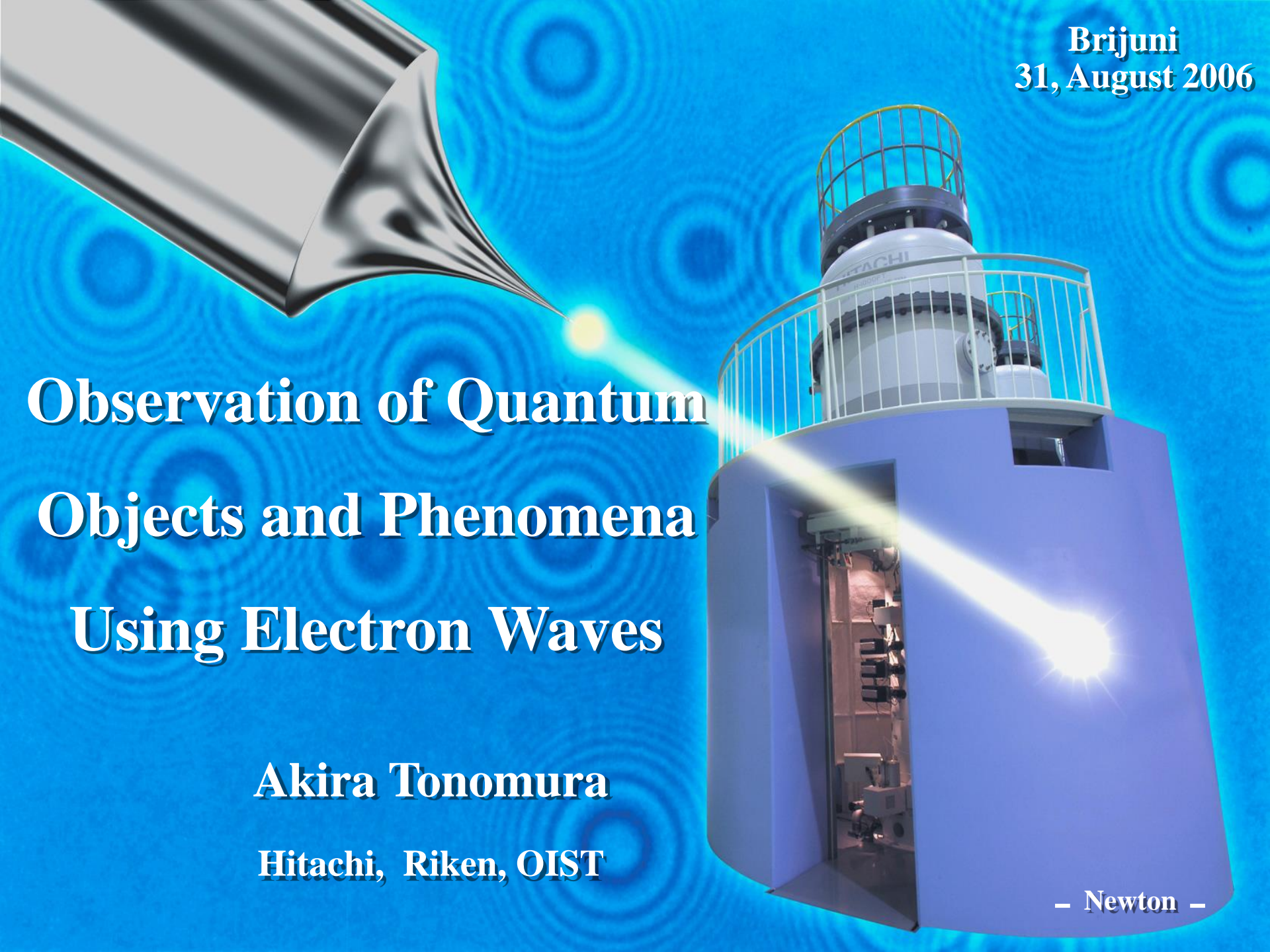


**Brijuni**  
**31, August 2006**



**Observation of Quantum  
Objects and Phenomena  
Using Electron Waves**

**Akira Tonomura**

**Hitachi, Riken, OIST**

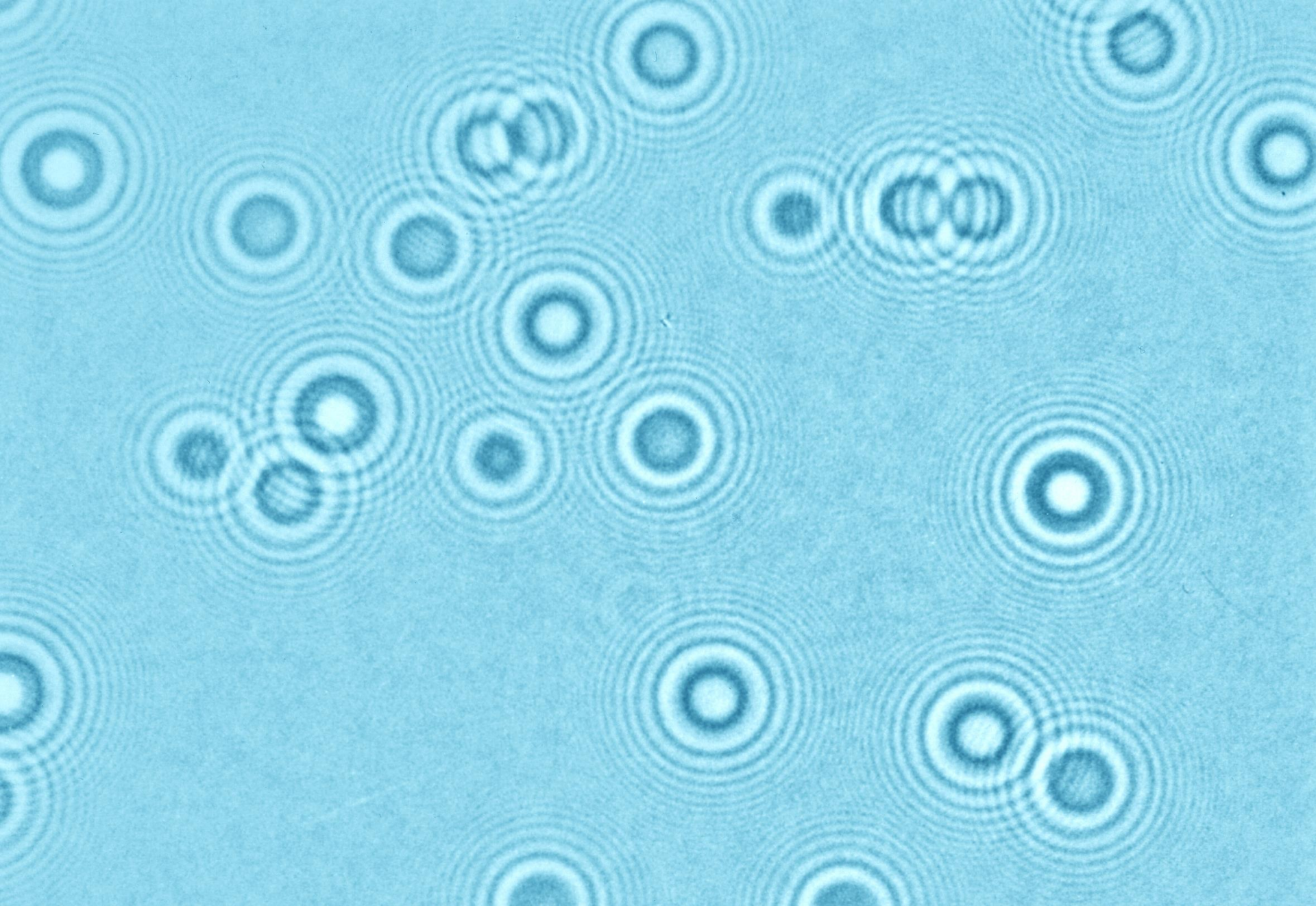
**– Newton –**

# Hitachi Central Research Lab.

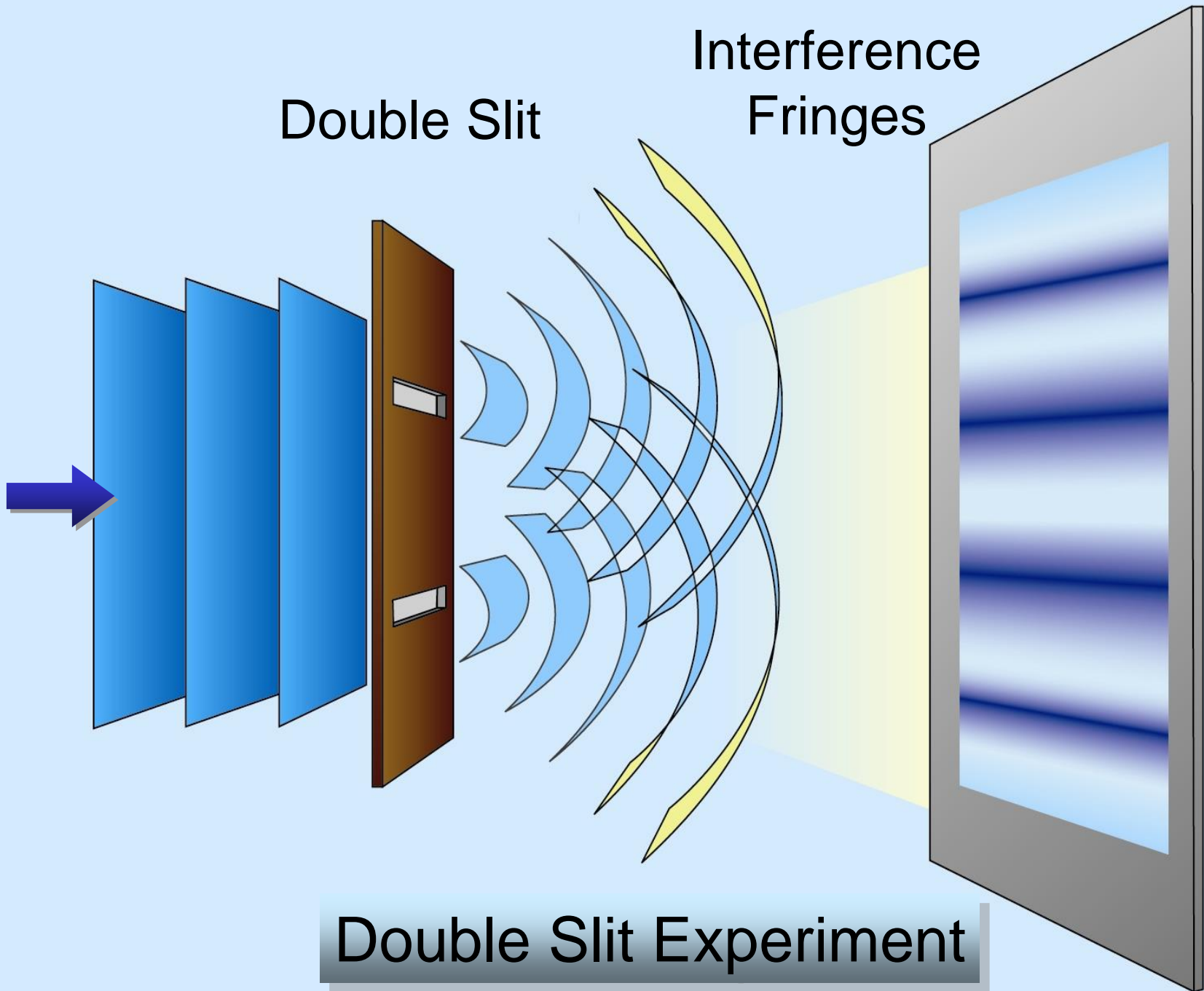
■ Established in April, 1942

■ Principles: Aiming at making researches 10 or 20 years ahead, to support to the present business.





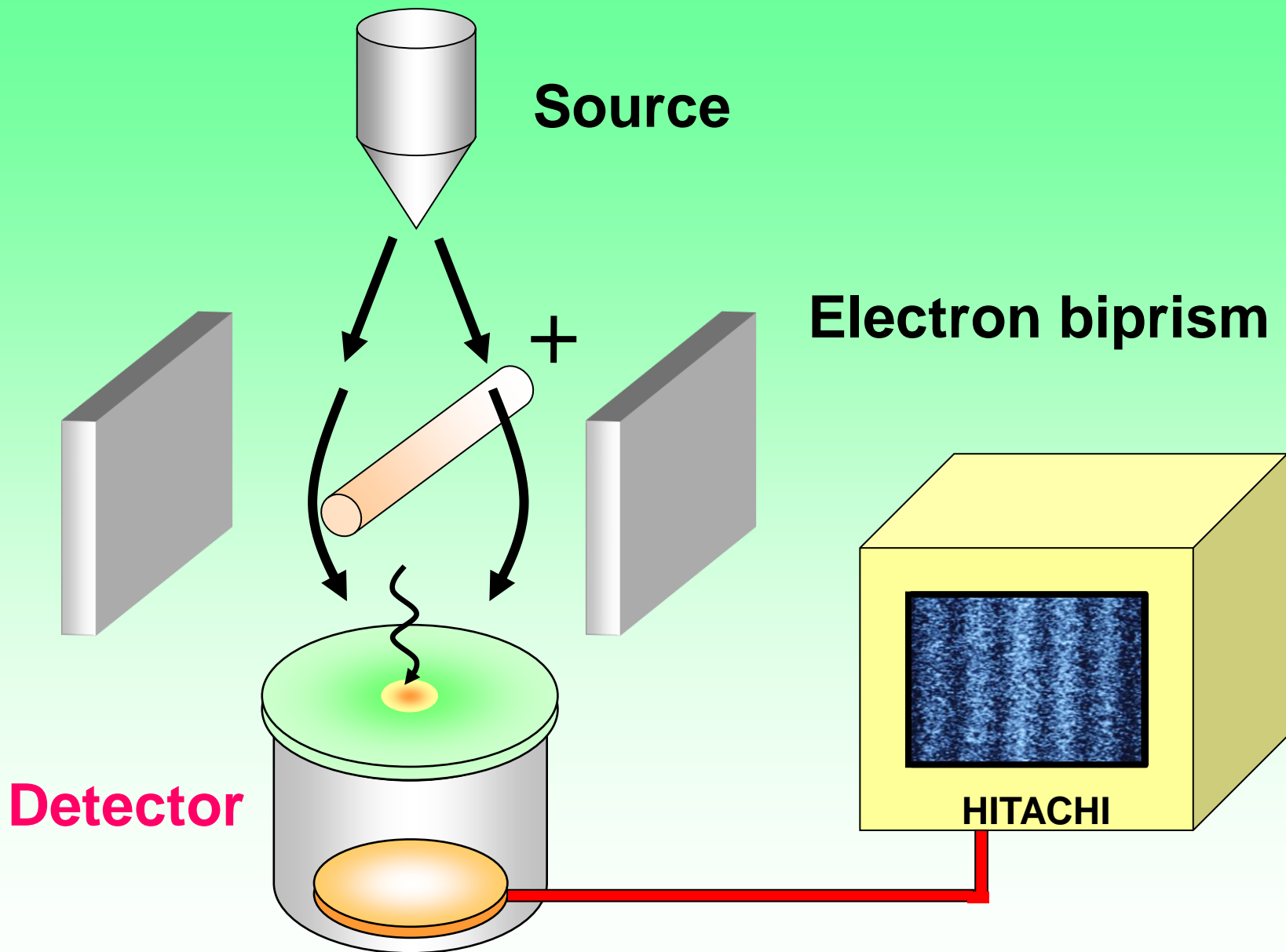
**Electron Ripples Produced at Small Holes in Collodion Film**



Double Slit

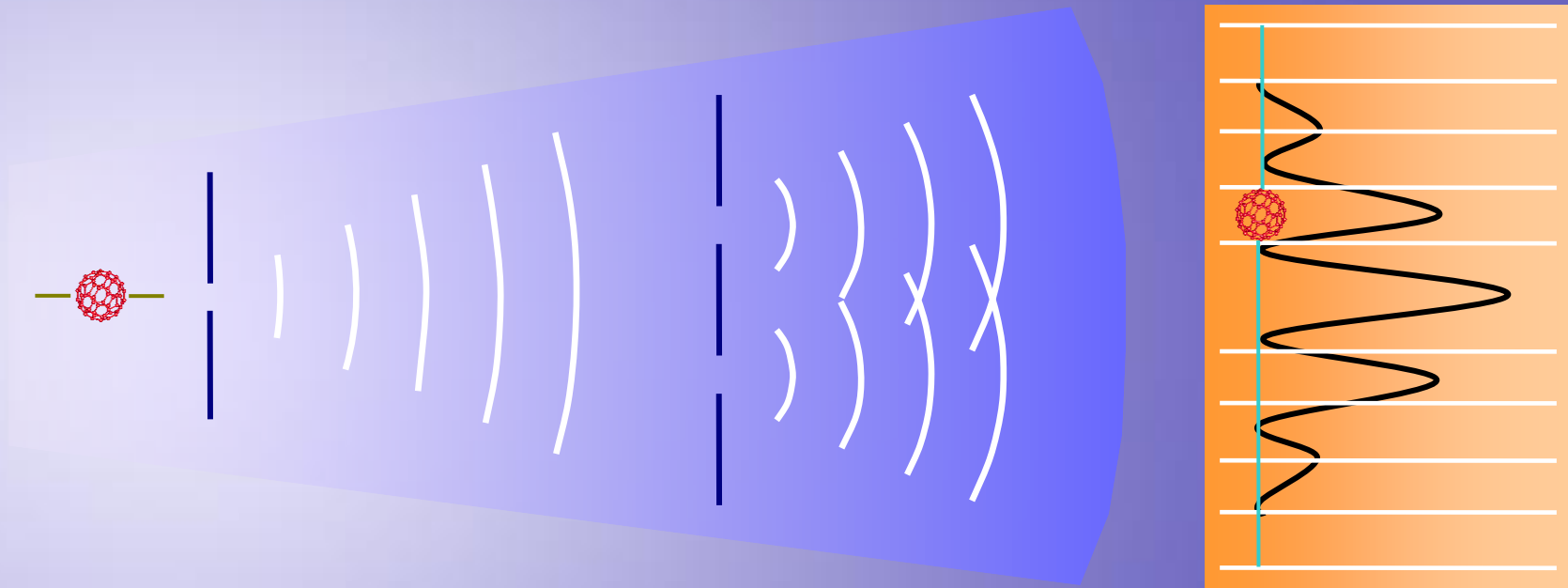
Interference Fringes

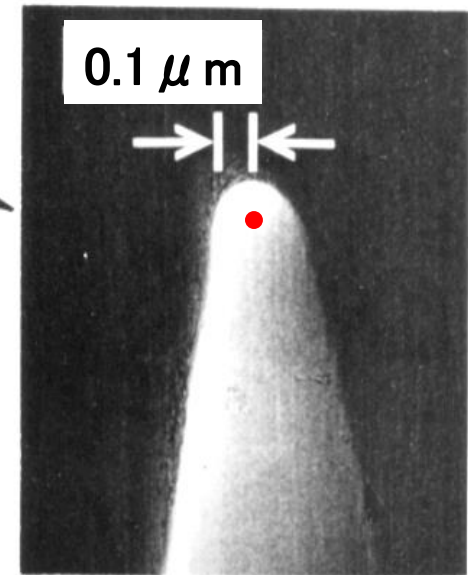
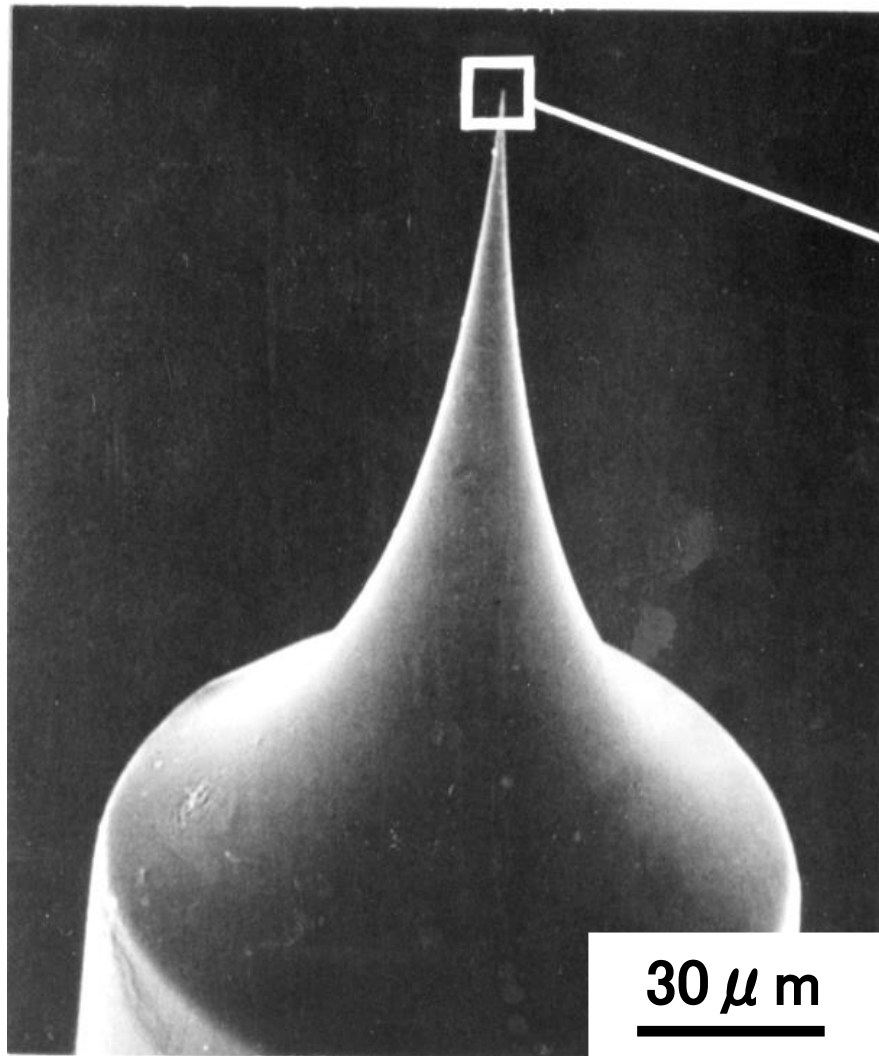
Double Slit Experiment



# Wave-particle Duality of $C_{60}$ Molecules

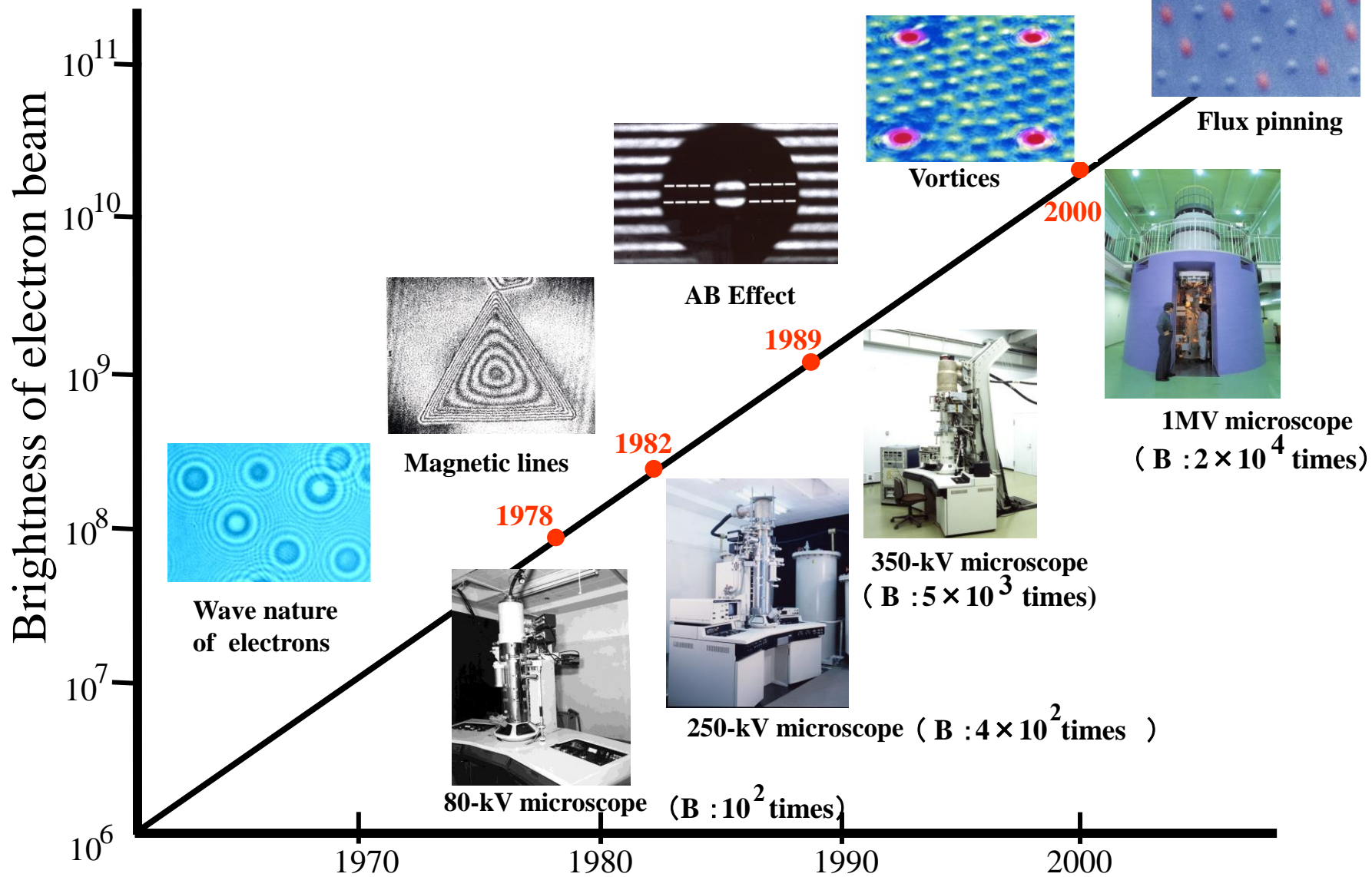
Markus Arndt, Olaf Nairz, Julian Vos-Andreae,  
Claudia Keller, Gerbrand van der Zouw & **Anton Zeilinger**





**Enlarged Image**

**Field-Emission Tip (SEM Image)**



**History of Developments of Field-Emission Electron Microscopes**

# History of Development of Bright Electron Beams

- 1968   ▪ Experiments on Electron Holography

$$B = 10^6 \text{ A / cm}^2 \cdot \text{ster}$$

- 1968   ▪ Development of Coherent FE Electron Beams

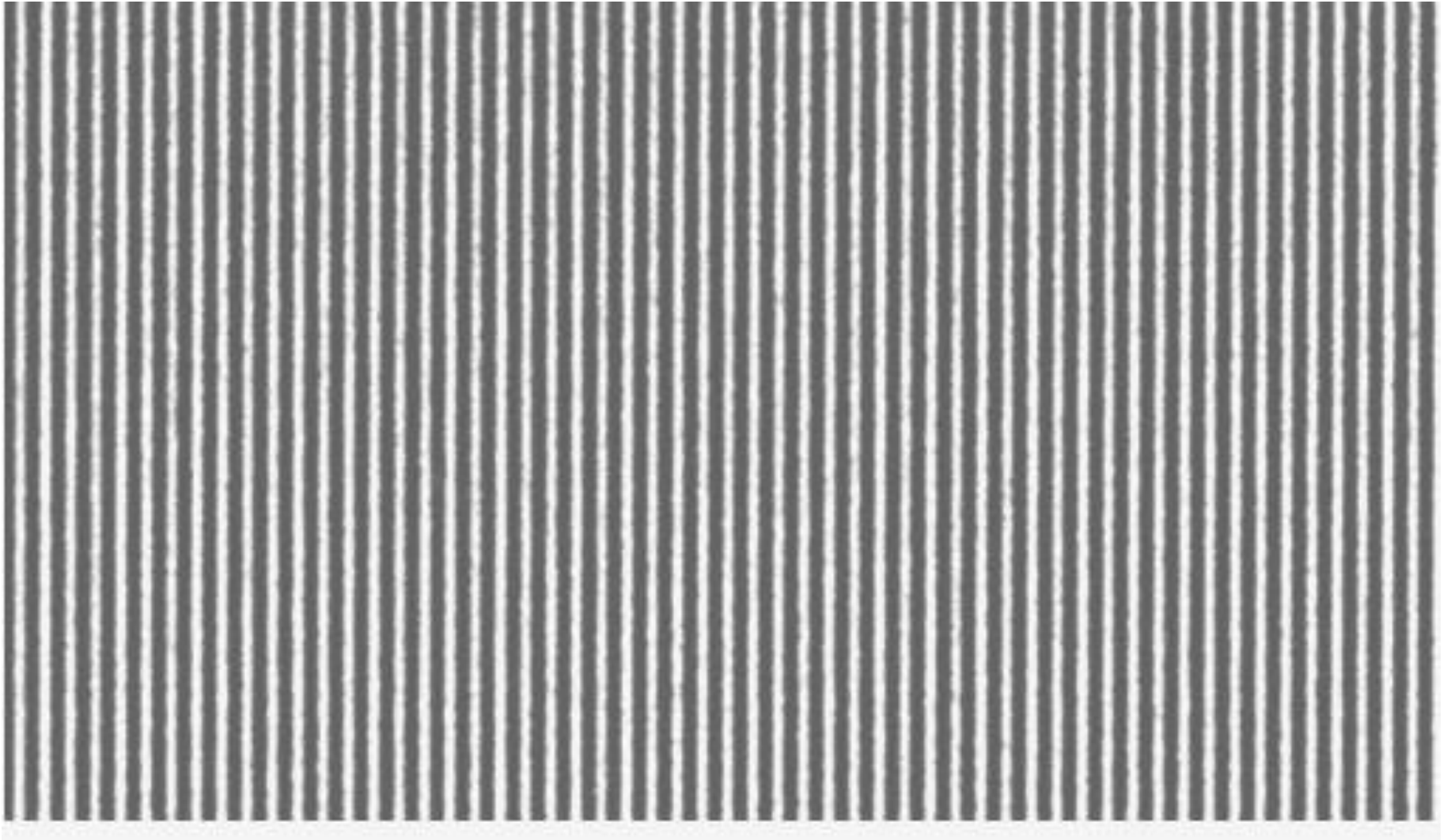
- 1978   ▪ 80-kV FE Electron Microscope

$$B = 10^8 \text{ A / cm}^2 \cdot \text{ster}$$

- 1982   ▪ 250-kV FE Electron Microscope

- 1989   ▪ 350-kV FE Electron Microscope

- 2000   ▪ 1-MV FE Electron Microscope



**Electron interference pattern**

# History of Development of Bright Electron Beams

- 1968    ■ Experiments on Electron Holography

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- 1968    ■ Development of Coherent FE Electron Beams

