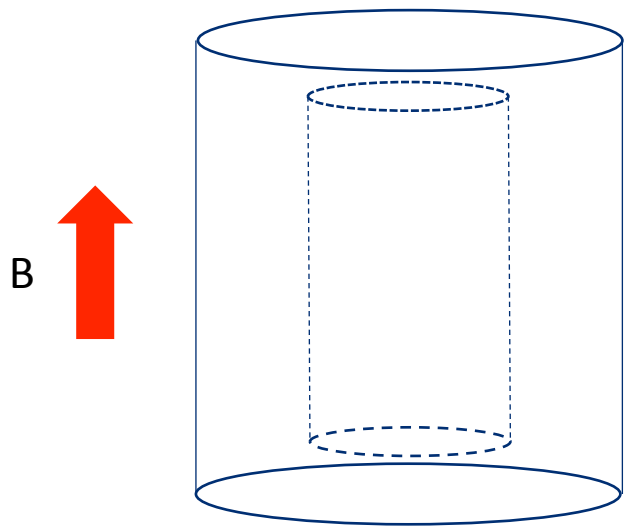
Vortex motion in hollow superconducting tube

Won-Jun Jang

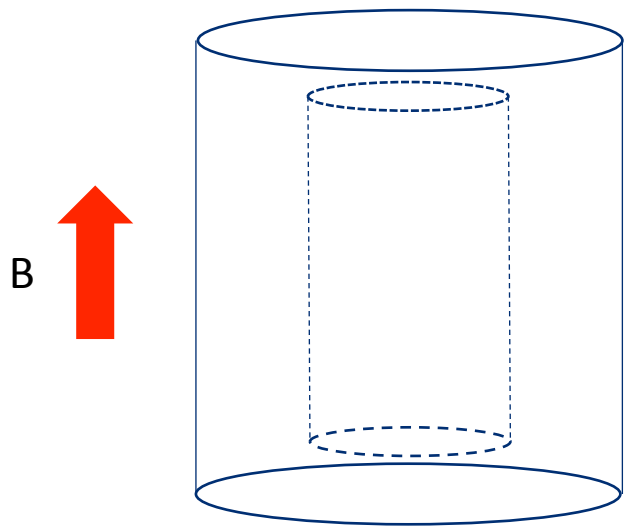
CAPP, IBS

High Q - Superconducting cavity under high magnetic field



- Type 2 superconductor with high upper critical field and high critical temperature.
- Type 2 superconductor with S-wave superconducting gap symmetry.
- Superconducting material with low RF surface resistivity in Vortex state.

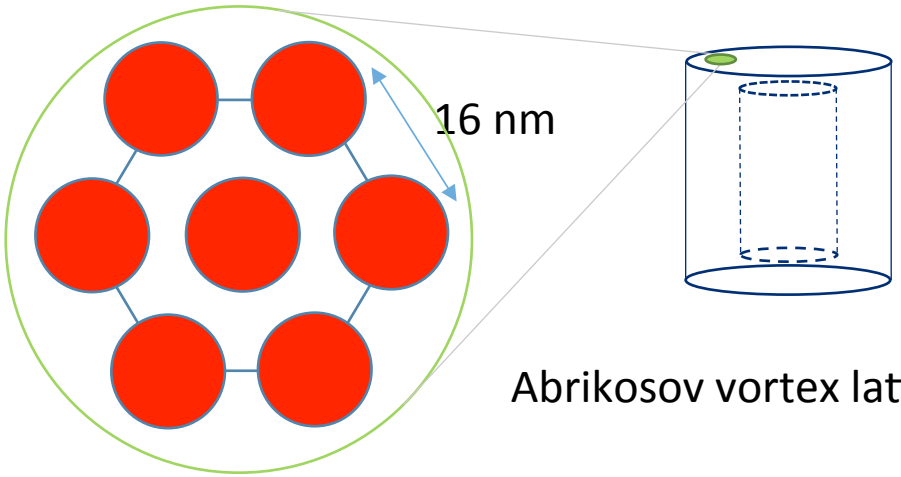
Selection of Vortex structure



- Source of vortex motion
  - Meissner current near surface.
  - Spatial distribution of votices.
  - Radio frequency electromagnetic field.

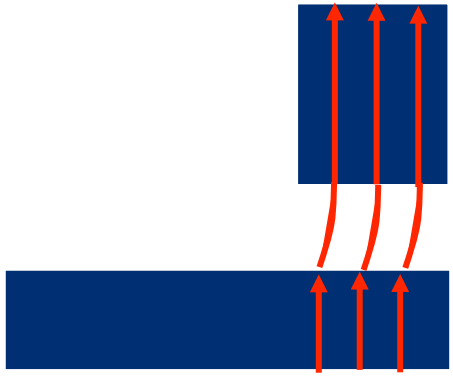
Limitation of Vortex pinning

- Narrow distance between vortices at high magnetic field.



Abrikosov vortex lattice at 8 T.

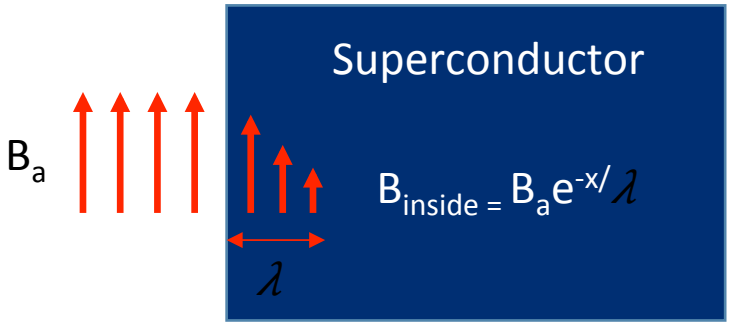
- Vortex mismatching between end caps and cavity wall.



