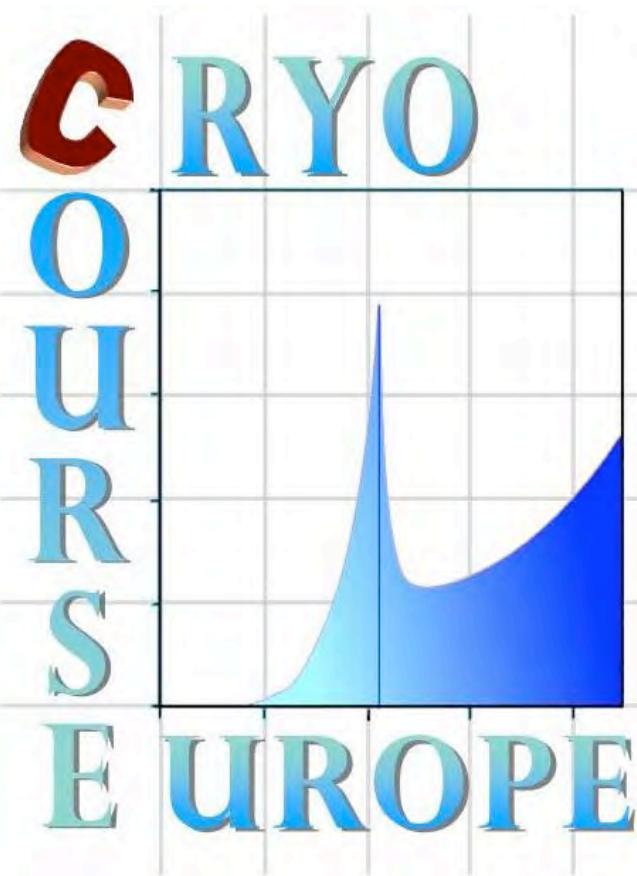
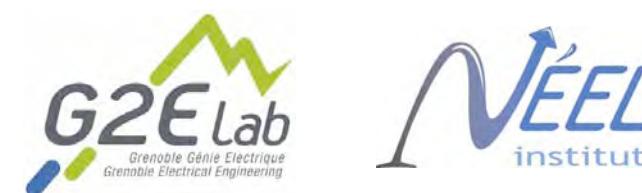


Cryocourse 2011

Grenoble September 2011



Applied
superconductivity
P. Tixador



2011

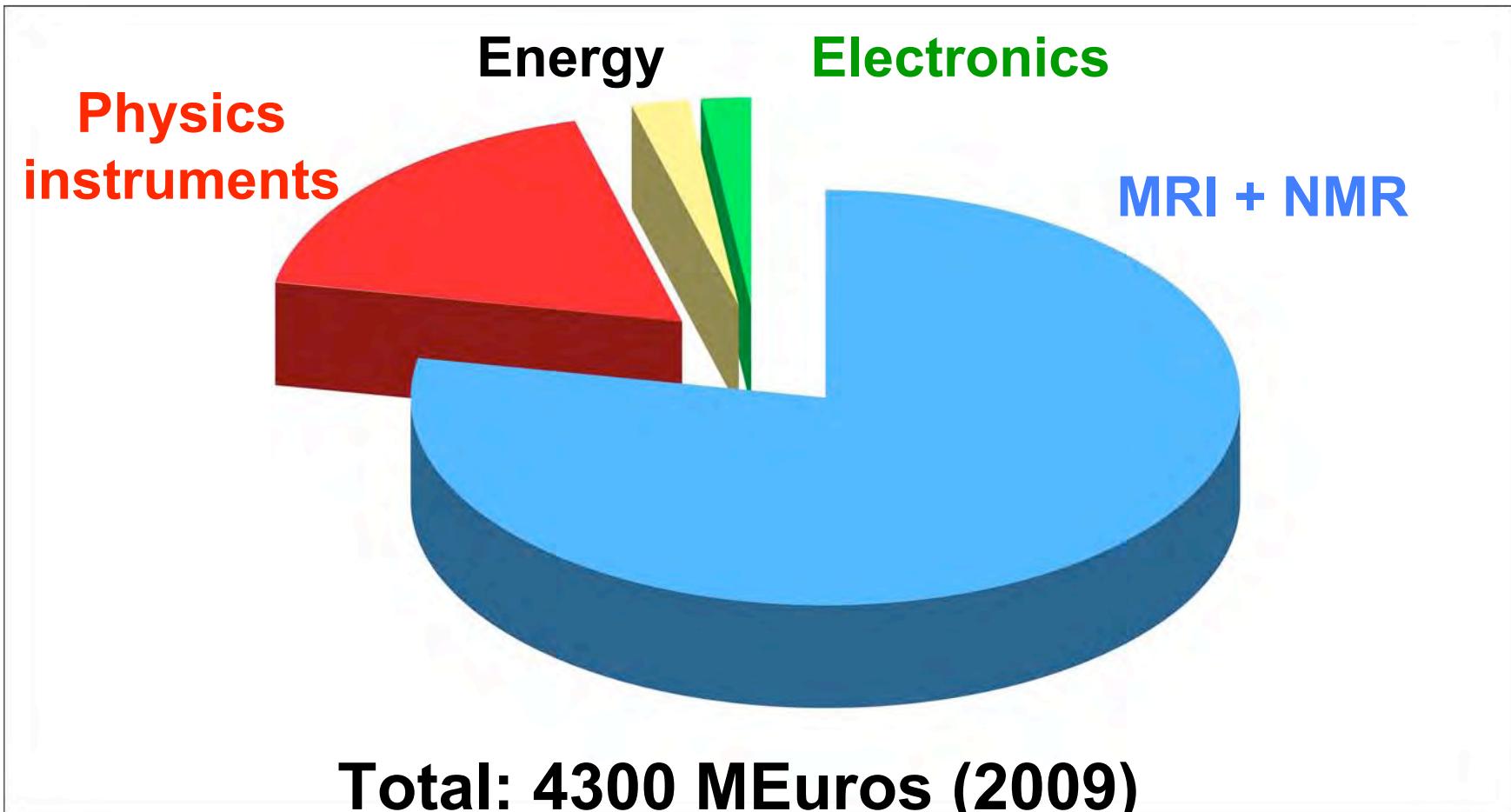
2011: very special year

One Hundred Years of Superconductivity

(April 8, 2011)



SC market



Main SC applications

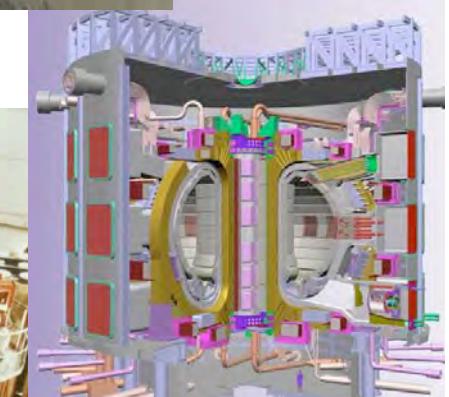
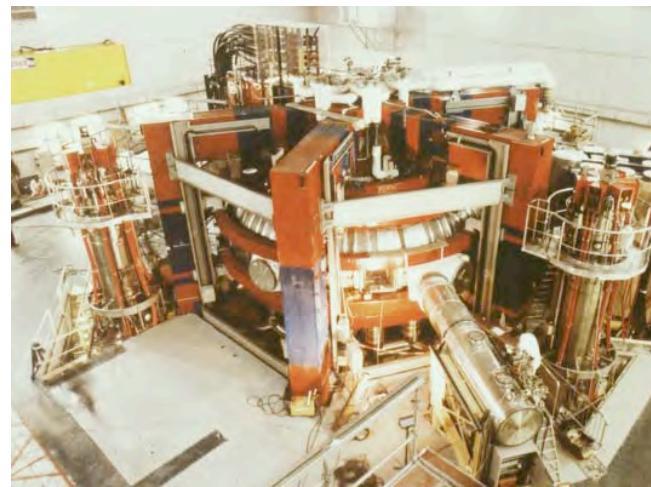


26 000



27 km
(100 km)

40 MW
(900 MW)



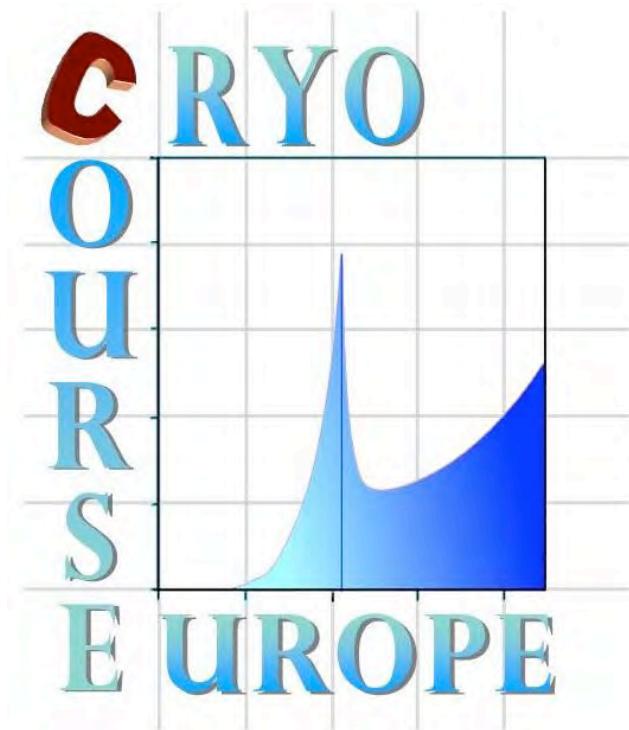
Outline



- Part I: Introduction
- Part II: SC electromagnetic behavior
- Part III: Composite structure
- Part IV: AC losses
- Part V: Quench
- Part VI: SC conventional materials
- Part VII: High T_c superconductors

Cryocourse 2011

Grenoble Sept. 2011

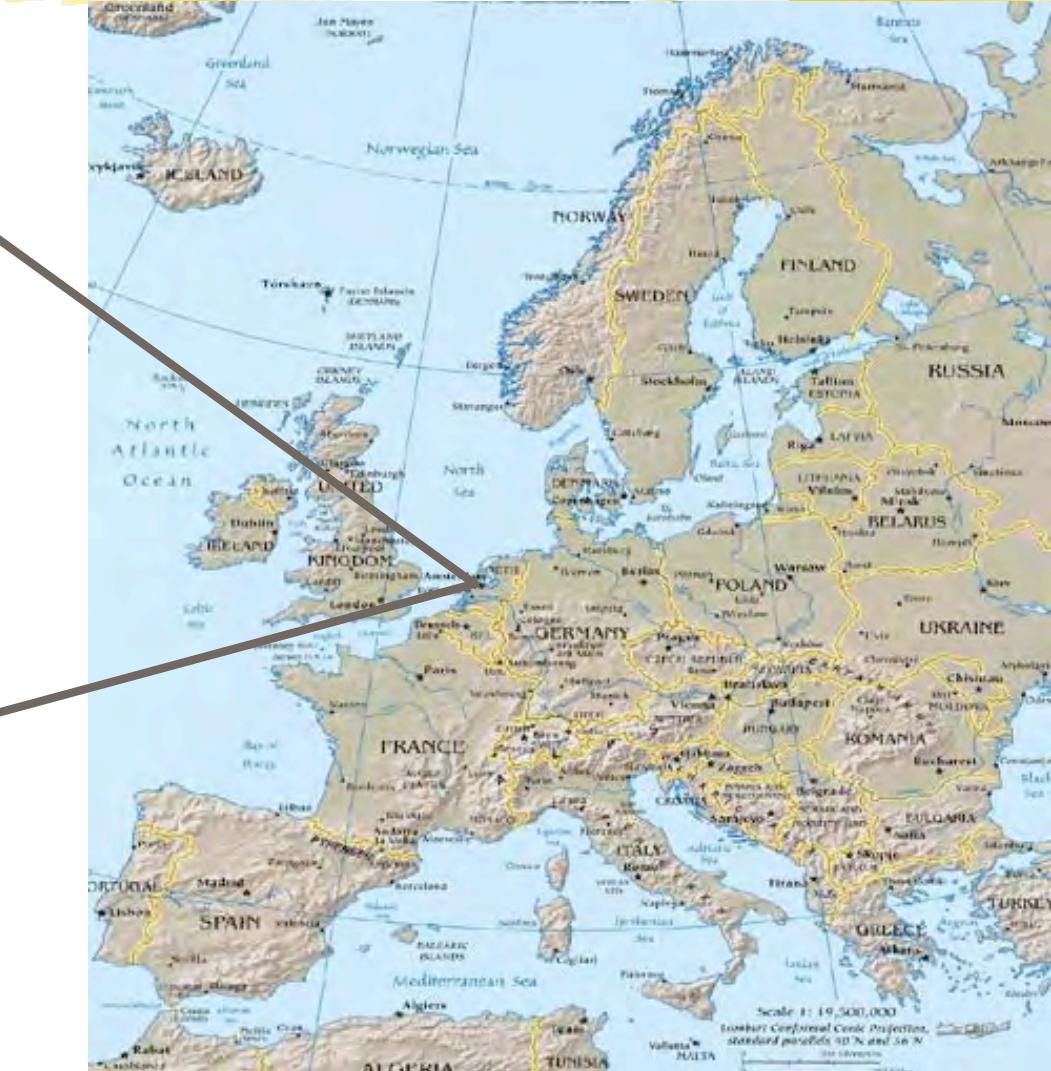


Applied
superconductivity

I. Introduction

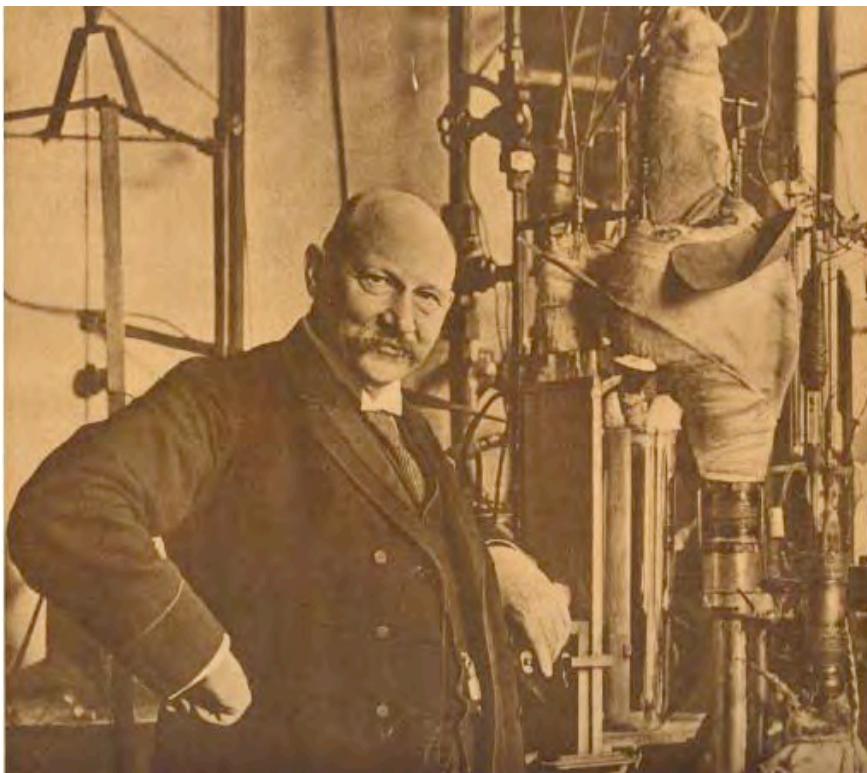
The beginning

Once upon a time
in Leiden ...



Step 1: July 10, 1908

First production of liquid helium



HKO invented big science:
lab. of international status (cold factory) with a strong and numerous technical support

Introduction - history



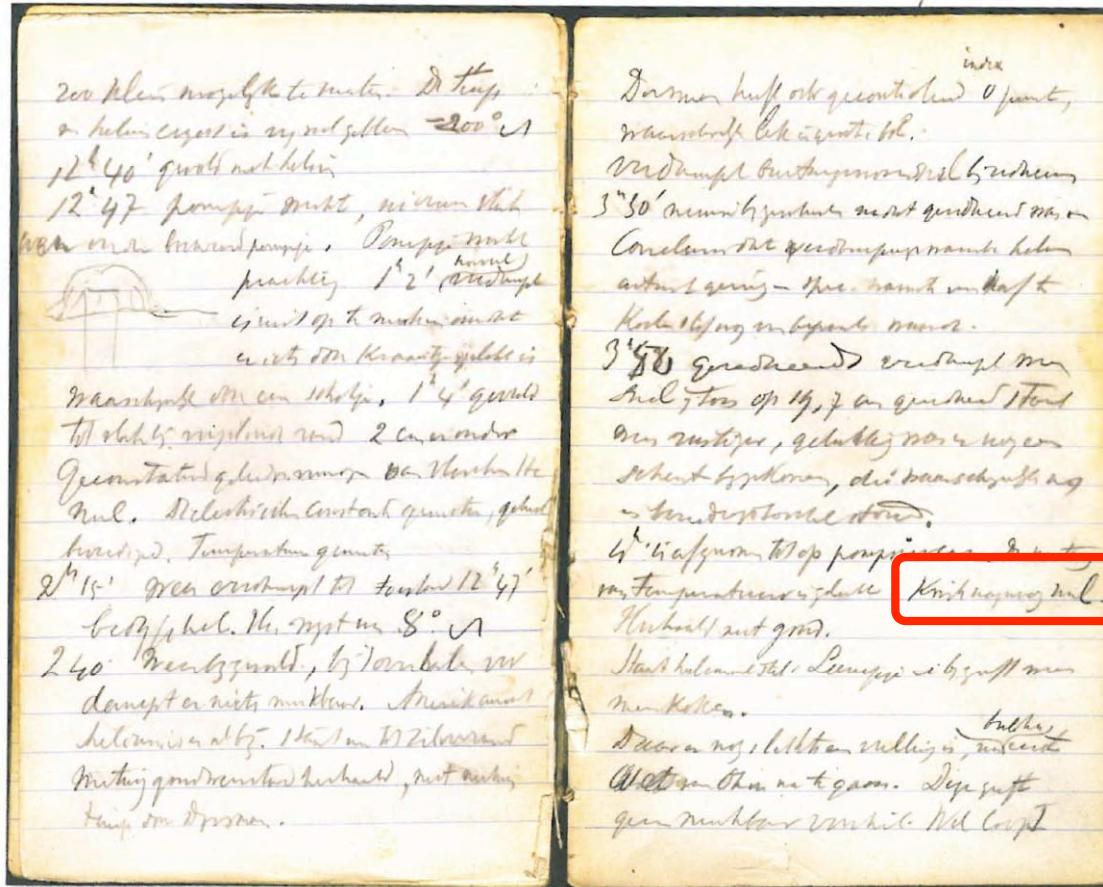
■ 1908

- First He liquefaction by H. Kammerling Onnes
 - New unexplored territories opened
 - Leiden "coldest place on earth" up to 1923

■ 1911

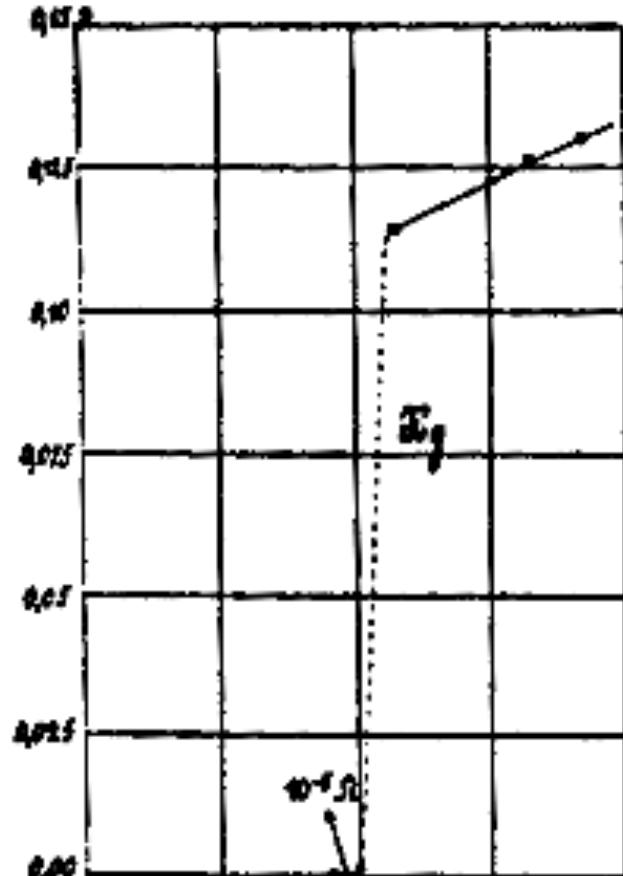
- Discovery of superconductivity for Mercury (Hg)
 - April 8, 1911 "Mercury practically zero"

Kammerling Onnes's notebook



"Mercury practically zero"

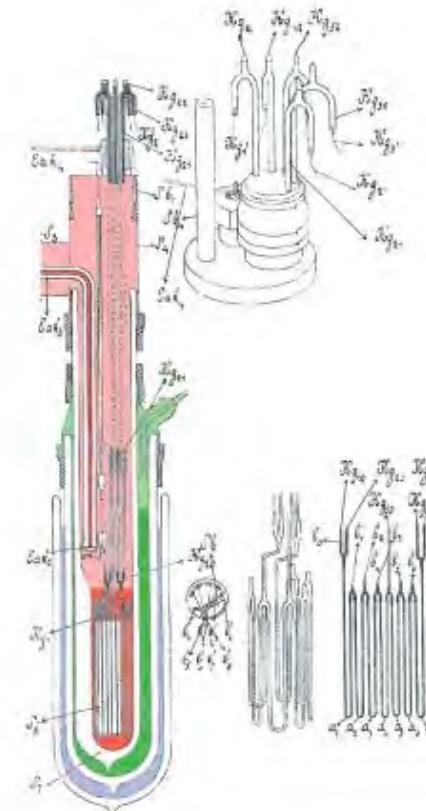
Discovery of superconductivity



October 26, 1911

G. Holst

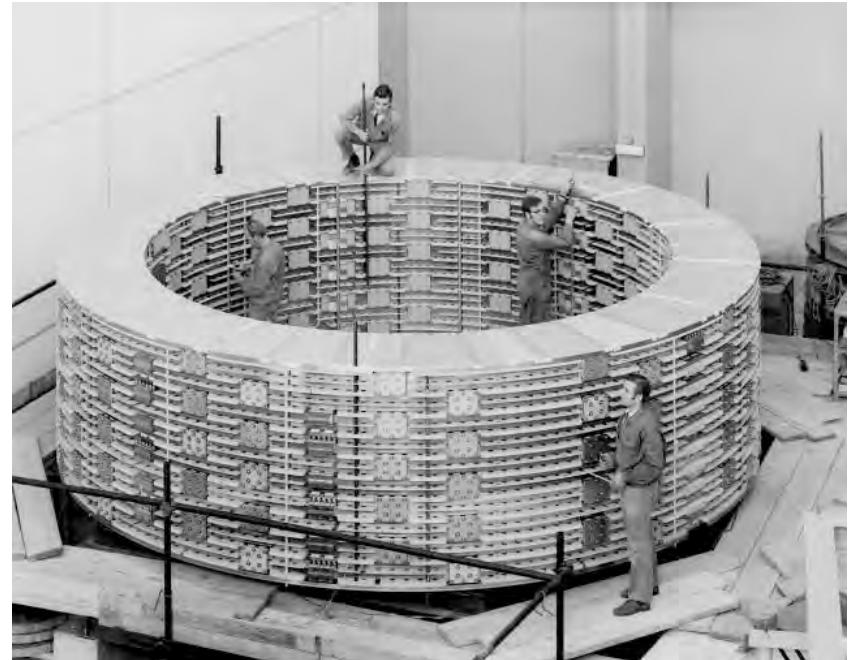
■ $\rho(T)$ metal studies



Introduction - history

- 1908 : He liquefaction
 - 1911 : superconductivity discovery
 - 1933 : Meissner effect
 - 1957 : BCS microscopic theory
 - 1958 : type II superconductors (NbSn, NbZr)
 - 1960 : high current density in NbSn
 - 1963 : quantum effects predictions by B. Josephson
 - 1964 : first large scale SC application (Argonne bubble chamber)
 - 1968 : multifilament composite definition (Rutherford Lab.)
 - 1974 : CERN bubble chamber (830 MJ)
-

CERN bubble chamber (BEBC)



$$\emptyset_{\text{int}} = 3.7 \text{ m}$$

$$B_0 = 3.5 \text{ T}$$

$$W_{\text{mag}} = 800 \text{ MJ}$$

Introduction - history

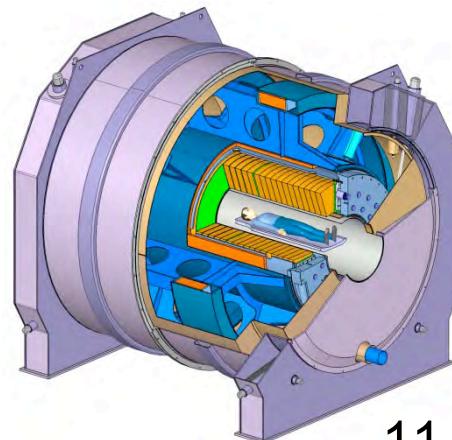


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- 1968 : multifilament composite definition (Rutherford Lab.)
- 1974 : CERN bubble chamber (830 MJ)
- 1982 : first MRI images (commercial SC application)

