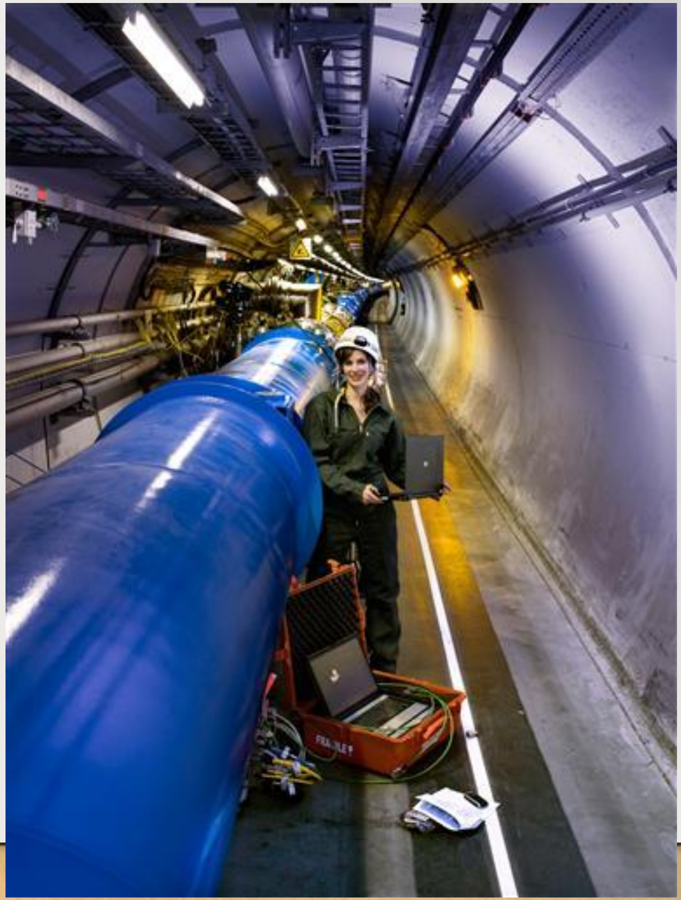
1

Superconducting Magnet I Conductor



CERN LHC

Item

- Superconductivity
- Superconducting Wire and Cables
- Stability and Quench Protection
- Summary

Item

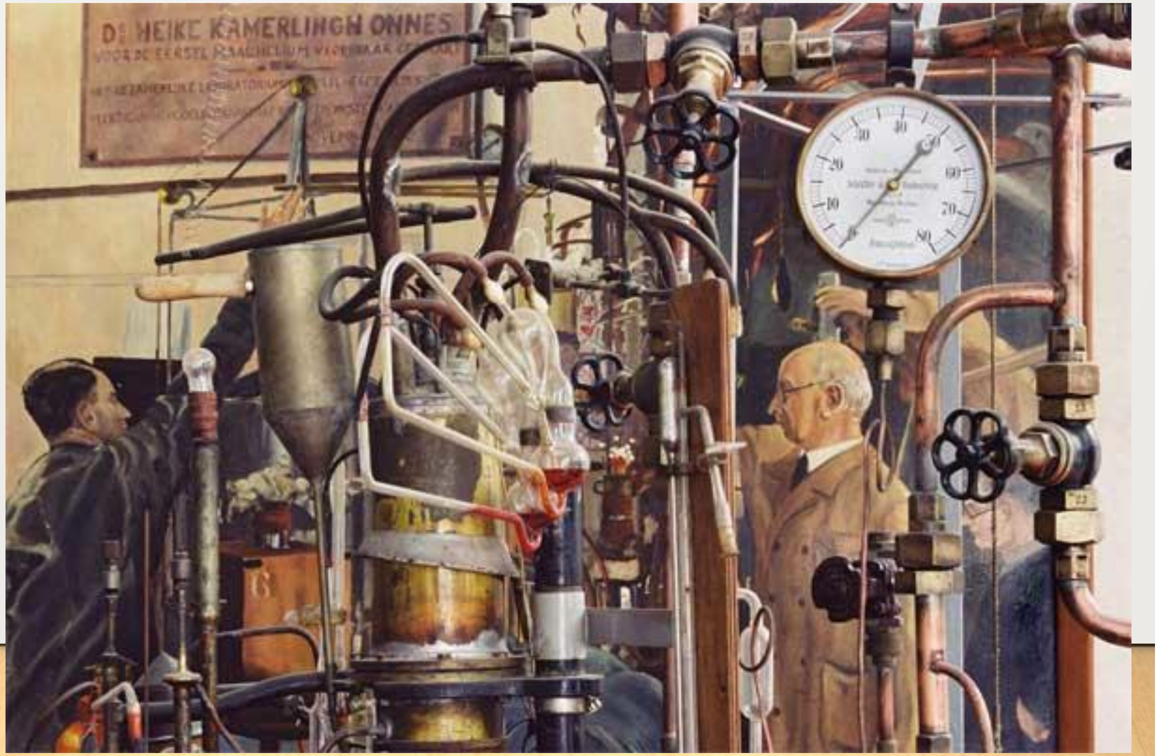
- **Superconductivity**
- Superconducting Wire and Cables
- Stability and Quench Protection
- Summary

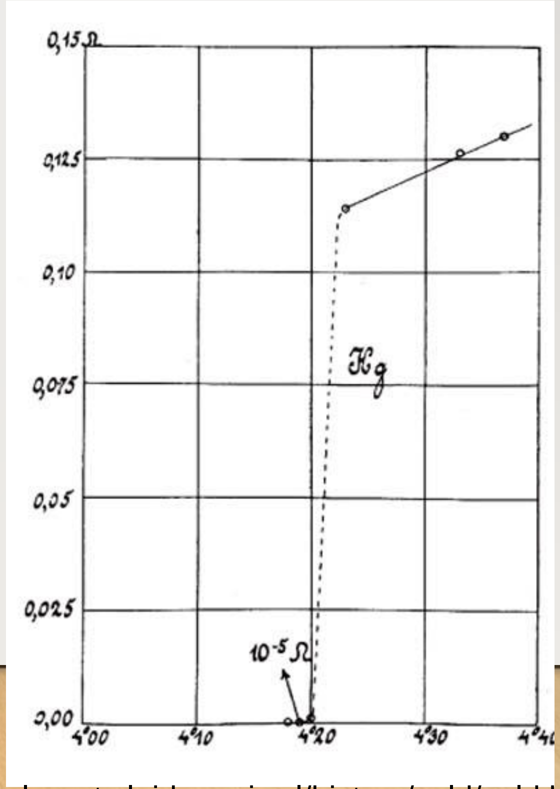
1911 Discovery!

- 1908 Helium liquified
- 1911 April 8th Discovery of Hg Supercon.
- 1913 10T Pb SC magnet proposal

  →Not realized (Critical Field: 0.08T)

Heike Kamerlingh Onnes (1853-1926)

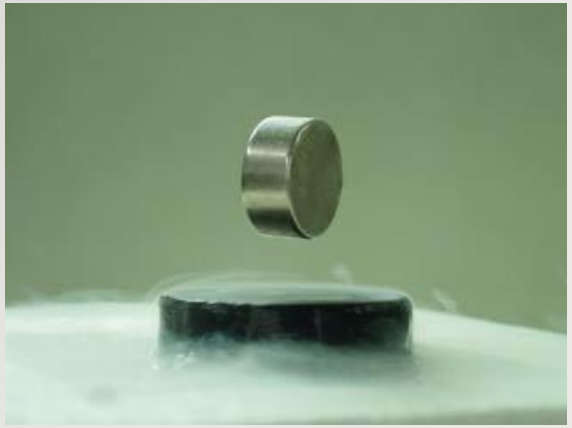


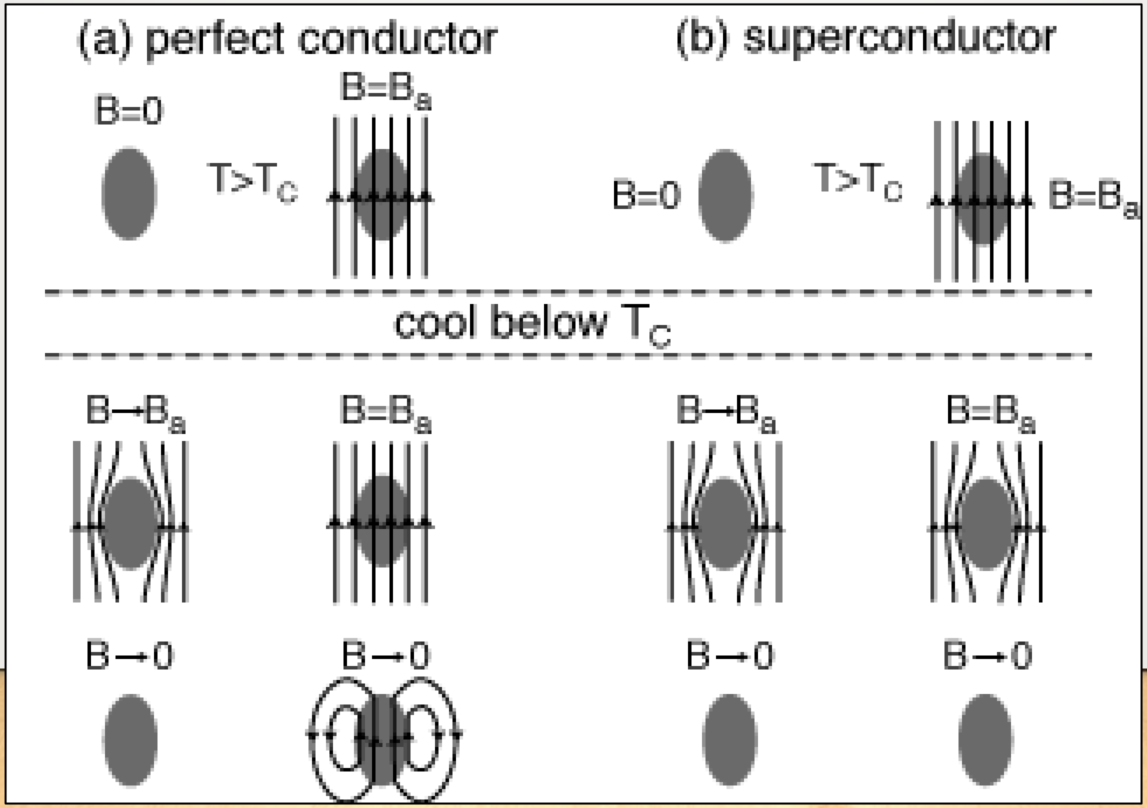


http://www.lorentz.leidenuniv.nl/history/cold/cold.html

5 1933 Meissner Effect

- Found by Fritz Meissner and Robert Ochsenfeld
- Perfect Diamagnetism



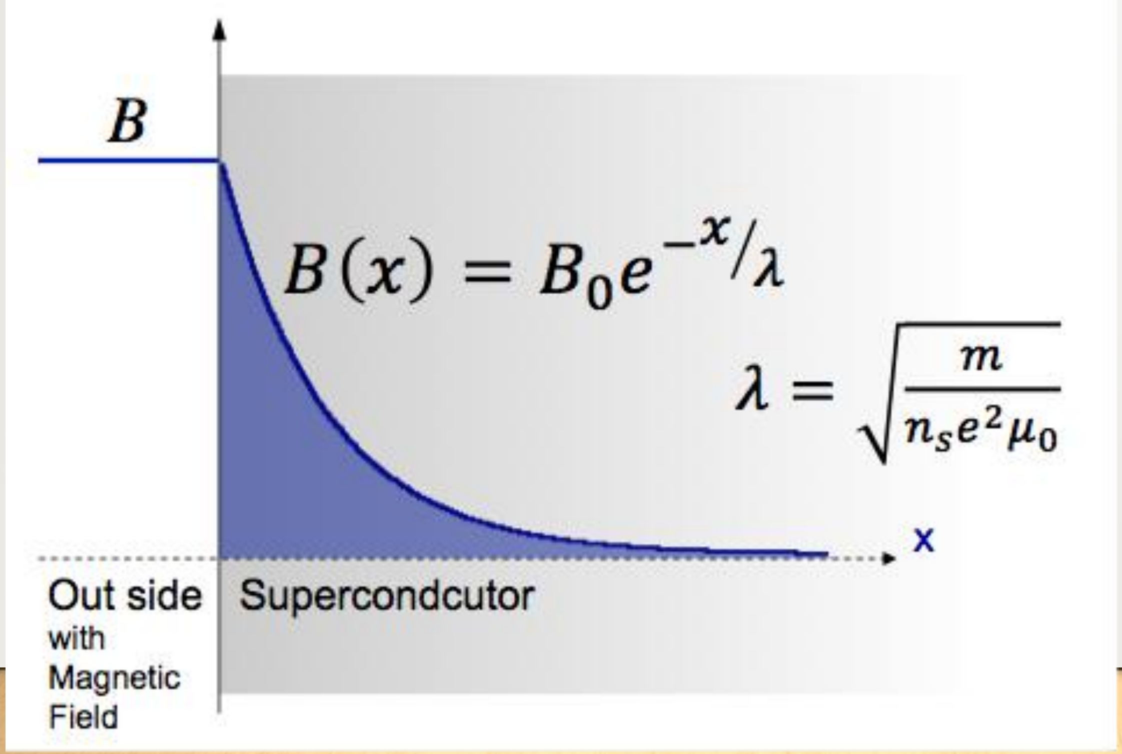


Fritz Walther Meissner (1882 –1974)

Robert Ochsenfeld (1901-1093)

1935 London Penetration Depth

- Derived by London Brothers
  - Phenomenological Explanation of Meissner effect



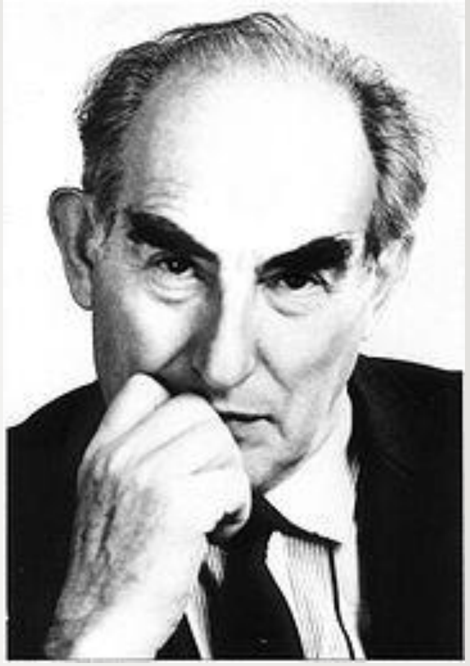
Fritz London (1900-1954)

Heinz London (1907-1970)

1950 GL Theory

- Expand London Theory
  - Coherence Length
  - Characteristic length of superconductivity

$$\xi = \sqrt{\frac{\hbar}{2m|\alpha|}}, \quad \alpha = \frac{(\mu_0 e \lambda H_c)^2}{m}$$

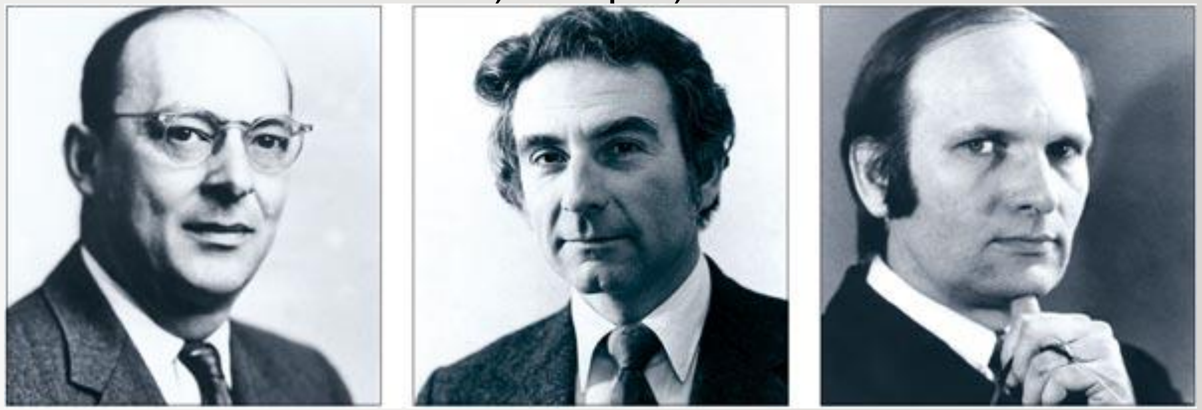


Vitaly Lazarevich Ginzburg (1916~2009)

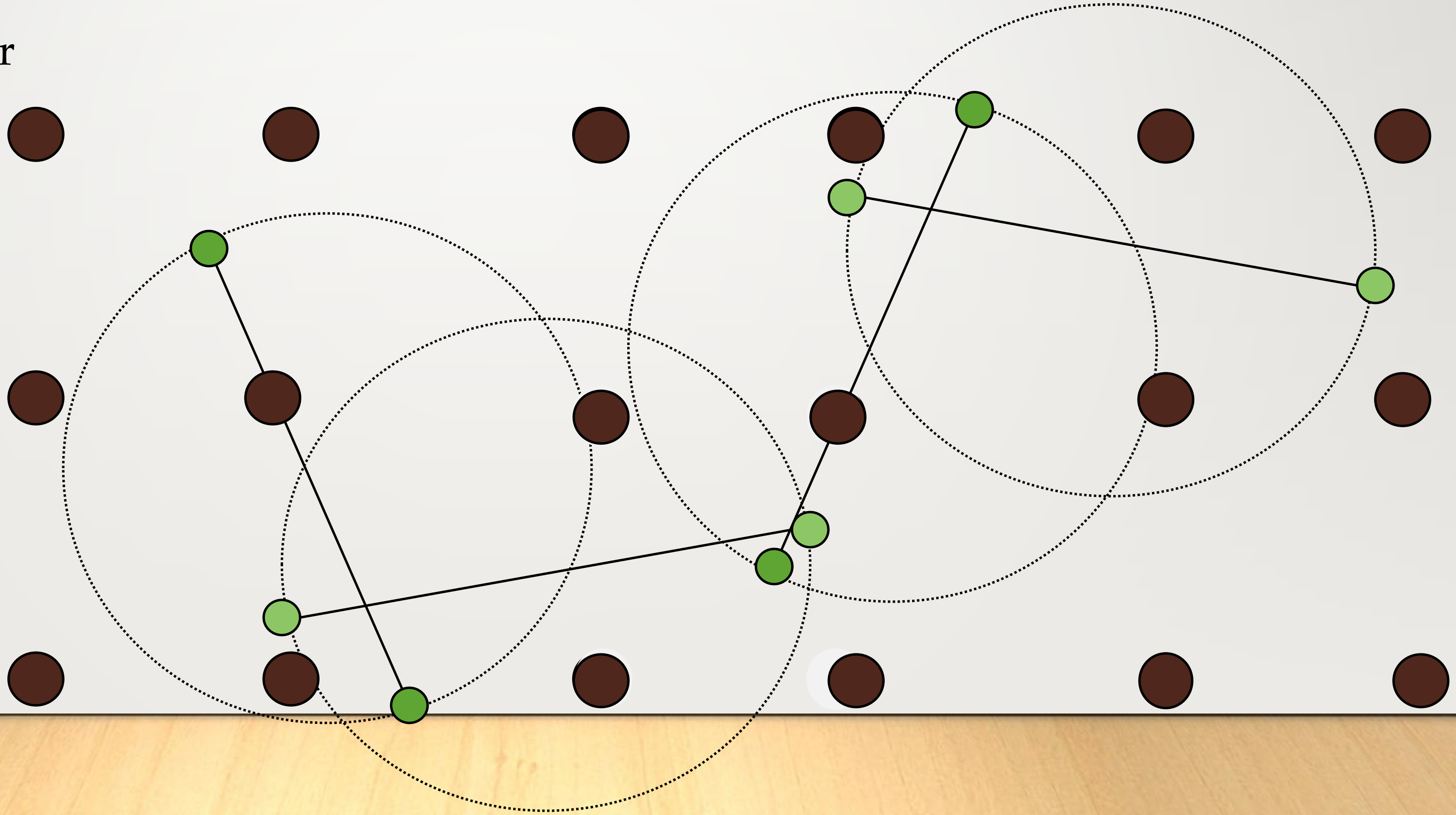
Lev Davidovich Landau (1908~1968)