$$dB/dx = \mu_0 J_c$$

Type 1 superconductor vs Type 2 superconductor

- Penetration length



$$\lambda = \sqrt{\varepsilon_0 mc^2 / ne^2}$$

,n = superconducting electron density

- Coherent length

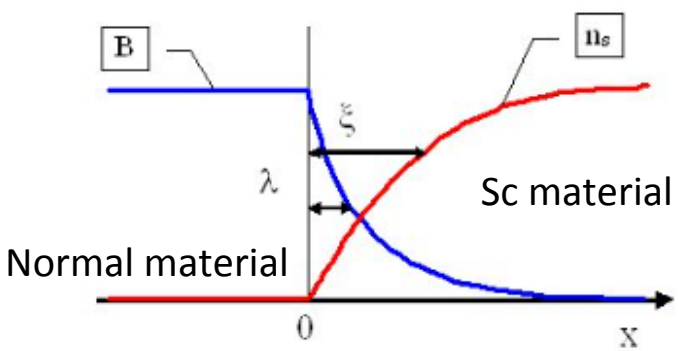
$$\xi_0 = 2\hbar v_F / \pi\Delta$$

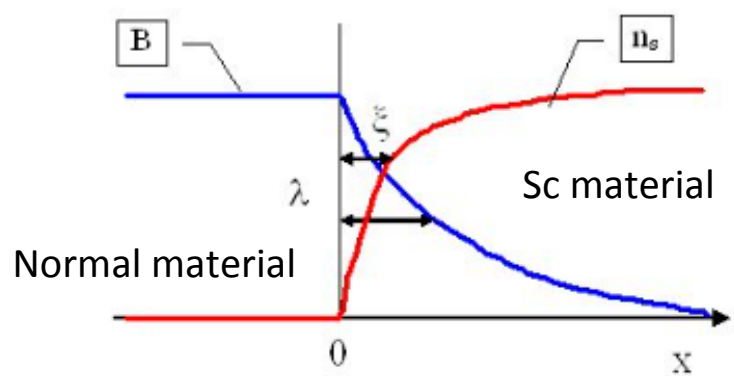
,Δ = Superconducting gap

- Ginzburg-Landau parameter

Type 1 superconductor ($\lambda/\xi_0 < 1/\sqrt{2}$)

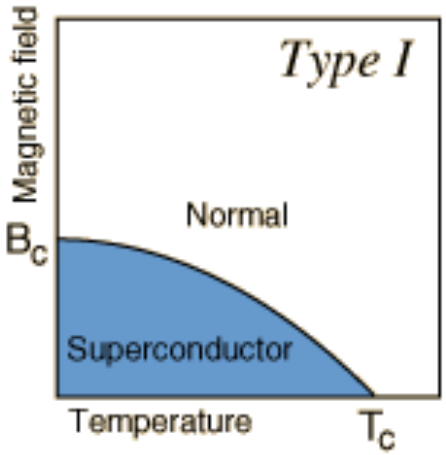
Type 2 superconductor ($\lambda/\xi_0 > 1/\sqrt{2}$)

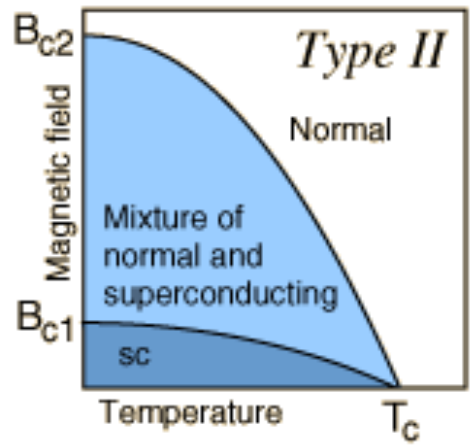




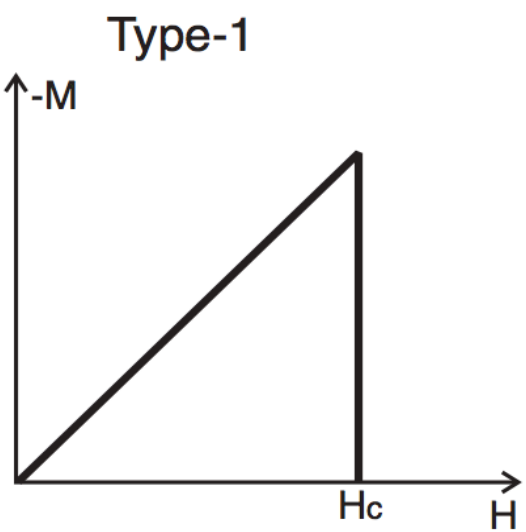
Magnetic behavior of Type 1 superconductor and Type 2 superconductor

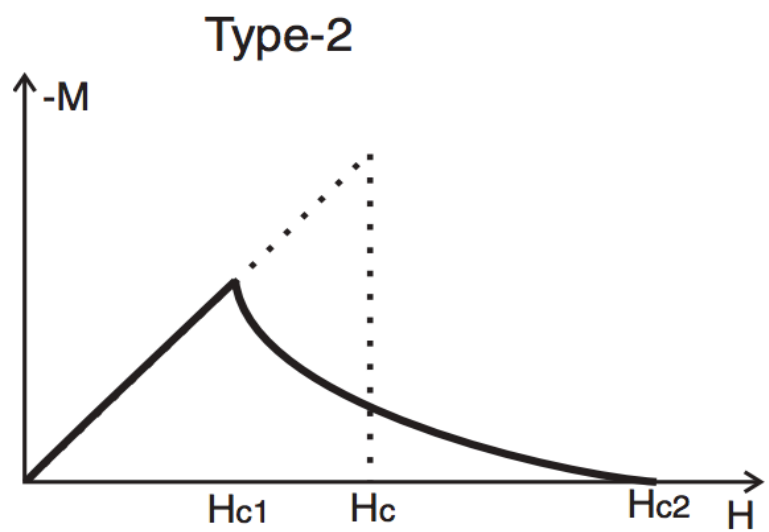
- Critical magnetic field and temperature