SC applications MRI & NMR



26 000
in operation



11.7 T CEA



600 MHz
14.1 T

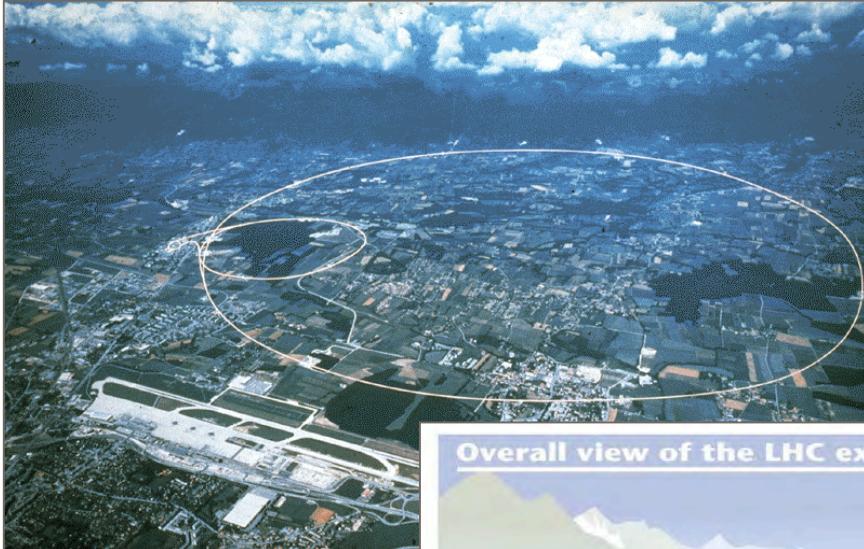


1 GHz
23.4 T

Introduction - history

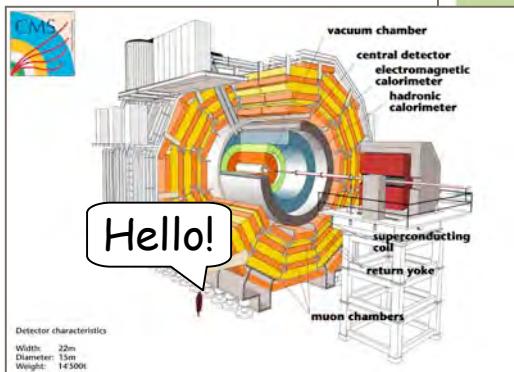
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- 1974 : CERN bubble chamber (830 MJ)
- 1982 : first MRI images (commercial SC application)
- 1987 : high T_c discovery
- 2007 : LHC starting, the biggest cryogenic and SC system

LHC the biggest cryogenic and SC system

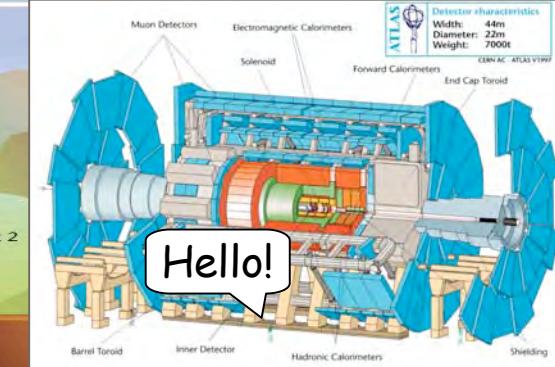
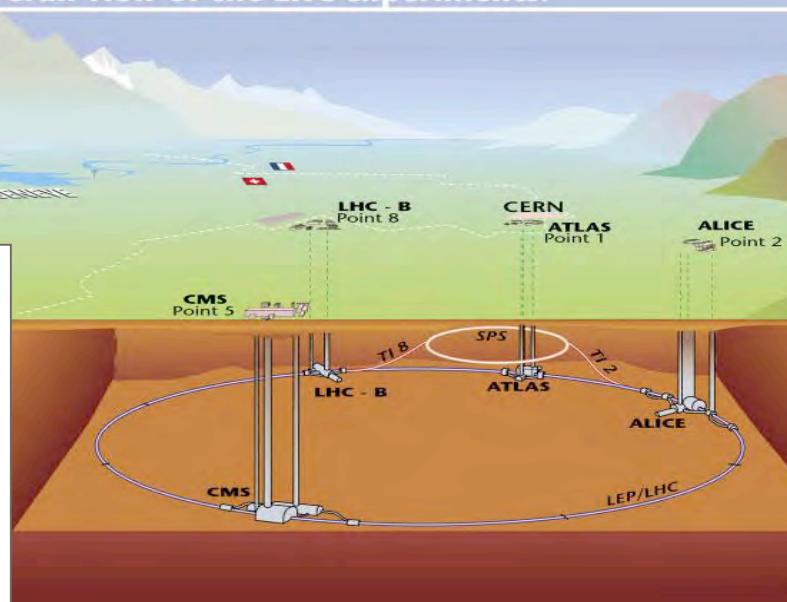


1232 dipoles
392 main quadrupoles
+ experiences (ATLAS,
CMS....)

CMS

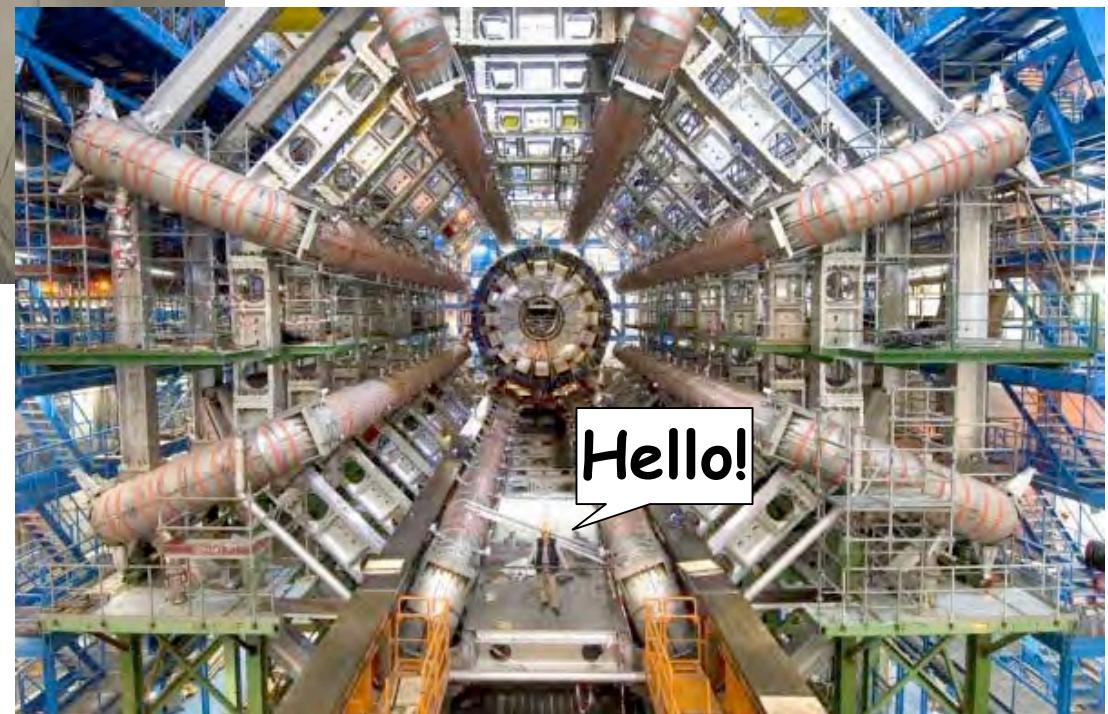


Overall view of the LHC experiments.

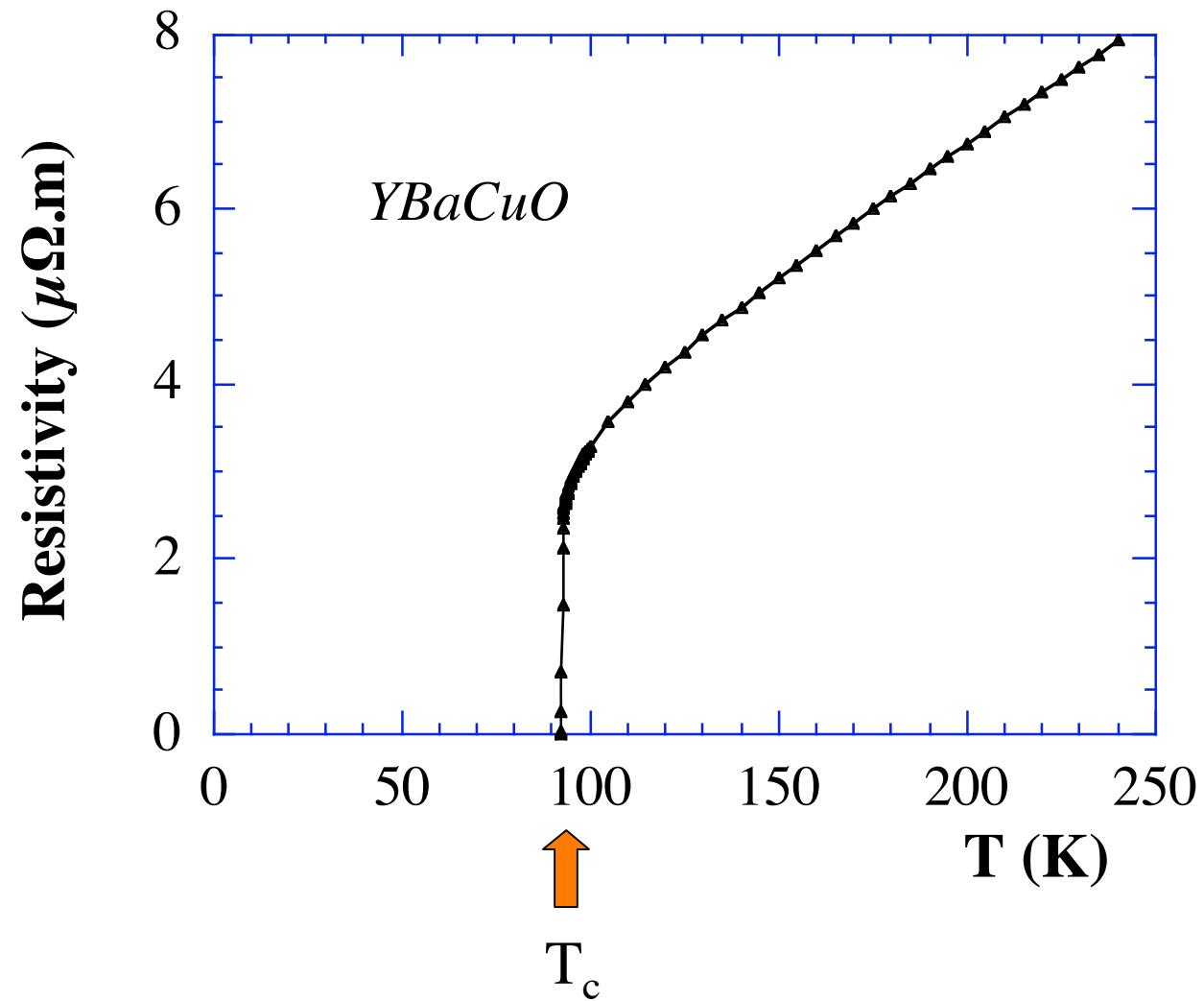


ATLAS

LHC the biggest cryogenic and SC system

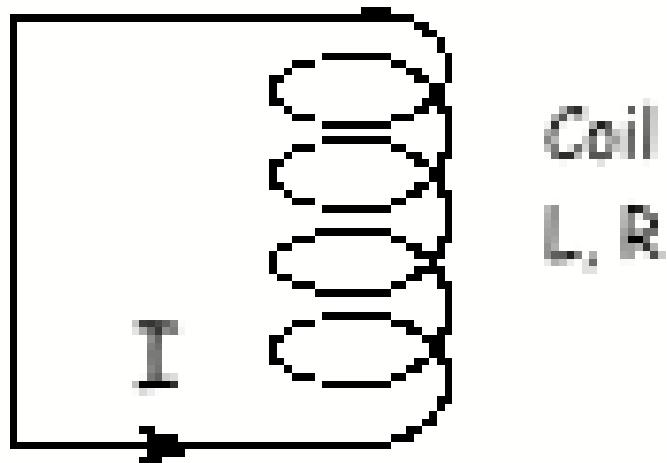


Zero resistivity



Zero resistivity ?

Zero : no sense from experimental point of view
==> lower value



$$RI + L \frac{dI}{dt} = 0$$

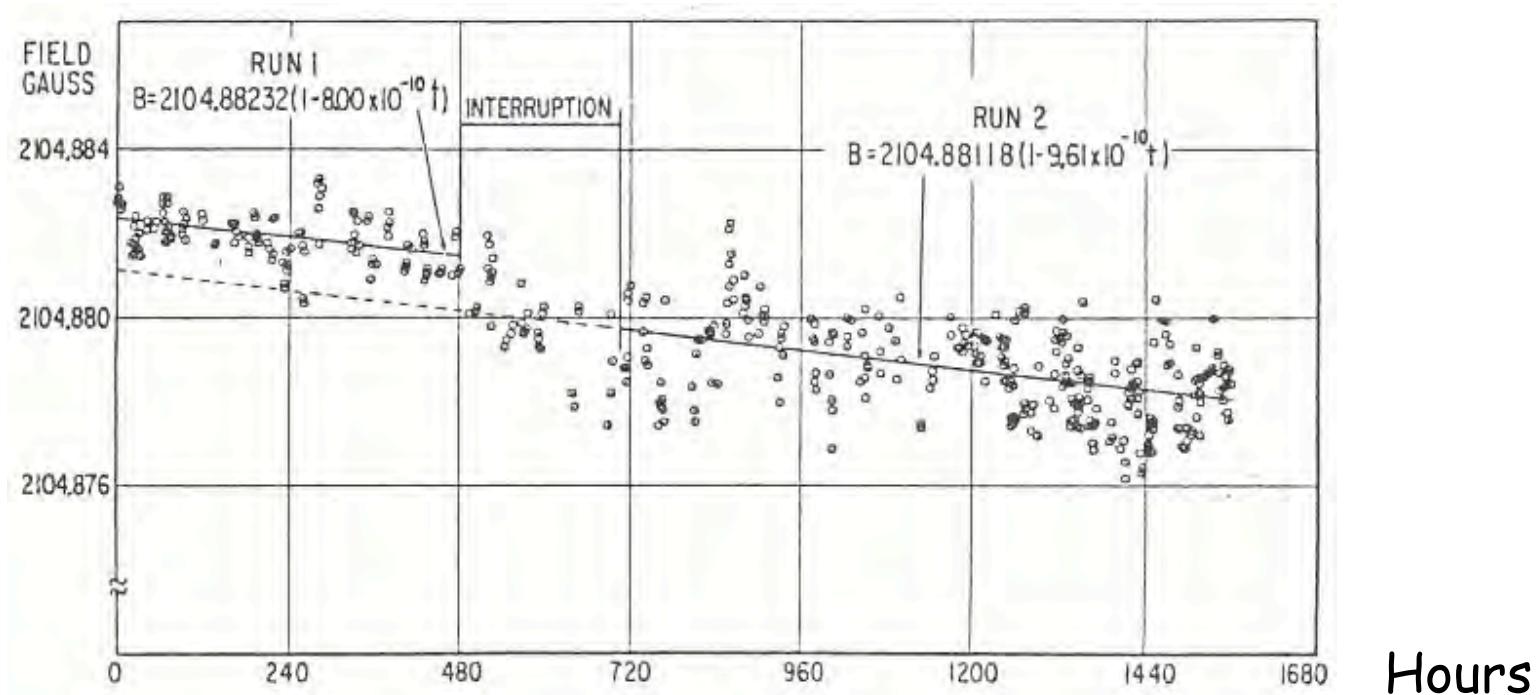
$$I = I_o e^{-\frac{t}{\tau}} \quad \tau = \frac{L}{R}$$

I. C. : $t = 0$; $I = I_o$

τ measurement ==> $R(\rho)$ meas.

Miles and Files experiment (1962)

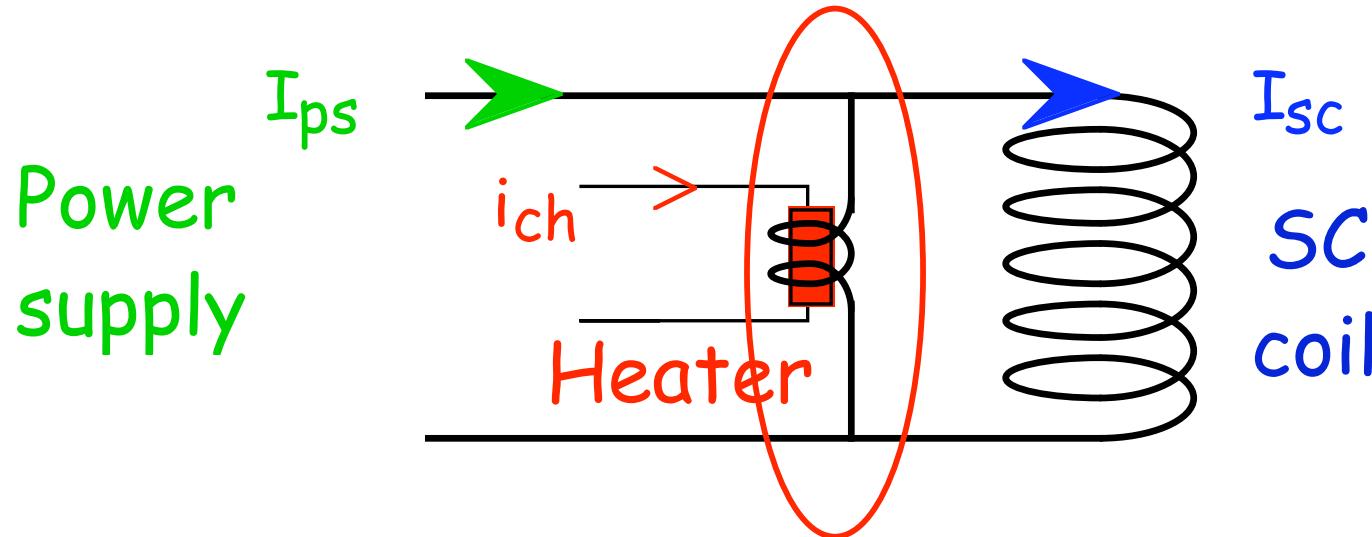
Field decreasing measurement ==> τ



Experimental time constants :

Run 1 : $\tau = 144\ 000$ years ==> $\rho < 10^{-25} \Omega m$

Current supply

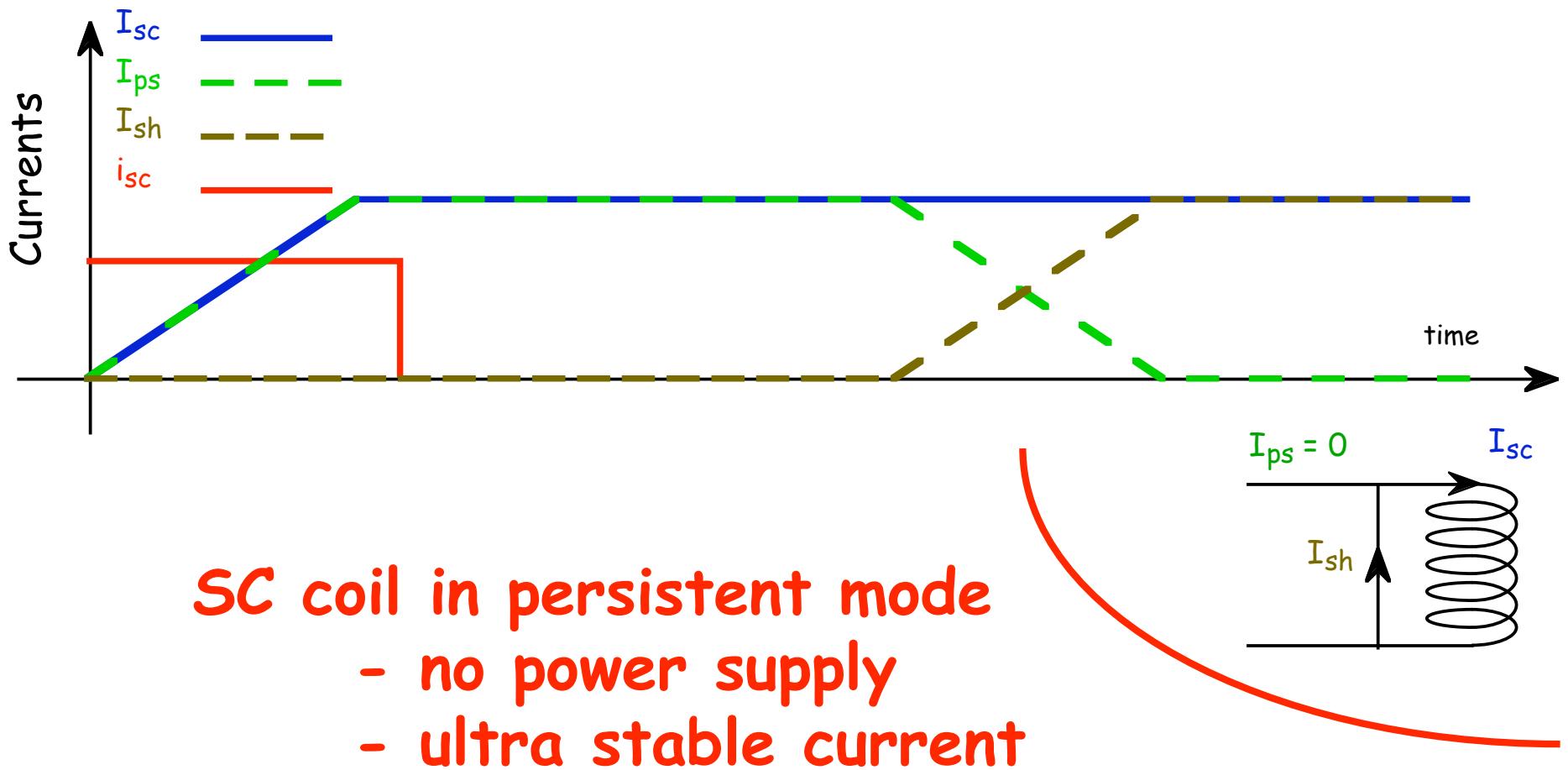


SC shunt with thermal control

- heating : normal state, high resistance
- no heating : SC state

(SC shunt with magnetic control too)

