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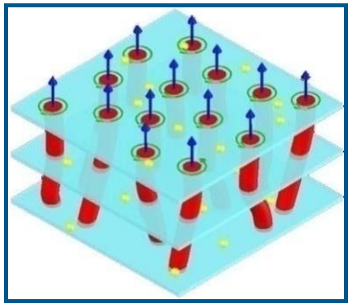
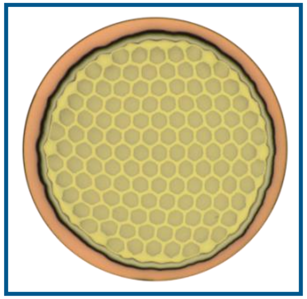
Superconductivity and its applications

Summary





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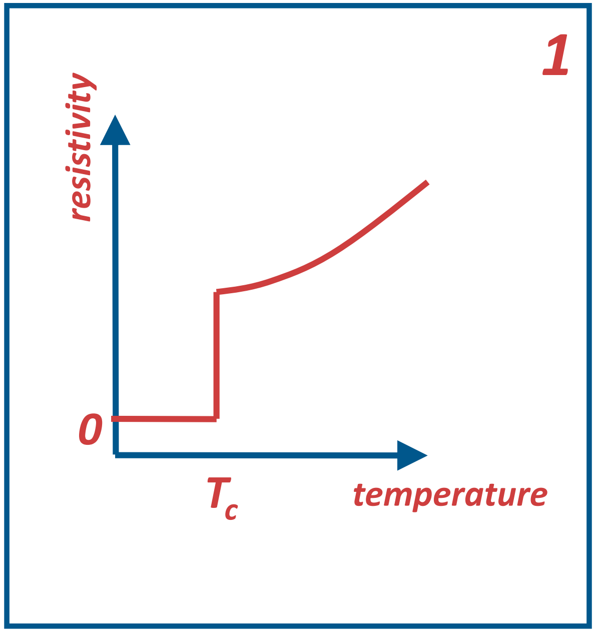
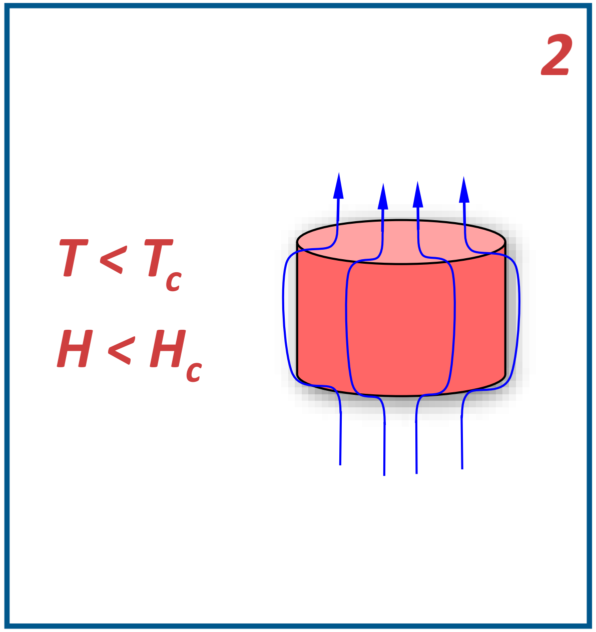
PART I* - *From the phenomena to the phenomenological models

PART II* - *From the materials to the wires

PART III* - *From the wires to the devices

If it is a superconductor, then…





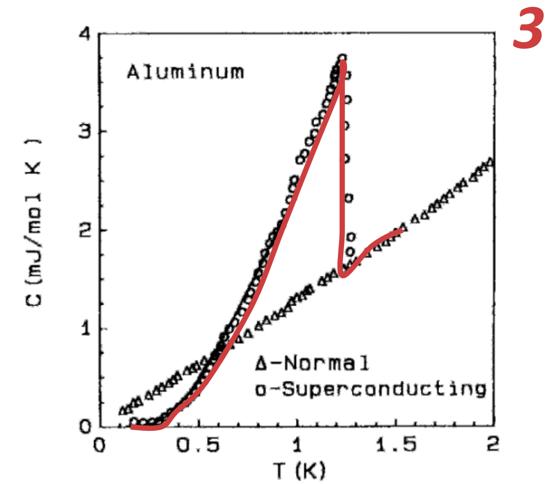


Figure 4.5 Specific heat jump in superconducting Al compared with the normal-state specific heat (Phillips, 1959; see Crow and Ong, 1990, p. 225).

A thermodynamic state: Perfect conductor with perfect diamagnetism

The jump at T_c was predicted from thermodynamic considerations

The 1st phenomenological model: The London Theory

Drude model $$\frac{d\vec{v}}{dt} = -\frac{e}{m}\left[\vec{E} + \frac{1}{c}\vec{v}\times\vec{h}\right] - \frac{\vec{v}}{\tau}$$

In the London model the friction term is neglected

$$\frac{d\vec{v}_S}{dt} = -\frac{e}{m}\left[\vec{E} + \frac{1}{c}\vec{v}_S\times\vec{h}\right]$$

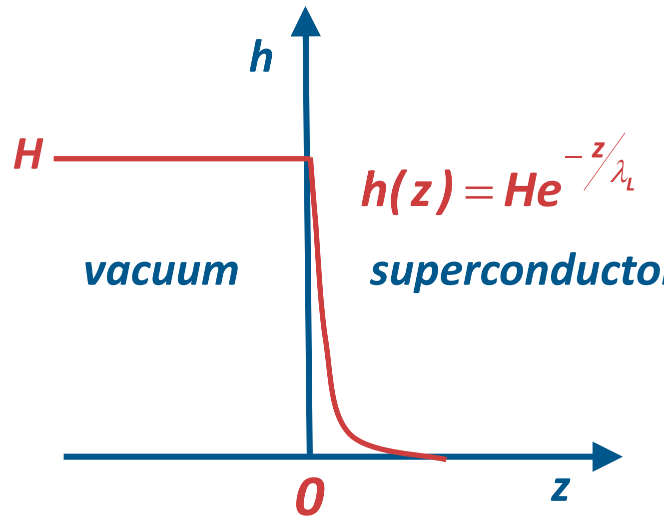
The main achievement: it shows how the magnetic field diffuses in a superconductor

$$\vec{h} - \lambda_L^2\nabla^2\vec{h} = 0$$

with $$\lambda_L = \sqrt{\frac{\Lambda c^2}{4\pi}} = \sqrt{\frac{m^* c^2}{4\pi\ n_S e^{*2}}}$$

penetration depth

superfluid density



A further step: the Ginzburg-Landau Theory

In the London model the superfluid density n_s does not depend on the position

This is the main new ingredient of the G-L theory: $n_s(\vec{r}) = |\psi(\vec{r})|^2$

