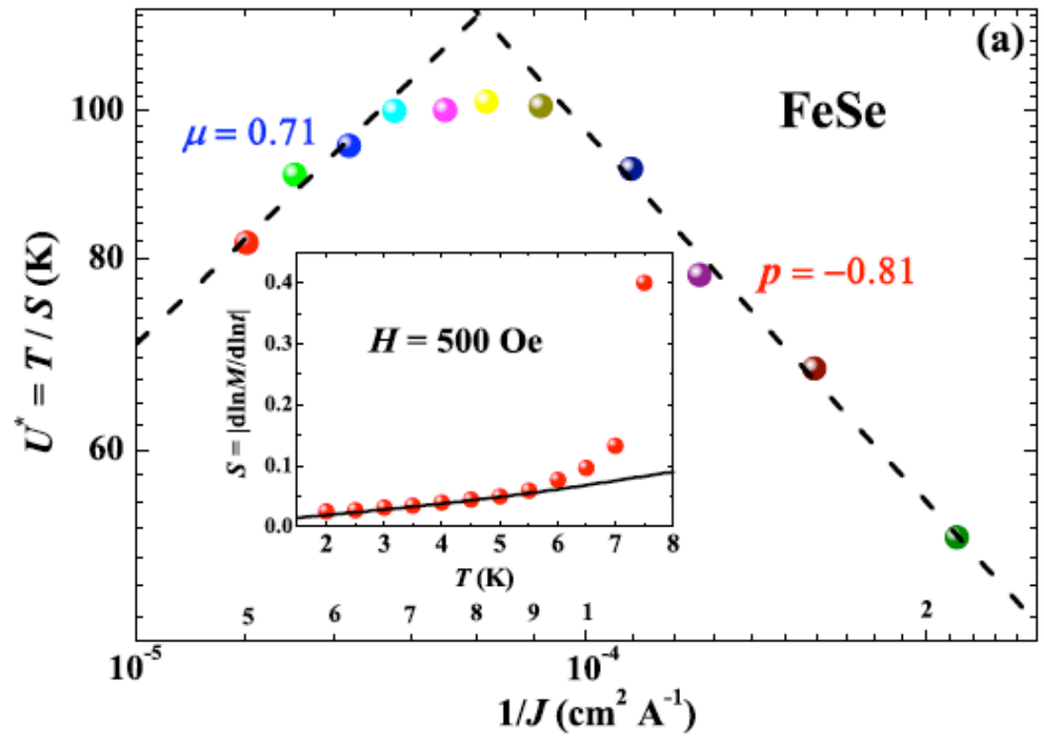


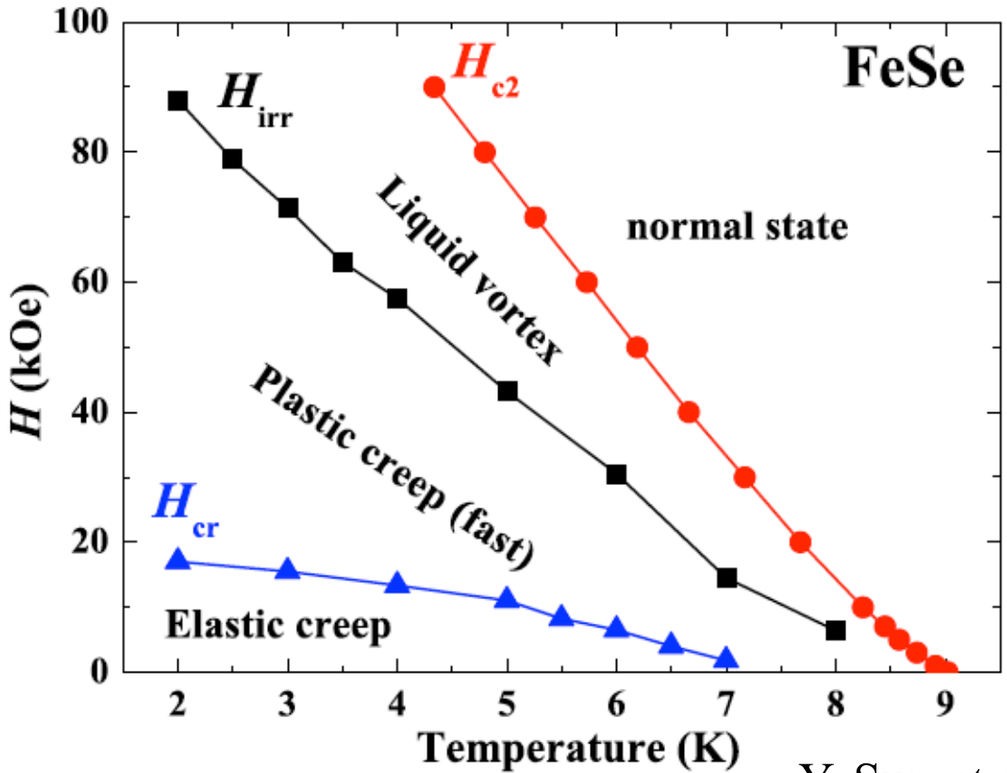
Y. Sun *et al.*, SUST **26**, 015015 (2013).

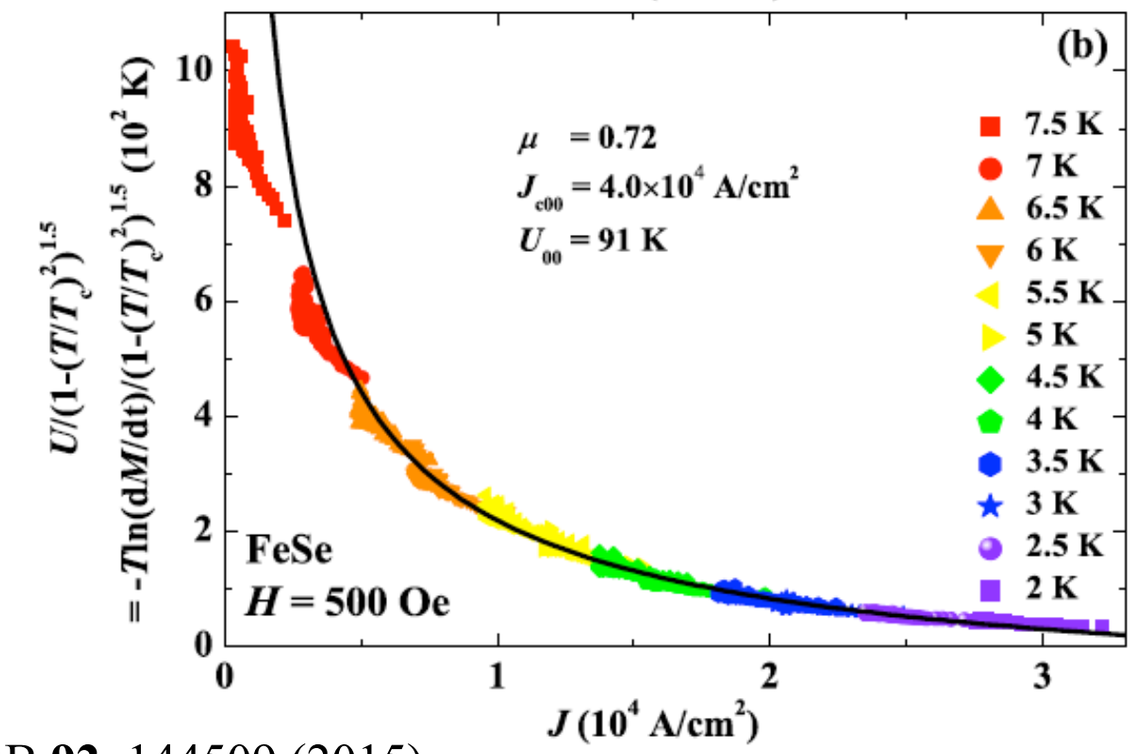
Analyses of Vortex Dynamics in High-Quality FeSe

J_c ~ 3x10^4 A/cm^2 (2 K, sf)









Y. Sun *et al.*, PRB **92**, 144509 (2015).

Introduction of Pinning Centers by Swift Particle Irradiations

Introduce artificial defects

Heavy-ion irradiation

Au, Xe, U

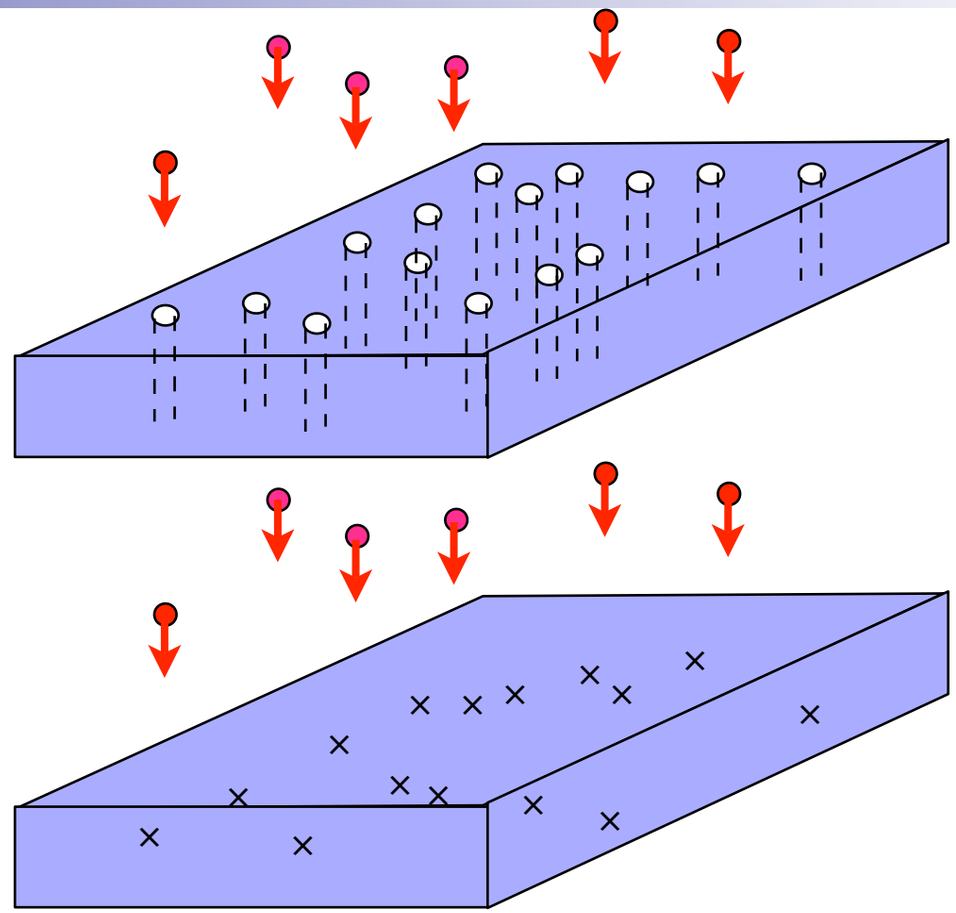
Columnar defects

Light-particle irradiation

proton, neutron

Point defects

⇒ Enhancement of J_c



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Introduce artificial defects