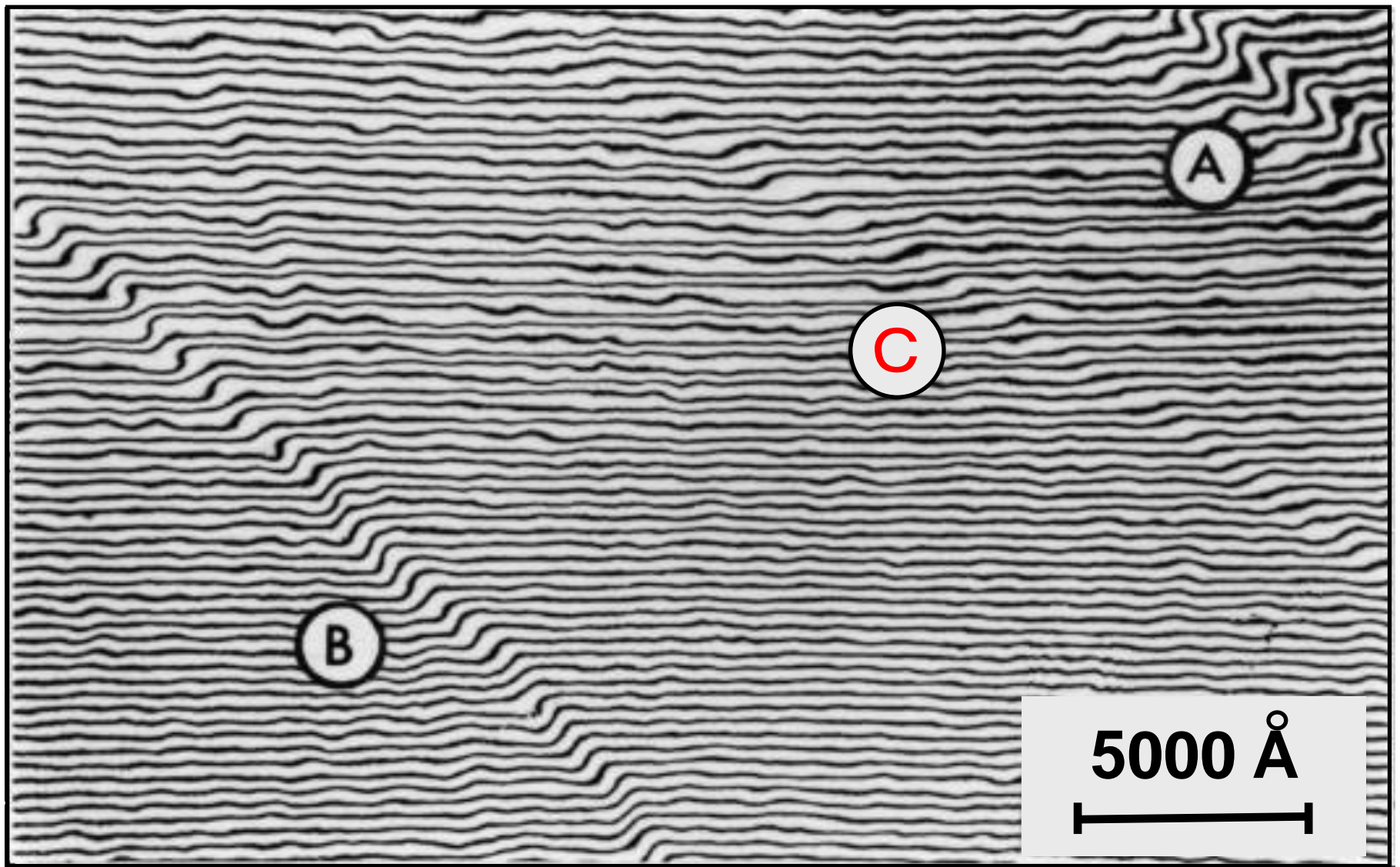
- 1978    ■ 80-kV FE Electron Microscope

- 1982    ■ 250-kV FE Electron Microscope

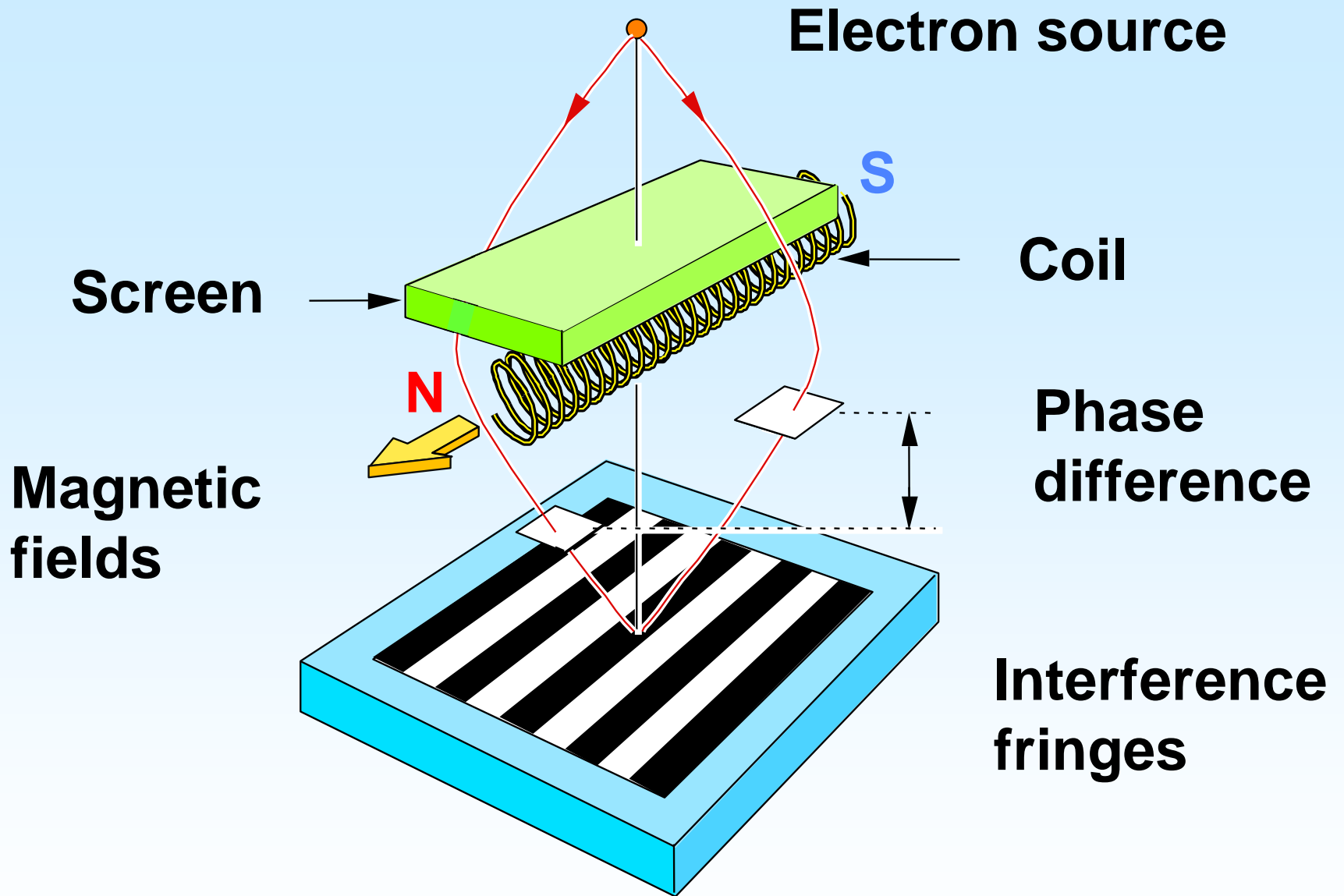
- 1989    ■ 350-kV FE Electron Microscope

- 2000    ■ 1-MV FE Electron Microscope

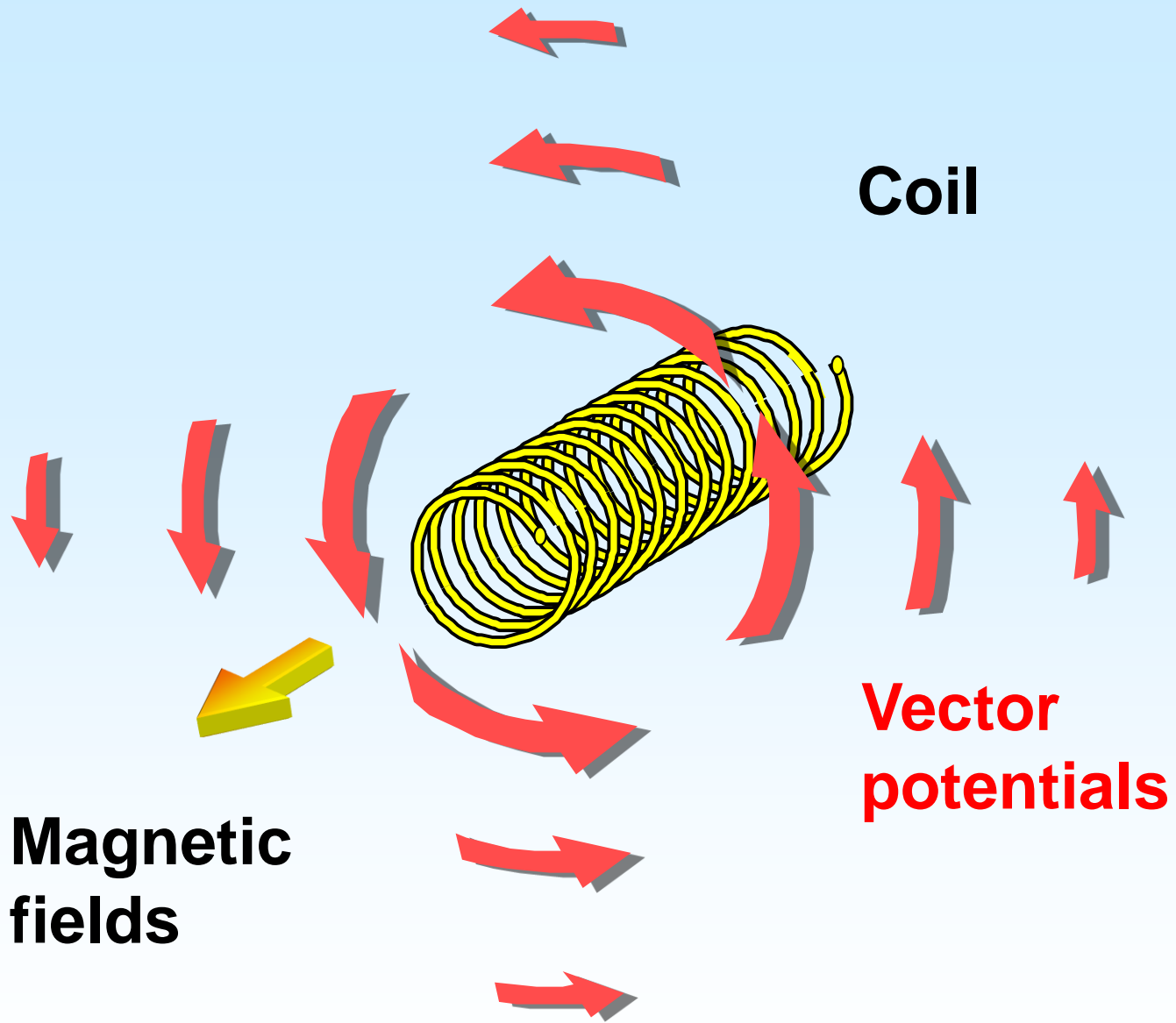
$$B = 2 \cdot 10^{10} \text{ A / cm}^2 \cdot \text{ster}$$



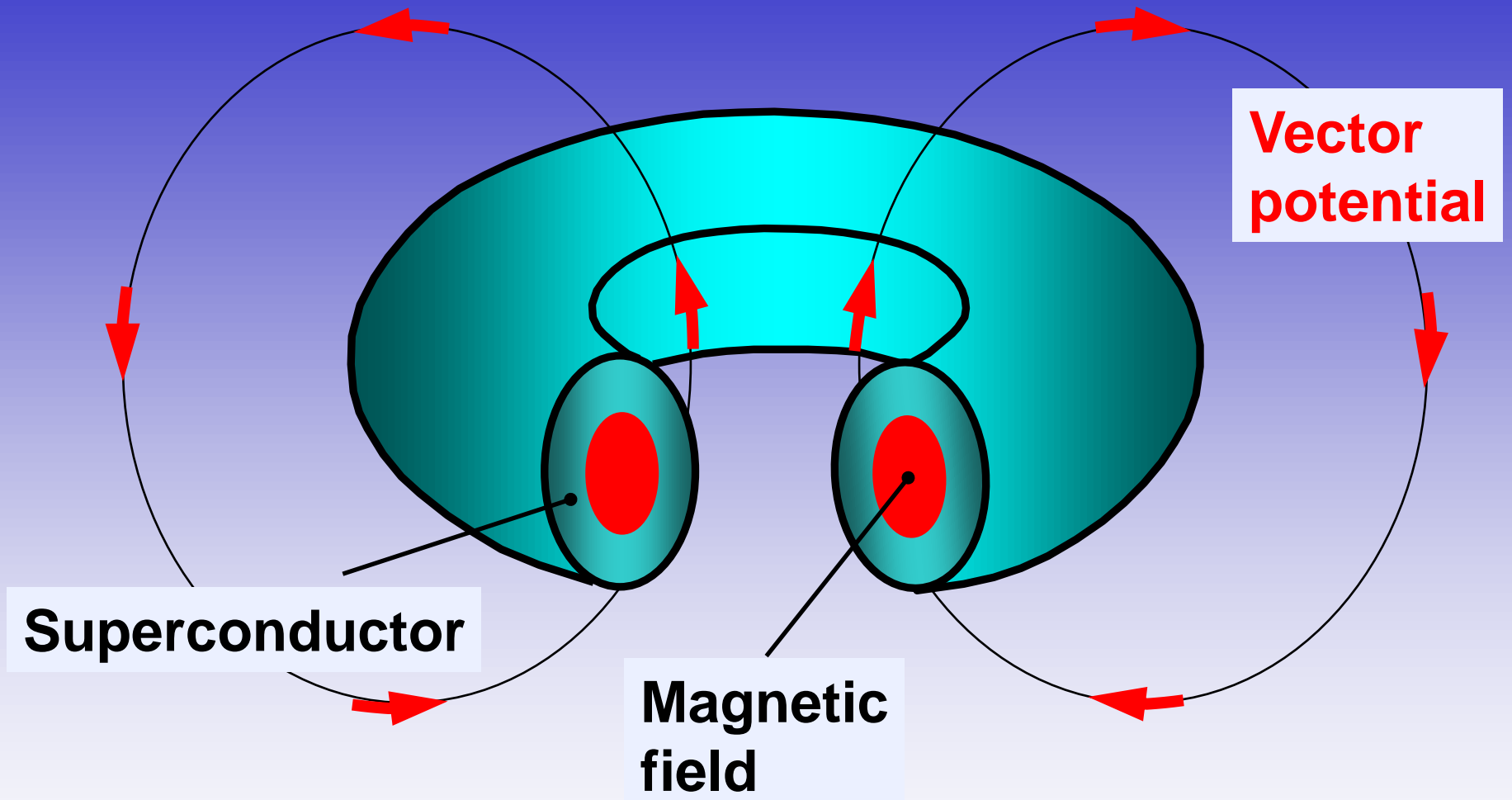
**Observation of Surface Steps on MoS<sub>2</sub> film**



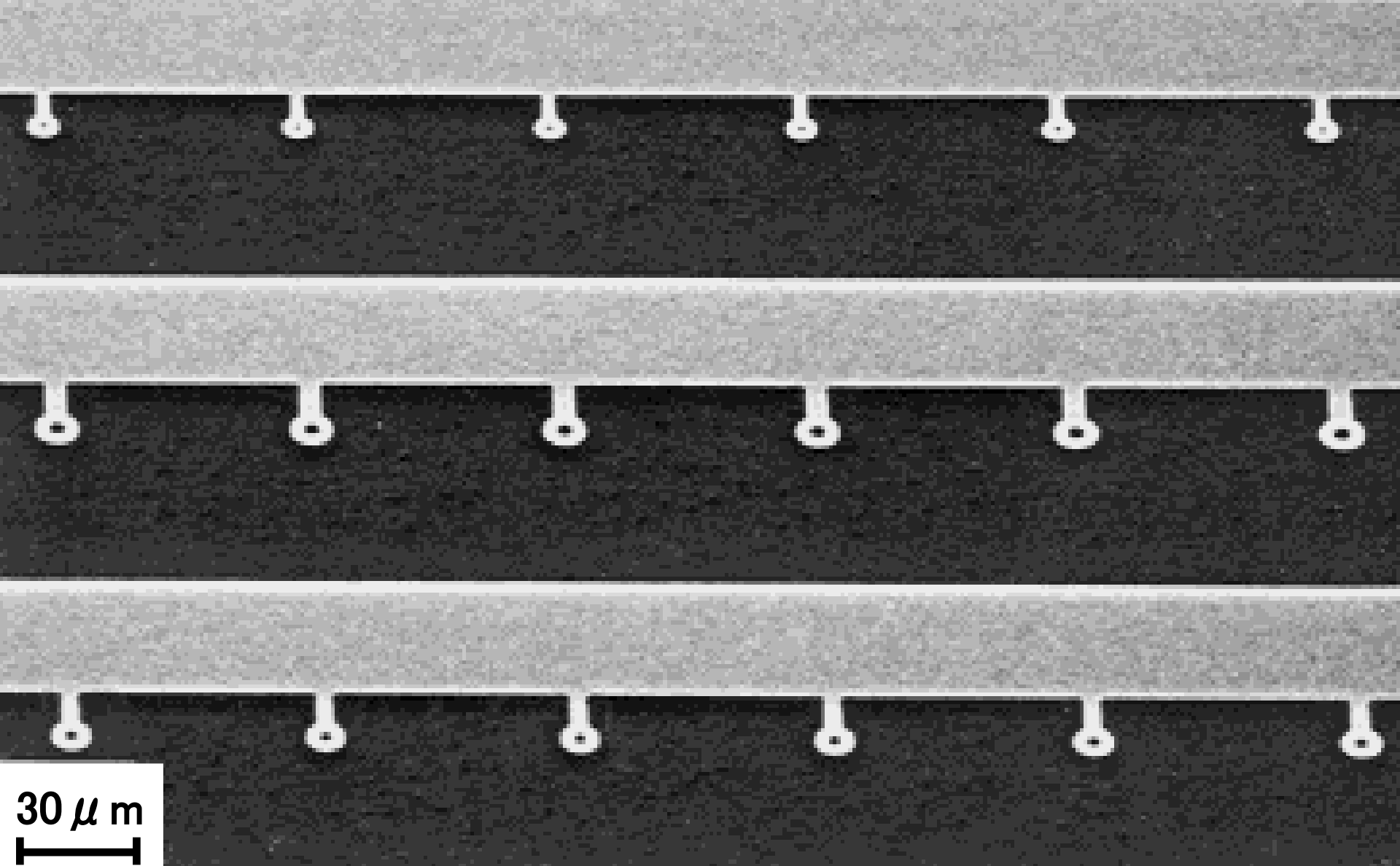
# Aharonov-Bohm Effect



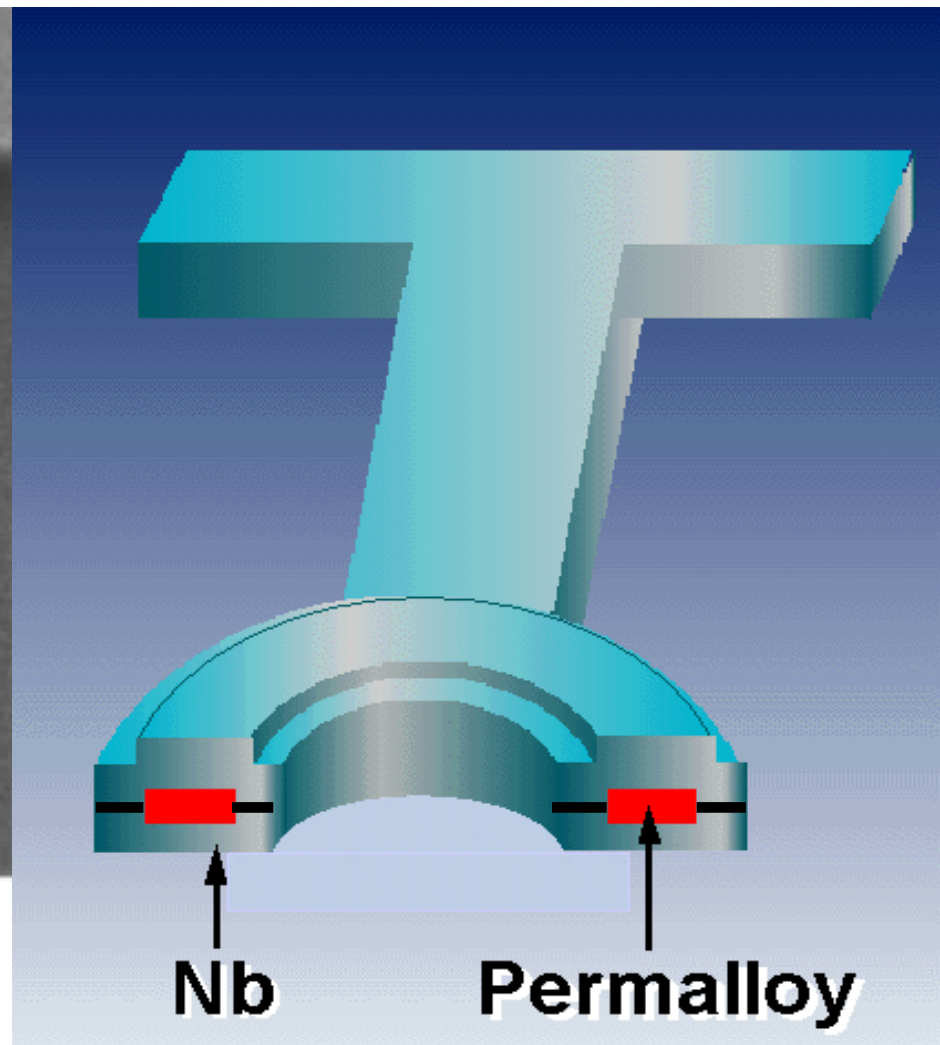
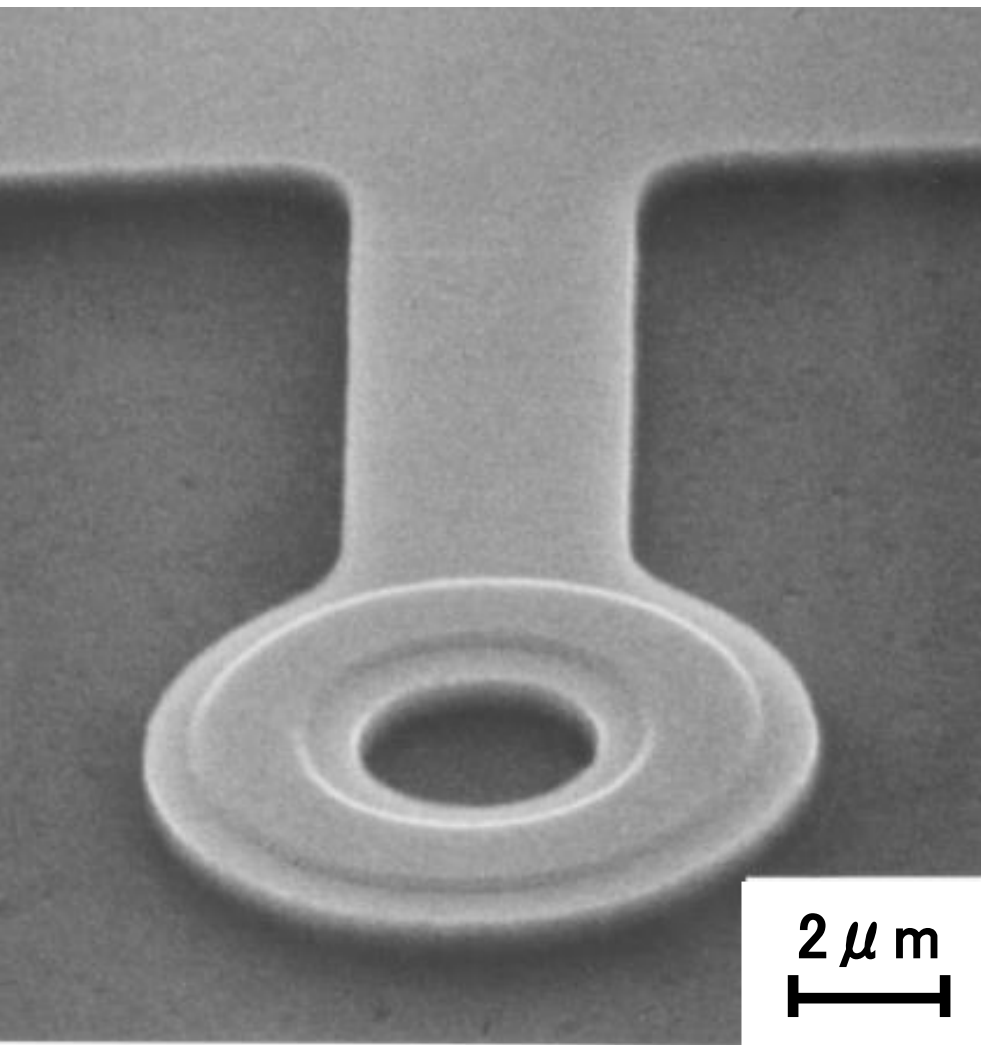
# Vector Potentials