8 BCS Theory

Bardeen, Cooper, Schrieffer



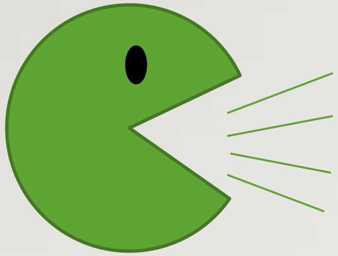
- BCS Theory（１９５７）
  - Cooper Pair

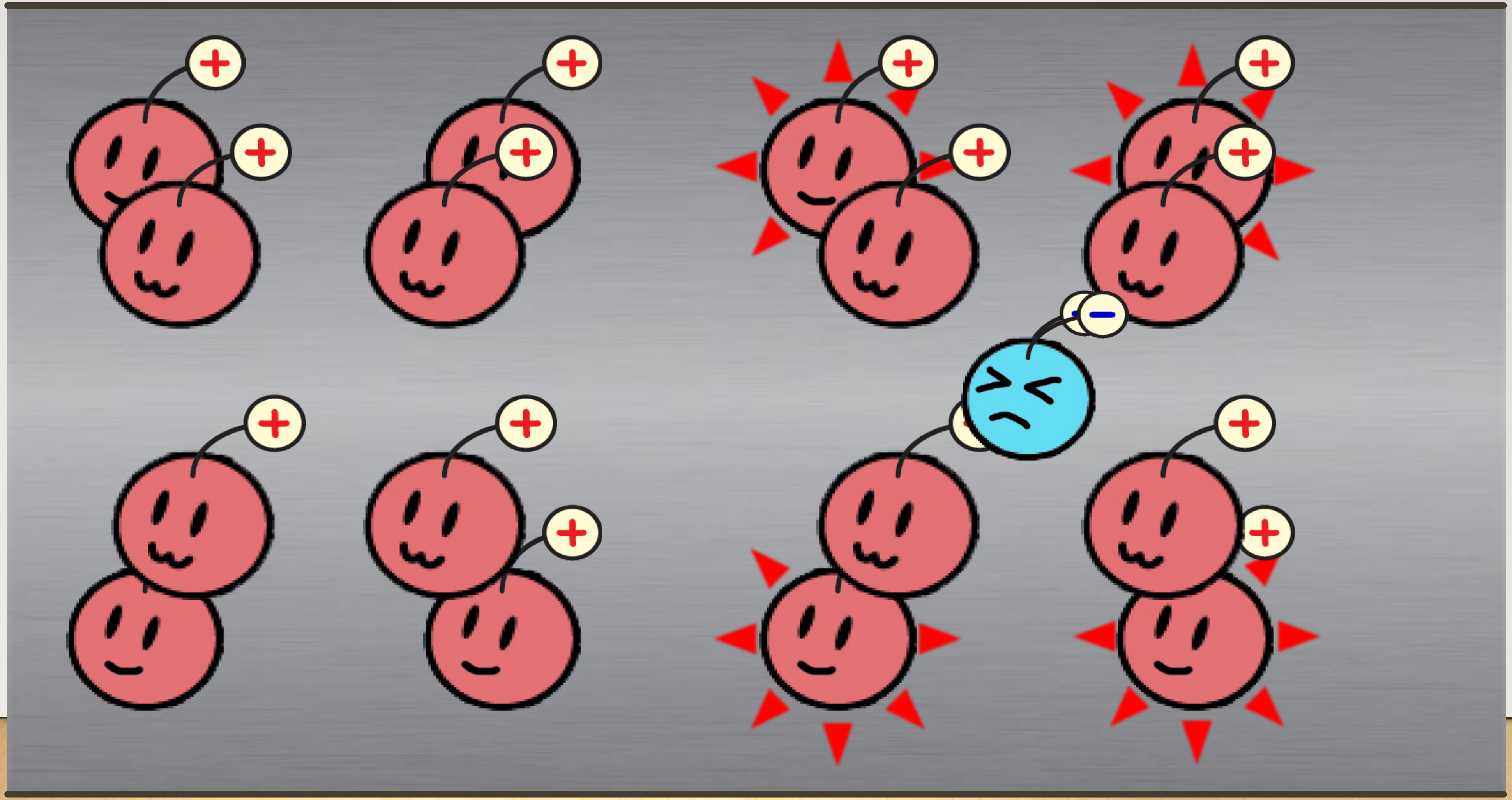


Normal Conductor

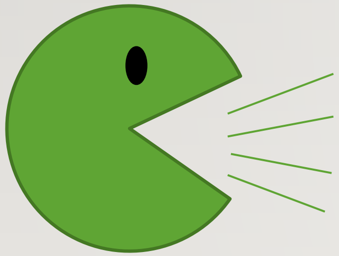
$W = VI = RI^2$

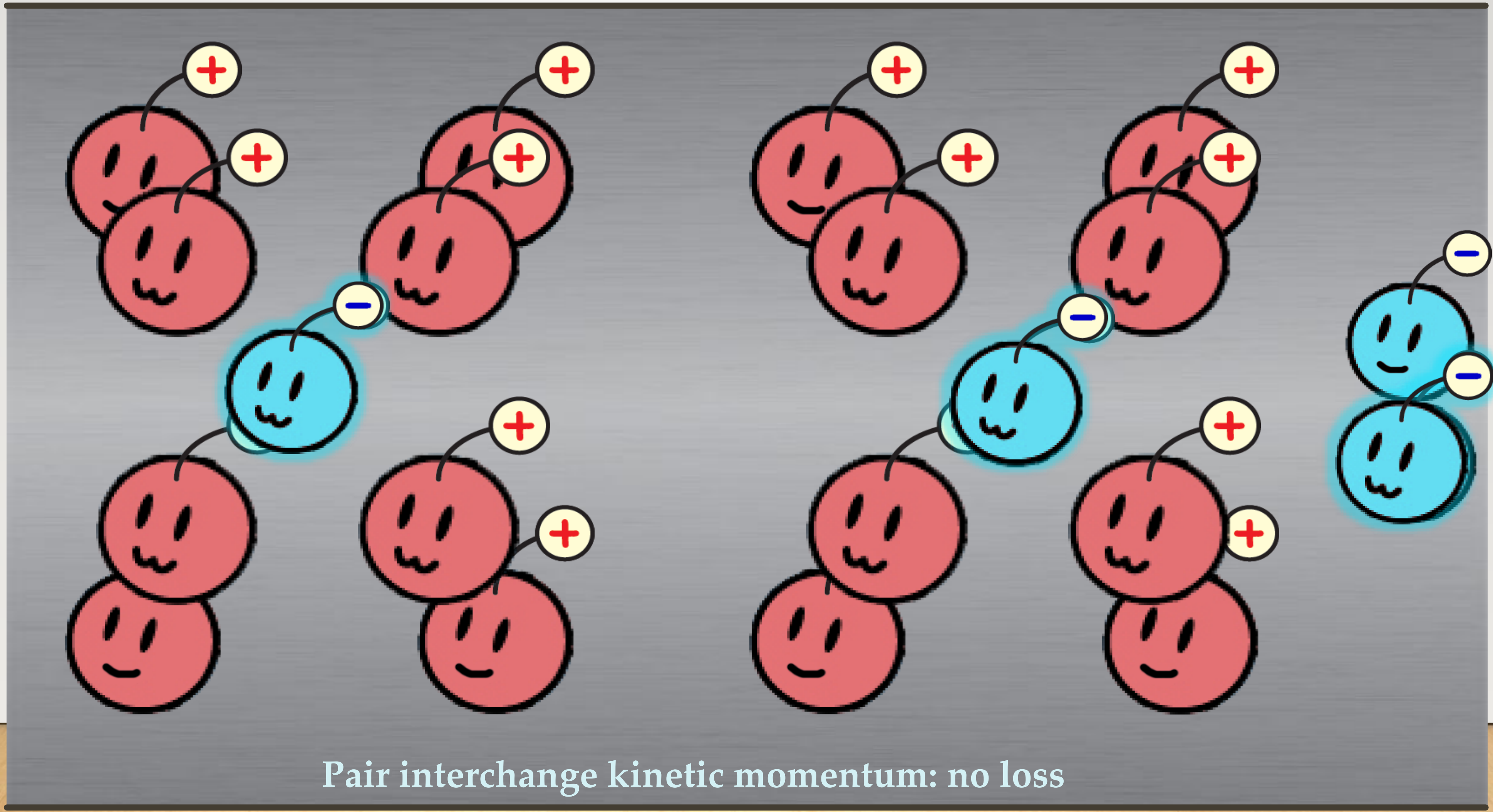
$V = RI$



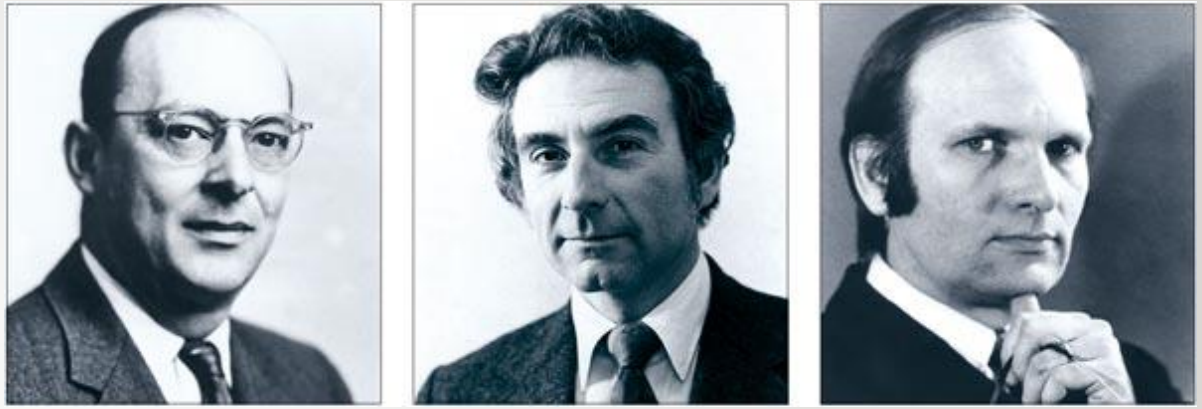


Superconductor





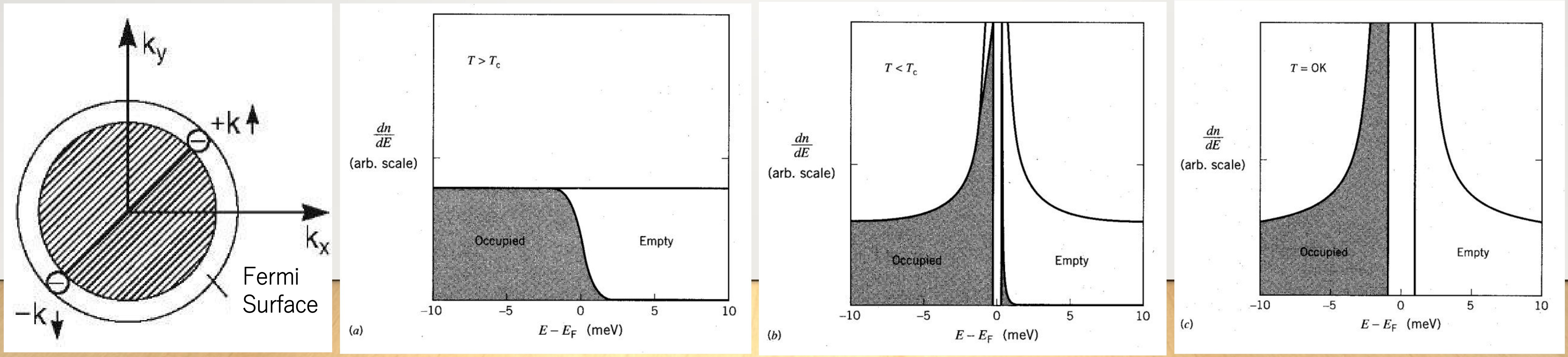
Bardeen, Cooper, Schrieffer



11 | BCS Theory

- Based on Cooper pair
- Bose–Einstein condensation
  - All Cooper pairs have the same momentum
  - Energy Gap $\Delta(T=0) = 1.764\,k_B T_c,$
- Second Order Phase Transition
  - Specific Heat Jump at Transition

- Low thermal conductivity
  - No heat transfer by cooper pairs
- Tends to be high resistivity at normal state
  - Large interaction between electron and lattice



12 | Type I Superconductor

Type I superconductor

$$\xi >> \lambda$$

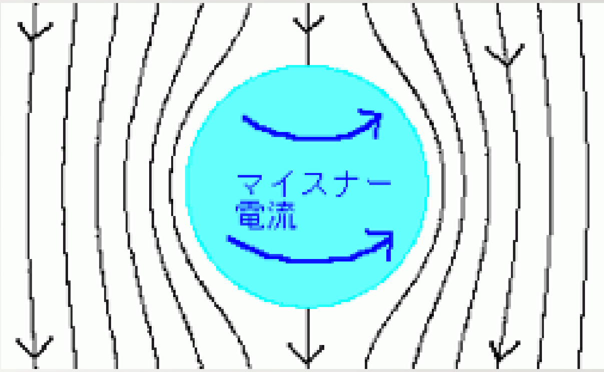
Positive surface energy

⇩

Decrease boundary

⇩

Expel flux



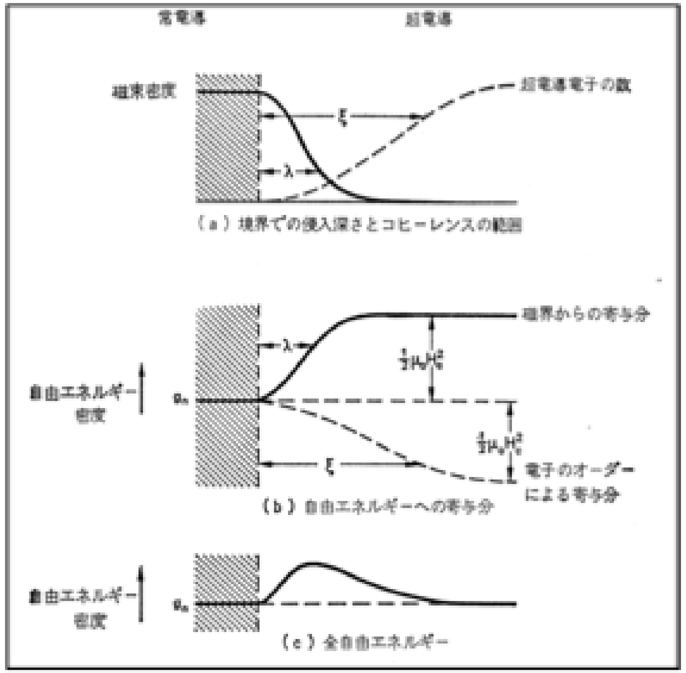
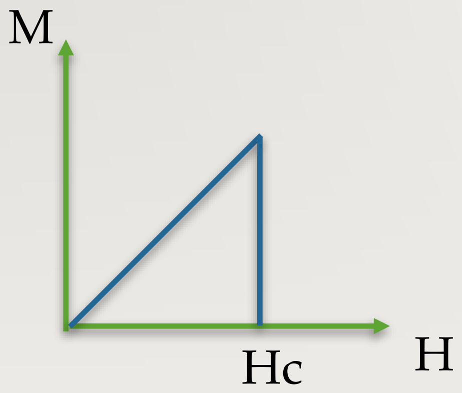


Fig. 2-3 第１種超伝導体の界面[18]

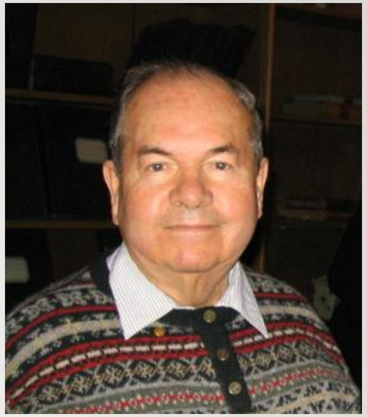


1957 Type II Superconductor

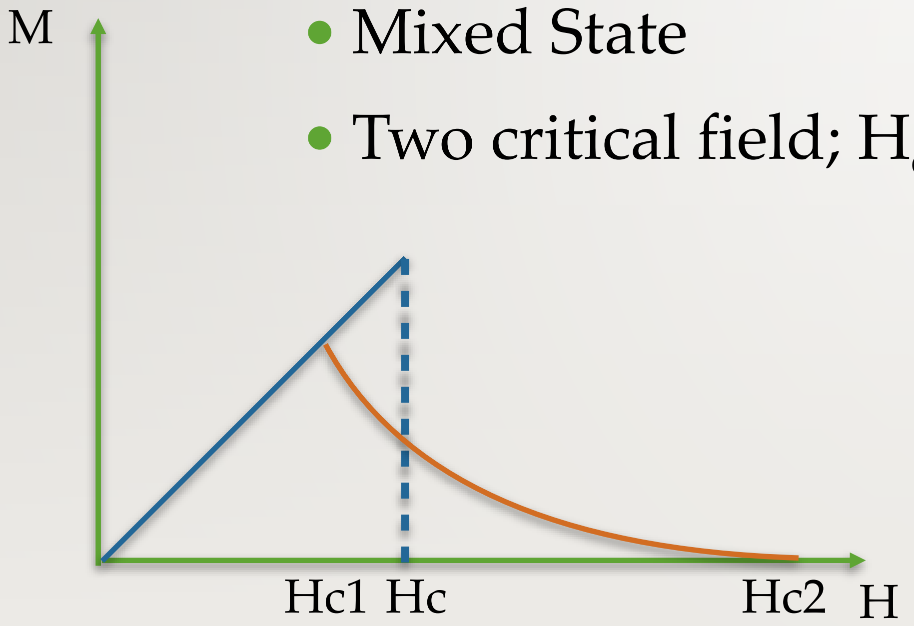
- Derived by Abrikosov from GL theory

$$\sqrt{2}\,\xi < \lambda$$

  - Boundary Surface Energy: Negative
  - Mixed State
  - Two critical field; H_{c1}, H_{c2}



Alexei Alexeyevich Abrikosov



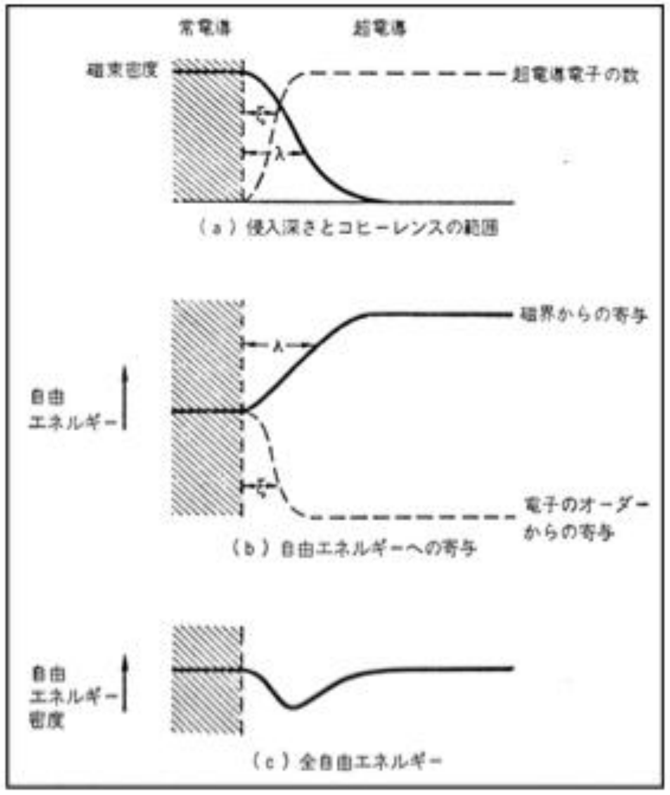
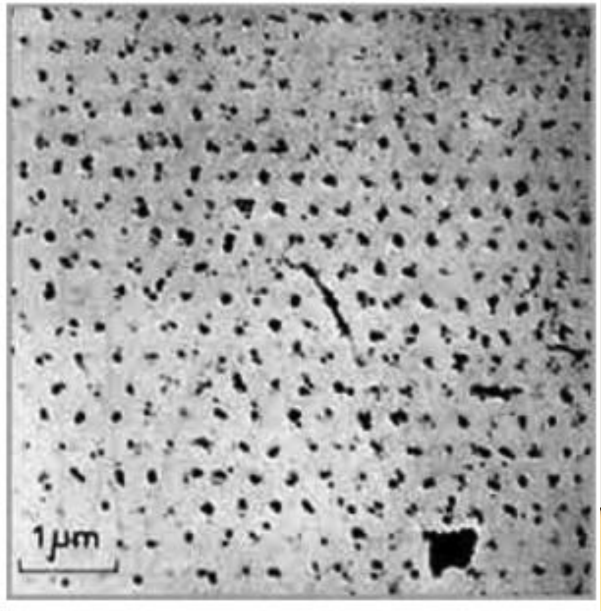
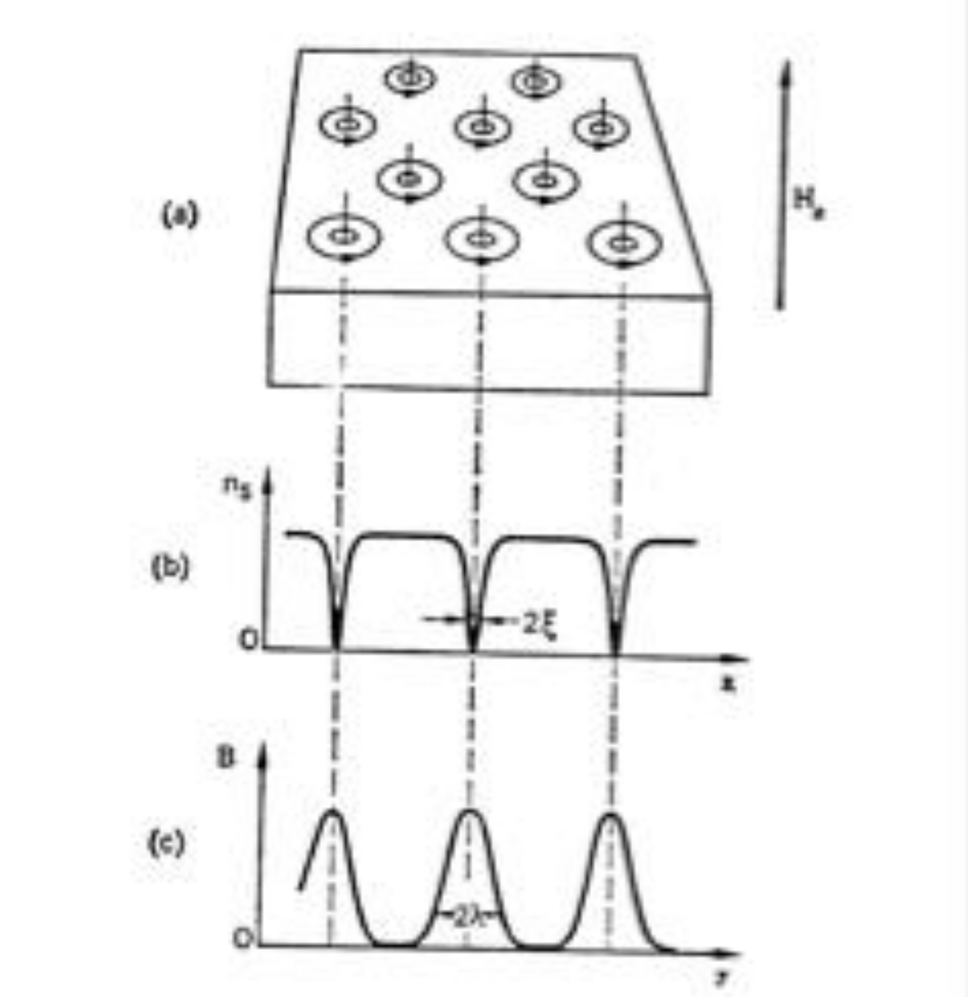