The free energy of a superconductor is written as:

$$F_s = F_n + \text{Condensation energy} + \text{Kinetic energy} + \text{Field energy}$$

$$F_S(\vec{r},T) = F_N(\vec{r},T) + \alpha\, |\psi|^2 + \frac{\beta}{2}\, |\psi|^4 + \frac{1}{2m^*}\left|\left(-i\hbar\vec{\nabla} - \frac{e^*}{c}\vec{a}\right)\psi\right|^2 + \frac{h^2}{8\pi}$$

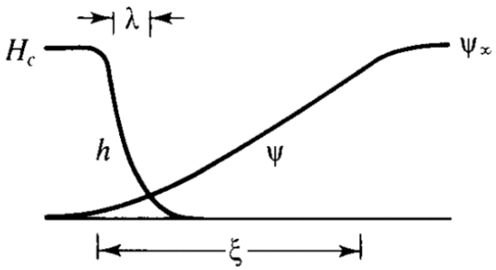
The correct predictions of the models are

- *Two characteristic lengths:* λ *and* ξ
- *Two types of superconductors*
- *Flux quantization and vortices*

Ginzburg-Landau parameter $\kappa = \dfrac{\lambda}{\xi}$

Type-I and Type-II superconductors

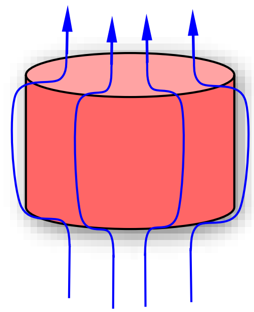
Type-I superconductor

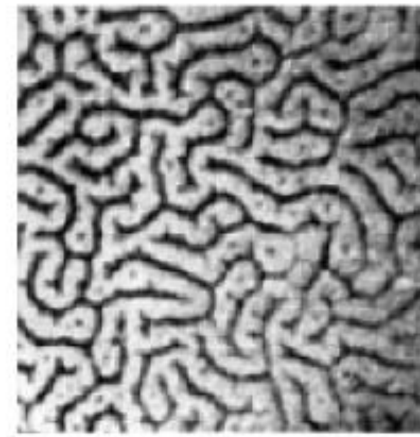


$\kappa \ll 1$

At a domain wall $\Delta E = A\dfrac{H_c^2}{8\pi}(\xi - \lambda) > 0$

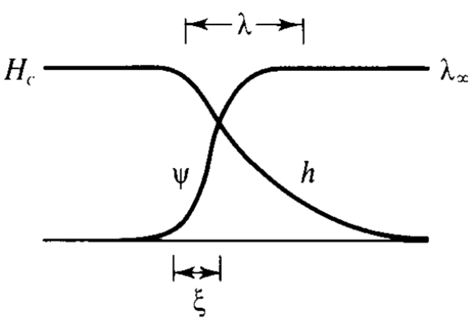
$H < H_c$





Laminar intermediate state

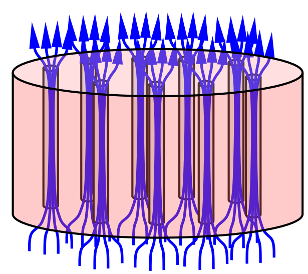
Type-II superconductor

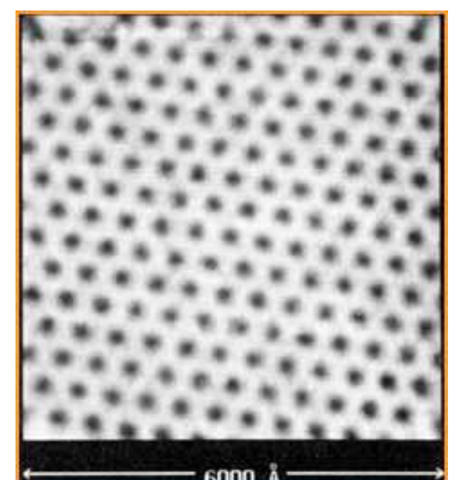


$\kappa \gg 1$

At a domain wall $\Delta E = A\dfrac{H_c^2}{8\pi}(\xi - \lambda) < 0$

$H_{c1} < H < H_{c2}$

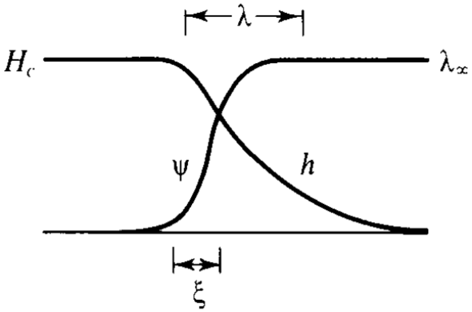




Mixed state

Type-II superconductors: critical fields

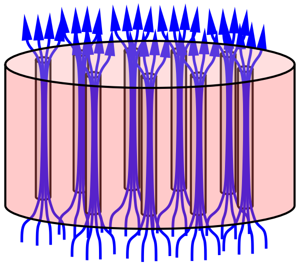
Type-II superconductor

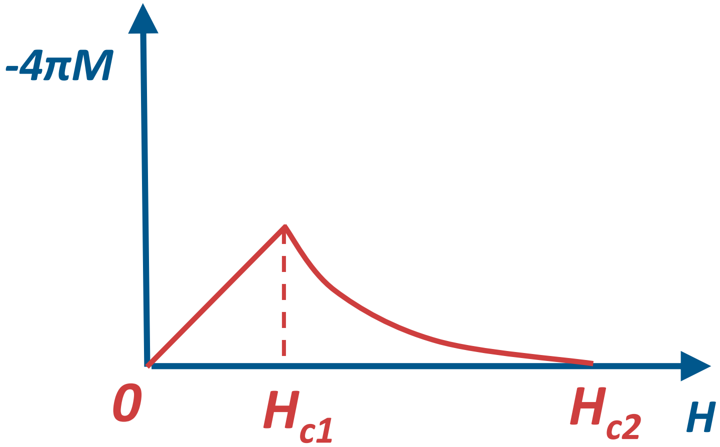


$\kappa \gg 1$

At a domain wall $\Delta E = A\dfrac{H_c^2}{8\pi}(\xi - \lambda) < 0$

$H_{c1} < H < H_{c2}$





Lower critical field

$$H_{c1} = \frac{\Phi_0}{4\pi\lambda^2} \ln\kappa = \frac{H_c}{\sqrt{2}\kappa} \ln\kappa$$

