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量子化磁束動力学シミュレーション研究グループ第四回研究会

Investigation of the flux lines motion in superconductors in a longitudinal magnetic field by the computer simulation using the Time-Dependent Ginzburg-Landau equations

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Time-Dependent Ginzburg-Landau (TDGL) equations

✓ Description of the vortex dynamics in type-II superconductors

★ Introduction of study about vortex dynamics by TDGL equations

➢ A. E. Koshelev [Argonne National Laboratory] (2016)[1]

- ✓ Visualizing the flux lines in nano-particles doped superconductor
- ✓ Investigation of optimal parameters (PC size and density) for the pinning to maximize the critical current density J_c

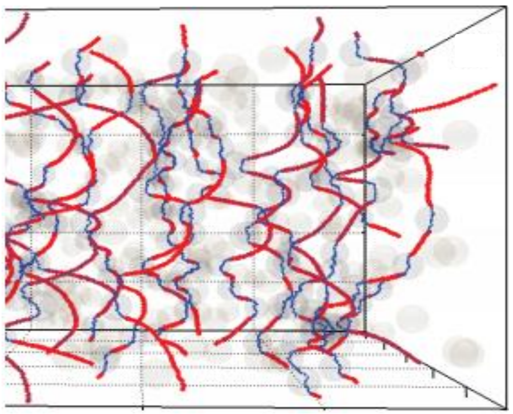

Fig. Snapshot of the flux lines through the nano-particles. (The particles are shown as transparent spheres, and the flux lines outside particles are red and inside particles are blue.)

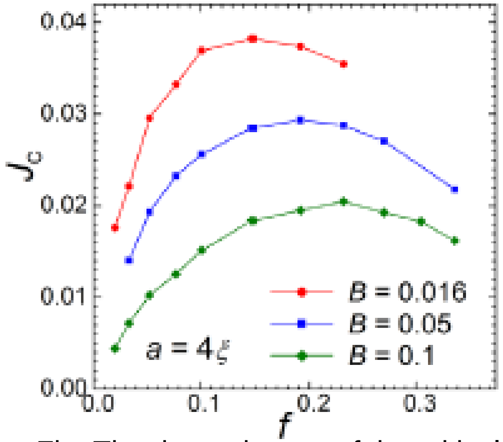

Fig. The dependences of the critical current J_c on the particle volume fraction f.

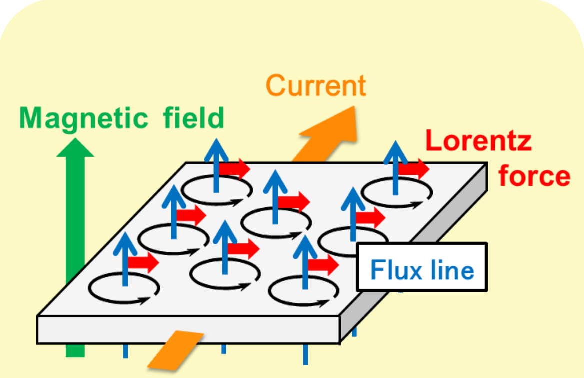

Fig. Schematic view of the type II superconductor in the LMF state. ($B \perp I$)

[1] A. E. Koshelev et al.: Phys. Rev. B. **93** (2016) 060508

Introduction ~ Longitudinal Magnetic Field Effect ~

Longitudinal magnetic field (LMF) state

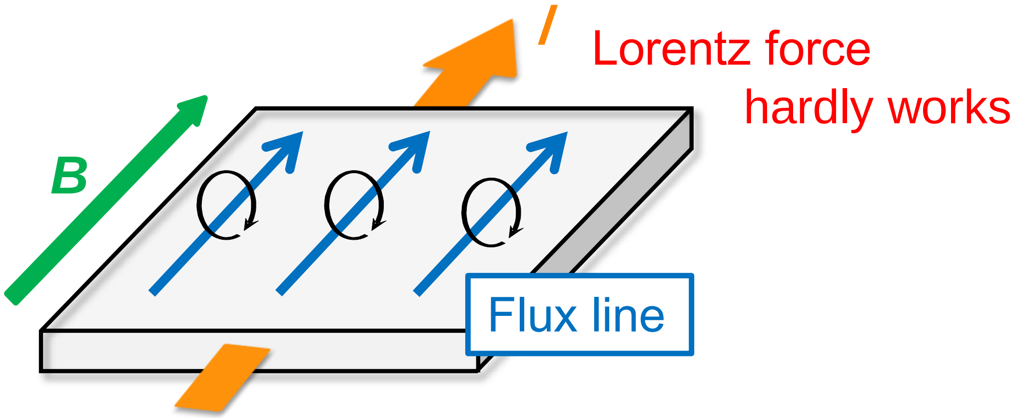

Fig. Schematic view of the type II superconductor in the LMF state. (*B* // *I*)

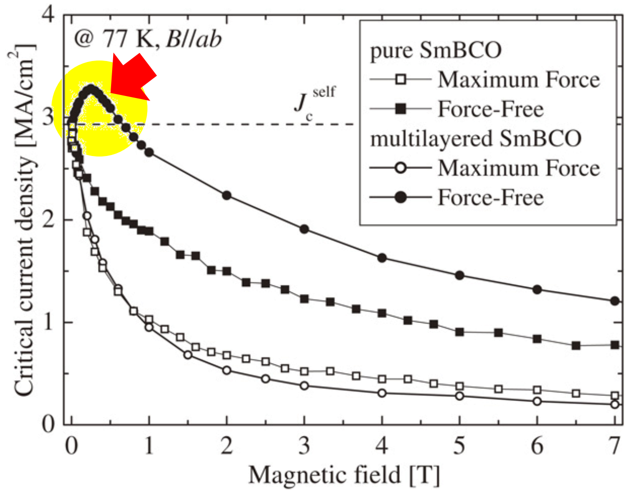

Fig. Magnetic field dependence of J_c in maximum force state and the LMF state of the pure $SmBa_2Cu_3O_y$ film and multilayered $SmBa_2Cu_3O_y$ film at 77K under *B//ab* [2],[3].