Heavy-ion irradiation

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Columnar defects

Light-particle irradiation

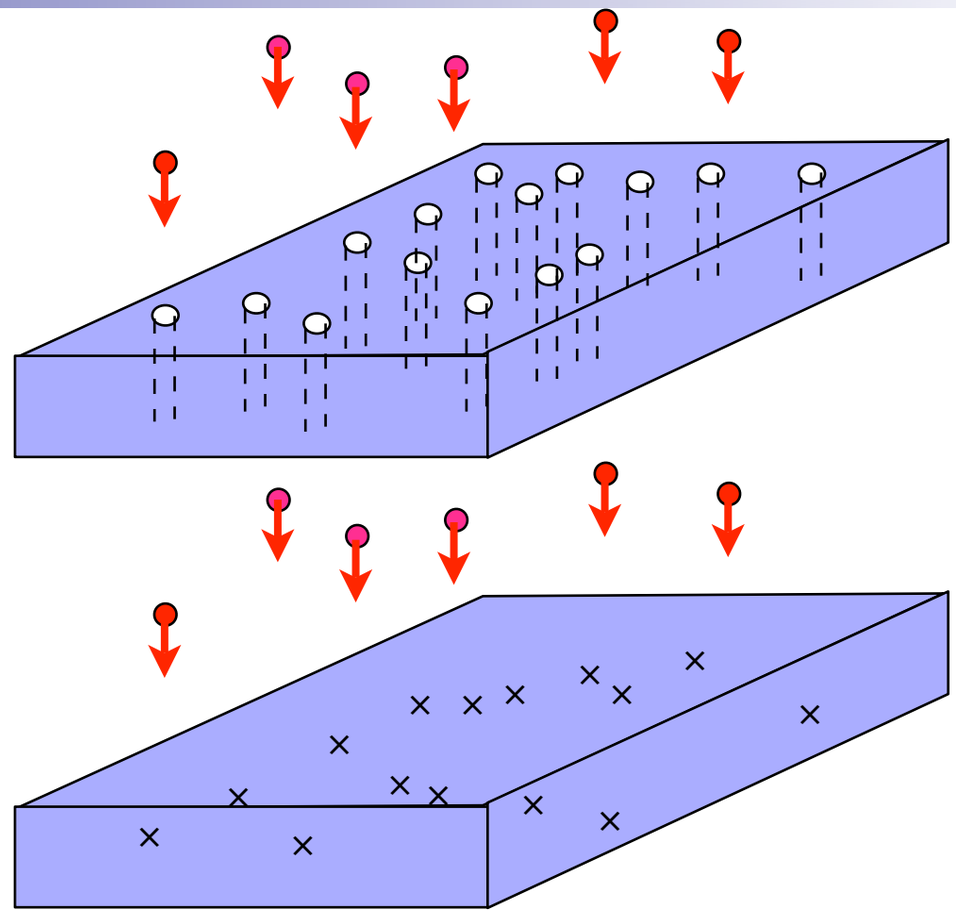
proton, neutron

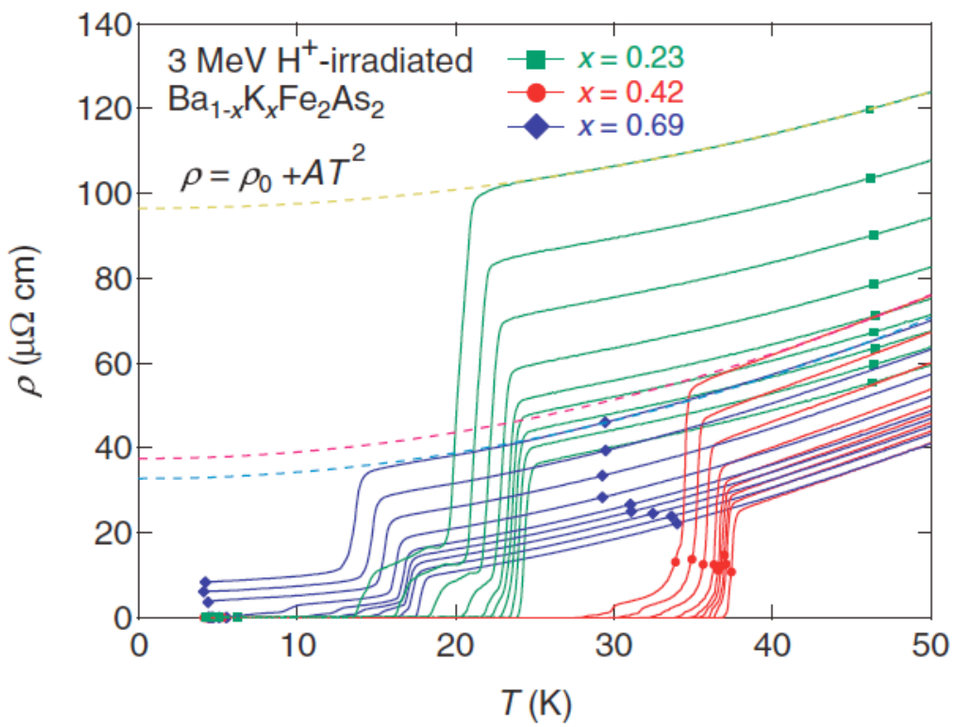
Point defects

→ Enhancement of J_c

Introduce scatterings in the system

→ Suppression of T_c

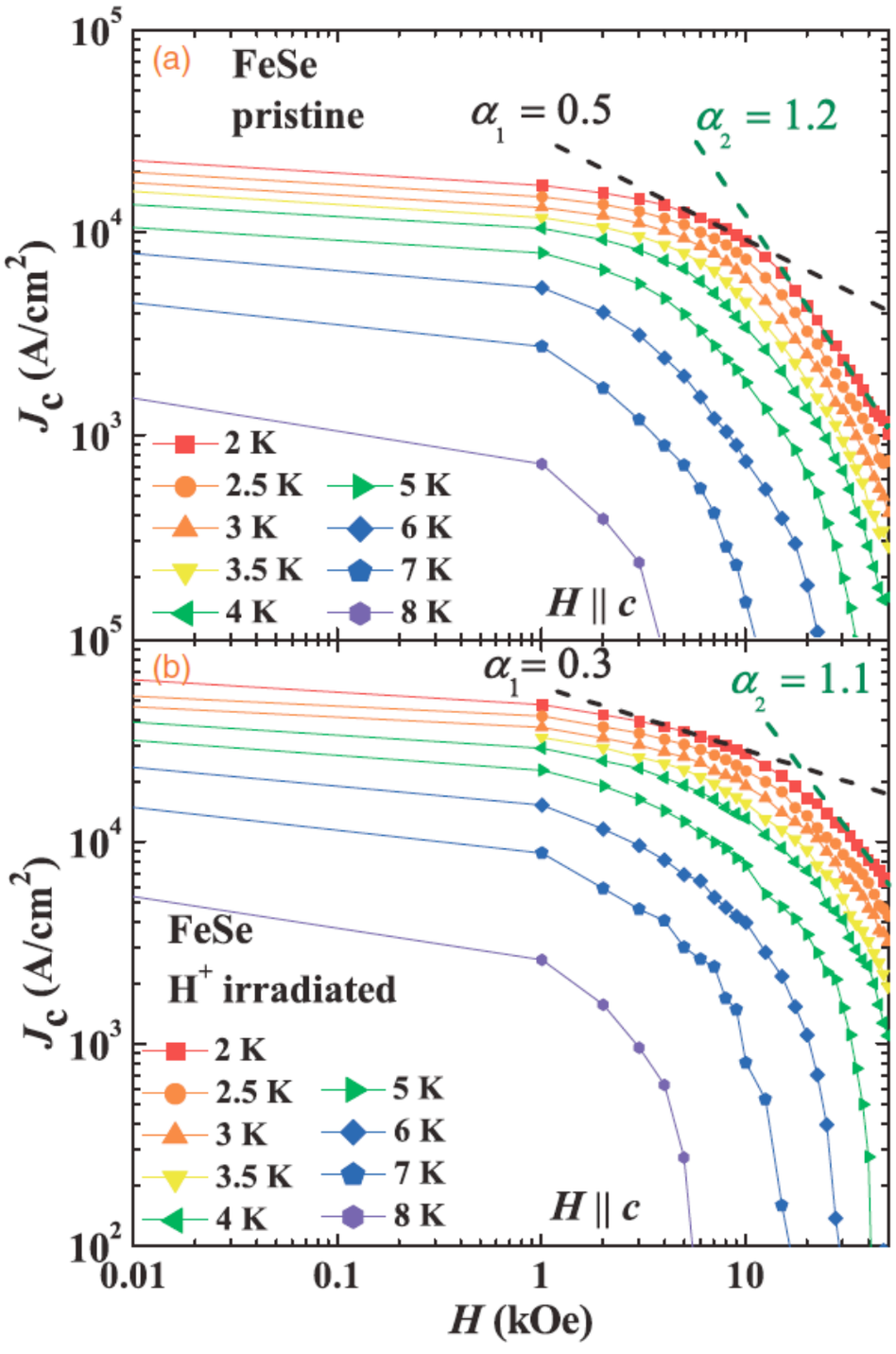


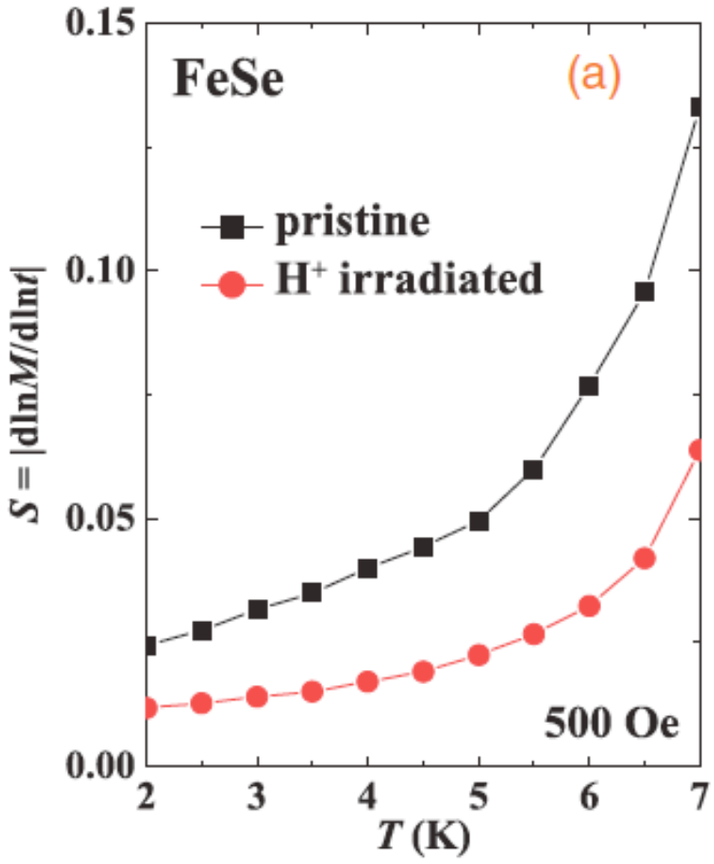


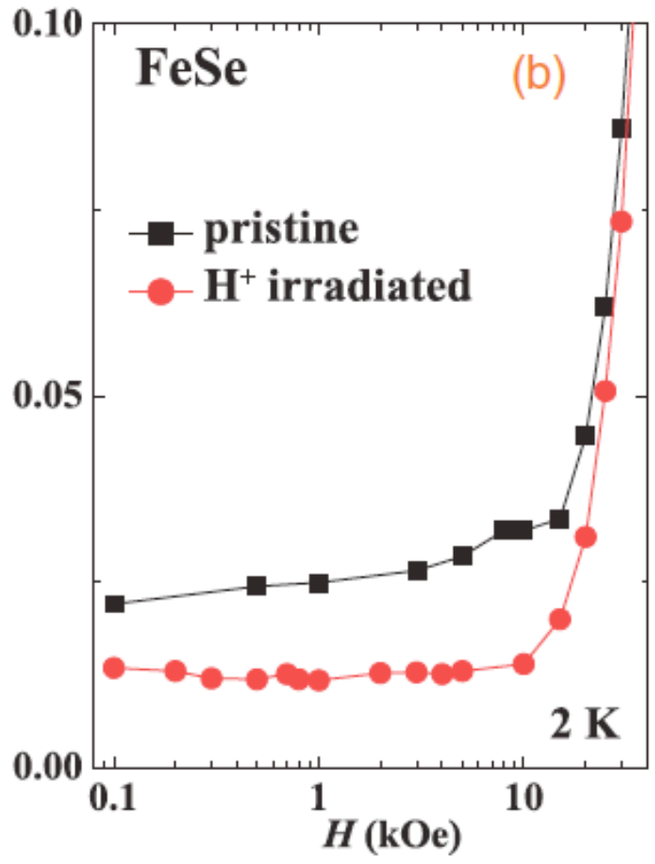
T. Taen *et al.*, PRB **88**, 224514 (2013).

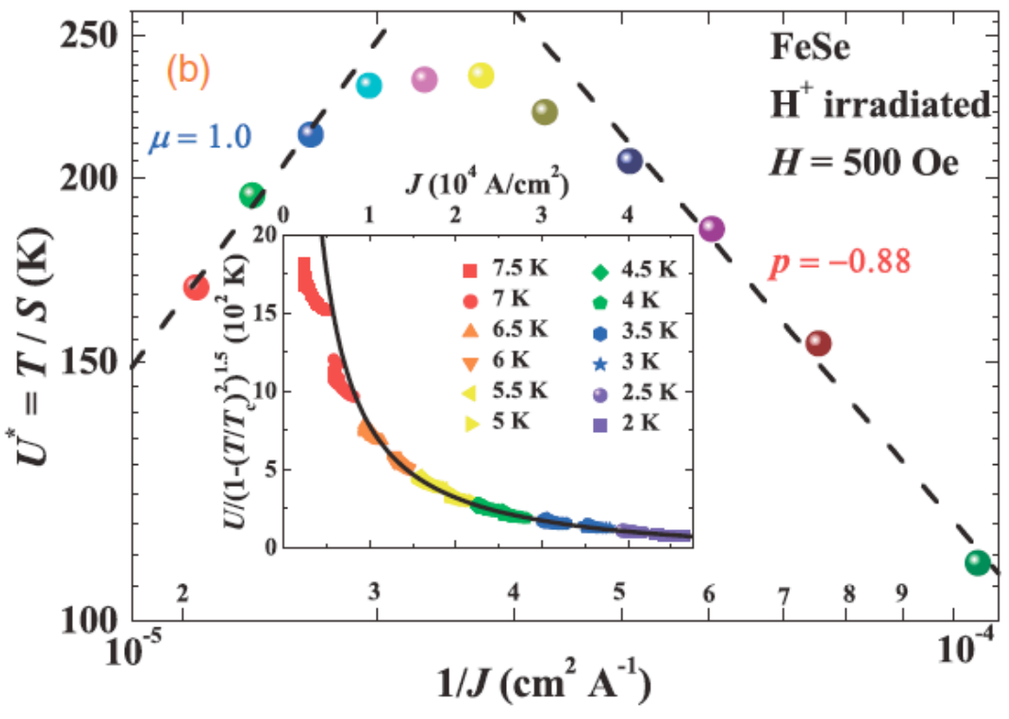
Effects of Proton Irradiation on FeSe

3 MeV proton, 5x10^{16} cm^{-2}





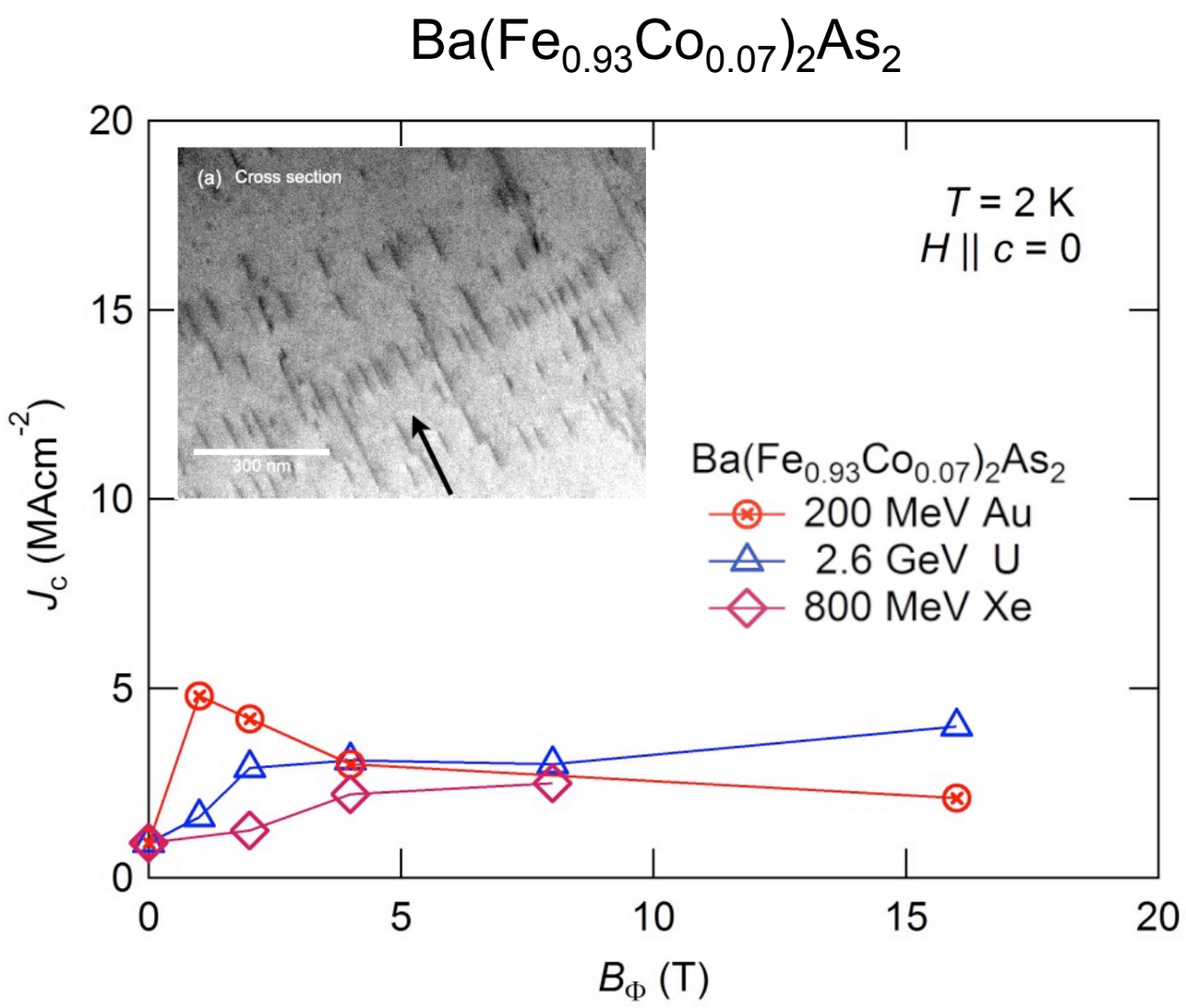


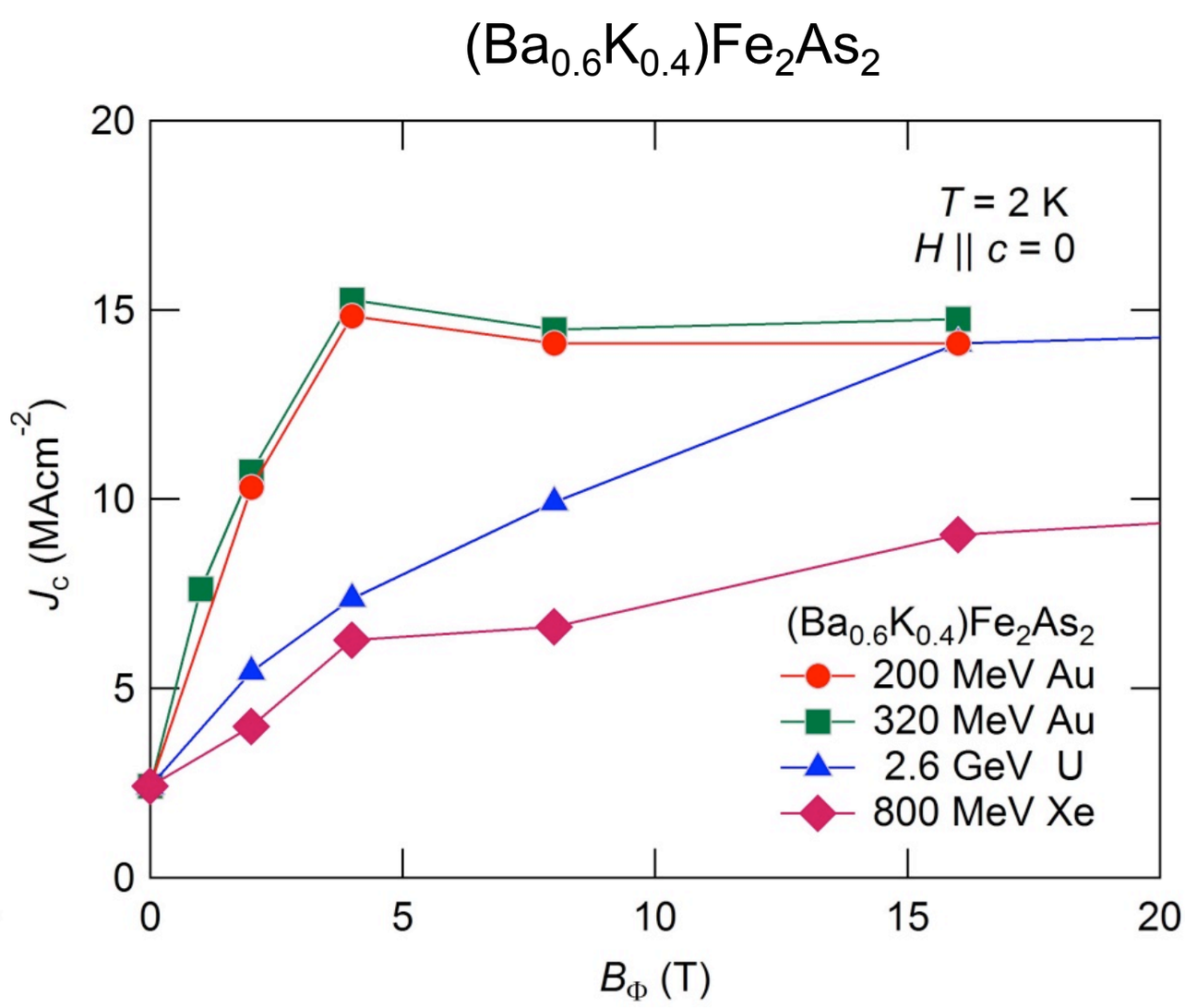


x2 enhancement of J_c (2 K, sf)

Y. Sun *et al.*, APEX **8**, 113102 (2015).

Summary of Heavy-Ion Irradiations for 122 System





T. Tamegai *et al*., SUST **25**, 084008 (2012).

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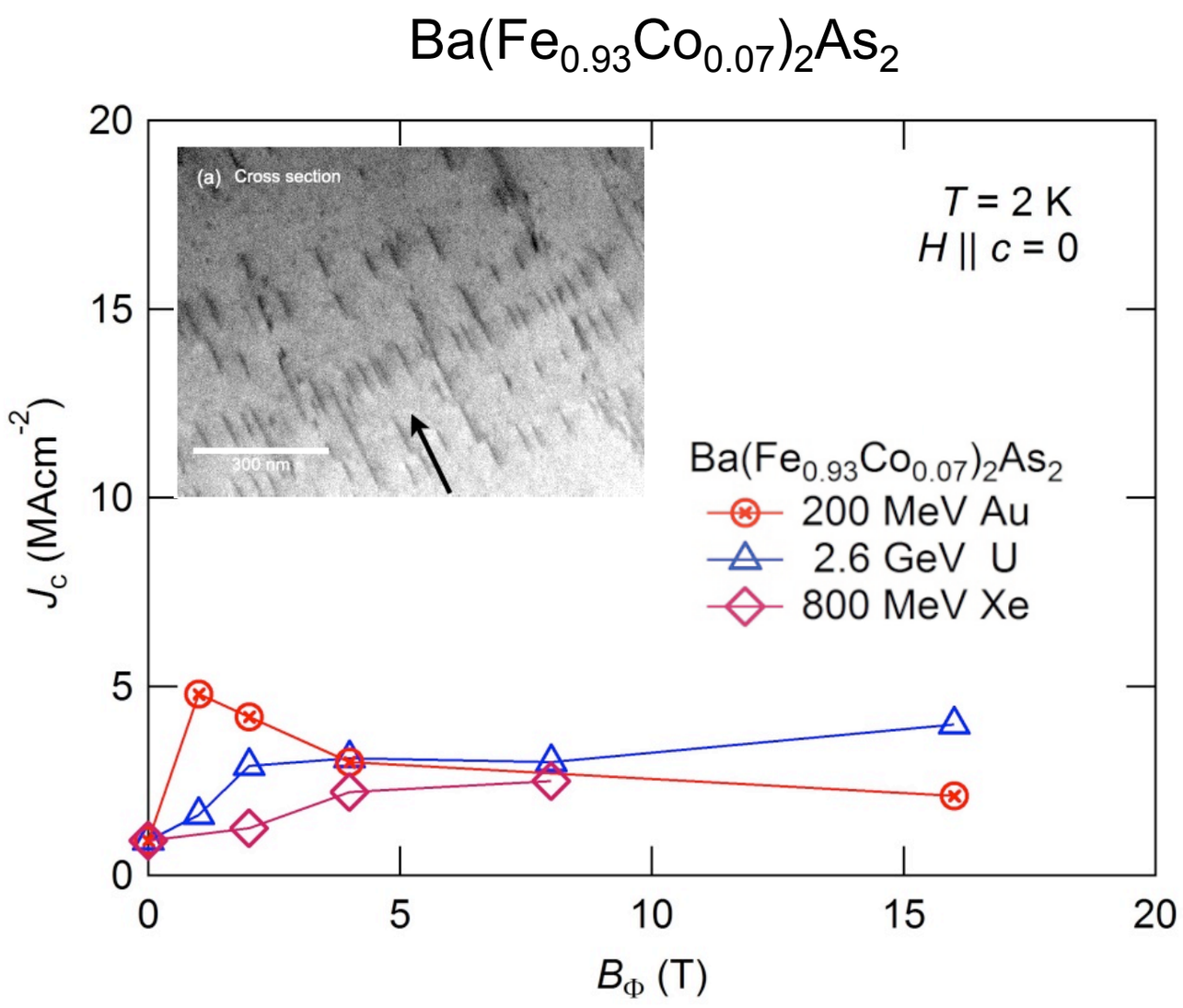