Fig. 2-4 第 2 種超伝導体の界面[18]

Mixed State

- Negative Surface Energy
- Maximize NS boundary
- minimum flux
  - Cooper Pair: Vortex





Type II Superconductor

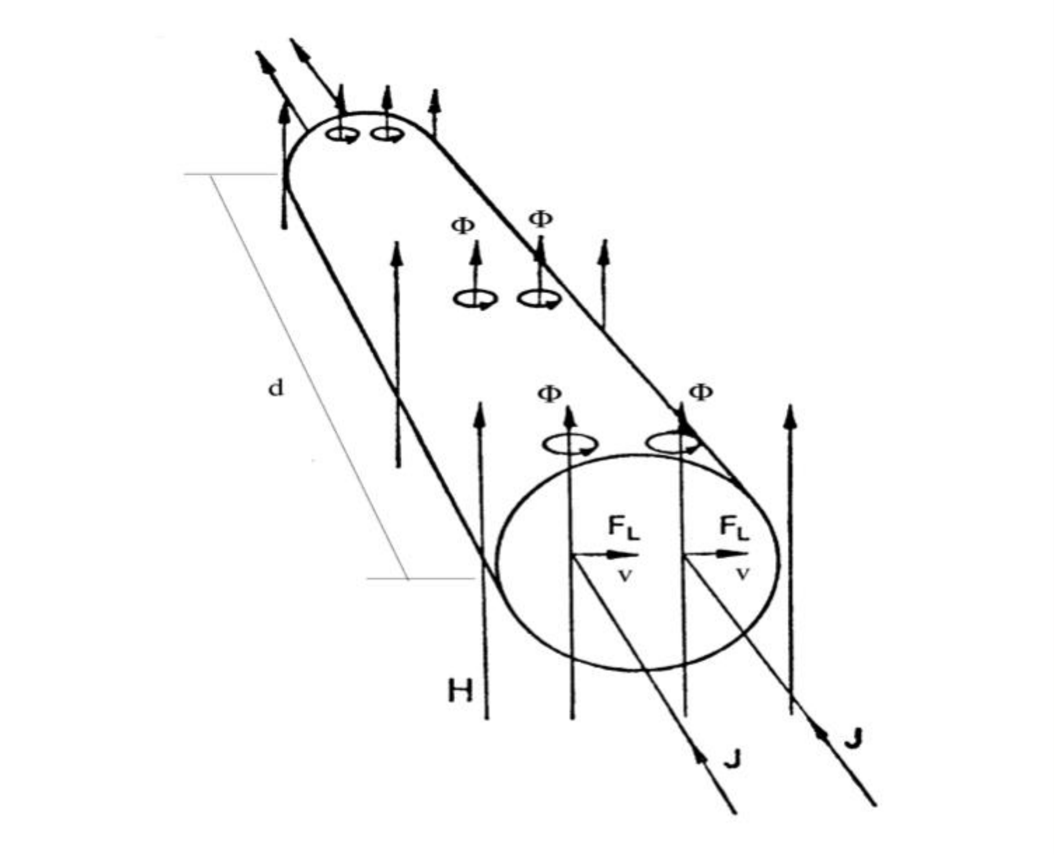
- Coherence Length by Pippard

$$\frac{1}{\xi} \approx \frac{1}{\xi_0} + \frac{1}{L}$$

- where $\xi_\circ \approx \frac{\hbar v_F}{\pi\Delta(0)} \approx 0.18\frac{\hbar v_F}{k_B T_c}$ is coherence length of ideal material, L is electron mean free path
- Dirtier Material: shorter coherence length: type II conductor

Flux Flow

- Field × Current = Lorentz Force
- Flux may move: Flux Flow
- Flux Flow = Electric Field = Loss

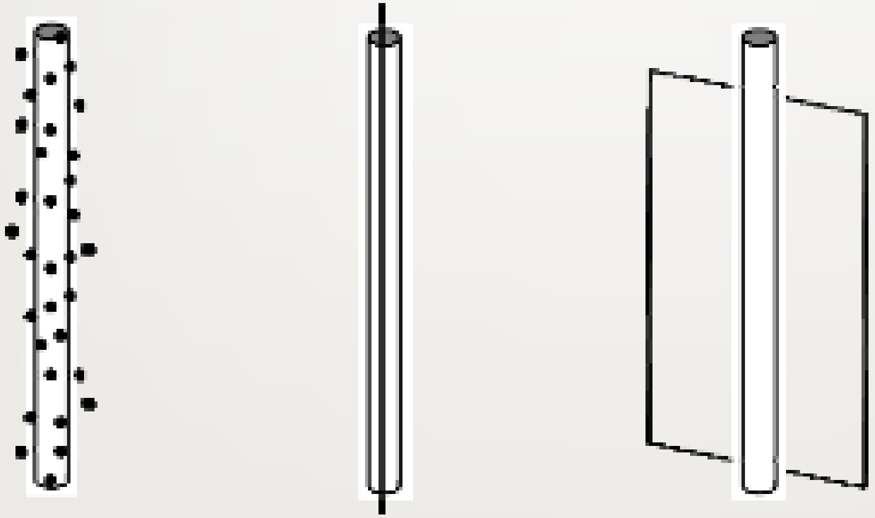


$$V = n\Phi v d$$

Voltage along current direction

Pinning and Critical Current

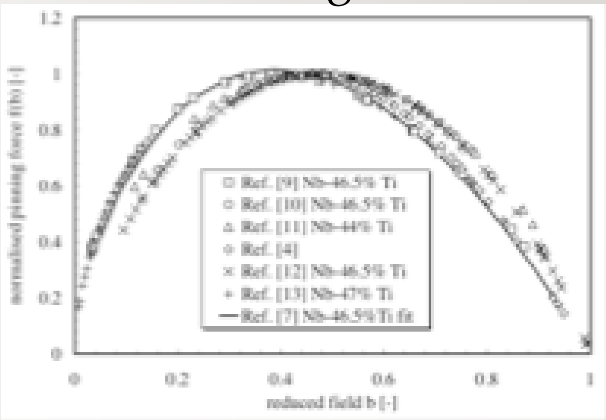
- Defect: easier to be normal state
  - Create Pinning Potential
- Type of Defects



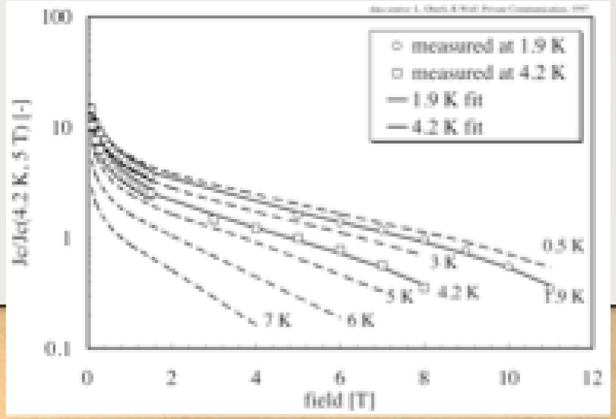
Point Defects Dislocation Grain Boundary

Pinning Potential

Pinning Force



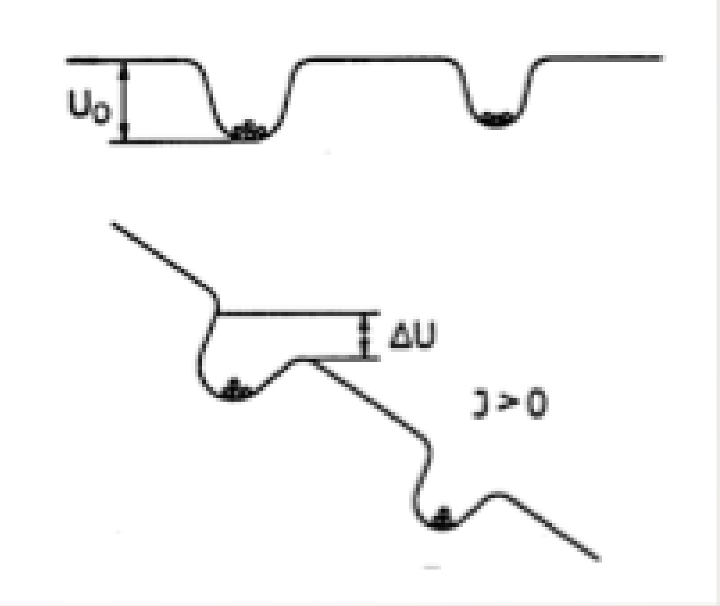
Critical Current Density

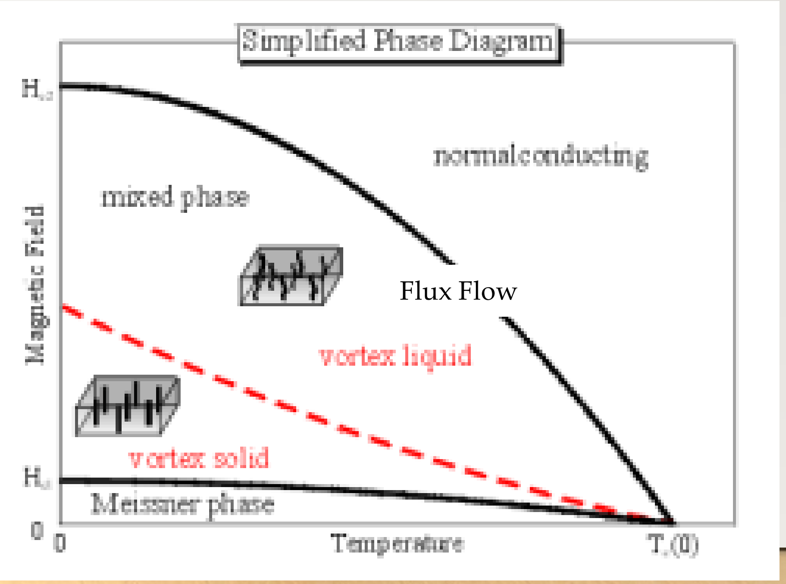


Flux Creep, Melting & Flow

18

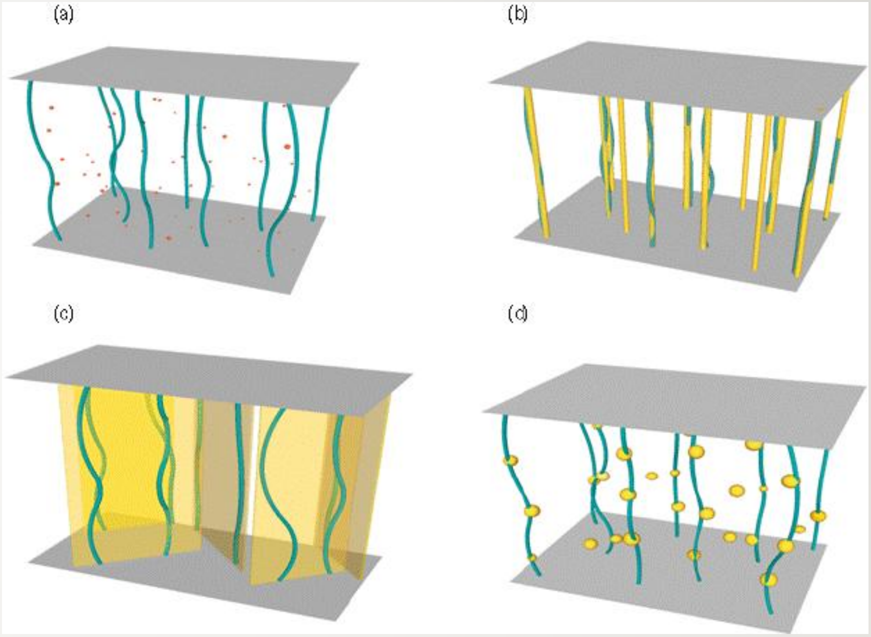
- Flux pinning potential: U_0
  - Lorentz force potential difference: ΔU
- Flux Creep ($U_0>\Delta U$, T: Low)
  - Thermal excitation of flux
  - Flux move: Logarithmic decay
- Flux Melting ($U_0>\Delta U$, T: High)
  - Higher Temperature
    - Larger excitation of flux
  - Flux move: Continuous
- Flux Flow ($U_0<\Delta U$)
  - Flux move: Continuous





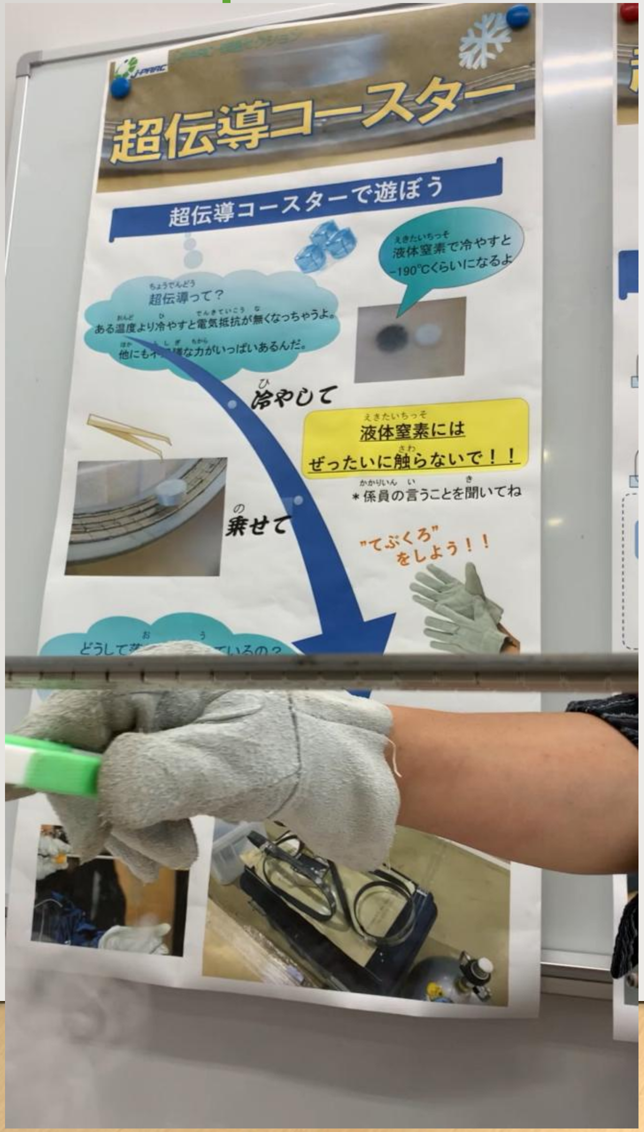
Artificial Pinning

- To Create Deeper Pinning Potential
- Artificially insert normal conducting nano-structure
  - Nano Rod
  - Nano Particle



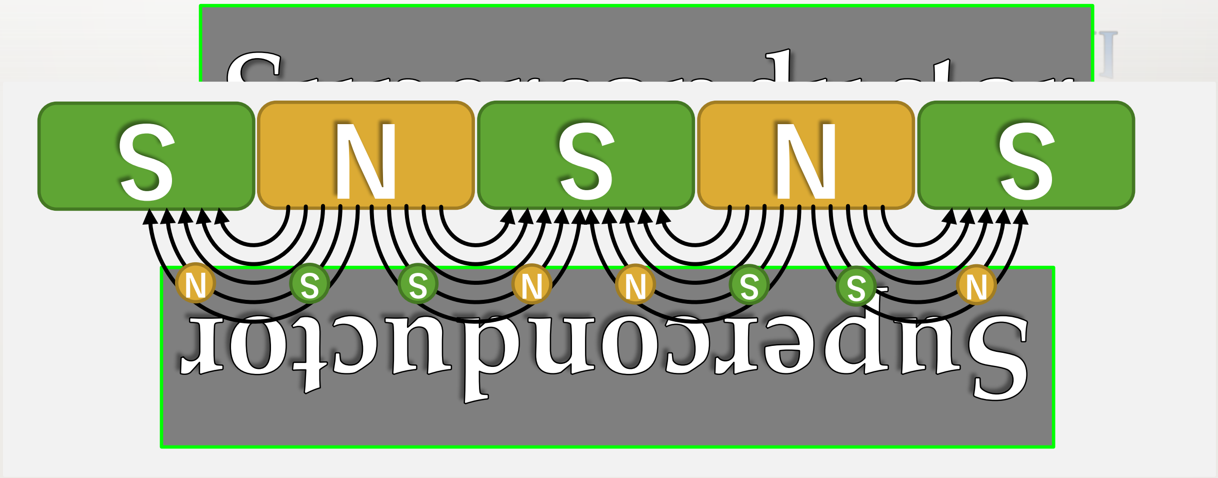
Sketch of the dimensionality of several artificial pinning centers (APCs) with examples of typical defects for each case. (a) OD-PC, oxygen vacancies, element substitutions, point defects (b) 1D-PC such as dislocations and columnar defects, (c) 2D-PC, like grain boundaries, twin boundaries or planar defects and (d) 3D-PC, precipitates, secondary phases or local strain.