➢ J_c increases in a magnetic field more than the one at zero field

Objective

✓ To visualize the quantized flux lines motion in the LMF state
➡ the computer simulation solving the 3D-TDGL equations

✓ To investigate the effective APC shape in the LMF state

[2] A. Tsuruta et al.: Jpn. J. Appl. Phys. **53** (2014) 078003 [3] K. Sugihara et al.: Supercond. Sci. Technol. **28** (2015) 104004

TDGL Equations

TDGL equations[4]

✓ Calculation of time development of the order parameter and vector potential

$$\begin{cases} \dfrac{\partial \Delta(\boldsymbol{r},t)}{\partial t} = -\dfrac{1}{12}\left[\left(\dfrac{\nabla}{i} - \boldsymbol{A}(\boldsymbol{r},t)\right)^2 \Delta(\boldsymbol{r},t) - (1-T)(\alpha + \beta|\Delta(\boldsymbol{r},t)|^2)\Delta(\boldsymbol{r},t)\right] \\ \dfrac{\partial \boldsymbol{A}(\boldsymbol{r},t)}{\partial t} = (1-T)\mathrm{Re}\left[\Delta^*(\bar{\boldsymbol{r}},\bar{t})\left(\dfrac{\nabla}{i} - \boldsymbol{A}(\boldsymbol{r},t)\right)\Delta(\boldsymbol{r},t)\right] - \kappa^2 \nabla \times \nabla \times \boldsymbol{A}(\boldsymbol{r},t) \end{cases}$$

(Δ : order parameter, $\boldsymbol{A}$: vector potential)

Parameter[5]

$$\alpha = \begin{cases} -1 : \text{superconductor} \\ \left(\dfrac{\xi_0}{\xi_n}\right)^2 = \alpha_n : \text{normal conductor} \end{cases} \qquad \beta = \begin{cases} 1 : \text{superconductor} \\ 0 : \text{normal conductor} \end{cases}$$

- Calculation of the motion of the flux lines with the progress at time
- Arranging artificial pinning centers (APCs) arbitrarily

[4] R. Kato et al.: Phys. Rev. B. **47** (1993) 13

[5] T. Matsushita et al.: Adv. Cryog. Eng. Mater. **36** (1990) 263

Condition of the Numerical Simulation

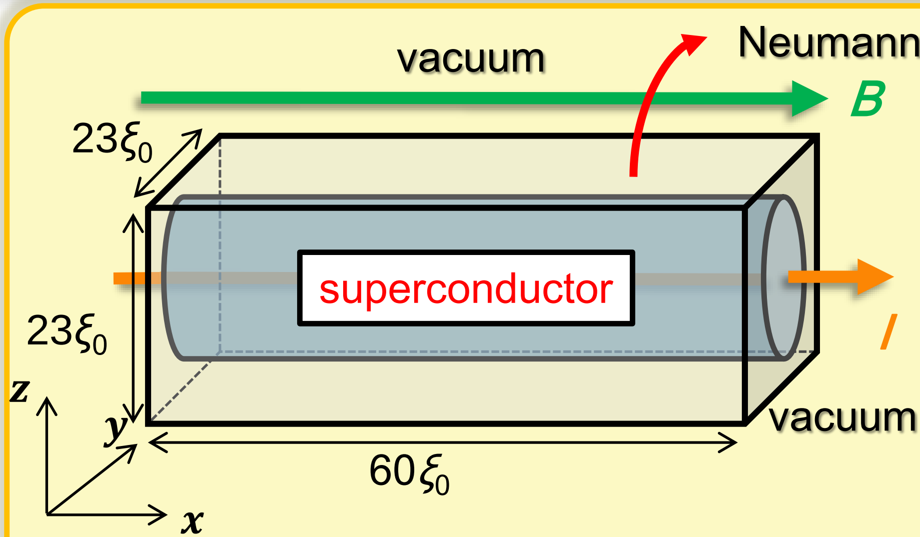

Fig. Simulation scale and external condition.

Table Conditions of this simulation.

Size	$60\xi_0 \times 23\xi_0 \times 23\xi_0$
GL parameter	$\kappa = \lambda/\xi = 3$
Boundary condition	vacuum
Temperature	$0.5T_c$
Applied magnetic field, B	$0.20B_{c20}$
Applied current, I	$0.0025\text{-}0.015J_{d0}\xi_0^2$

- **Cylindrical shape**

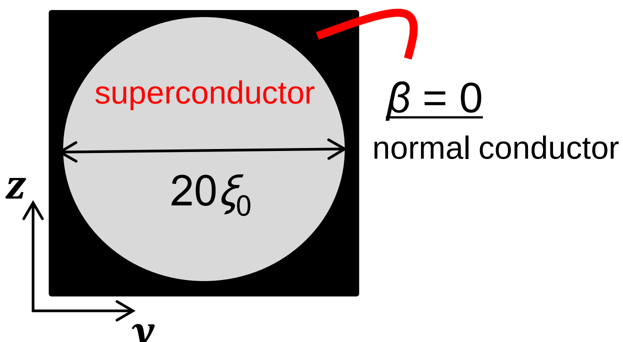

Fig. The model of cylindrical shape.