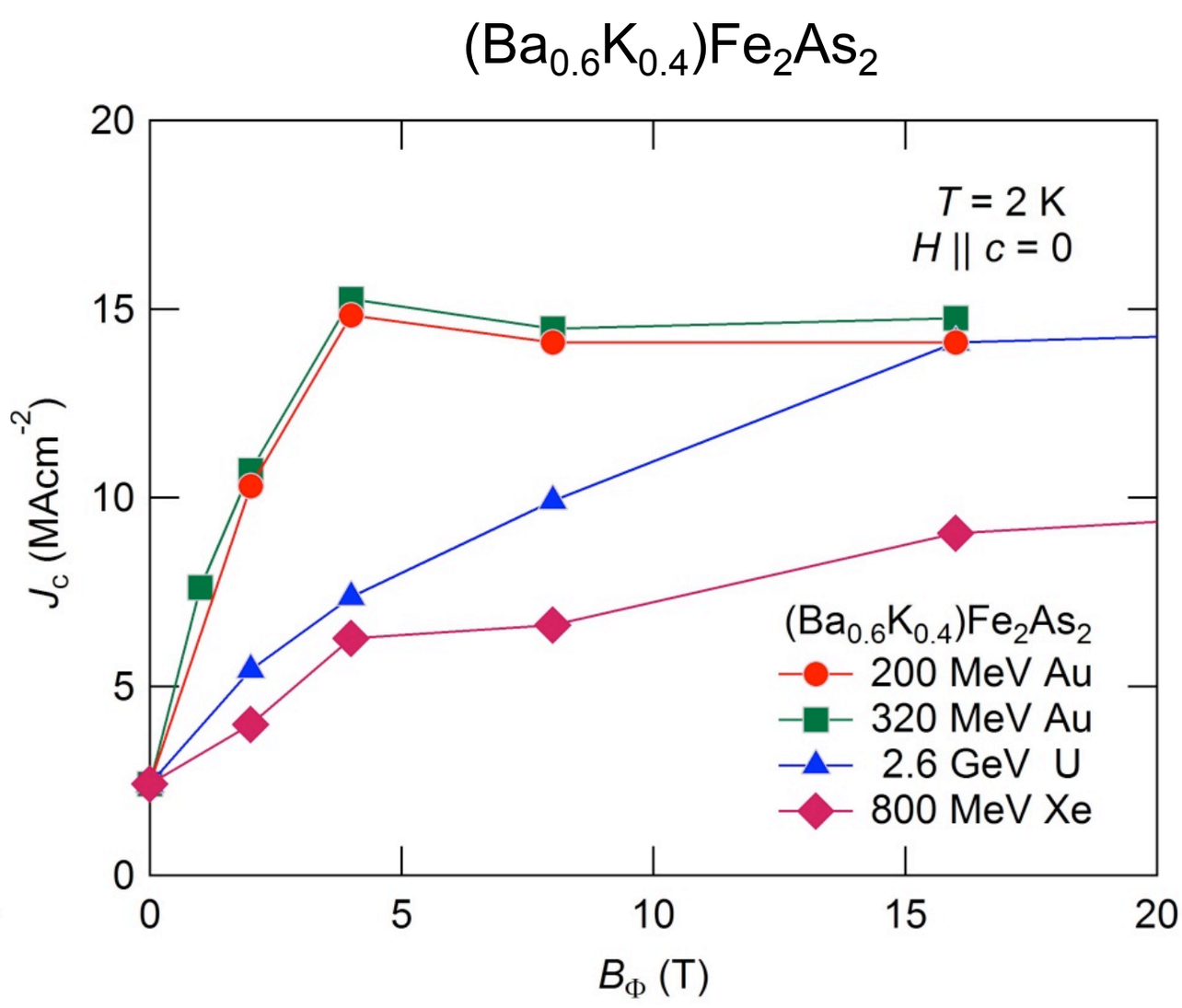

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- Columnar defects (CDs) are created by heavy-ion irradiation
- J_c is enhanced by introducing CDs
- Large J_c is sustained even at B_Φ = 10 T (averaging spacing between CDs ~ 14 nm)

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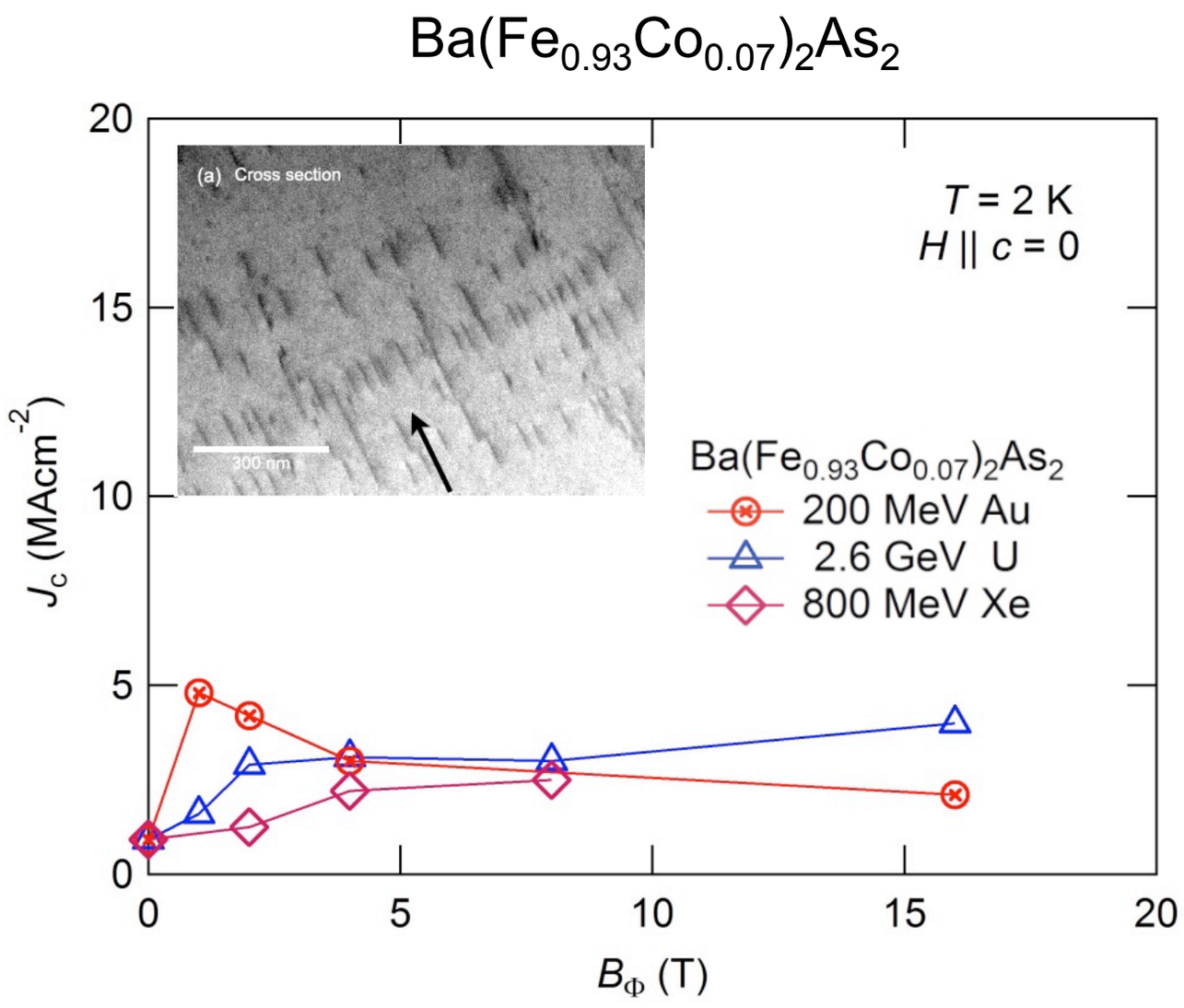

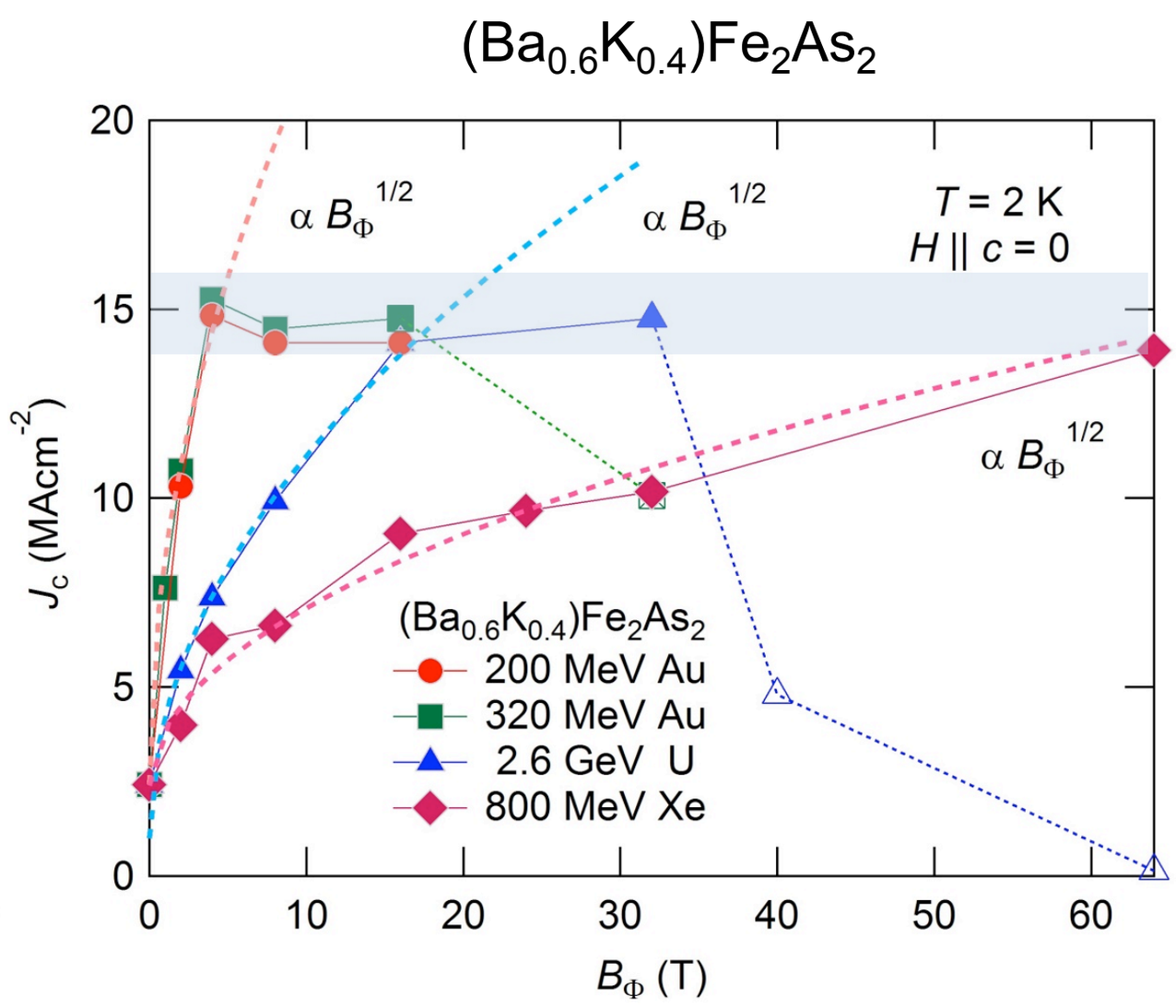

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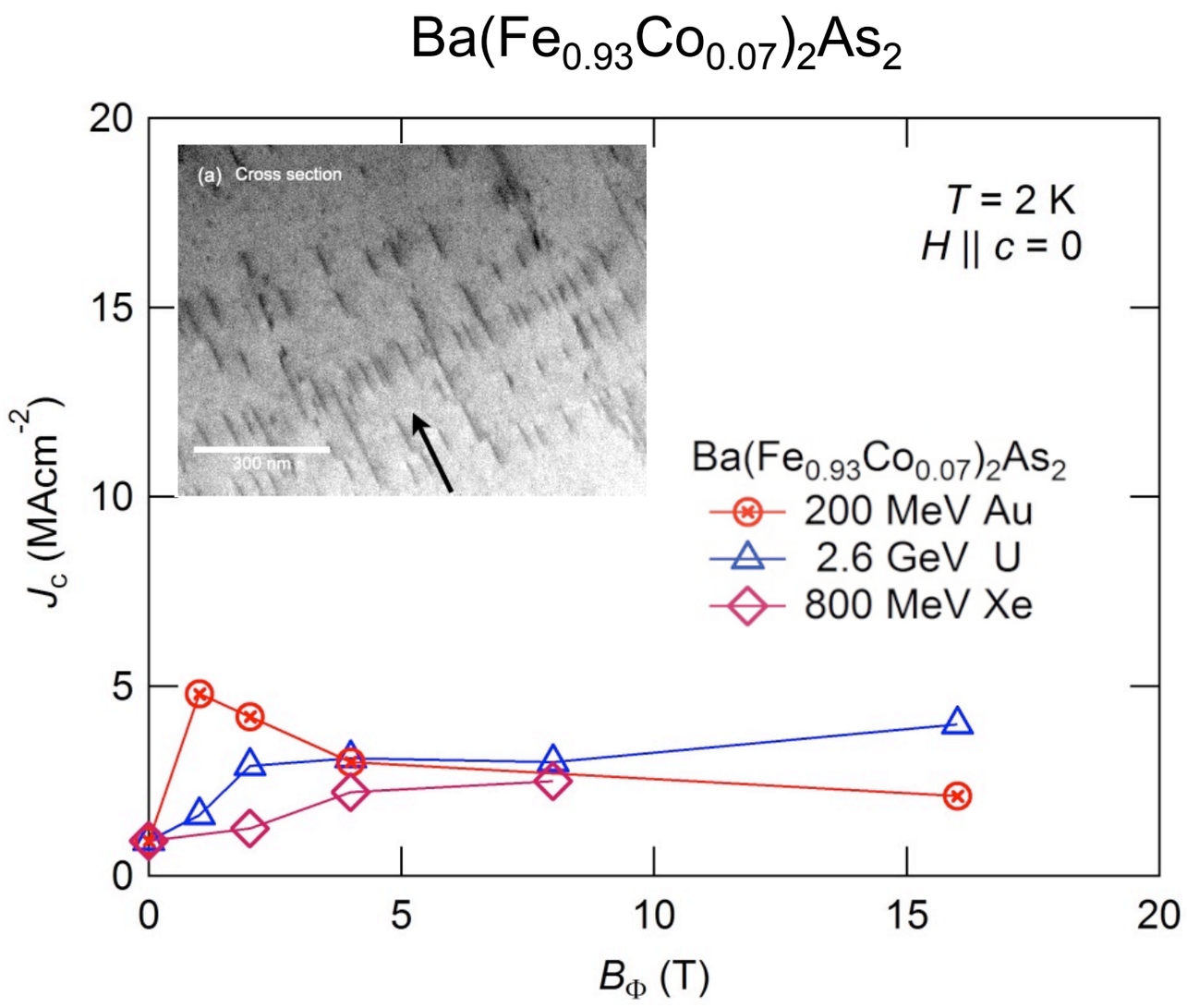
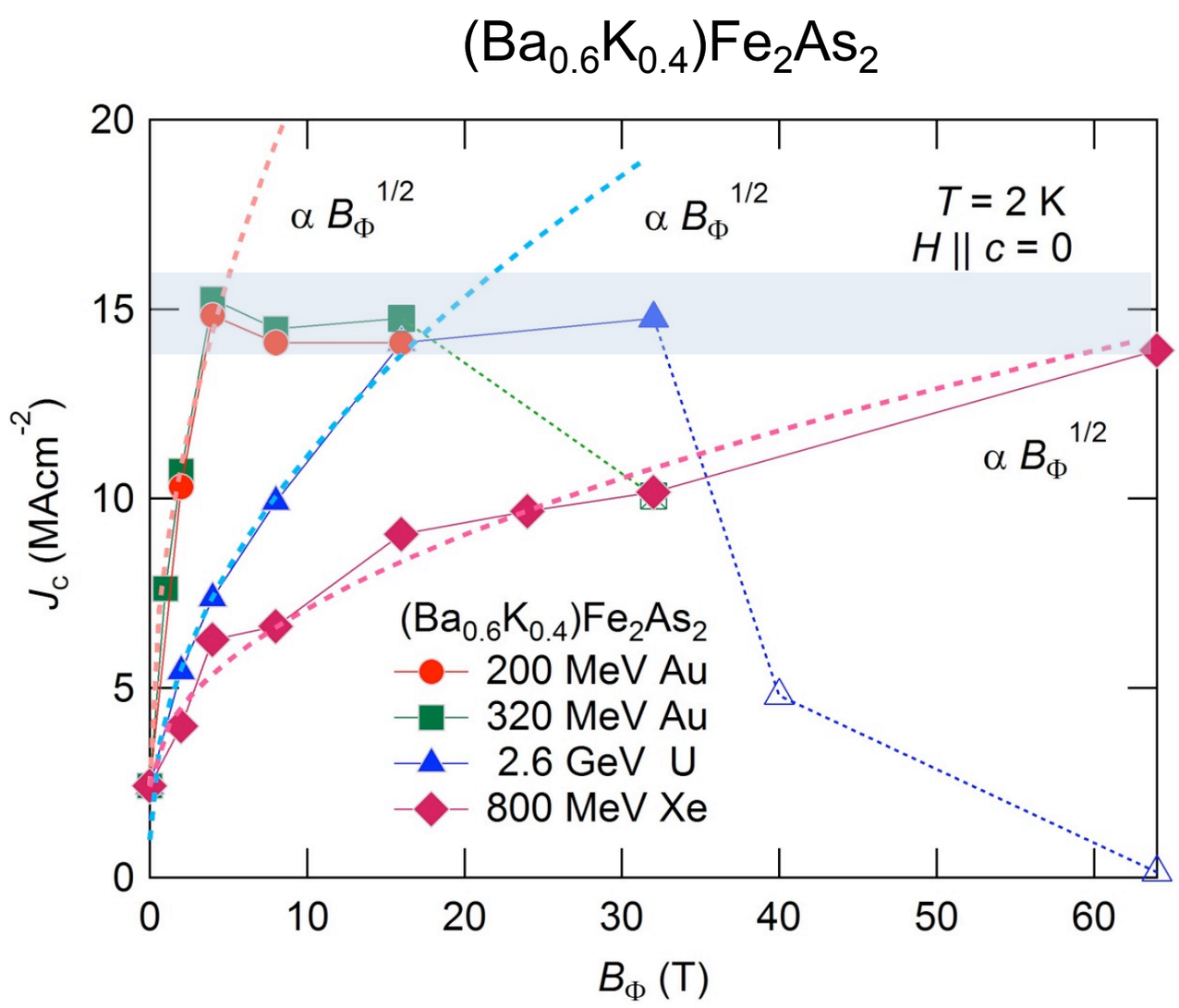


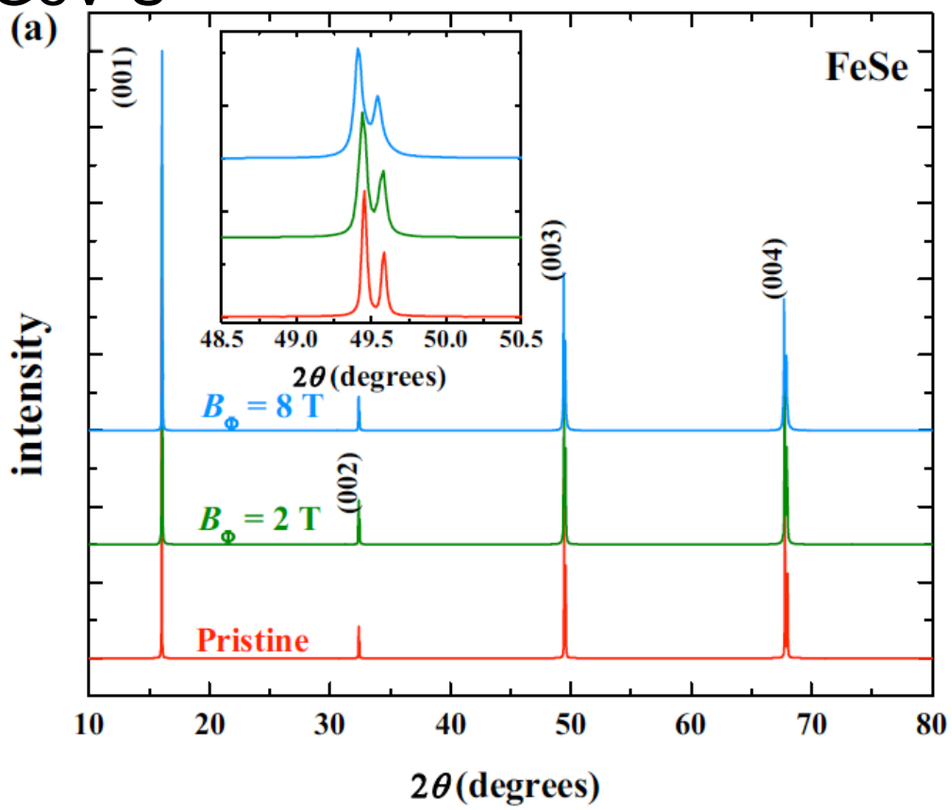


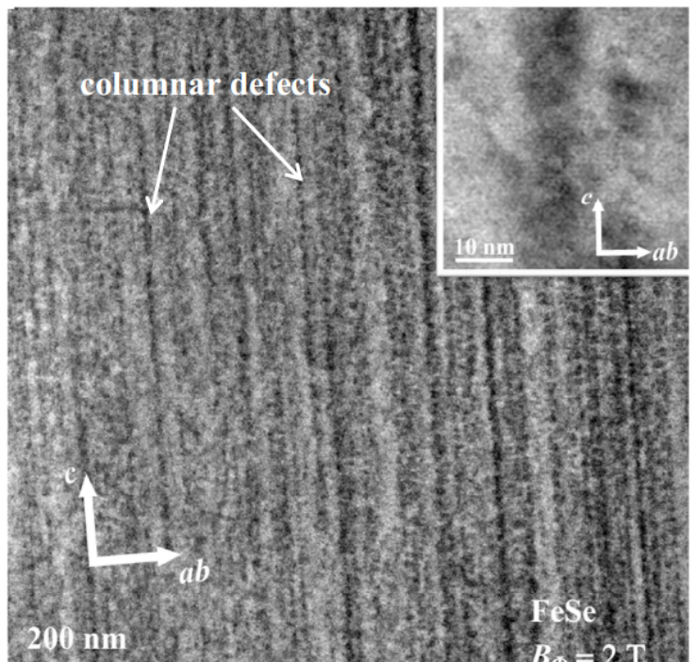
T. Tamegai *et al*., SUST **25**, 084008 (2012).