SC coil supply : end of cycle

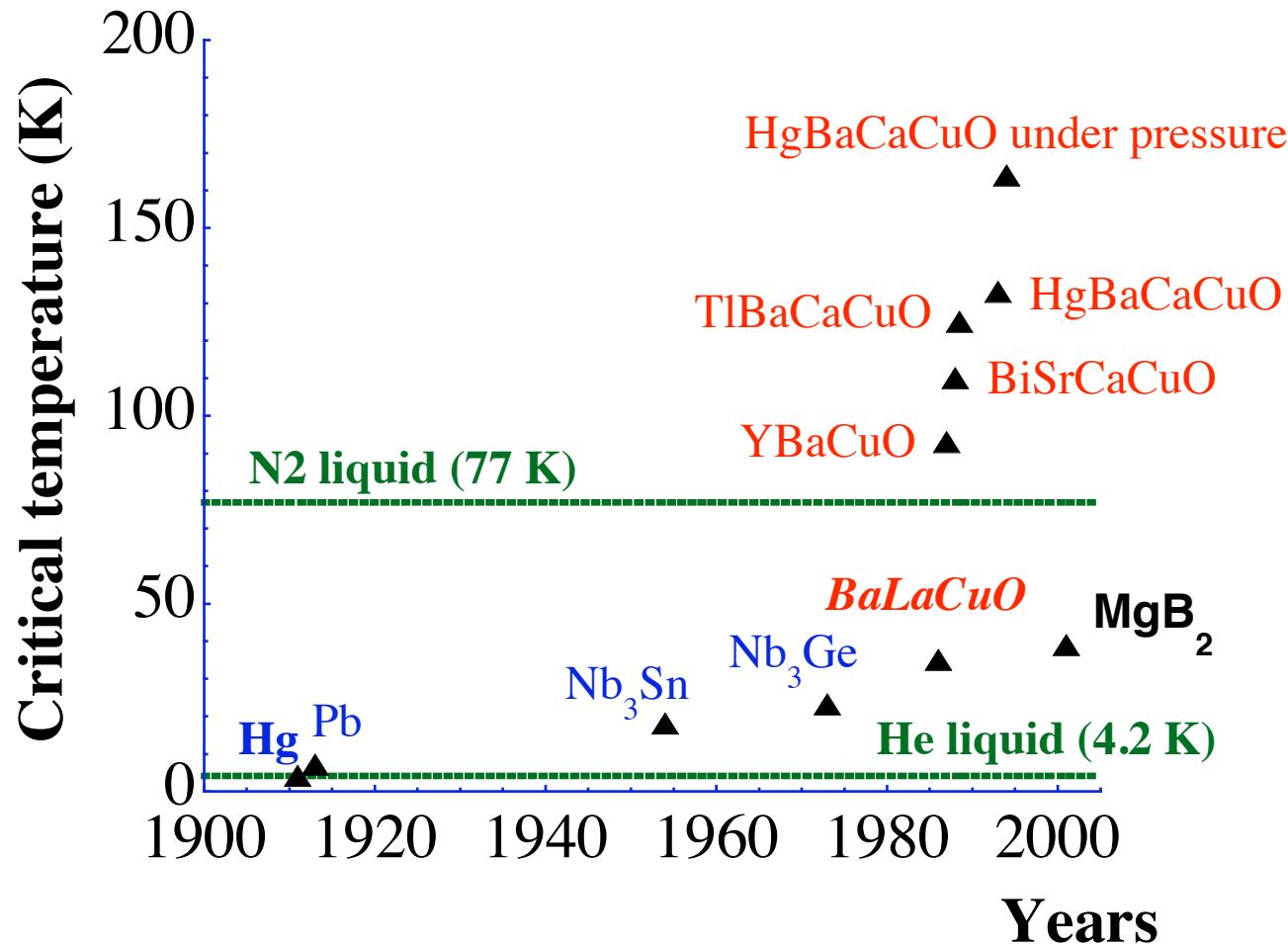


Limits of non dissipative state



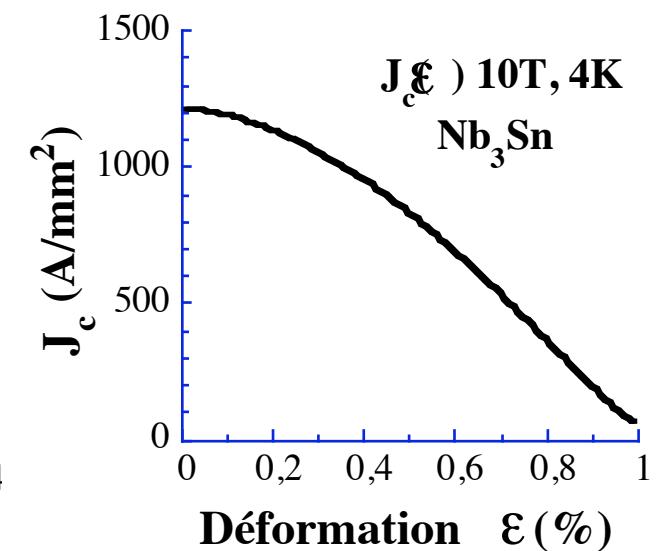
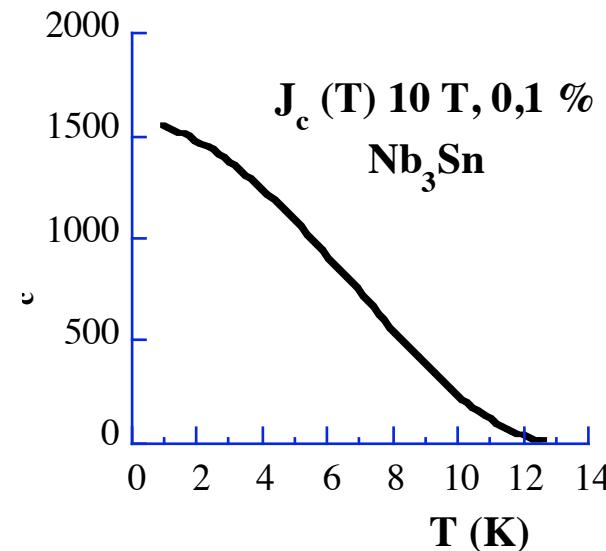
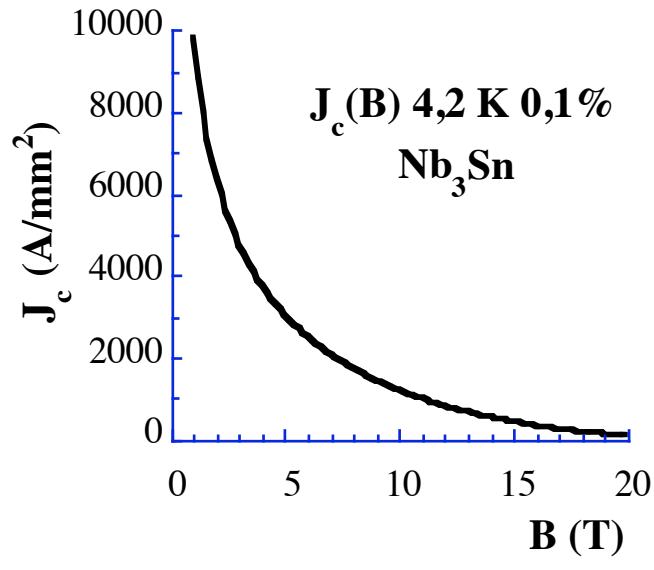
- Three main limits
- Temperature - T_c
- Magnetic field - H_c / H^*
- Current density J_c

Critical temperature



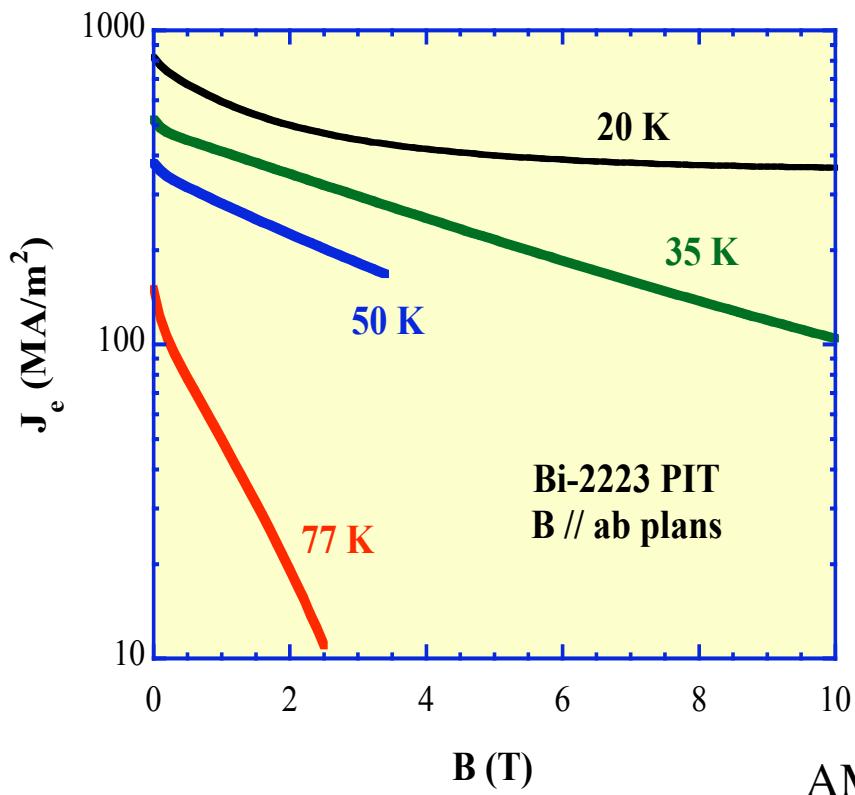
Critical current density J_c

$$J_c = J_c(T, B, \varepsilon) + \text{orientation (SHTS)}$$

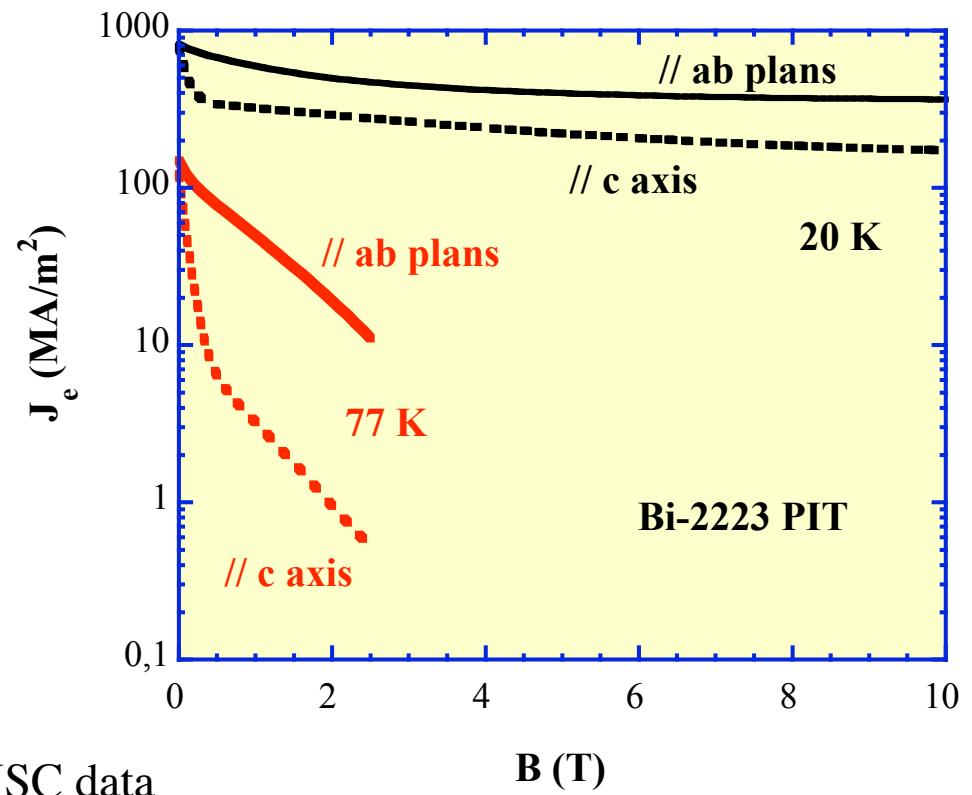


Critical current density J_c

$$J_c = J_c(T, B, \theta, \varepsilon)$$

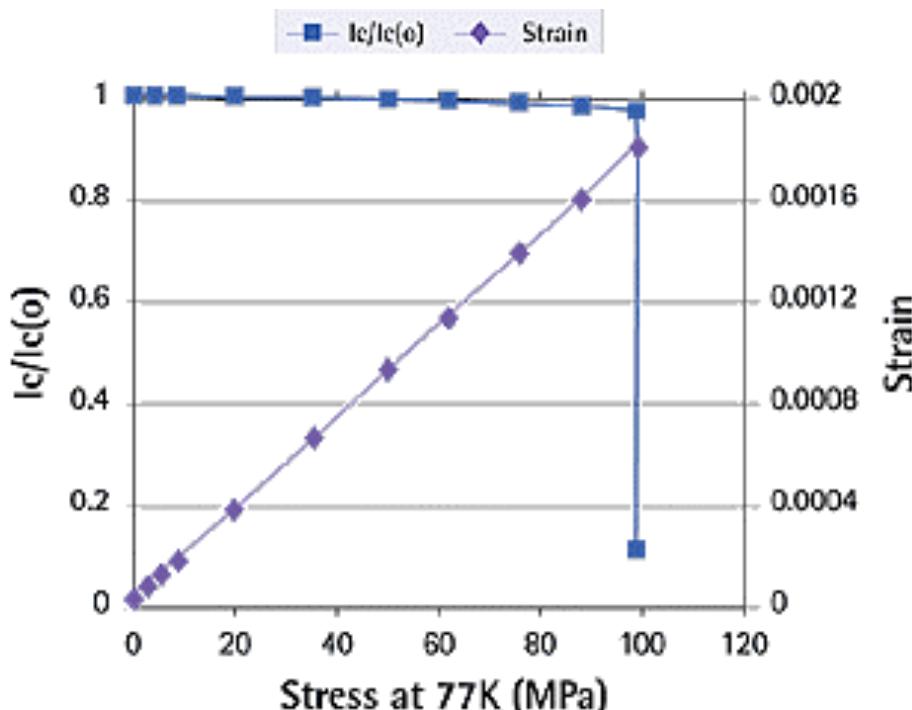


AMSC data



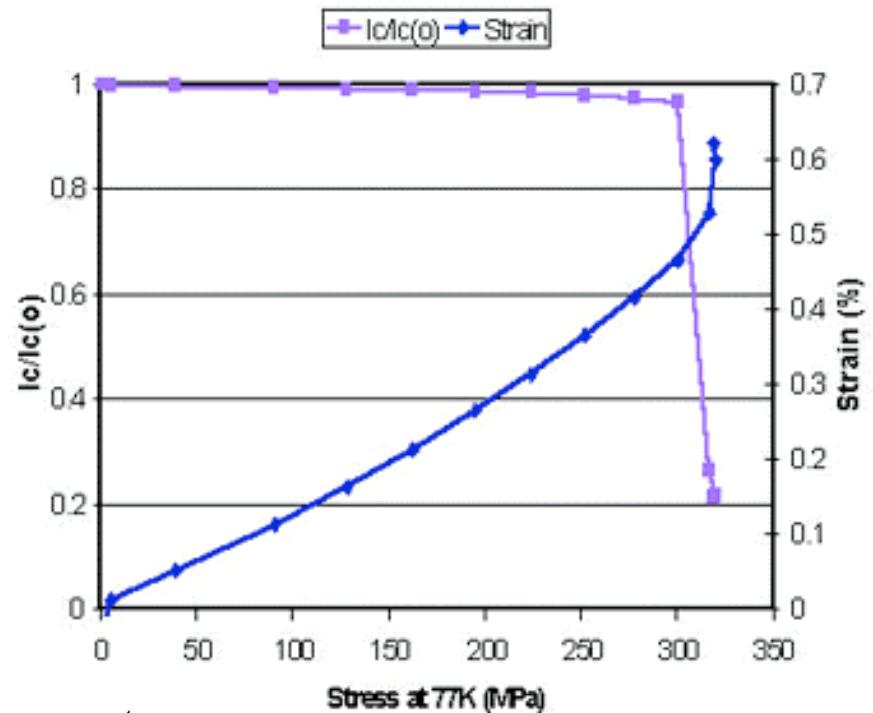
Critical current density J_c

$$J_c = J_c(T, B, \theta, \varepsilon)$$



Conventional PIT

Stress effect

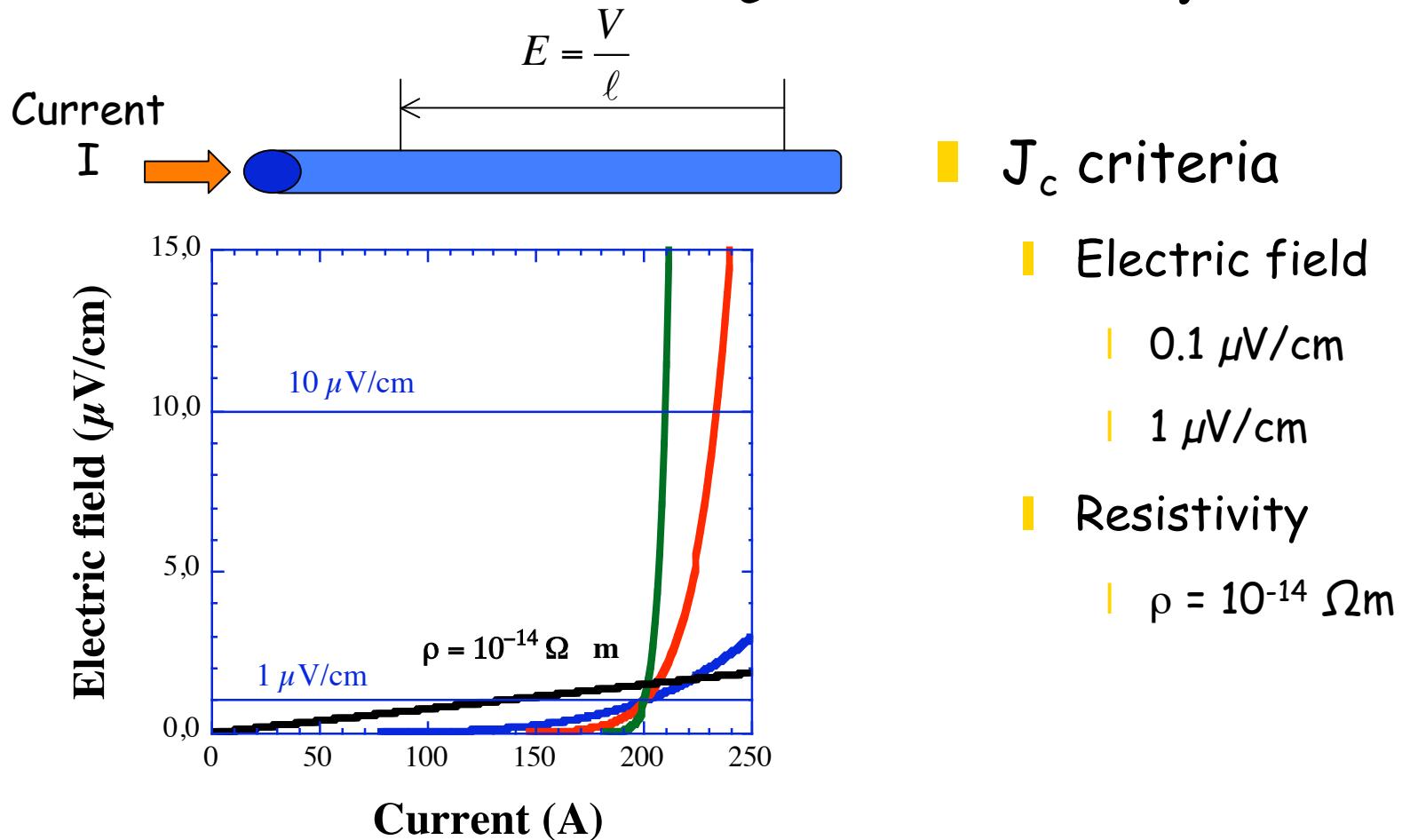


AMSC documents

Reinforced PIT

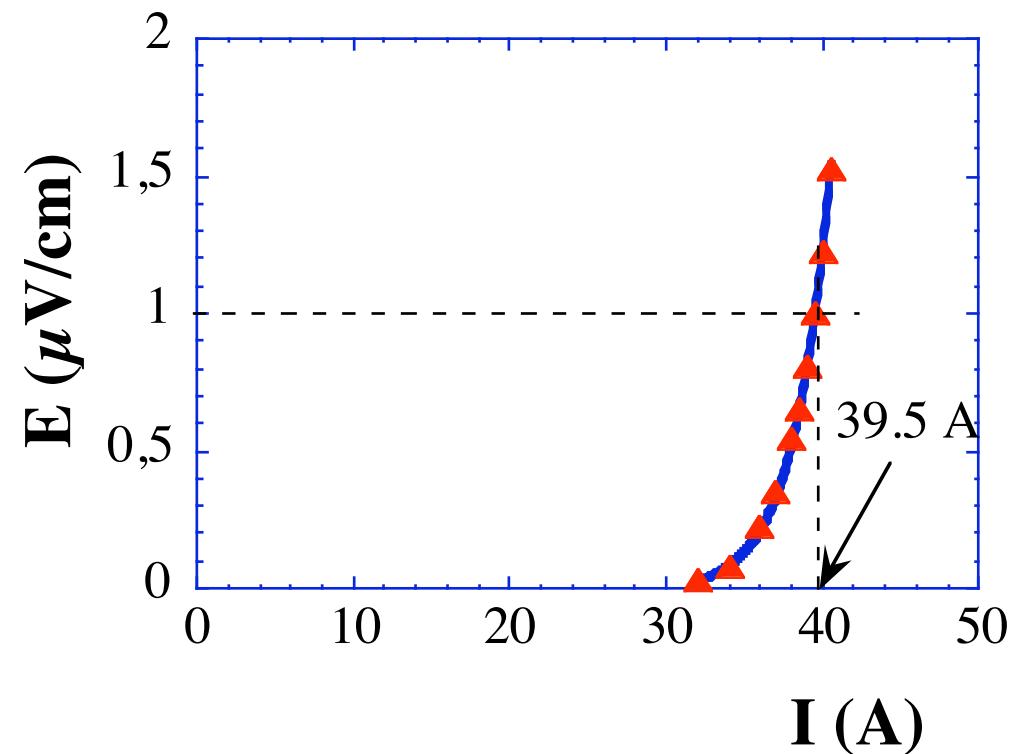
What is J_c ?

Above J_c SC is dissipative

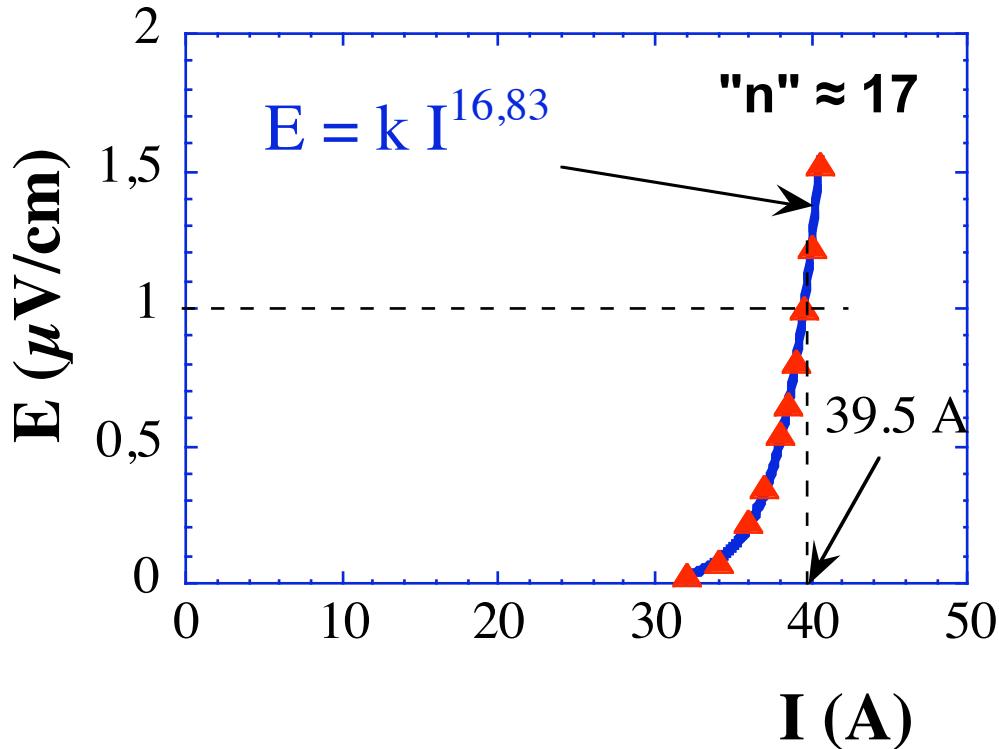


Empirical $E(J)$ law - "n" value

Experimental $E(I)$ curve (Bi-2223 /PIT @ 77 K, 0 T)



Empirical E(J) law - "n" value



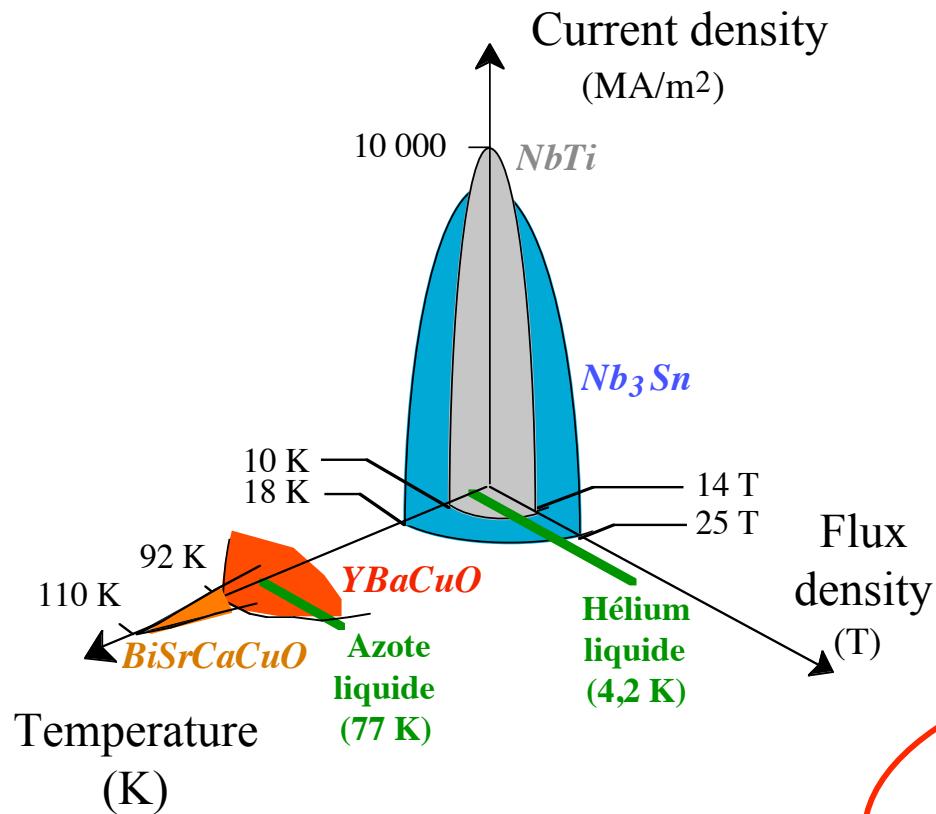
" n " is called also
resistivity transition index

Empirical law
around I_c (J_c) :

$$E = E_c (I/I_c)^n$$

Exponent n : "n value"
Important quantity
"quality" criteria
Magnet design, stability

Critical surface



- T_c & H_c : intrinsic
- J_c : elaboration
- Surface (deformation)

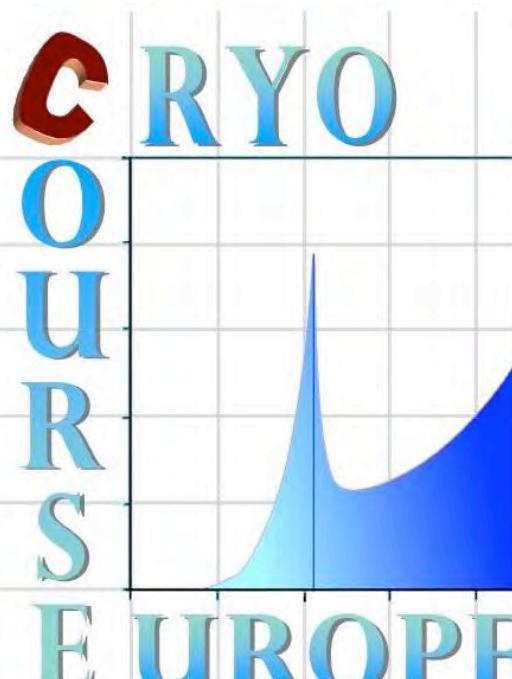
■ SC in normal state :