Meissner Effect and Pinning Effect



Stick by Pinning Effect

Enforce flux pinning by pushing superconductor to magnet rail



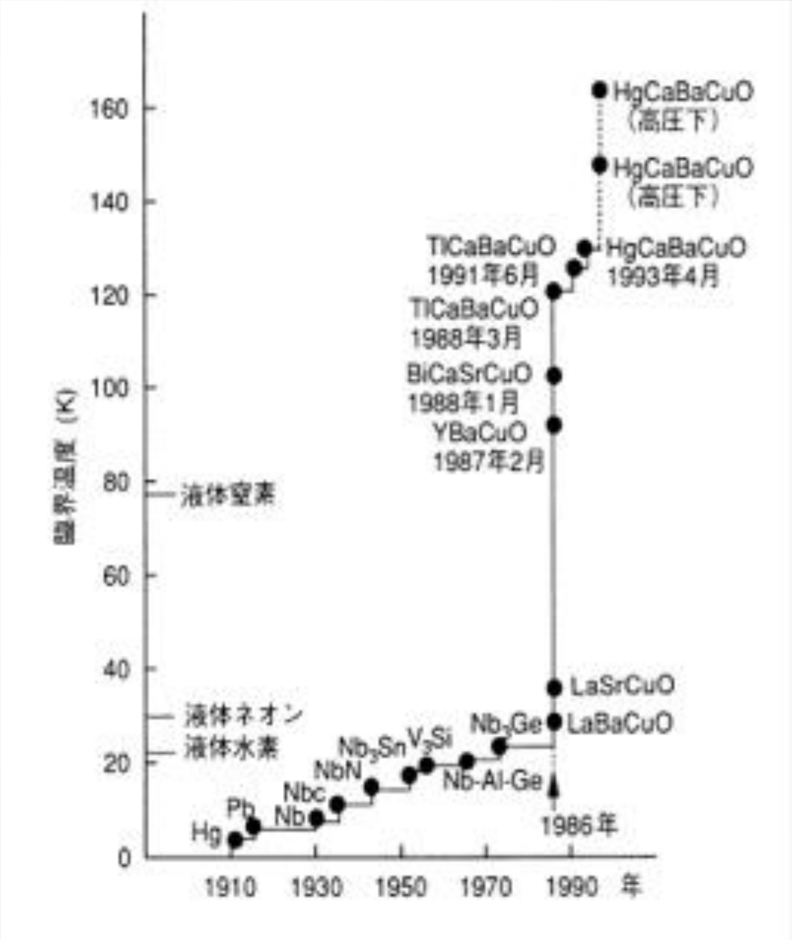
Float by Meissner Effect

Cross Section

21

Superconductor

- Type I
  - Hg 4.153K
  - Pb 7.163K
- Type II
  - Nb 9.46K
  - Nb_3Sn 18.1K
  - MgB_2 39K
  - $YBa_2Cu_3O_7$ 92K



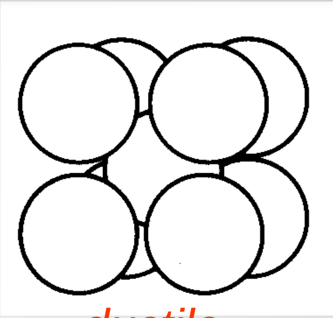
Superconductor Application

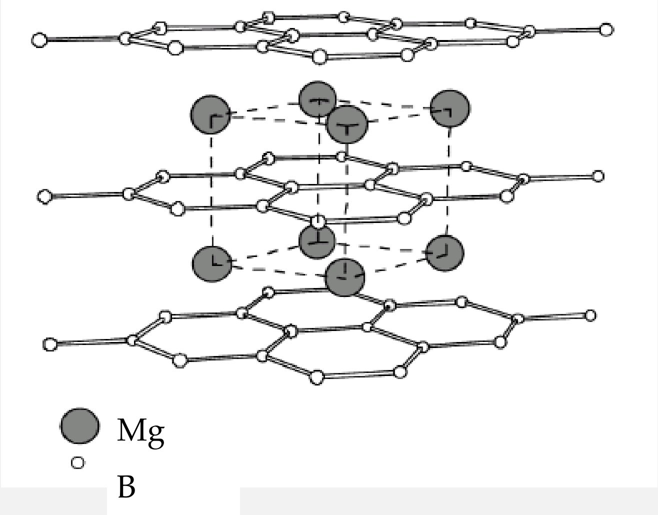
- for Superconducting RF
  - Meissner state, high H_{c1}
  - Pure, Clean, no Defects
- for Superconducting Magnets
  - Mixed State, high H_{c2}
  - Strong Pinning Force, high J_c
  - Dirty and lot of Defects

Item

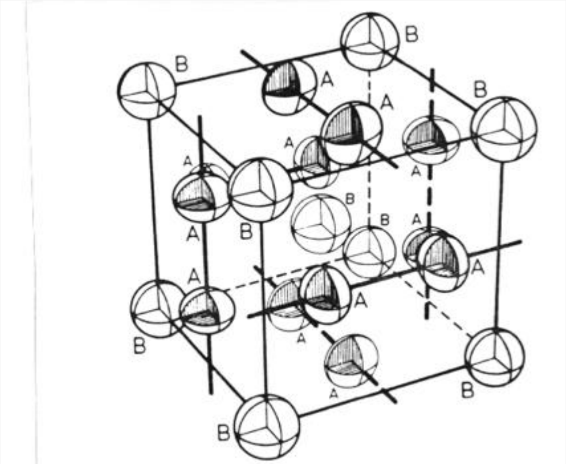
- Superconductivity
- **Superconducting Wire and Cables**
- Stability and Quench Protection
- Summary

24 Superconductors



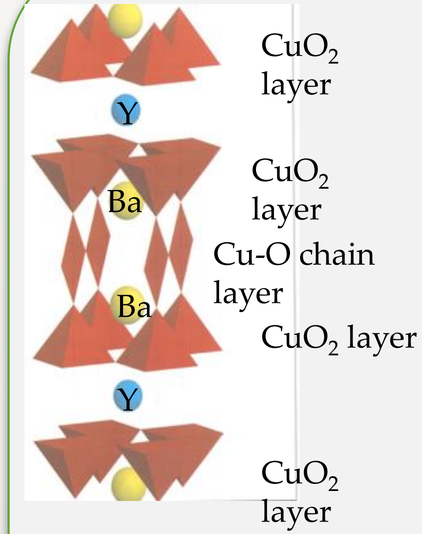


Tc:39 K MgB_2



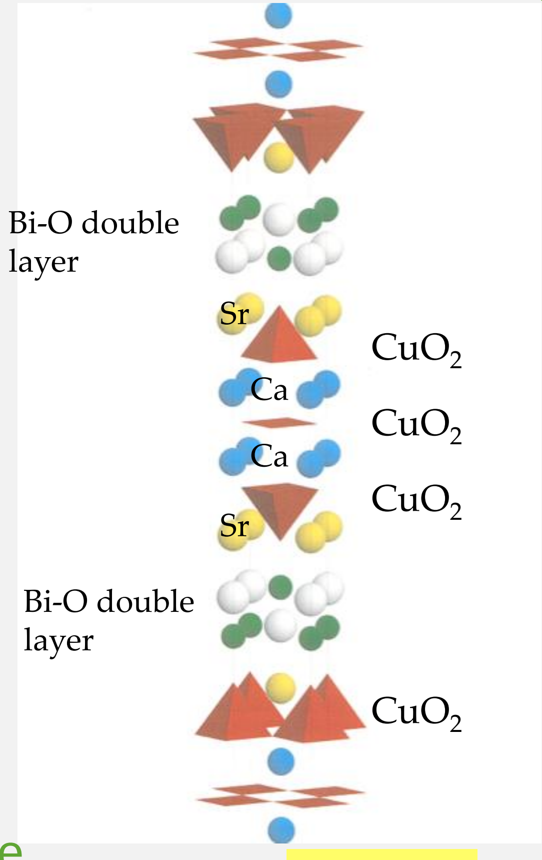
Tc:18 K Nb3Sn

Metallic Compound



Tc: 92-95 K

YBCO



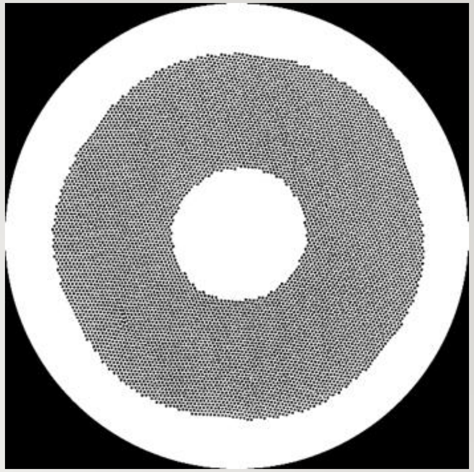
Tc:110 K BISCO

Cuprate-perovskite Ceramic

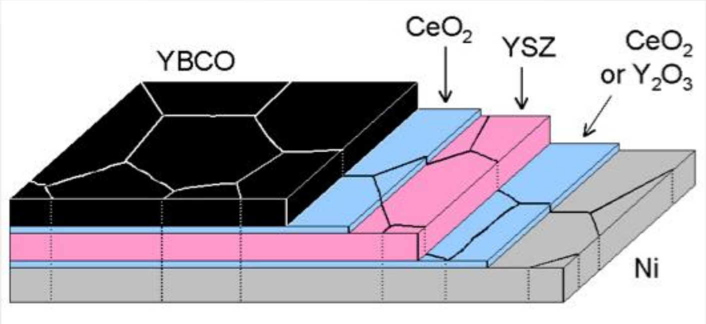
25

Actual Superconductors

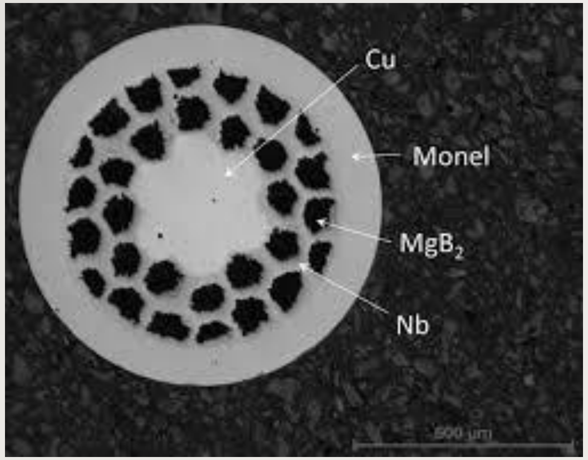
Nb-Ti



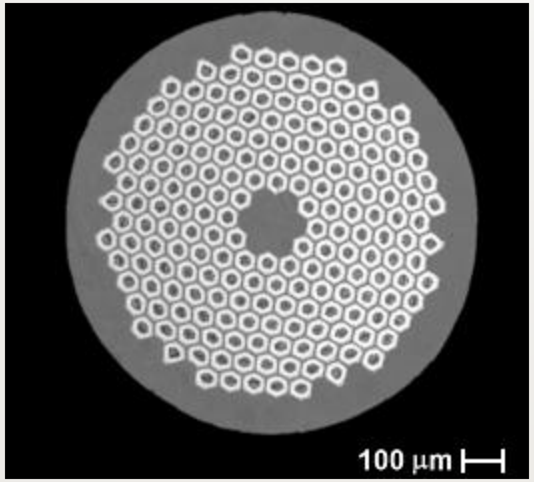
Coated conductor. (IBAD, RABiTS or ISD)



MgB_2

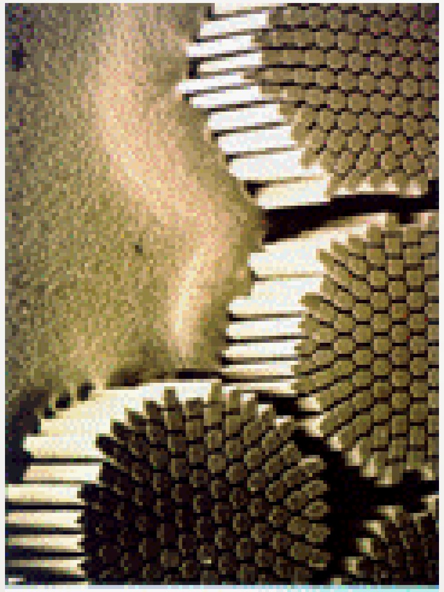


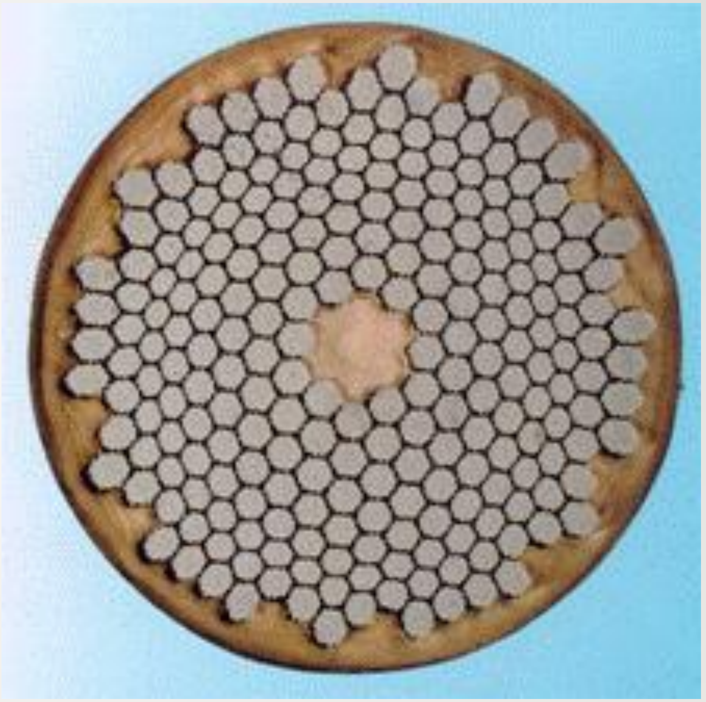
Nb_3Sn



Bi-2223

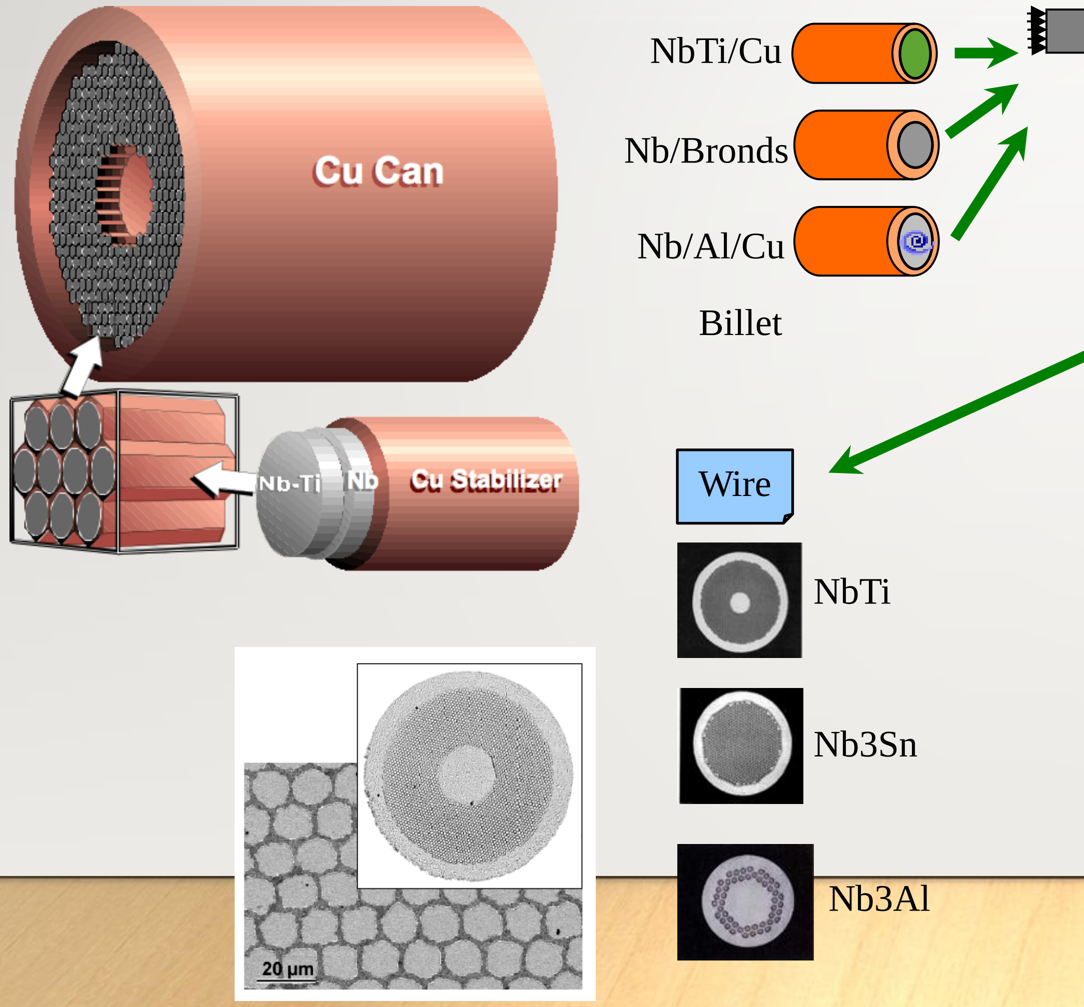
NbTi Multi-filamentary Composite Wire (Strand)

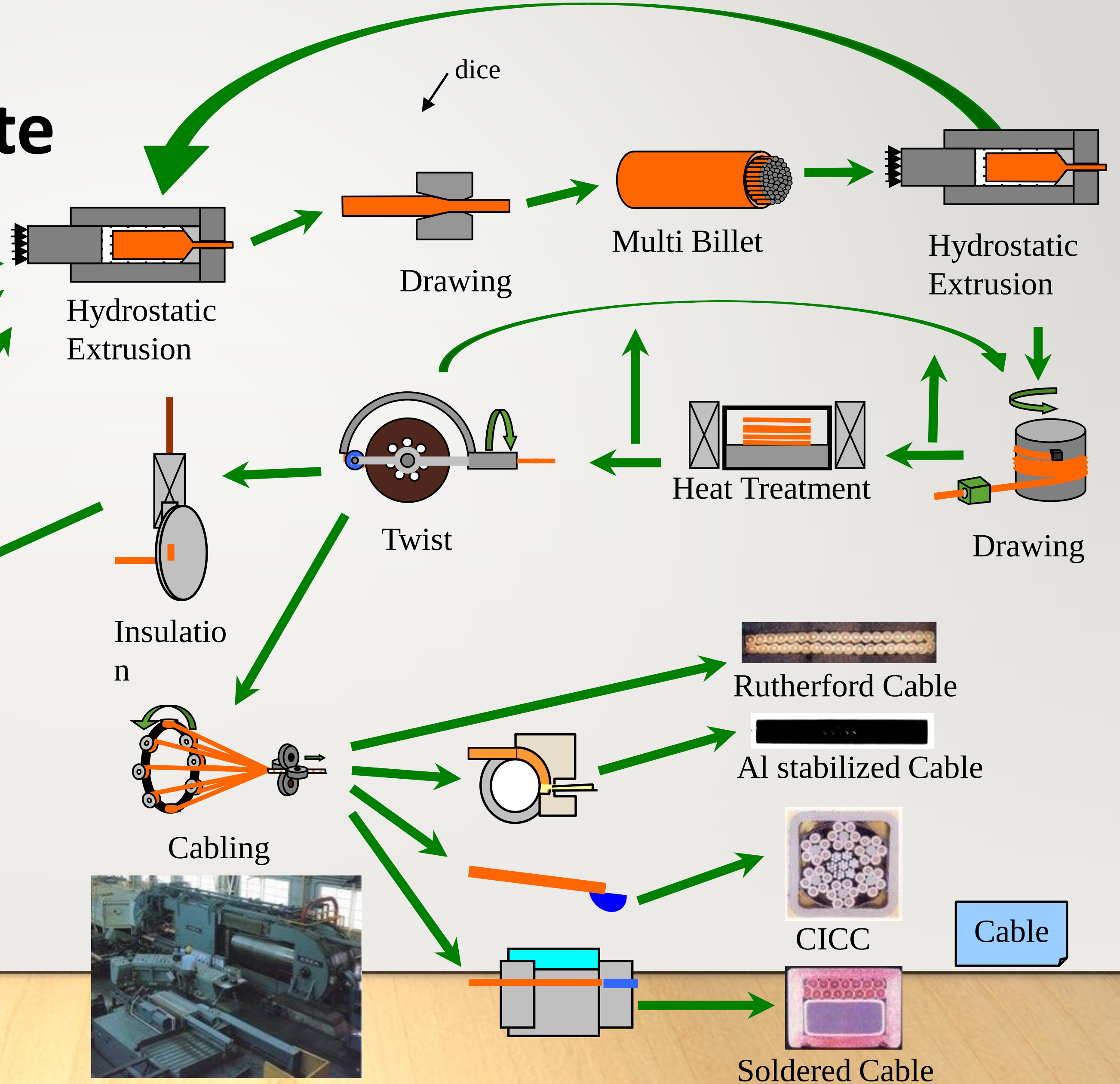




- Fine multi-filament embedded in copper matrix
  - Filament Diameter ：100~1 μm
    - Depending on purpose

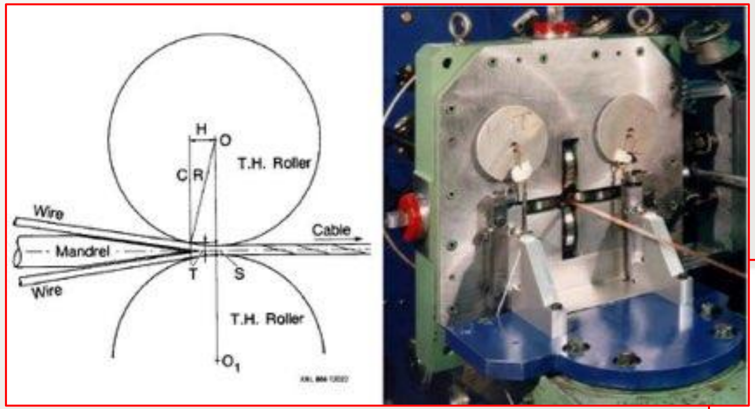
How to Make Multi-filamentary Composite

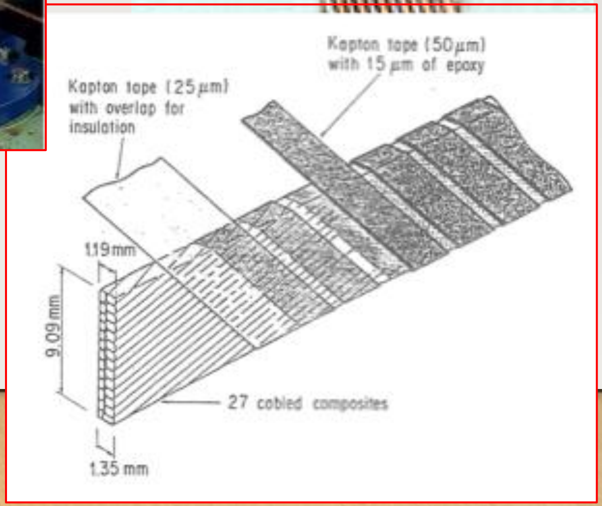




Rutherford Cable

- 10~60 Strand twisted together into flat squad cable
- Eventual Keystone angle





Why such a complicated structure?