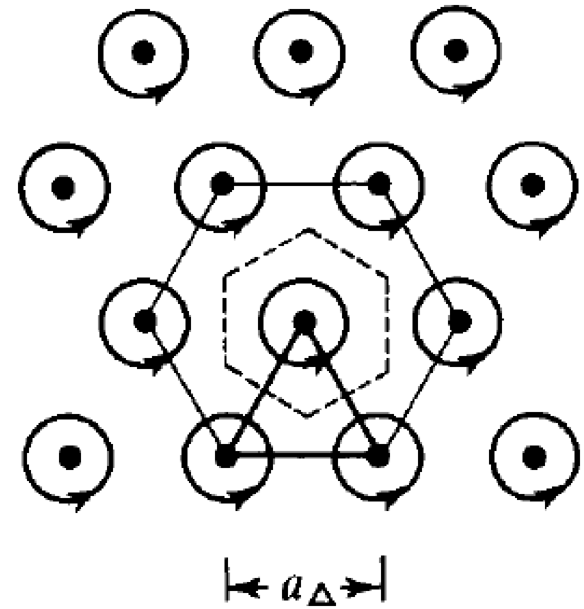
Upper critical field

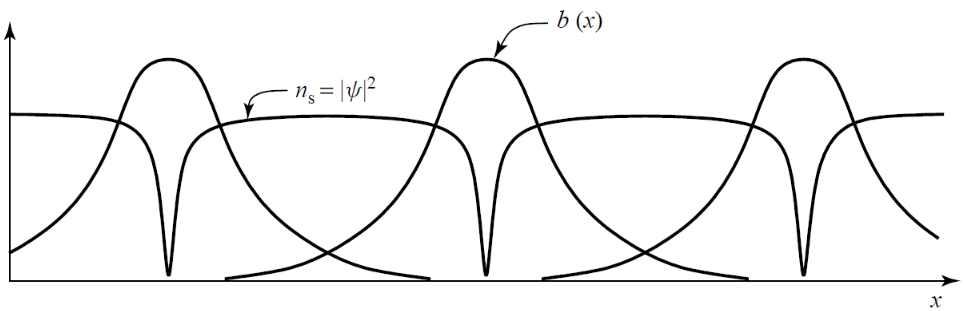
$$H_{c2} = \frac{\Phi_0}{2\pi\xi^2} = \sqrt{2}\kappa\, H_c$$

The structure of the vortex lattice

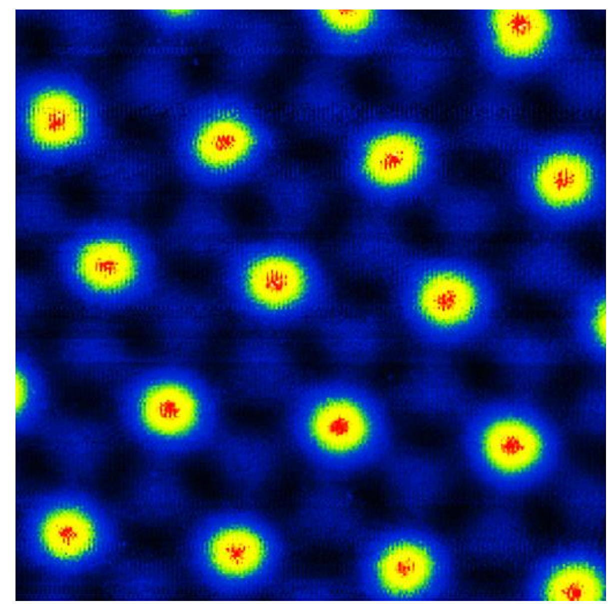
In a type-II superconductor, magnetic flux penetrates in the form of quantized vortices

$$\Phi_0 = \frac{hc}{2e}$$





$$|\psi(r)| = \psi_\infty \tanh\frac{r}{\sqrt{2}\xi} \qquad h(r) \approx \frac{\Phi_0}{2\pi\lambda^2}\left[ln\frac{\lambda}{r} + 0.12\right]$$



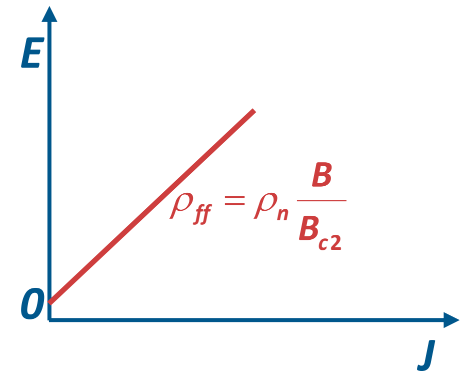
Vortex motion and dissipation

1) In the presence of a current, vortices experience a force

$$F = J_{ext} \times \frac{B}{c}$$

2) Vortex motion (flux flow) induces dissipation

$$\rho_{ff} = \rho_n \frac{B}{B_{c2}}$$

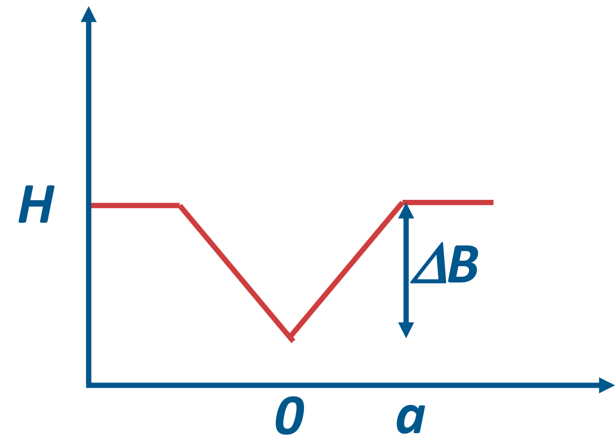


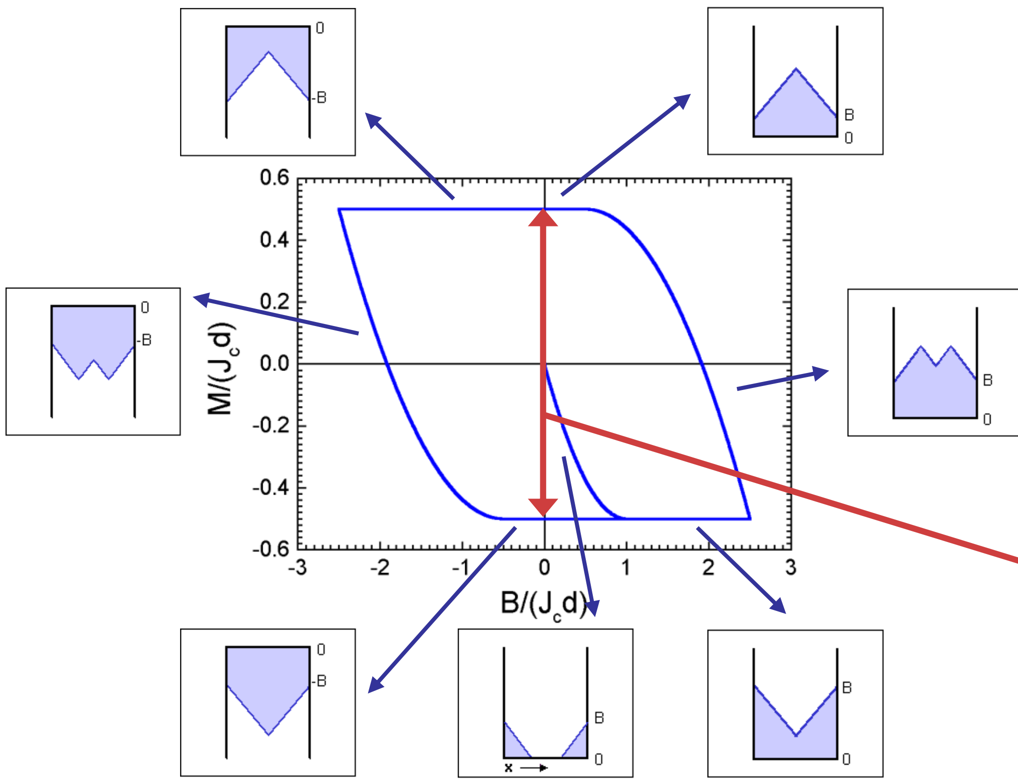
3) An array of defects with appropriate dimensions and distribution may impede vortex motion