# Aharonov-Bohm Effect



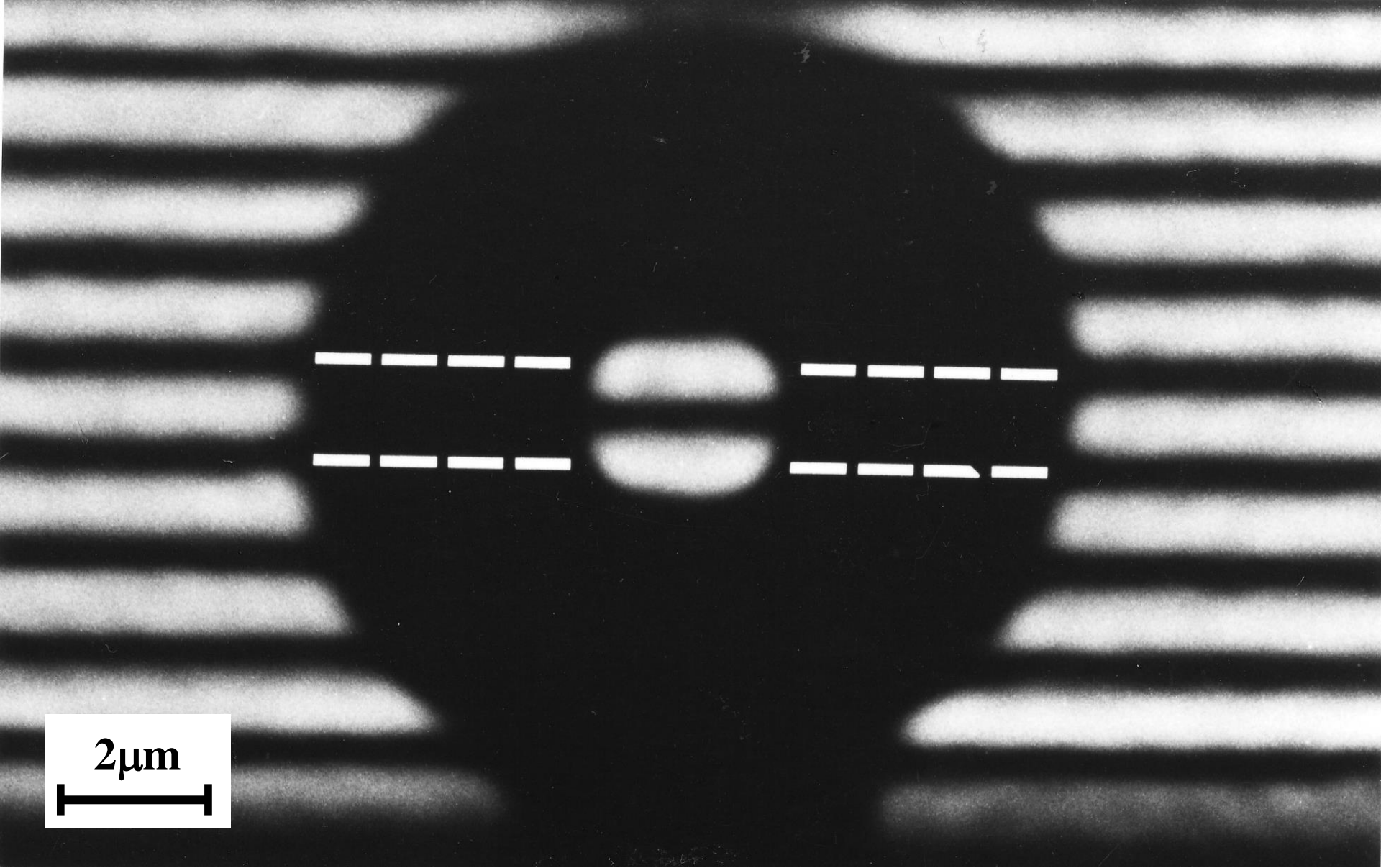
**Toroidal Magnets Covered With Superconductors**



Scanning electron micrograph

Schematic

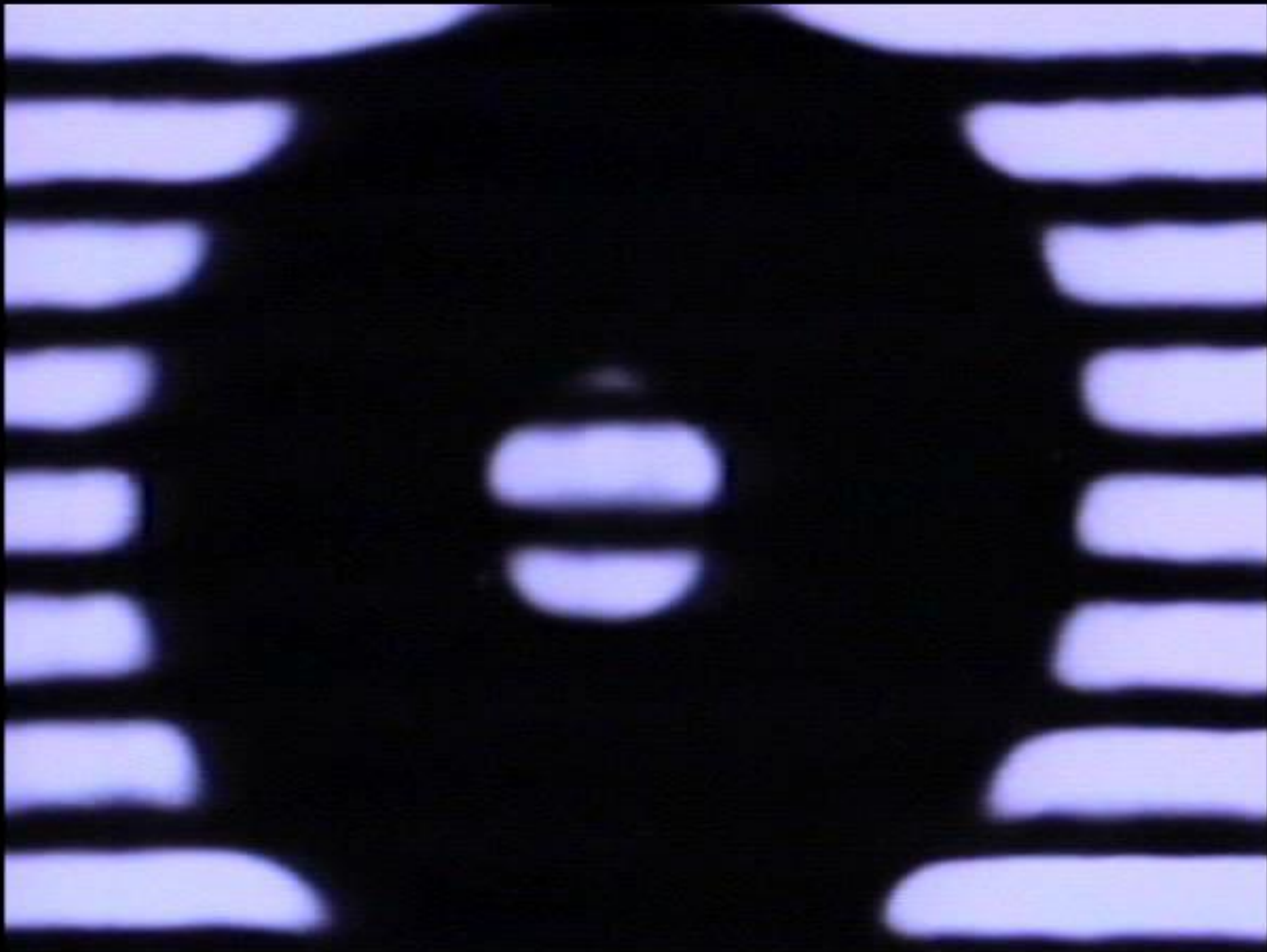
**Toroidal Ferromagnet Covered with a Superconductor**



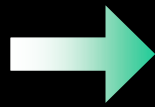
2 $\mu$ m



**Photographic Evidence for AB Effect**



**Phase difference =  $0.8\pi$**   
**at  $T = 15 \text{ K}$**



**Phase difference =  $\pi$**   
**at  $T = 5 \text{ K}$**

**Öffentliche Vorträge an der Universität Ulm:**

**So. 14. März 19:30.30 Uhr**

**Einstein Lecture (Hörsaal H22)**

**“Einstein’s Impact on Theoretical Physics  
of the 21st Century” – C.N.Yang –**



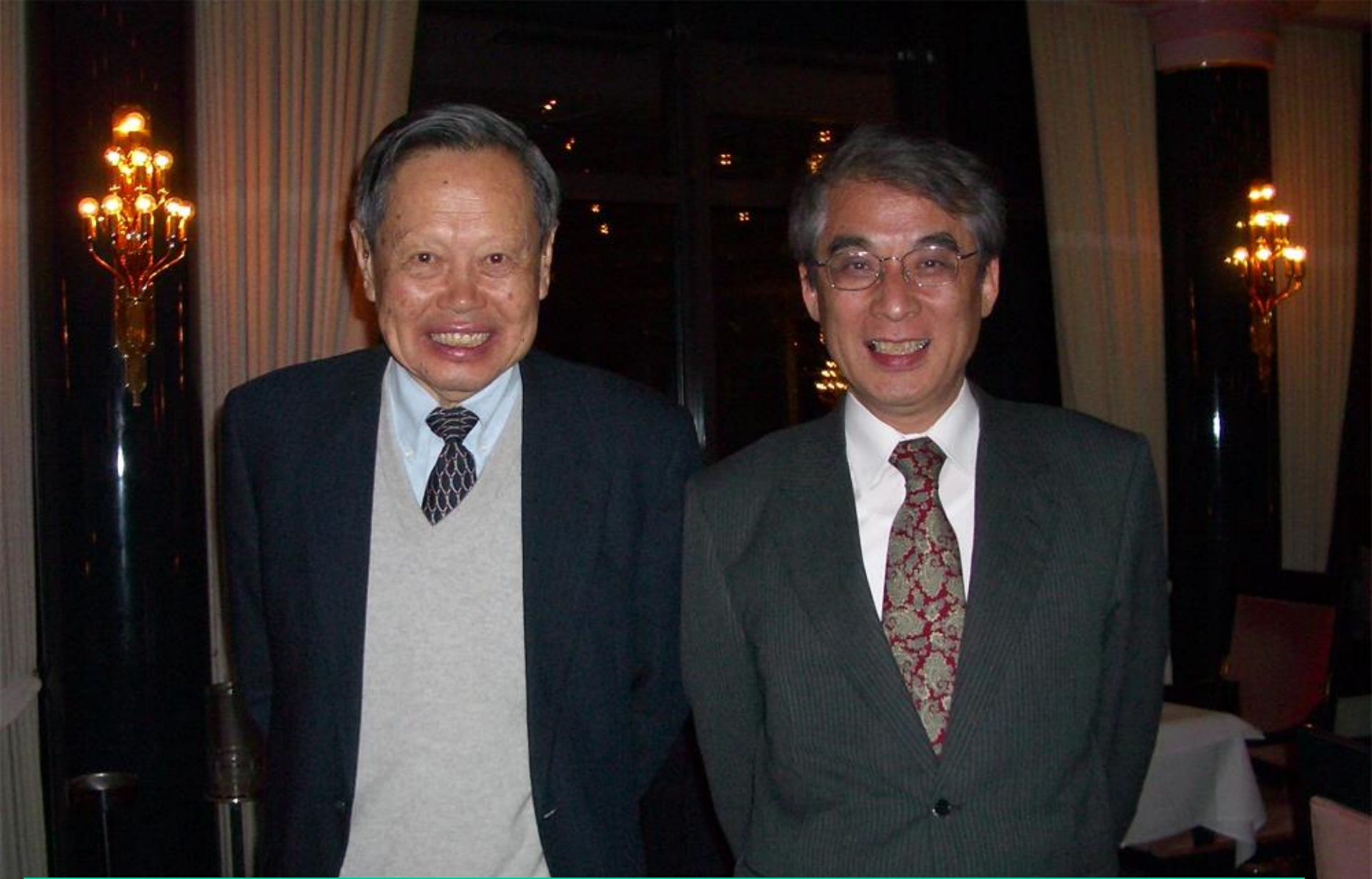
Festakt

anlässlich des 125. Geburtstags  
von Albert Einstein

Sonntag, 14. März 2004, 11.00 Uhr  
Congress Centrum Ulm,  
Einstein Saal

Parkett links  
Reihe 6  
Platz 0016

**Einstein  
125.**



**At Memorial Symposium of 125<sup>th</sup> Birthday of Einstein**

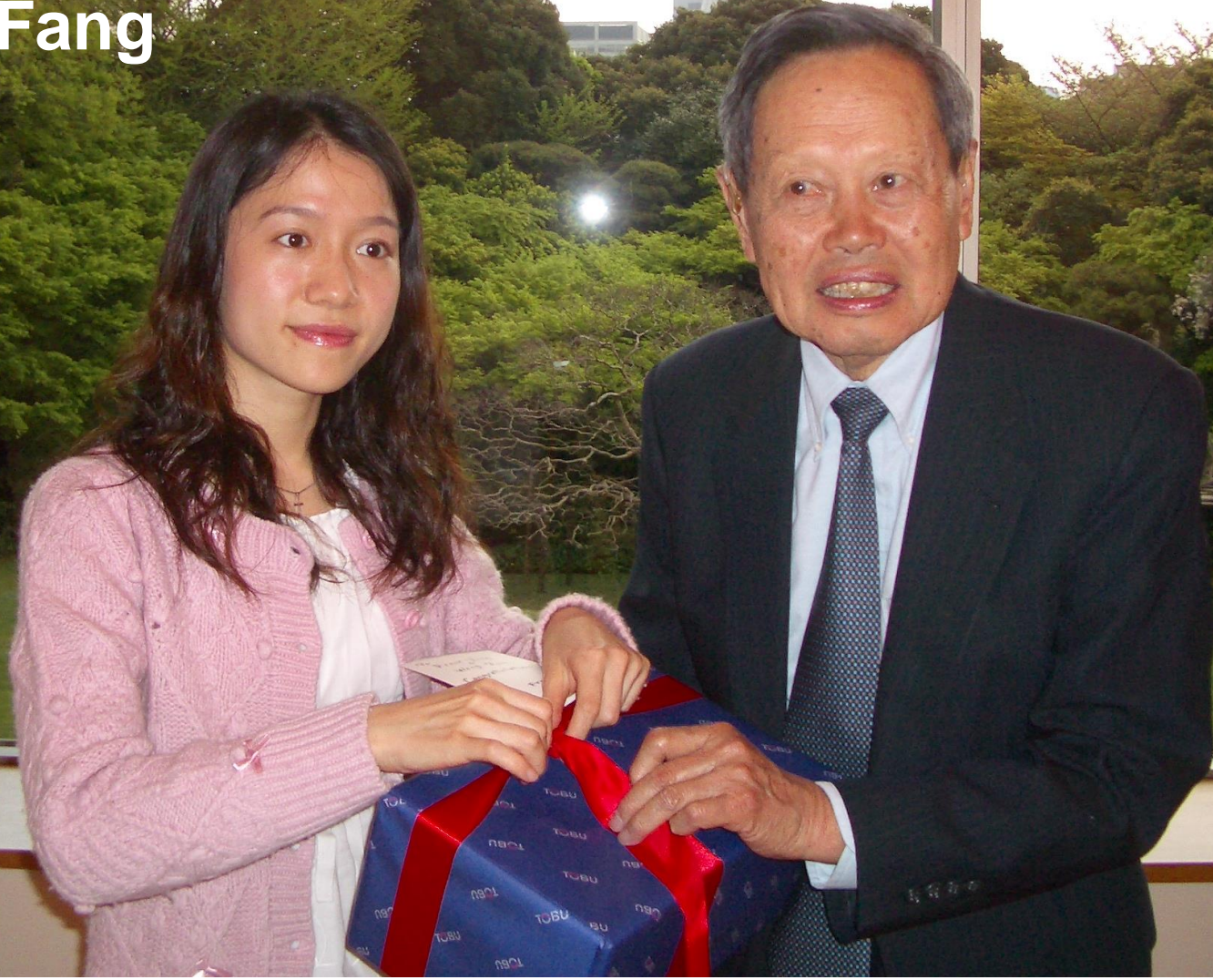
**— C. N. Yang —**

**Ulm Germany 2004.3.14**

**Professor Chen Ning Yang**

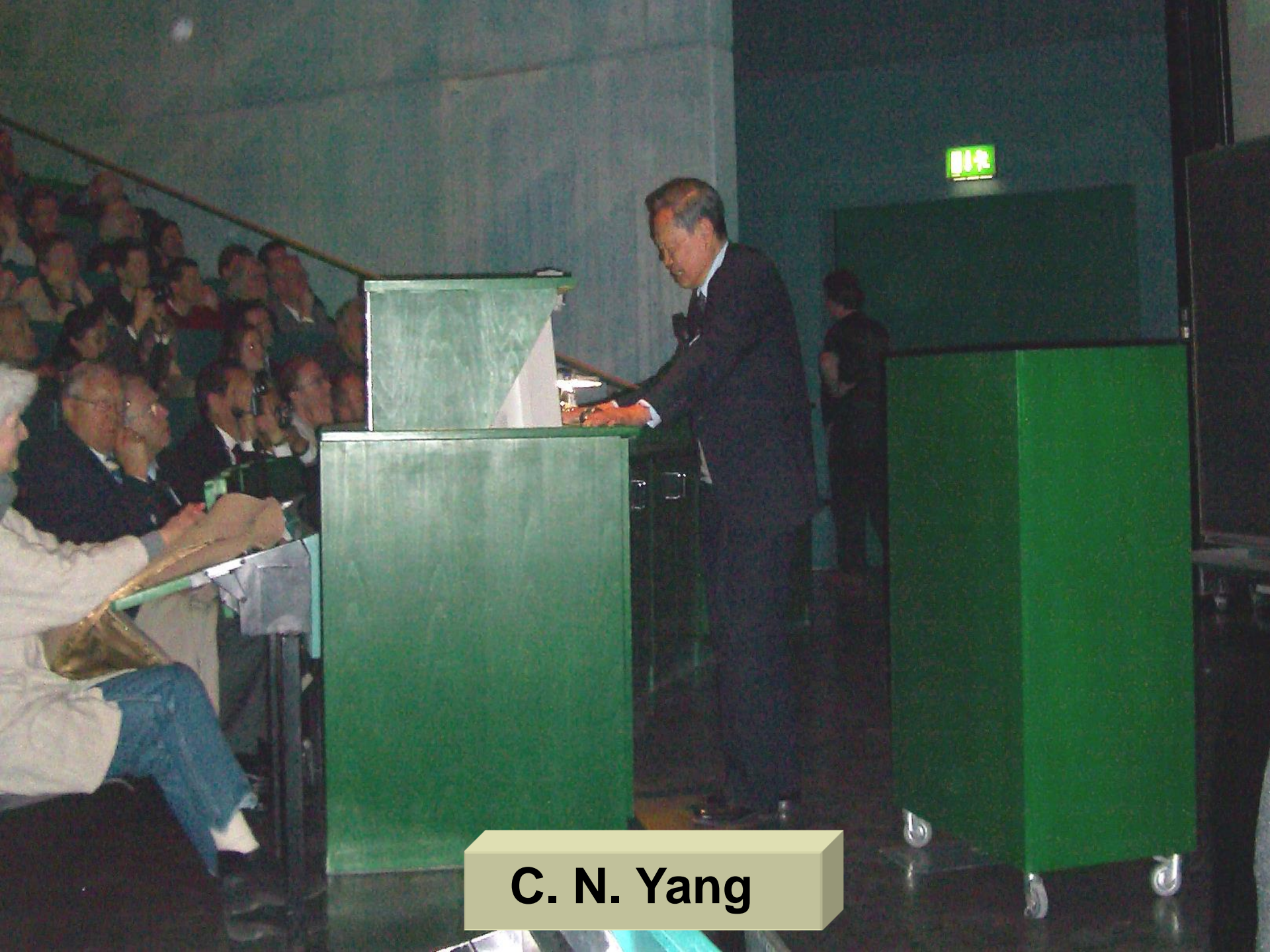
**Nobel Laureate in Physics (1957)**

**Weng Fang**



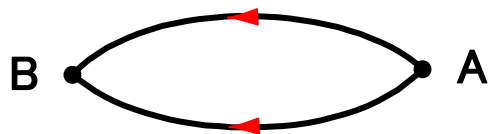


**Paul Einstein**

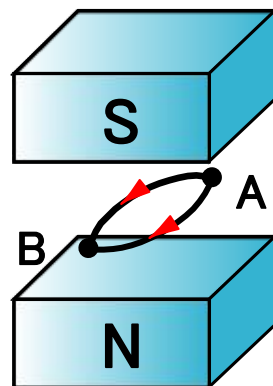


**C. N. Yang**

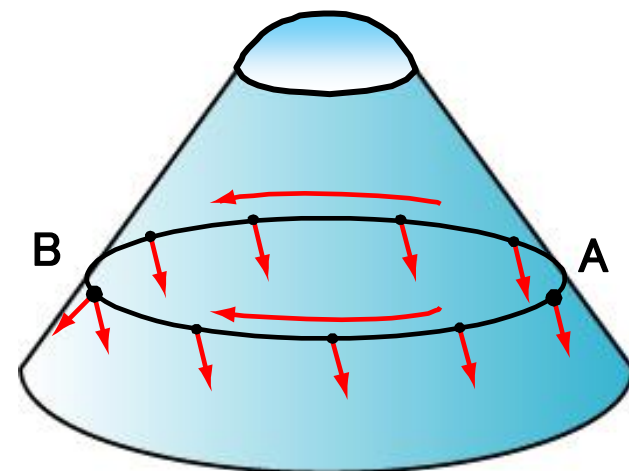
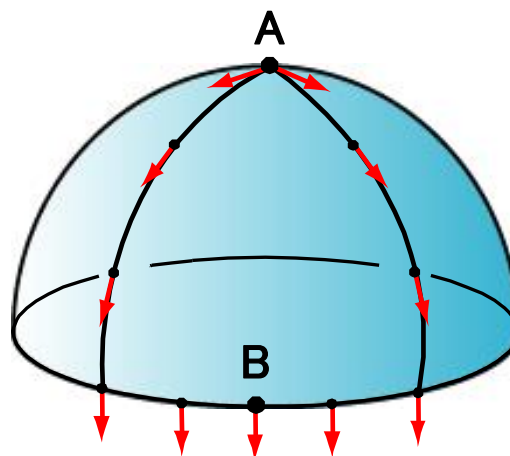
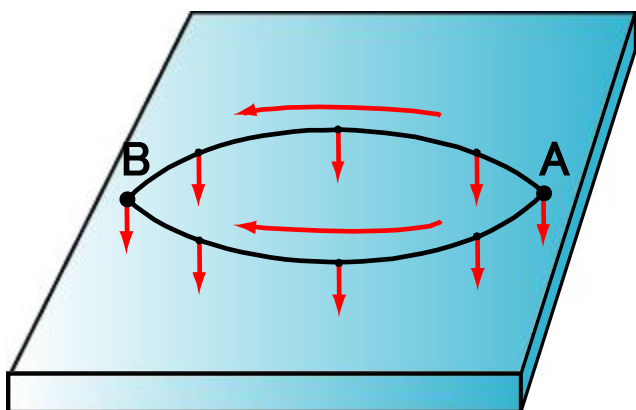
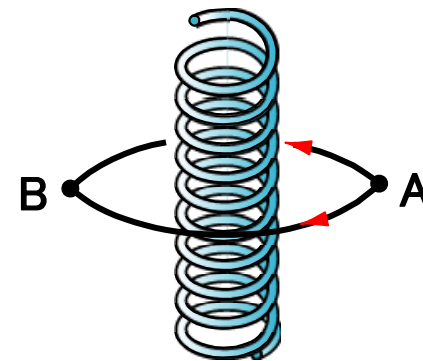
Free space



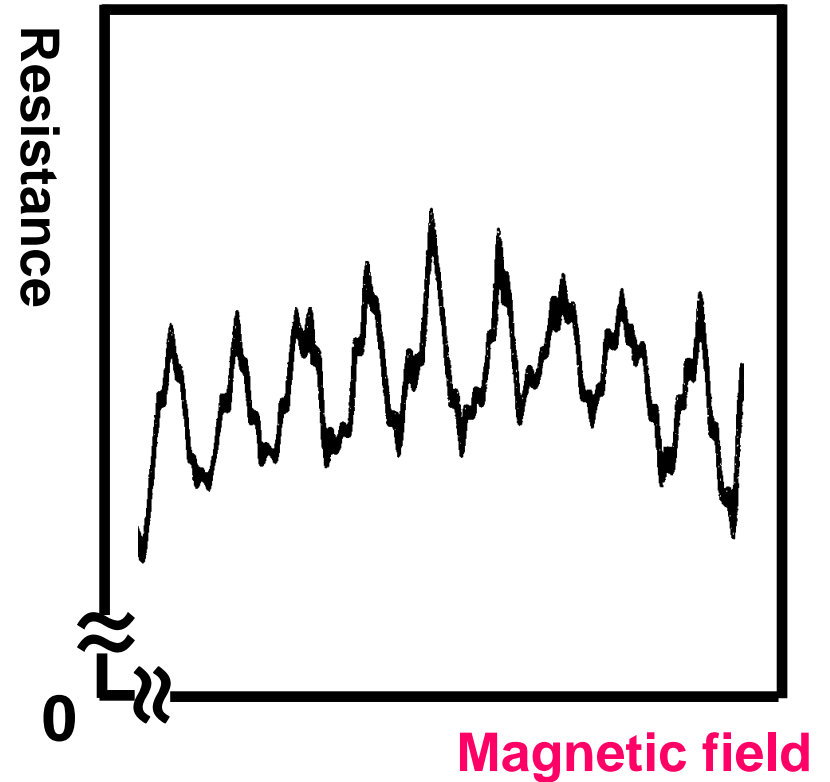
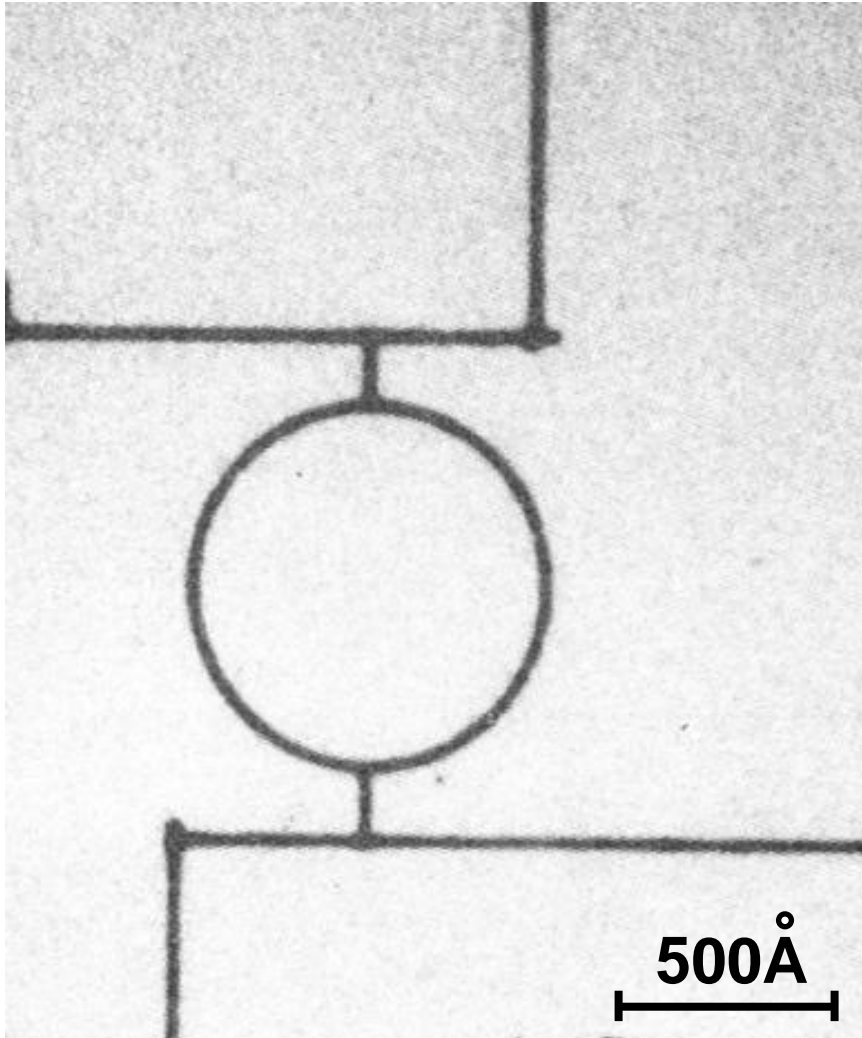
Uniform magnetic field