- Improve Critical Current Density
  - **Pinning Center**
- Optimize Magnetization Properties
  - **Minimize Diamagnetic Magnetization of Superconductor**
    - Minimize Errors to Magnetic Field (Class 2)
    - Minimize AC-Loss by Hysteric Loss
- Stabilization
  - **Minimize Disturbance**
    - Magneto-Thermal Instability = Flux Jump
  - **Stabilize Against Disturbances**
    - Improve electric conductivity at normal state: less ohmic heating
    - Improve thermal conductivity: better cooling
- Quench Protection
  - **Guarantee safe shut down of magnet**
    - Improve electric conductivity at normal state: less ohmic heating
    - Increase heat capacity: Less temperature increase
    - Improve thermal conductivity: better heat distribution

Critical Current Density

- Critical Current Density

↓

- Pinning Force

$$F_{PC} = n\Phi J_C = BJ_C$$

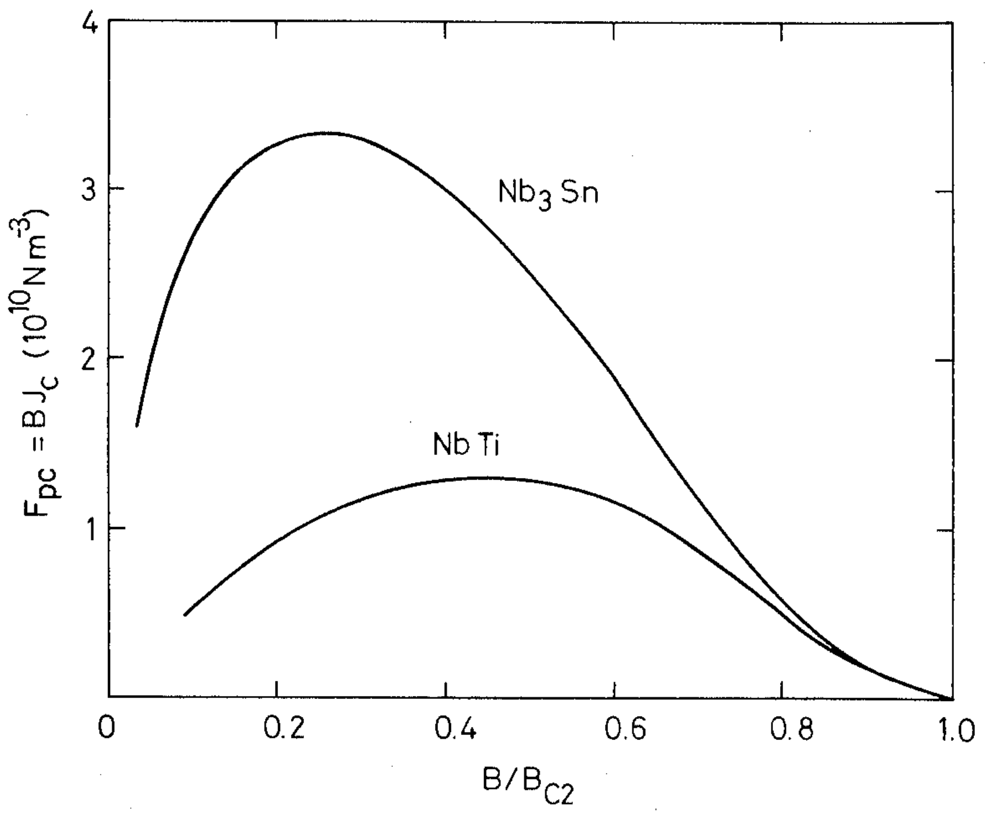


Fig. 12.3. Pinning force per unit volume, as a function of reduced field, for niobium titanium and niobium tin.

Introducing Pinning Centers

Drawing Process

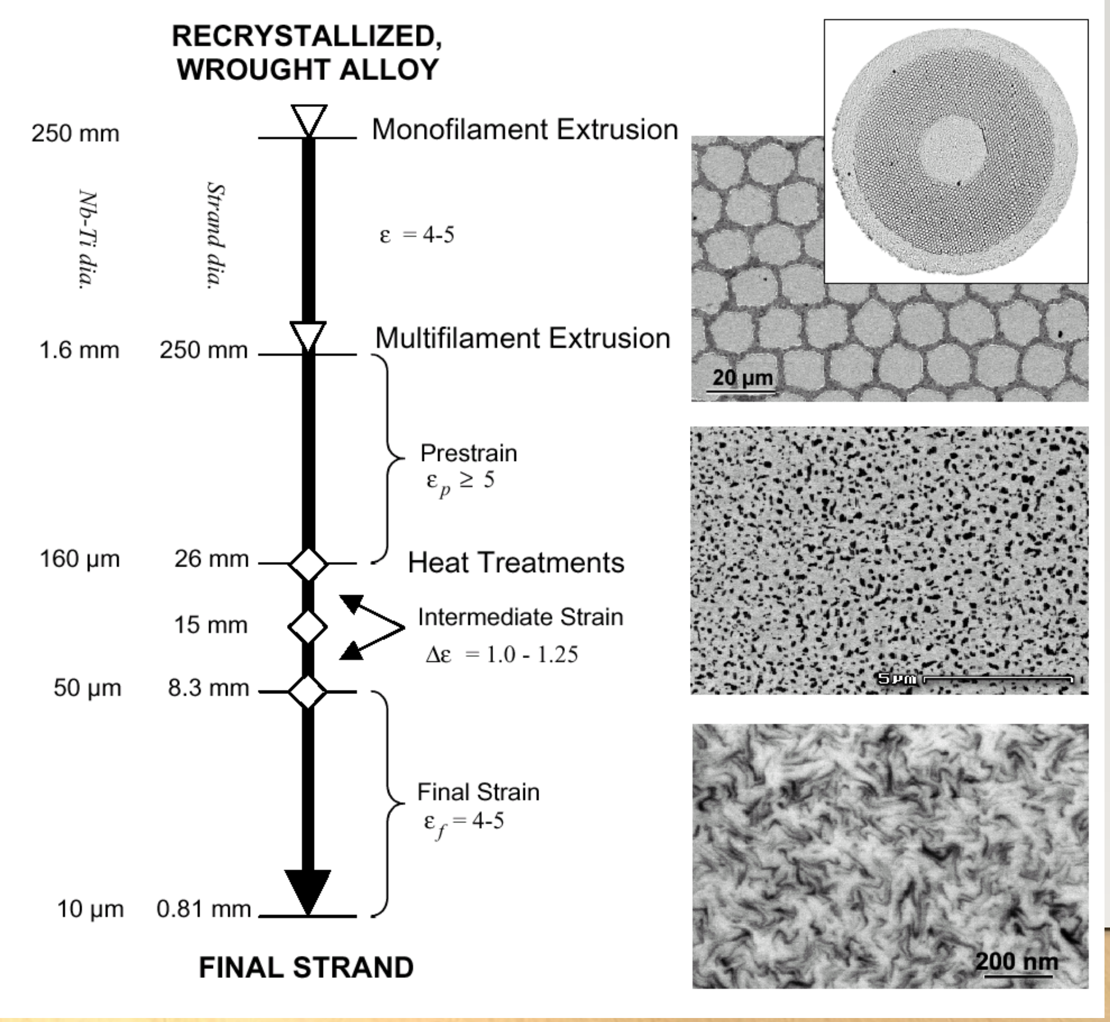
Draw

↓↑

Heat Treatment

⇩

Lattice Defects



Introducing Pinning Centers?

- Conductor electric characteristic

$$V \propto I^n$$

- n-value
  - Bad n-value
  - = bad critical current
  - Filament Damage?
- Definition of critical current
  - Multiple Definition

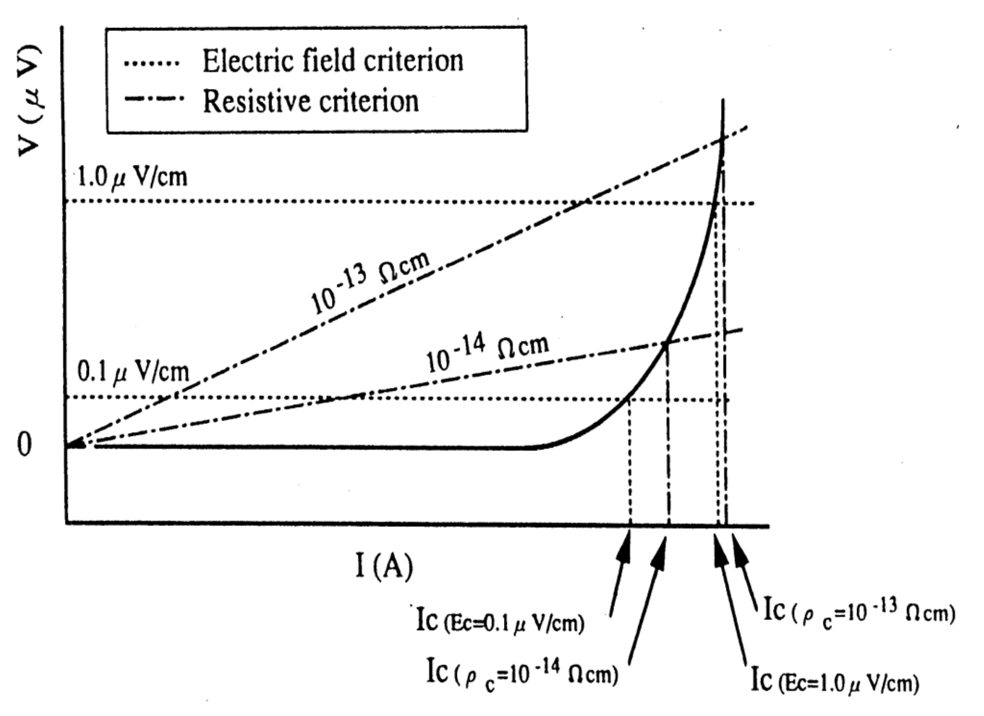


Fig. 7 Schematic *I–V* characteristic and two kinds of standard definition of critical current I_c.

Critical Surface

- Critical Current Density is function of
  - Temperature
  - Magnetic Field
- NbTi: 3000A/mm² @ 4.2K, 5 T

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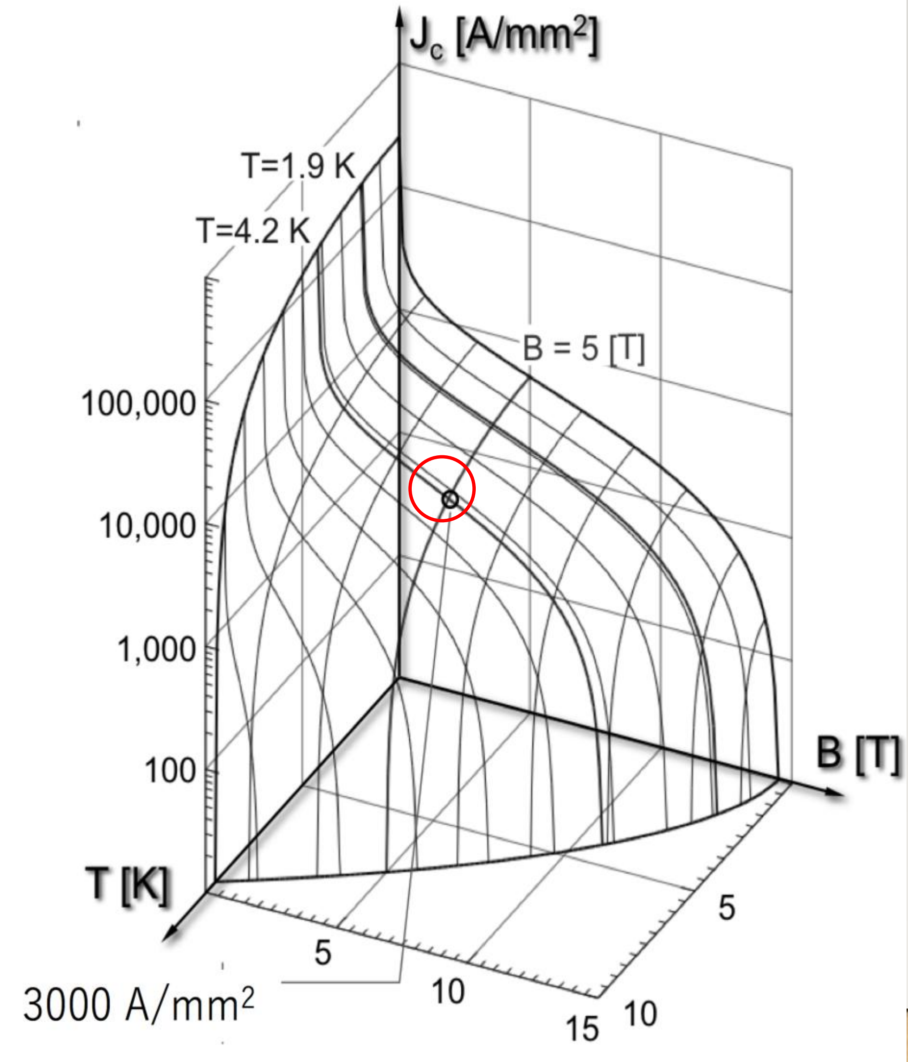
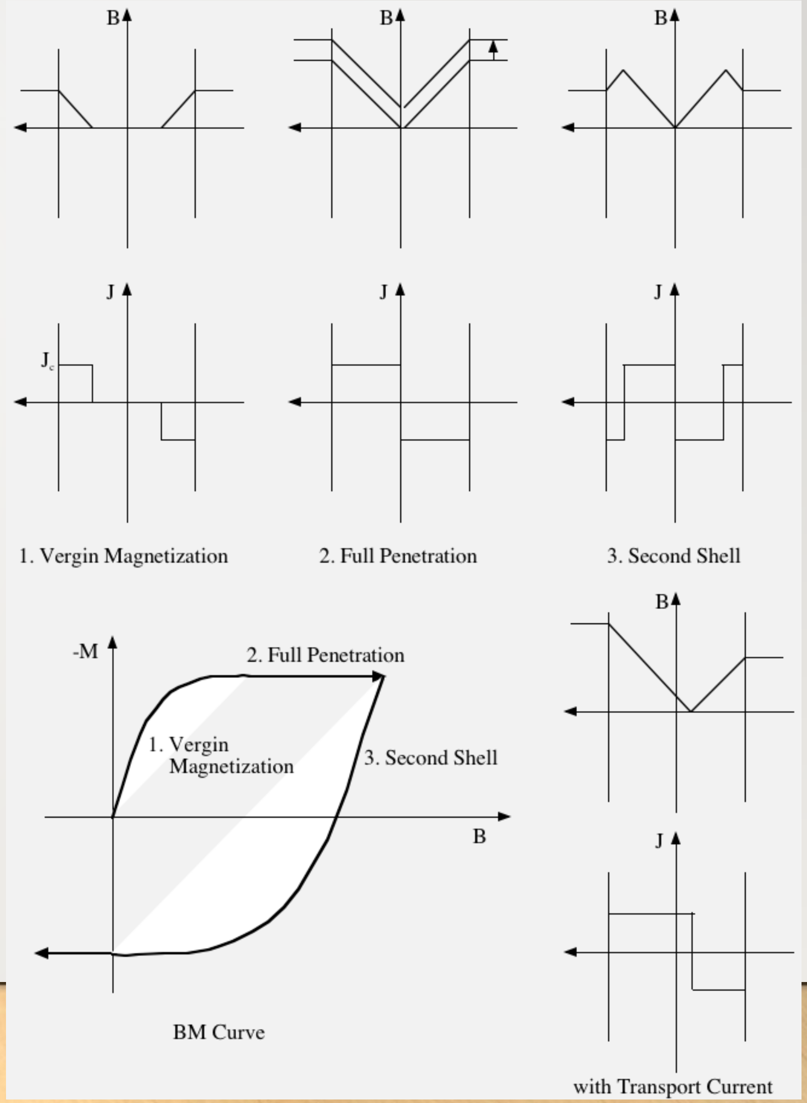


Critical State Model: Magnetization

- By Bean and London
  - Flat panel model
  - thickness: a
  - Magnetization: M

$$-! \quad = ! \, ! \, _! \, !_! \, /2$$



  - proportional to a and Jc
  - fine filament: smaller magnetization

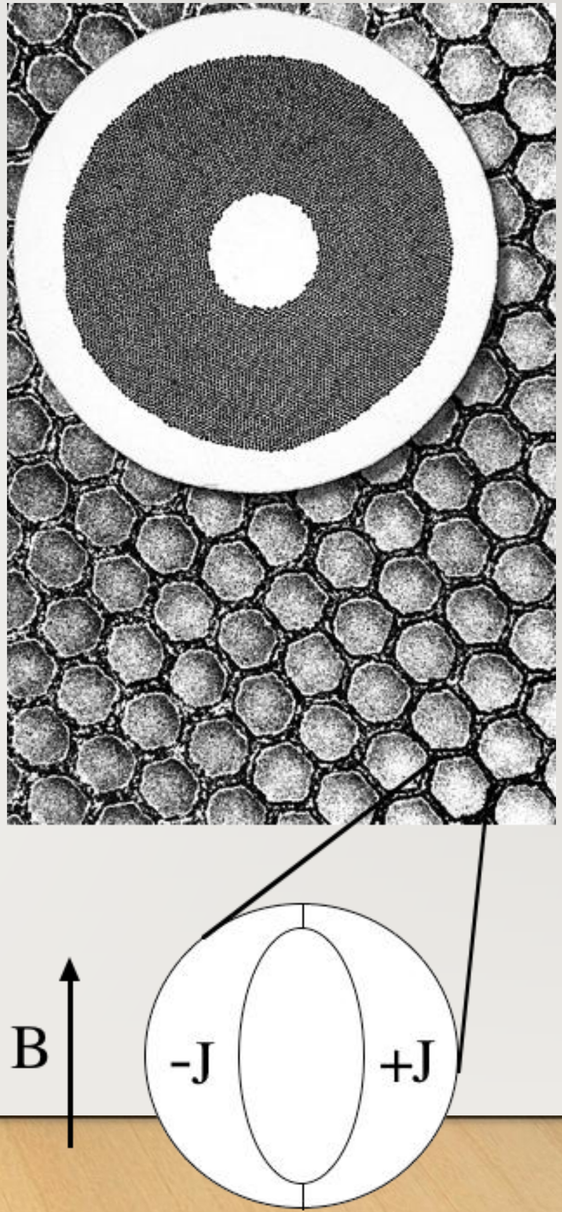
Multi-filament composite

- Wire magnetization
  - Filament magnetization

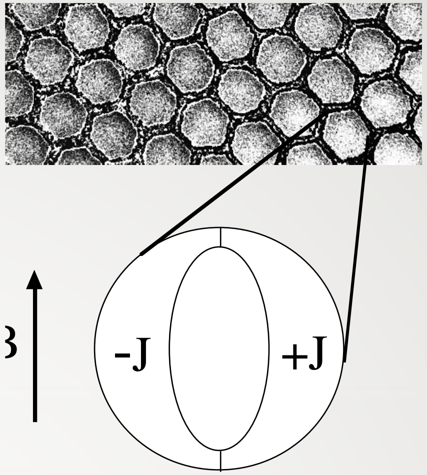
$$M = \begin{cases} \frac{4}{3p} m_0 J_c r_f \left[1 - \left(1 - B_0 / B_p \right)^3 \right] & (B_0 < B_p) \\ \frac{4}{3p} m_0 J_c r_f & (B_0 \geq B_p) \end{cases}$$

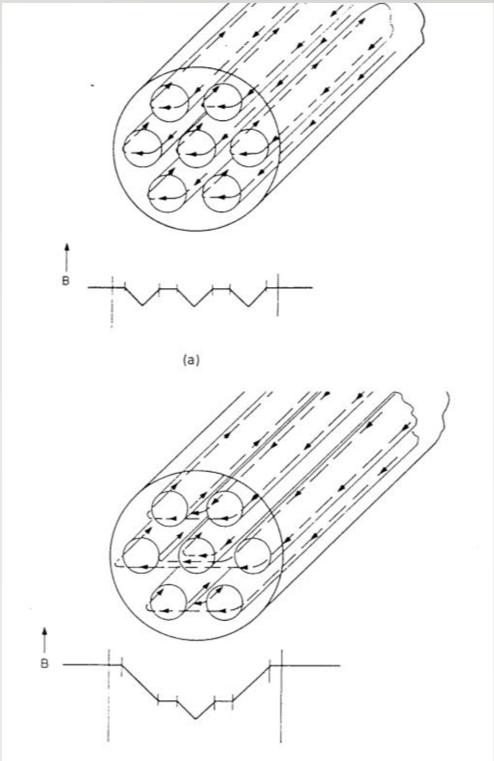
where $B_p = 2 m_0 J_c r_f / p$

  - Magnetization proportional to filament size



AC-Loss





- Hysteresis loss
  - Roughly proportional to saturated magnetization: M_s ($\propto \mu_0 a J_c$)
  - Proportional to field change
- Coupling loss
  - Roughly proportional to time constant: τ
    - For strand $\tau \propto L_p^2/\varrho$ (L_p: twist pitch)
  - Proportional to field change square