- ρ_n high
- λ low

Important for SC strand structure

Cryocourse 2011

Grenoble September 2011



Applied
superconductivity
II. SC electromagnetic
behaviour

Superconductor behavior

- Maxwell equations valid

- $\text{Curl } \mathbf{E} = -\partial \mathbf{B} / \partial t$

- $\text{Curl } \mathbf{H} = \mathbf{j}$

- Superconductor relation

- $\mathbf{B} (\mathbf{H})$

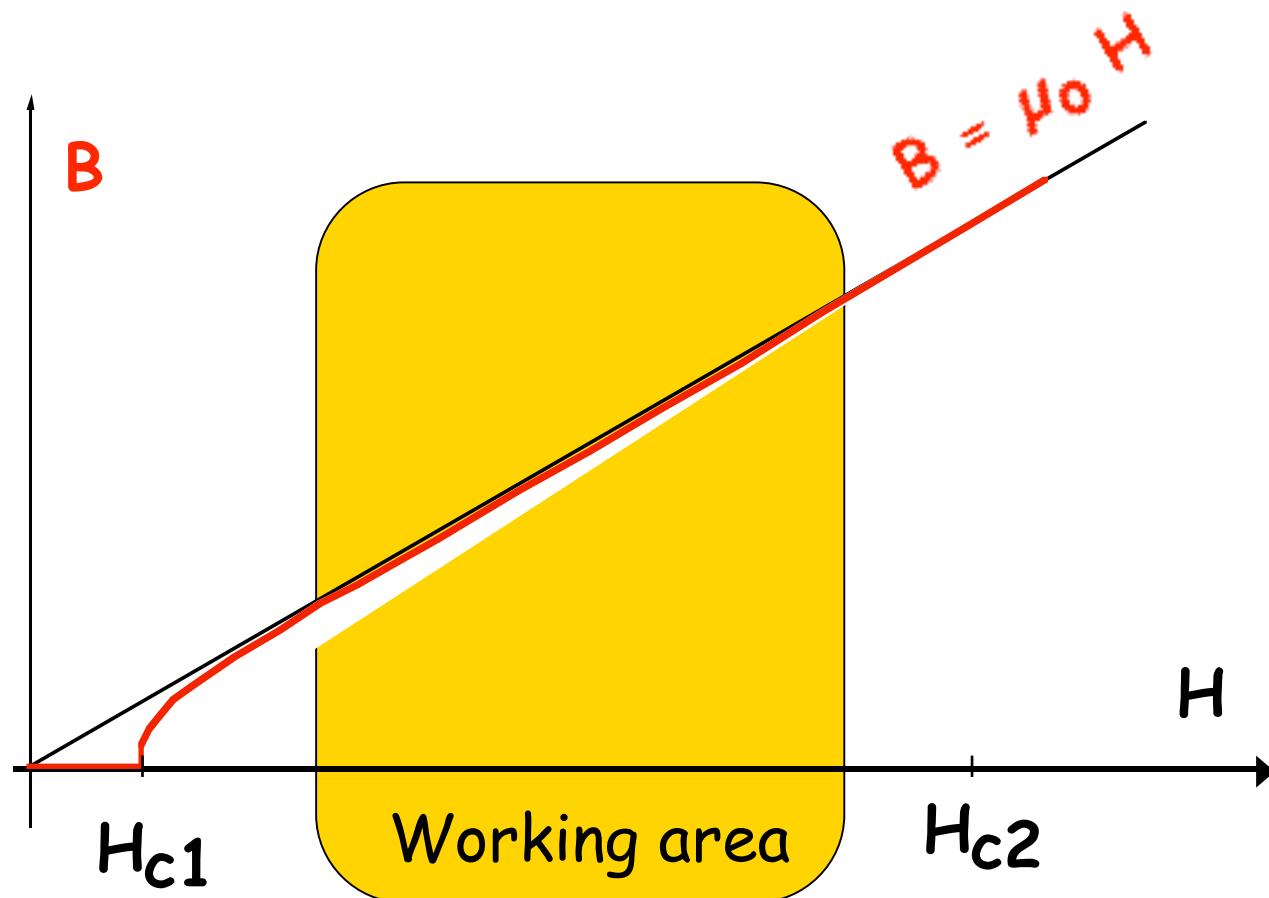
- $\mathbf{E} (\mathbf{J})$

Macroscopic SC B(H) relation

MACROSCOPICALLY ($> 1/100 \mu\text{m}$)
a superconducting material
can be considered as non magnetic
except for very little fields

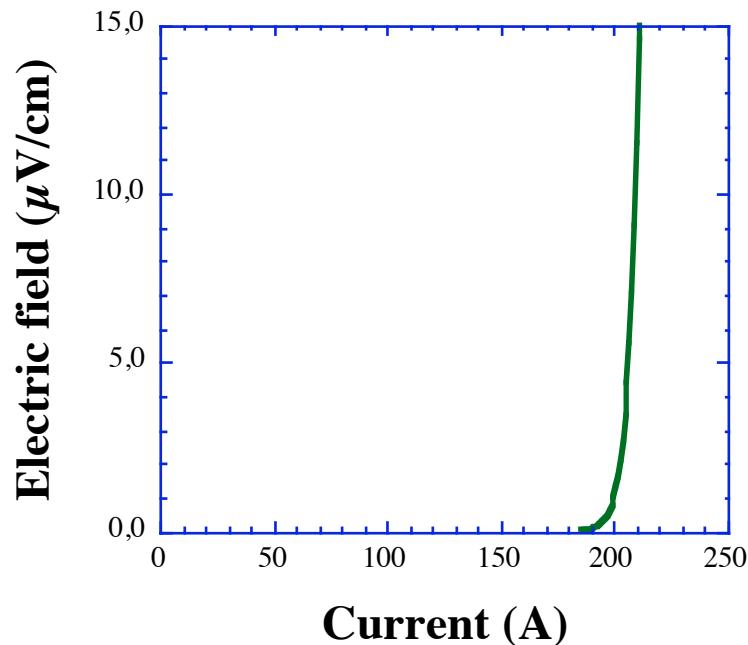
$$B = \mu_0 H$$

Macroscopic SC $B(H)$ relation

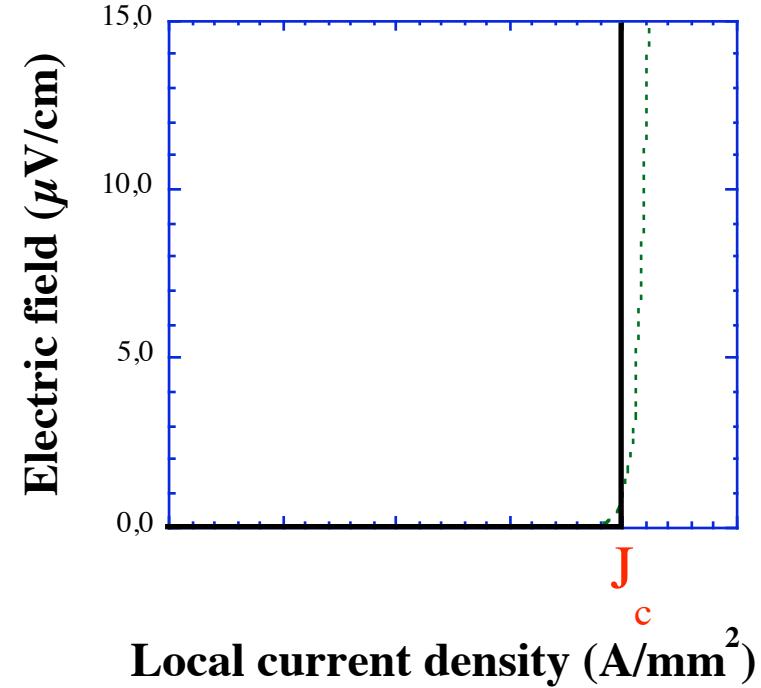


Macroscopic SC $E(J)$ relation

Experimental $E(I)$ curve

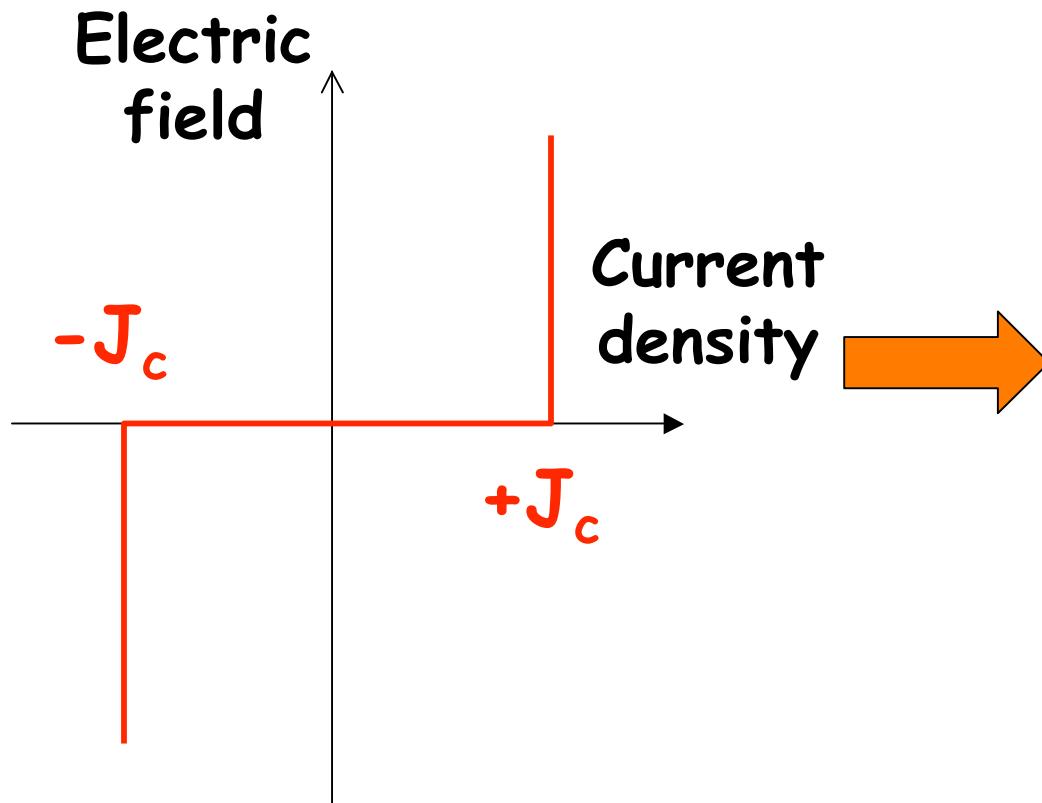


MODEL



- Relation valid for local current density
- Infinite stiffness

$E(J)$ relation - Critical State Model



Local current density

ONLY THREE VALUES

- 0
- $+ J_c$
- $- J_c$

Critical state
model

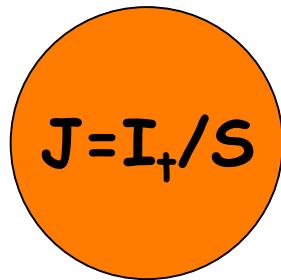
$E(J)$ relation - Bean model

Bean model:
Critical state model
+
 J_c constant (B independent)

**Bean model very used
for analytical relations**

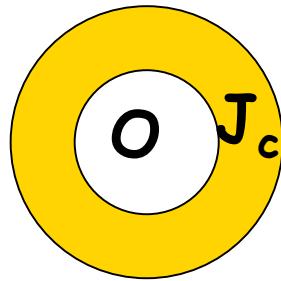
Bean model application

Transport current (I_t) distribution



Resistive wire :

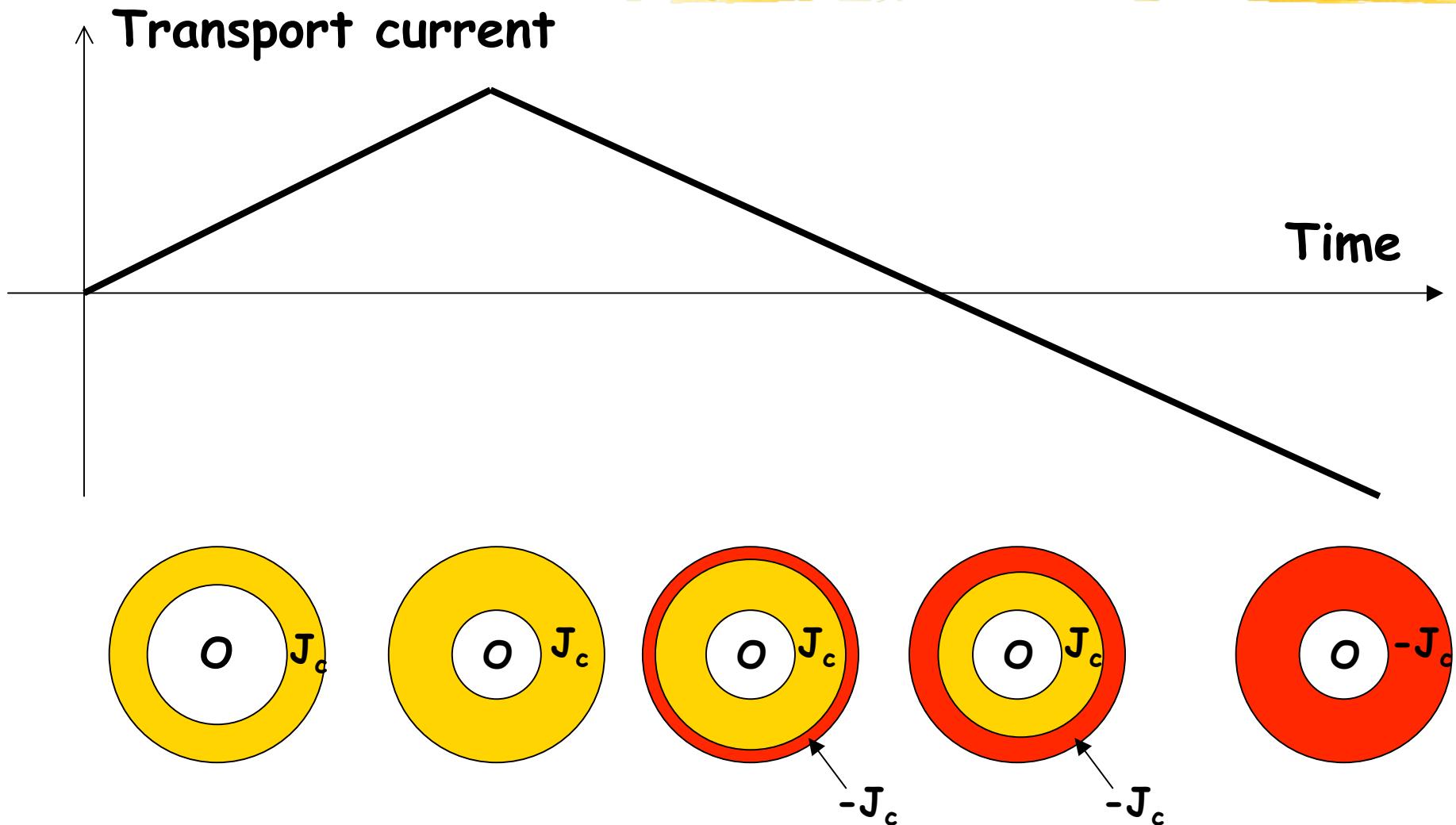
- uniform current density $J = I_t / S$



Superconductive wire :

- current density $0 / +J_c / -J_c$ (CSM)

Transport current distribution



Critical state model - "n" value

SC model in a finite element code FLUX3D®

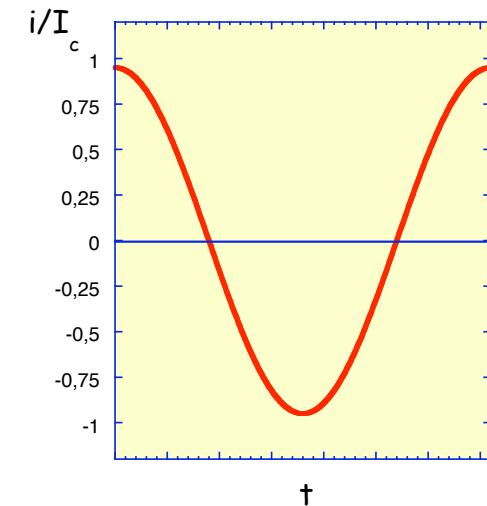
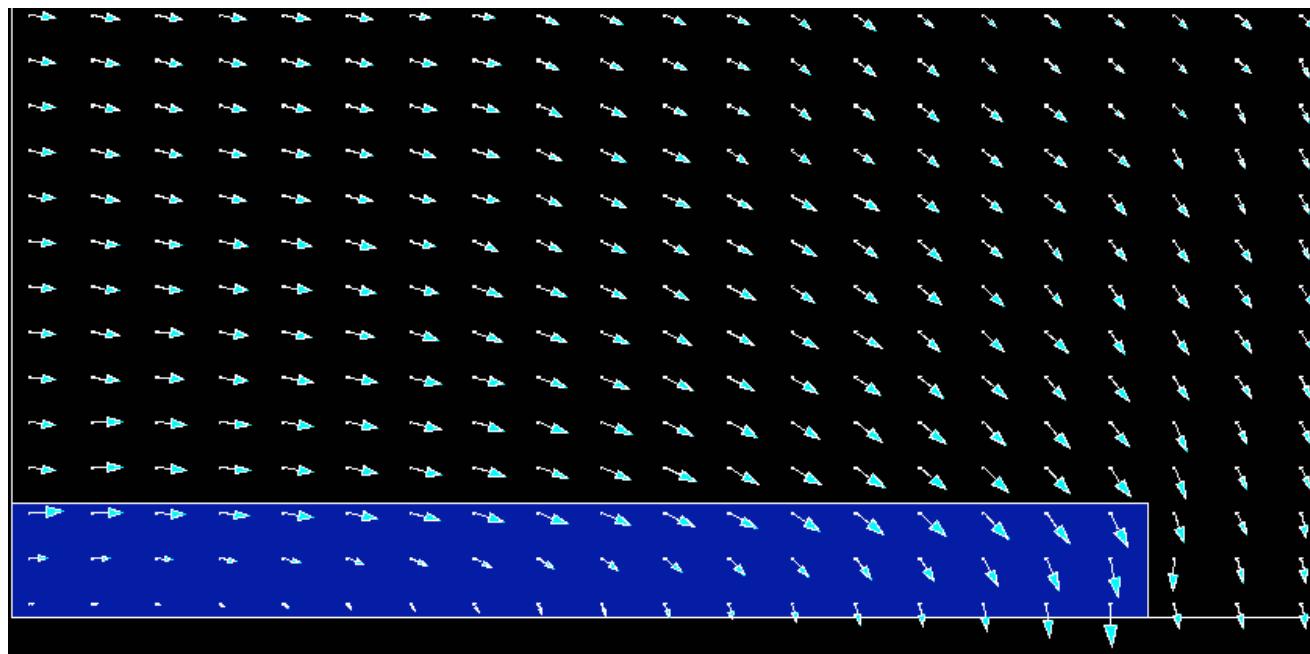
Superconducting element:

- non magnetic material, $B = \mu_0 H$
- power law for $E(J)$, $E = E_c (J/|J|) (|J|/J_c)^n$

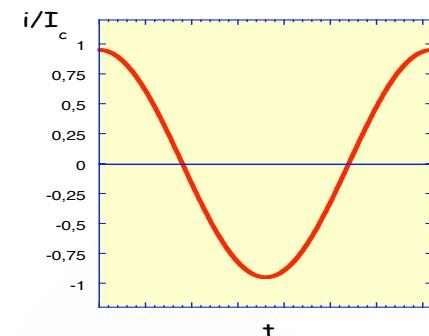
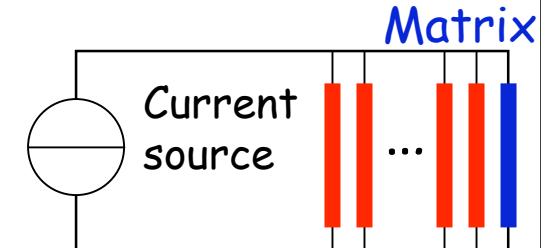
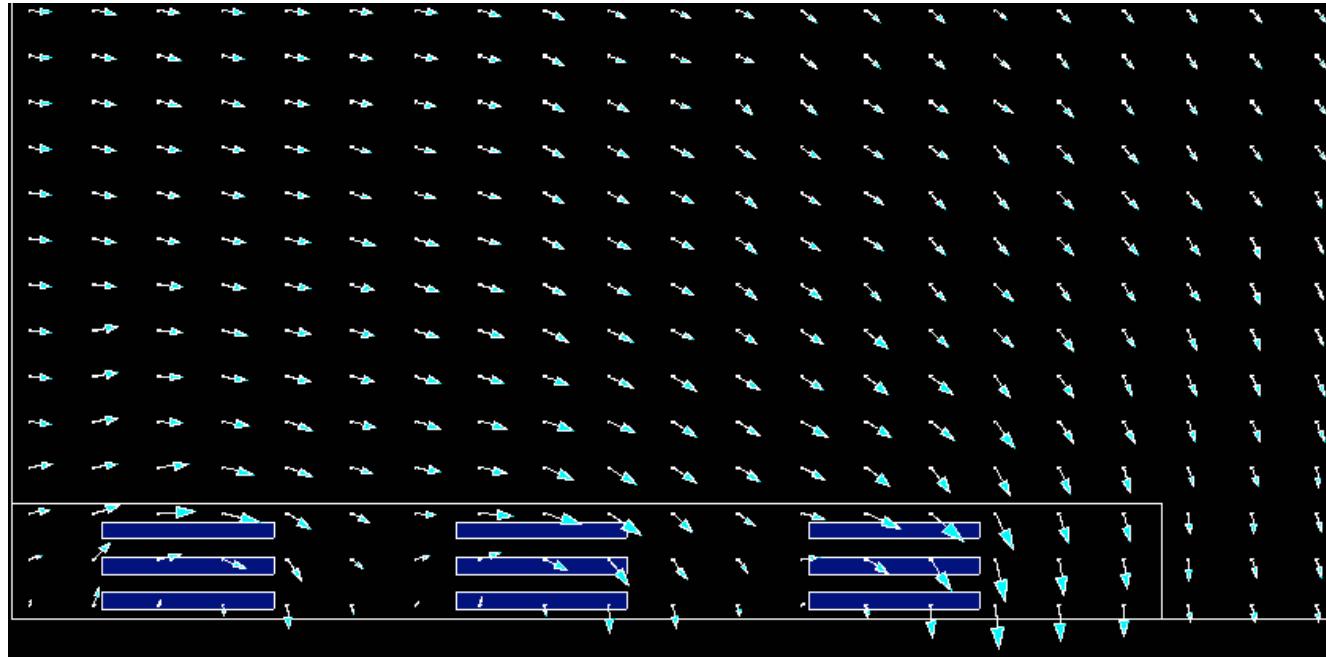
$n = 1$ resistive material

$n = \infty$ (high) critical state model

Current distribution - single filament



Current distribution - multi filament

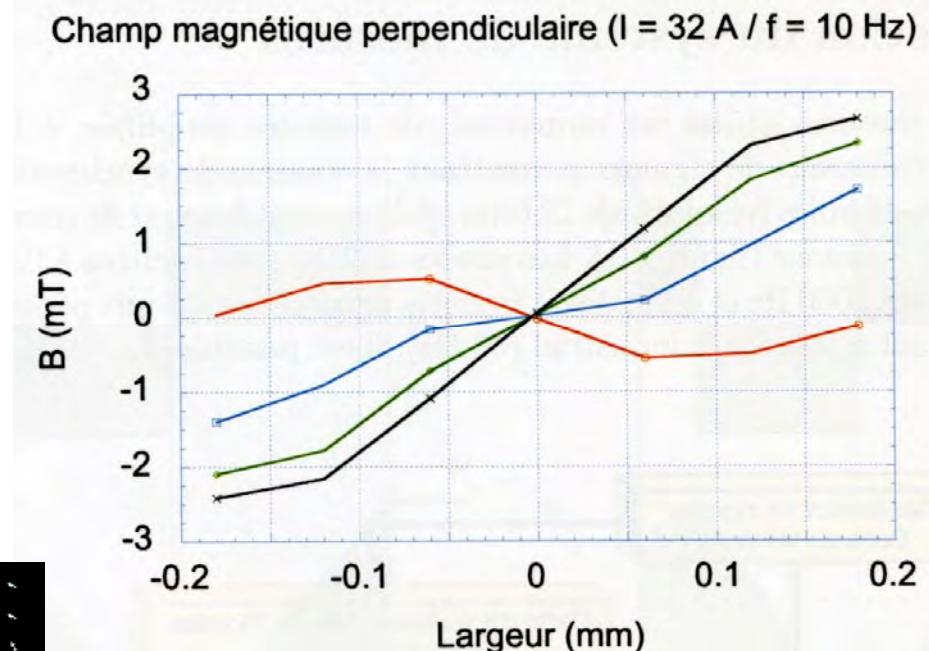
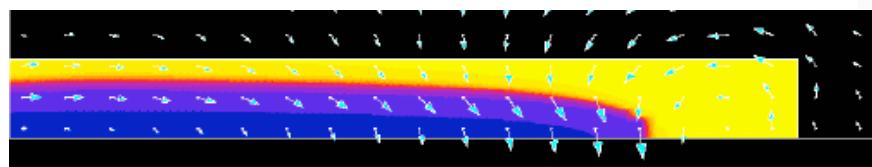
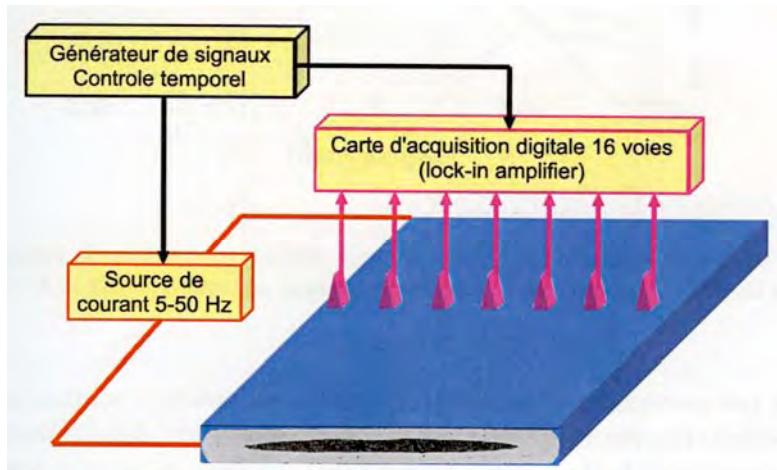