AB effect

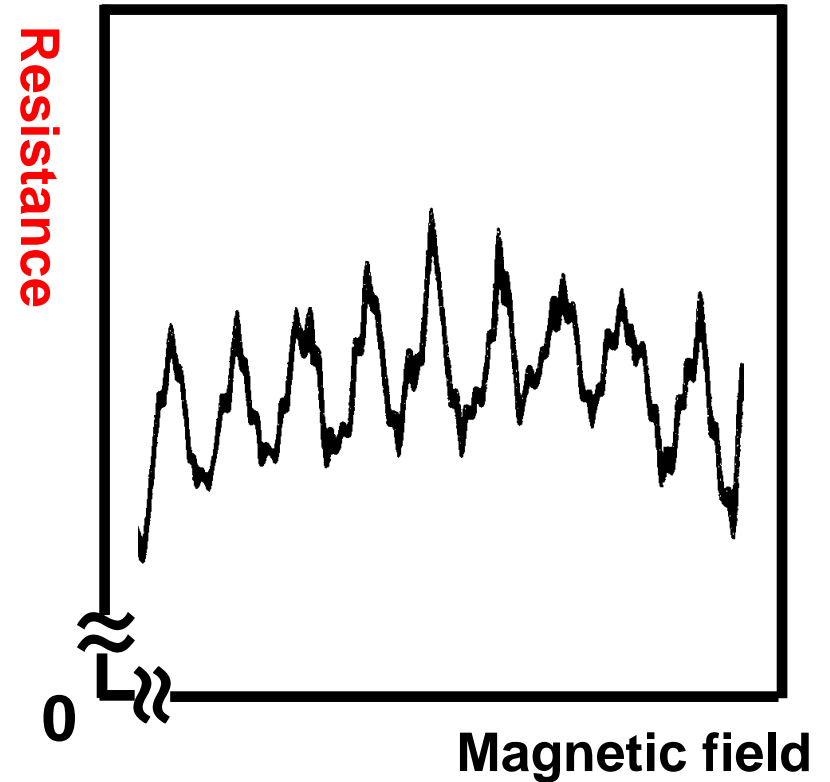
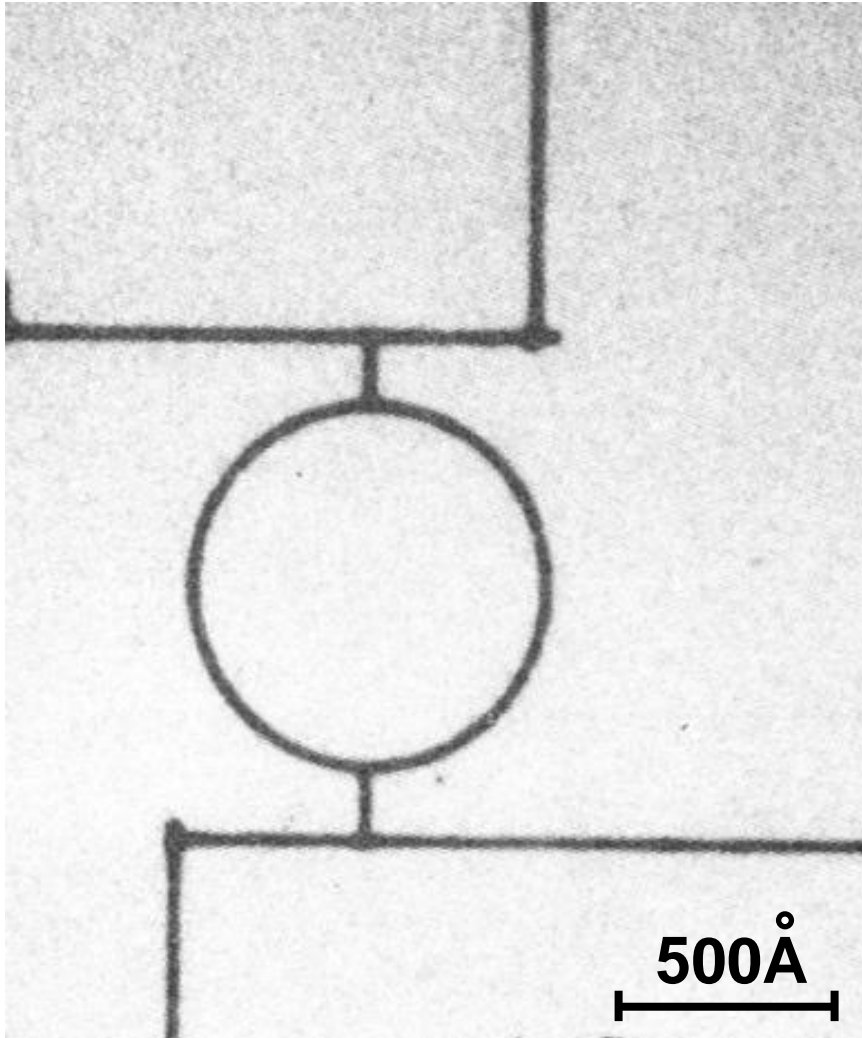


Parallel Transport of Arrows in 2D Surfaces



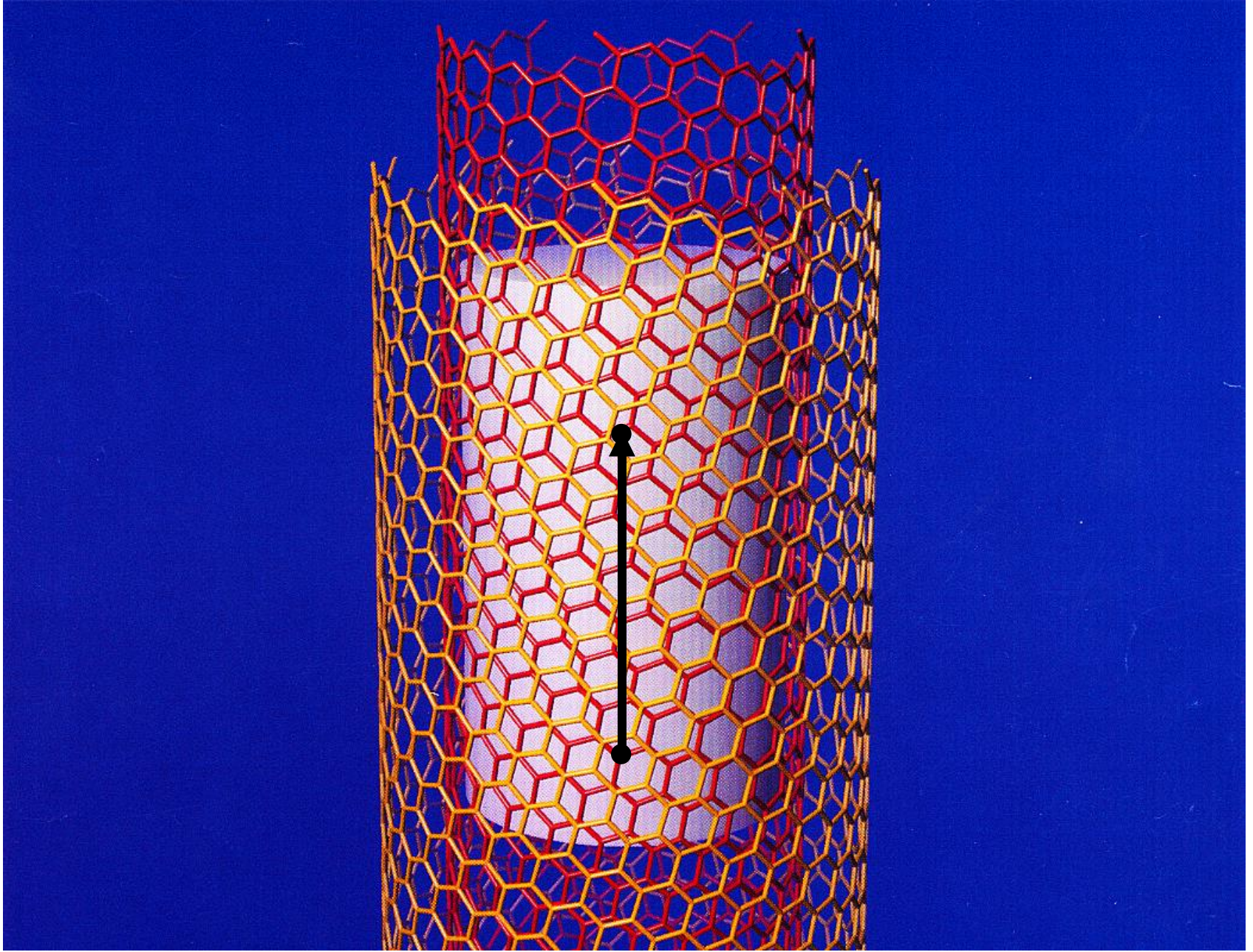
Oscillation of resistance  
due to interference effect

# The Aharonov - Bohm Effect in Metals



Oscillation of resistance  
due to interference effect

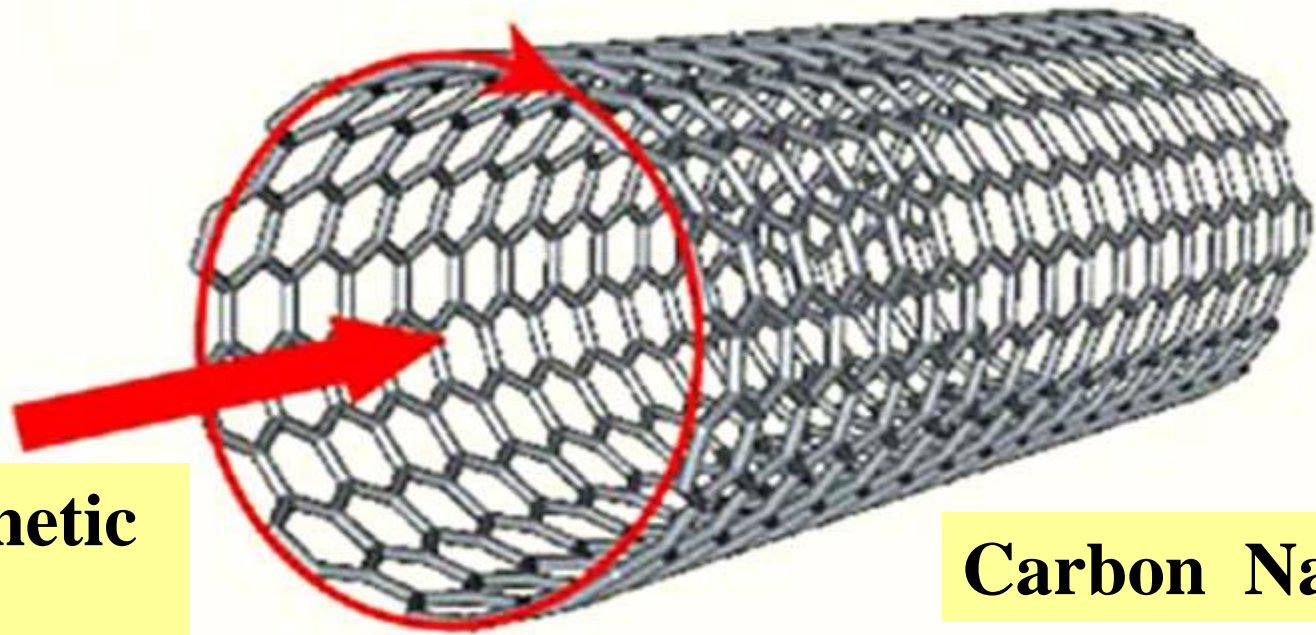
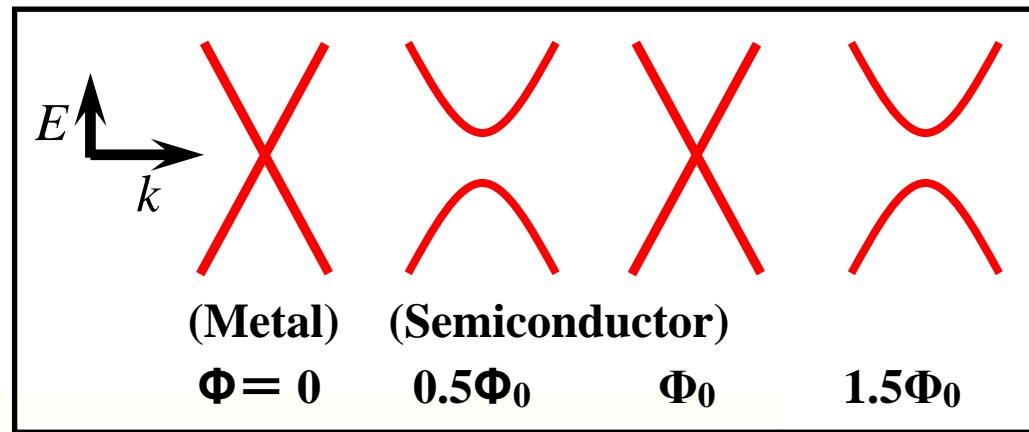
# The Aharonov - Bohm Effect in Metals



**Carbone Nanotube**

(Nature)

- Merinot *et al.*: Nature **428** (2004) 536 -

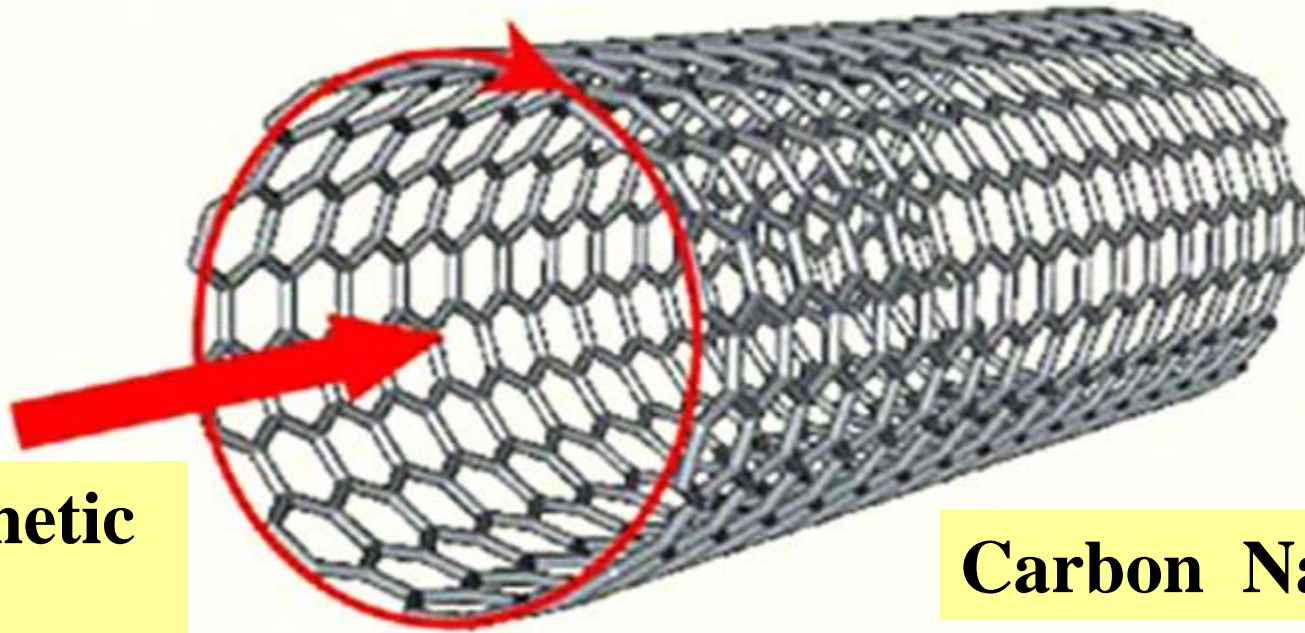
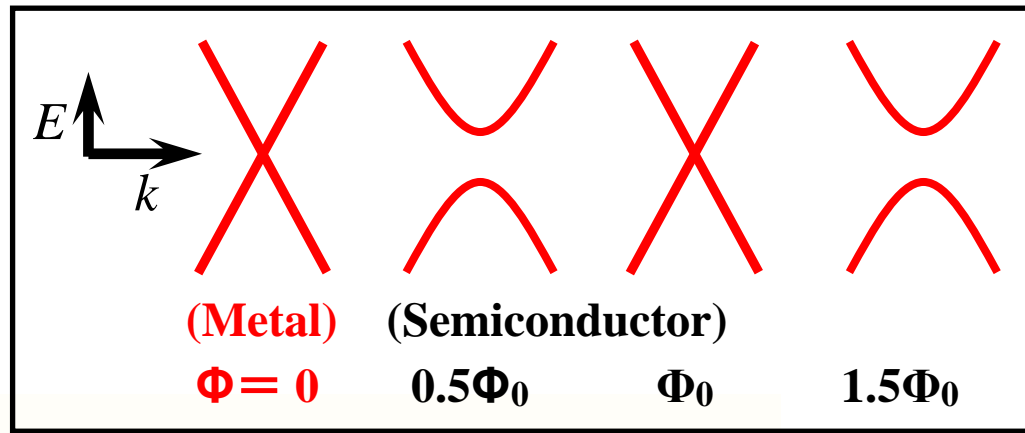


**Magnetic field**

**Carbon Nanotube**

**Electronic State Changes due to Magnetic Field**

- Merinot *et al.*: Nature **428** (2004) 536 -

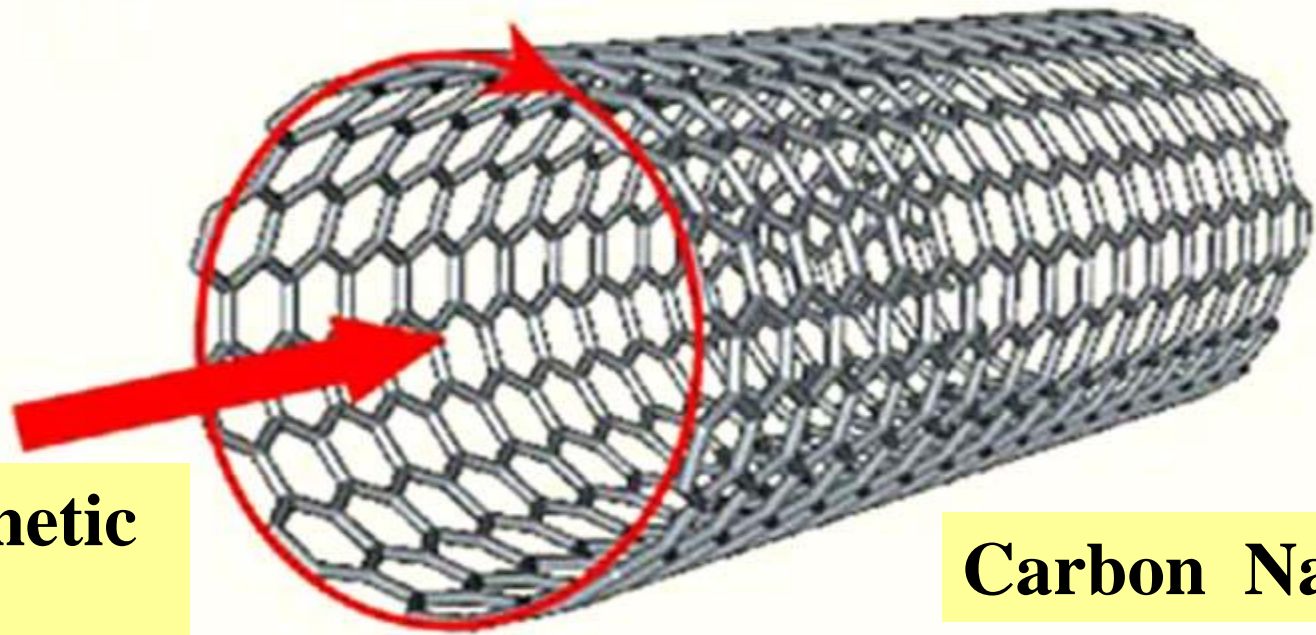
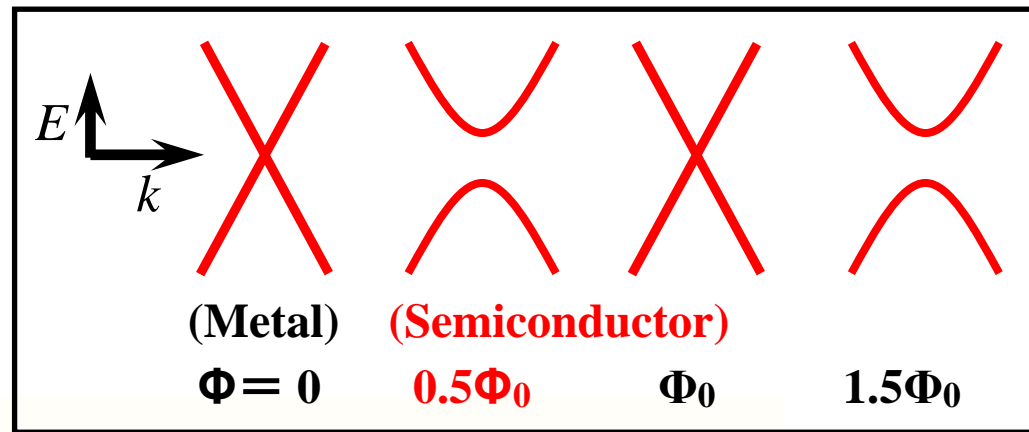


**Magnetic field**

**Carbon Nanotube**

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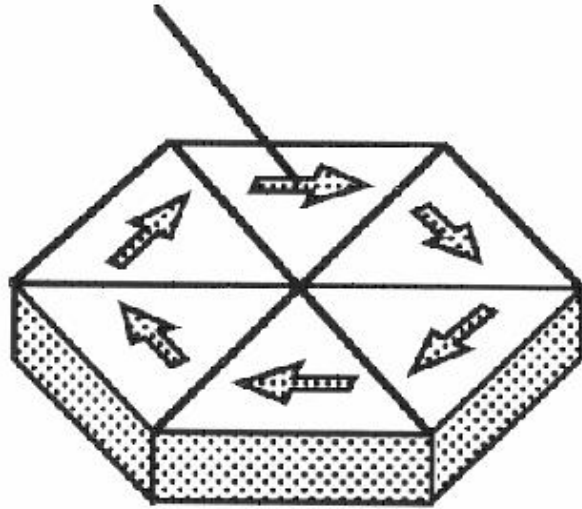


**Magnetic field**

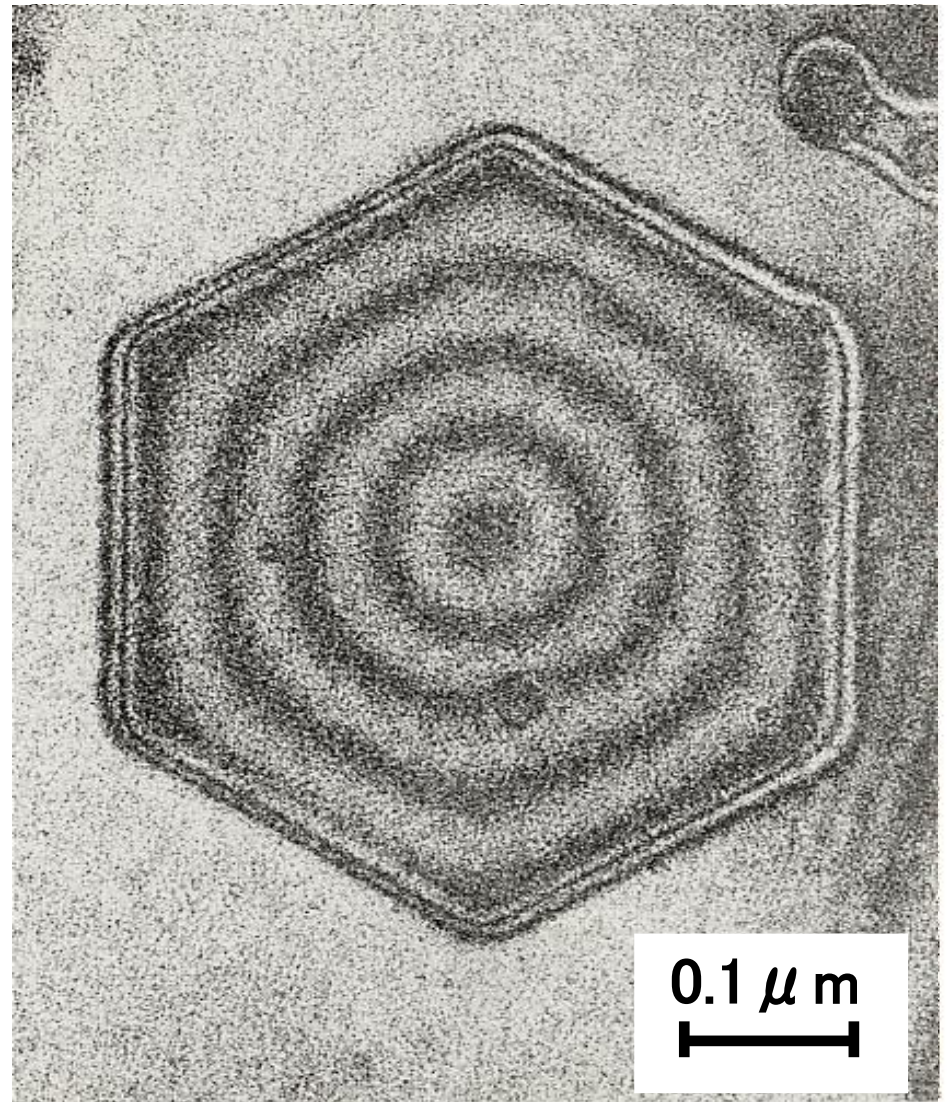
**Carbon Nanotube**

**Electronic State Changes due to Magnetic Field**

# Magnetization



## Schematic



**Interference Micrograph of Cobalt Particle**

# Quantized Vortices in Superconductors

- 1957**   ▪ **Prediction (Abrikosov)**
- 1964**   ▪ **Observation of vortex lattice**
  - Neutron diffraction —
- 1967**   ▪ **Theoretical investigation of direct observation**
  - 72
    - Hirsch   ▪ Wohleben   ▪ Yoshioka
    - Colliex & Jouffrey   ▪ Pozzi & Valdré
- 1969**   ▪ **Detection of a vortex by electron phase shift of  $\pi$** 
  - Wahl, Lischke
- 1992**   ▪ **Dynamic observation of vortices by Lorentz microscopy (350-kV microscope)**



# Quantized Vortices in Superconductors

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- 1964   ▪ Observation of vortex lattice  
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— 72       ▪ **Hirsch**   ▪ **Wohleben**   ▪ **Yoshioka**  
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      microscopy (350-kV microscope)