4) There is no dissipation if the force on the vortices does not exceed the pinning force $F_p = J_c \times B$

Vortex pinning and critical state

In the critical state $F = F_p \;\Rightarrow\; \dfrac{dB}{dx} = \dfrac{4\pi}{c} J_c$





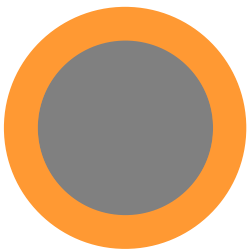
$$\boxed{\Delta M = J_c a}$$

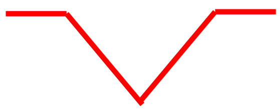
The critical state is a metastable state

Magnetization relaxes with a time-log law at $T \neq 0$

Superconducting wires are multifilamentary. WHY ?

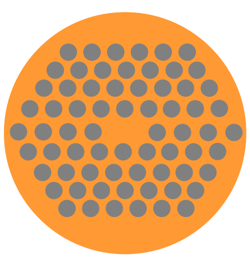
1st reason: To reduce hysteretic losses





$$\Delta M \propto J_c d$$

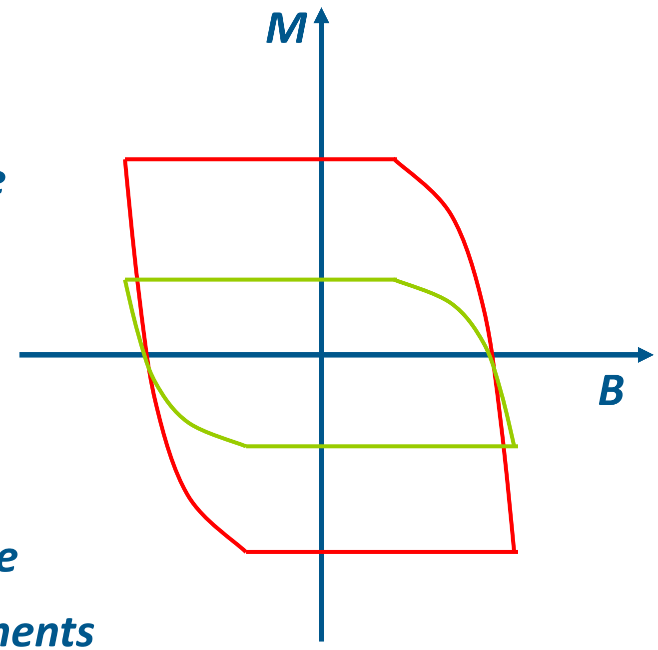
d is the filament size



$$\Delta M \propto n J_c d$$

d is the filament size

n is the number of filaments

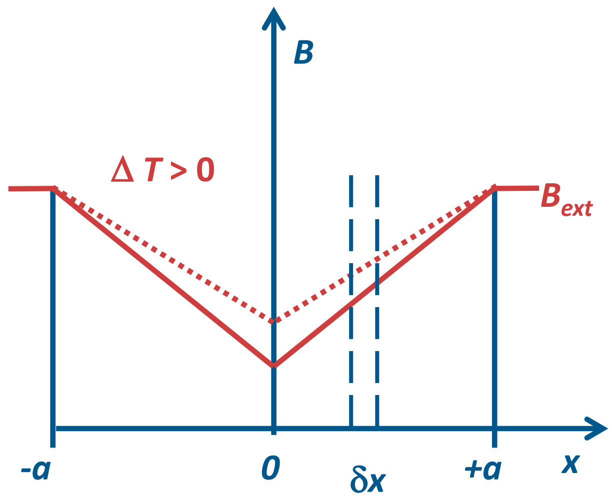


Superconducting wires are multifilamentary. WHY ?

2nd reason: To reduce flux jumps

In the adiabatic approximation

$$\begin{array}{ccc} \Delta T > 0 & \Rightarrow & \Delta J_c < 0 \\ \Uparrow & & \Downarrow \\ \Delta Q > 0 & \Leftarrow & \Delta E > 0 \end{array}$$



If ΔQ_{ext} is the initial perturbation, the heat balance for the slab is

$$\Delta Q_{ext} + \frac{\mu_0 J_c a^2}{3\left(T_c - T_{op}\right)} \Delta T = c \Delta T$$

And thus the effective specific heat is

$$c_{eff} = \frac{\Delta Q_{ext}}{\Delta T} = c - \frac{\mu_0 J_c^2 a^2}{3\left(T_c - T_{op}\right)}$$

c_{eff} can become zero $\Rightarrow$ The solution is to reduce the size of the filaments