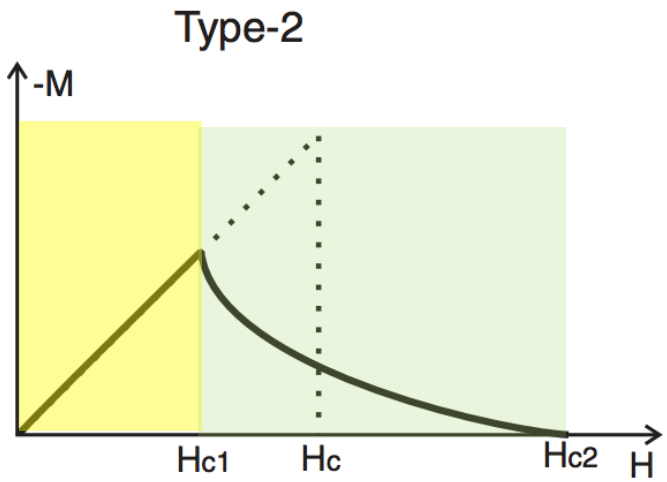


- Diamagnetism



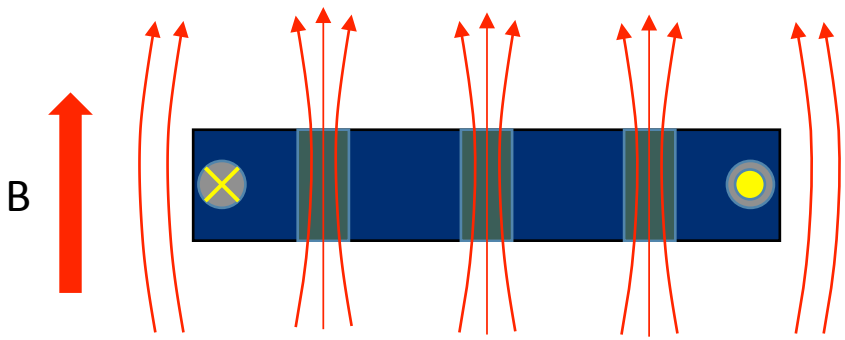


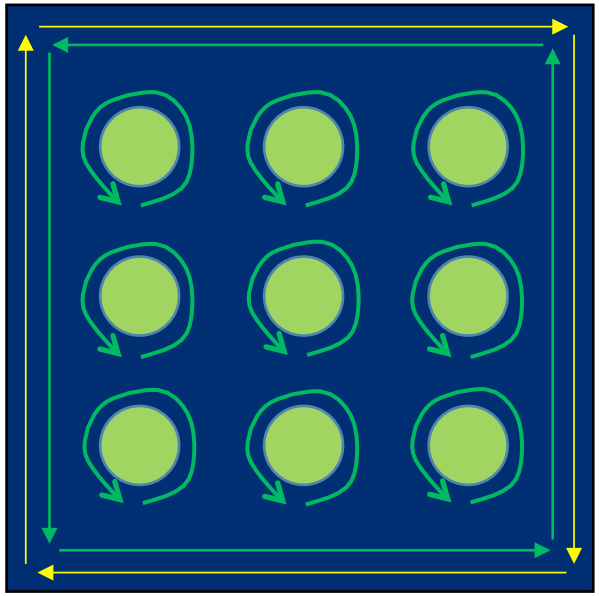
Vortex state: Meissner current, supercurrent



Meissner state

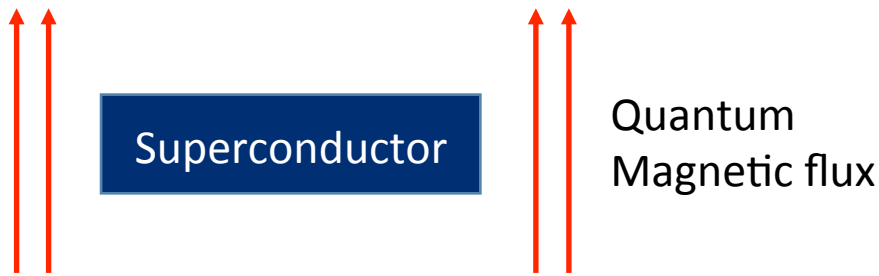
Vortex state



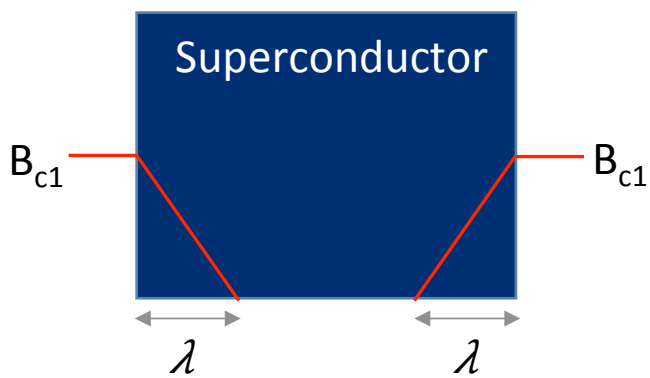


Vortex density inside Type 2 superconductor at $H < H_{c1}$

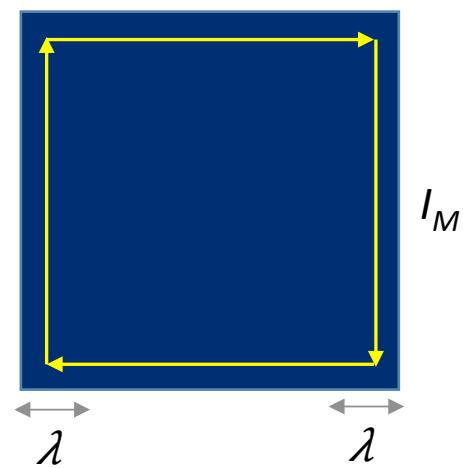
C. P. BEAN, Rev. Mod. Phys. ***36****, 31 (1964).*
Y. B. KIM el al., Rev. Mod. Phys. ***36****, 43 (1964).*
E. Zeldov et al., Phys. Rev. Lett. ***73****, 1428 (1994).*
M. Benkraouda et al., Phys. Rev. B ***53****, 5716 (1996).*
S. Oh et al. ArXiv:1612.04893 (2016).