Filaments "coupled" (twisted or not)

To "decouple": Litz wire
Full transposition

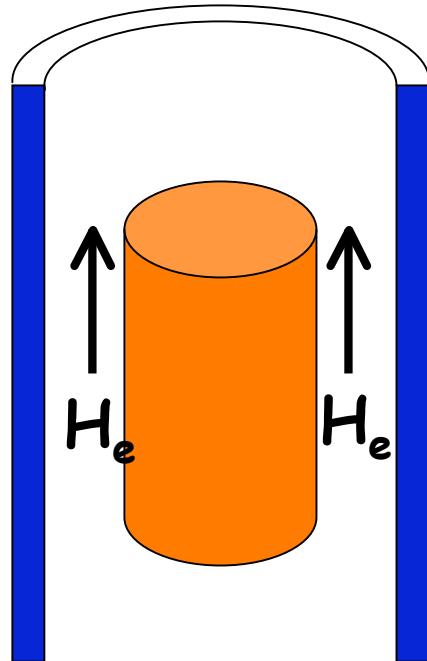


Current distribution in a tape



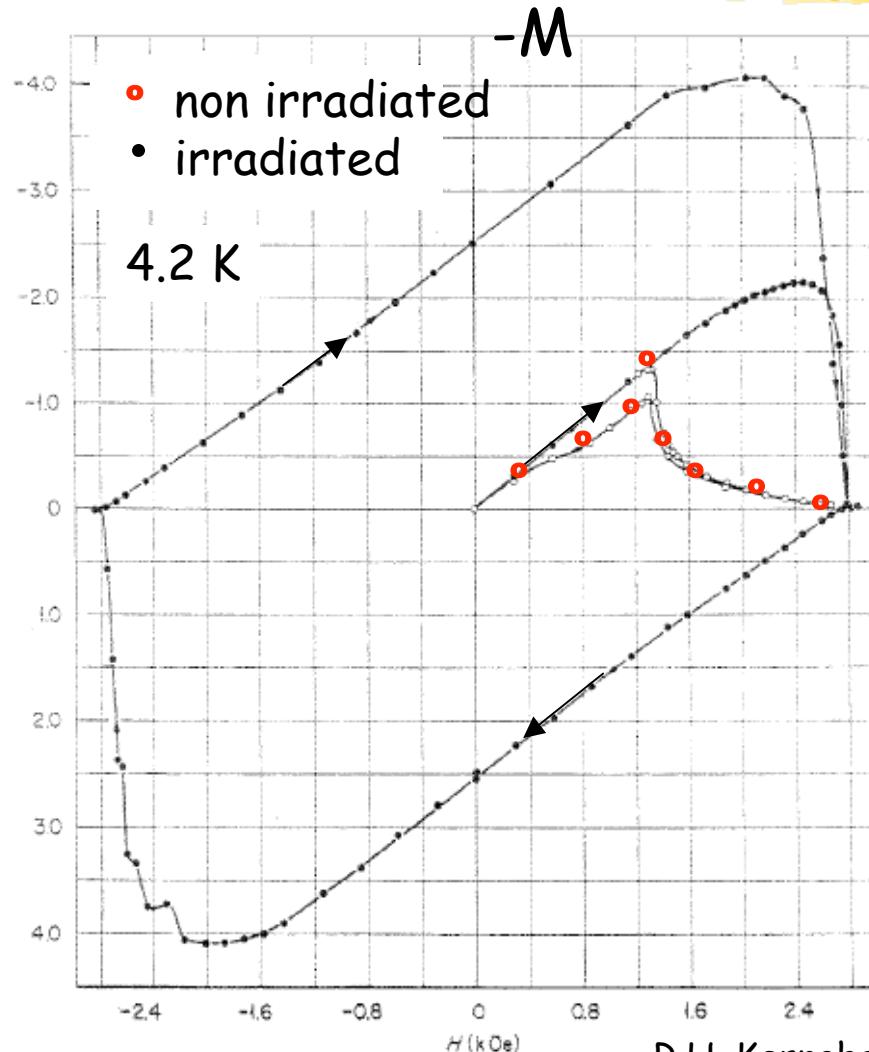
B. Dutoit, EPFL

Magnetization of a superconductor



- Response of a SC to a magnetic field
 - Lenz law
 - Critical state model
 - $J = 0 \text{ or } \pm J_c$
 - $\text{Curl } B = 0 \text{ or } \text{Curl } B = \mu_0 J_c$

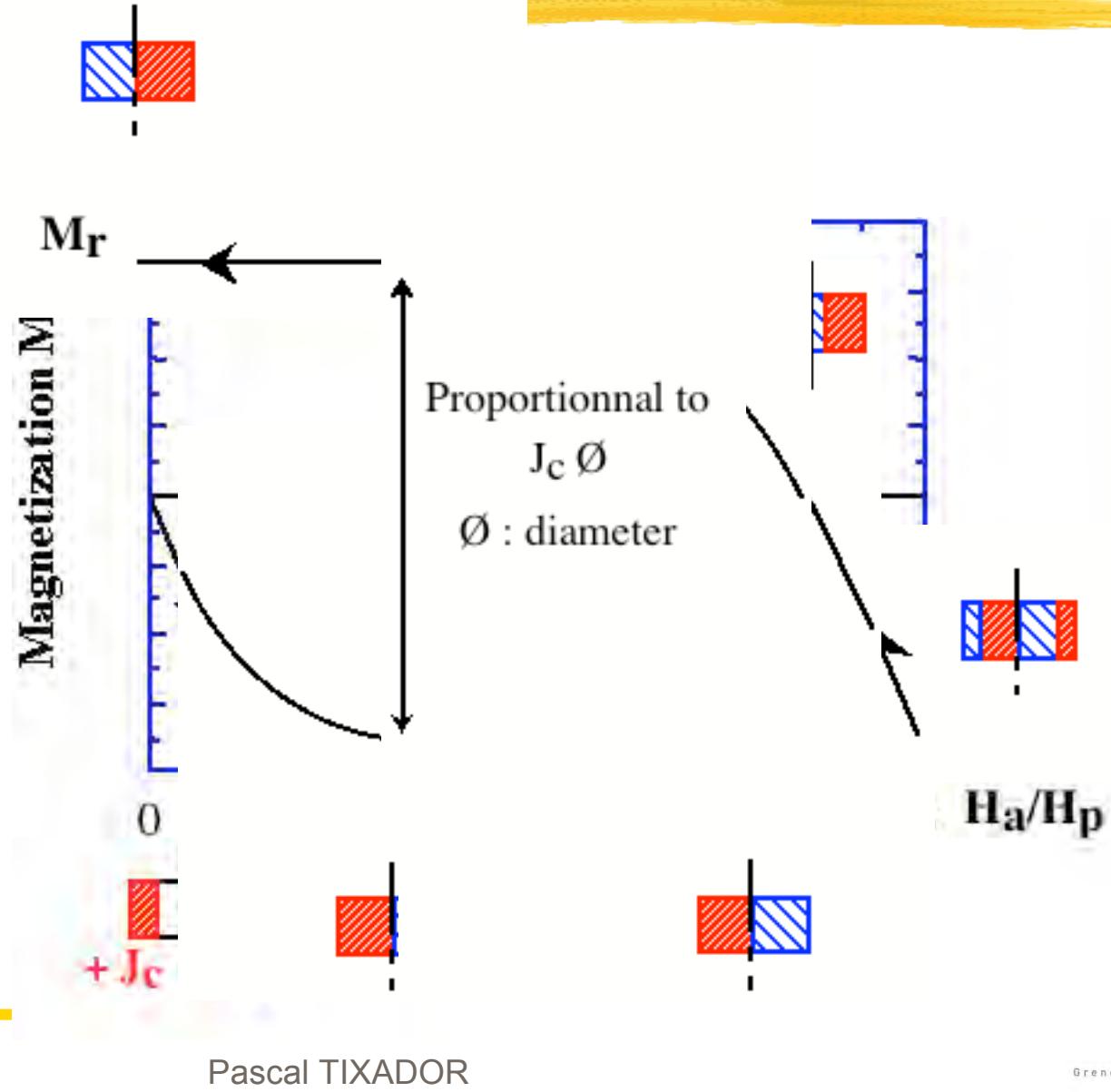
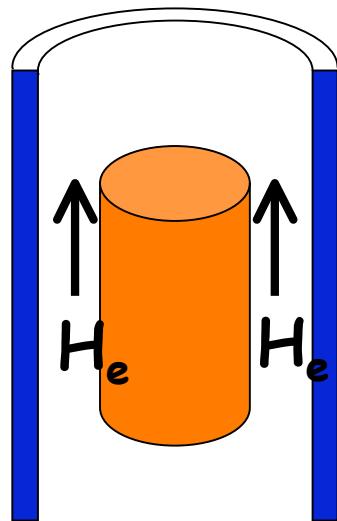
Magnetization of a superconductor



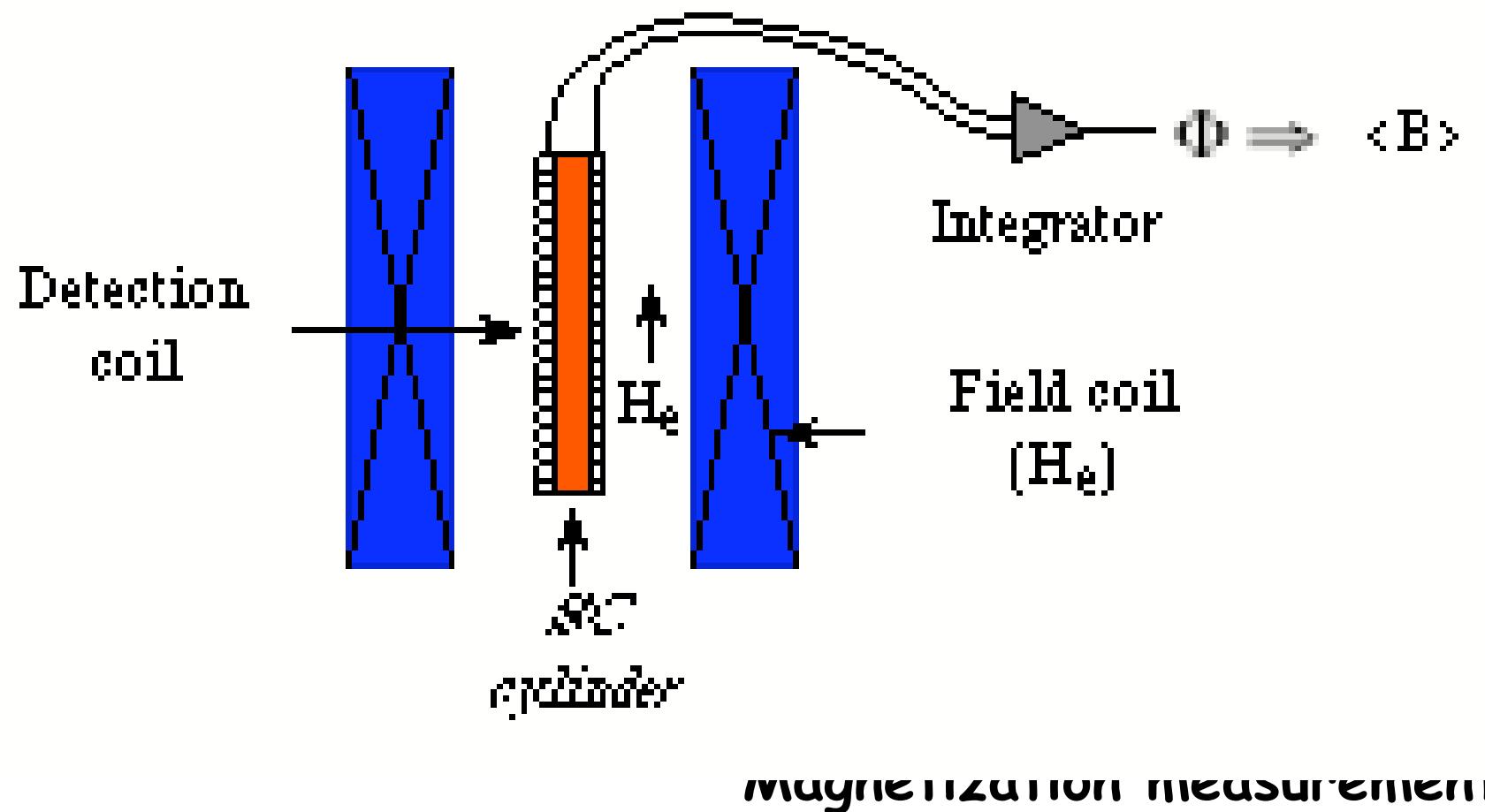
Experimental curve
- Nb

-R.H. Kernohan et S.T. Sekula, 1967

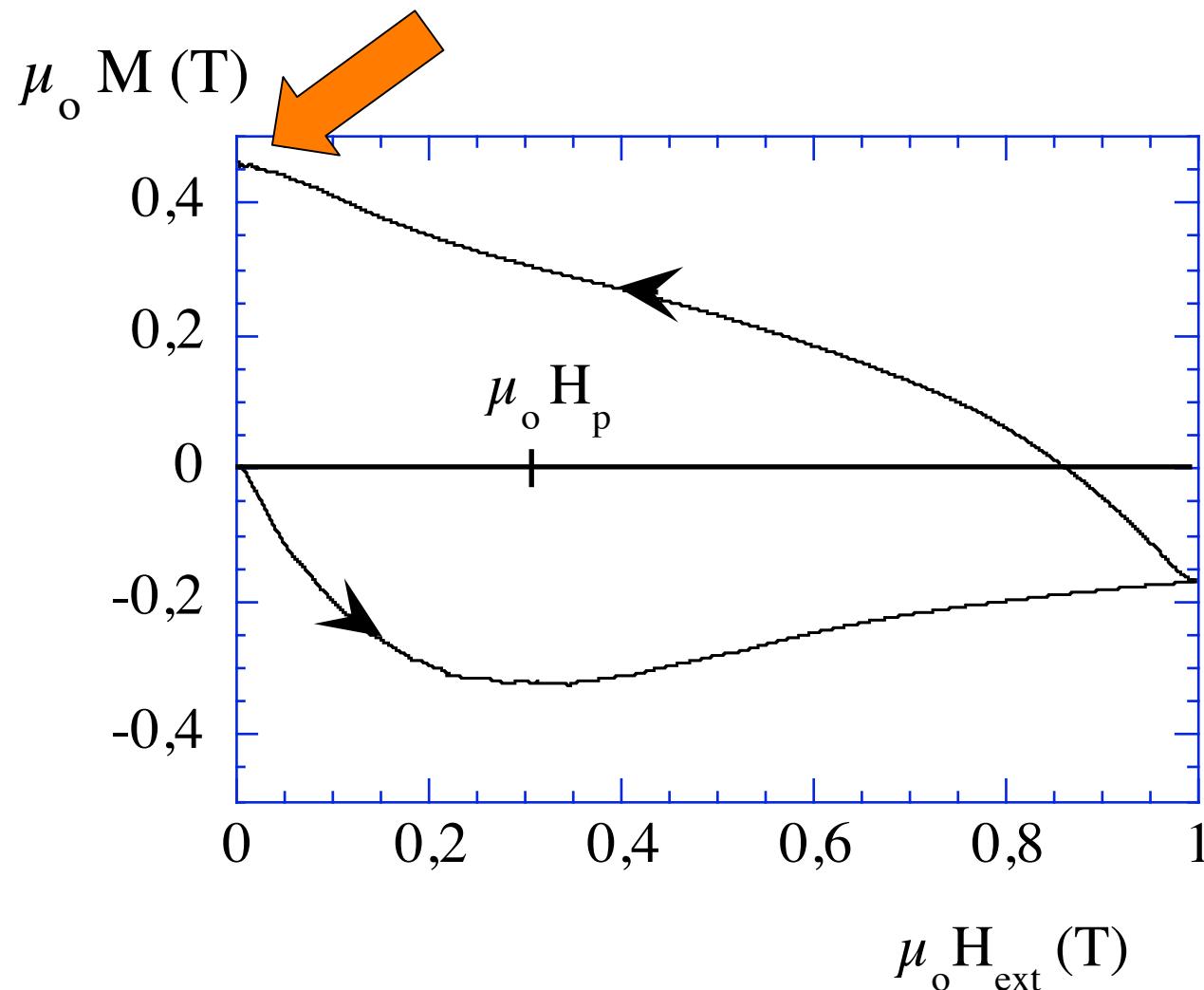
Magnetization of a superconductor



Experimental results

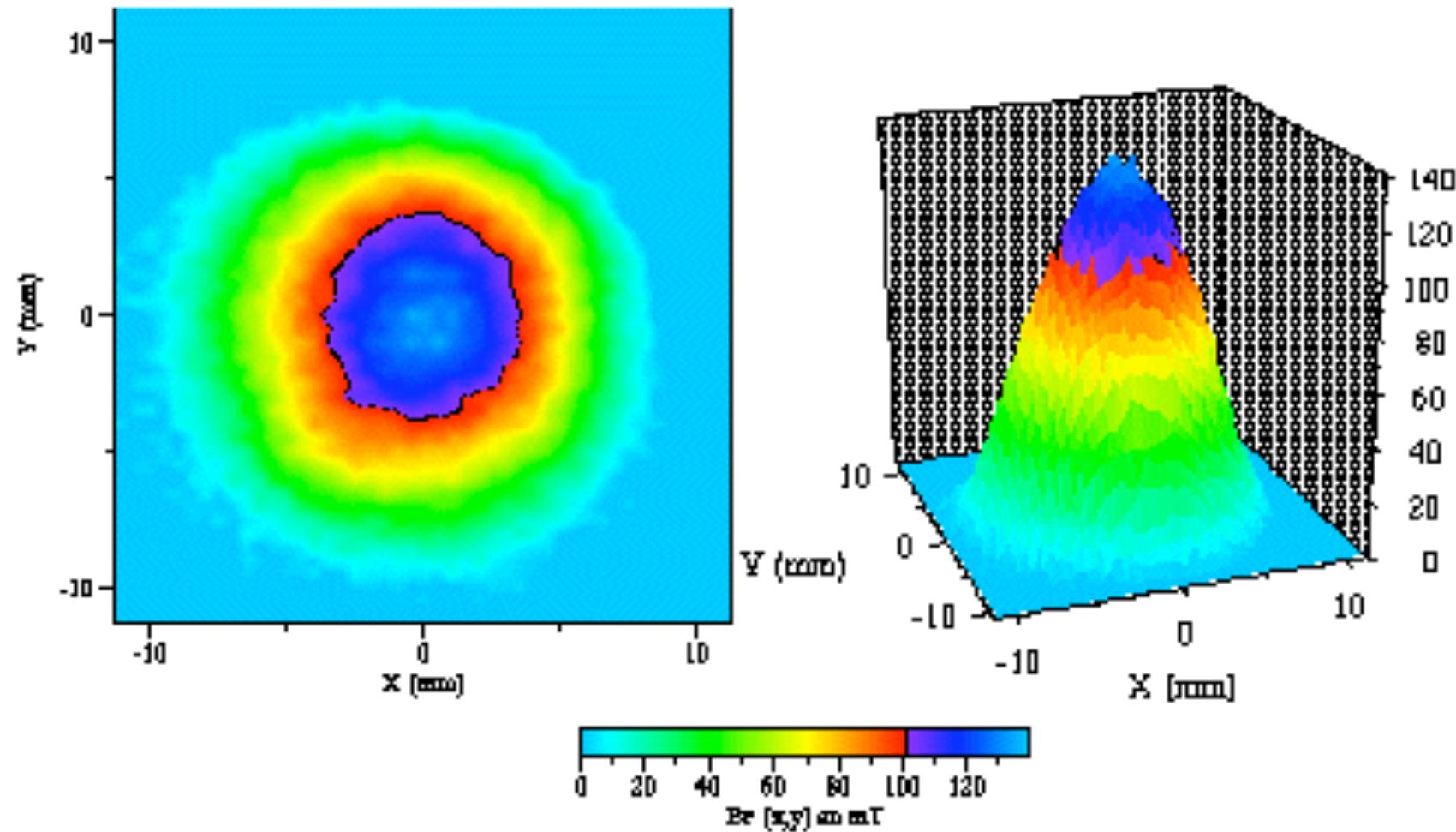


Magnetization curve (YBCO pellet)