< View of result >

Removing the cylindrical edge for ease of viewing.

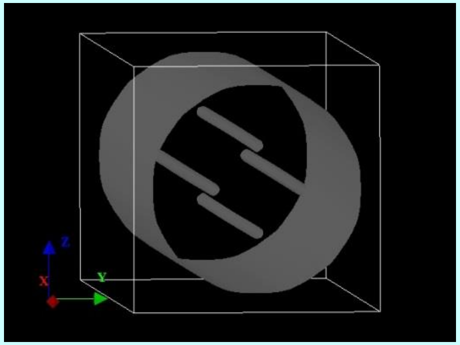

Fig. Simulation result.

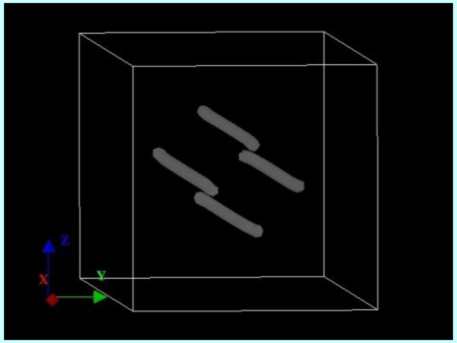

Fig. Simulation result after removing the cylindrical edge.

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Simulation Result (Non-doped)

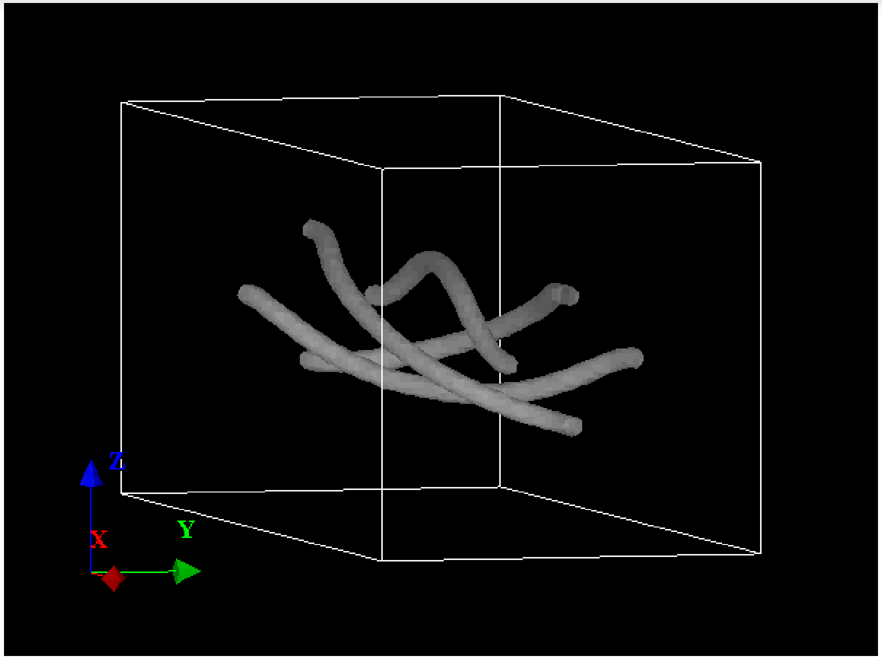

Fig. Flux motion at LMF state. ($I = 0.0075J_{d0}\xi_0^2$)

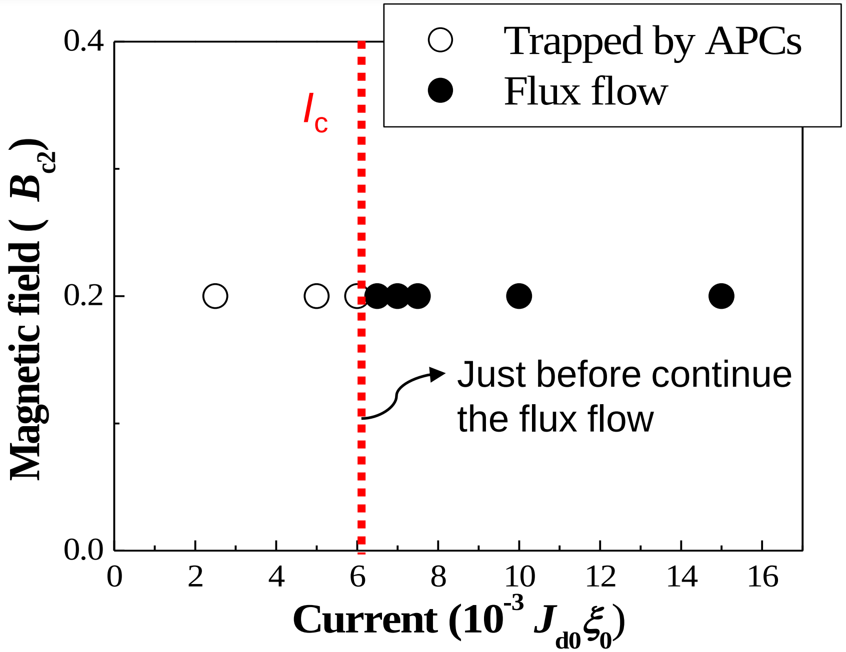

Fig. The relationship with current value and flux flow.