- Meissner current by Ampere's law, $dB/dx = \pm \mu_0 J_M$



λ: Penetration depth



Vortex density inside Type 2 superconductor at H > H_{c1}

C. P. BEAN, Rev. Mod. Phys. ***36****, 31 (1964).*
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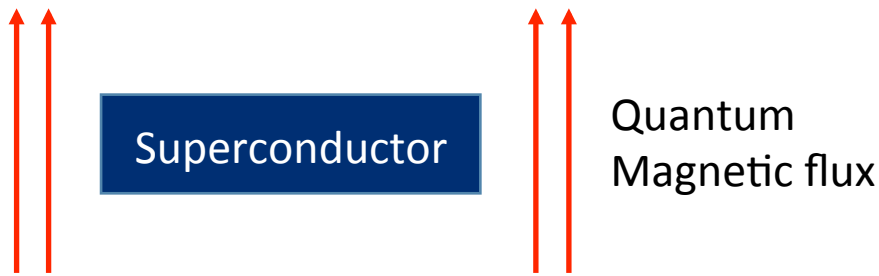
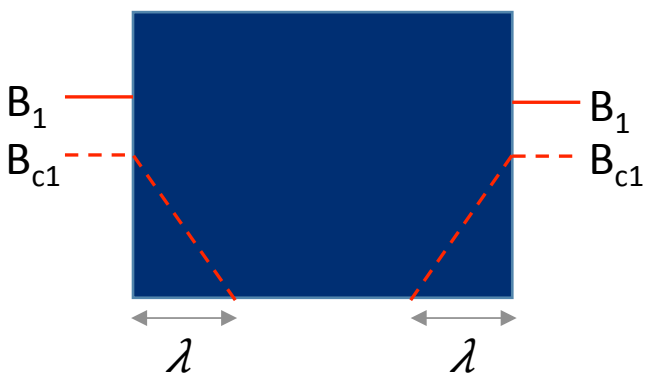
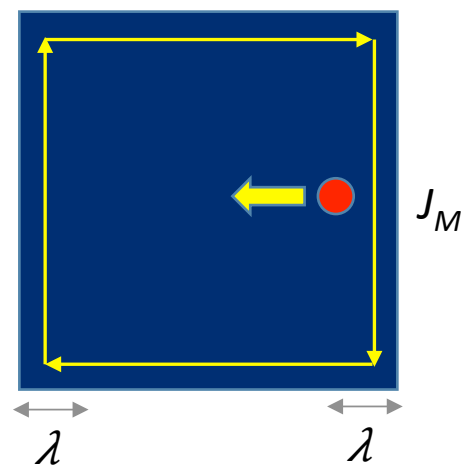


- Lorentz force by Meissner current



λ: Penetration depth



Vortex moves toward the center of superconductor.

Vortex density inside Type 2 superconductor at H > H_{c1}

C. P. BEAN, Rev. Mod. Phys. ***36****, 31 (1964).*
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E. Zeldov et al., Phys. Rev. Lett. ***73****, 1428 (1994).*
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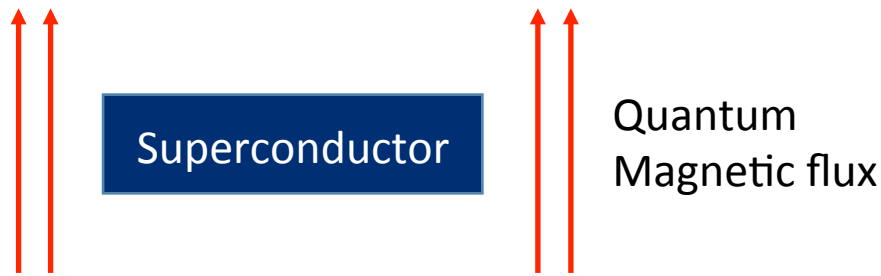
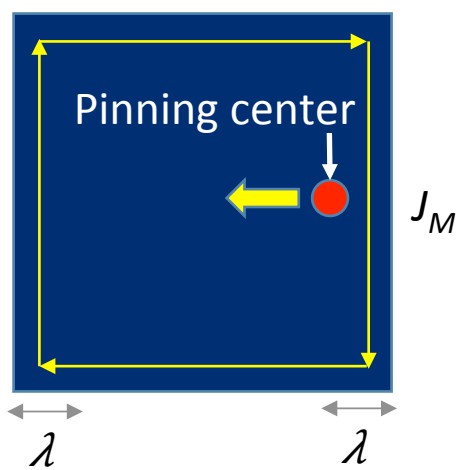
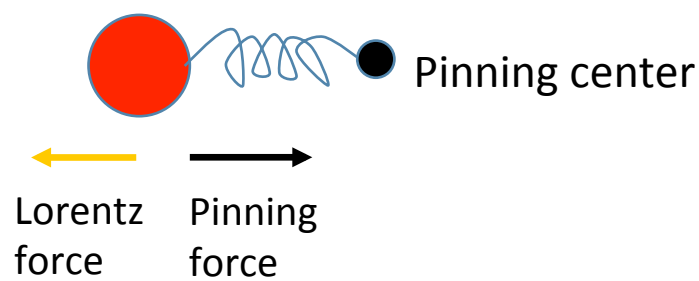


- Lorentz force by Meissner current vs pinning force.