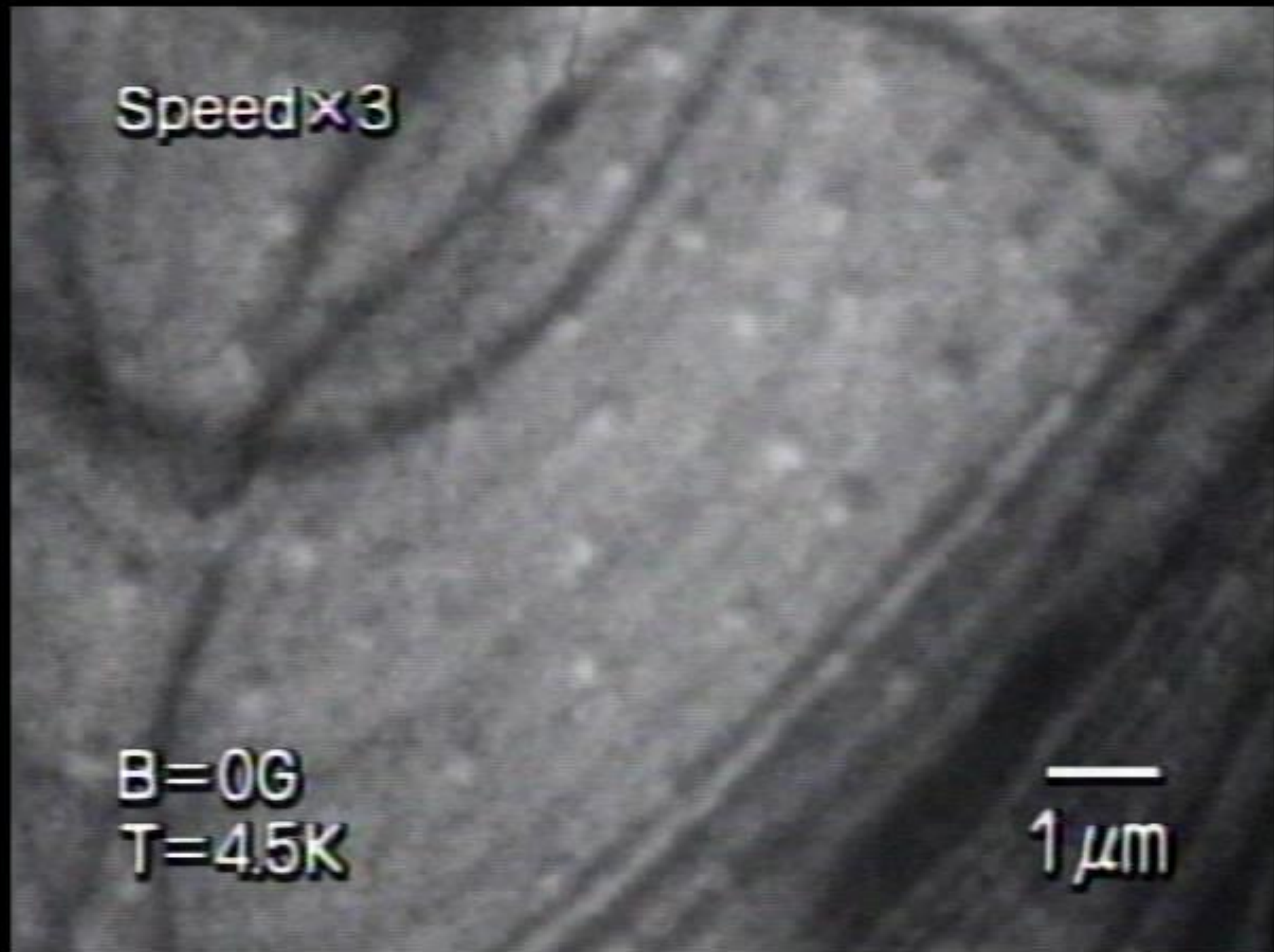
# Quantized Vortices in Superconductors

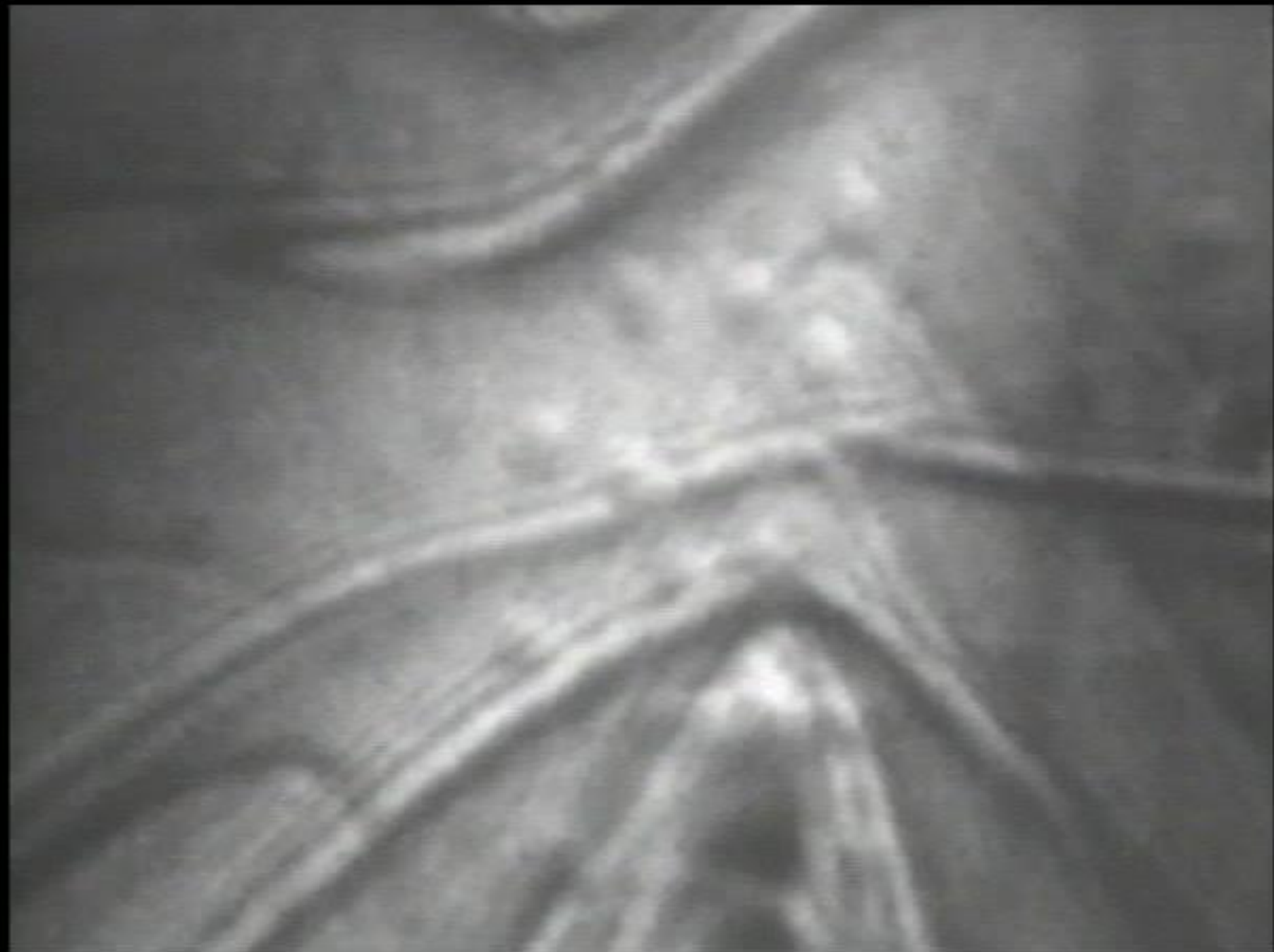
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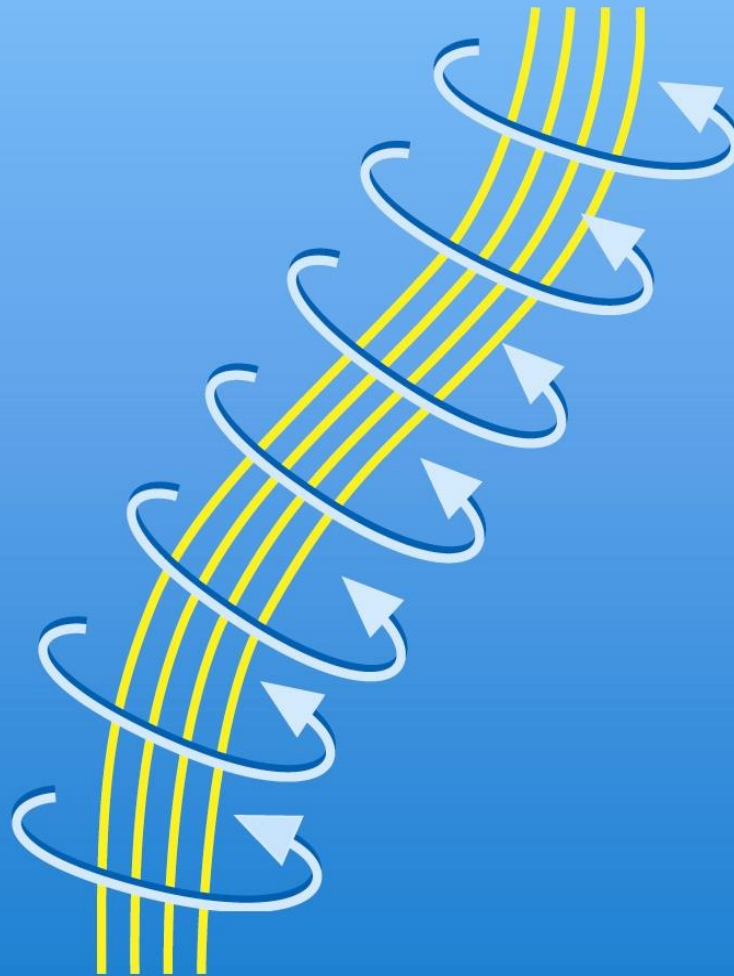
Speed  $\times 3$

$B=0G$   
 $T=4.5K$

—  
 $1\mu m$

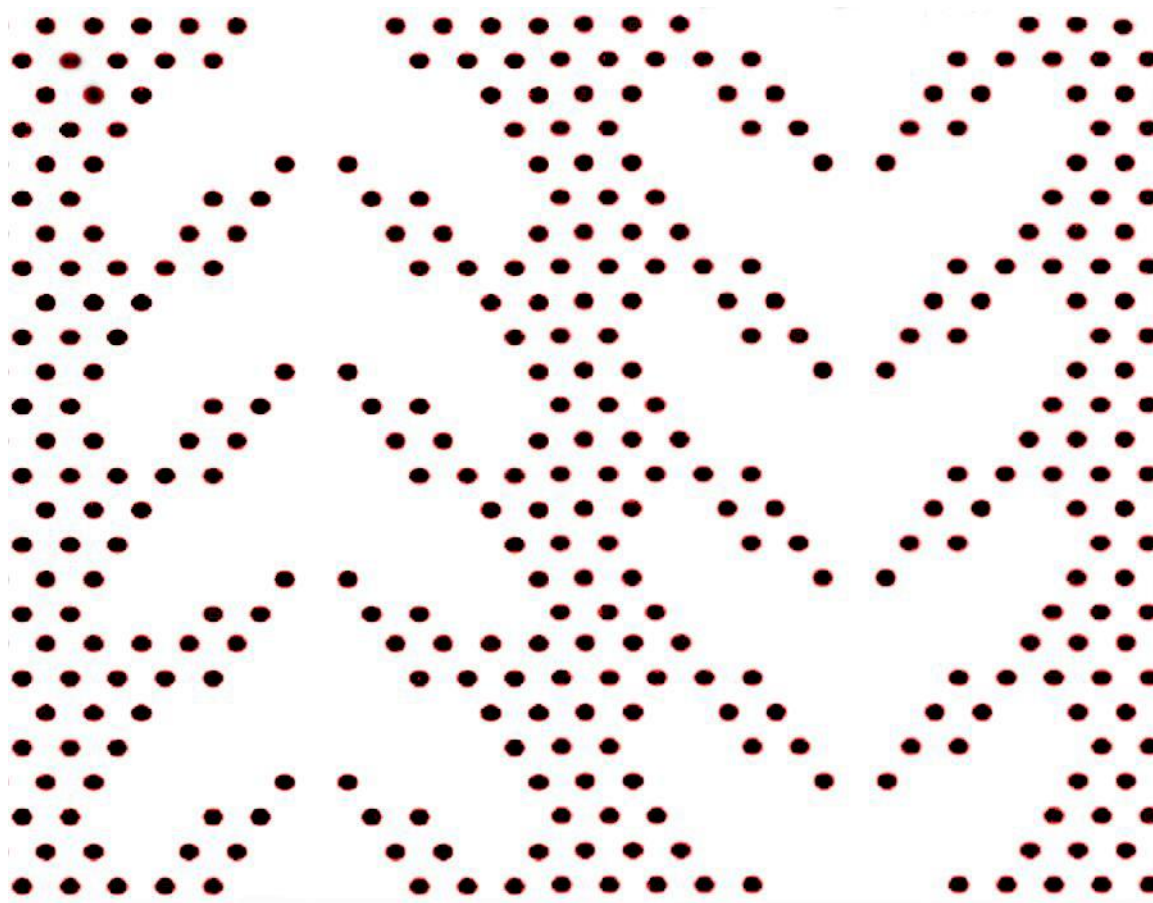
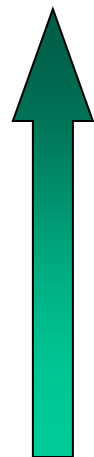






**Topological Defect**

Externally applied drive



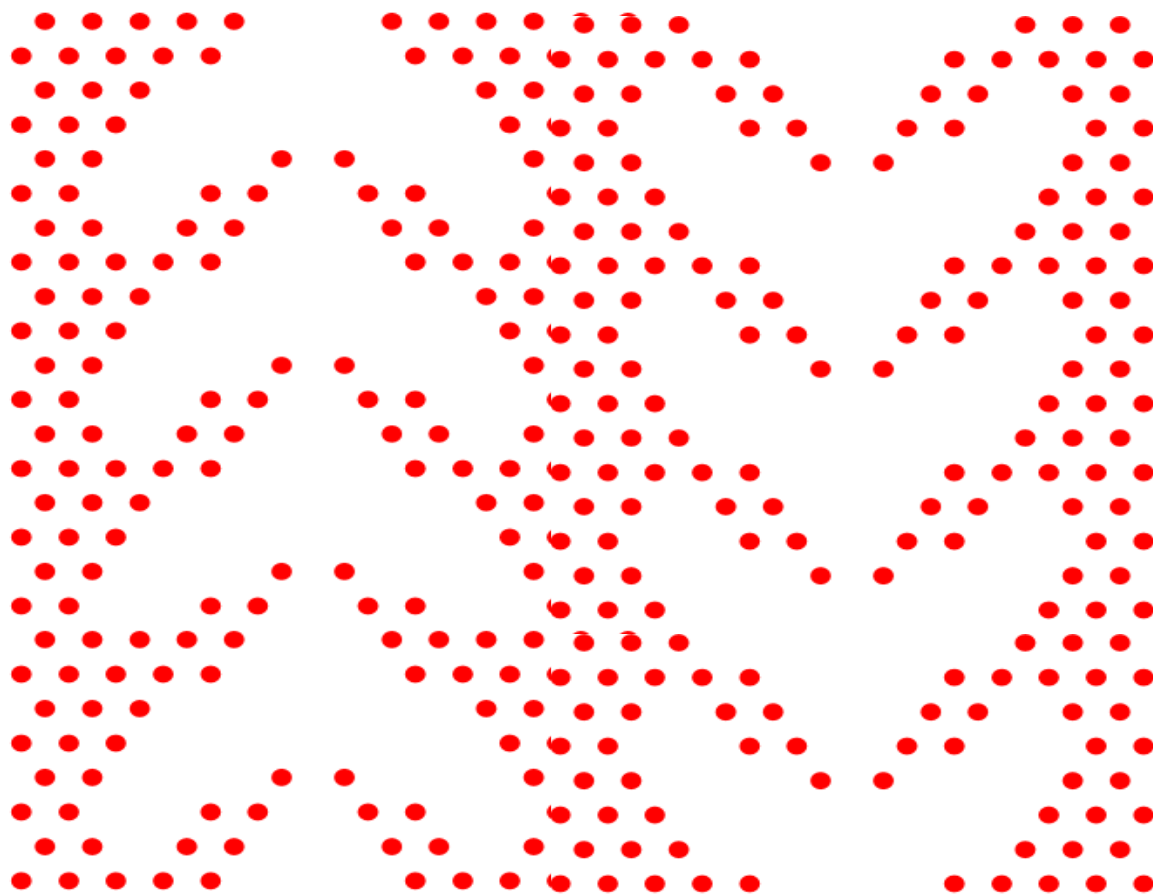
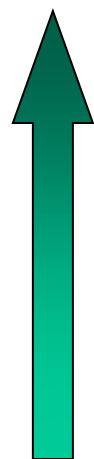
Array of  
Pinning  
Centers

“funnel”

“trap”

**Vortex ratchet system**

Externally applied drive



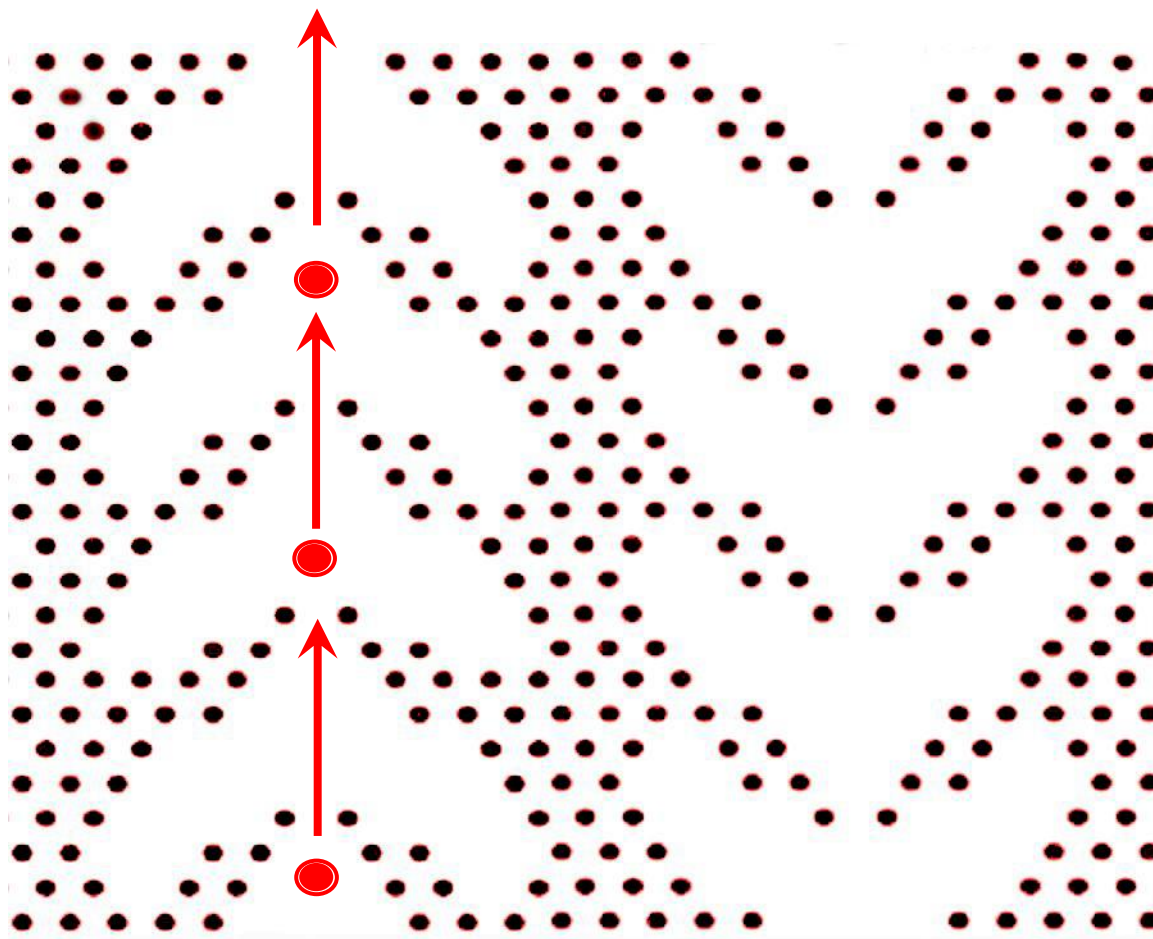
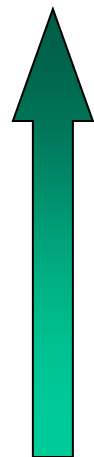
Array of  
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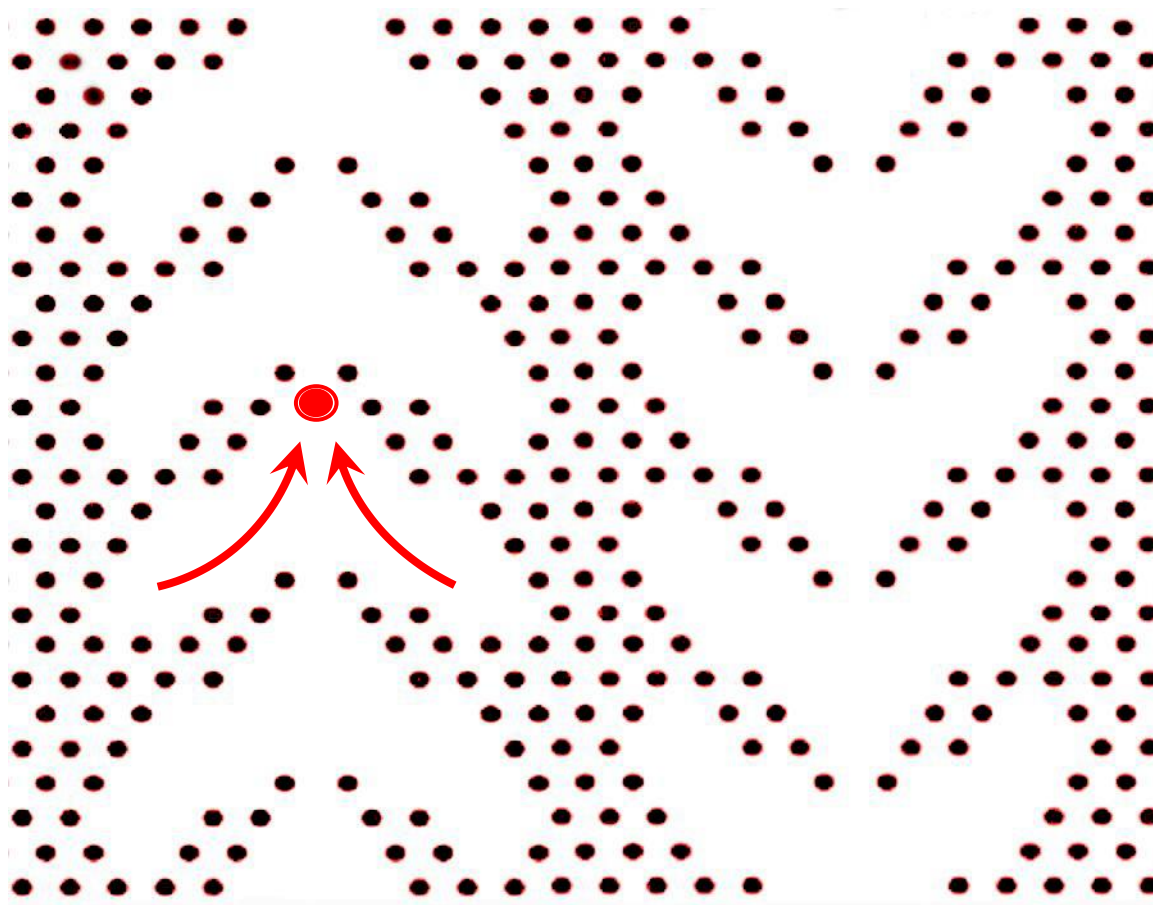
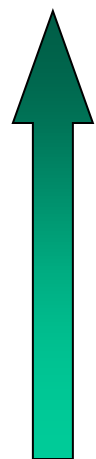
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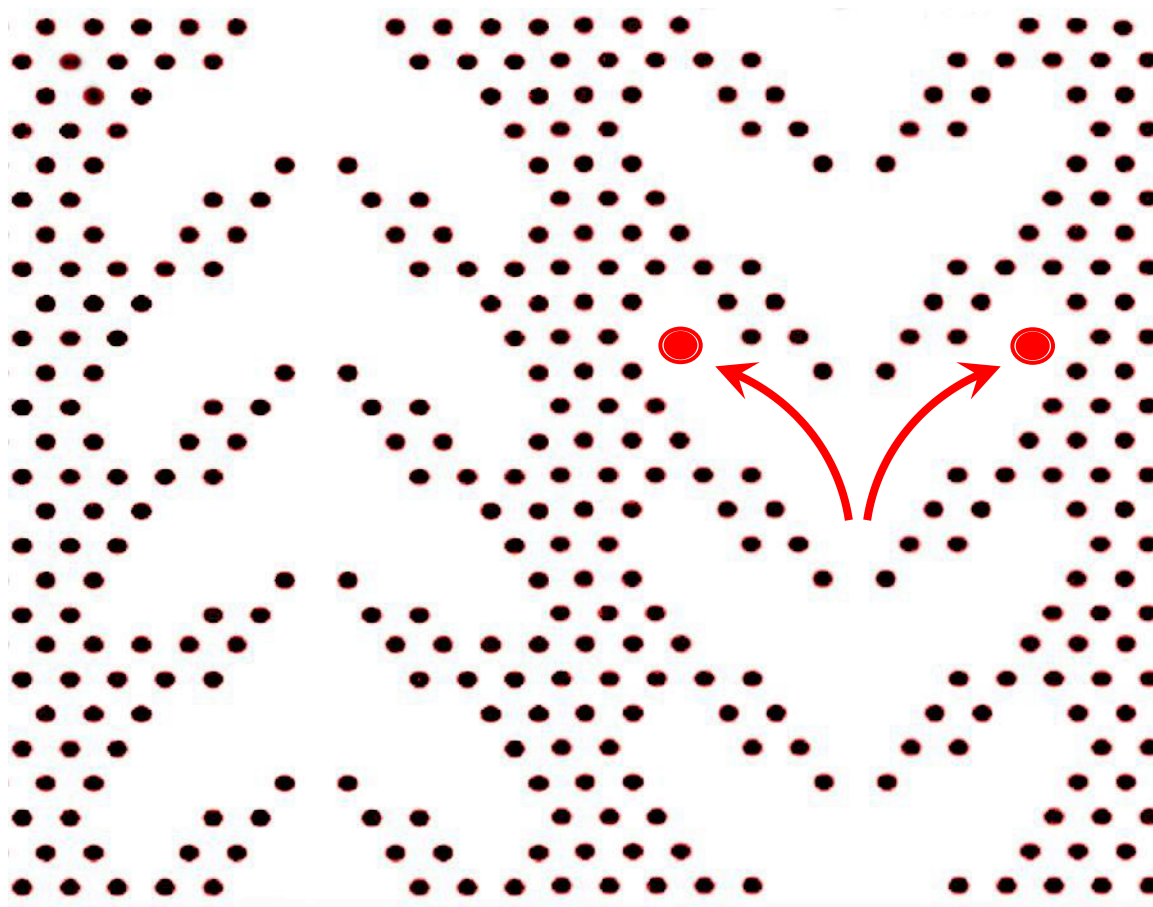
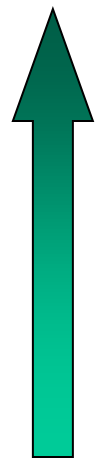
Array of  
Pinning  
Centers

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Externally applied drive



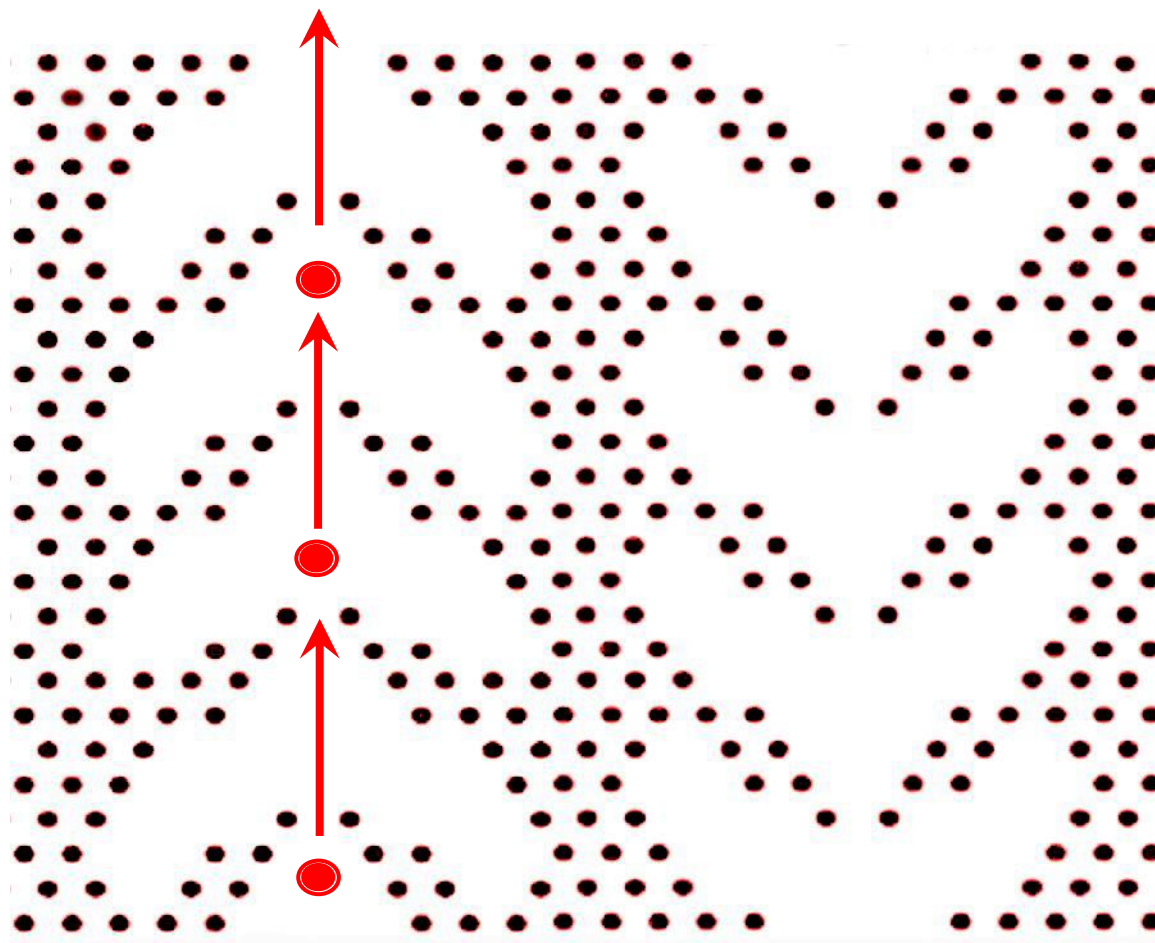
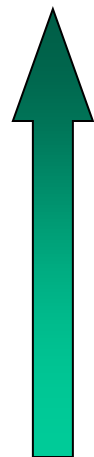
Array of  
Pinning  
Centers