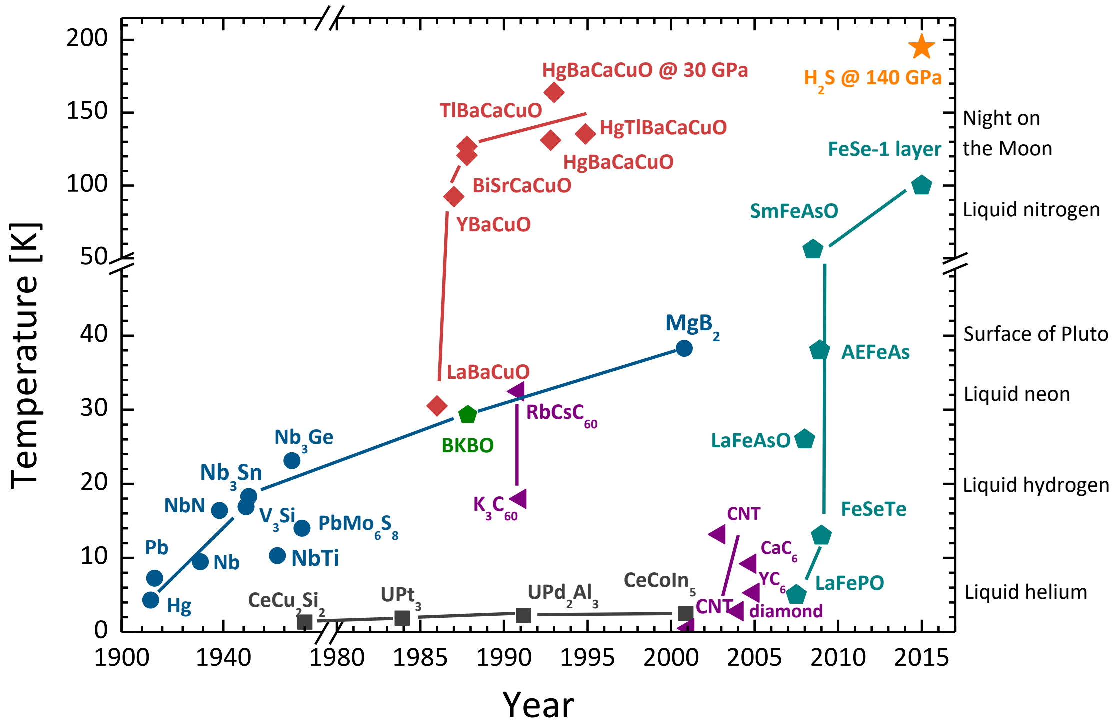
PART I - From the phenomena to the phenomenological models

PART II - From the materials to the wires

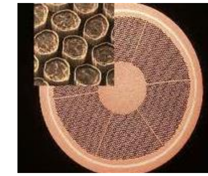
PART III - From the wires to the devices

From superconducting materials…

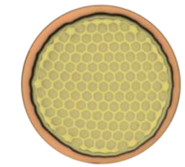
…to technical superconductors



NbTi

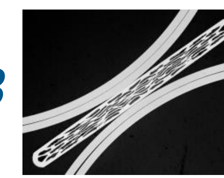


Nb_3Sn

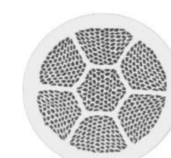


MgB_2

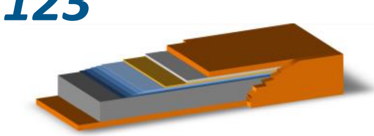
Bi2223



Bi2212



Y123



1.	***Superconducting ?***	***10’000***
2.	***T_c>4.2K & B_{c2}>10T ?***	***100***
3.	***J_c>1000 A/mm^2 ?***	***~10***

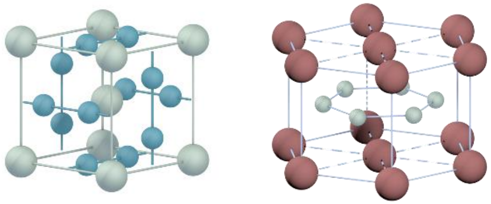
From superconducting materials…

…to technical superconductors

The six steps

1. *Discovery*
2. *Improvement of J_c performance*
3. *Co-processing with matrix metal*
4. *Multifilament form*
5. *I_c>100 A in length > 1 km*
6. *Thermal and mechanical stabilization*

LTS materials for applications



	T_c [K]	B_{c2} [T]
NbTi	9.8	10.5
Nb_3Sn	18.0	30+
MgB_2	39.0	10-60

NbTi:
- Alloy
- Easy to produce in multifilamentary wires
- Wires does not need reaction heat treatment

Nb_3Sn: Bronze Route, Internal Sn, PIT

MgB_2: PIT ex situ, PIT in situ, PIT IMD

Nb_3Sn, MgB_2:
- Intermetallic compounds
- Various fabrication methods
- Wires must be reacted after fabrication

Key parameter for J_c optimization

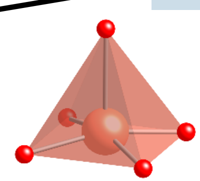
NbTi $\rightarrow$ α-Ti precipitates acts as pinning centers

Nb_3Sn $\rightarrow$ Grain morphology (pinning) and composition/doping (B_{c2})

MgB_2 $\rightarrow$ Doping (B_{c2}) and connectivity (densification)

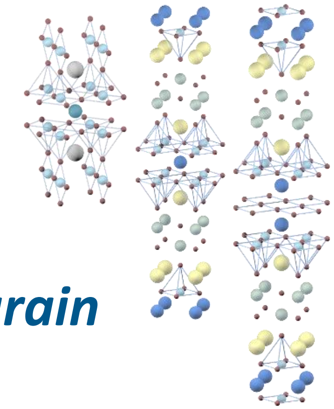
Relevant HTS families

		Compound	T_c [K]	Short name
hole-doped		$La_{1.85}Sr_{0.15}CuO_4$	39	LaSCCO
hole-doped	REBCO	$YBa_2Cu_3O_7$	92	Y123 or YBCO
hole-doped	Bi family	$Bi_2Sr_2CuO_6$	15	Bi2201
hole-doped	Bi family	$Bi_2Sr_2CaCu_2O_8$	91	Bi2212
hole-doped	Bi family	$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	Bi2223 or BSCCO
hole-doped	Tl families	$Tl_2Ba_2CuO_6$	90	
hole-doped	Tl families	$Tl_2Ba_2CaCu_2O_8$	110	
hole-doped	Tl families	$Tl_2Ba_2Ca_2Cu_3O_{10}$	125	Tl2223 or TBCCO
hole-doped	Tl families	$TlBa_2CaCu_2O_7$	91	
hole-doped	Tl families	$TlBa_2Ca_2Cu_3O_9$	116	
hole-doped	Tl families	$TlBa_2Ca_3Cu_4O_{11}$	122	
hole-doped	Hg family	$HgBa_2CuO_4$	95	
hole-doped	Hg family	$HgBa_2CaCu_2O_6$	122	
hole-doped	Hg family	$HgBa_2Ca_2Cu_3O_8$	133	Hg1223
electron-doped		$Nd_{1.85}Ce_{0.15}CuO_4$	25	NCCO

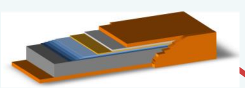


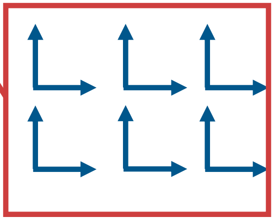
The key feature of HTS superconductivity is related to the CuO_2 planes

HTS materials for applications



Copper oxides with highly anisotropic structures, texturing (grain orientation) is required in technical superconductors

	T_c [K]	texture	
Bi2223	110	c-axis	
Bi2212	91	c-axis (radial)	
Y123	92	biaxial	



Bi2223:
- Produced by Powder-In-Tube method
- Ag matrix material
- Tape geometry to achieve c-axis texturing
- I_c depends on the magnetic field orientation