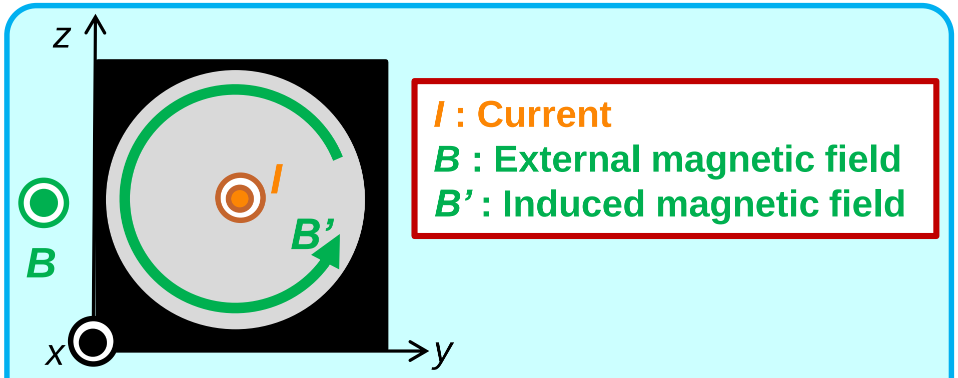

Fig. Induced magnetic field image.

B' is induced by the applied current

The flux lines are leaned for direction of *B*'

Lorentz force works on the flux lines

The flux lines are distorted by spiral shape

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Condition of the Numerical Simulation with APCs

- **APCs Shape & Size & Volume**

① Random nano-particles

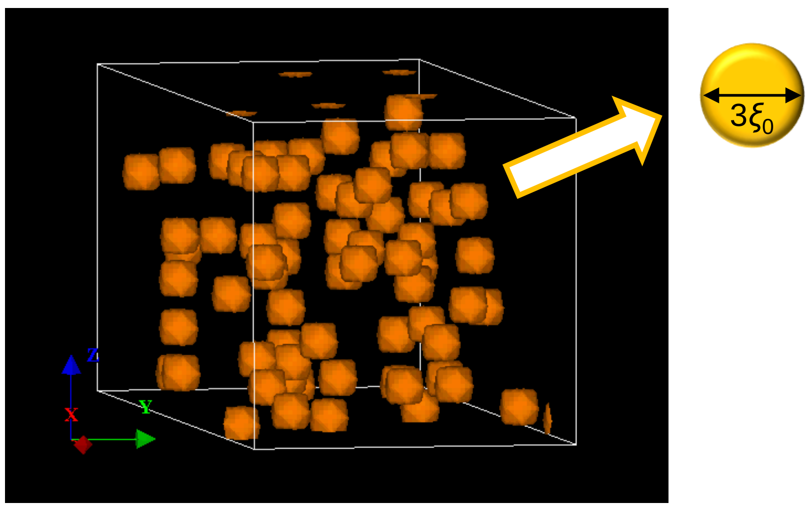


Fig. The snapshot of random nano-particles (3.0 vol.%).

② Multi layers

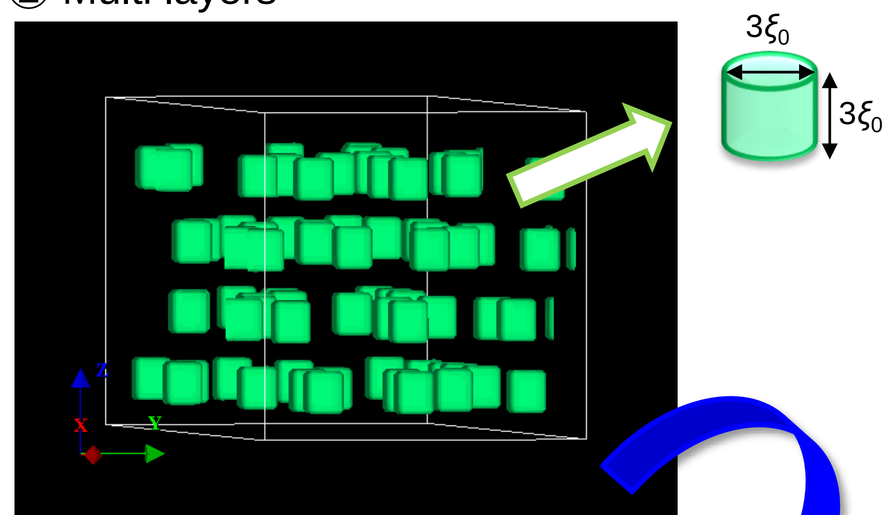


Fig. The snapshot of multi layer (6.1 vol.%).

- **Shape** : ① Random nano-particles
  ② Multi layers
- **Size** : ① The diameter is $3\xi_0$
  ② The diameter & the height are $3\xi_0$
- **Volume** : ① 3.0, 6.0, 9.0 vol.%
  ② 6.1, 8.9, 11.9 vol.%