- Columnar defects (CDs) are created by heavy-ion irradiation
- J_c is enhanced by introducing CDs
- Large J_c is sustained even at B_Φ = 10 T (averaging spacing between CDs ~ 14 nm)
- J_c is suppressed at very large B_Φ

Crystal Structure and Columnar Defects after Irradiation in FeSe

2.6 GeV U





diameter ~ 10 nm

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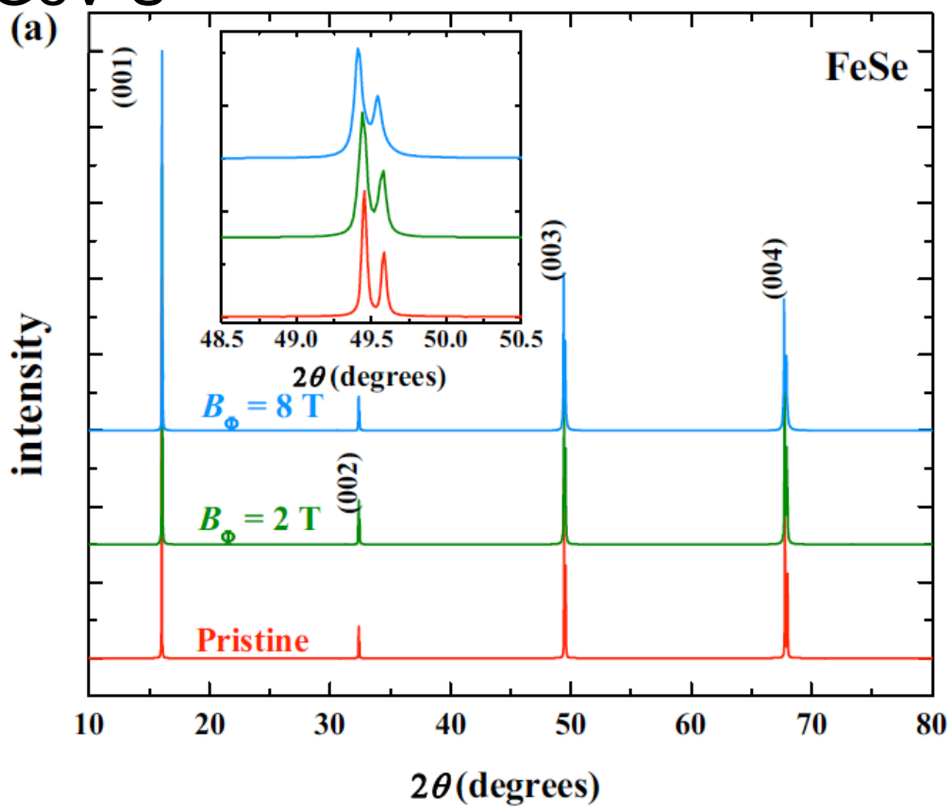
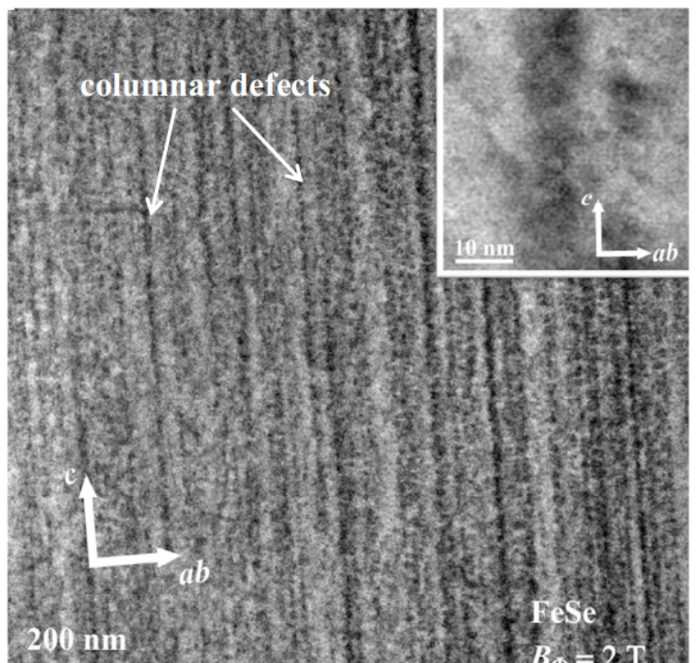
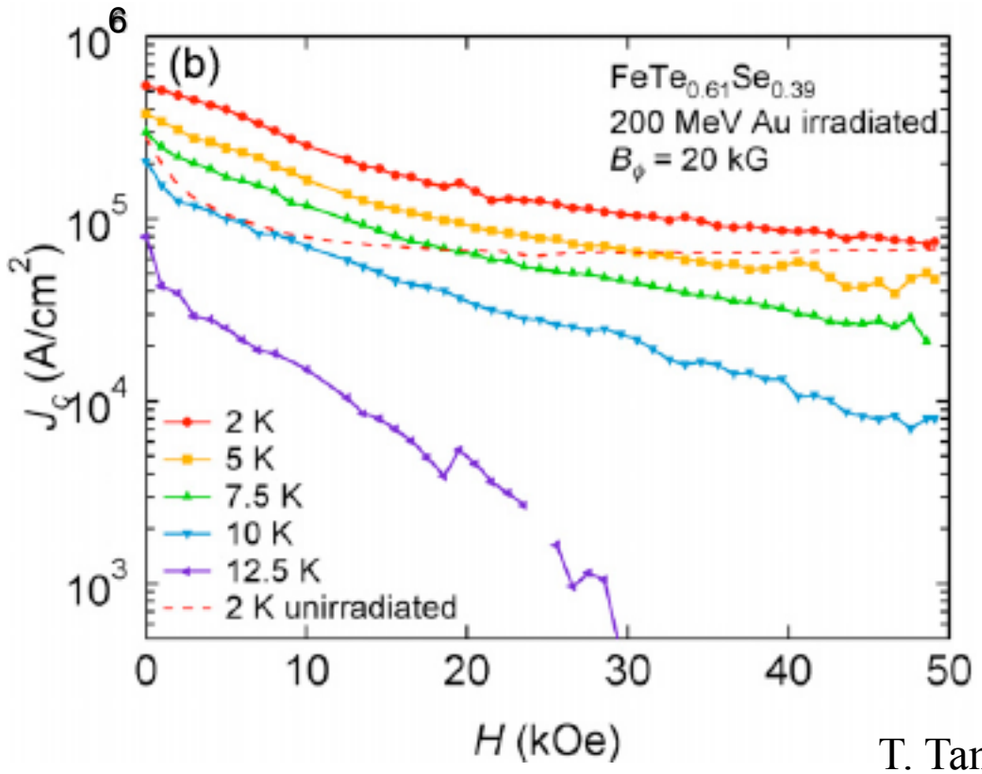
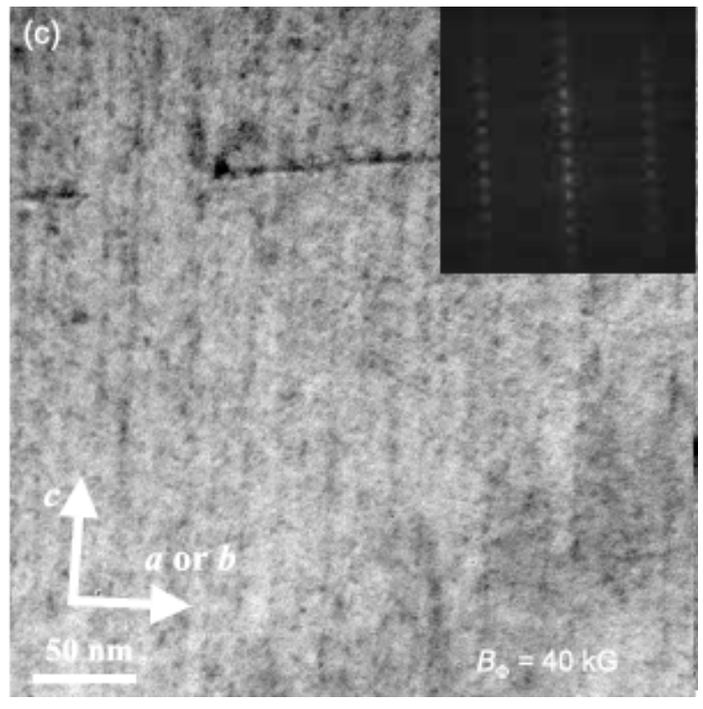




diameter ~ 10 nm

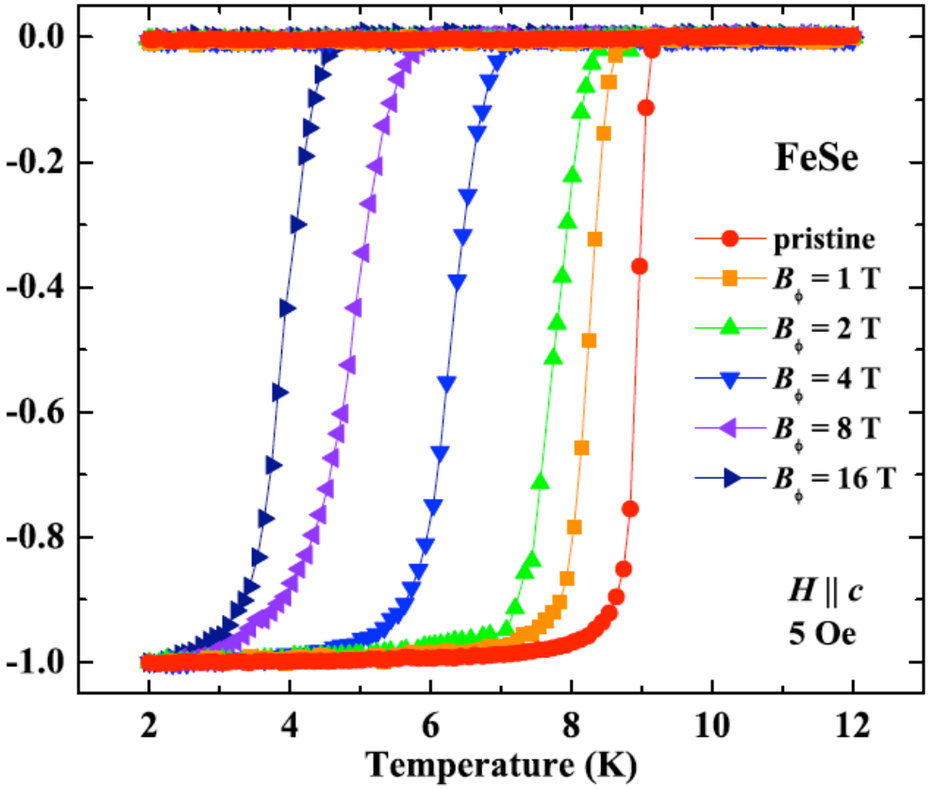




T. Tamegai *et al*., SUST **25**, 084008 (2012).

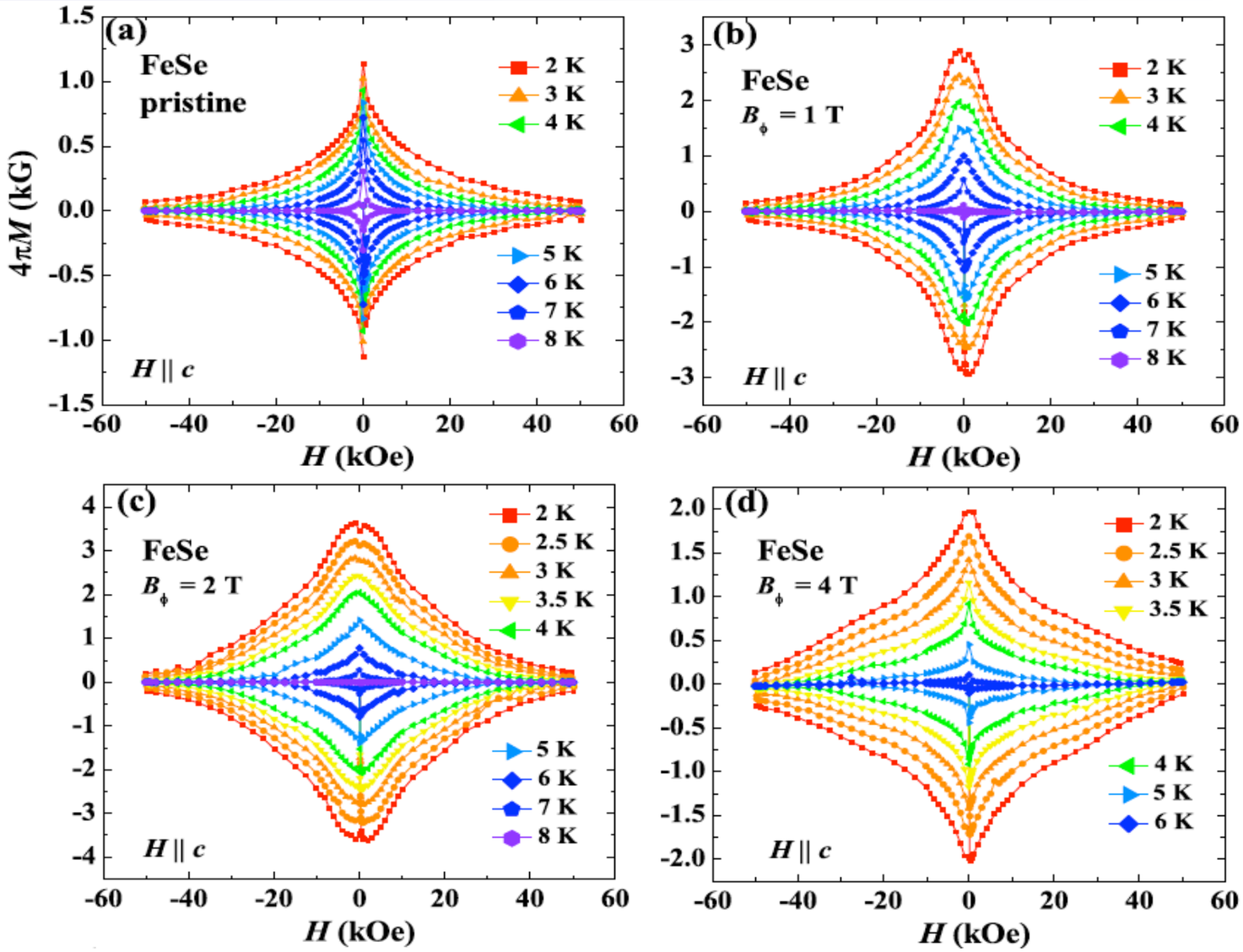
B_Φ-Dependence of T_c and J_c in FeSe

2.6 GeV U



T_c is suppressed with increasing B_Φ

Y. Sun *et al.*, PRB **95**, 104514 (2017).



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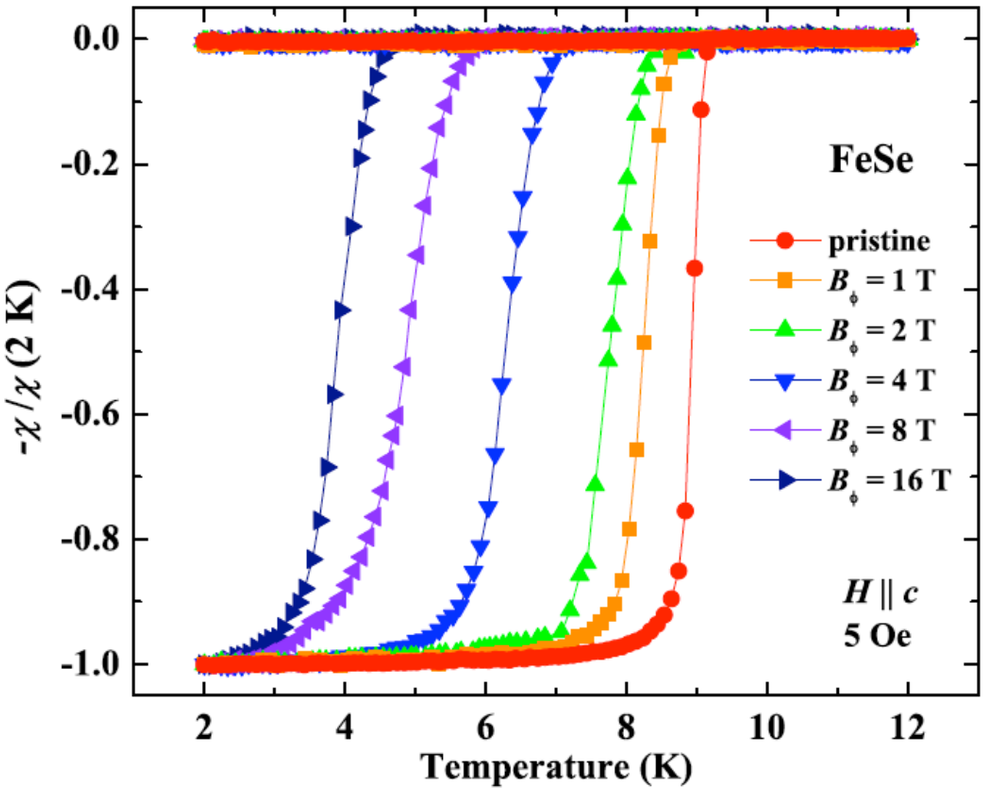