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**Vortex ratchet system**

Externally applied drive

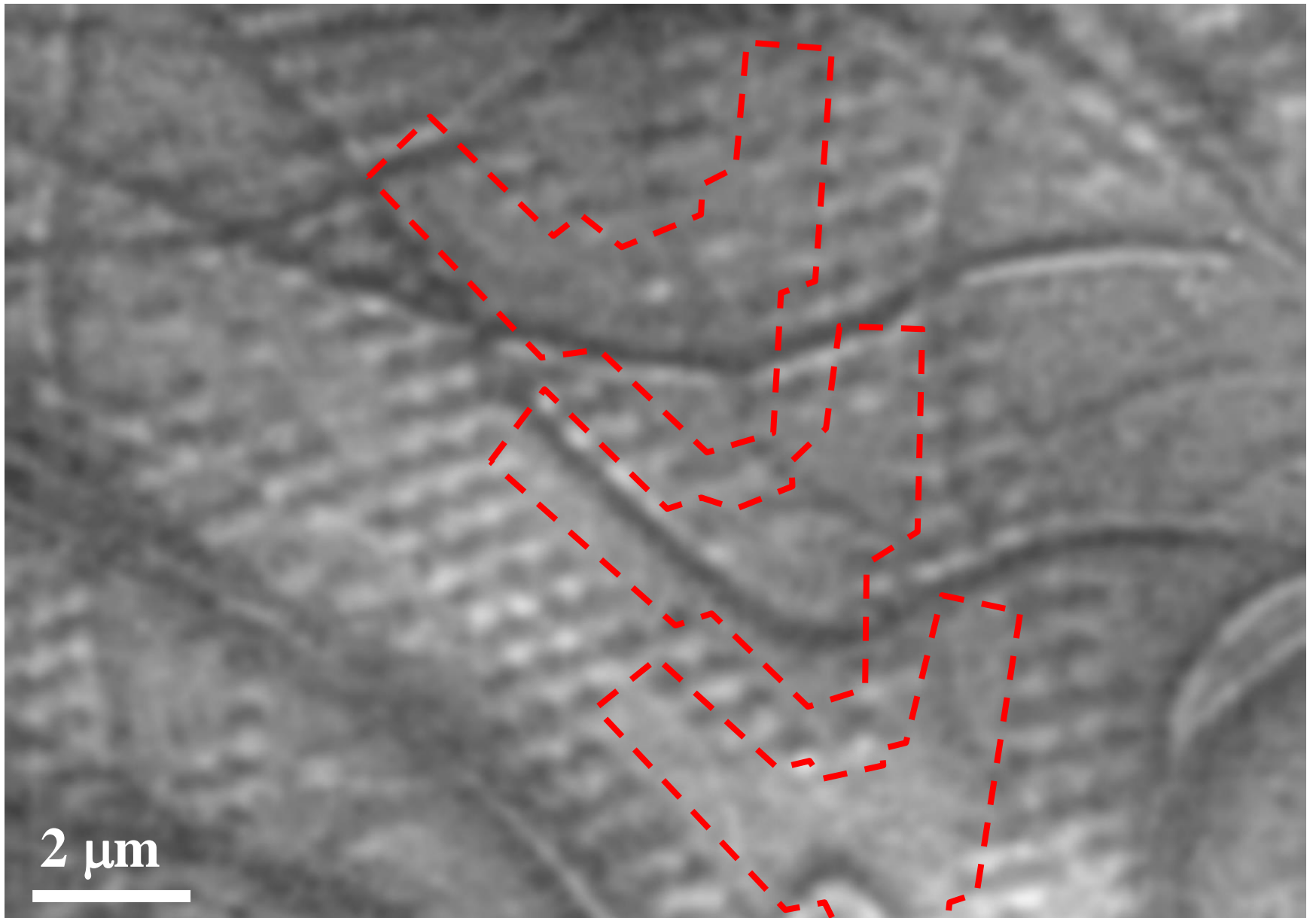


Array of  
Pinning  
Centers

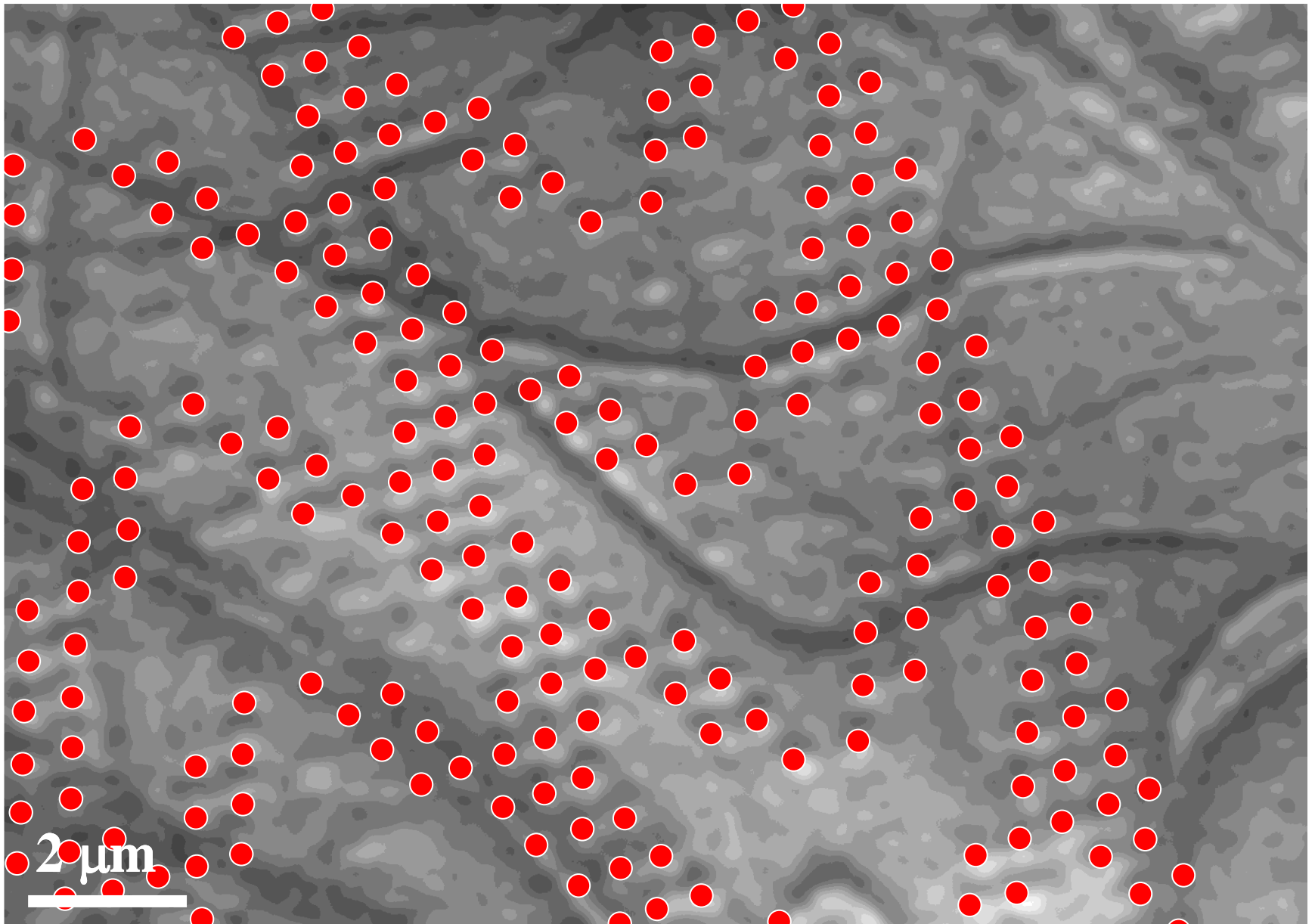
“funnel”

“trap”

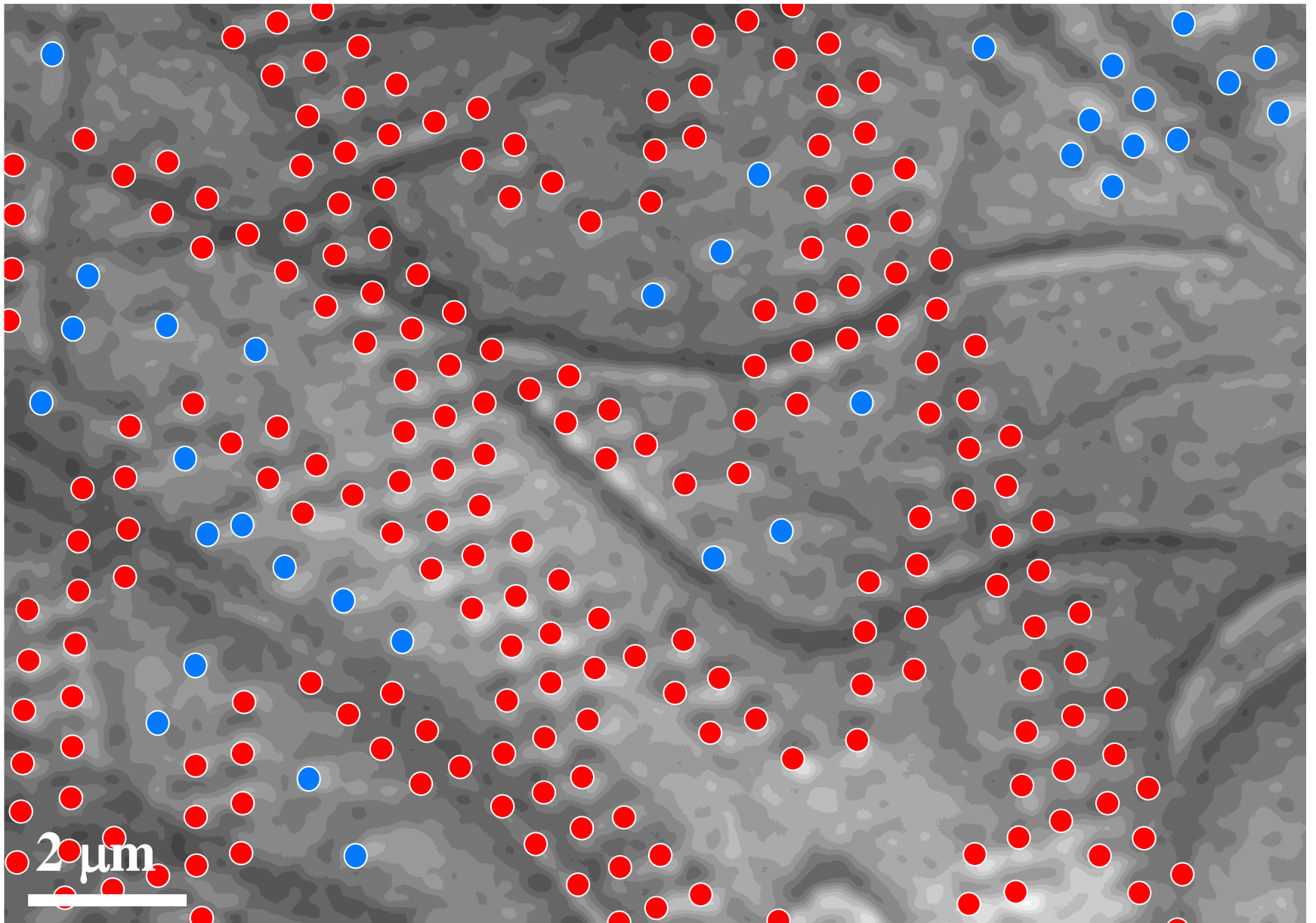
**Vortex ratchet system**



**Lorentz Micrograph of Vortices in Ratchets**

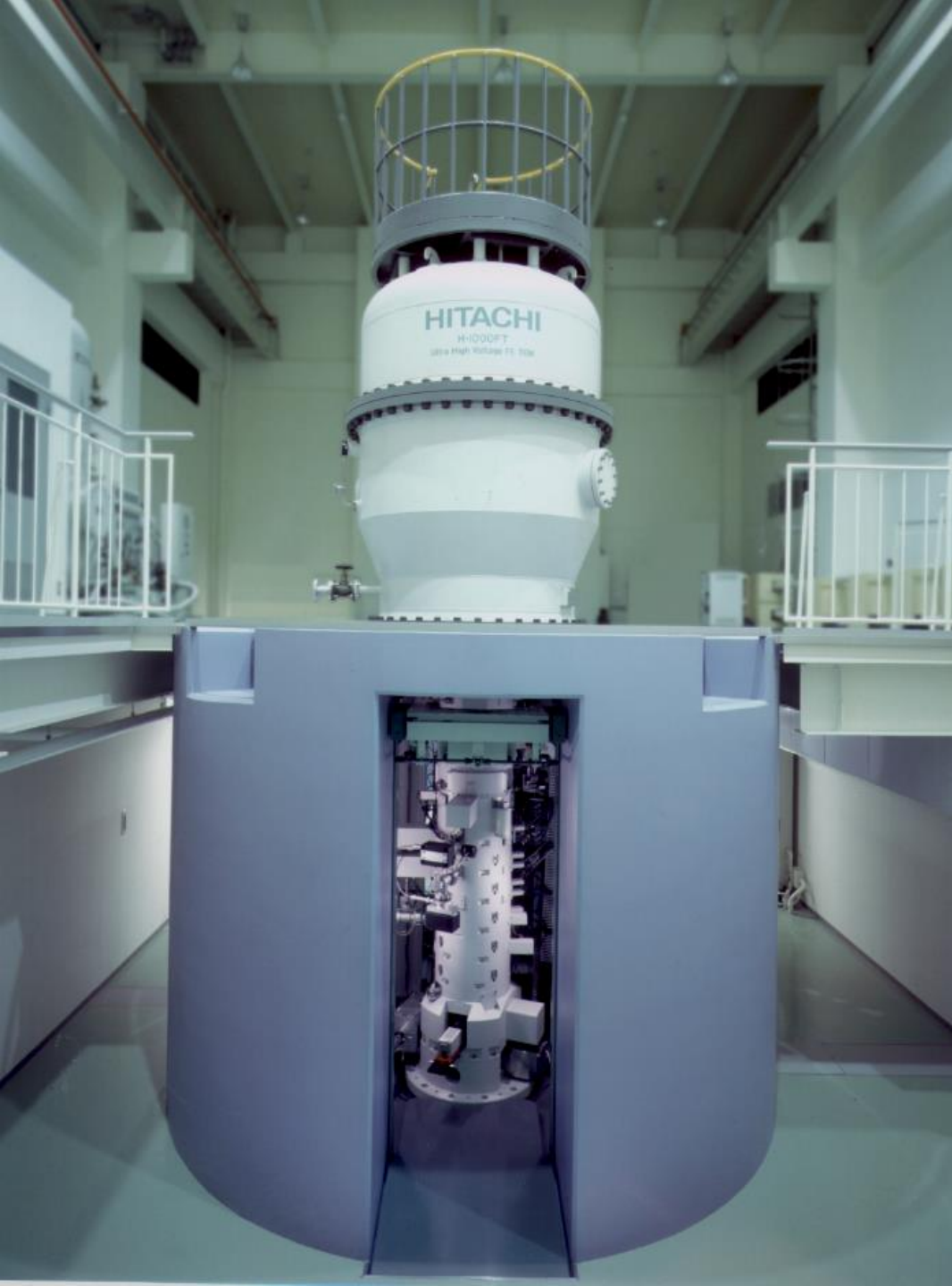


**Lorentz Micrograph of Vortices in Ratchets**

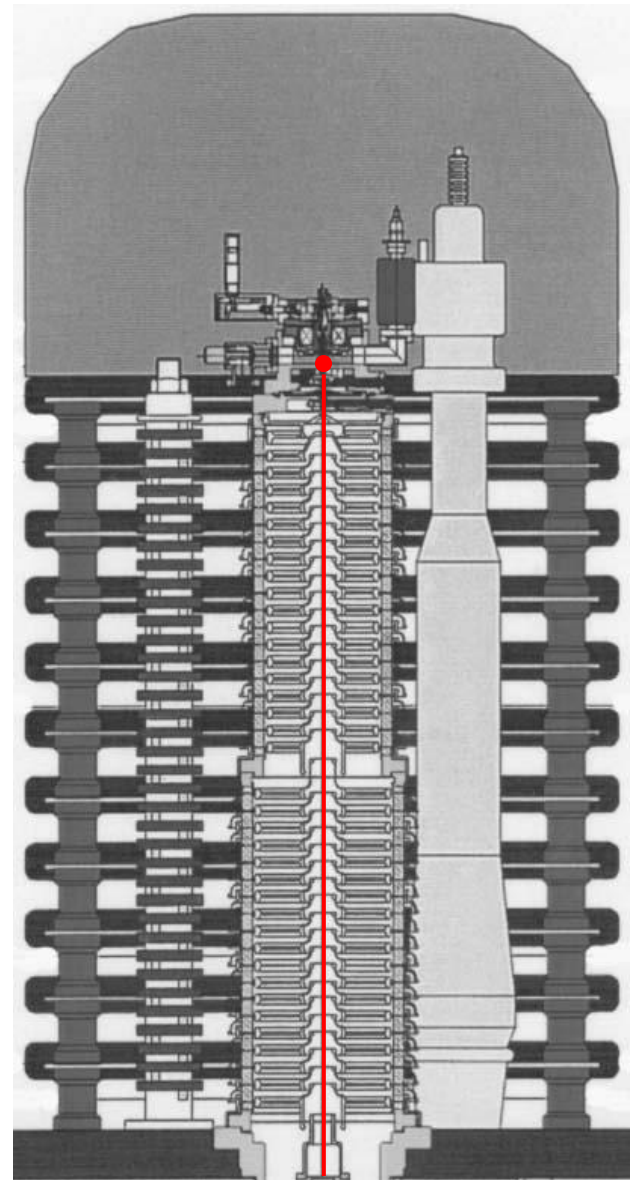
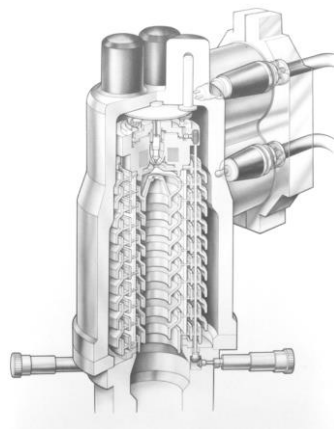
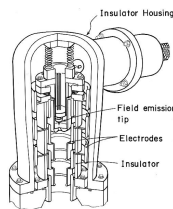
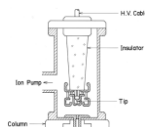
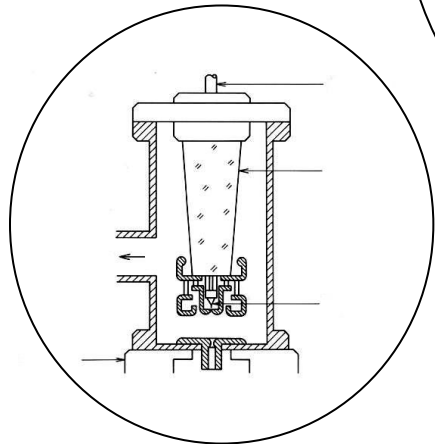
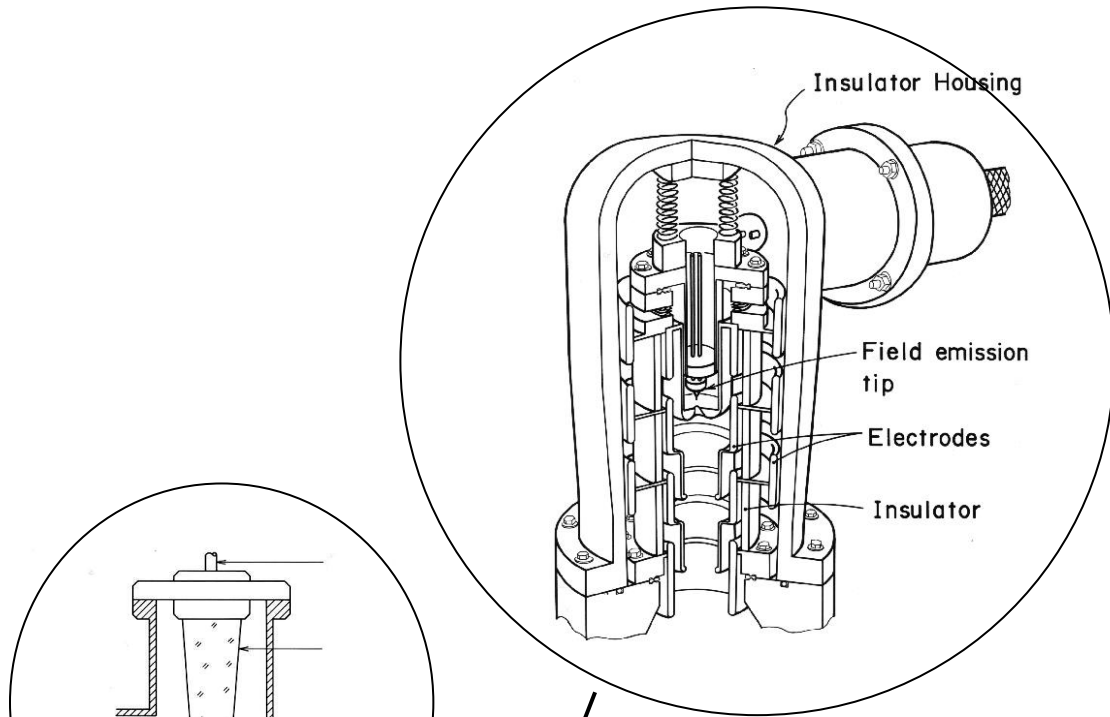