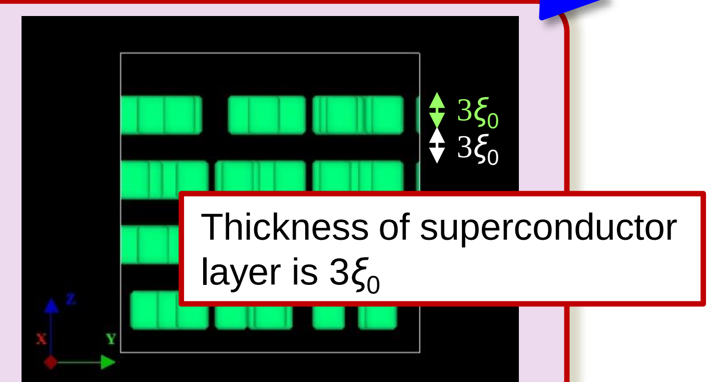
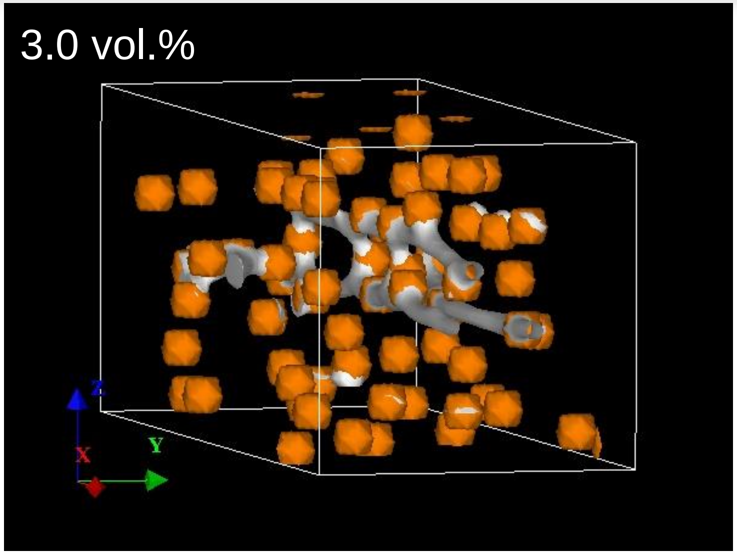


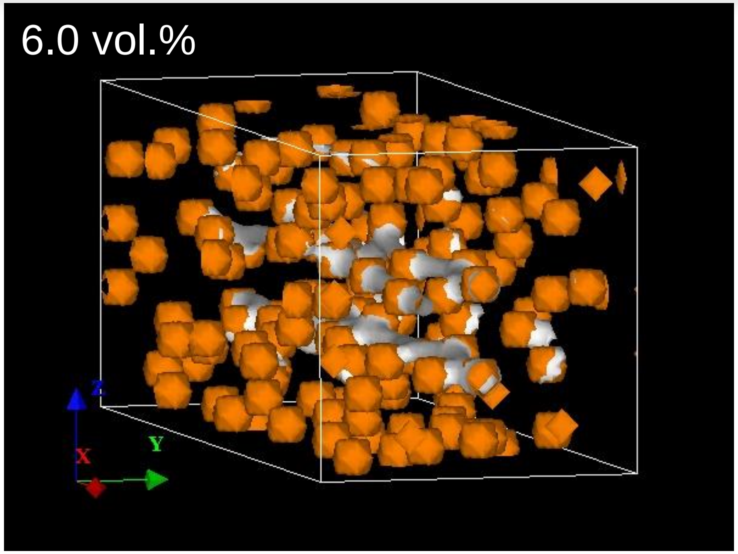
Fig. The snapshot of multi layer.

Simulation Results (Random nano-particles)

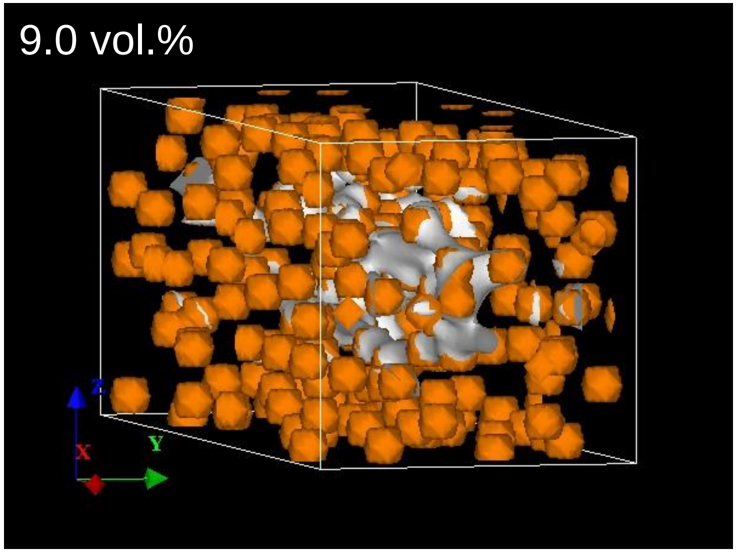
(a)



(b)



(c)