Inhomogenuous spatial distribution of vortices = spatially varying Lorentz force

Vortex density inside Type 2 superconductor at H > H_{c1}: Pinned case

C. P. BEAN, Rev. Mod. Phys. ***36****, 31 (1964).*
Y. B. KIM el al., Rev. Mod. Phys. ***36****, 43 (1964).*
E. Zeldov et al., Phys. Rev. Lett. ***73****, 1428 (1994).*
M. Benkraouda et al., Phys. Rev. B ***53****, 5716 (1996).*
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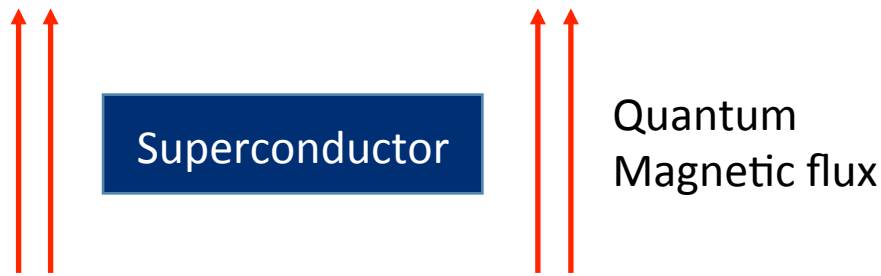
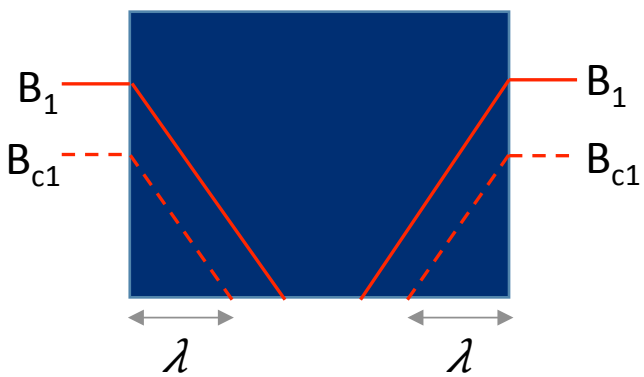
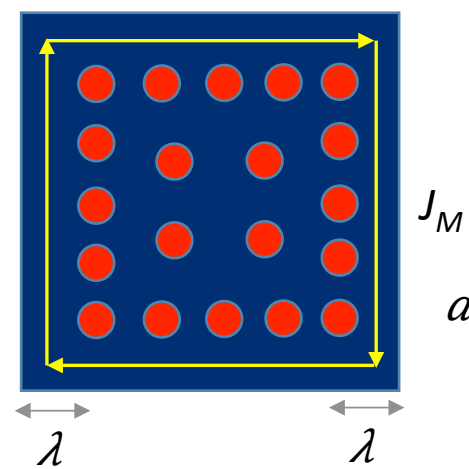


- Nonuniform vortex lattice



λ: Penetration depth

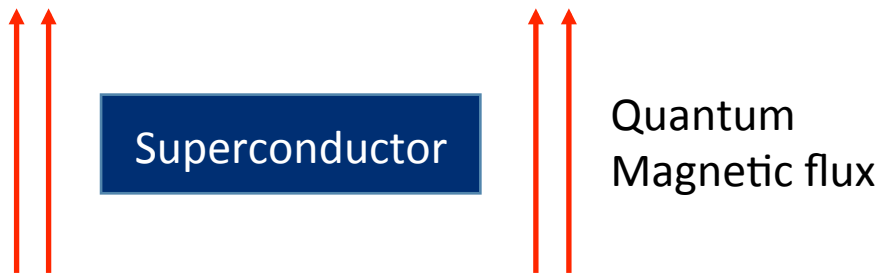


$$dB/dx = \pm \mu_0 J_M$$

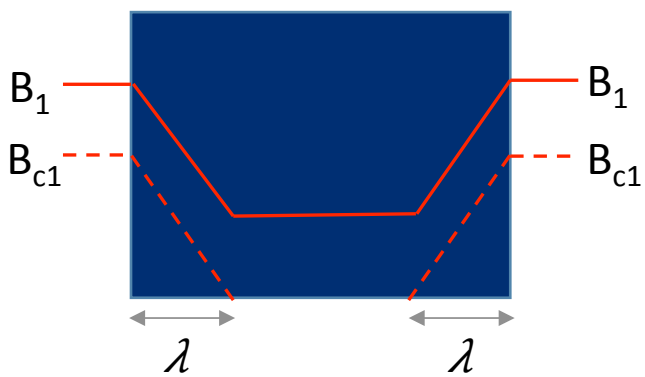
Competition between pinning force and Lorentz force by Meissner current.

Vortex density inside Type 2 superconductor at H > H_{c1}: Unpinned case

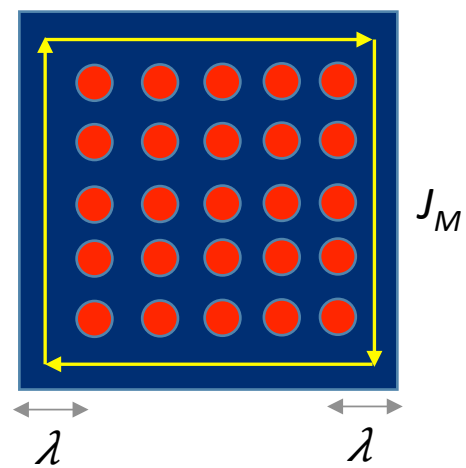
C. P. BEAN, Rev. Mod. Phys. ***36****, 31 (1964).*
Y. B. KIM el al., Rev. Mod. Phys. ***36****, 43 (1964).*
E. Zeldov et al., Phys. Rev. Lett. ***73****, 1428 (1994).*
M. Benkraouda et al., Phys. Rev. B ***53****, 5716 (1996).*
S. Oh et al. ArXiv:1612.04893 (2016).



- Uniform vortex lattice



λ: Penetration depth



The repulsive force between vortices gives rise to the uniform distribution.