Bi2212:
- Produced by Powder-In-Tube method
- Ag matrix material
- Round wire, spontaneous radial texturing of the c-axis
- Isotropic properties of I_c

Y123:
- Coated conductors
- Y123 layer deposited on a metallic substrate
- Texturing along c and in the ab plane
- I_c depends on the magnetic field orientation
- Various fabrication processes

***PART I* - From the phenomena to the phenomenological models**

***PART II* - From the materials to the wires**

***PART III* - From the wires to the devices**

Basic design and operation issues of a superconducting device

Superconducting magnets, field shapes and winding configurations

- *Solenoids (NMR, MRI and laboratory magnets)*
- *Transverse fields (particle accelerators)*
- *Toroids (fusion magnets)*

From the wire to the magnet

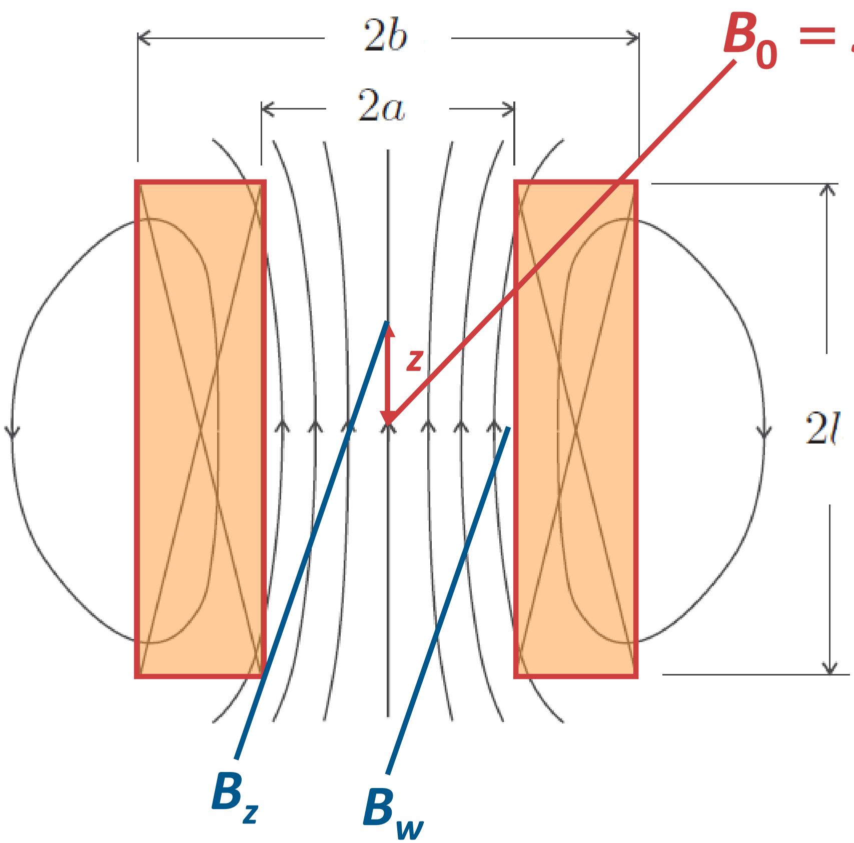
Superconducting wire
- *Superconductor*
- *Matrix metal*
- *Non-matrix metal*

Superconducting magnet
- *Superconducting wire*
- *Reinforcing elements and structure*
- *Insulation and filling materials*
- *(Coolant)*

Superconducting magnets, field shapes and winding configurations

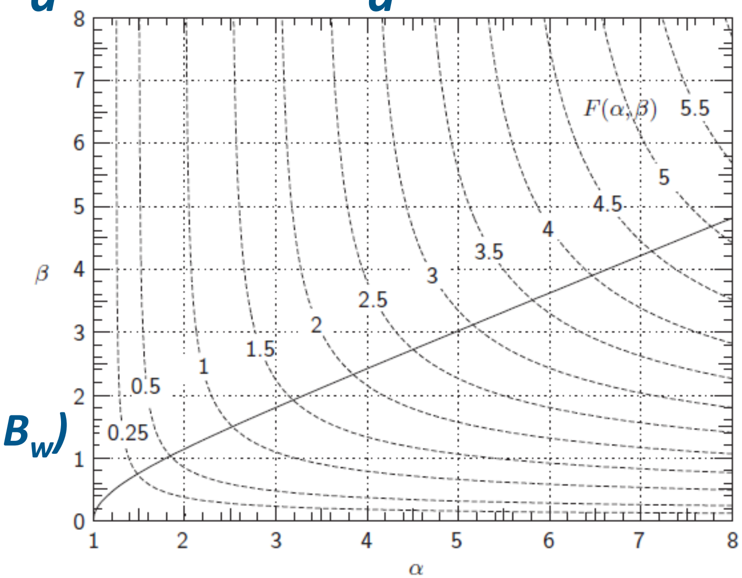
Solenoids (NMR, MRI and laboratory magnets)

$$B_0 = JaF(\alpha,\beta) \quad \textit{where} \quad J = \frac{NI}{2l(b-a)}$$



$$F(\alpha,\beta) = \mu_0 \beta \ln\left[\frac{\alpha + \sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}}\right]$$

$$\alpha = \frac{b}{a} \qquad \beta = \frac{l}{a}$$



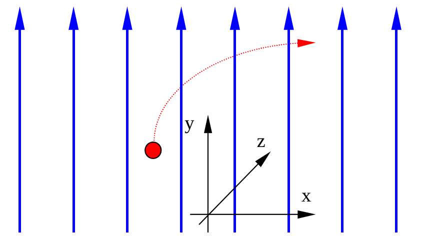
α and β have an influence on the field uniformity (B_z and B_w)

Superconducting magnets, field shapes and winding configurations

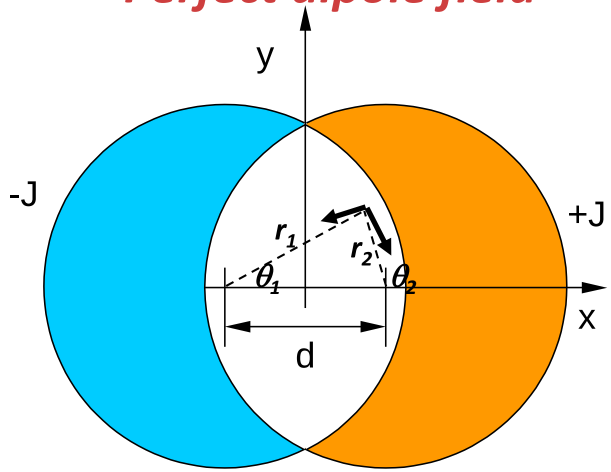
Transverse fields (particle accelerators)

Bending the beam

Uniform field (dipole)