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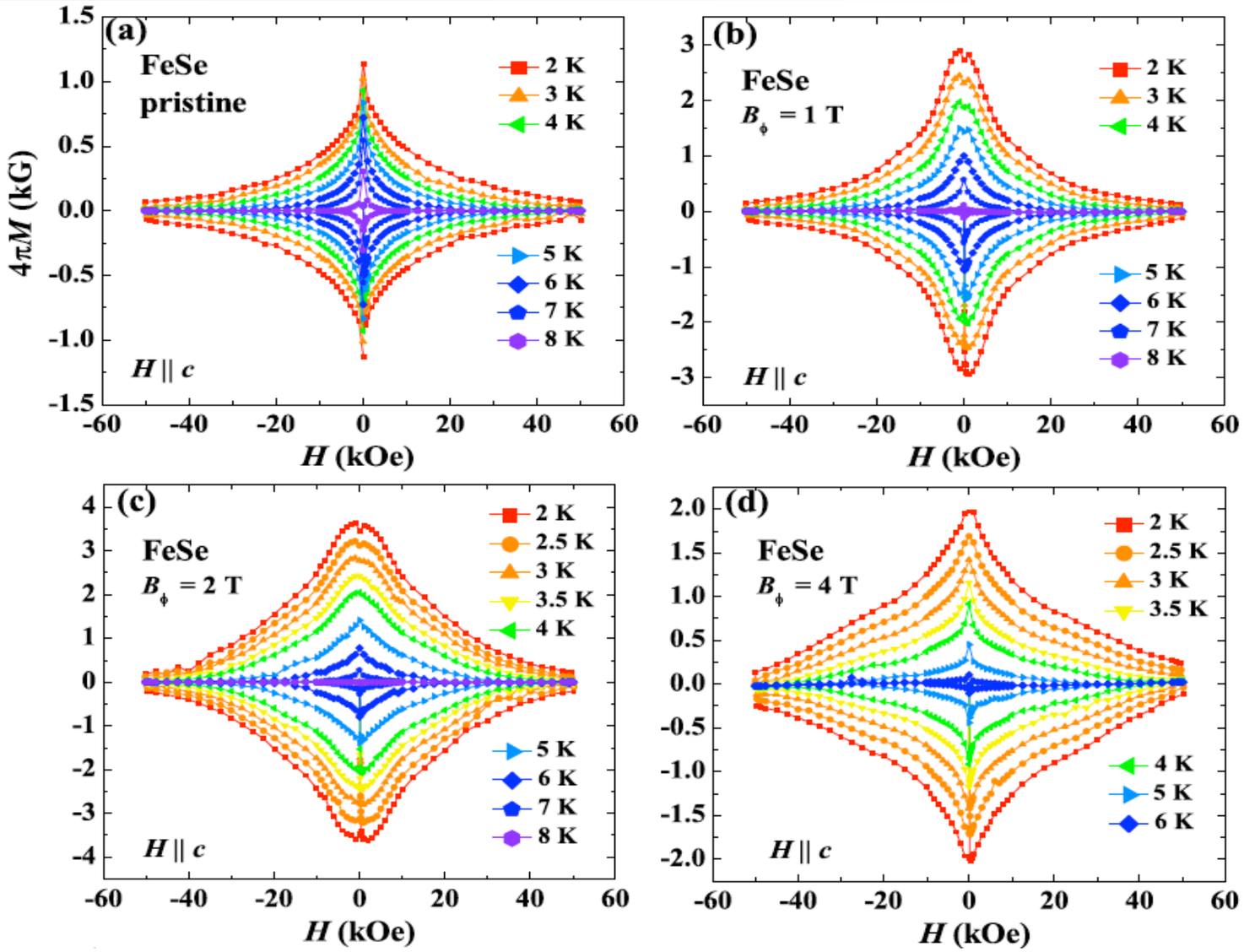
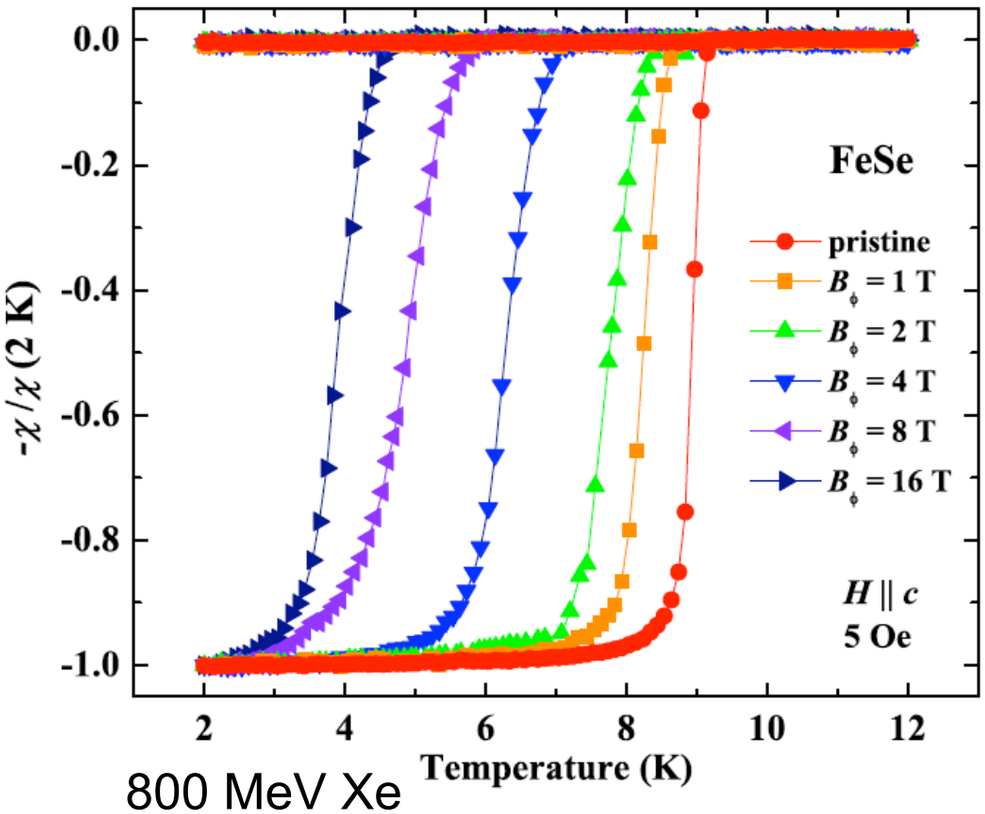
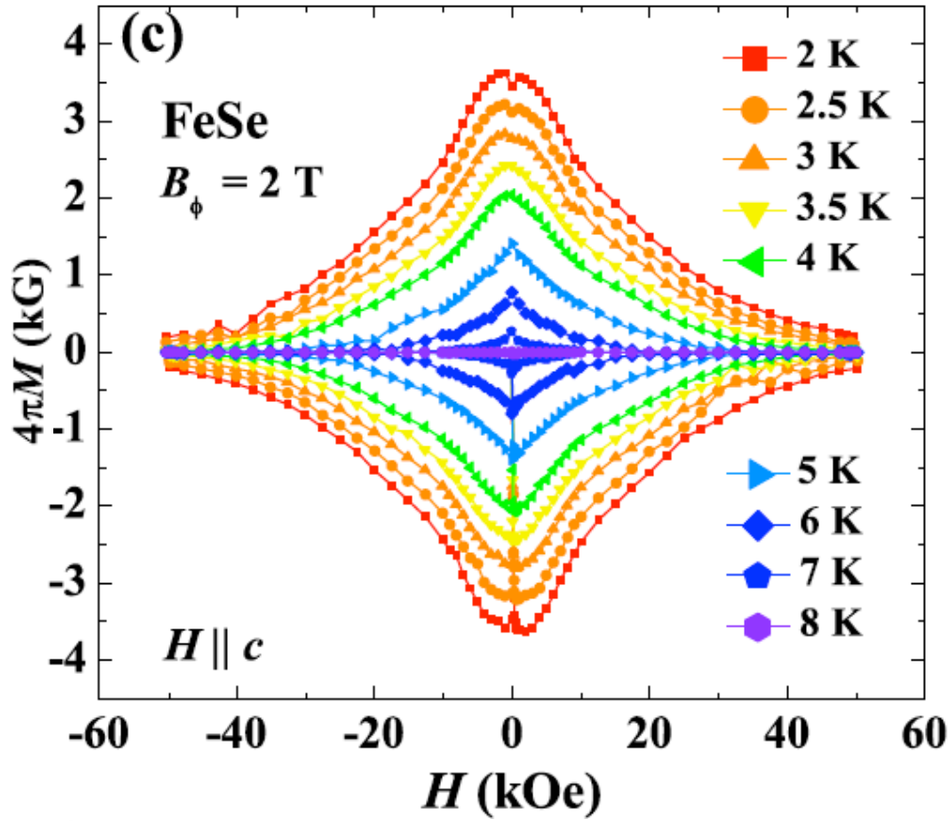


J_c shows non-monotonic B_Φ dependence

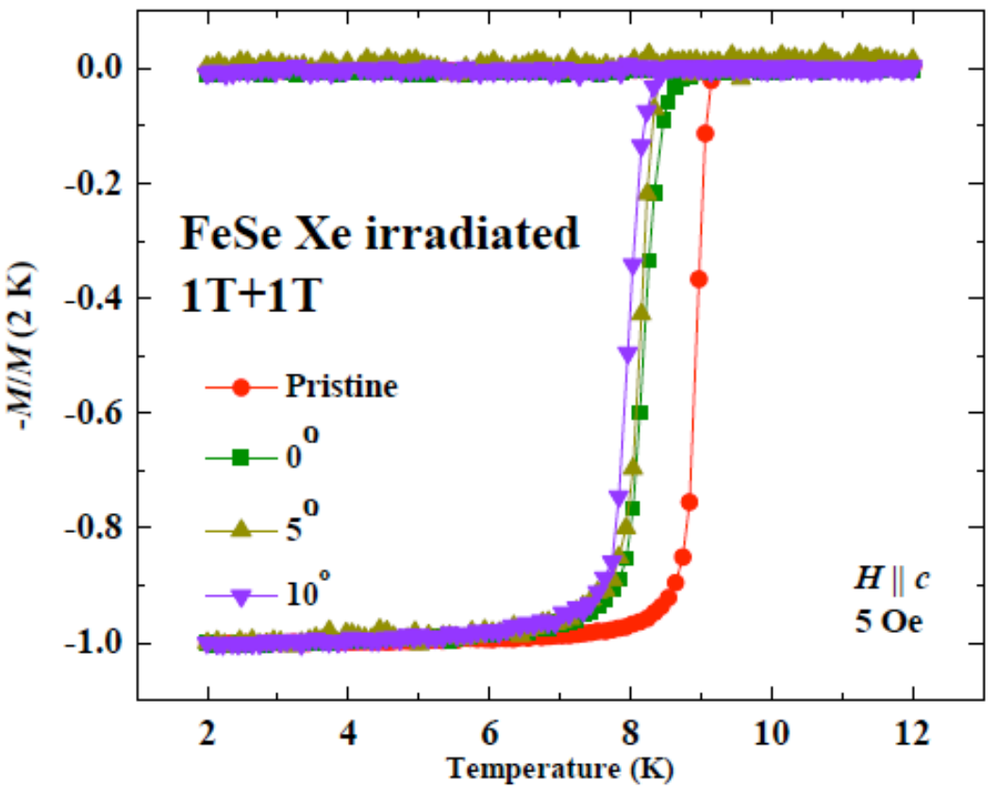
Comparison of Effects of 2.6 GeV U and 800 MeV Xe Irradiations