Vortex trap and exiting inside Type 2 superconductor

C. P. BEAN, Rev. Mod. Phys. ***36****, 31 (1964).*
Y. B. KIM el al., Rev. Mod. Phys. ***36****, 43 (1964).*
E. Zeldov et al., Phys. Rev. Lett. ***73****, 1428 (1994).*
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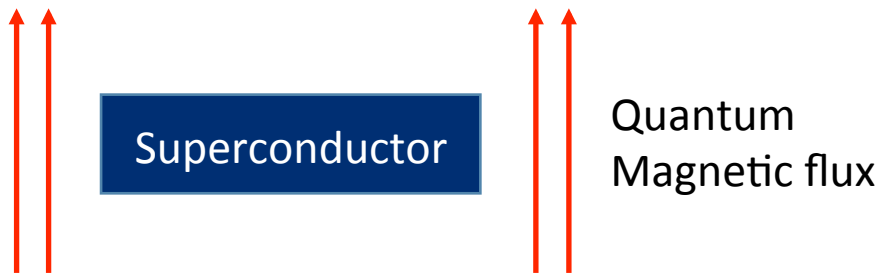
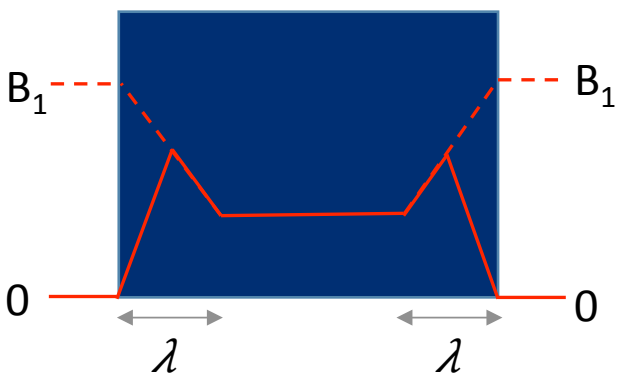
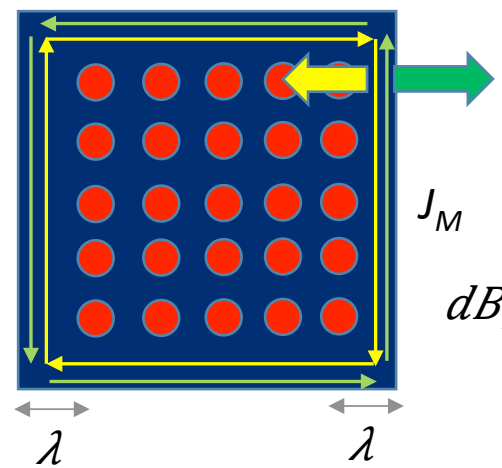


- Two Lorentz forces

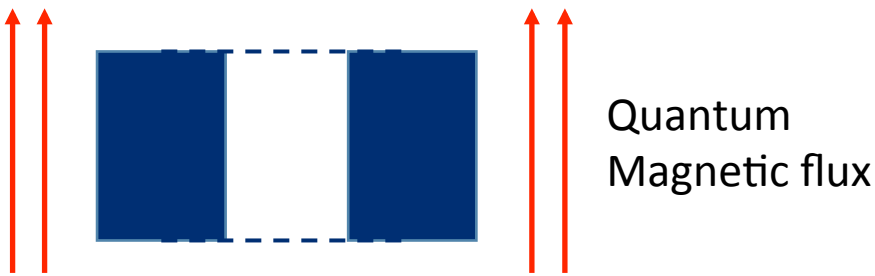


λ: Penetration depth

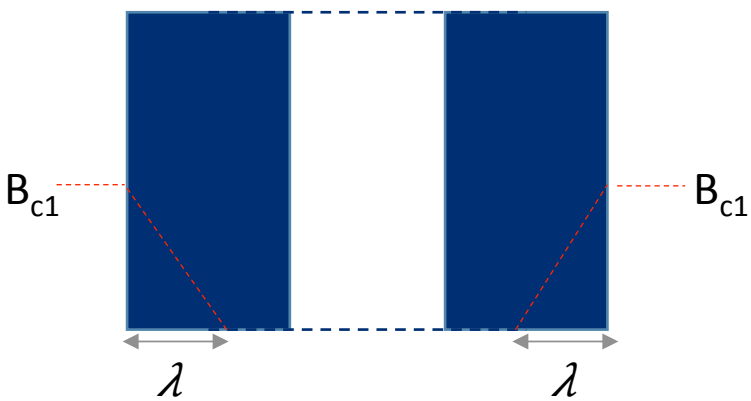


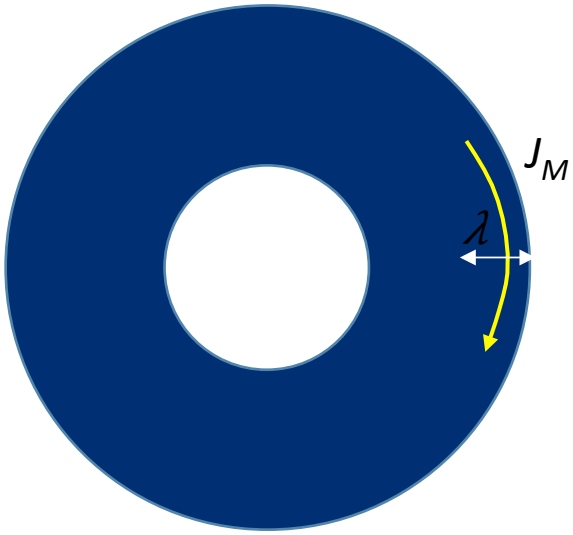
$dB/dx = \pm \mu_0 J_M$

Vortex density inside Type 2 hollow superconducting tube at H < H_{c1}: Unpinned case