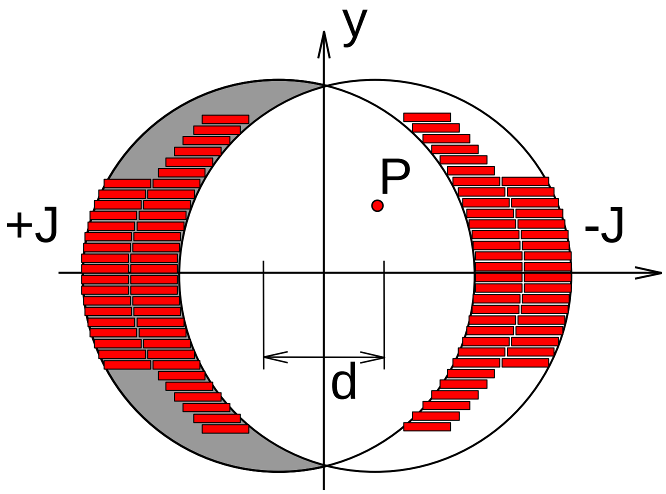


Perfect dipole field



$$B_y = -\mu_0 \frac{Jd}{2} \qquad B_x = 0$$

Real dipole magnet



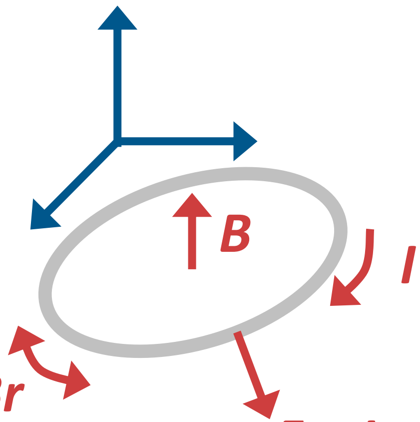
Basic design and operation issues of a superconducting device

- ***Superconducting magnets and mechanical stability***
- ***Superconducting magnets and thermal stability***

Electromechanical properties of superconducting wires

Stresses in superconductors arise from

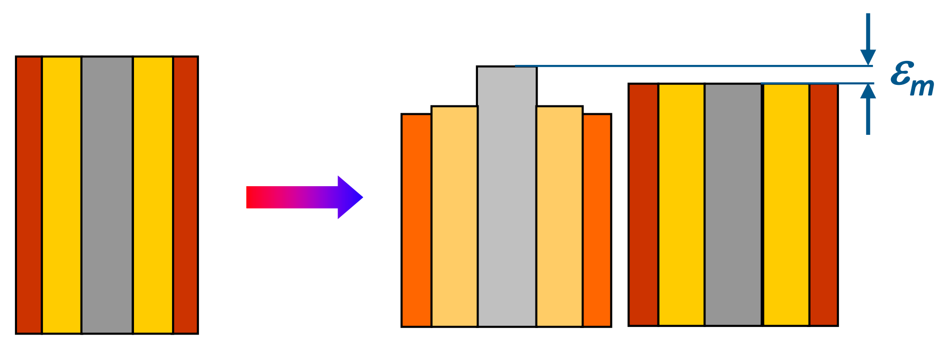
Magnetic forces within the magnet windings



$$\sigma_{hoop} = \frac{I}{S_{wire}} Br$$

$$F = I \times B$$

Mismatch in thermal contraction within the composite



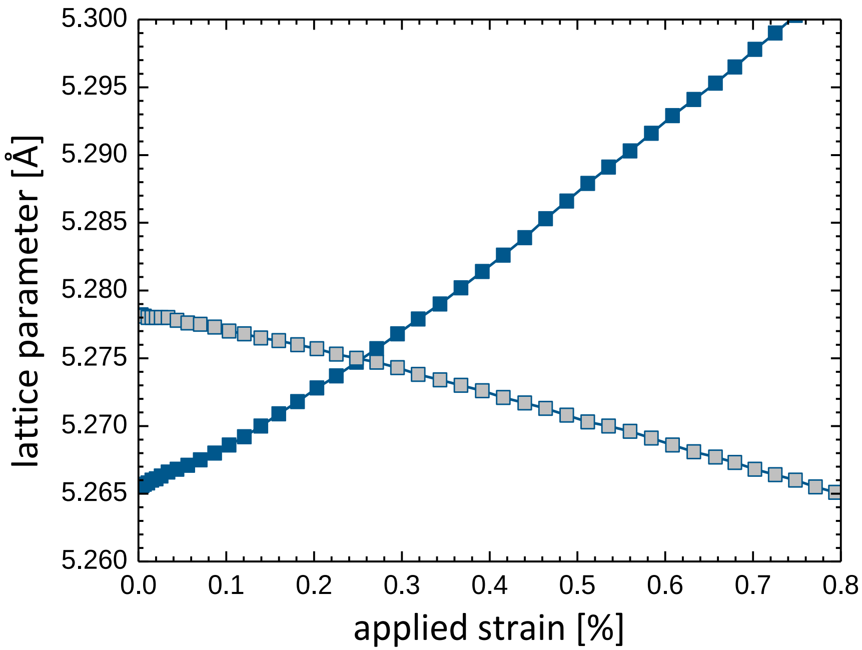
650°C

4.2 K

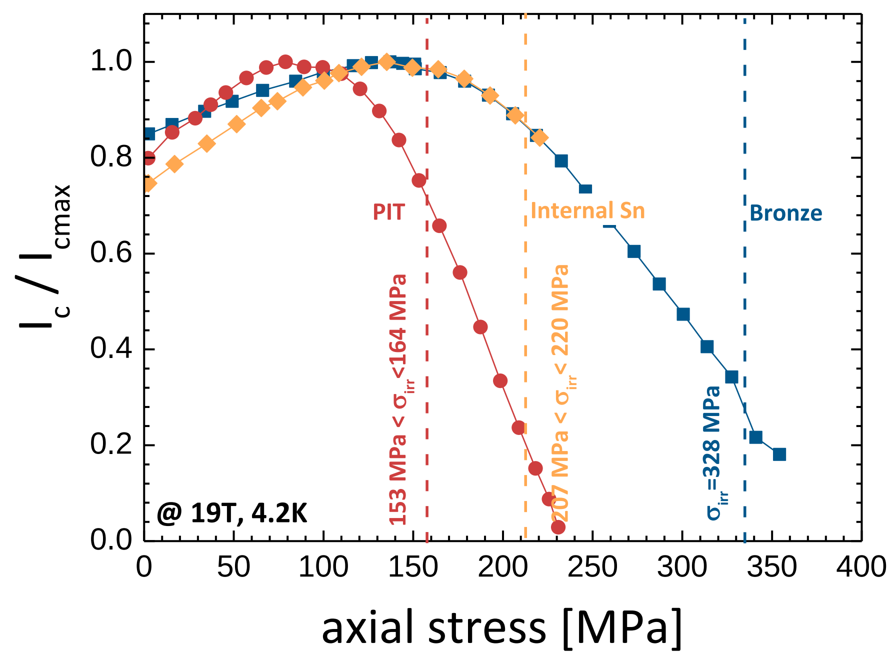
Nb_3Sn wires under axial stress

Bronze Route, Internal Sn and PIT: a comparison

Nb_3Sn lattice parameters vs strain @ 4.2K



I_c vs. axial stress



Technology	σ_{irr}
Bronze Route	330 MPa
Internal Sn	210 MPa
Powder-In-Tube	120 MPa