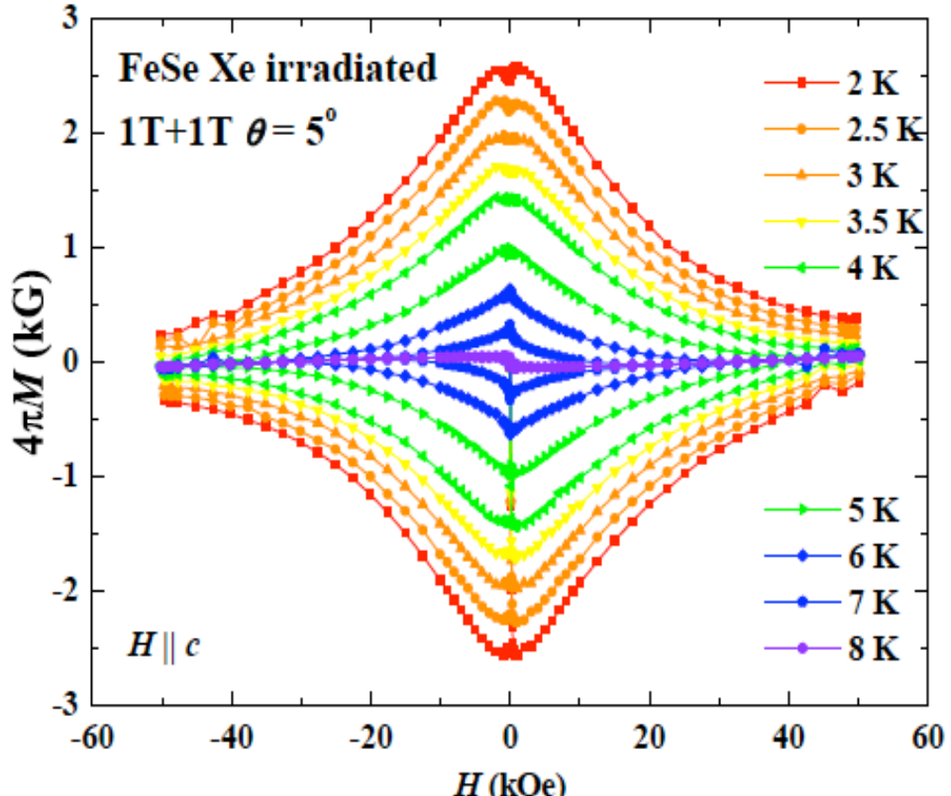
2.6 GeV U



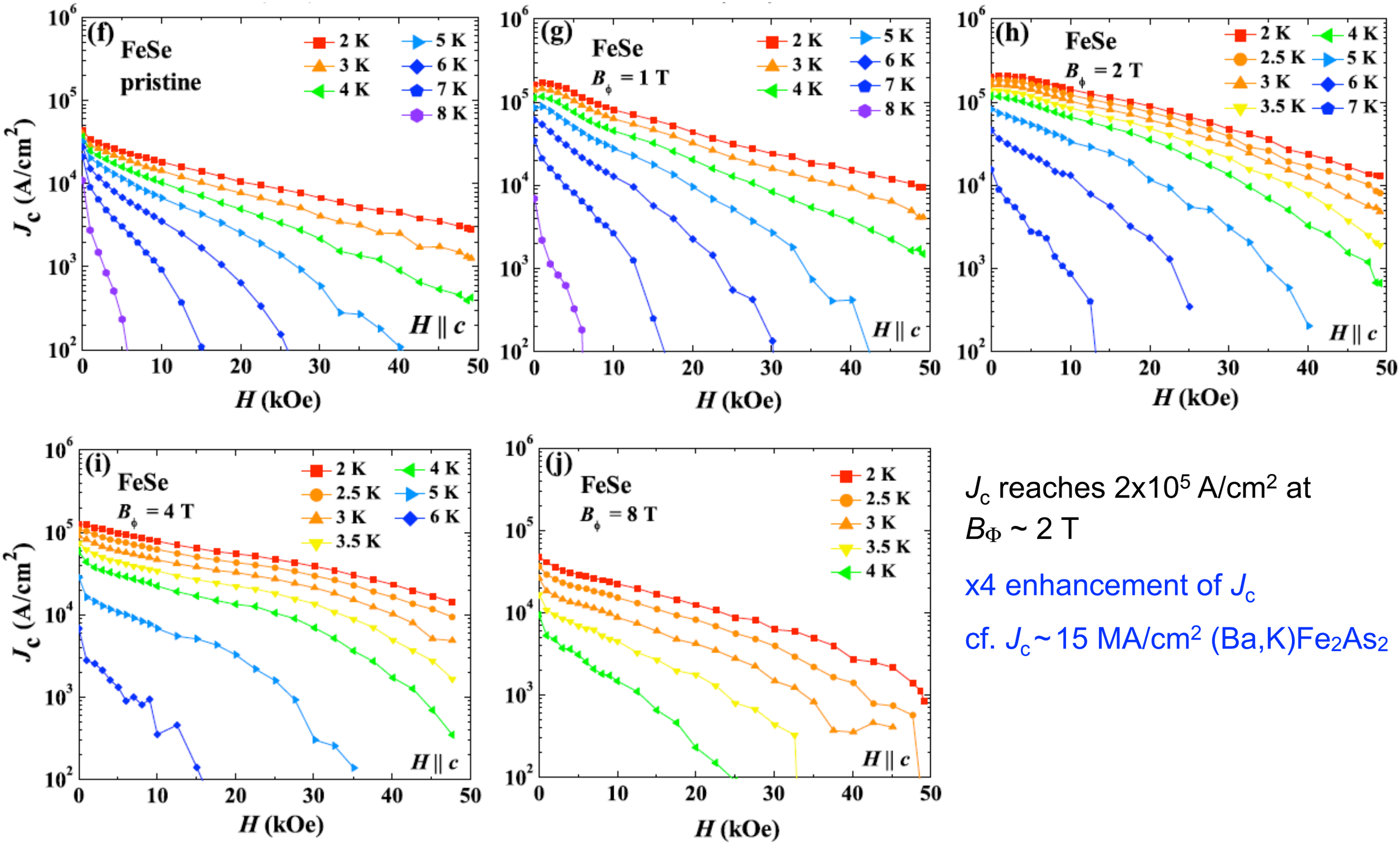


800 MeV Xe





B_Φ-Dependence of J_c in FeSe



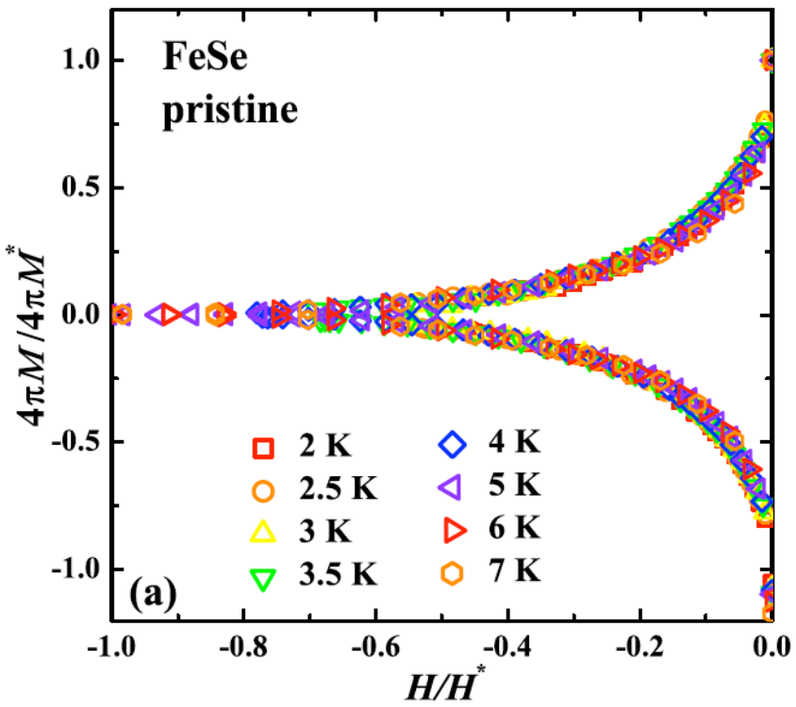
J_c reaches 2x10^5 A/cm^2 at B_Φ ~ 2 T

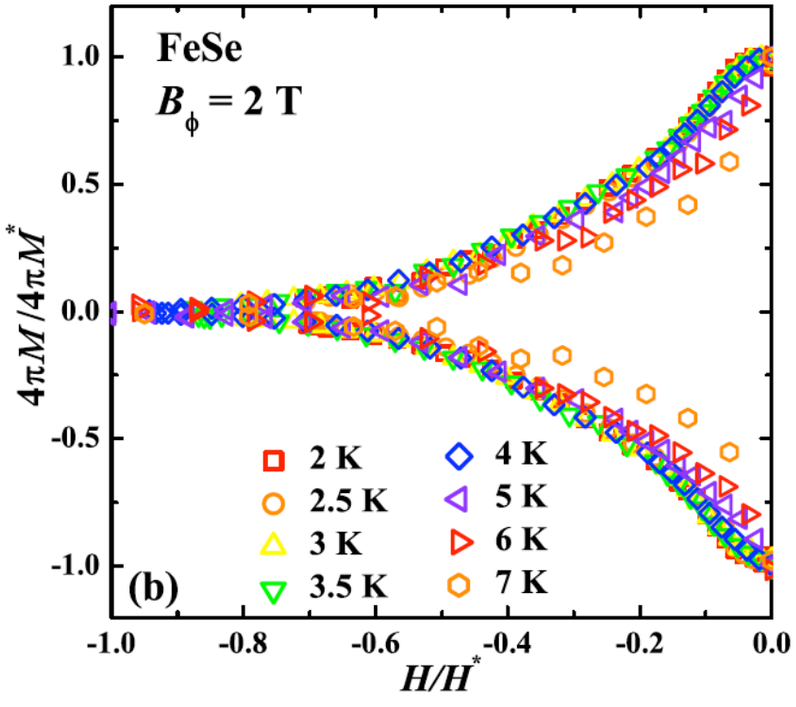
x4 enhancement of J_c

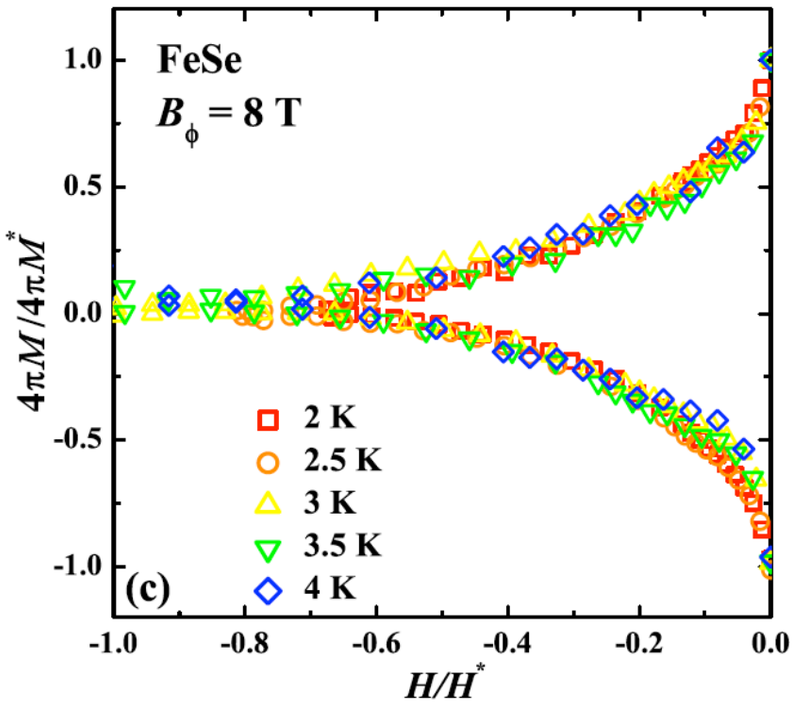
cf. J_c ~ 15 MA/cm^2 (Ba,K)Fe$_2$As$_2$

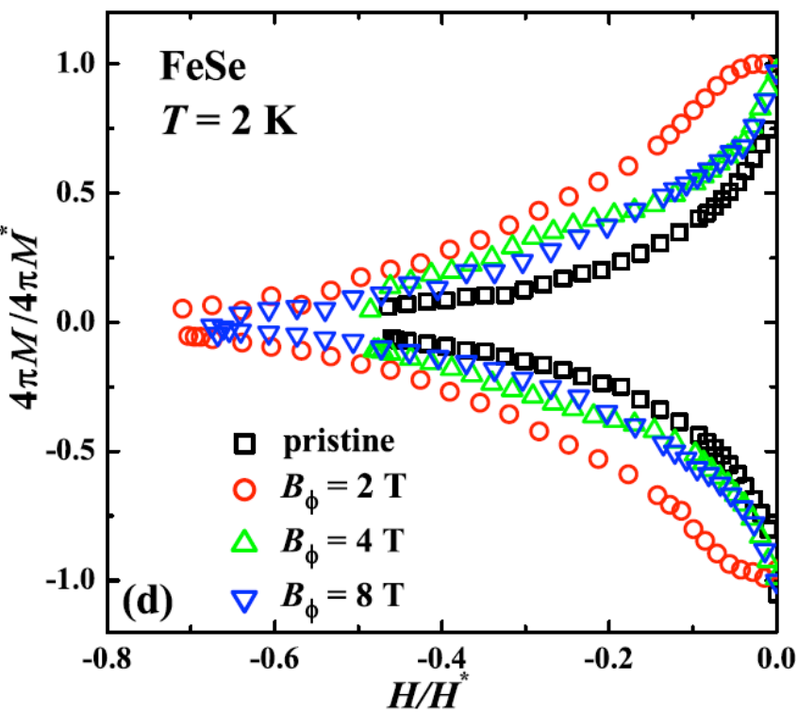
Scaling of *M-H* Hysteresis Curves

2.6 GeV U









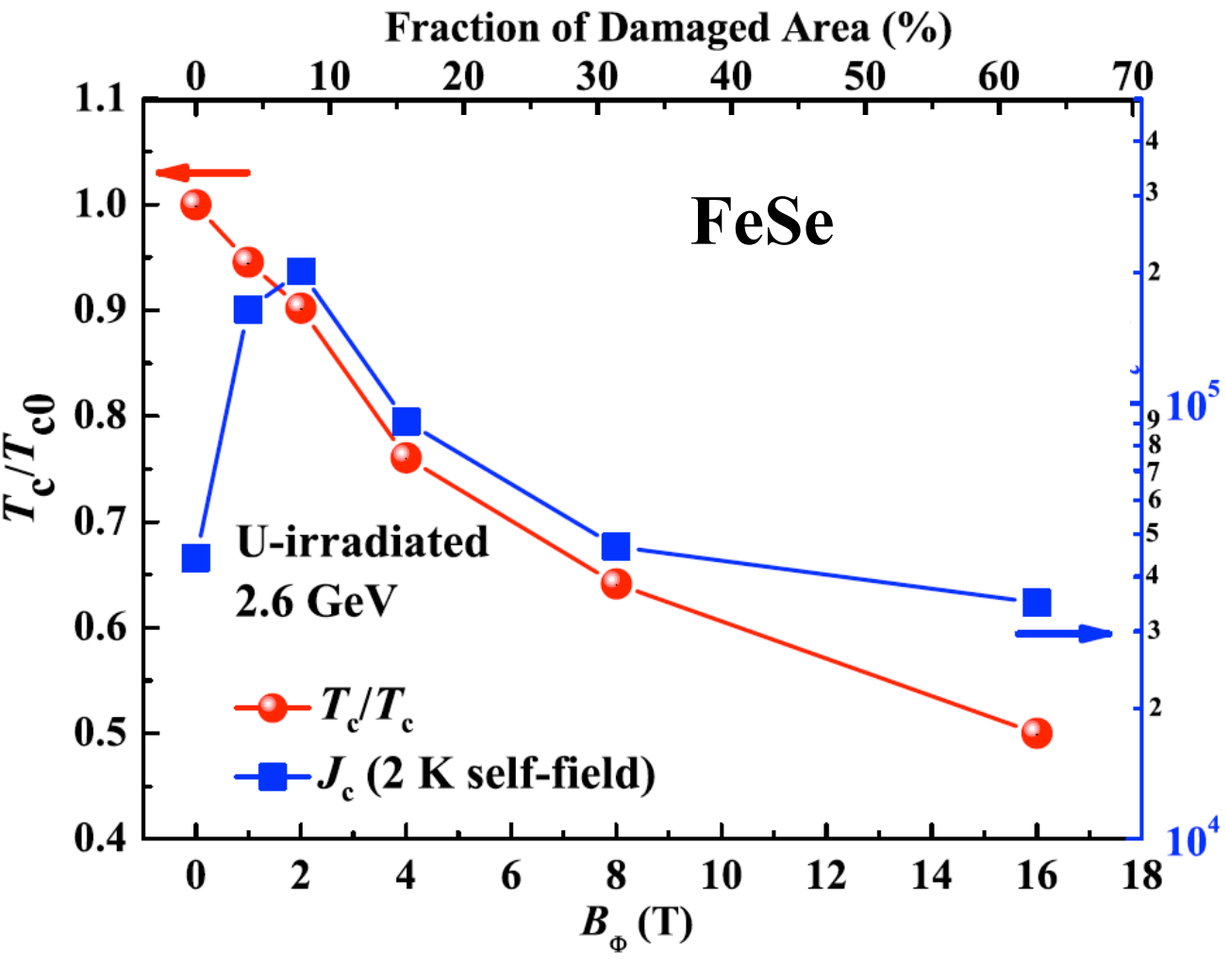
Good scaling of J_c at $B_\Phi < 1$ T and $B_\Phi > 4$ T

Scaling of J_c breaks down at 1 T < B_Φ < 4 T

Two strong pinnings, naturally-present and induced by CDs compete in FeSe with 1 T < B_Φ < 4 T

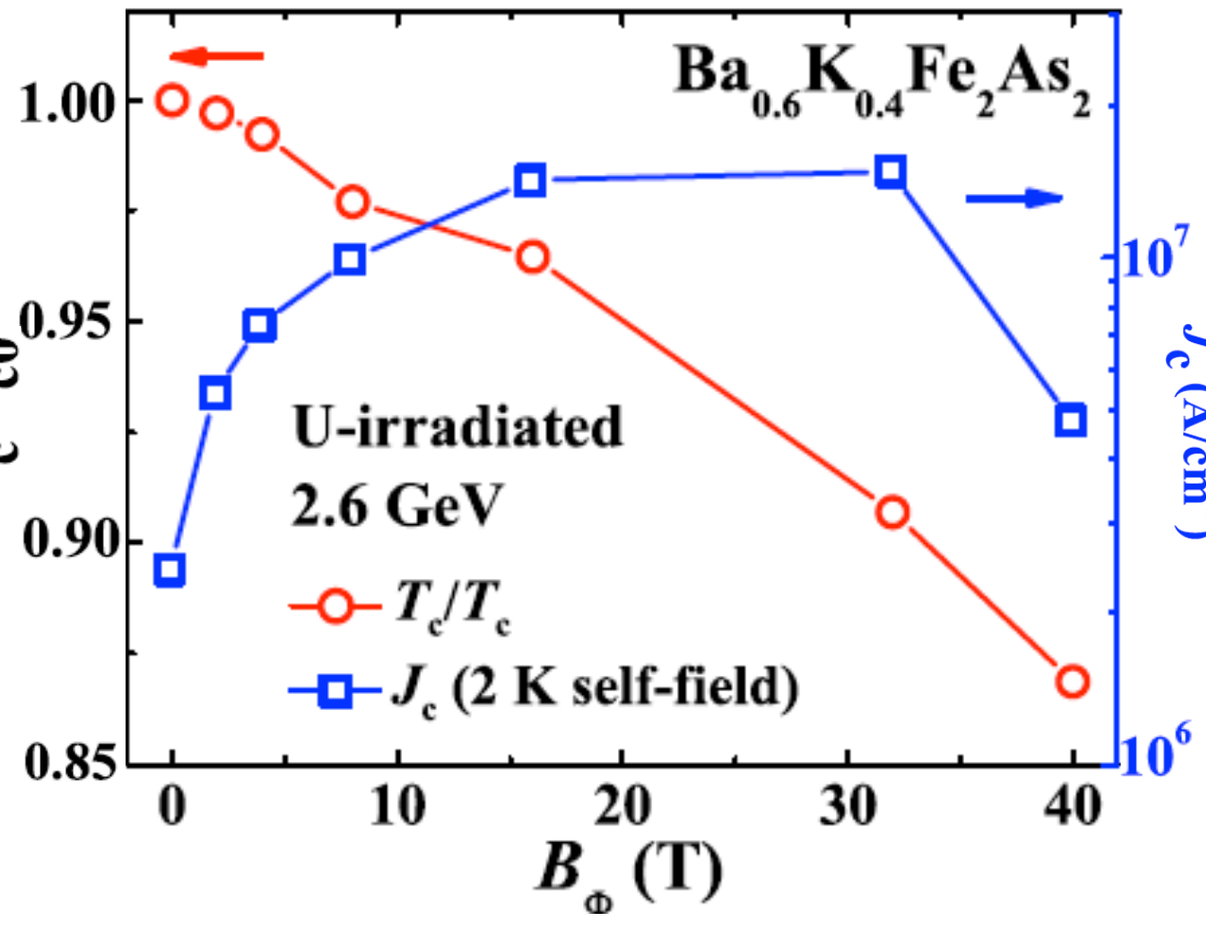
Large self-field (~1 kG) in FeSe with 1 T < B_Φ < 4 T makes magnetic field dependence of J_c weaker at low temperatures