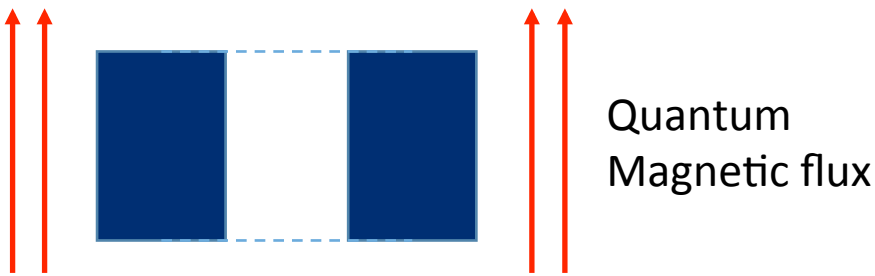


- Meissner current by Ampere's law

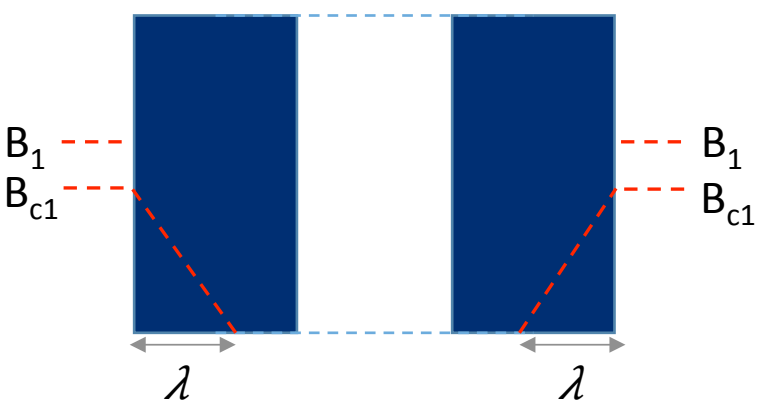


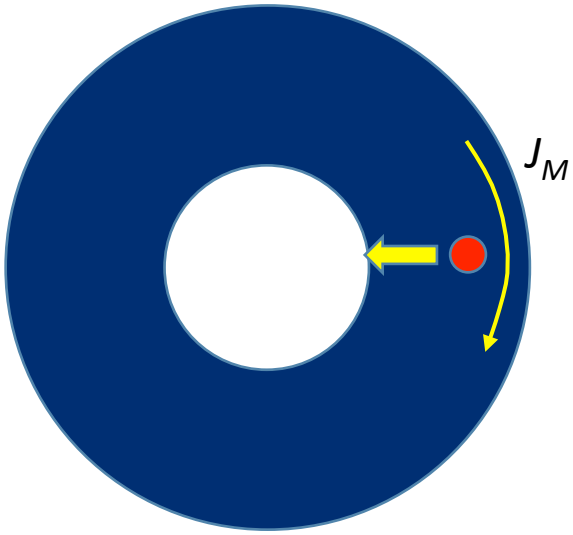


Vortex density inside Type 2 hollow superconducting tube at H > H_{c1} : Unpinned case



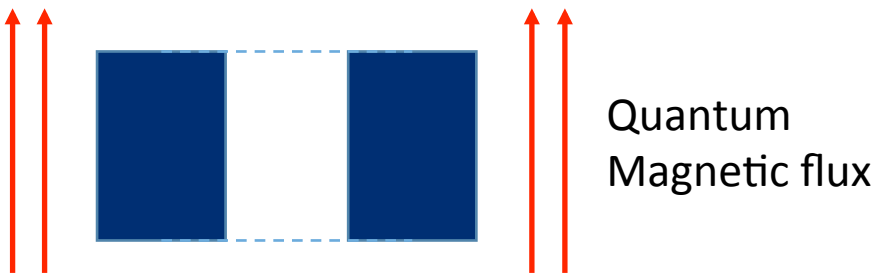
- Lorentz force by Meissner current



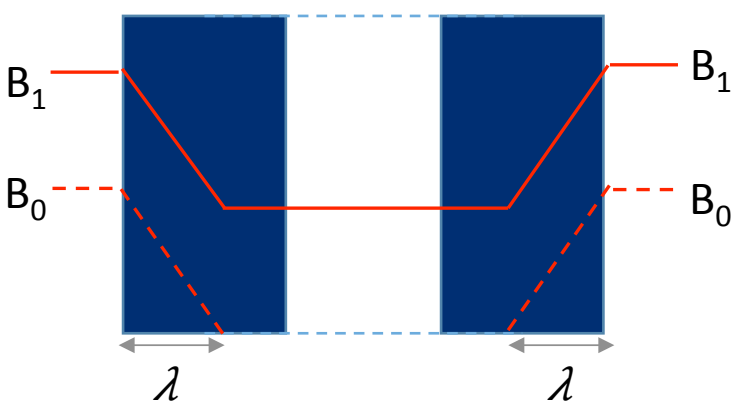


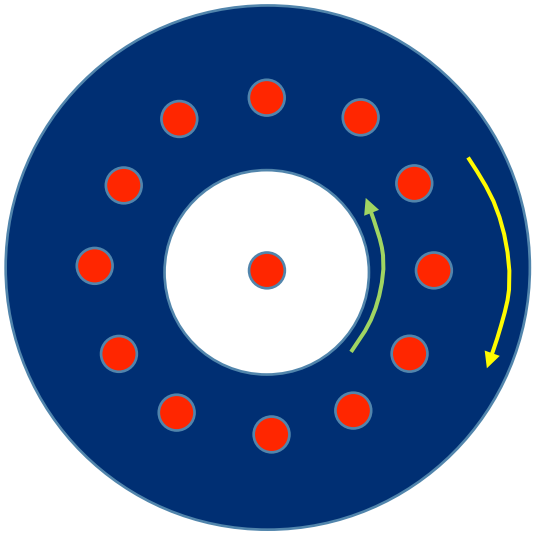
Vortex moves toward hollow region of superconducting tube by Lorentz force.