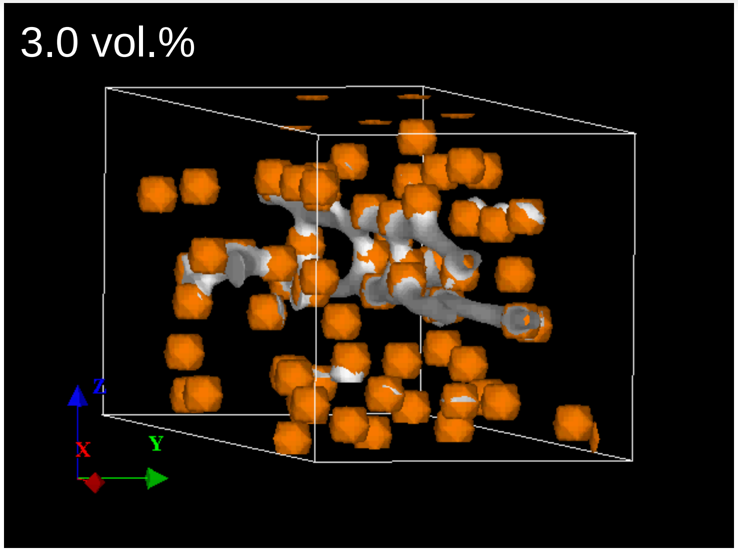


- Removing the APCs for ease of viewing in 6.0 and 9.0 vol.%

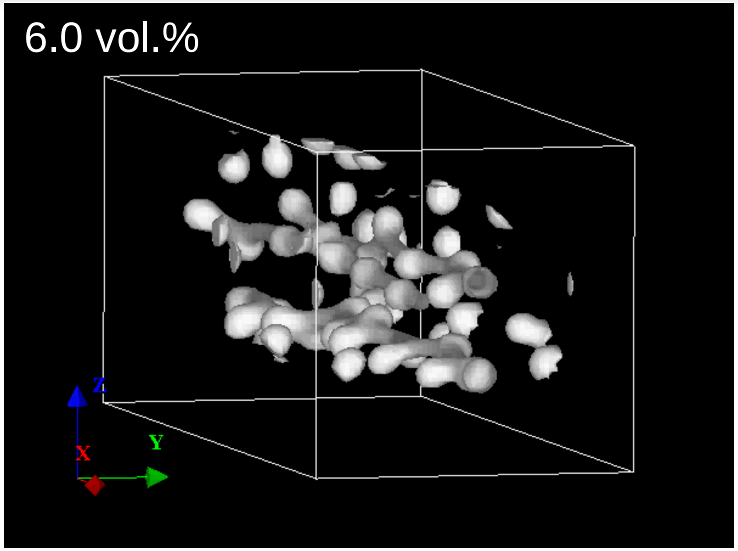
Fig. Snapshot of the flux lines in superconductors with random nano-particles. (a)3.0 vo.l% (b) 6.0 vol.% (c) 9.0 vol.%

Simulation Results (Random nano-particles)

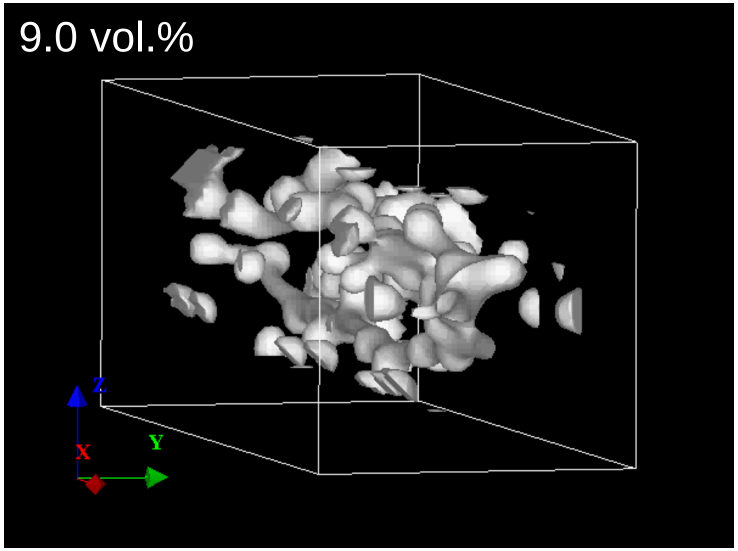
(a)



(b)



(c)



- The flux lines are trapped by APCs
- In 9.0 vol.%, the flux lines keep on moving through the dense APCs

Fig. Flux motion at LMF state in random nano-particles doped superconductor. ($I = 0.0075J_{d0}\xi_0^2$) (a)3.0 vol.% (b) 6.0 vol.% (c) 9.0 vol.%

Discussion (Random nano-particles)

◆ I_c and APC volume

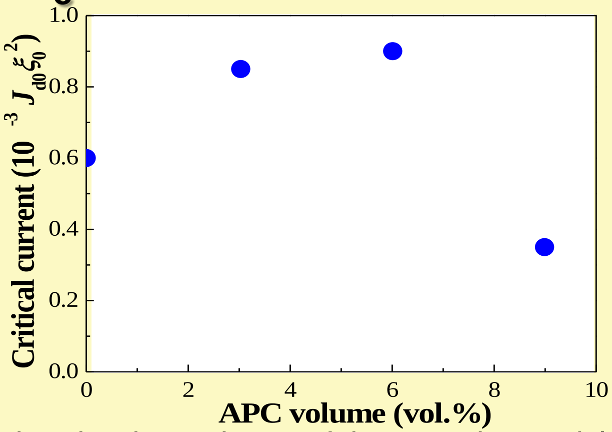


Fig. The dependence of the I_c on the particle volume.

- ➢ The I_c ($0.009J_0\xi_0^2$) increase from the pure system ($0.006J_{d0}\xi_0^2$)
- ➢ The I_c decrease at 9.0 vol.%

◆ I_c and mean distance between APCs (d)

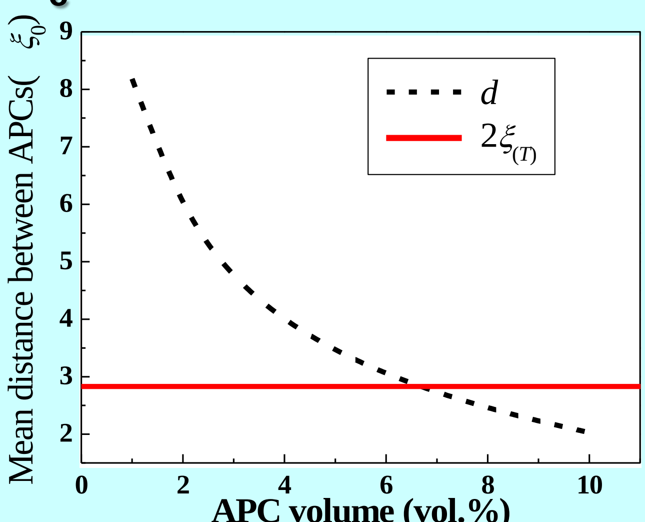


Fig. The relationship between d and $2\xi(T)$.