B_Φ-Dependence of T_c and J_c in FeSe



T_c decreases almost linearly with B_Φ

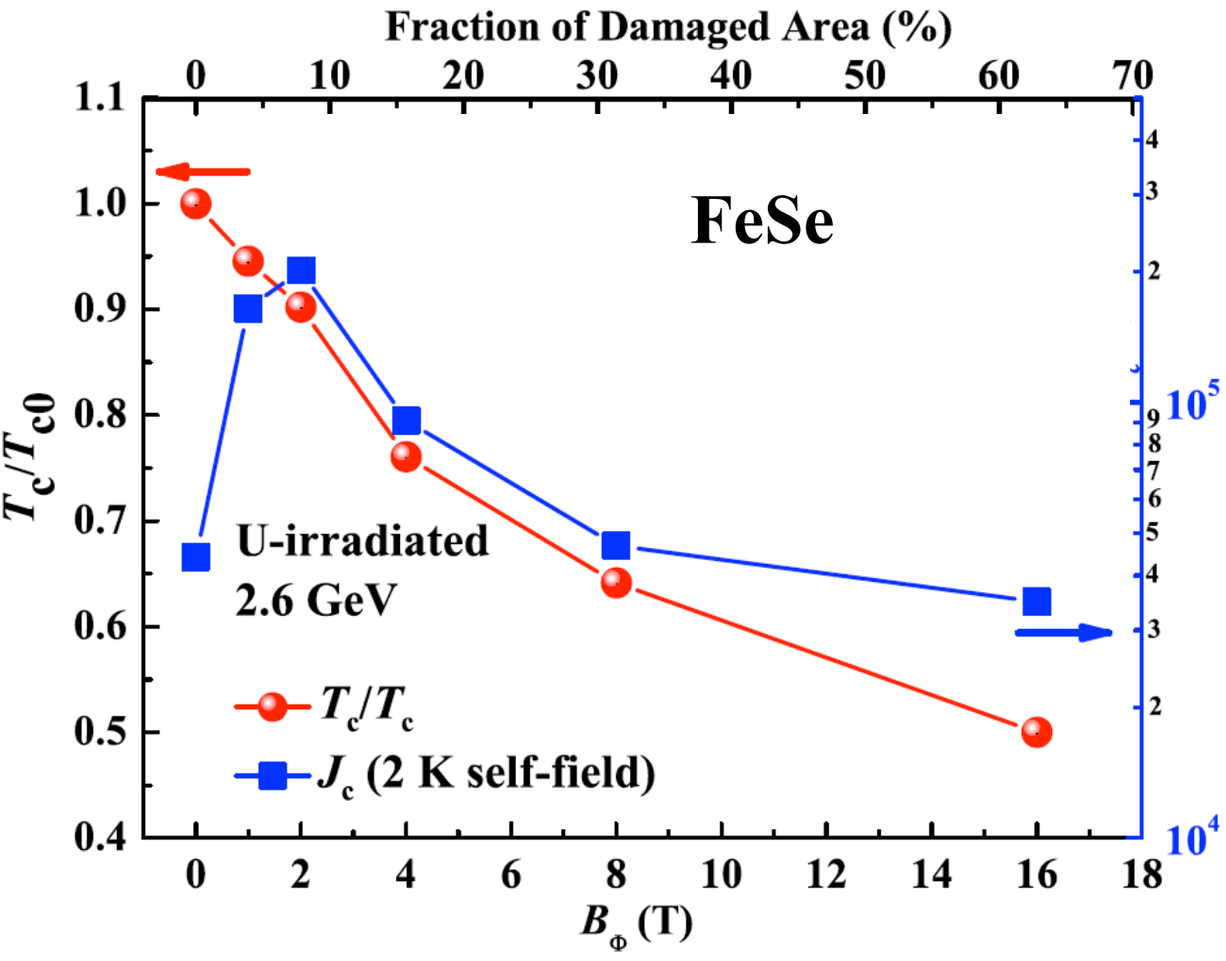
dT_c/dB_Φ ~ -0.5 K/T



T_c decreases almost linearly with B_Φ

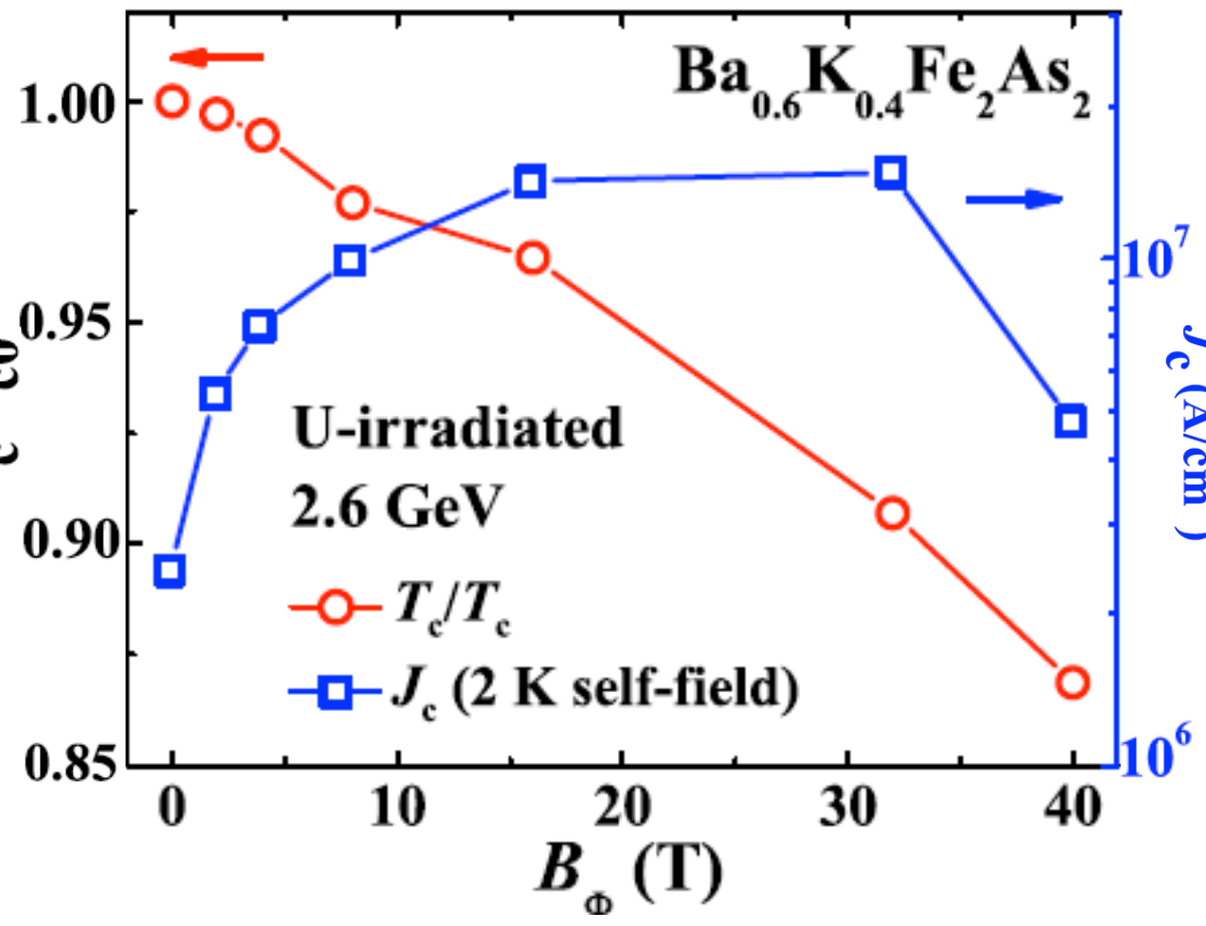
dT_c/dB_Φ ~ -0.08 K/T

B_Φ-Dependence of T_c and J_c in FeSe



T_c decreases almost linearly with B_Φ

dT_c/dB_Φ ~ -0.5 K/T



T_c decreases almost linearly with B_Φ

dT_c/dB_Φ ~ -0.08 K/T

Ideally CDs do not affect T_c

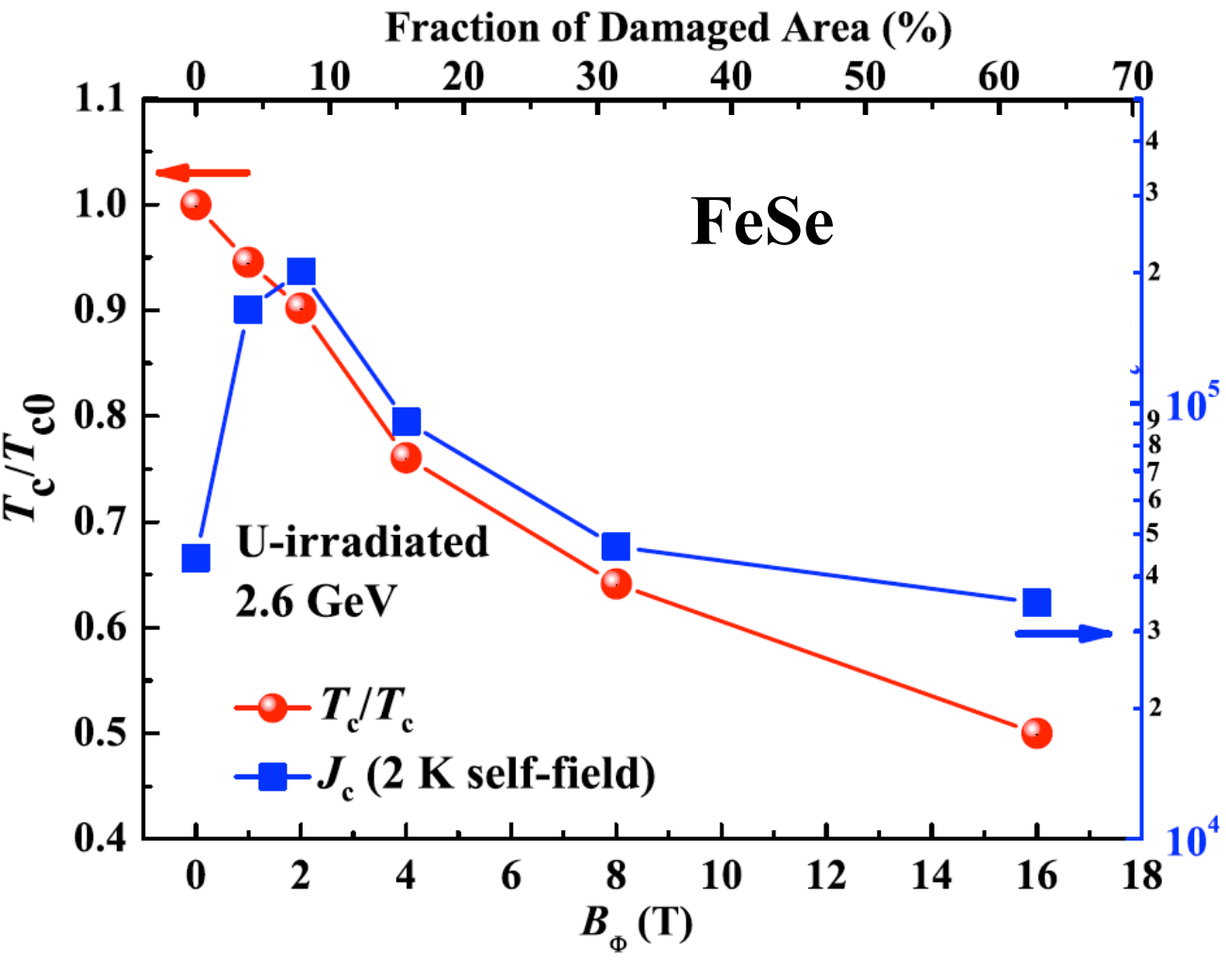
Possible effect of secondary electrons

Light particle irradiations do not suppress T_c in FeSe

electron S. Teknowijoyo *et al*., PRB **94**, 064512 (2016).

proton Y. Sun *et al*., unpublished.

B_Φ-Dependence of T_c and J_c in FeSe



T_c decreases almost linearly with B_Φ

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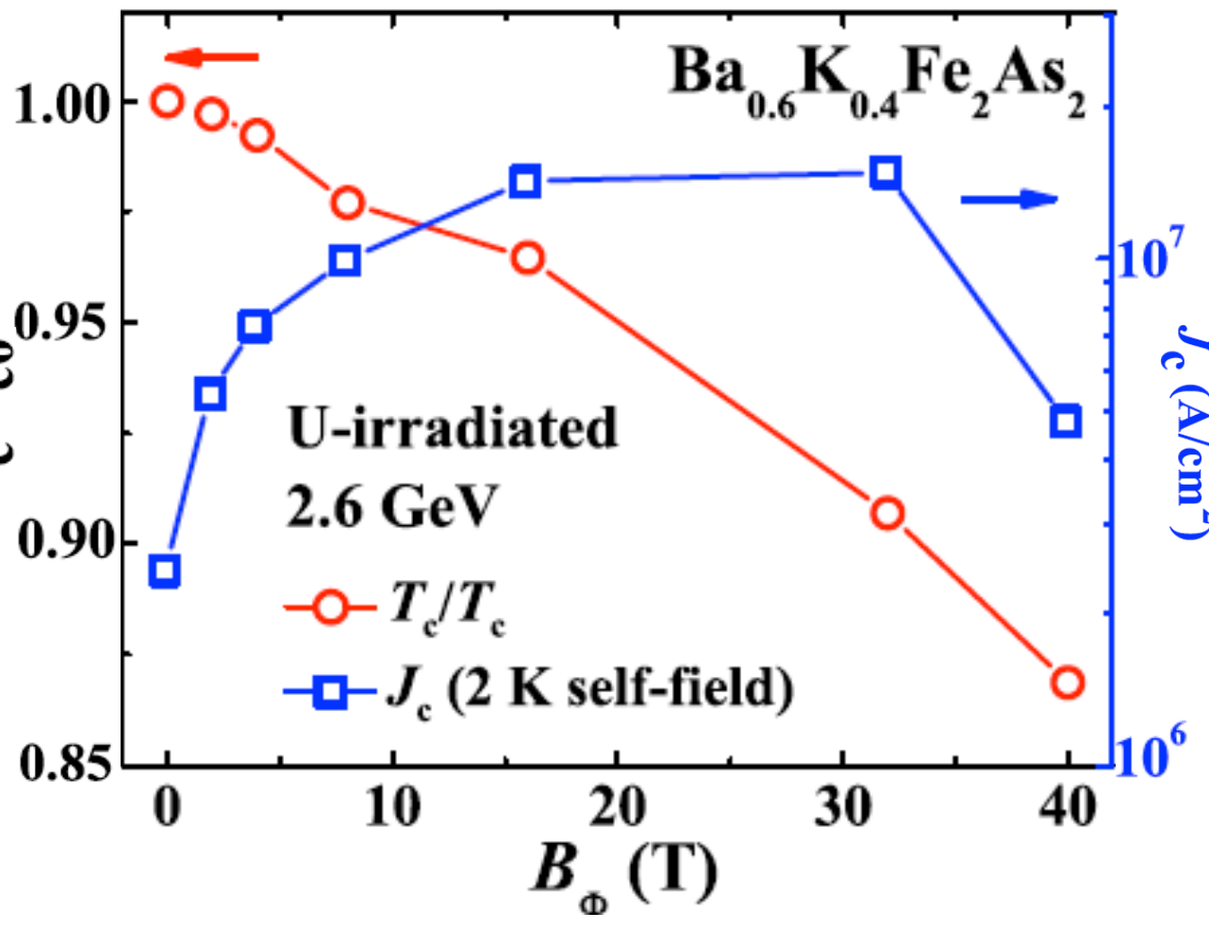

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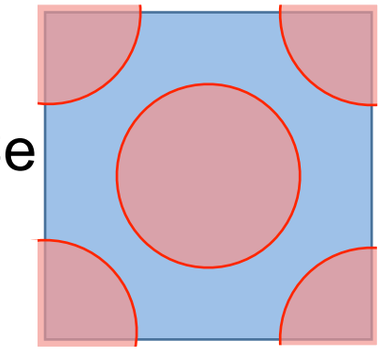
proton Y. Sun *et al.*, unpublished.

VF ~ 40 % at B_Φ = 16 T

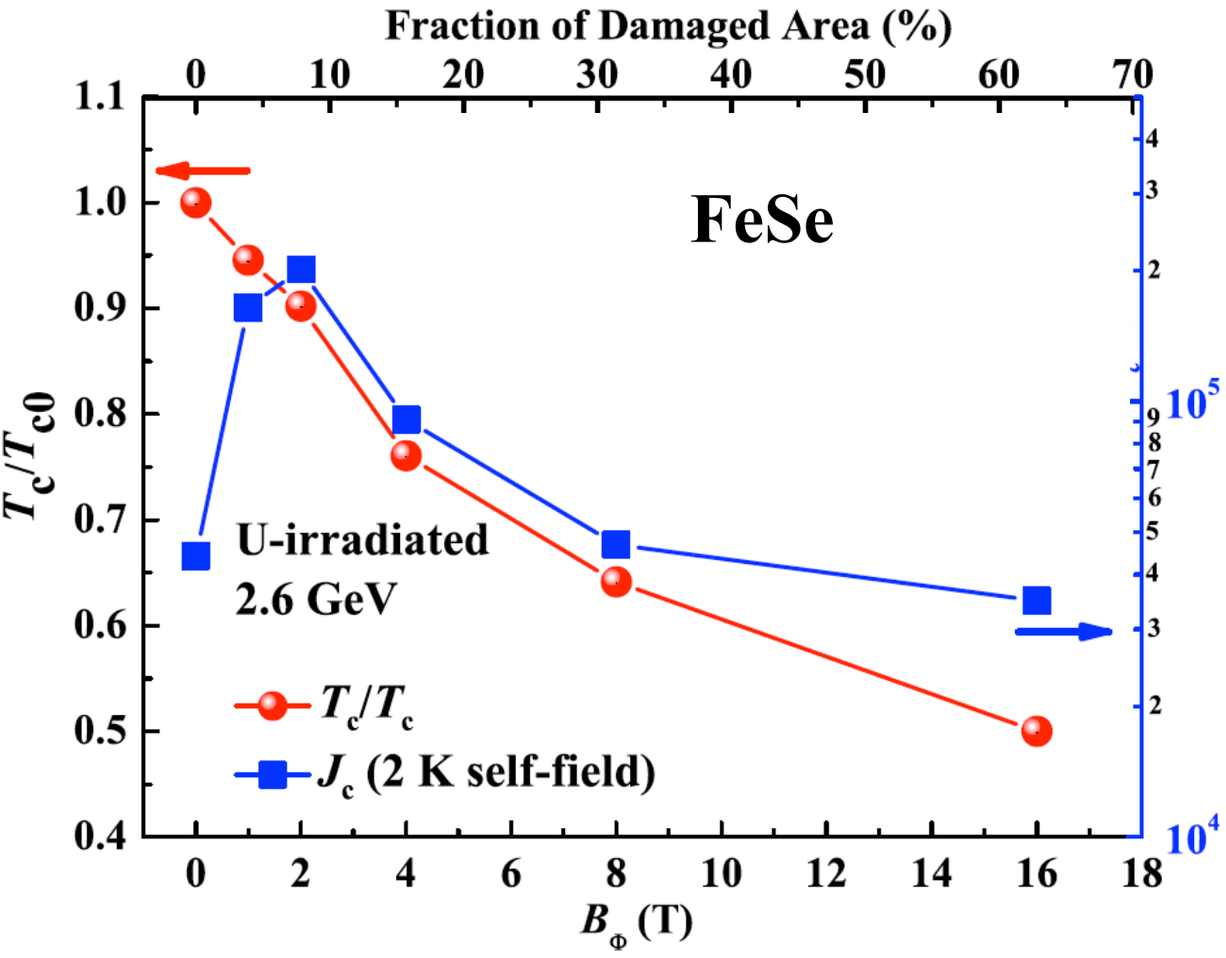
(diameter of CD: 10 nm)