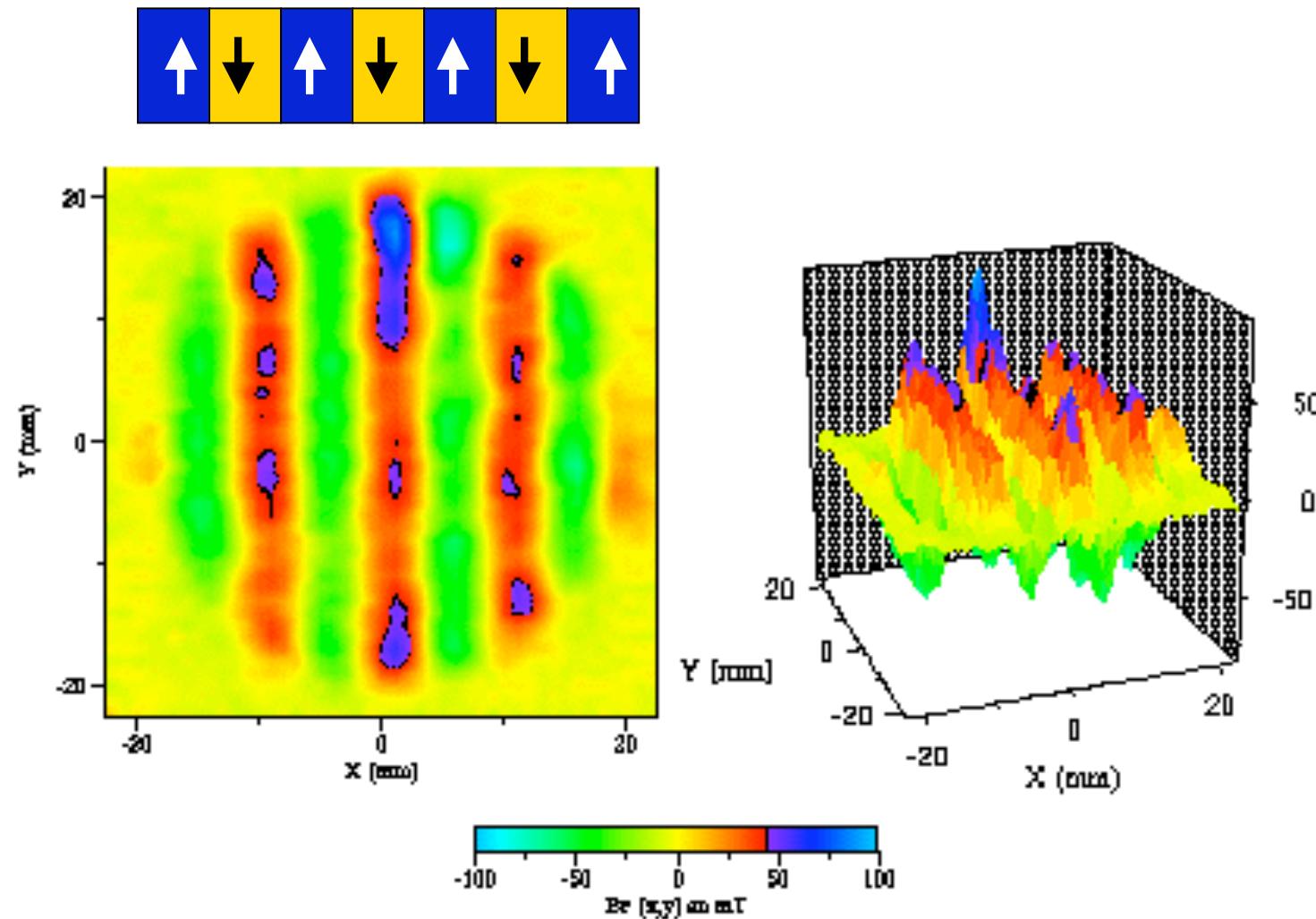


Courtesy
X. Chaud

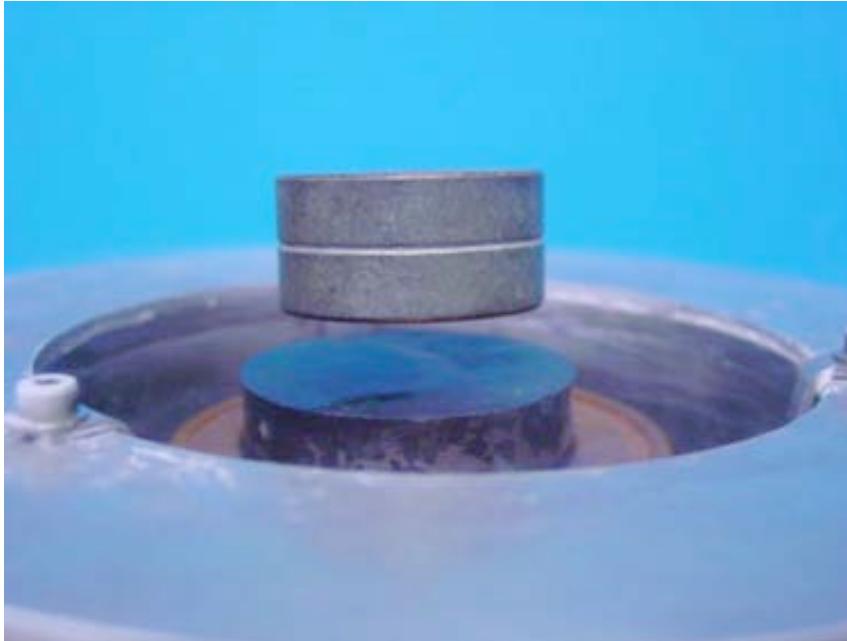
Remanent magnetization



Remanent magnetization, field profile 2/2

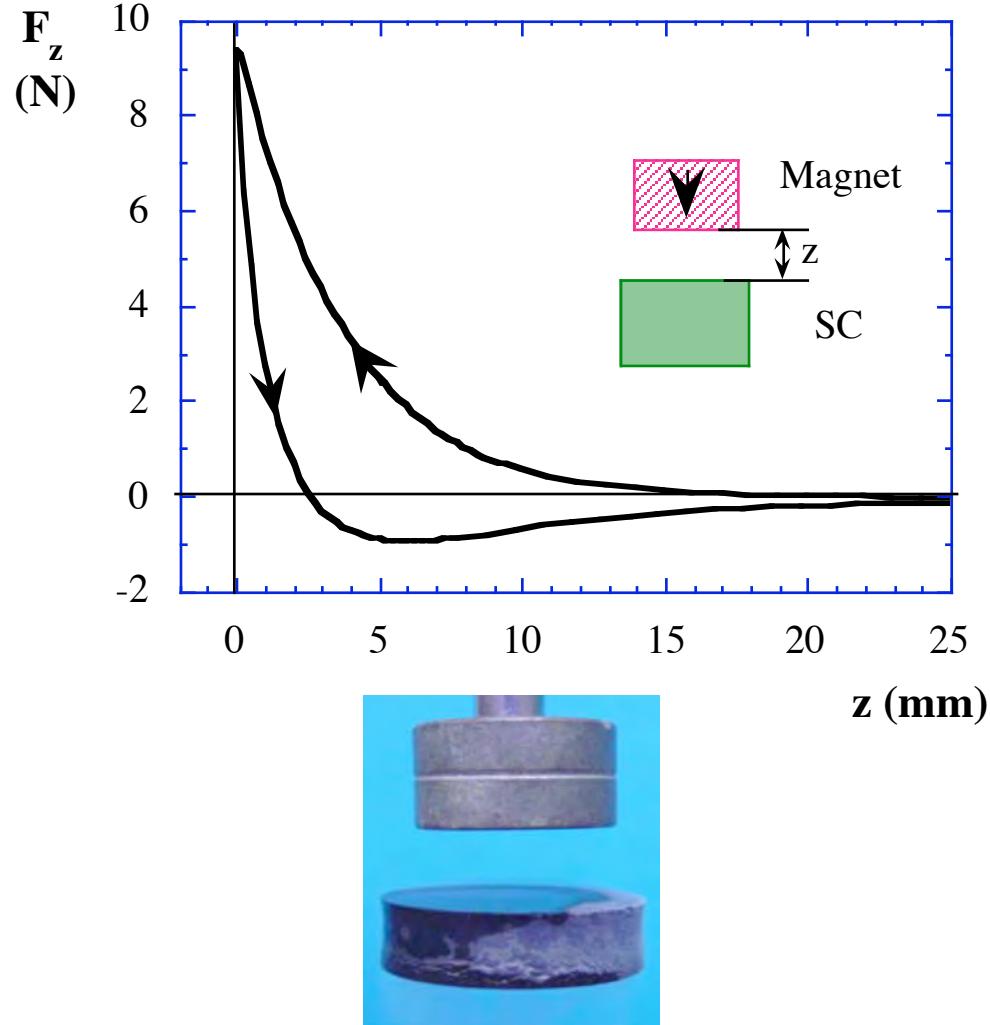


Floating magnet experiment

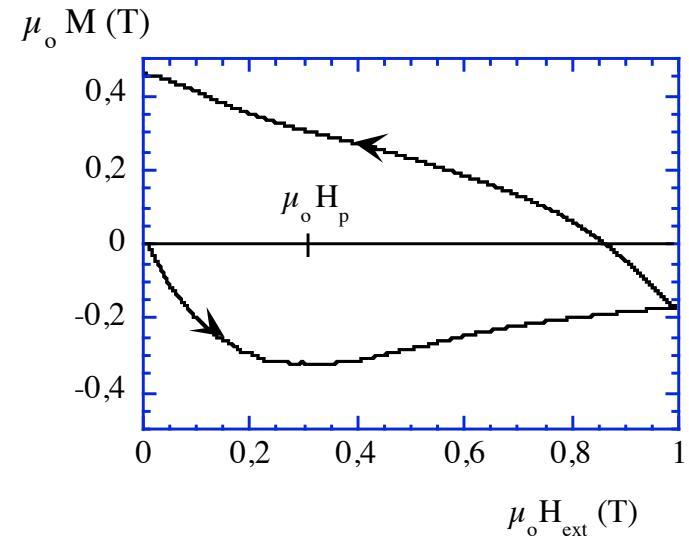


Interactions between
a YBCO pellet and
a permanent magnet

Floating magnet - $F(z)$



$$F \approx M \operatorname{Grad} H_e V_{sc}$$



Critical state model - "n" value

SC model in a finite element code FLUX3D

Superconducting element :

- non magnetic material, $B = \mu_0 H$
- power law for $E(J)$:

$$E = E_c \left(\frac{|J|}{J_c} \right)^n \frac{J}{|J|}$$

$n = 1$ resistive material $\left(\rho = \frac{E_c}{J_c} \right)$

$n = \infty$ (high) critical state model

Plate submitted to an external field

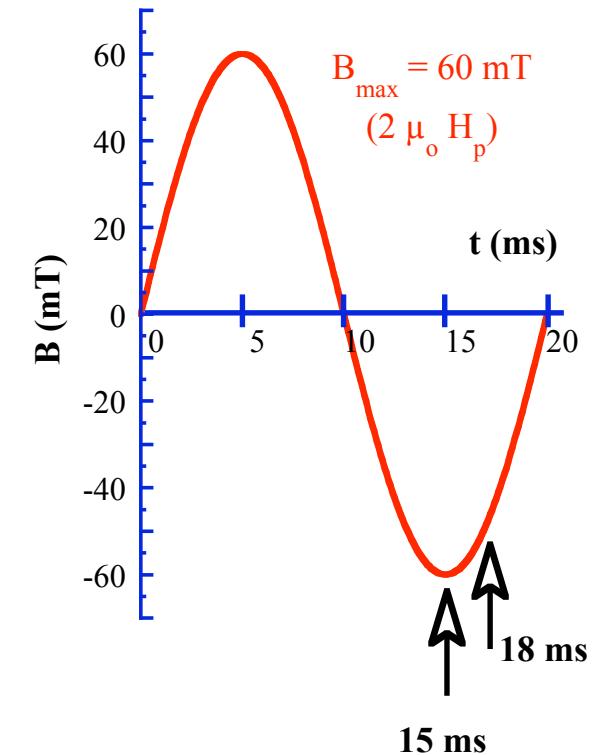
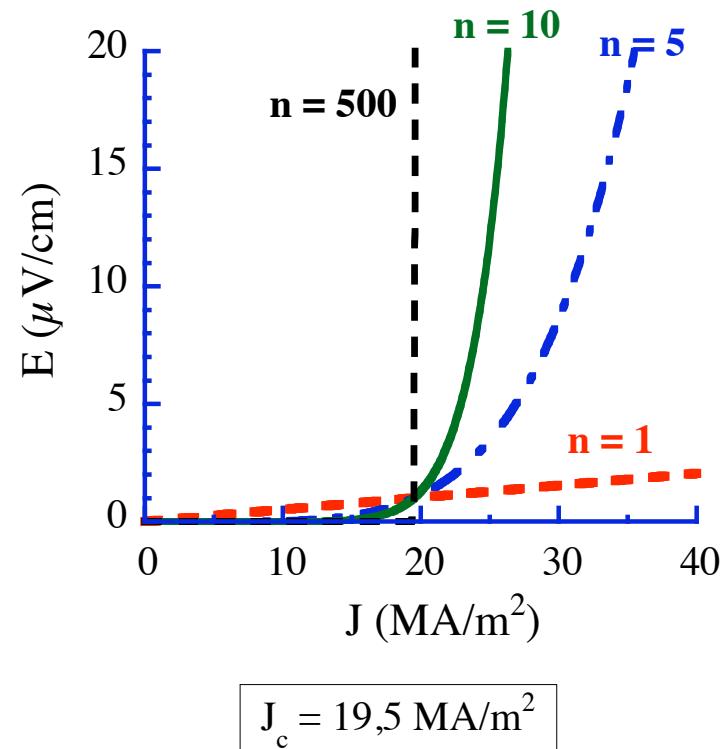
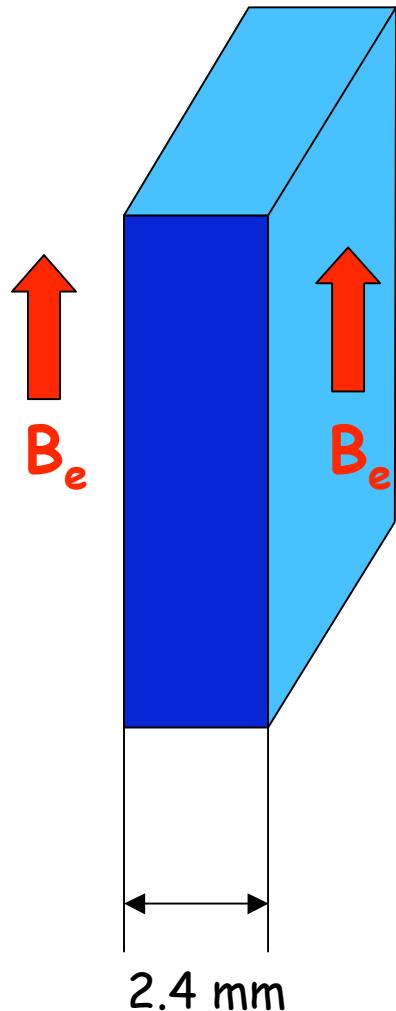
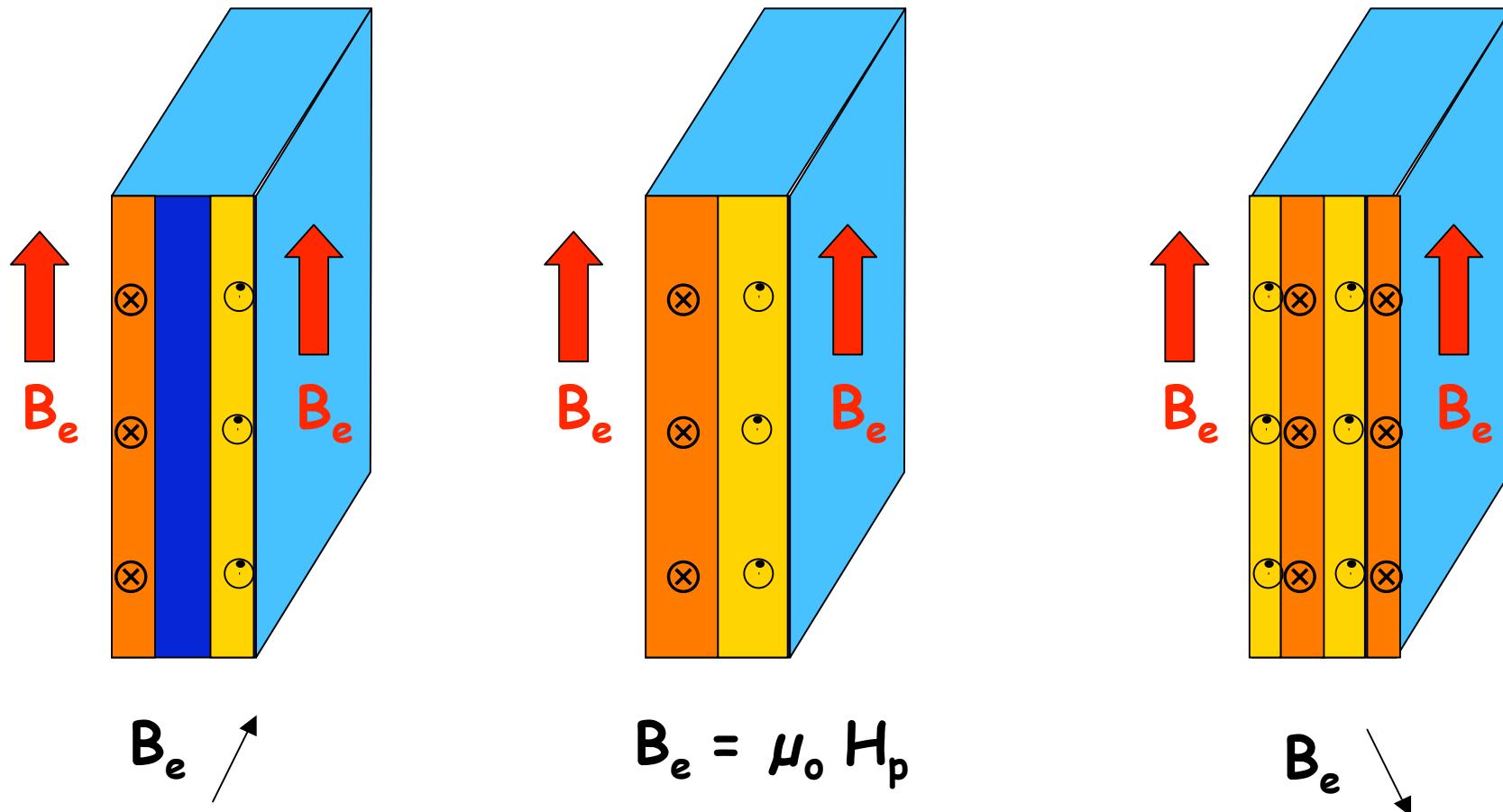
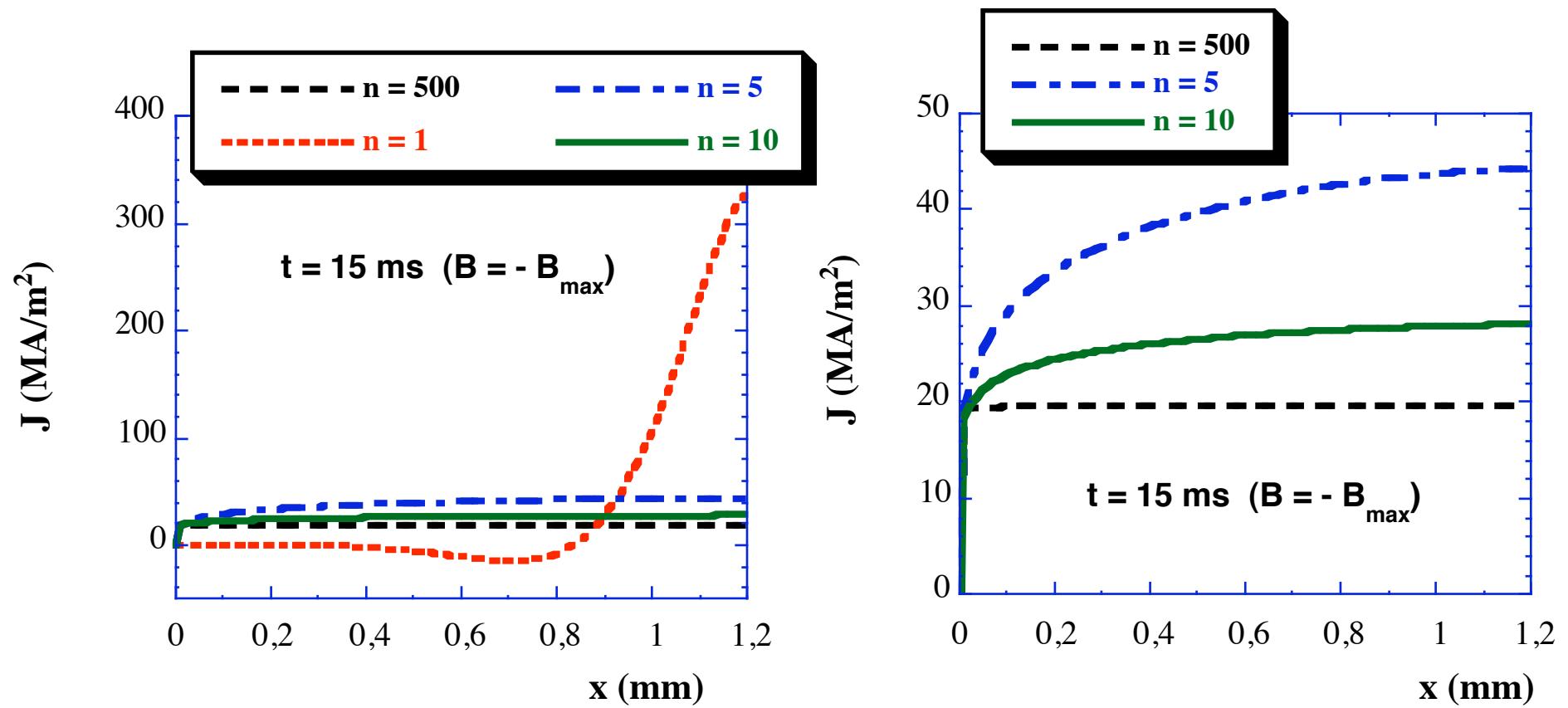


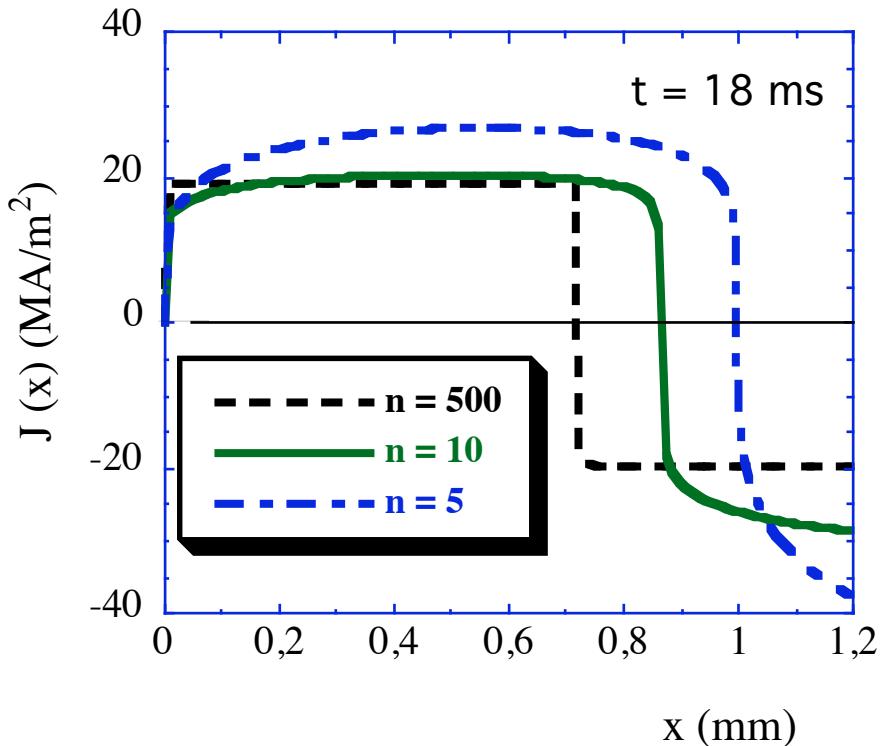
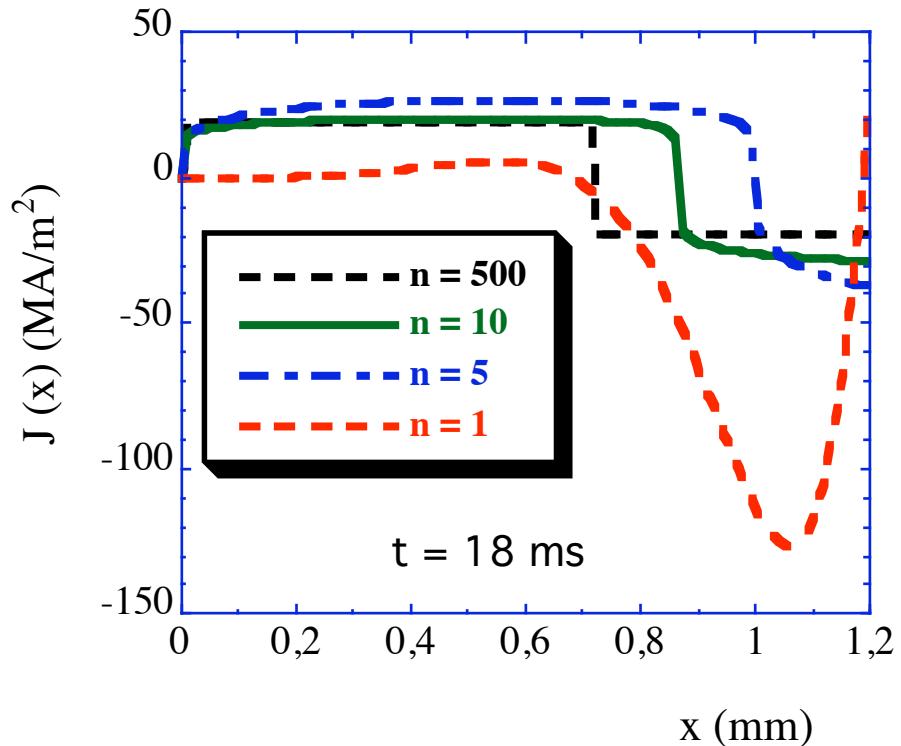
Plate submitted to an external field



Current distribution at $t = 15$ ms



Current distribution at $t = 18$ ms



Critical state model : conclusion

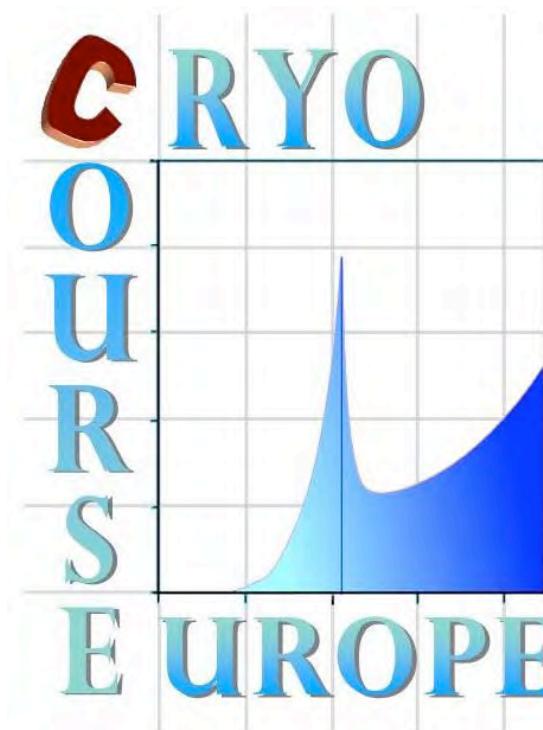
Critical state model valid for “n” > 10

Valid for superconducting materials

Critical state model valid for HTS
superconducting materials

Cryocourse 2011

Grenoble September 2011

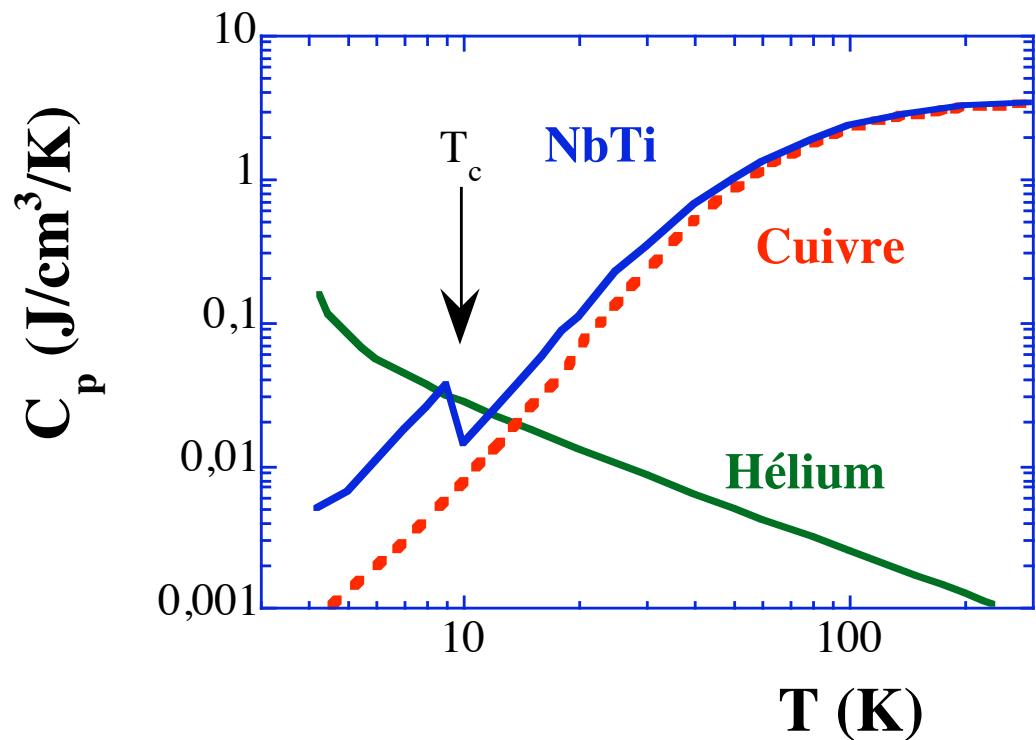


Applied
superconductivity

III. Composite structure

Orders of magnitude 1/4

Conventional superconductors operate at temperatures close to zero (5 K) and the specific heats are very low