Vortex entering inside Type 2 hollow superconducting Tube at $H > H_{c1}$



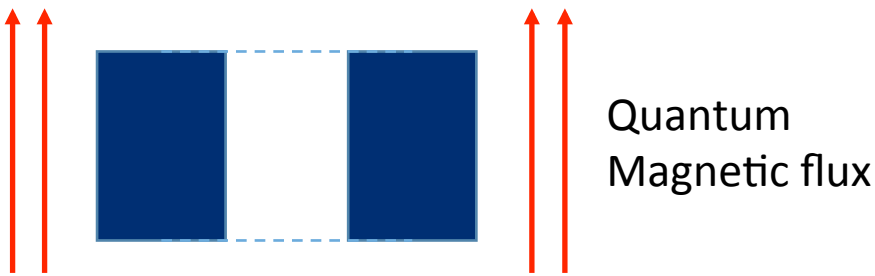
- Lorentz force by Meissner current



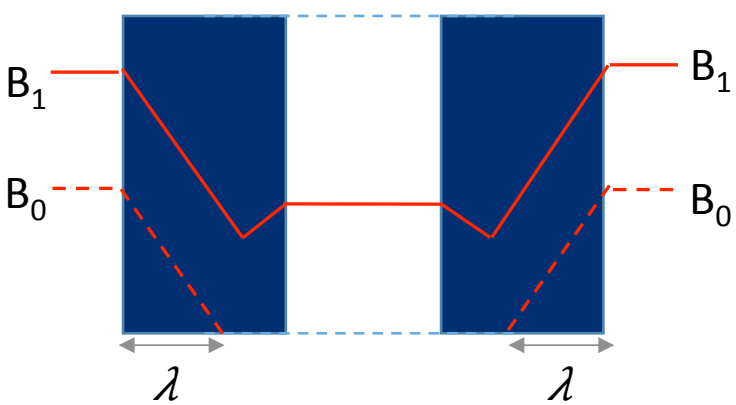


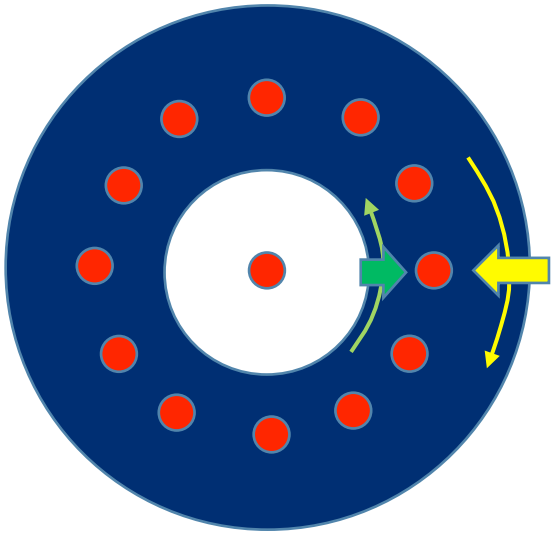
Vortex in the hollow region make the surface current inner surface.

Vortex entering inside Type 2 hollow superconducting Tube at $H > H_{c1}$

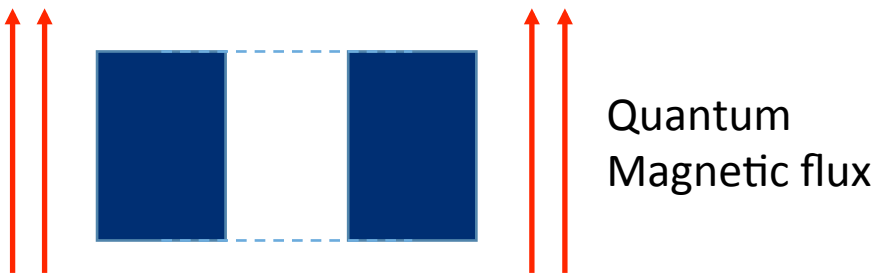


- Two Lorentz forces

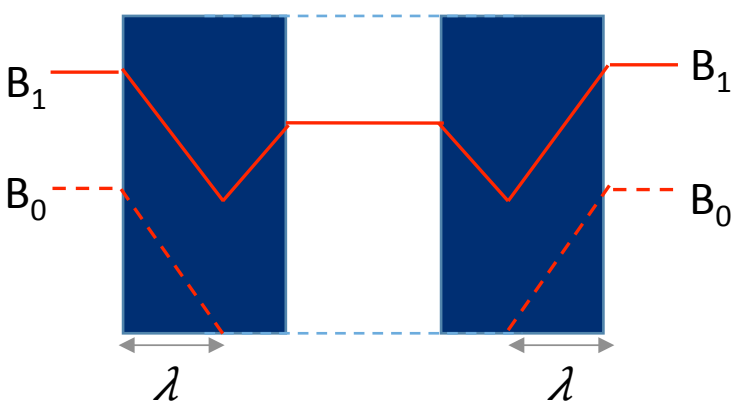


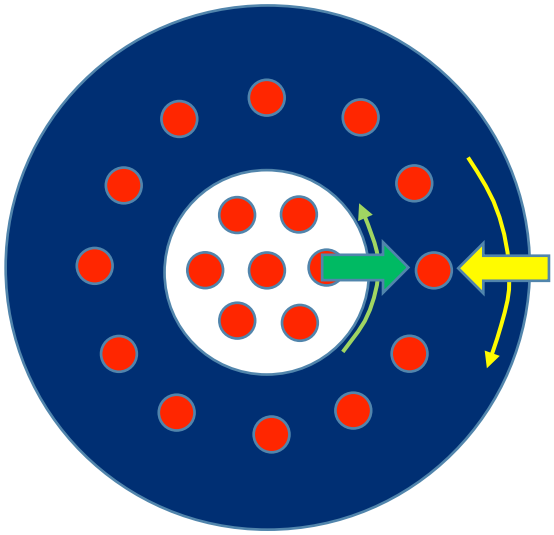


Vortex entering inside Type 2 hollow superconducting Tube at $H > H_{c1}$



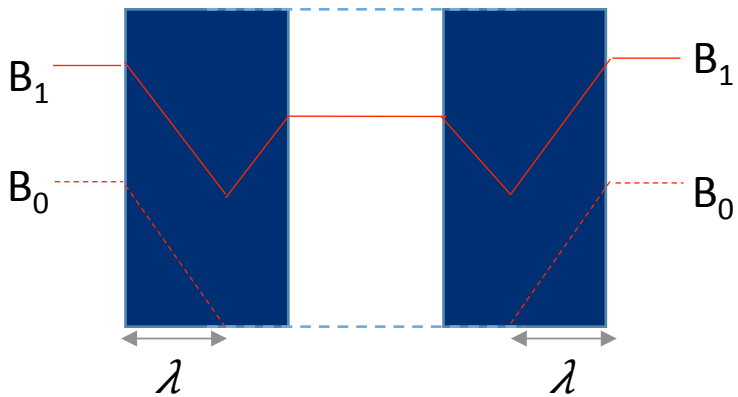
- Equilibrium of two Lorentz force.

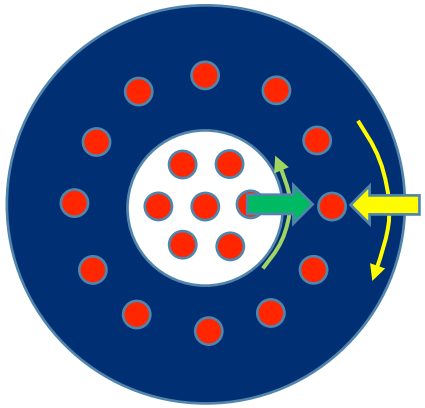




Stable vortex lattice without pinning potentials.

Summary





1. Vortex motion by Meissner current.
2. Equilibrium of vortex motion by two Meissner currents at inner and outer surface.

- Future work
    1. Selection of thickness of SC cavity wall for equilibrium of vortex motion.
    2. Ultra clean SC cavity with uniform thickness.
    3. Study of Magnetic field distribution inside and outside SC cavity.