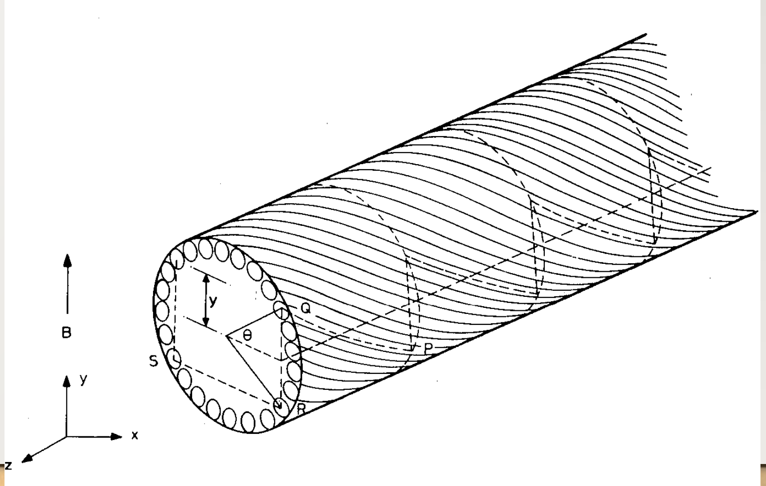
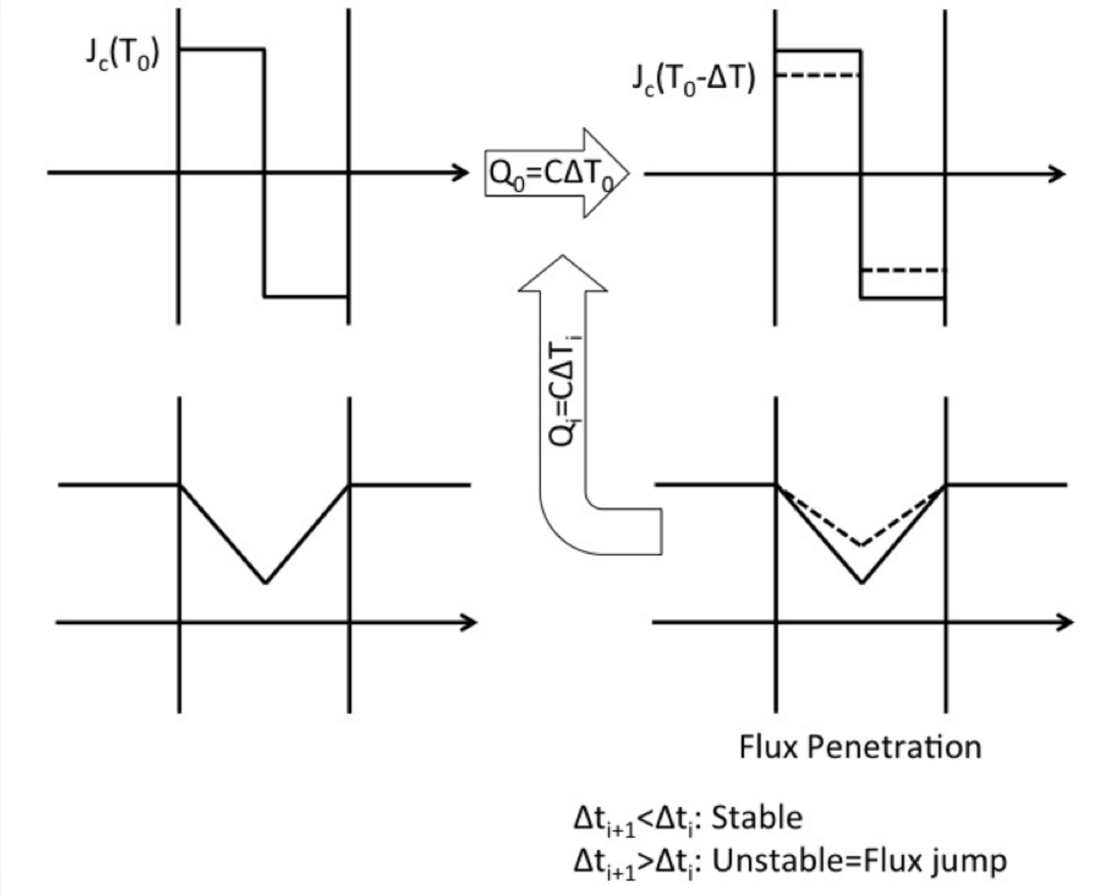


Fig. 8.15. Twisted filamentary composite in changing transverse field showing zig-zag path used to calculate flux linkages.

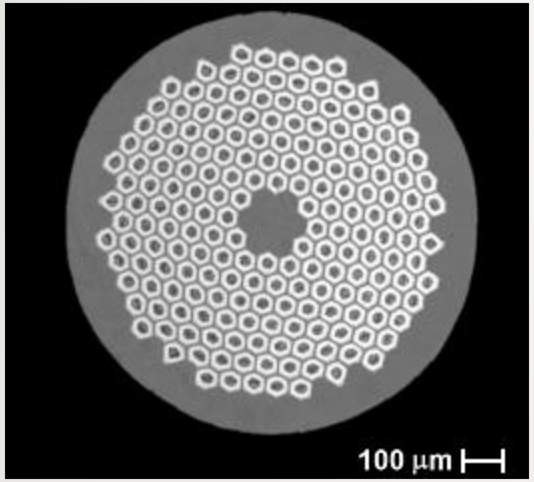
Flux Jump

- Magneto-thermal instability
- Observed with
  - Large filament
  - High Jc
  - Bad RRR
  - Low temperature operation

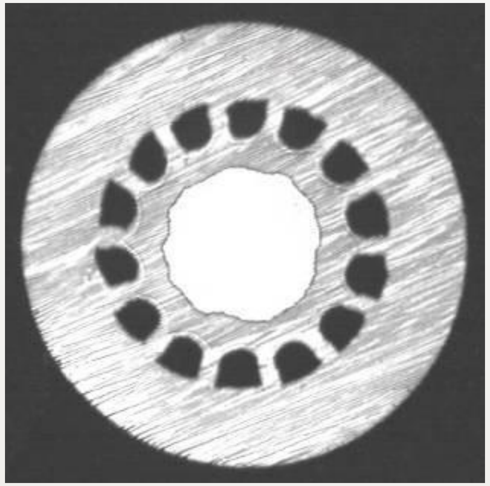


38 Advanced Conductors

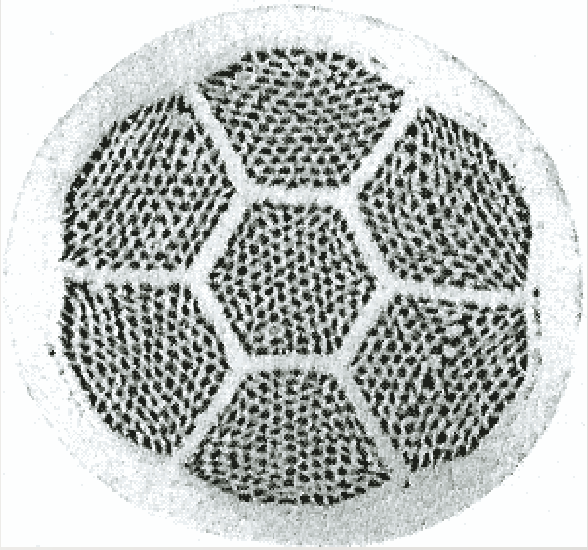
Nb_3Sn



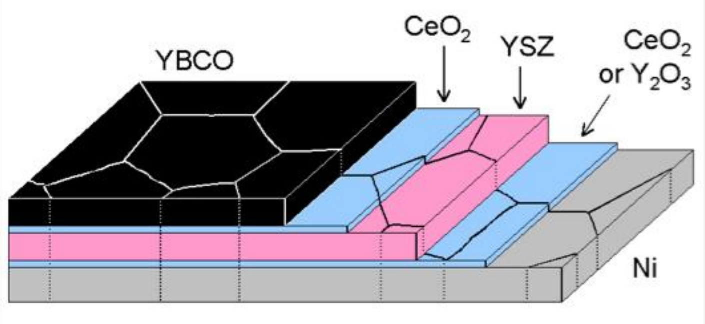
MgB_2



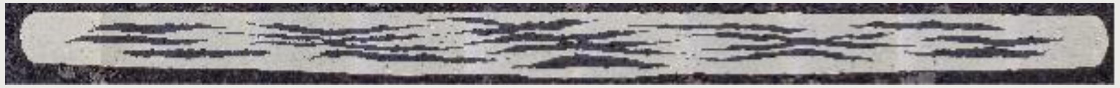
Bi-2212



Coated conductor. (IBAD, RABiTS or ISD)

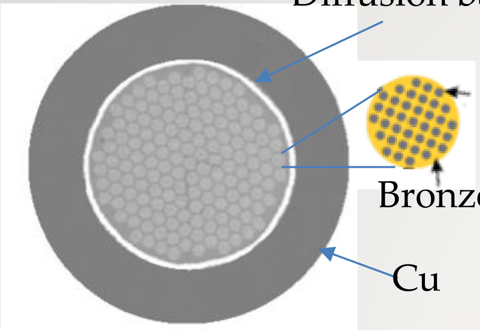


Bi-2223



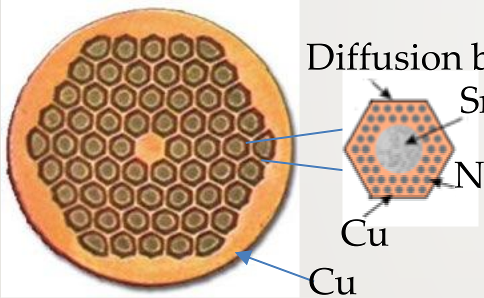
Nb_3Sn industrial wires

➢ Bronze Route



Small filaments (Φ < 5 μm)
Jc limited (~ 1-1.2 kA/mm^2 @ 12 T, 4.2 K) by the solubility of Sn in Cu (~15.5 wt %)

➢ Internal Tin



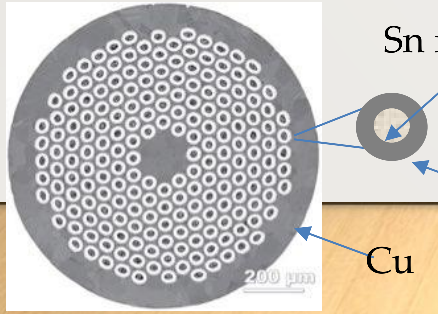
OXFORD INSTRUMENTS

The Business of Science®

RRP ®

High Jc Nb_3Sn wires for accelerator magnets

➢ Powder In Tube



BRUKER

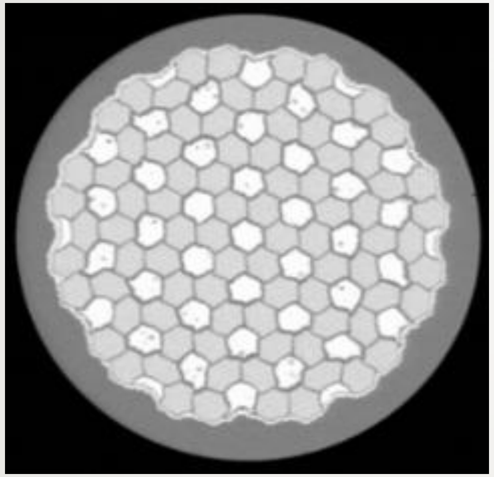
PIT

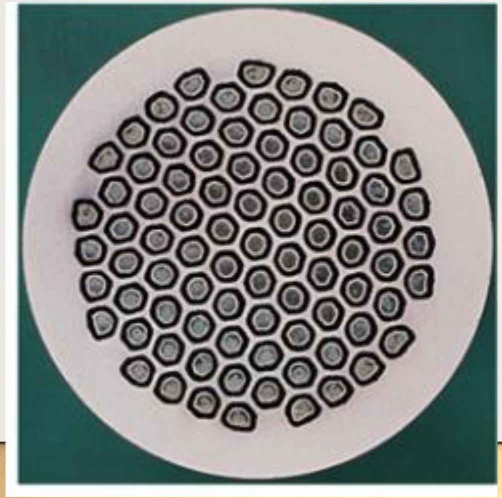
Nb3Sn development
CERN world wide collaboration

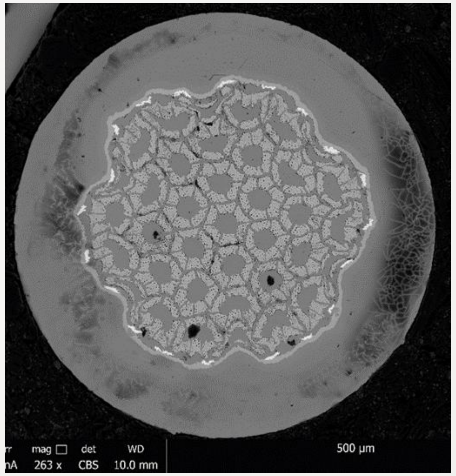
KOBELCO
KOBE STEEL GROUP

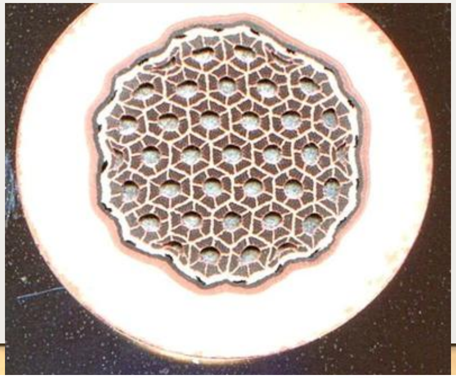
JASTEC
SUPERCONDUCTOR

FURUKAWA
ELECTRIC

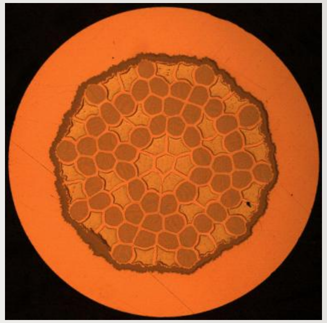


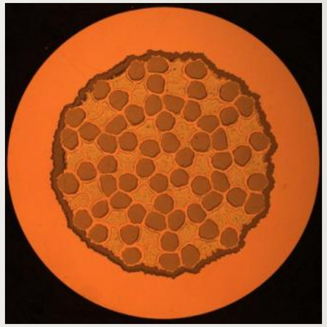


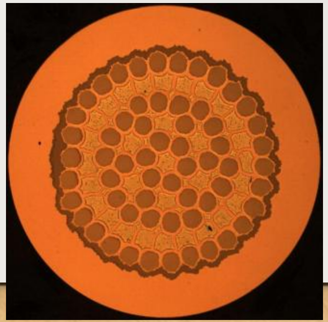




KISWIRE







ROSATOM
TVEL
BOCHVAR INSTITUTE OF INORGANIC MATERIALS
JSC VNIINM
NATIONAL NUCLEAR CORPORATION "ROSATOM"

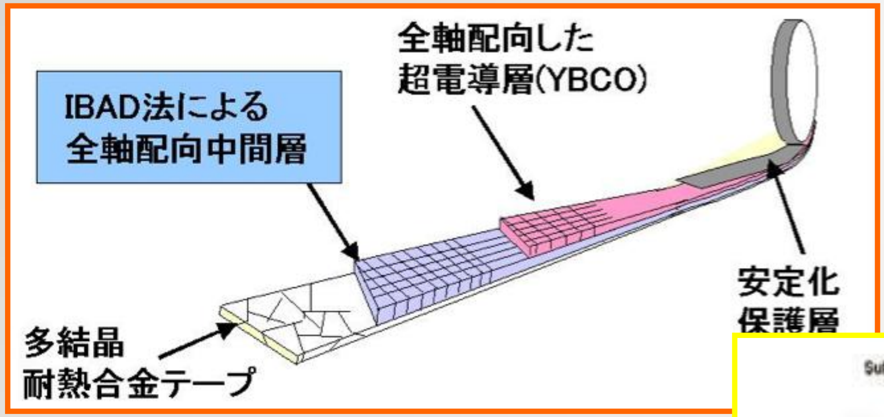
HTS conductor BISCCO

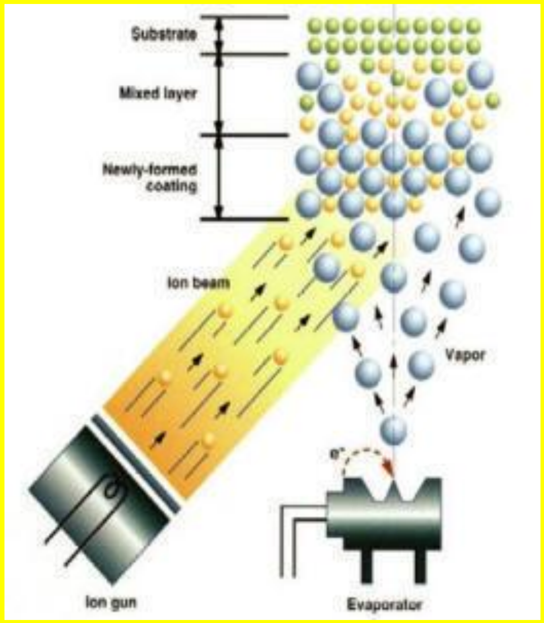
- Bi2223
  - Tape Shape
  - Magnetic Anisotropy
  - React and Wind
  - Mechanical Reinforcement
- Bi2212
  - Developed by Japanese Company: improved by USA
  - Round Wire
    - Rutherford Cable
  - Wind and React
    - under high pressure O_2

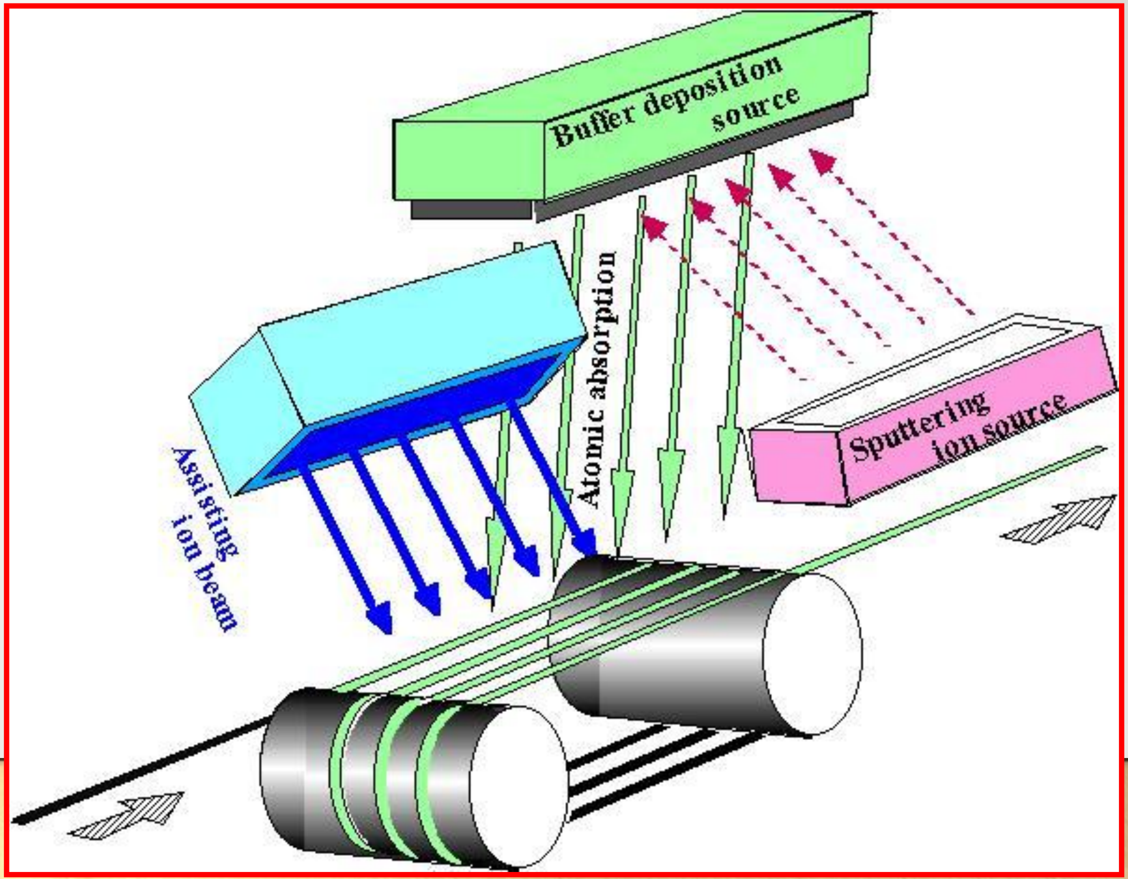
HTS Conductor YBCO Coated Conductor

Tape Shape：Magnetic Anisotropy
Wide superconductor: Big Shielding current against perpendicular field