✓ The I_c decrease when $d < 2\xi(T)$ (9.0 vol.%)
⇒ Flux channeling become easy

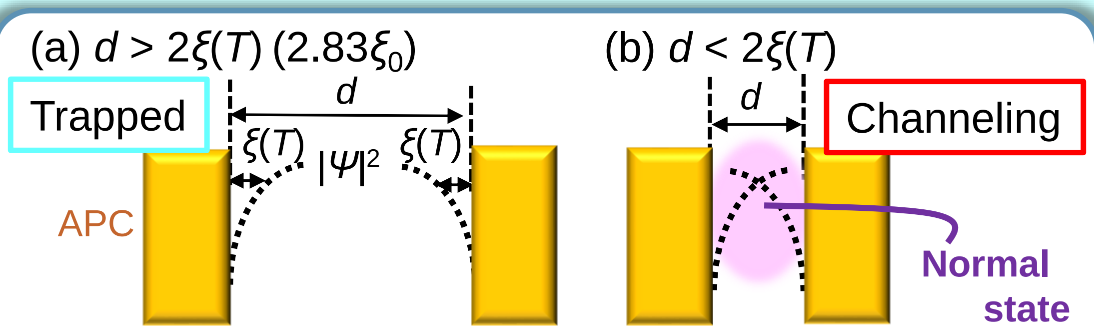


Fig. Image of the decaying cooper pair density in APCs.

The cooper pair density $|\Psi|^2$ decay into APCs with $\xi(T)$

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Simulation Results (Multi Layers)

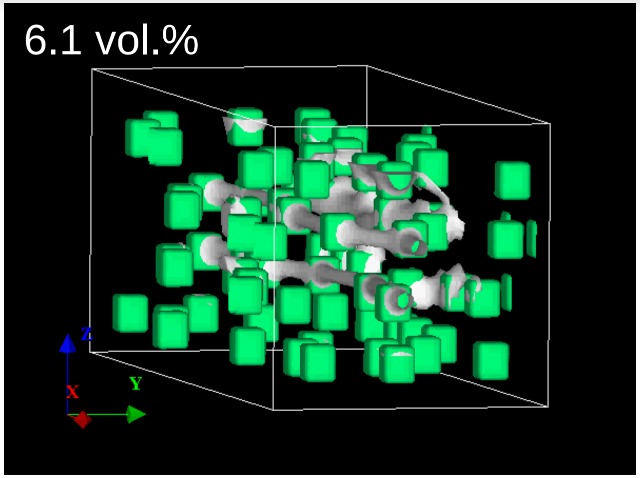

Fig. Flux motion in multi layers (6.1 vol.%) superconductor.
($I = 0.006 J_{d0} \xi_0^2$)

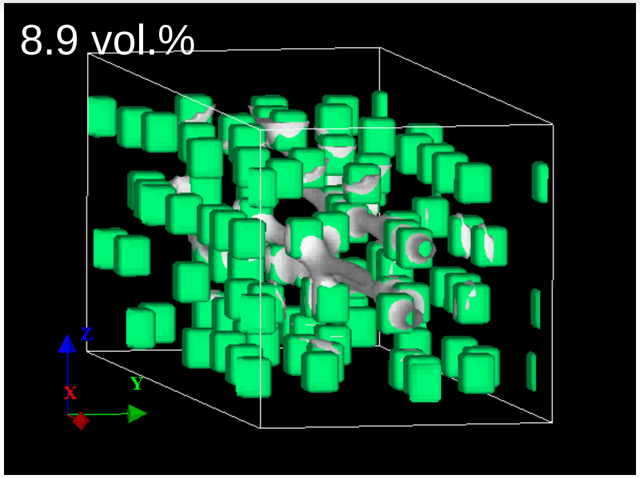

Fig. Flux motion in multi layers (8.9 vol.%) superconductor.
($I = 0.006 J_{d0} \xi_0^2$)

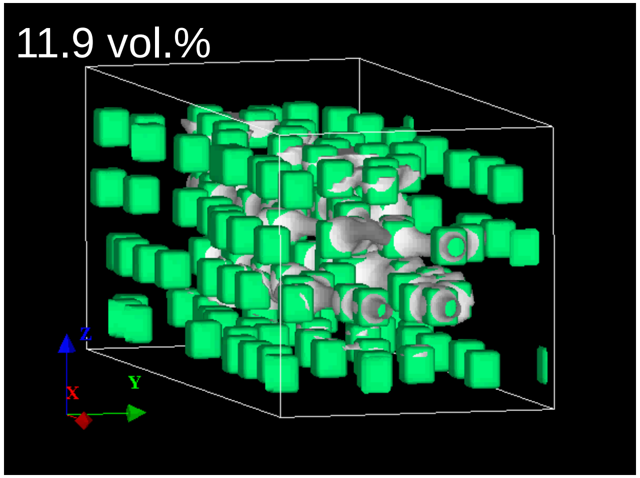

Fig. Flux motion in multi layers (11.9 vol.%) superconductor.
($I = 0.006 J_{d0} \xi_0^2$)