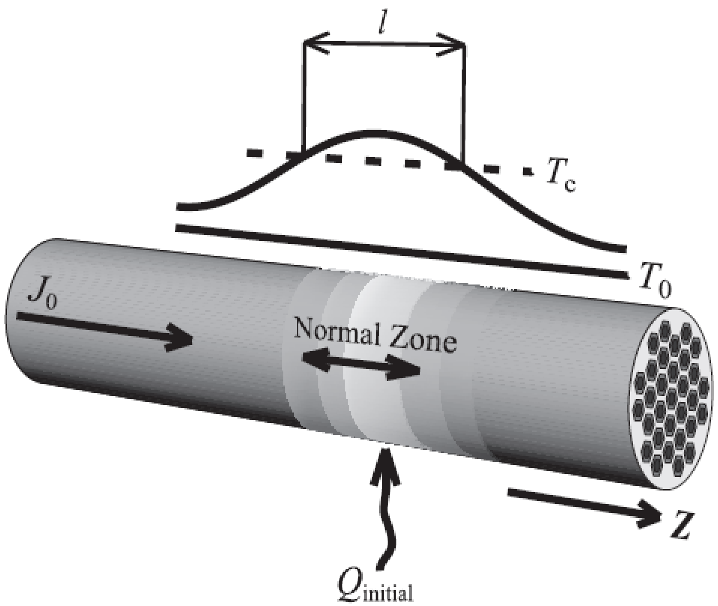
MAXIMUM OF I_c

The maximum of the critical current occurs when the cubic cell is restored (the deviatoric stress is minimum)

IRREVERSIBLE BEHAVIOUR

The irreversible limit (filament breakage) is related to the microstructure of the superconducting filaments, that depends on the fabrication process

Thermal properties of superconducting wires



A thermal disturbance Q_{in} induces a temperature rise above T_c over a length l

The minimum length needed for this normal zone to propagate (for heat generation to exceed cooling) is defined as the minimum propagation zone l_{MPZ}

$$l_{MPZ} = \frac{1}{J}\sqrt{\frac{2\kappa}{\rho}\left(T_{cs} - T_{op}\right)}$$

The energy necessary to form a propagating zone is $MQE = A\int_{l_{MPZ}} dz \int_{T_{op}}^{T_{cs}} dT\; C\left(T\right)$

The propagation velocity of the normal zone is $v_{NZ} = \frac{J}{C}\sqrt{\frac{\rho\kappa}{T_{cs} - T_{op}}}$

$$\underbrace{C\frac{\partial T}{\partial t}}_{\text{Thermal Inertia}} = \underbrace{\frac{\partial}{\partial x}\left(\kappa\frac{\partial T}{\partial x}\right)}_{\text{Conduction}} + \underbrace{\rho J^2}_{\text{Joule Heating}} + \underbrace{p_{initial}}_{\text{Thermal disturbance}}$$

Thermal properties of superconducting wires

Once a non-recovering normal zone is formed, it is desirable to make the normal-zone propagation (NZP) velocity "fast", to limit the hot spot temperature

MQE and v_{NZ} depend on the operation conditions and have to be engineered through the heat capacity C, the thermal conductivity κ and the electrical resistivity ρ of the composite

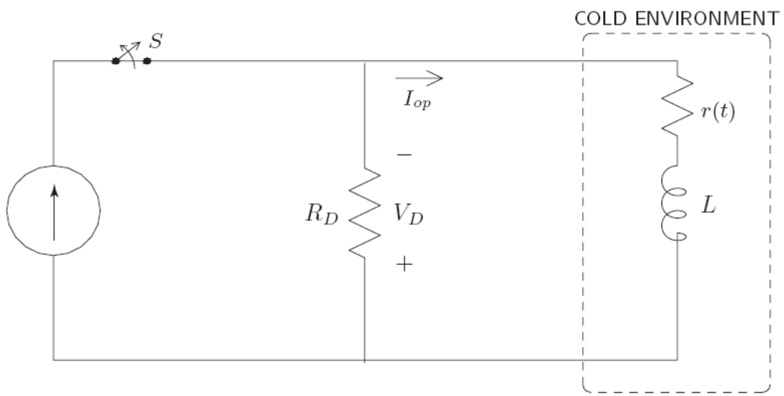
Examples

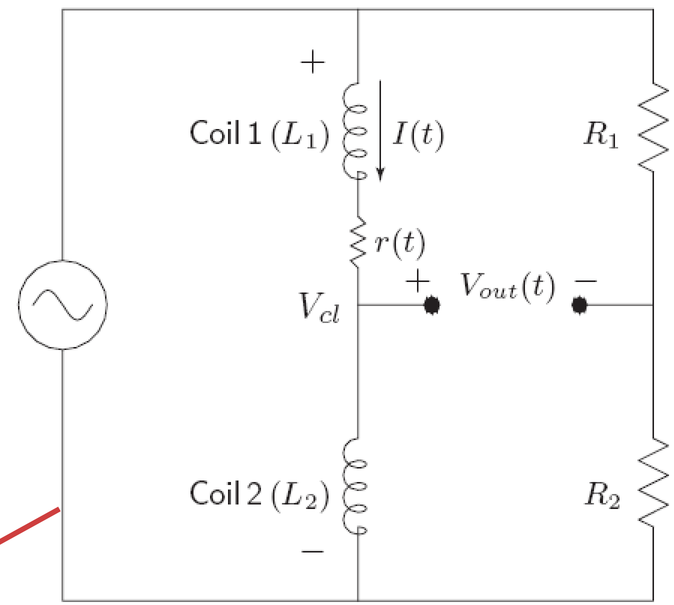
v_{NZ} ***is 20 m/s for NbTi @ 4K, 4T and 800 A/mm²***

v_{NZ} ***is 10^{-2} m/s for Y123 @ 77K, s.f. and 100 A/mm²***

How to protect a magnet in case of quench

Active Protection Technique: Detect-and-Dump





A simple protection circuit with a switch S and external dump resistor R_D
When the start of a quench is detected, S opens and the current decays through R_D
If we make R_D larger than the internal quench resistance, it will dominate the current decay giving

$$I = I_{op} e^{-R_D t/L} = I_{op} e^{-t/t_D}$$

What we have learned

1. What a superconductor is
2. How to make a wire out of a superconductor
3. How to design a superconducting magnet
4. How to determine the effects of magnetic stresses on a superconducting wire
5. How to protect a magnet in case of quench