**Lorentz Micrograph of Vortices in Ratchets**

**Dynamics of Untrapped Vortices (  $\times 1.5$  )**



# **1-MV Holography Electron Microscope**



**80kV('78)**

**125kV('80)**

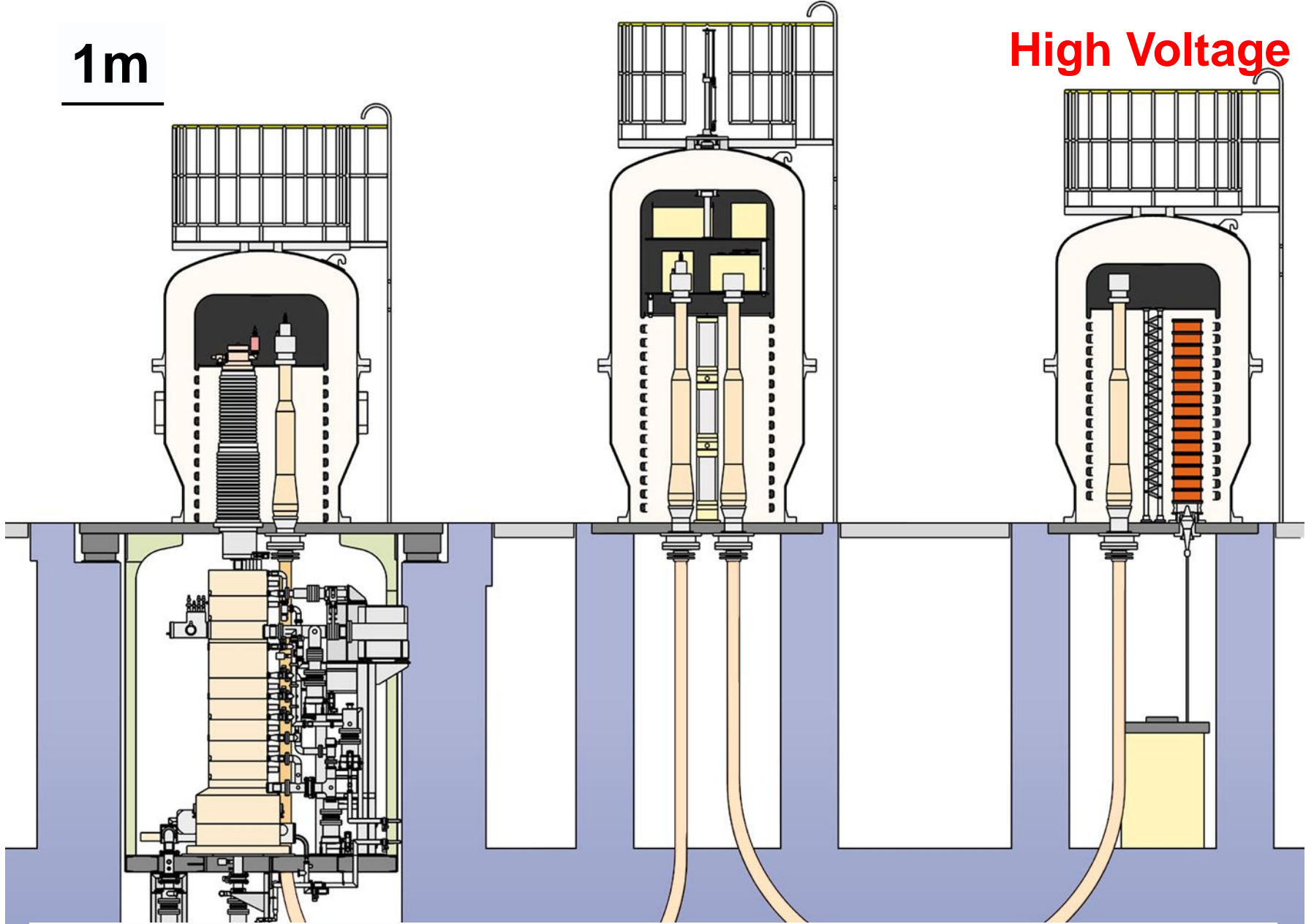
**350kV('89)**

**1MV('00)**

# Field Emission Electron Guns

1m

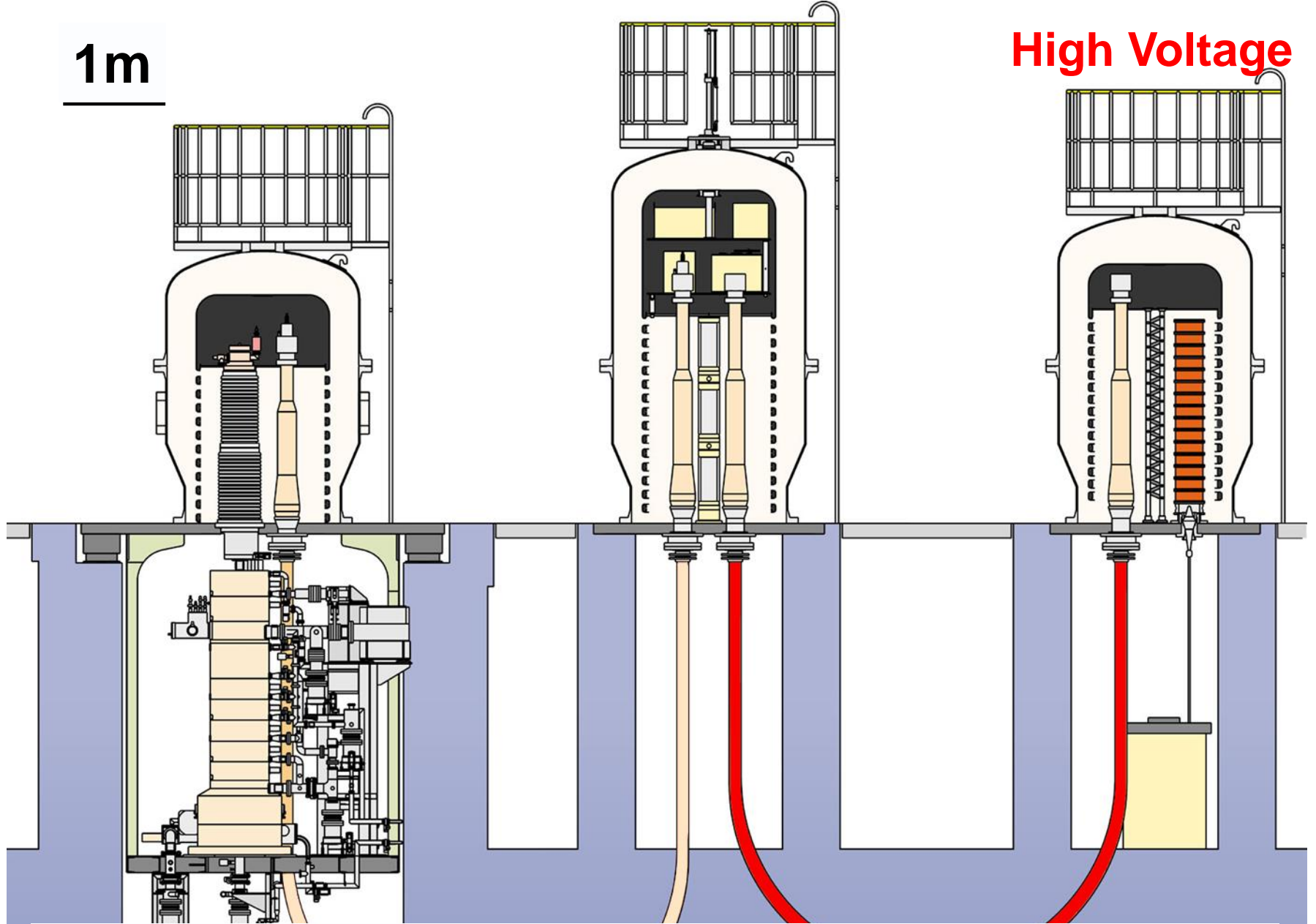
High Voltage



**1-MV Holography Electron Microscope**

1m

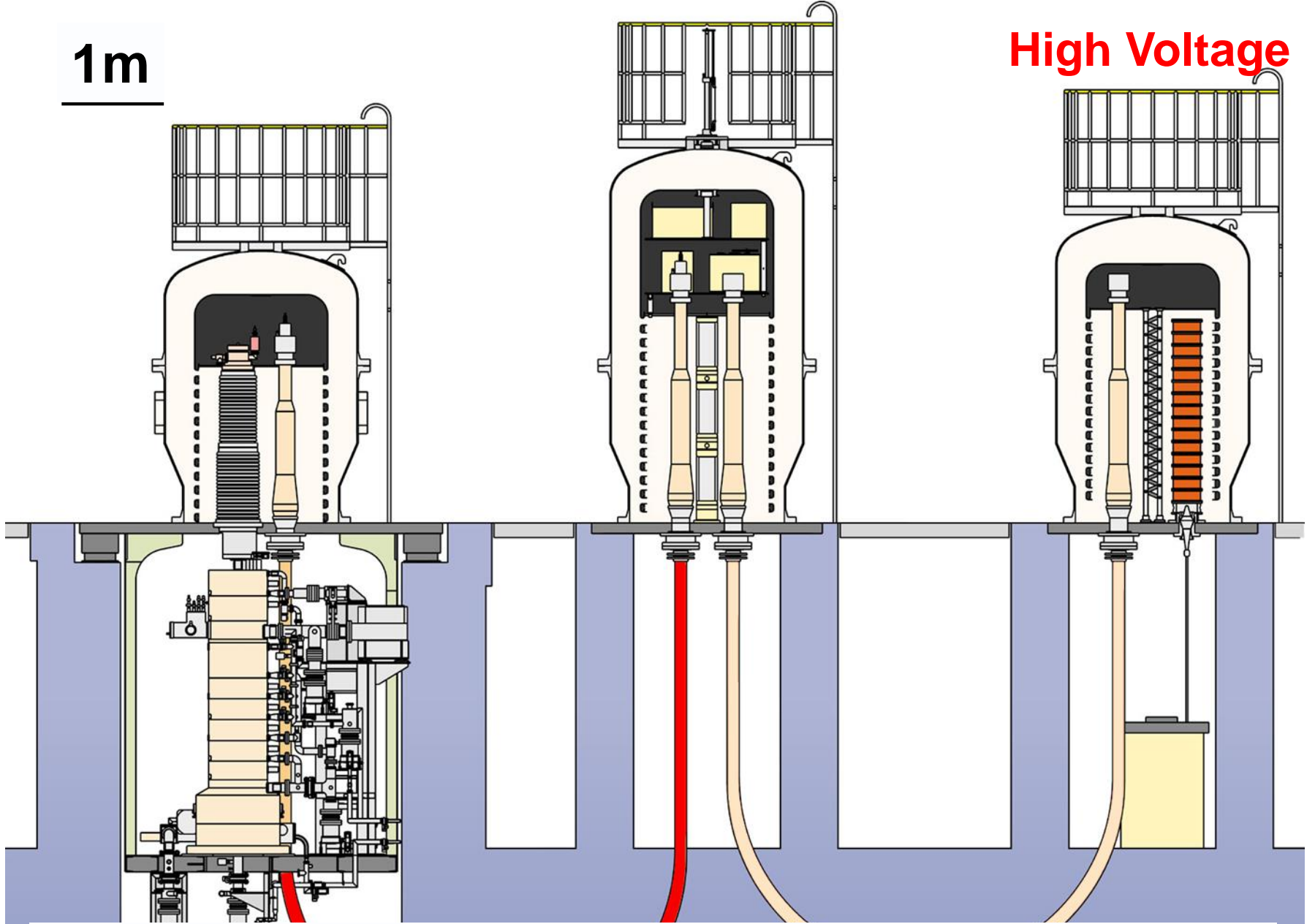
High Voltage



**1-MV Holography Electron Microscope**

1m

High Voltage



**1-MV Holography Electron Microscope**

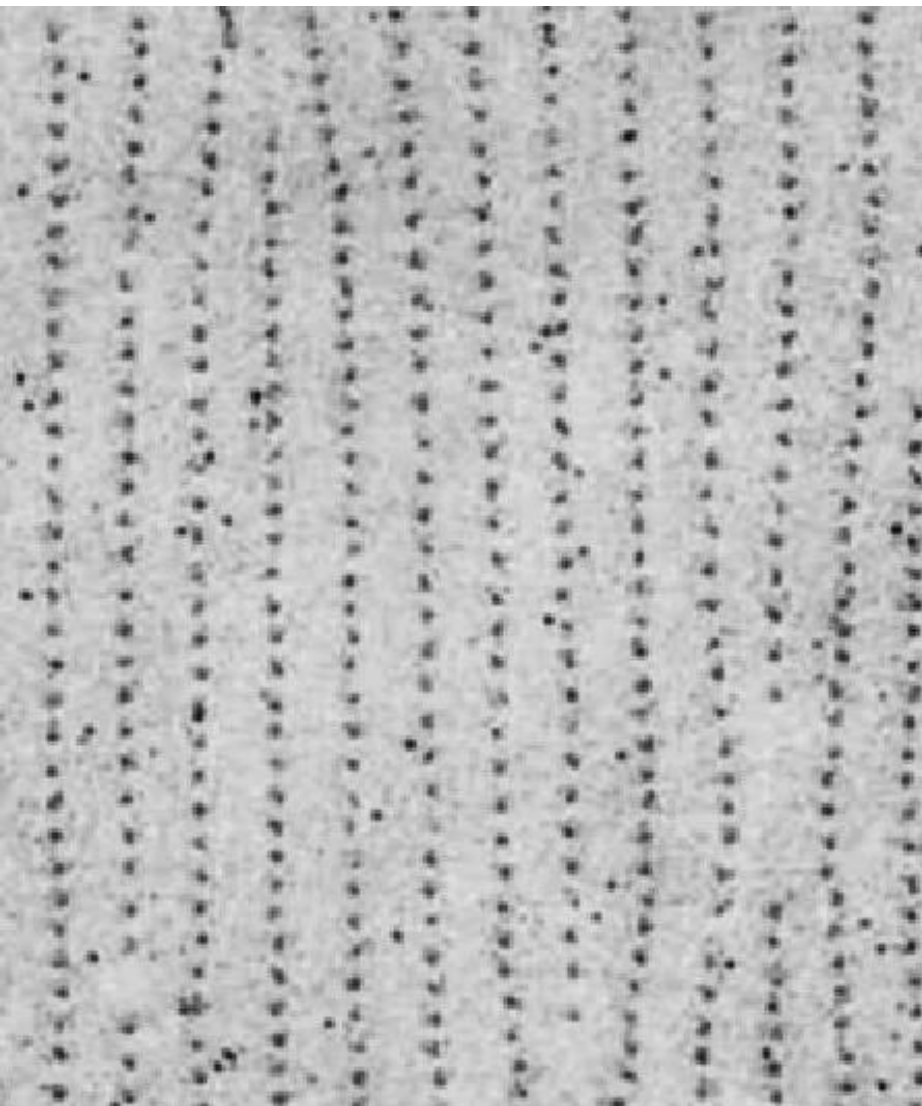


# 1MV Holography Electron Microscope

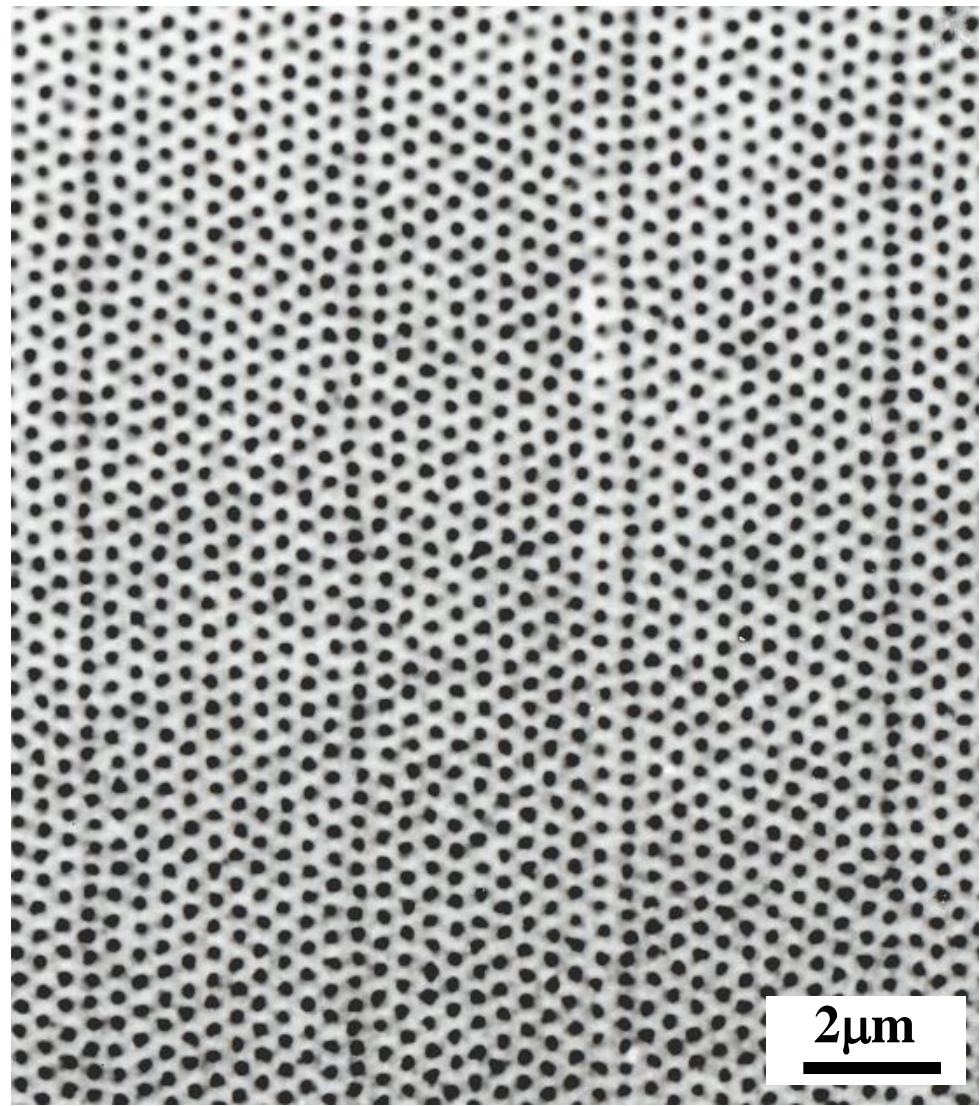
- Brightest electron beam
- Highest lattice resolution



**Bitter Figure of Triangular Lattice of Vortices**



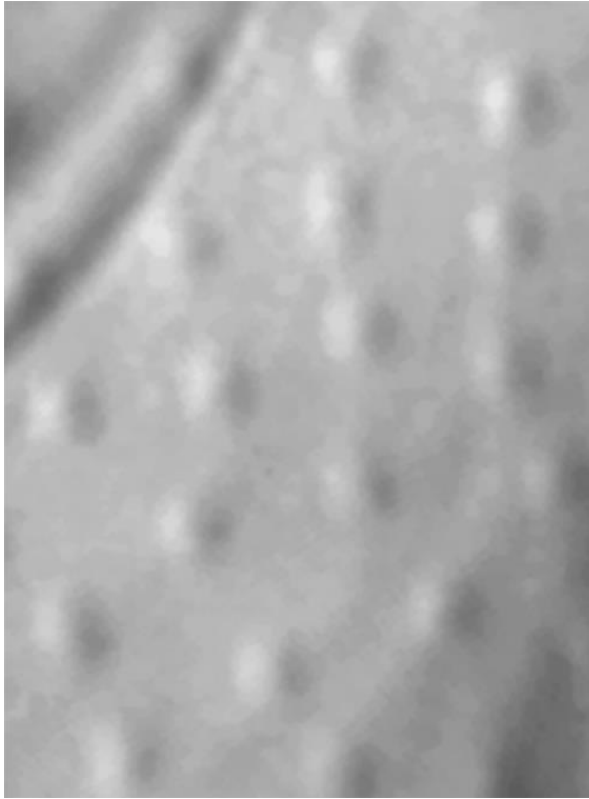
**YBCO**



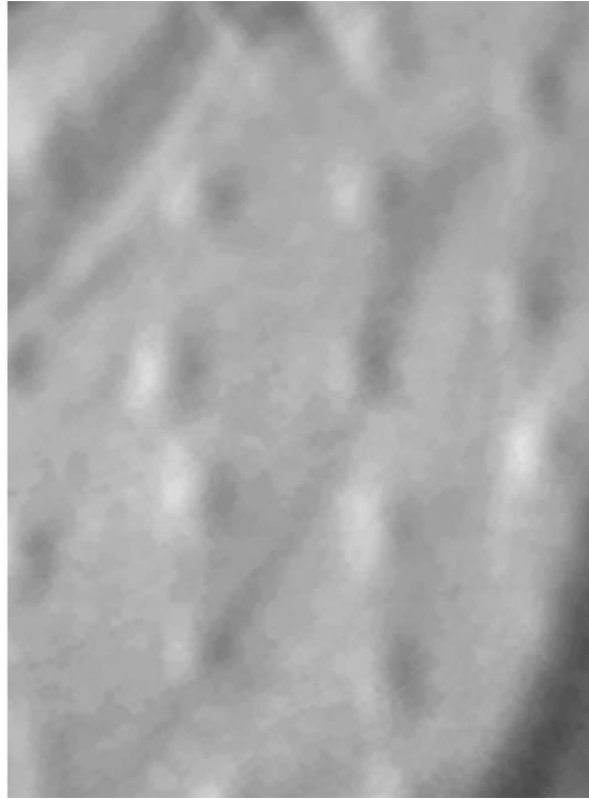
**Bi-2212**

**Observation of Chain Structures of Vortices by Bitter Method**

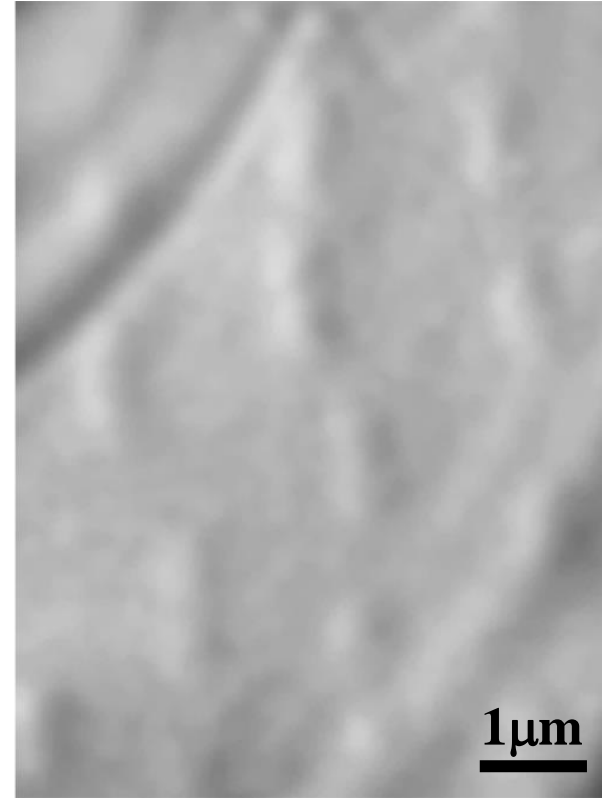
(Gammel *et al.*)



$$\theta = 75^\circ$$



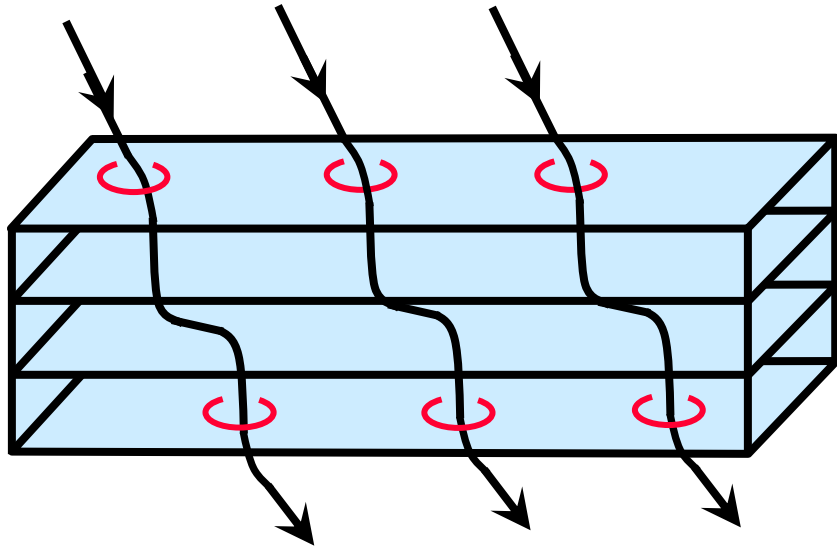
$$\theta = 82^\circ$$



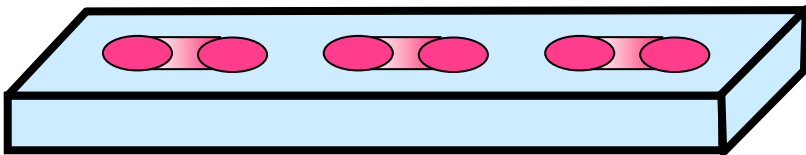
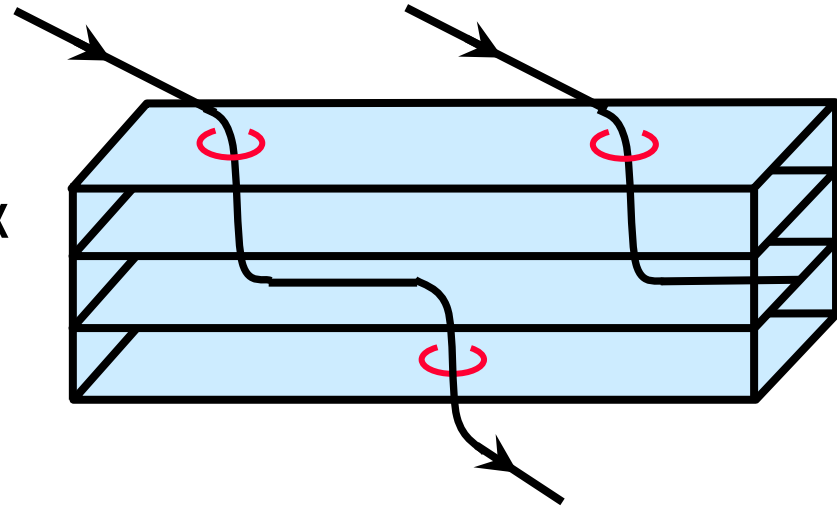
$$\theta = 83^\circ$$