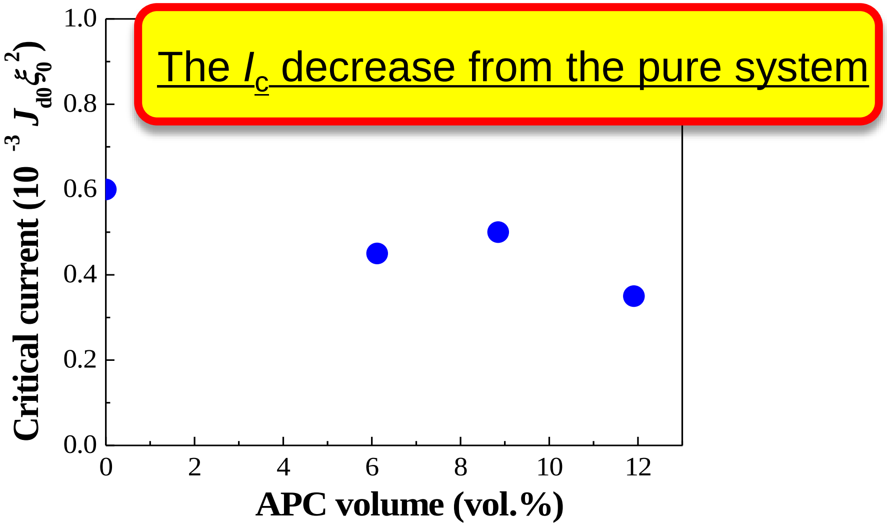

Fig. The dependence of the I_c on the particle volume.

Discussion (Multi Layers)

◆ I_c and mean distance between APCs ($d_{x\text{-}y}$, d_z)

◆ Definition of $d_{x\text{-}y}$

Mean distance between APCs in *x-y* plane

◆ Definition of d_z

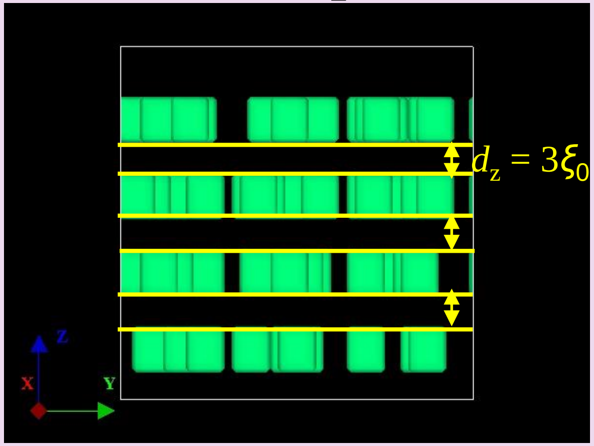

Fig. The snapshot of multi layers.

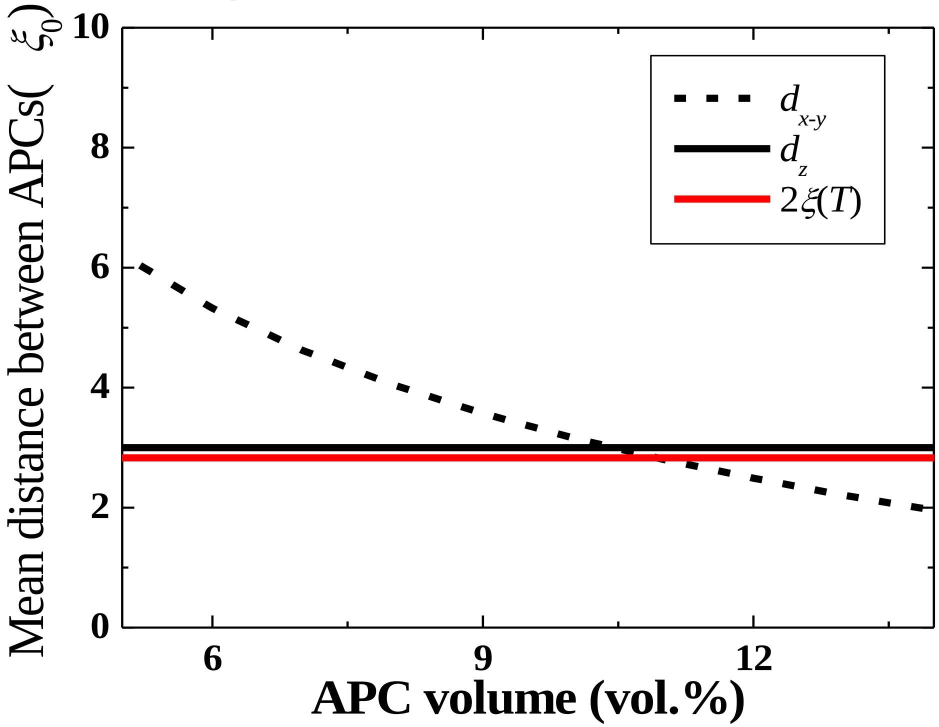

Fig. The relationship between distance between APCs ($d_{x\text{-}y}$, d_z) and $2\xi(T)$.

✓ The d_z is almost $2\xi(T)$

⇒ Flux channeling become easy in *z* plane in our simulation.

✓ The $d_{x\text{-}y}$ is shorter than $2\xi(T)$ at about 12.0 vol.%.

⇒ Flux channeling become easy toward the all direction at about 12.0 vol.%.

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Summary

In this study, we visualized flux motion and calculated I_c at LMF state in superconductors by using TDGL equations. Moreover, we simulated flux motion in APCs-doped superconductors as well, and compared I_c with pure system. Consequently, we obtained following findings.

- In LMF state, the flux lines are distorted in a spiral shape by a current-induced magnetic field.
- In the case of introducing random nano-particles as APCs, the I_c increased from the pure system.
- In the case of introducing multi layers as APCs, the I_c decreased from the pure system, because of short inter-layer distance of APC doped layers.
- Each APC distance is important parameter to consider the optimal APC volume or shape, it need at least over $2\xi(T)$ in our simulation.