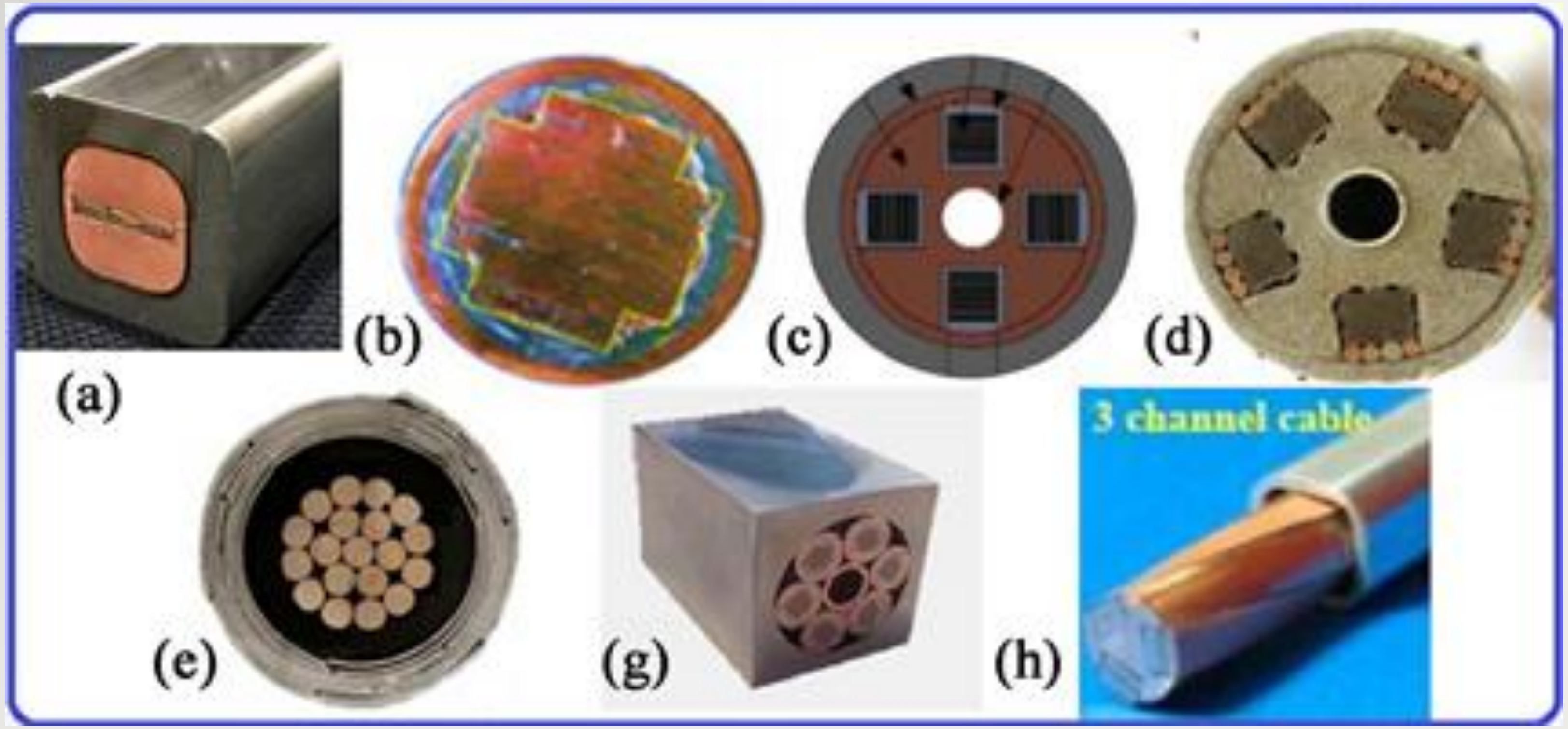
React and Wind
Strong against longitudinal force
Week against tearing force







HTS Cables

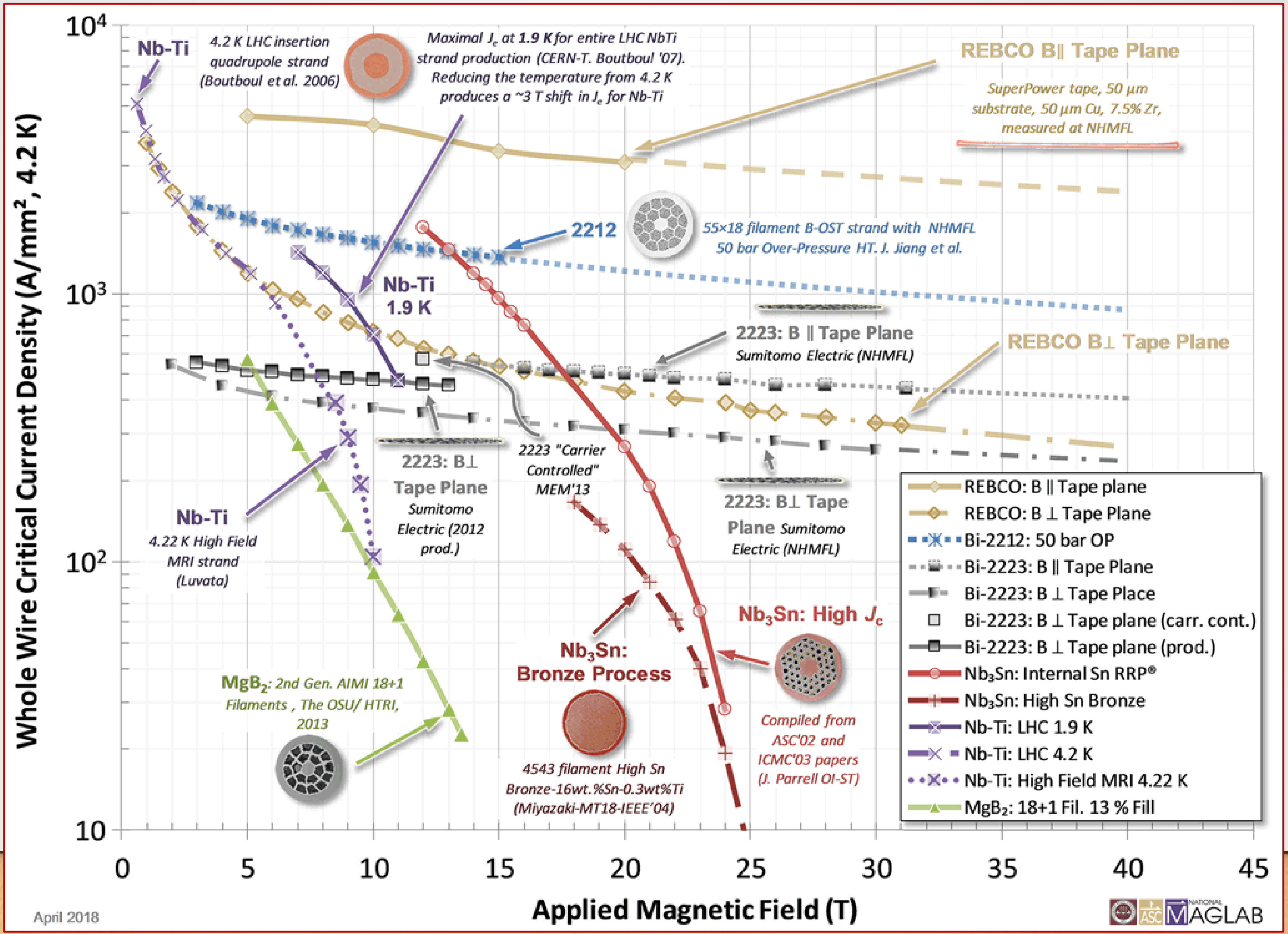


Cross sections of various HTS high-current Cables

Roebel Cable

CORC Cable

Performance of Superconductors



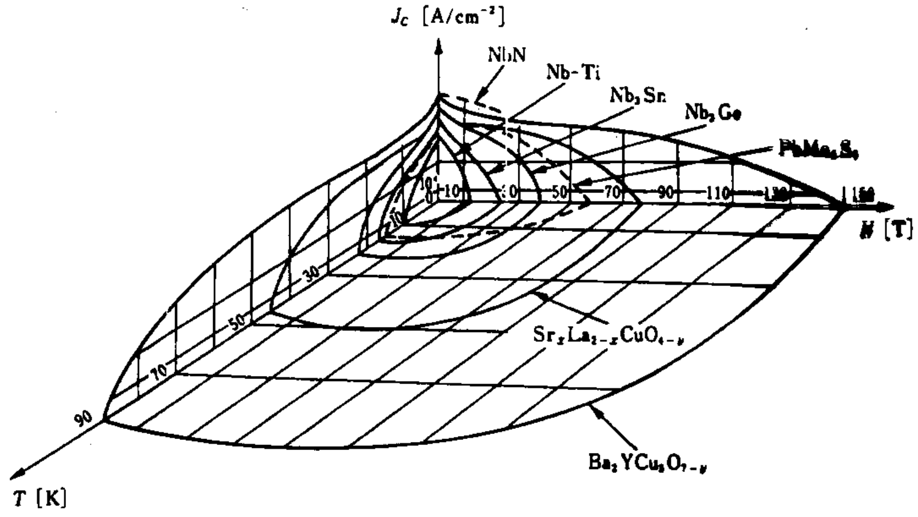
Item

- Superconductivity
- Superconducting Wire and Cables
- **Stability and Quench Protection**
- Summary

46

Quench？

- Superconductor
  - Critical Surface
  - Exceeding critical surface = Quench



典型的な超伝導体の臨界特性 [2]

- Real operation point must have margin
  - Temperature margin ⇔ Heat disturbance
  - Disturbance：Time and Space distribution

	Point	Distributed
Transient	Joules	Joules/m^3
Continuous	Watts	Watts/m^3

  - Cooling Condition：Direct by coolant or indirect
- Quench ← Depends on those conditions
  - **Quench Stability: important research item**

Adiabatic
vs
Distributed Disturbance

- Transient
  - Heat capacity

$$Q \Leftrightarrow C\Delta T$$

  - Heat capacity at low temperature is very low
- Continuous
  - For adiabatic condition it raise temperature continuously

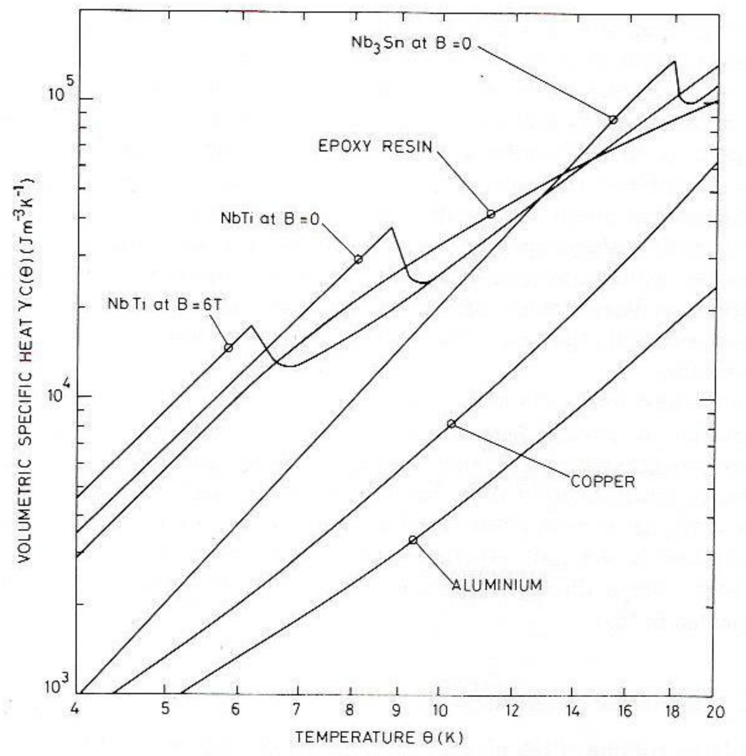


Fig. 5.3. Volumetric specific heat of some materials commonly used in magnets. Data for NbTi are average values based on measurements by J. Corsan, National Physical Laboratory (private communication) and R. Lagnier and E. Bonjour, CEN Grenoble (private communication). Data for Nb_3Sn is from Grigsby D. L. (US Department of Commerce NTIS Report AD-838469) and remaining data is from Johnson (1961).

Adiabatic vs Point Disturbance

Heat conduction

vs

Joule heating

$$2kA(q_c - q_0)/l = J_c r A l$$

Minimum Propagating Zone (MPZ)

$$2kA(q_c - q_0)/l = l^2 J_m r\left[J_m - J_c(q)\right]/(1 - l)Al$$

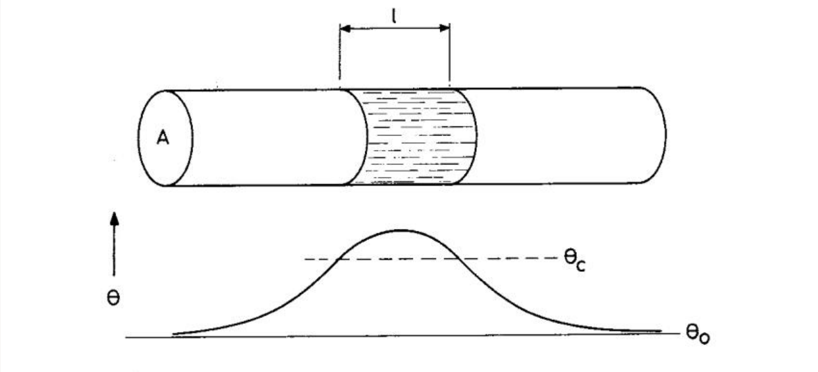
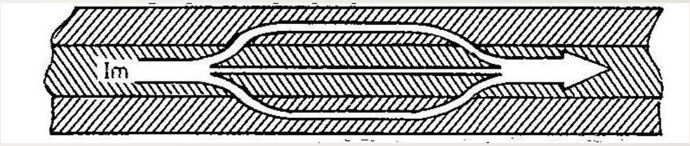


Fig. 5.8. A small normal zone created by a point disturbance in a current-carrying wire.



Current Sharing in Composite Conductor

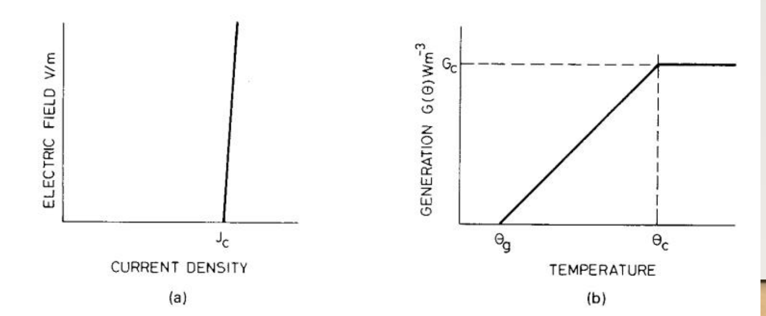


Fig. 5.9. (a) The development of flux flow resistance in a superconductor at current densities above critical; (b) temperature dependence of power generation in a composite conductor.

With Cooling

- Disturbance → Continuous or Transient?

- Continuous
  - Cooling power vs Heat input

- Transient
  - Heat capacity vs Heat Disturbance → Size of normal zone → Joule heating
  - Cooling power vs Joule heating (MPZ)

Cooling Condition: Pool Boiling Helium

- Heat Transfer
  - Nucleus boiling
    - Wet surface
    - Critical heat transfer
    - Sub-cool → some margin to start boiling
  - Film boiling
    - Dry surface
    - Transition from nucleus boing
    - Significantly lower heat transfer

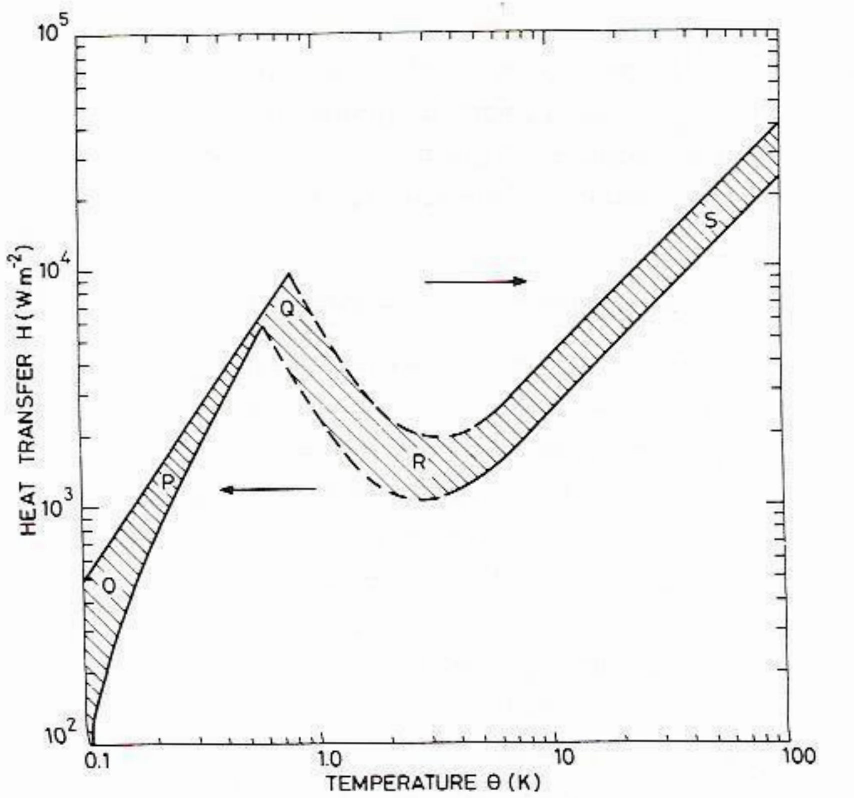


Fig. 6.3. Heat transfer from a metal surface to liquid helium boiling at 4.2 K under normal atmospheric pressure (shaded areas indicate spread of results).

Cooling Condition: Super Fluid Cooling

- Heat Transfer
  - Kapitsa resistance
    - Material boundary → Heat resistance
    - By Phonon Scattering
  - Heat Transfer in Helium
    - Very big
    - No nucleus boiling
      - Kapitsa resistance dominate heat transfer upto film boiling
- Saturated vs Pressurized
  - Pressurized Super Fluid
    - Bigger critical heat transfer
    - The best condition is
      - 1.8~1.9K
      - 0.1 MPa

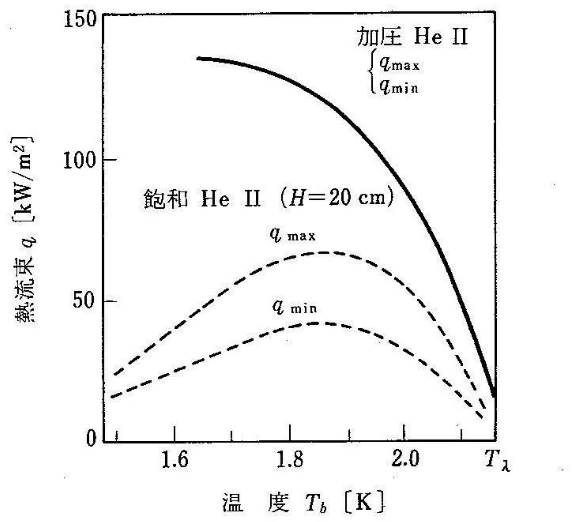


図 5・54 q_{max} および q_{min} の温度依存性［Kobayashi, et al. 1980］

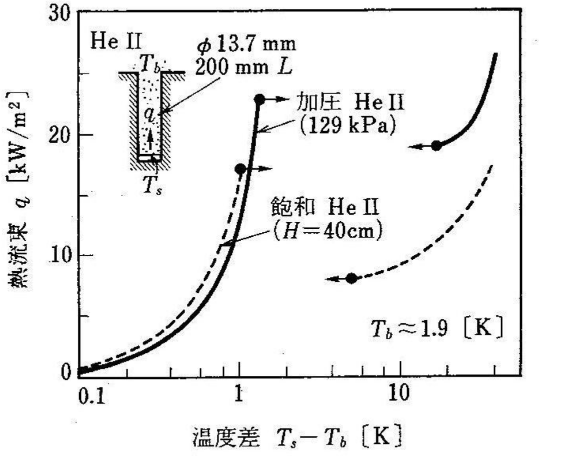
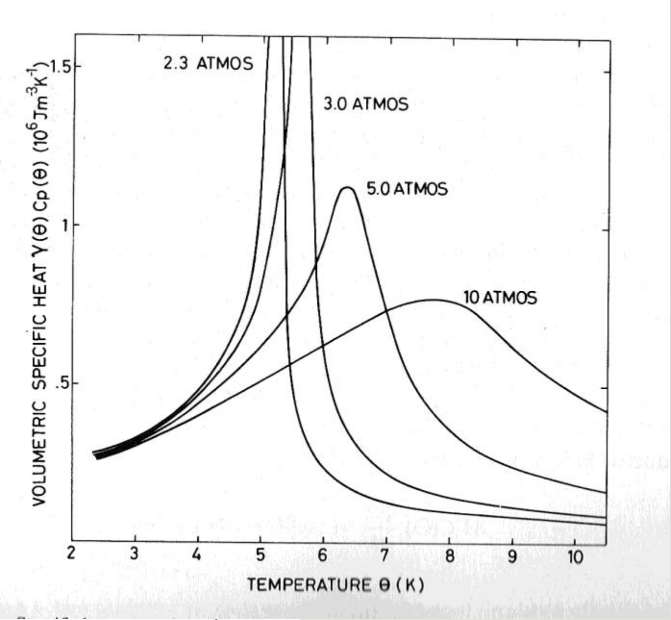


図 5・55 加圧 He II の熱伝達特性［Van Sciver 1978］

Cooling Condition: Supercritical

- Forced Flow Cooling
- Supercritical
  - No boundary between liquid and gas
  - No phase transition
- Heat Capacity
  - Peak at 0.3 MPa, 5~6K
- Heat Transfer
  - Peak around 0.3 MPa, 5~6K
- ~0.3MPa Operation
  - Maximum temperature 5~6K



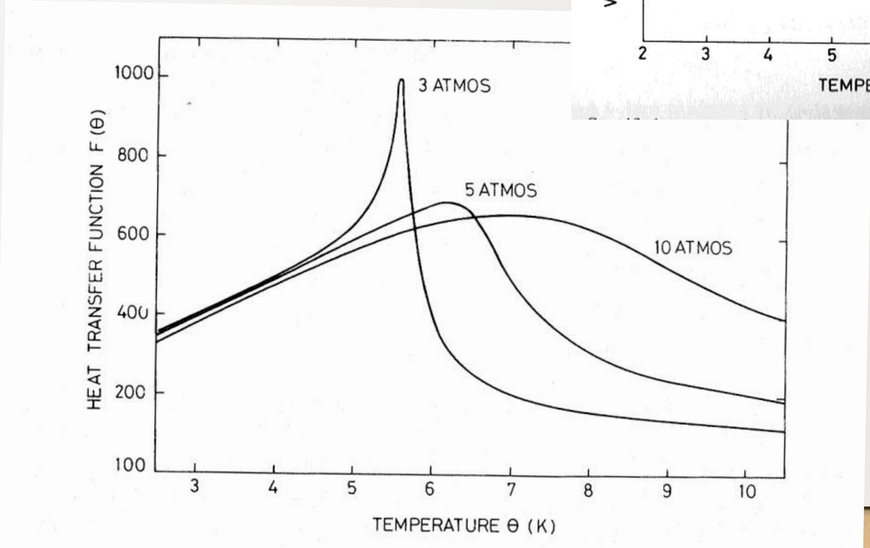


Fig. 6.25. Heat transfer function defined by eqn (6.52) (data from McCarty 1972).