Blue : SC region

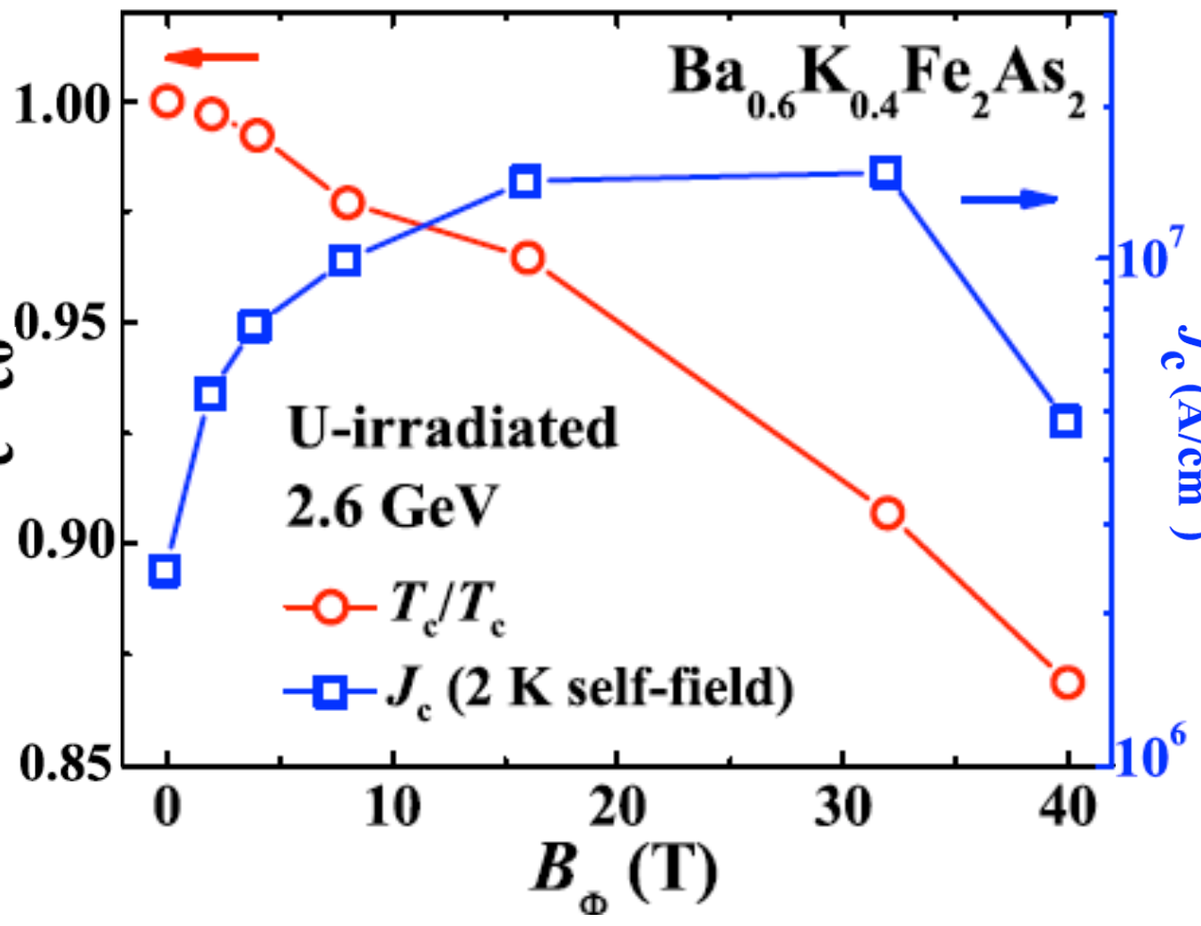
Red : Columnar defects

B_Φ-Dependence of T_c and J_c in FeSe



J_c reaches the maximum at $B_\Phi \sim 2$ T

$J_c^{max} \sim 0.2$ MA/cm^2



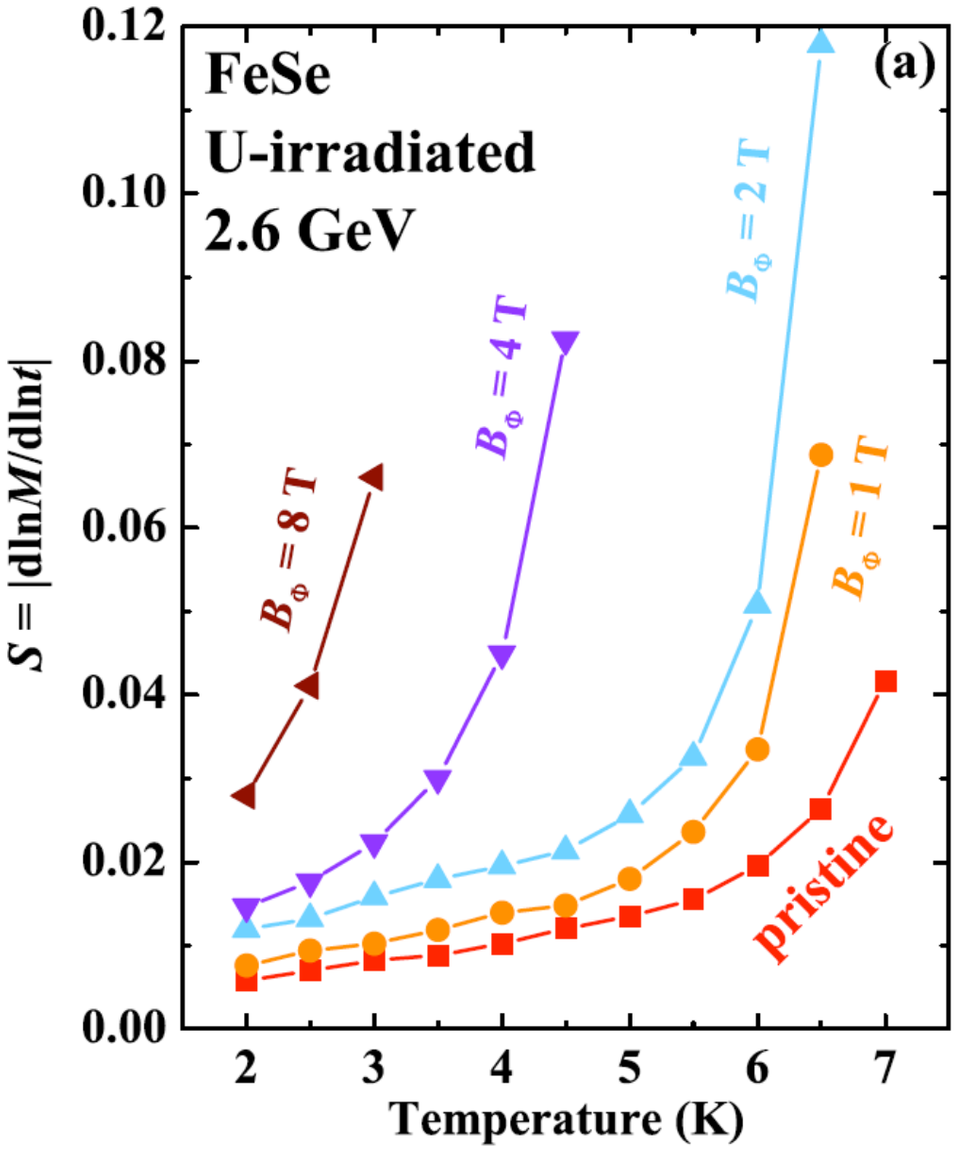
J_c reaches the maximum at $B_\Phi \sim 20$ T

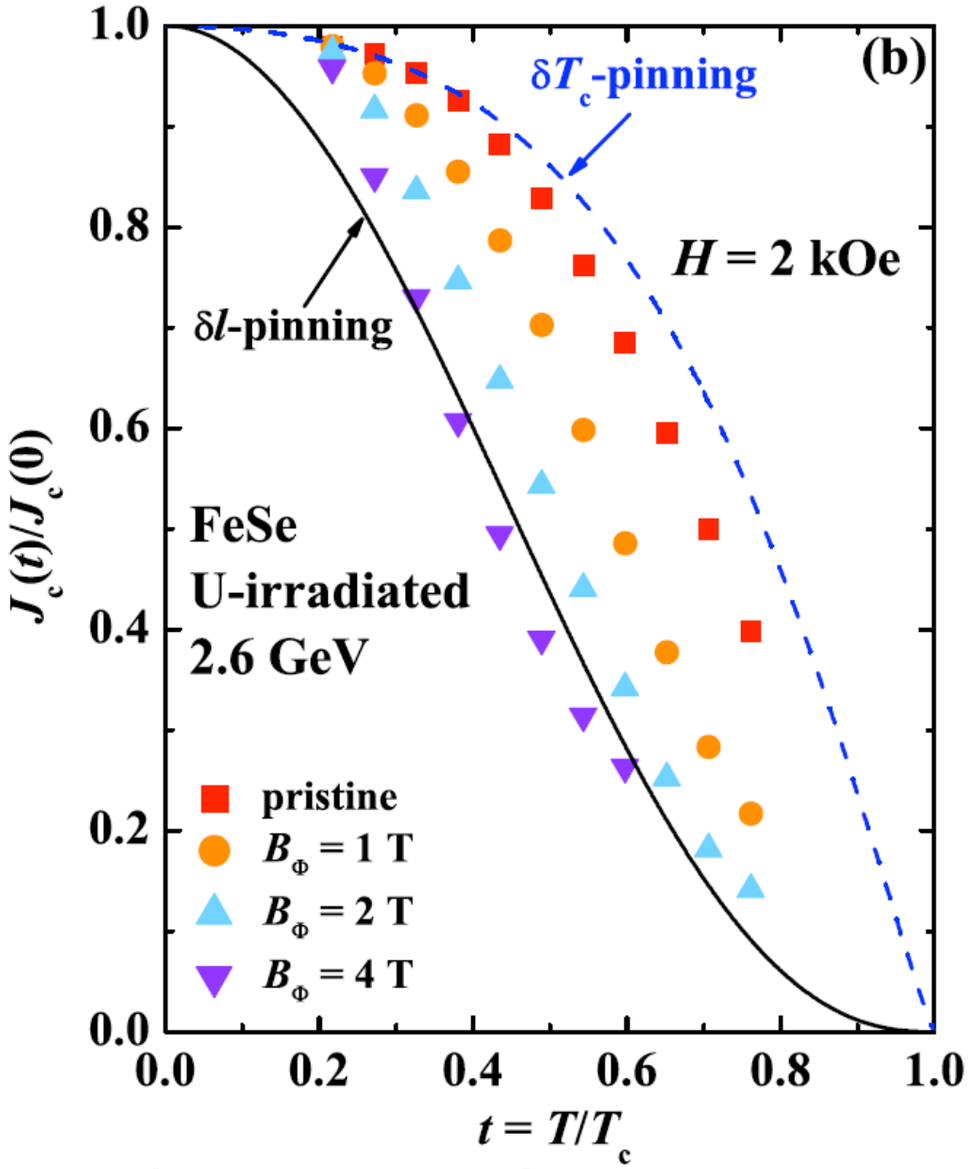
$J_c^{max} \sim 15$ MA/cm^2

Different pinning energy (U_p), size of columnar defects (radius r), and optimal B_Φ (B_Φ') in FeSe and (Ba,K)Fe_2As_2

$$U_p \sim \epsilon_0 \ln(r/\sqrt{2}\xi) \qquad J_c = \frac{cU_p}{\Phi_0 a_\Phi} = \frac{c}{\Phi_0 a_\Phi}\epsilon_0 \ln\left(\frac{r}{\sqrt{2}\xi}\right) \propto B_\Phi'^{1/2}/\lambda^2$$

Analyses of Vortex Dynamics in FeSe with CDs





J_c evaluated generalized inversion scheme

H. G. Schnack *et al.*, PRB **48**, 13178(R) (1993).

At low B_Φ, $J_c(T)$ is dominated by δT_c-pinning

At high B_Φ, $J_c(T)$ is dominated by δl-pinning

Summary

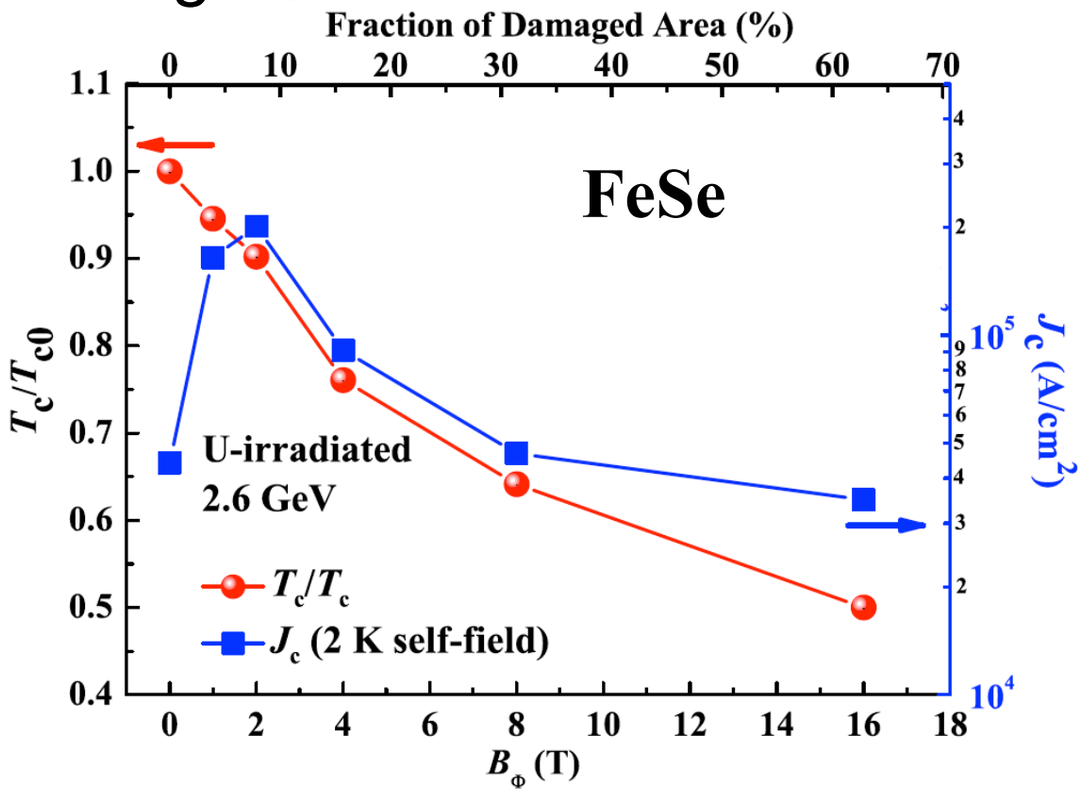
Effects of heavy-ion irradiations in high-quality FeSe single crystals are studied

- T_c is suppressed monotonically with increasing B_Φ

  dT_c/dB_Φ = -0.5 K/T (2.6 GeV U)

- J_c reaches the maximum at B_Φ ~ 2 T, and is suppressed above B_Φ = 2 T

  J_c^{max} ~2x10^5 A/cm^2 (2 K, sf)



- The behavior of J_c - B_Φ is similar to the case of 122-system with ~70 times difference in optimal B_Φ.

  Different condensation energy and size of columnar defects in 11 and 122 systems

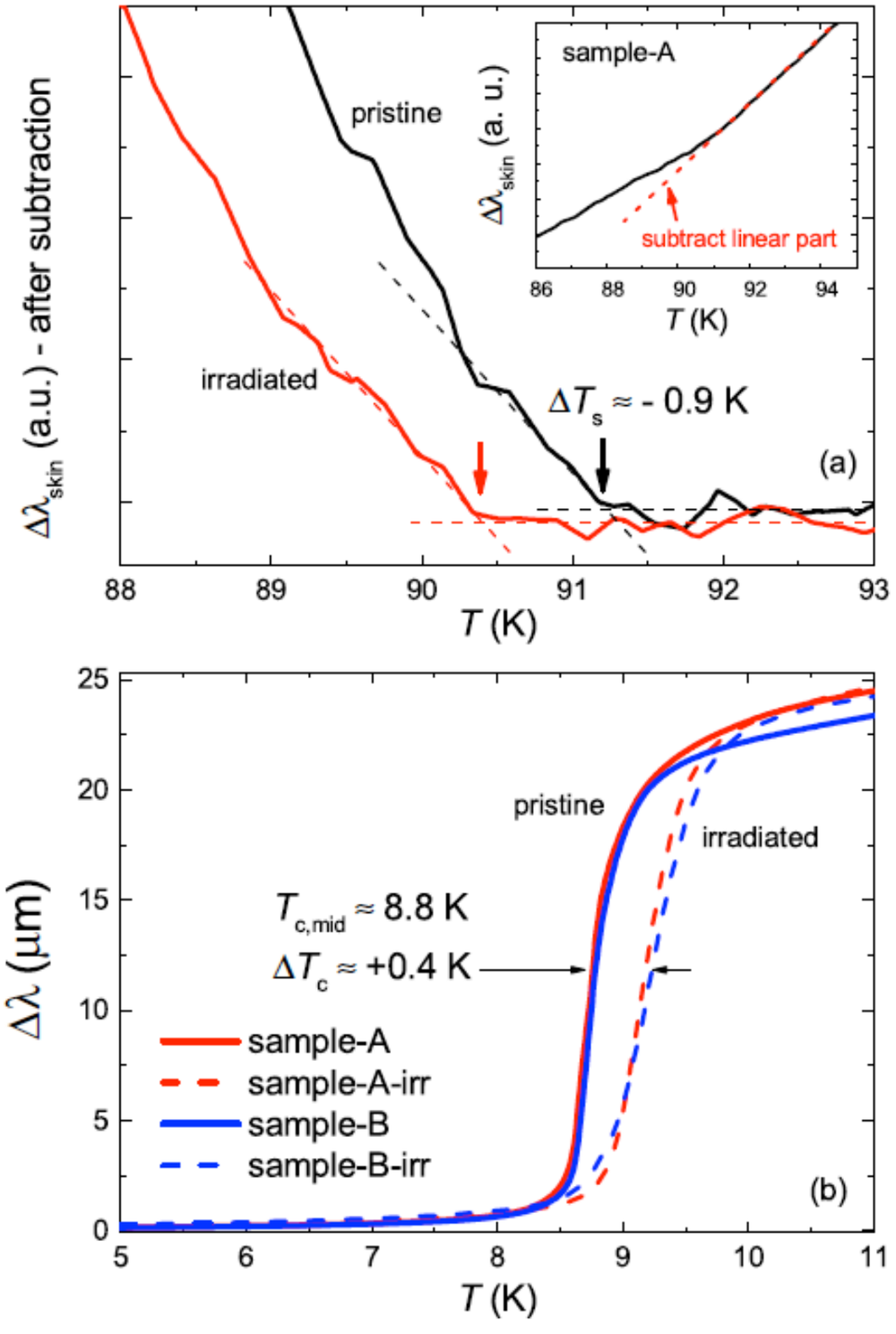
- δT_c-pinning and δl-pinning coexist in FeSe

  Pinning mechanism crossovers from δT_c-pinning at low B_Φ to δl-pinning at high B_Φ

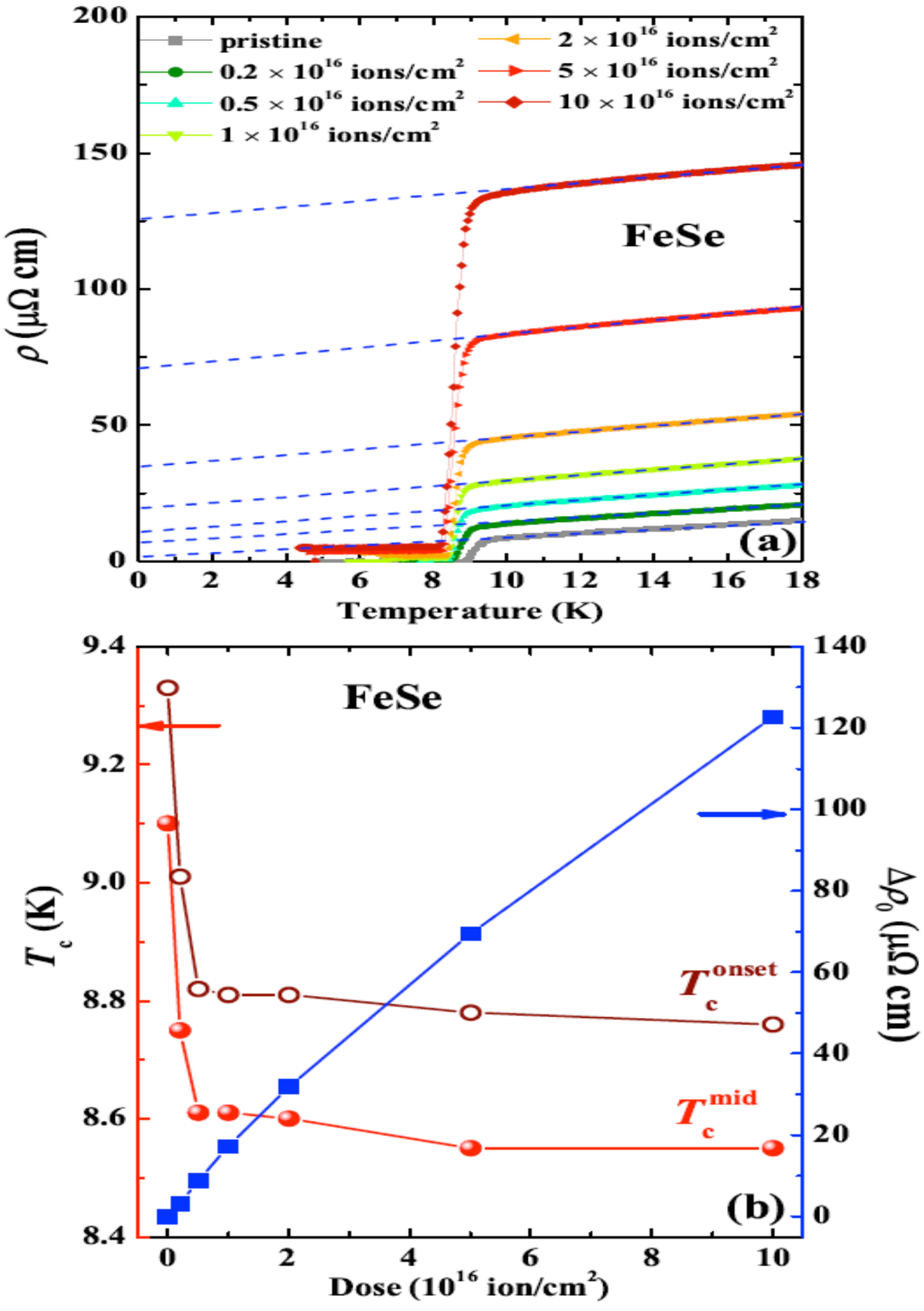
END

Effects of Light particle Irradiation on FeSe

3 MeV electron, 1.1x10^{19} cm^{-2}



3 MeV proton



S. Teknowijoyo *et al*., PRB **94**, 064512 (2016).