## Vortex Images in YBCO at Tilted Magnetic Field

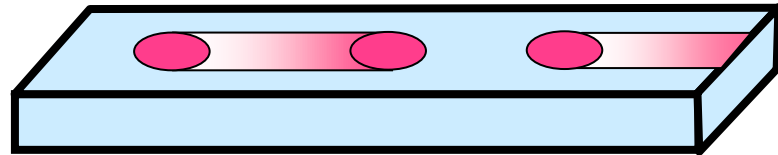
Magnetic field



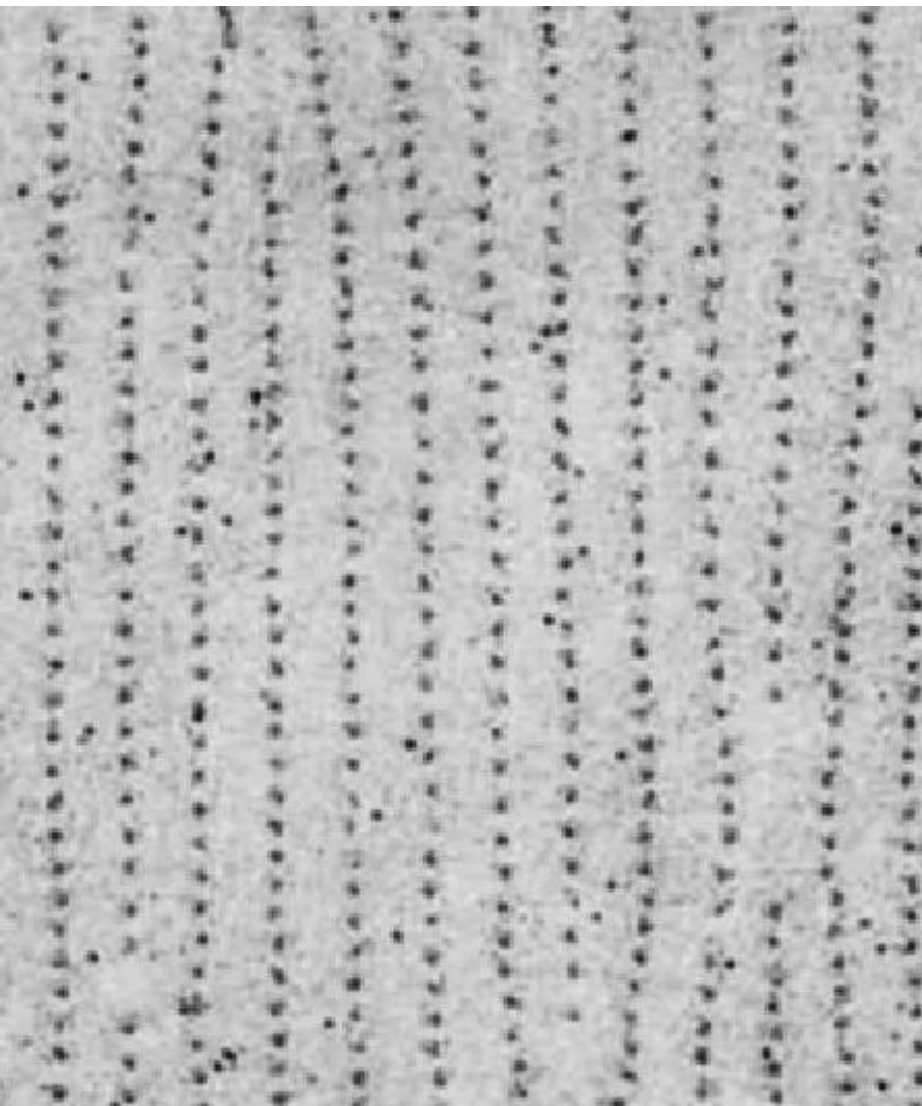
Vortex lines



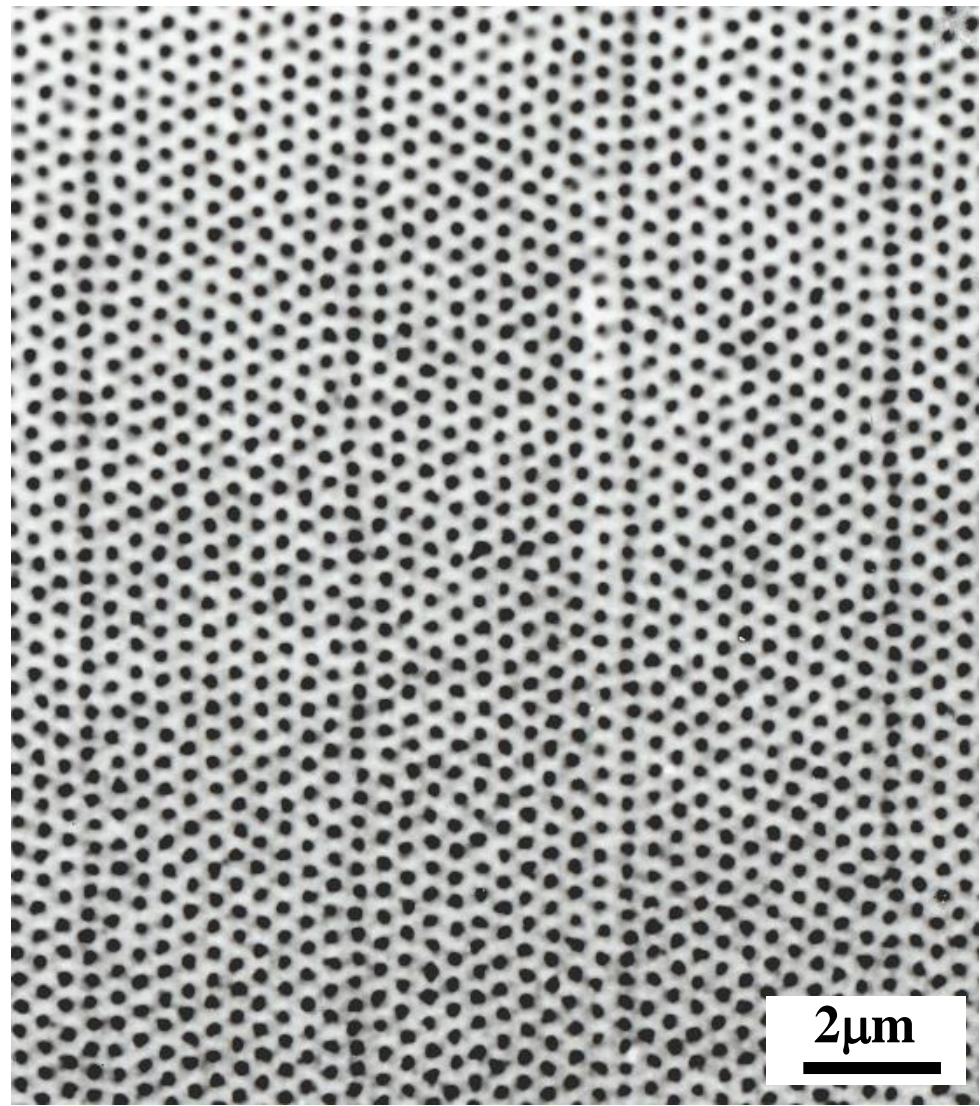
Lorentz micrograph



**What happens when the magnetic field tilts?**



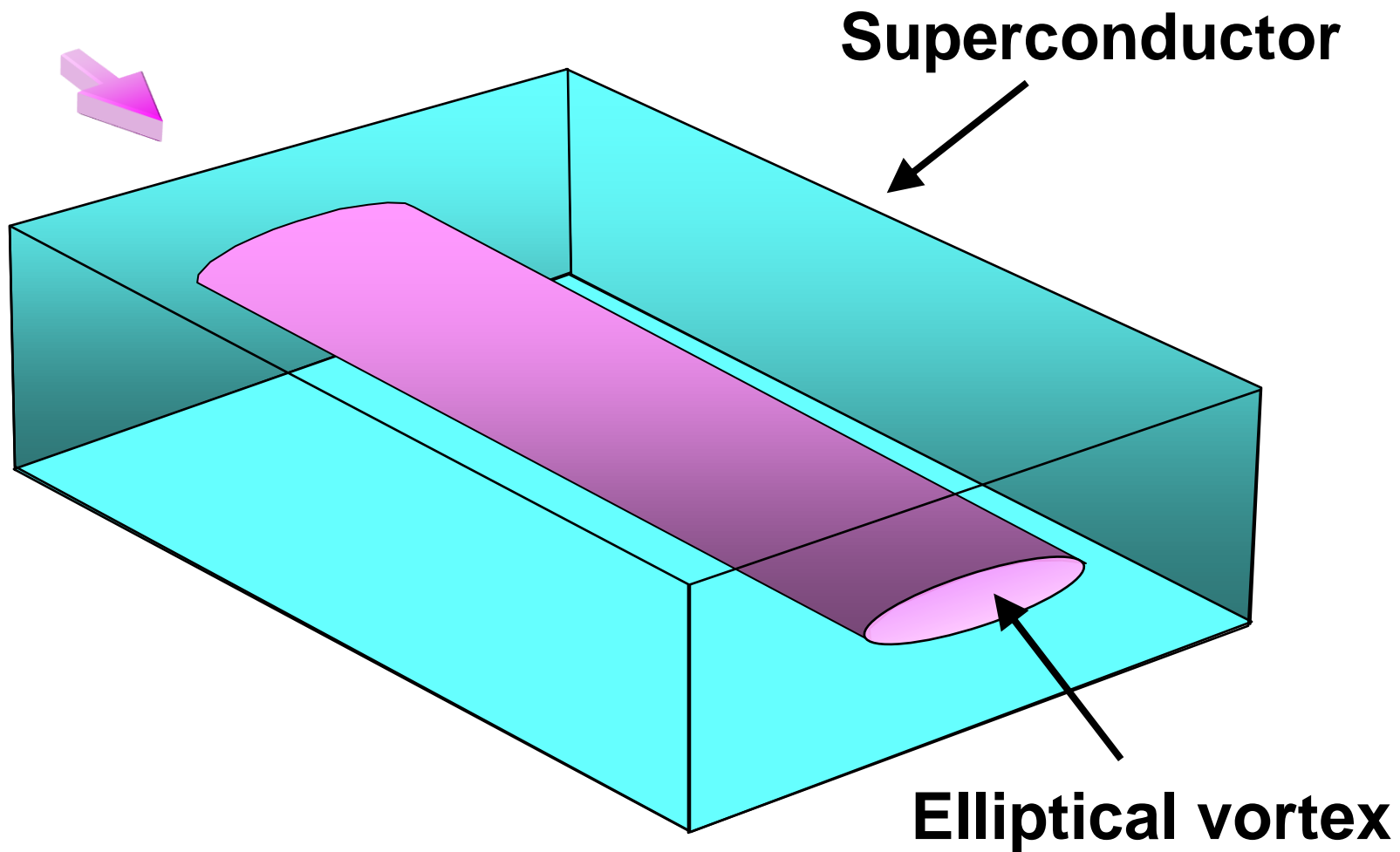
**YBCO**



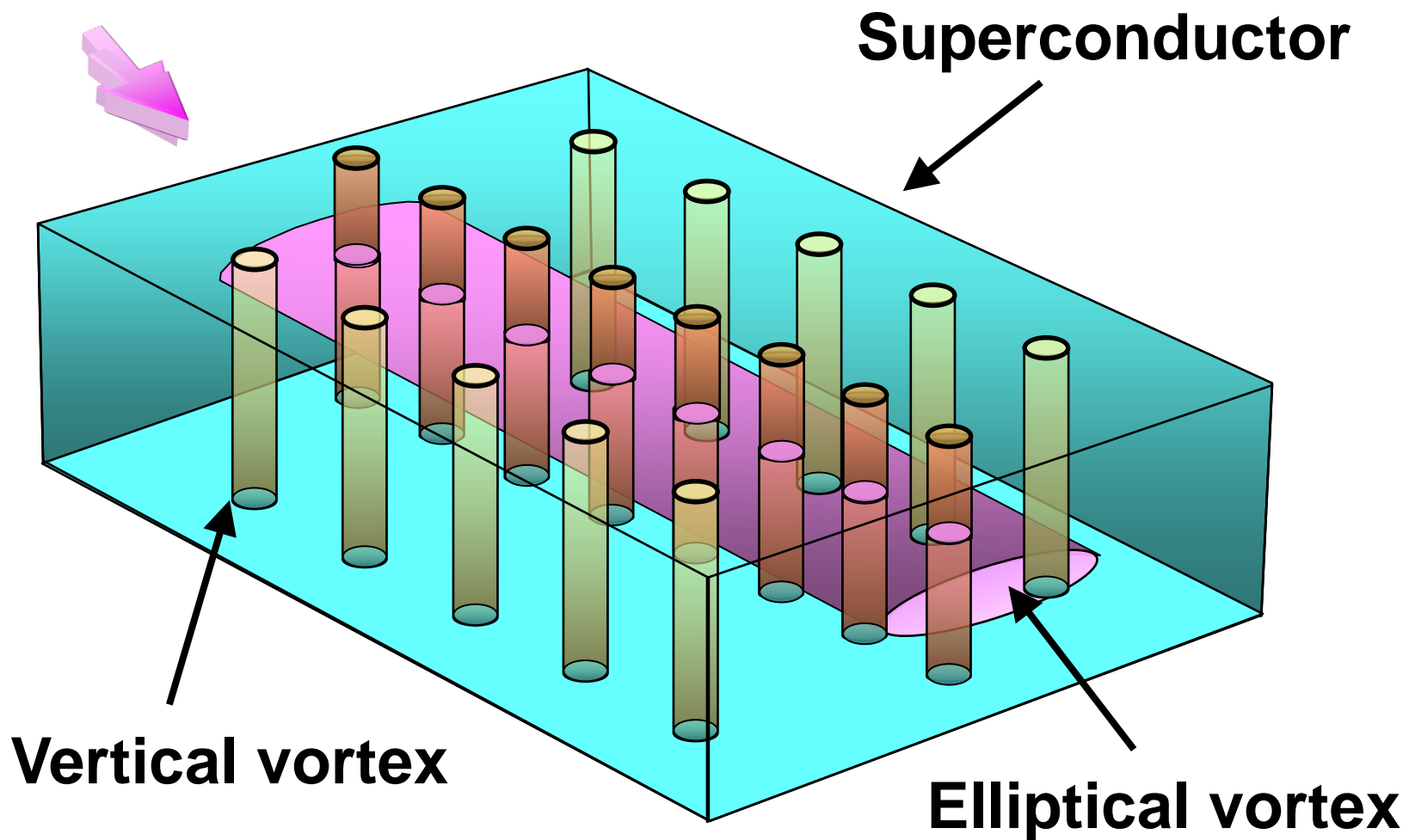
**Bi-2212**

**Observation of Chain Structures of Vortices by Bitter Method**

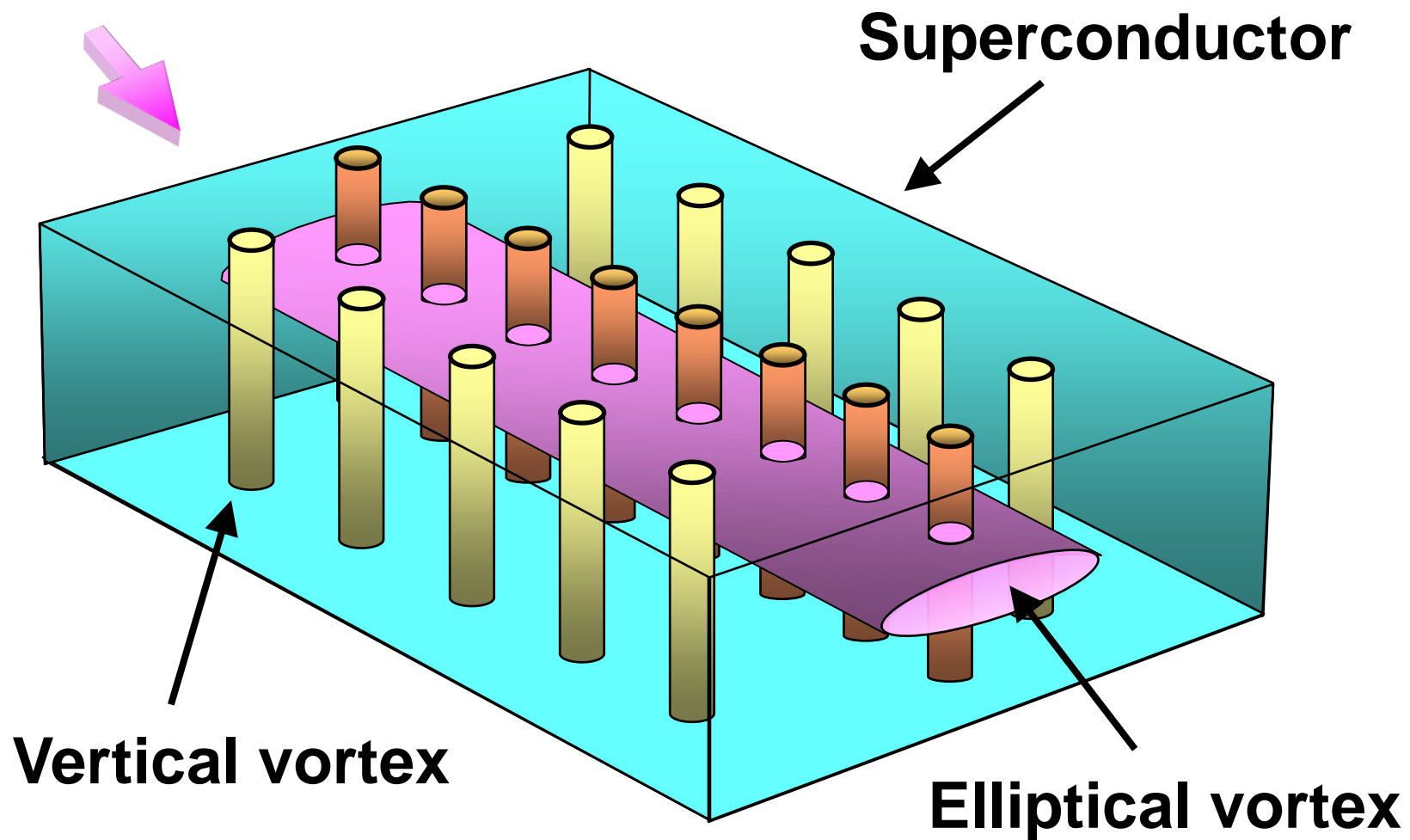
(Gammel *et al.*)



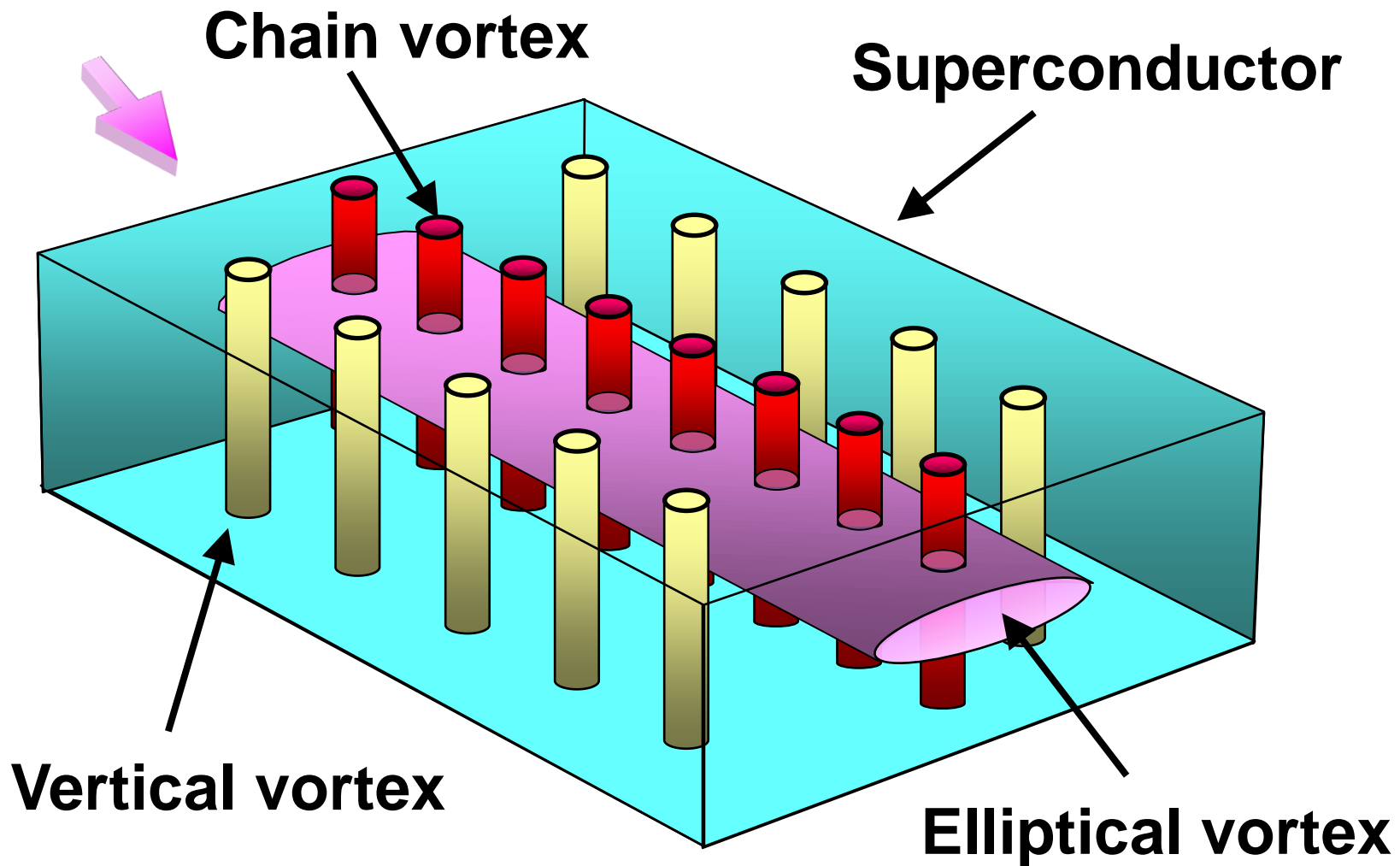
**Chain-Lattice State in Bi-2212**



**Chain-Lattice State in Bi-2212**



**Chain-Lattice State in Bi-2212**



**Chain-Lattice State in Bi-2212**

Chain



A



C

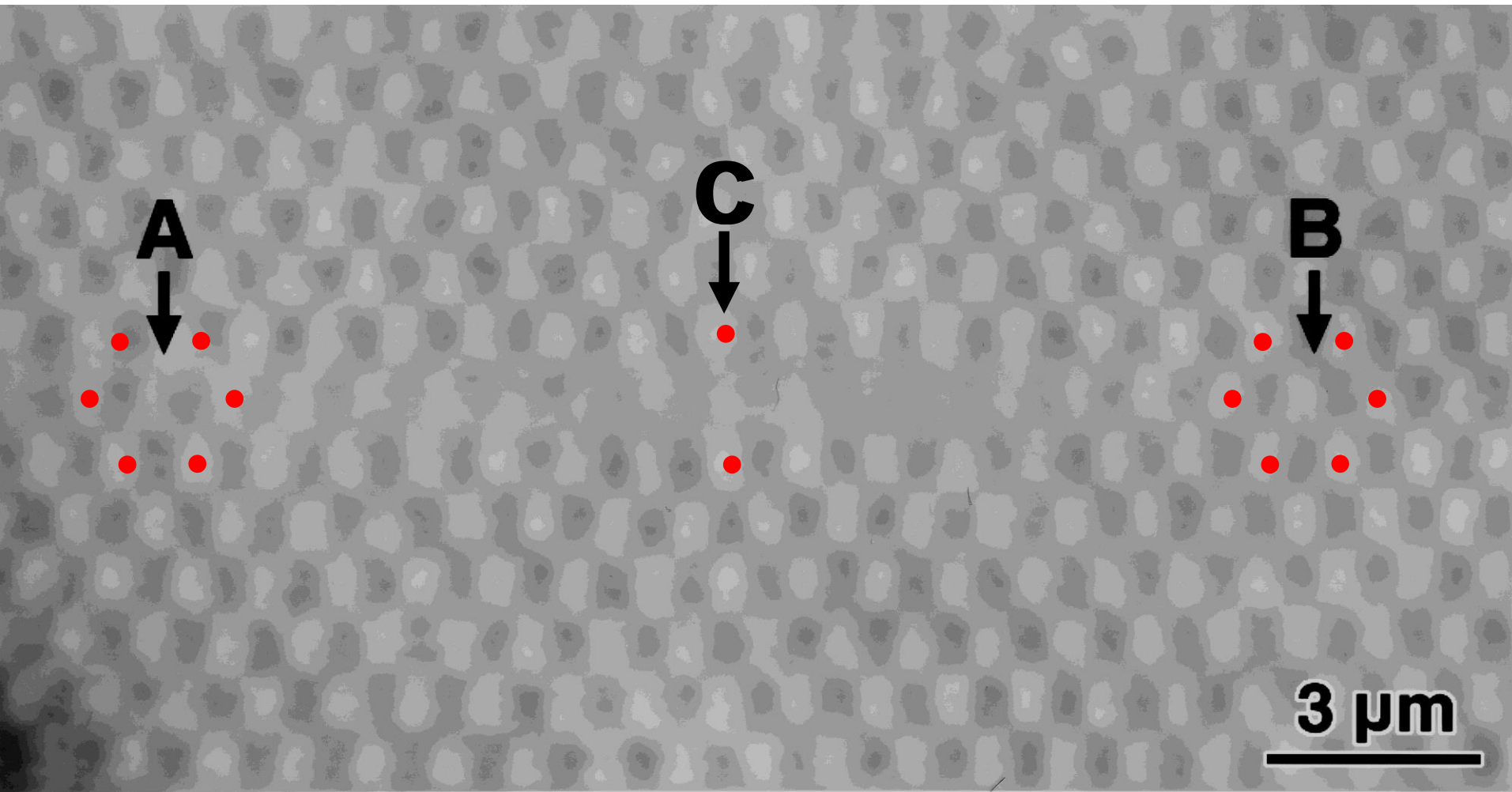


B



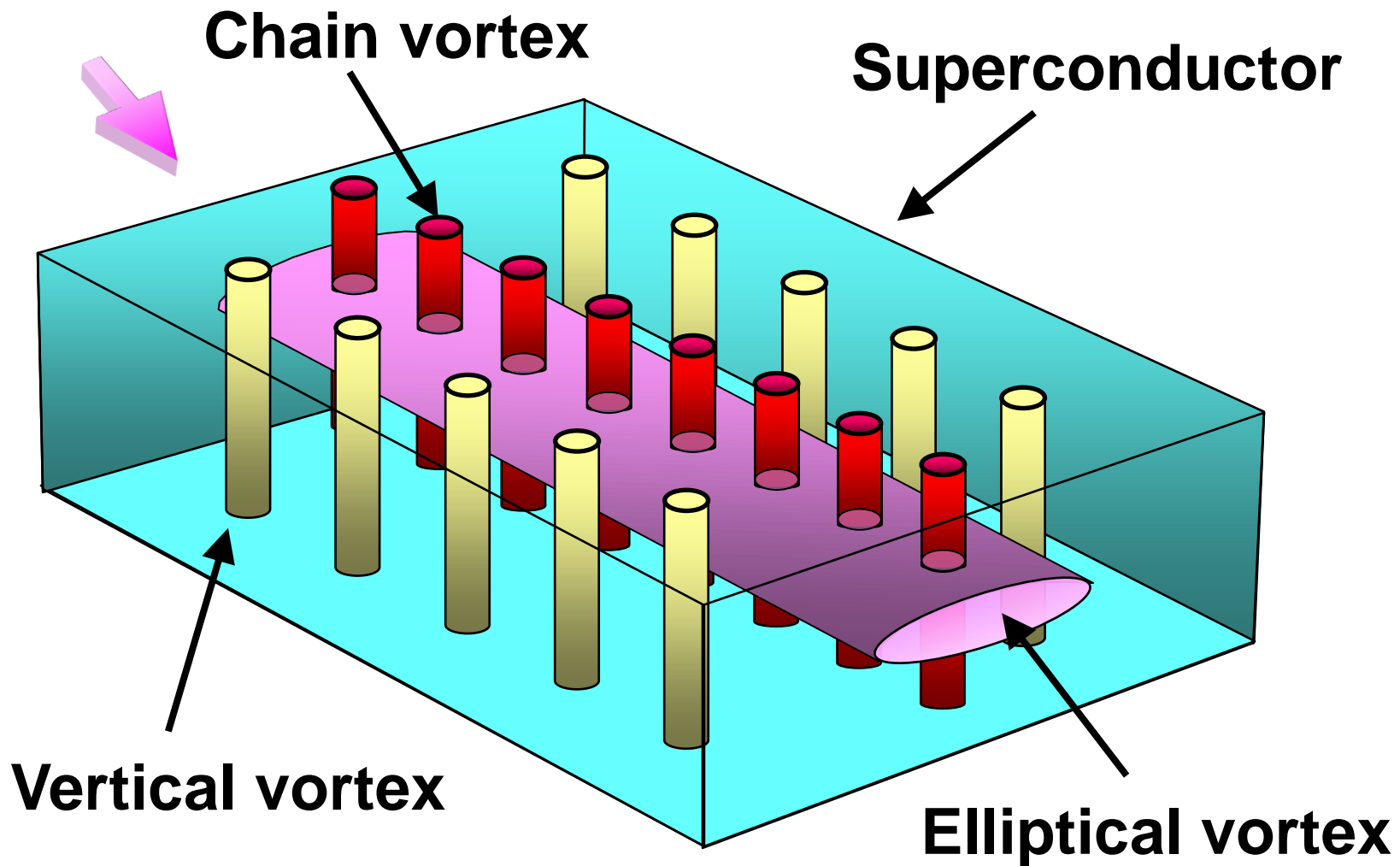
3μm

**Disappearance of Images of Chain Vortices (70K)**

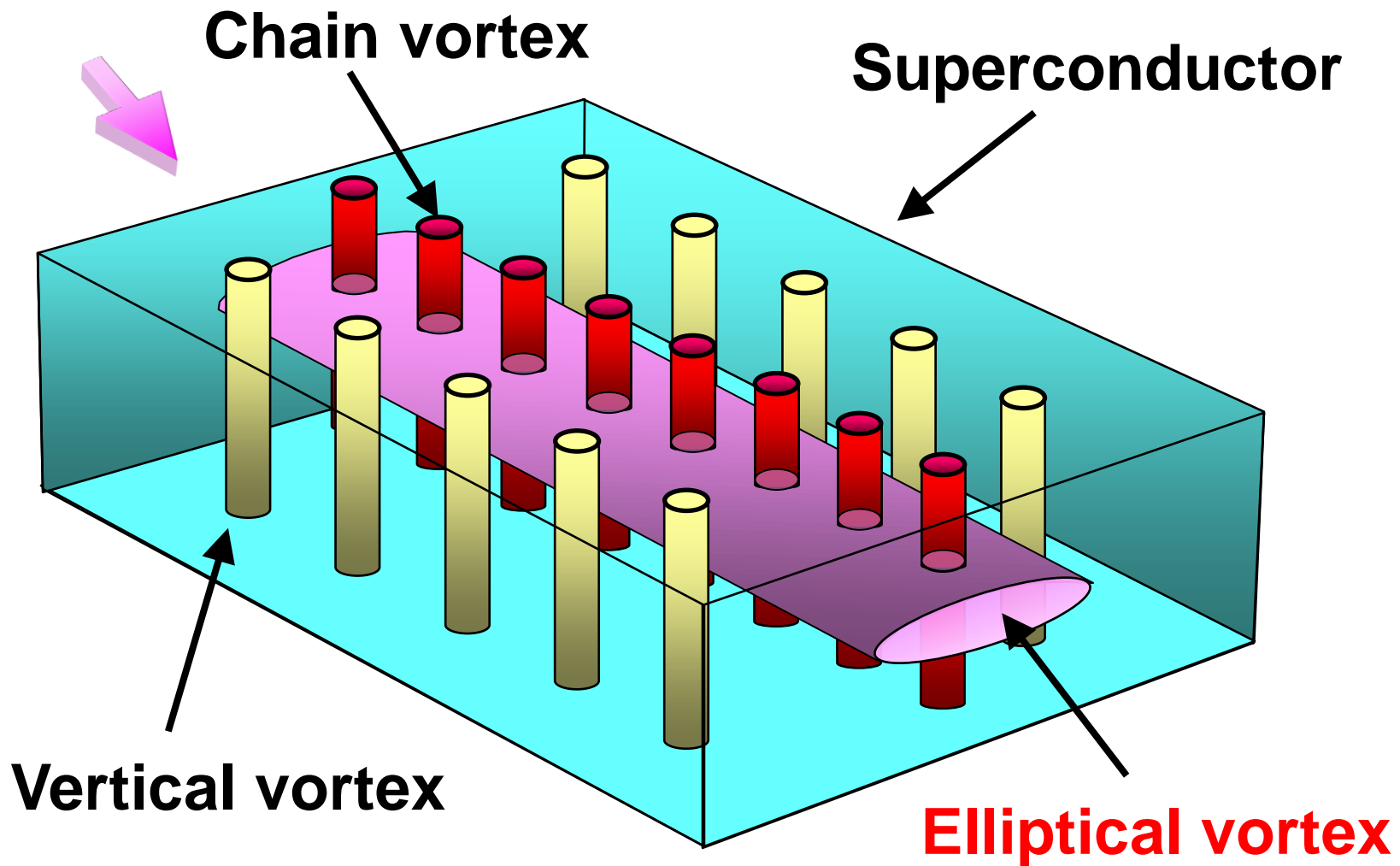


## Disappearance of Images of Chain Vortices (57 K)

Science, 294 (2001) 2041

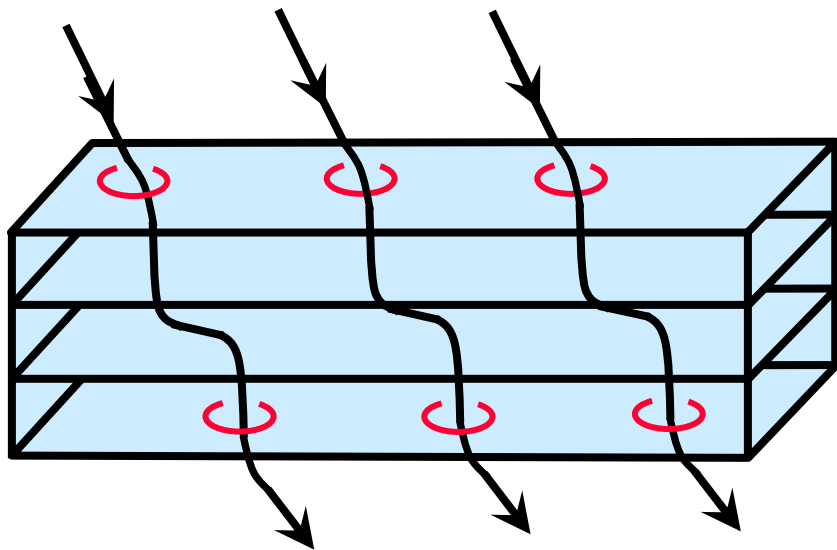


**Chain-Lattice State in Bi-2212**

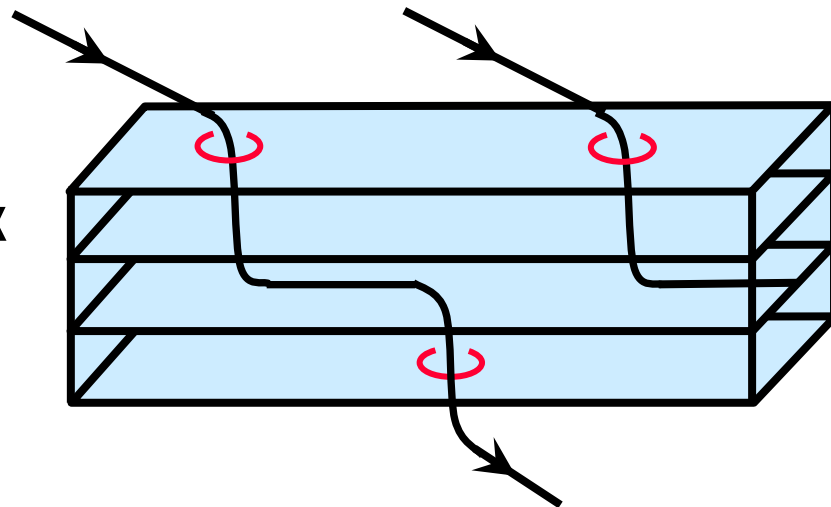


**Chain-Lattice State in Bi-2212**

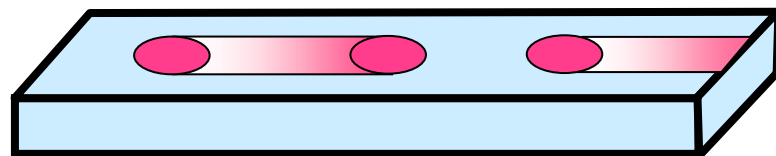
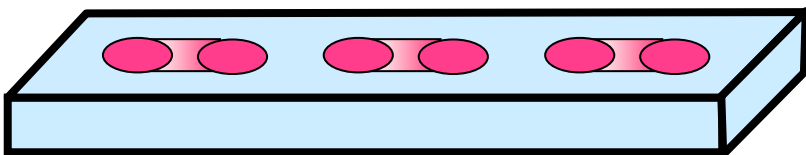
Magnetic field



Vortex lines



Lorentz micrograph



**What happens when the magnetic field tilts?**

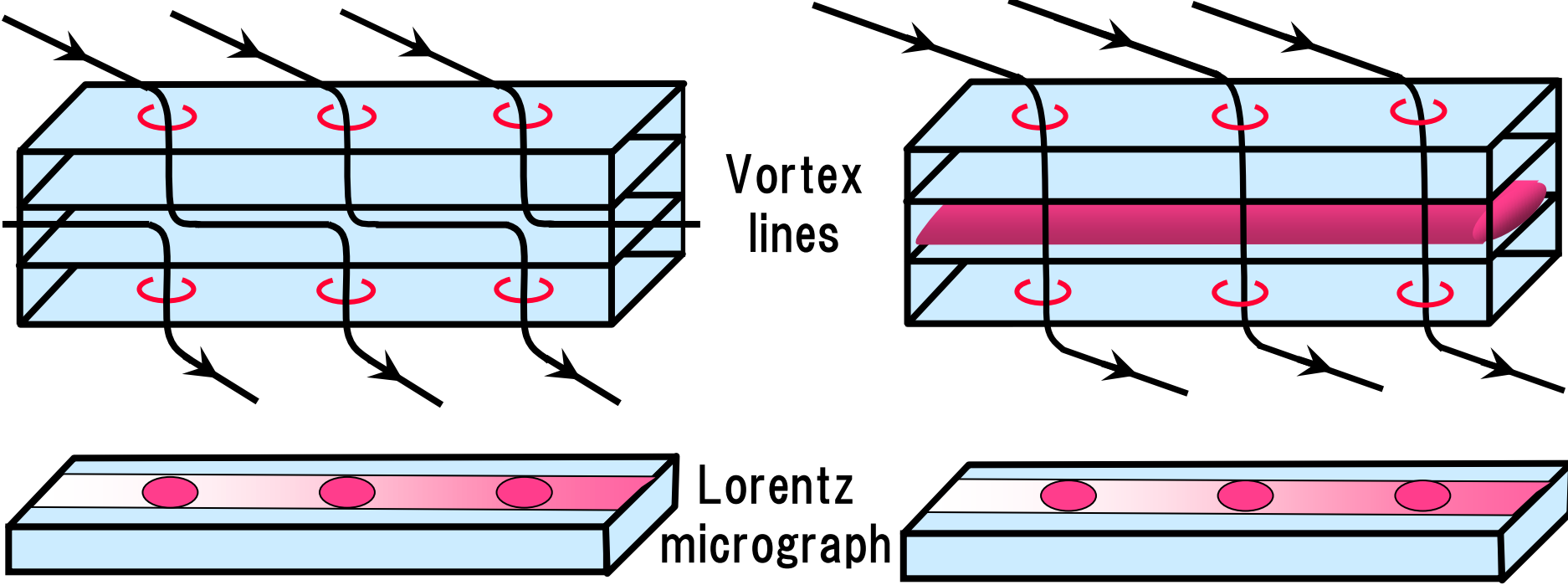
Magnetic field

Reconnected ?

Vortex lines

Lorentz micrograph

What happens when two neighboring vortices overlap ?



# RIKEN Frontier Research System

“Single Quantum Dynamics” (Leader : Akira Tonomura)



**Quantum Phenomena  
Observation Technology  
Team**

**Akira Tonomura**

**(Hitachi)**



**Macroscopic  
Quantum  
Coherence Team**

**Jaw-Shen Tsai**

**(NEC)**



**Digital Materials  
Team**

**Franco Nori**

**(Univ. of Michigan)**



**Quantum Nano-Scale  
Magnetics Team**

**Yoshichika Otani**

沖縄大学院大学先行的研究事業



# Initial Research Project

## Okinawa Institute of Science and Technology



## Principal Investigator

**Doya Unit**  
**Neural Computation Unit**

**A Computational  
Approach to Molecular  
Mechanism of the Mind**



**Dr. Kenji Doya**

**Endo Unit**  
**Molecular Neurobiology  
of Learning & Memory**

**Genetic and Molecular  
Dissection of Learning and  
Memory**



**Dr. Shogo Endo**

**Tonomura Unit**  
**Electron Microscopy Unit**

**Holography Electron  
Microscopy Dedicated  
to Nanotechnology**



**Dr. Akira Tonomura**

**Yanagida Unit**  
**Go Cell Unit**

**Cellular Strategy for  
Starved Go Arrest and  
Vegetative Proliferation**



**Dr. Mitsuhiro Yanagida**