Cooling Condition vs Distributed Disturbance

- Perfect stabilization：Stekley

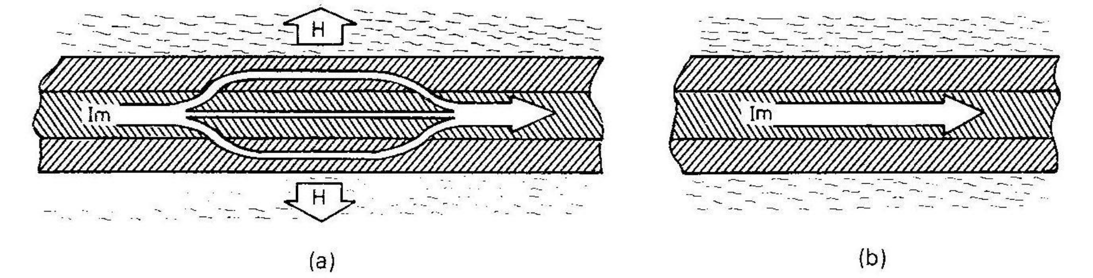


Fig. 6.1. (a) Cryogenic stabilization; following a disturbance current shares between copper and superconductor; ohmic heat generation is transferred to the coolant; (b) if the available cooling exceeds generation, temperature falls and current returns to the superconductor.

$$Ph(q - q_0) = l^2 J_m r\left[J_m - J_c(q)\right]/(1 - l)A$$

$$\text{if } J_c(q) = J_{c0}(q_c - q)/(q - q_0)$$

$$1 = \frac{l^2 J_c^2 r A}{(1 - l)Ph(q_c - q_0)} = \frac{G_c A}{Ph(q_c - q_0)} = a$$: Stekly parameter

Cooling Condition vs Semi-Distributed Disturbance

- Madock theorem
  - Cooling along conductor length
  - Basic equation

$$\frac{d}{dz}\left(Ak(q)\frac{d}{dz}\right) = PH(q) - AG(q)$$

- Equal-Area Theorem
  - Heat transfer curve vs Joule heating curve

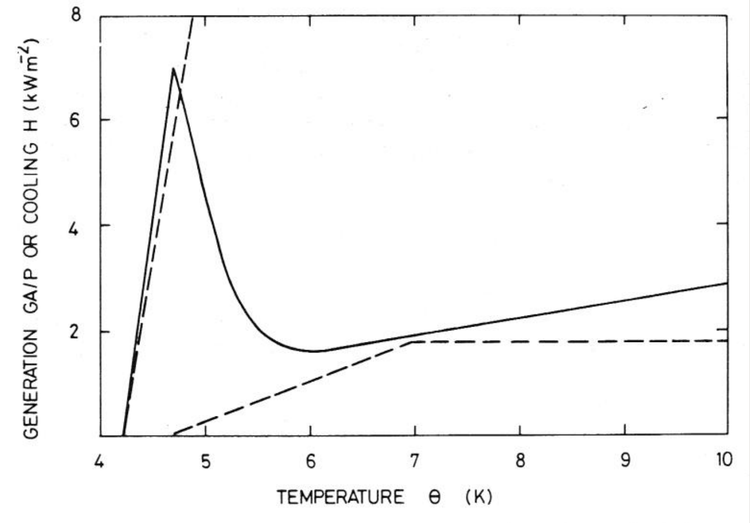
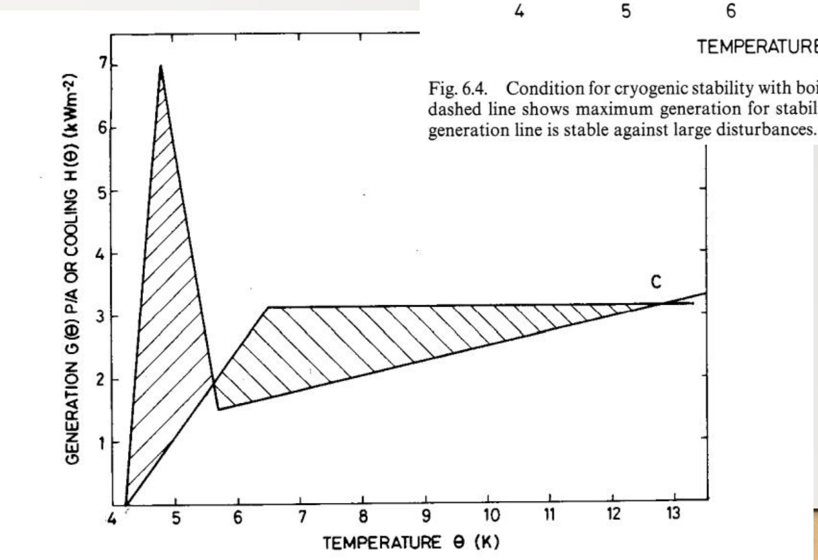


Fig. 6.4. Condition for cryogenic stability with boiling heat transfer (no heat conduction): upper dashed line shows maximum generation for stability against small disturbances; lower dashed generation line is stable against large disturbances.



6.6. Equal-area condition for cryogenic stability of a normal zone with cold superconduct- regions at either end (drawn for NbTi at 6 T, i.e. $\theta_c = 6.5$ K).

55

Cooling Condition vs Point Disturbance

- Extend Madock Theorem
  - Small normal zone
  - Shrink of normal zone
  - MPZ

- For Real magnets
  - 3D anisotorpy
    - Along conductor
    - Turn to turn
    - Layer to layer
  - Basic equation

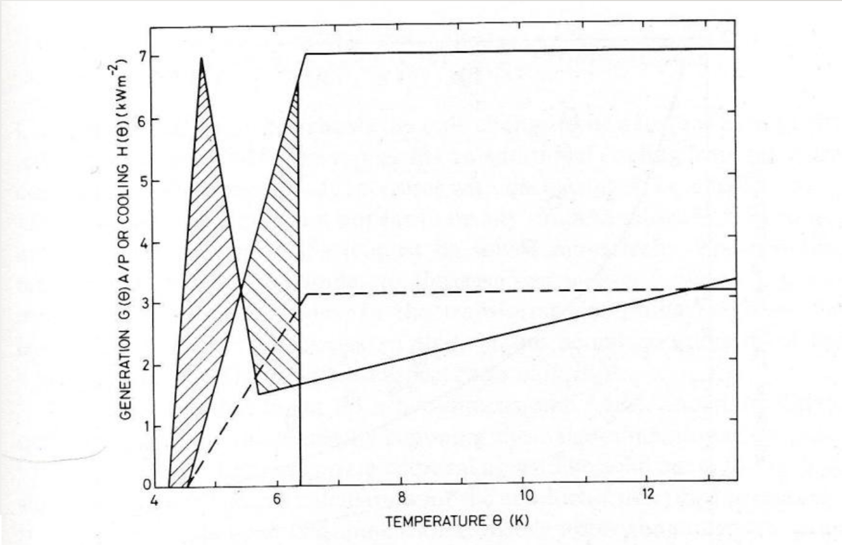
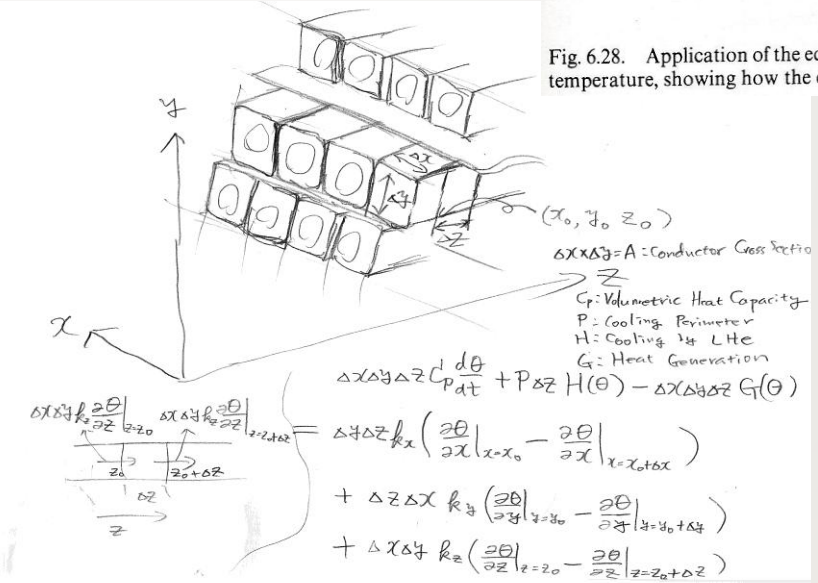


Fig. 6.28. Application of the equal-area theorem to a short normal zone with reduced maximum temperature, showing how the critical generation G_c may be increased in short zones.



$$\frac{\partial}{\partial x}\left(k_x(q)\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y(q)\frac{\partial}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z(q)\frac{\partial}{\partial z}\right)=C_p\frac{\partial q}{\partial t}+\frac{P}{A}H(q)-G(q)$$

Stability on Cable

- Cable = Multiple Strands
  - Inter-strand heat transfer
  - Inter-strand current sharing
- Better stability
  - with lower inter-strand resistance
  - AC-loss will increase

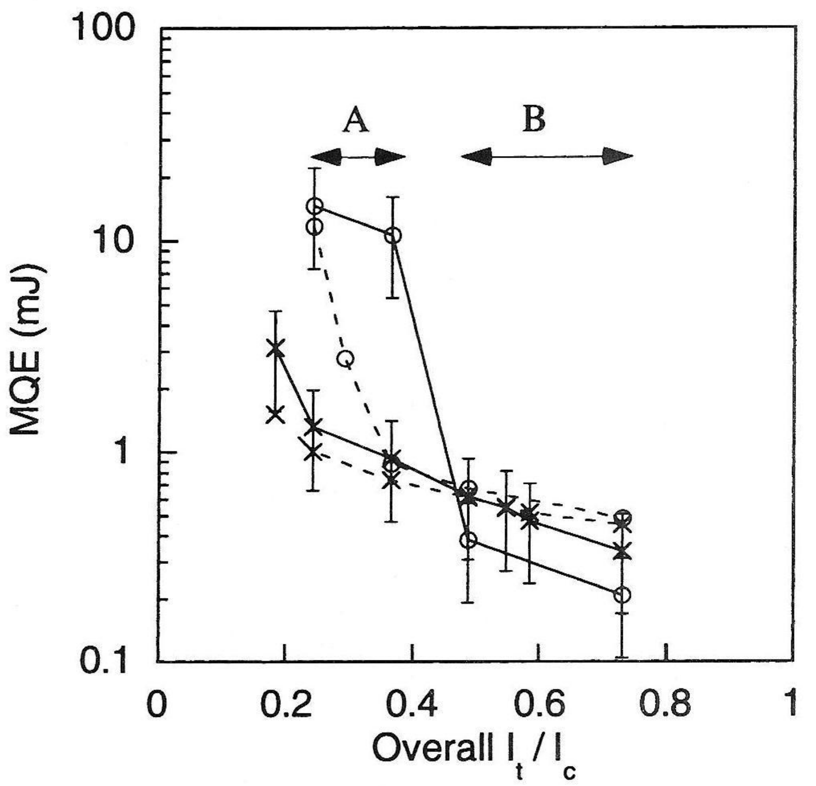


Figure 9 MQE vs. I_t/I_c. Lines with open circles denote MQE of triplex cable against local disturbance, and lines with crosses denote MQE of single strand. Solid lines denote experimental results, and broken lines denote numerical results where contact electrical conductance and contact thermal conductance are 1.36×10^5 S/m and 2 W/(Km), respectively. In region A, current re-distribution is observed in recovery process, and in region B, it is not observed

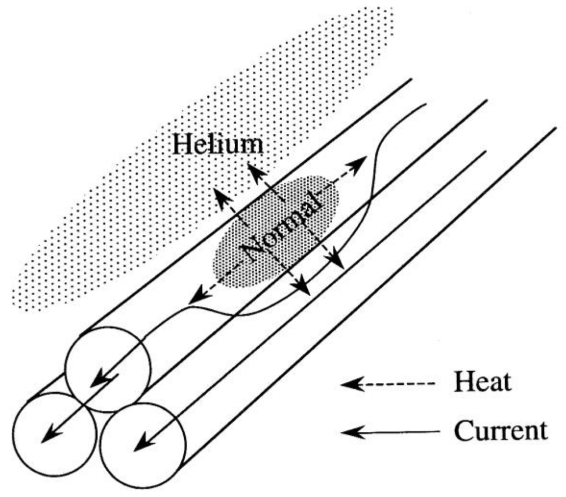


Figure 1 Current transfer and thermal conduction between strands following formation of local normal zone

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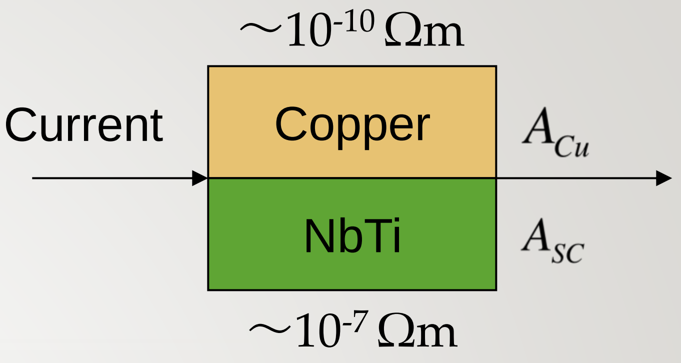
Quench and Protection



- Quench = Abrupt phase transition to normal
- Current flow in Copper → Still fast temperature rise
- Temperature rise depends: MIITs

$$\int_{t_{quench}}^{t_{end}} I^2 dt$$

$$= \int_{T_0}^{T_{\max}} \frac{C_{pCu} A_{Cu} + C_{pSC} A_{SC}}{r_{Cu} / A_{Cu}} dT$$

$$R = r_{Cu} l / A_{Cu}$$

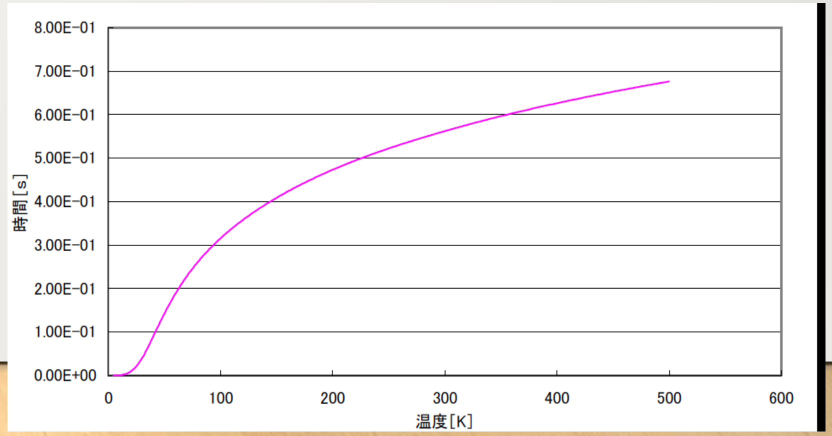
$$G = I^2 r_{Cu} l / A_{Cu}$$

$$= \Delta H$$

$$= (C_{p-Cu} A_{Cu} + C_{p-SC} A_{SC}) l \Delta T$$

- MIITs/I^2: time to reach a temperature

Cu/NbTi=1, 400 A/mm^2 →



Rapid detection of quench and shutting down current is needed

Quench Propergation

- Quench Propergation
  - Basic Equation (same as stability)

$$\frac{\partial}{\partial x}\left(k_x(q)\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y(q)\frac{\partial}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z(q)\frac{\partial}{\partial z}\right)=C_p\frac{\partial q}{\partial t}+\frac{P}{A}H(q)-G(q)$$

  - One dimensional adiabatic assumption

$$v_{ad}=\frac{J}{gC}\left\{\frac{r\,k}{q_s-q_0}\right\}^{\frac{1}{2}}$$

$$=\frac{J}{gC}\left\{\frac{L_0 q_s}{q_s-q_0}\right\}^{\frac{1}{2}}$$

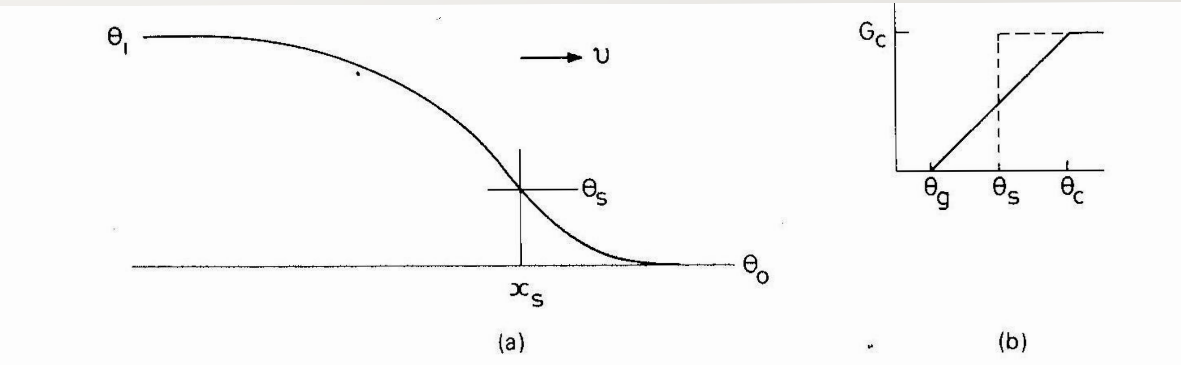


Fig. 9.3.(a) Temperature profile at the boundary of a normal zone advancing from left to right; (b) approximation of the generation curve by an abrupt transition.

Quench Stability and Protection Summary

- Stability Analysis
  - Well established
  - Surface or boundary condition is not clear
- Steckley, Madock conditions
  - Give good stability margin
    - Lower current density
    - More aggressive condition was actually used
    - For HTS; large heat capacity give a huge stability
- Quench Protection
  - Quench detection and current shut down with in MIITs limit
  - For HTS due to low quench velocity quench detection is issue

Item

- Superconductivity
- Superconducting Wire and Cables
- Stability and Quench Protection
- **<u>Summary</u>**

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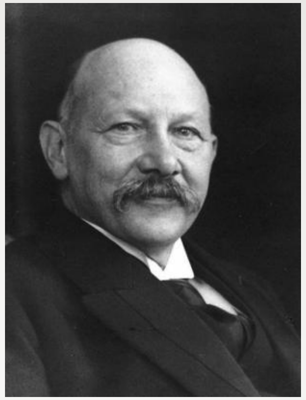
Summary

- SC Conductor and Magnet
- Developed supplementary
- Reached to NbTi limit
- Higher Field by Nb_3Sn (or IBS?)
  - FCC world wide development
- HTS (High Temperature Superconductor)
  - Still very expensive
  - Needs special usage
    - High Radiation
    - High Filed above 20 T
- **Game Change = New Chance!**



Kamerlingh Onnes
Find Superconductivity

Alvin Tollestrup
TEVATRON Magnet

Who's next
YOU?