Specific heat :
Internal material
brake against
temperature rise

Order of magnitude 2/4

THERMAL EQUATION IN ADIABATIC CONDITIONS

$$W = \text{Vol } c_p \Delta T \Rightarrow \Delta T = E / V c_p$$

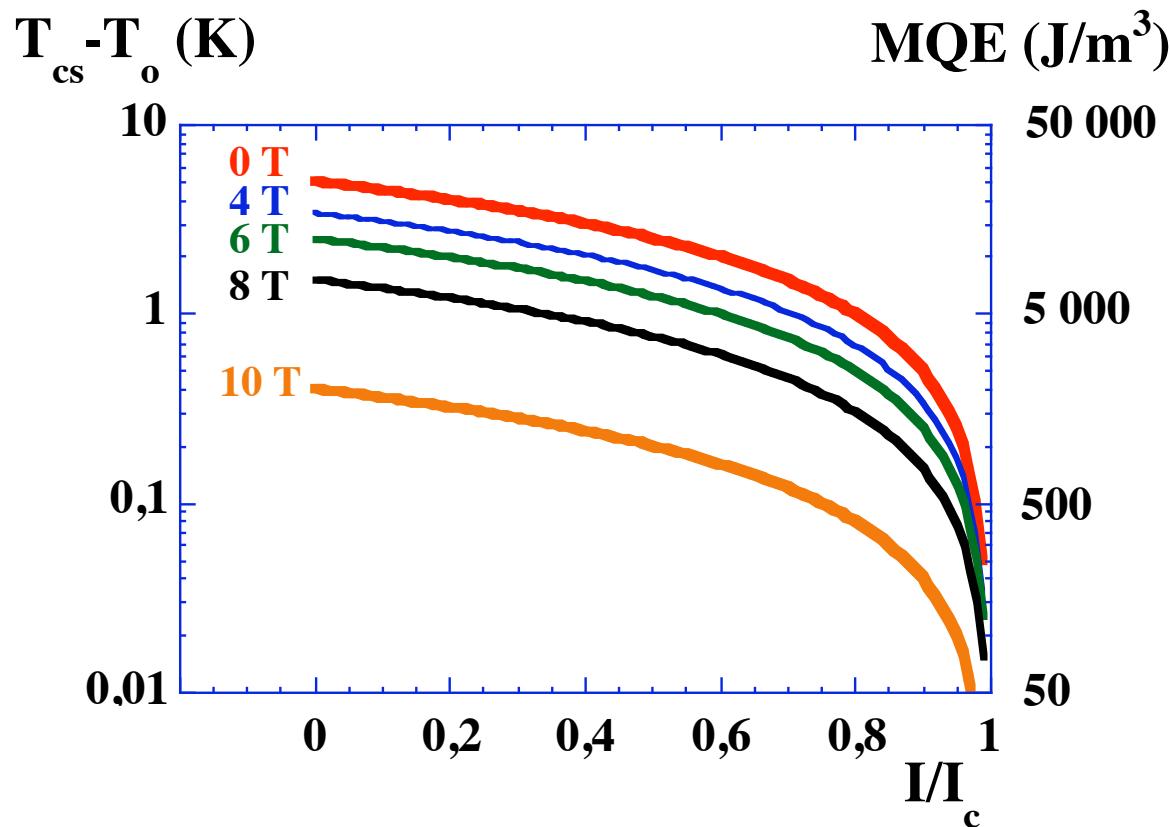
Energy Specific heat
Volume Temperature rise

NbTi @ 4 K: $c_p = 0.005 \text{ J/cm}^3/\text{K}$

$0.005 \text{ J/cm}^3 \Rightarrow \Delta T = 1 \text{ K}$

Order of magnitude 3/4

Temperature margin and related energy for NbTi



4 K and
Adiabatic
conditions

Perturbations - origins

■ Mechanics

- | wire motion under Lorentz force, micro-slips
- | winding deformations, isolation failures, cracks

■ Electromagnetic

- | flux-jumps
- | AC loss

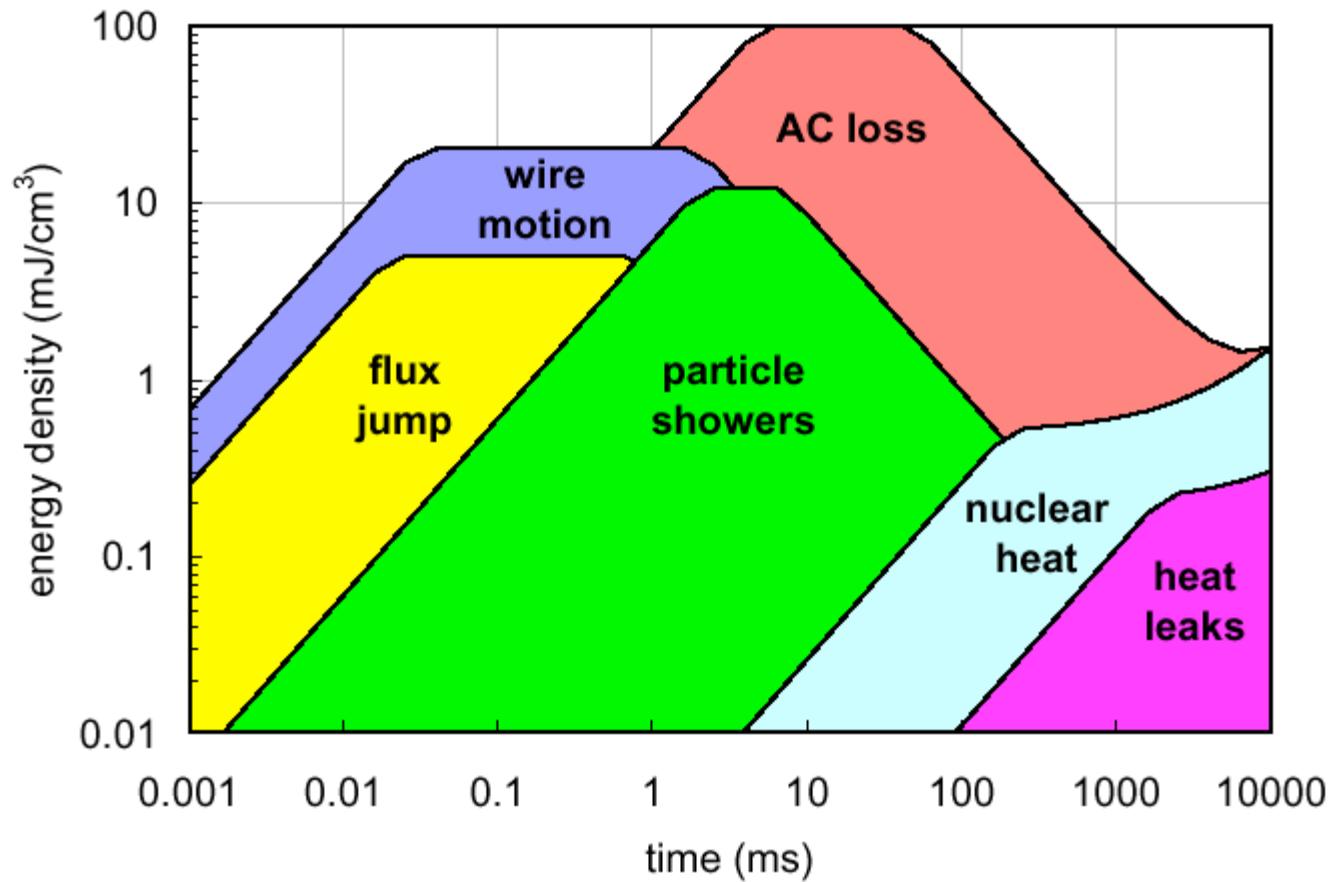
■ Nuclear events

- | particles in particle accelerator magnets
- | neutron flux in fusion

■ Thermics

- | current leads, instrumentation wires
- | heat leaks through thermal insulation, degraded cooling

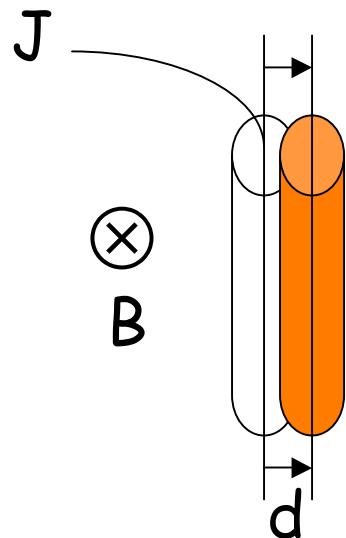
Perturbations - spectrum



Courtesy L. Bottura

Order of magnitude 4/4

Displacement of a SC strand of a distance d



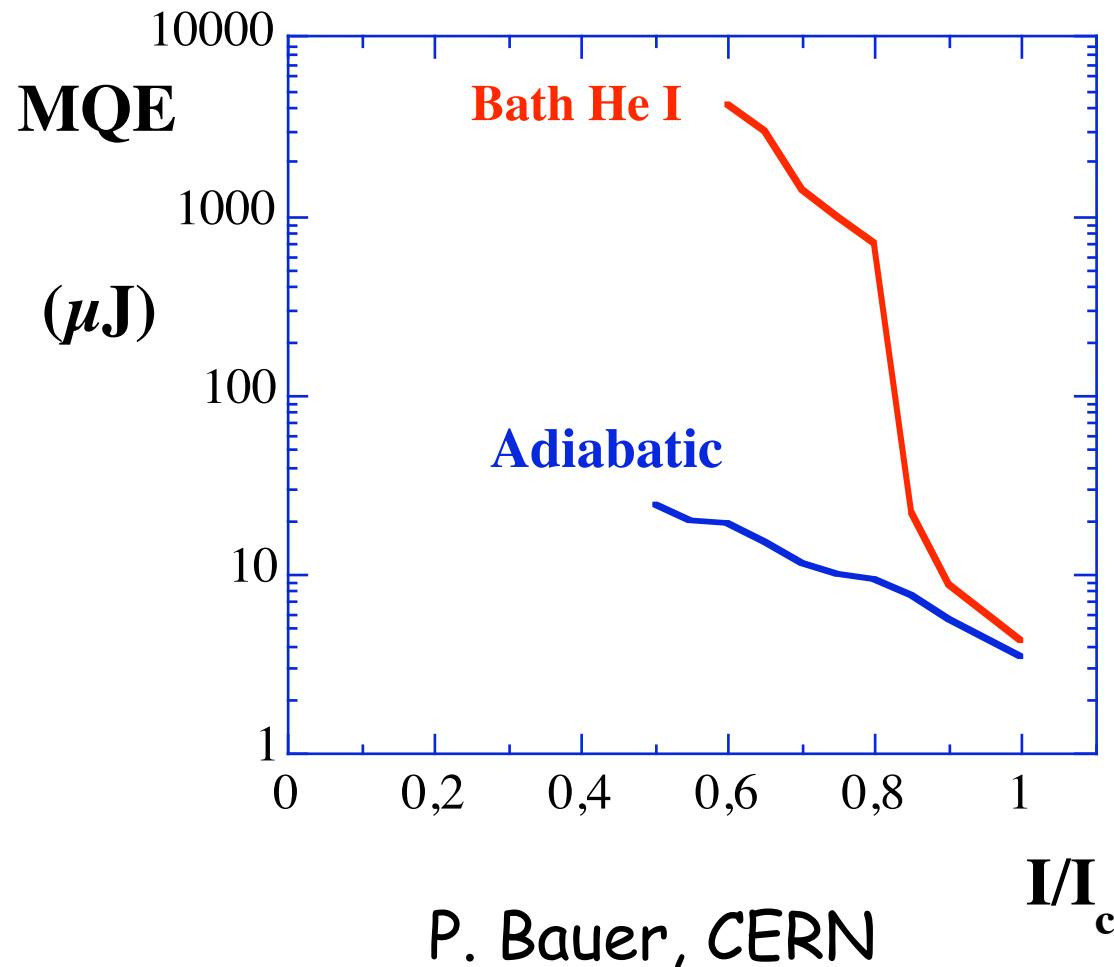
$$F = I B L = J B S L$$

$$W = F d = J B d \text{ Vol}$$

$$B = 5 \text{ T} ; J = 1000 \text{ MA/m}^2 ; d = 1 \mu\text{m}$$

$$J B d = 5000 \text{ J/m}^3 = 0.005 \text{ J/cm}^3 \Rightarrow \Delta T = 1 \text{ K}$$

Real conditions - cooling effects



NbTi strand
@ 1.8 K
LHC - CERN

Order of magnitude - conclusions

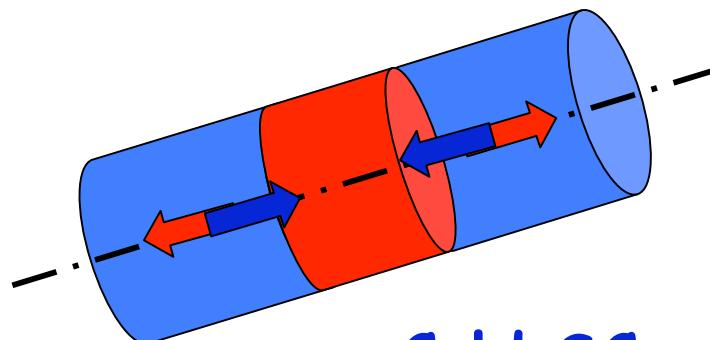
- SC state very “unstable”
 - Small temperature margins
 - Low energy absorption possibilities
- SC very sensitive to disturbances
 - No wire displacement

Suitable structure to stabilize the sensitive SC state

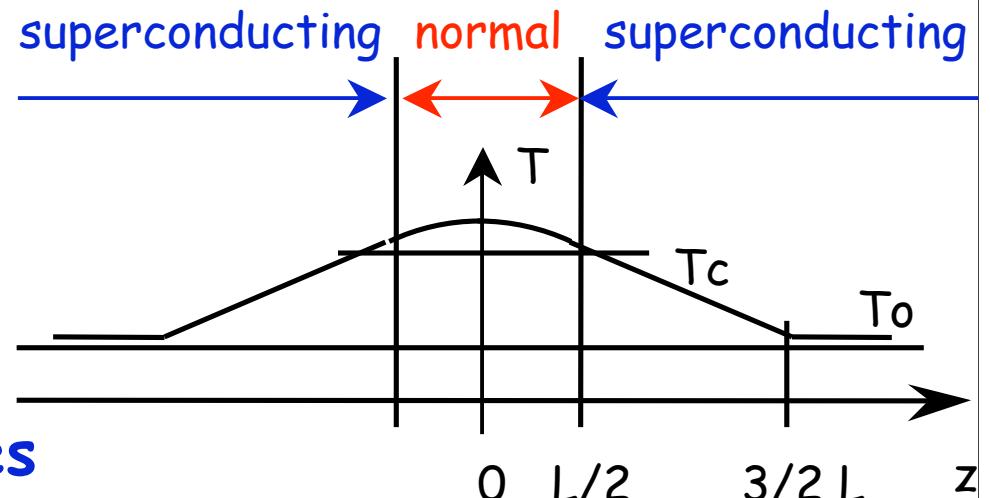
Multifilament twisted composite

Minimum propagating zone 1/3

Normal zone
Heating : propagation



Cold SC zones
cooling



Normal zone heating: $W_{\text{Joule}} = \rho_n J^2 L S$

Cooling by axial conduction: $W_{\text{cond}} = 2 \lambda S \delta T / \delta z$

Minimum propagating zone 2/3

Heating of the normal zone : $W_{Joule} = \rho_n J^2 L S$

Cooling by axial conduction : $W_{Cond} = 2 \lambda S \frac{\partial T}{\partial z}$

If $W_{Joule} > W_{cond} \Rightarrow$ zone extension

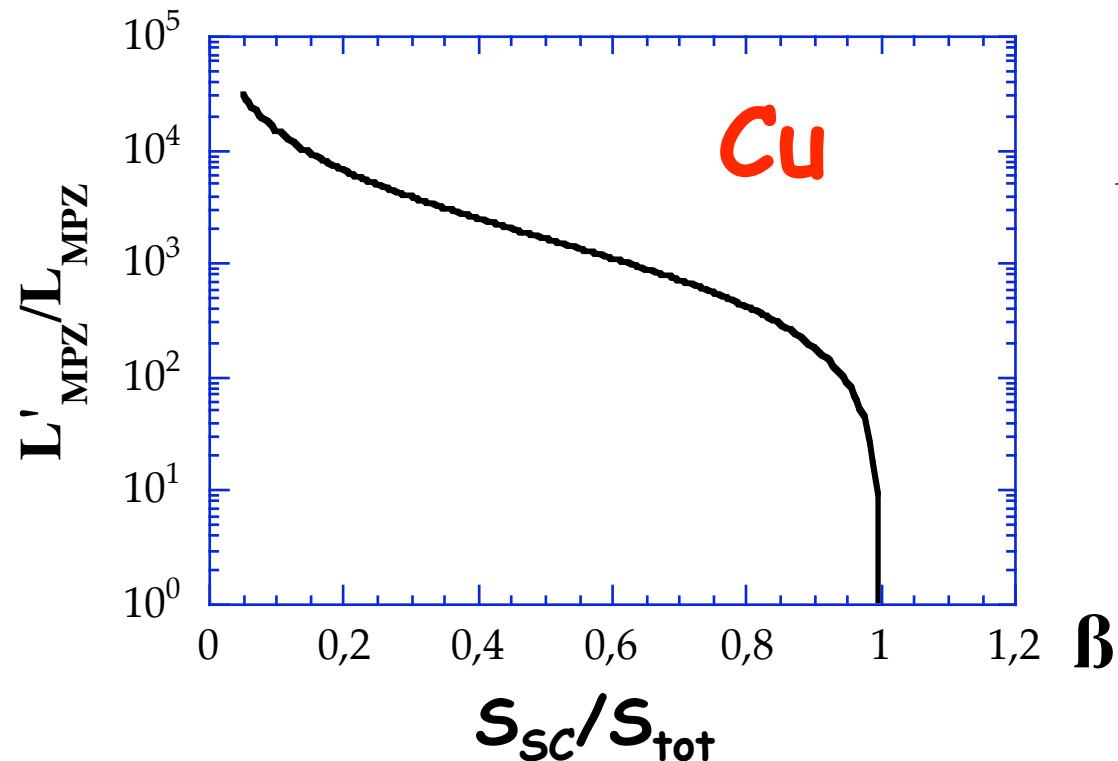
If $W_{Cond} > W_{Joule} \Rightarrow$ zone resorption

Minimum propagating length

$$L_{MPZ} = \sqrt{\frac{2 \lambda (T_c - T_o)}{\rho_n J^2}}$$

Minimum propagating zone 3/3

Great interest for a material
with high thermal and electrical conductivities



$$L_{MPZ} = \sqrt{\frac{2\lambda(T_c - T_o)}{\rho_n J^2}}$$

$$\rho_{SC} = 4 \cdot 10^{-7} \Omega m$$
$$\rho_{Cu} = 2 \cdot 10^{-10} \Omega m$$

$$k_{SC} = 0.3 \text{ W/m/K}$$
$$k_{Cu} = 400 \text{ W/K/m}$$

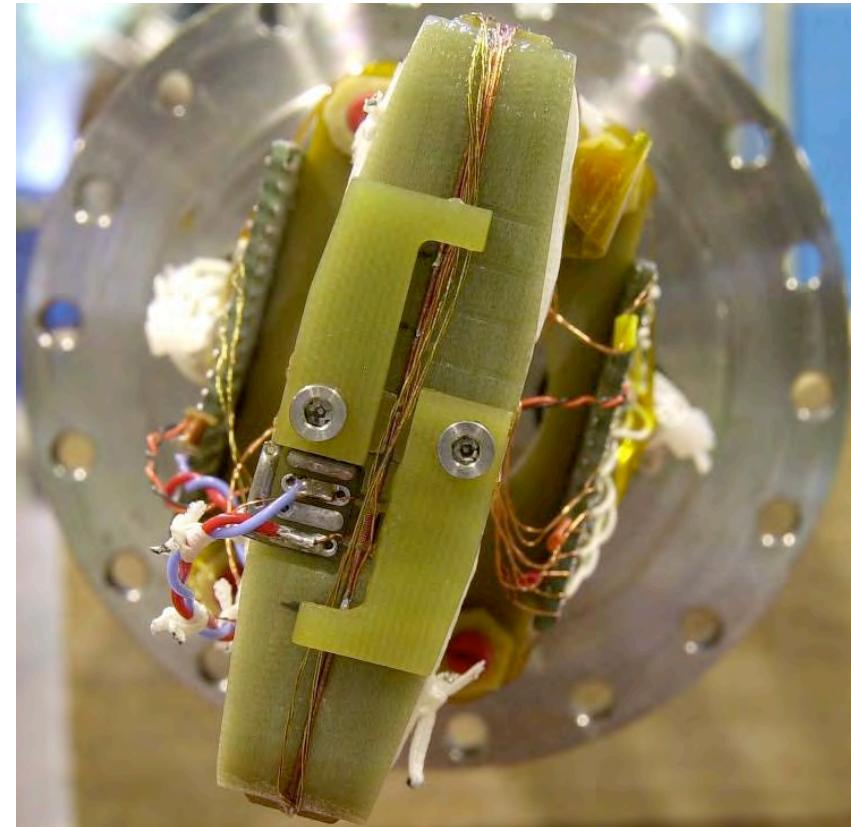
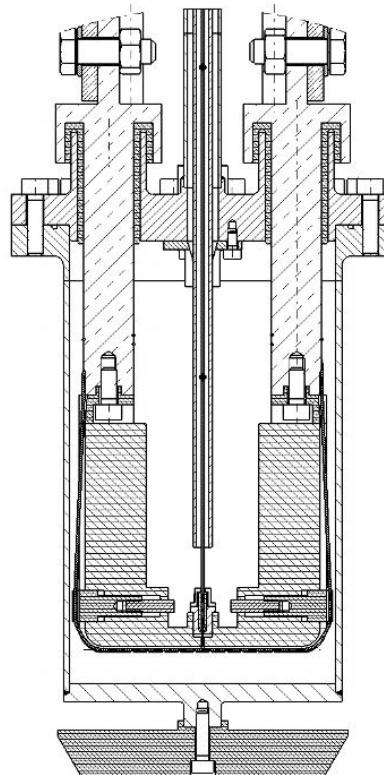
Mimimum propagation zone



Conclusion 1:

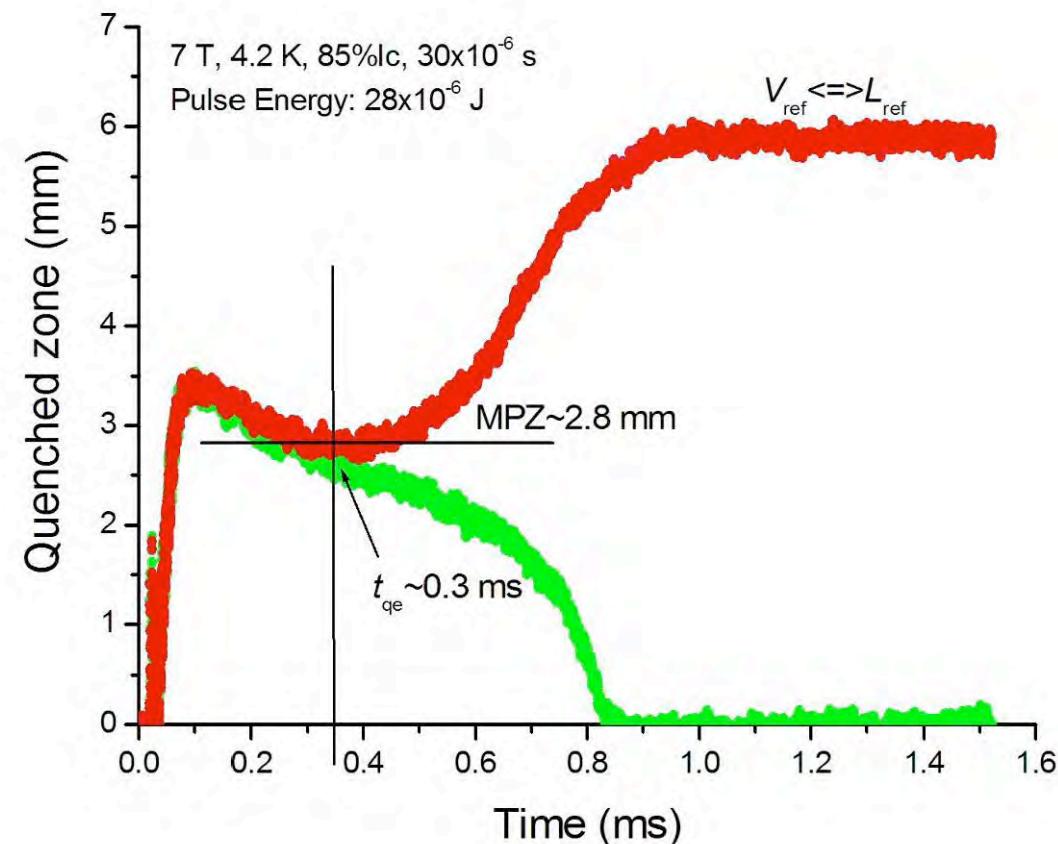
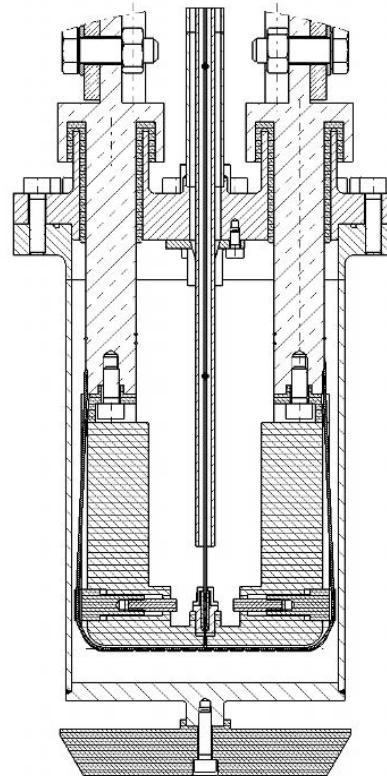
To embed the superconductor in a good
thermal and electrical conductor (Cu)

Minimum propagation quench energy



F. Trillaud, CEA Saclay

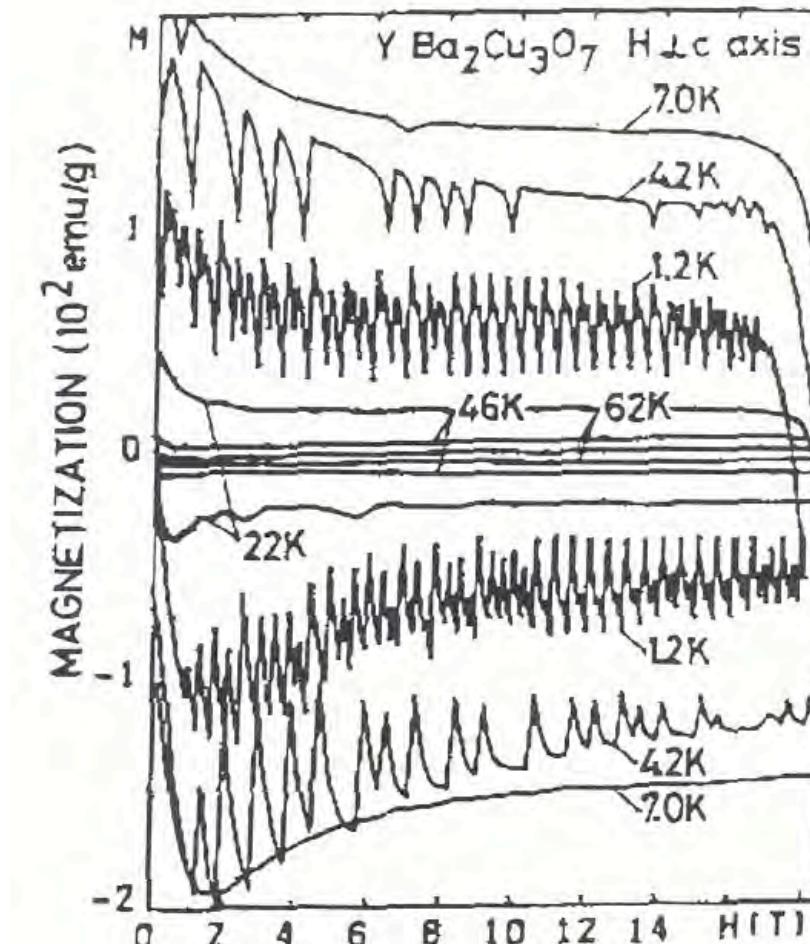
Minimum propagation quench energy



F. Trillaud, CEA Saclay

Flux jump 1/5

Experimental
Magnetization
curves



"Flux jumps"
at low temp.

J.L. Tholence et al.
Solid State Com.,
Vol. 65, 1988

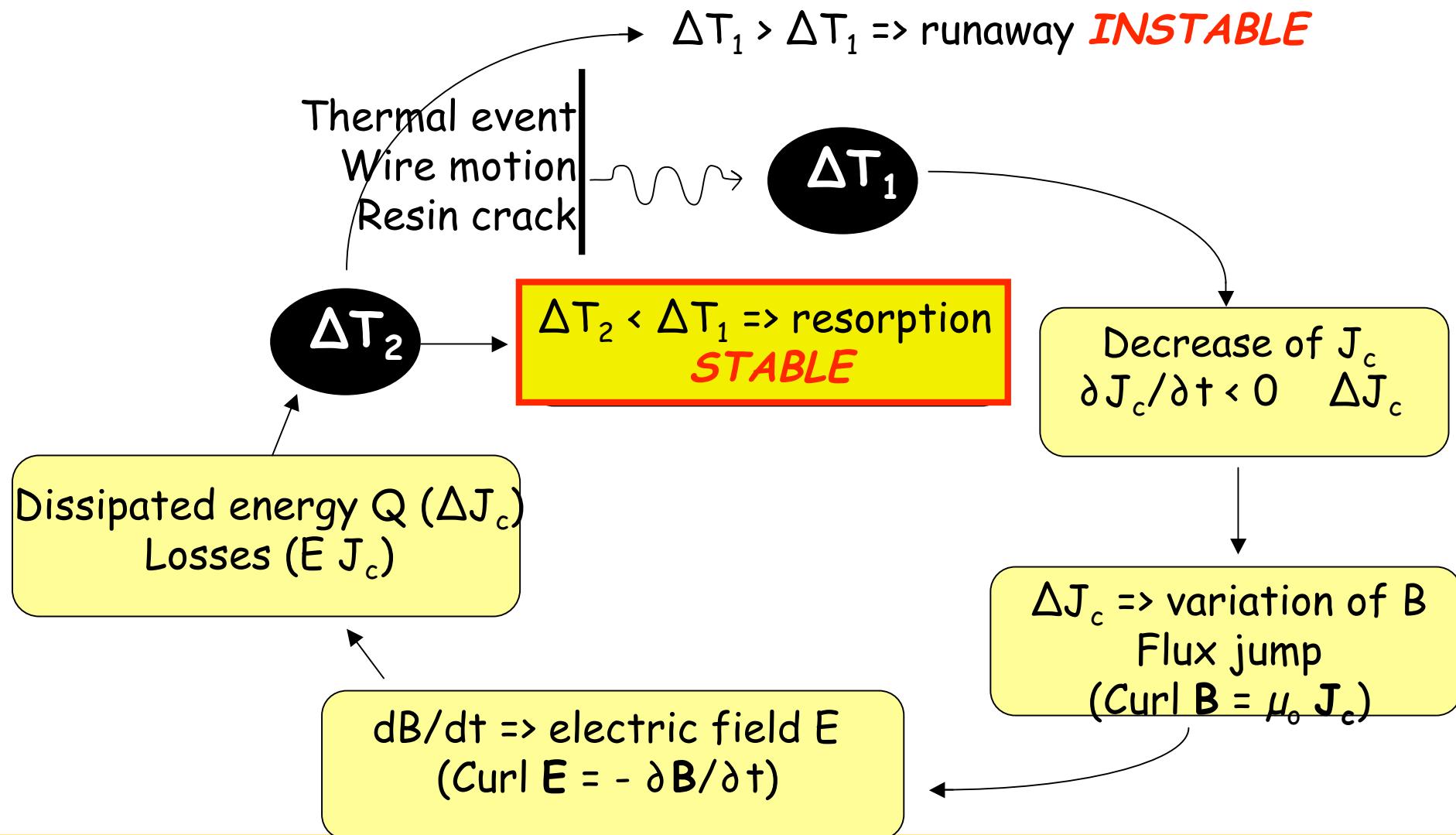
Flux jump 1/5

Flux jump :

thermal-magnetic instability due to

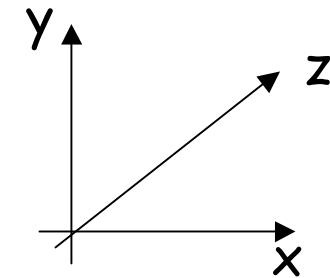
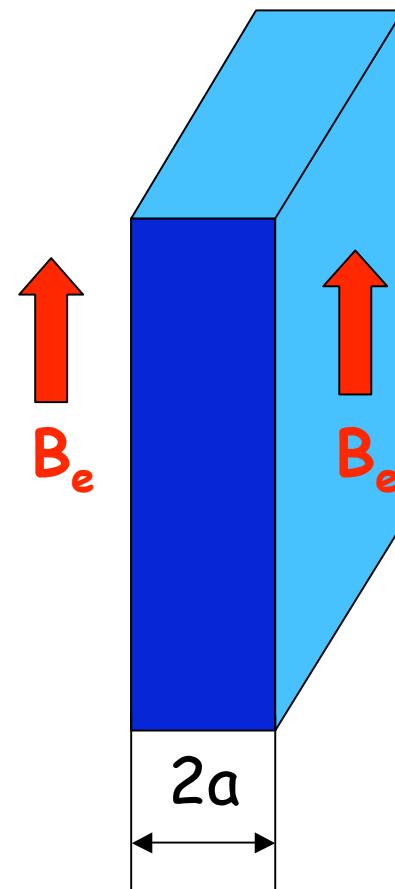
$$\partial_c J / \partial T < 0$$

Flux jump 2/5



Flux : calculation in a particular case

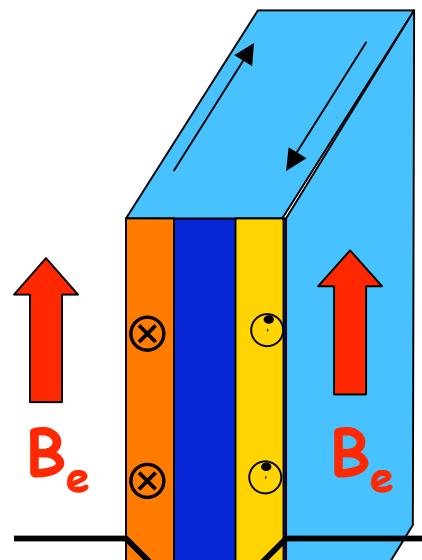
Slab



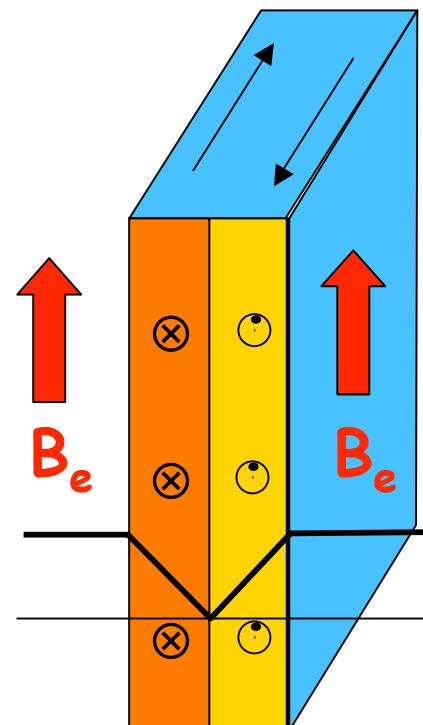
$$L_z = \infty$$

$$L_y = \infty$$

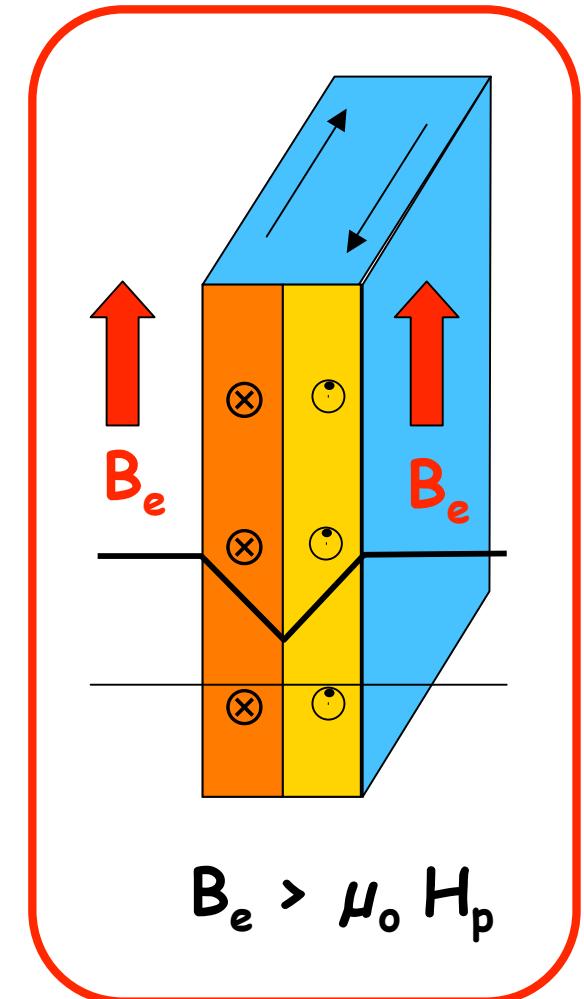
Slab submitted to an external field



B_e



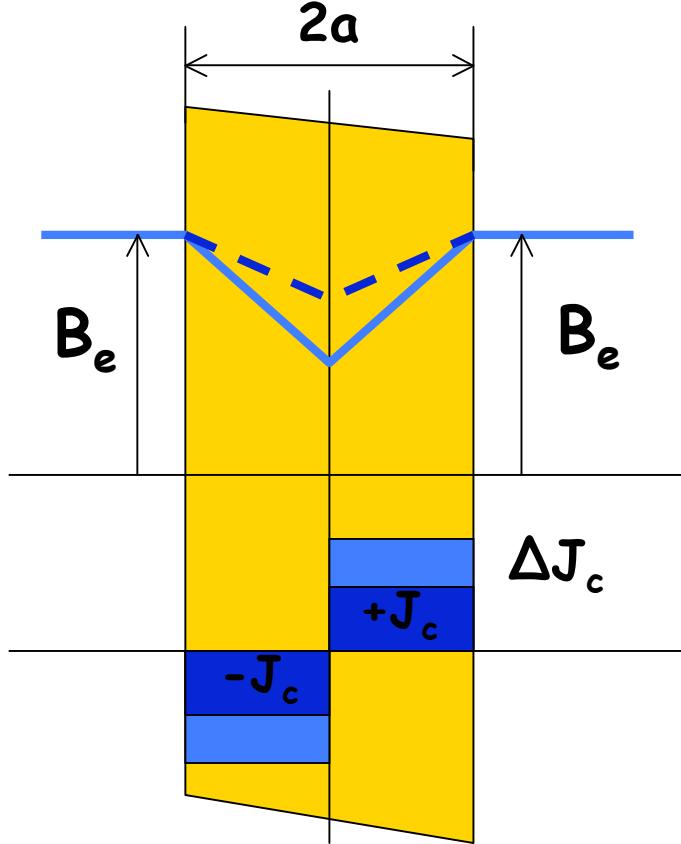
$$B_e = \mu_0 H_p$$



$$B_e > \mu_0 H_p$$

Flux jump

- Consequence of a J_c reduction (B_e constant)



$$0 \leq x \leq a$$

$$E(x) = \mu_o \frac{dJ_c}{dt} \left(\frac{1}{2} x^2 - a x \right)$$

$p = E J_c$: losses

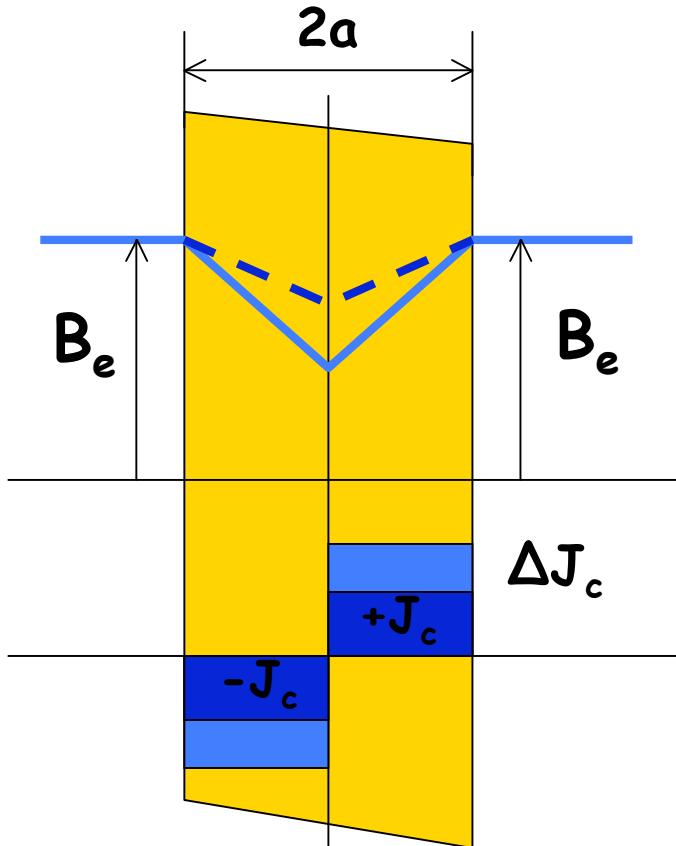
$$p(x) = \mu_o J_c \frac{dJ_c}{dt} \left(\frac{1}{2} x^2 - a x \right)$$

$$p_{total}(t) = \iiint_{\text{slab}} p(x) dx dy dz$$

$$p_{total}(t) = \mu_o J_c \frac{dJ_c}{dt} \frac{2a^3}{3} L_y L_z$$

Flux jump

- Consequence of a J_c reduction (B_e constant)



$$p_{total}(t) = \mu_o J_c \frac{dJ_c}{dt} \frac{2a^3}{3} L_y L_z$$

$$p_{total}(t) = \frac{dQ}{dt}$$

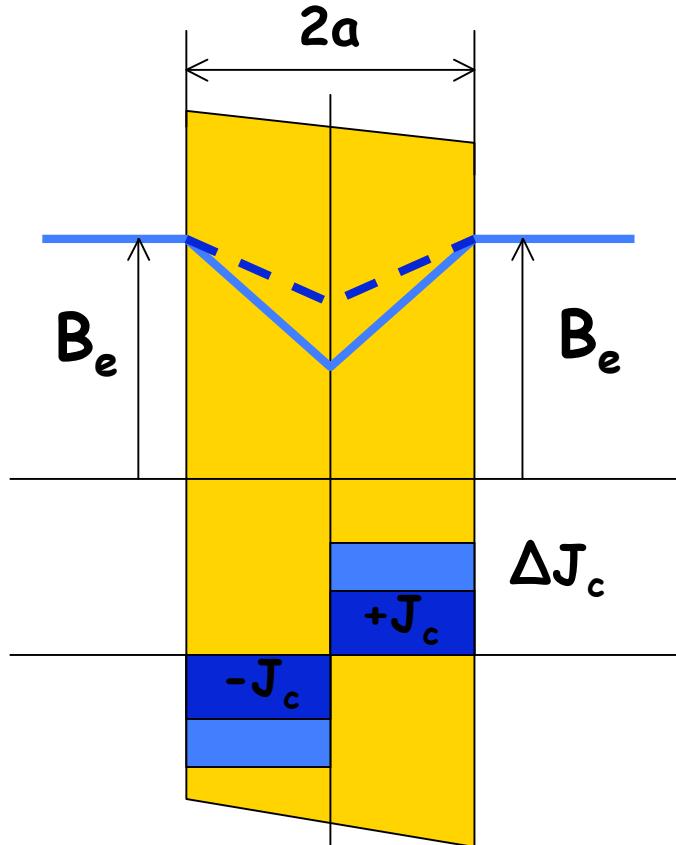
Energy dissipated by ΔJ_c :

$$Q_{total} = \mu_o J_c \Delta J_c \frac{a^2}{3} 2a L_y L_z v_{slab}$$

$$Q_{total} = \mu_o J_c \Delta J_c \frac{a^2}{3} v_{slab}$$

Flux jump

Slab in fully penetration

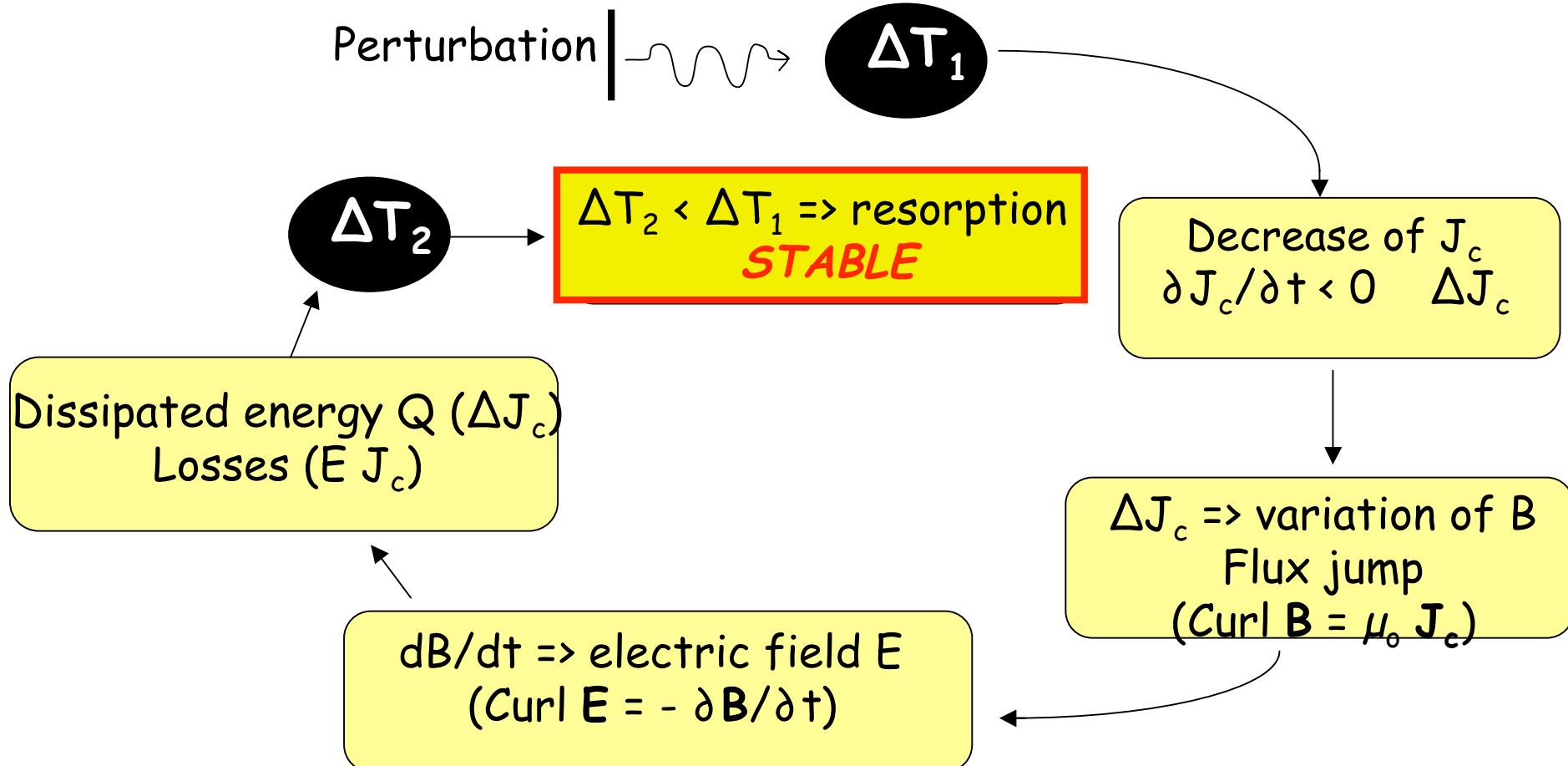


Energy dissipated by ΔJ_c :

$$Q_{total} = \mu_o J_c \Delta J_c \frac{a^2}{3} v_{slab}$$

$$Q_{total} = \mu_o J_c \left(\frac{\partial J_c}{\partial T} \right) \Delta T \frac{a^2}{3} v_{slab}$$

Flux jump



Flux jump

$$\Delta T_1 \quad ==> \quad Q_{total} = \mu_o J_c \left| \frac{\partial J_c}{\partial T} \right| \Delta T_1 \frac{a^2}{3} v_{slab}$$

Worst conditions : adiabatic conditions,
energy absorbed only by the SC

Temperature rise of the SC: $\Delta T_2 = \frac{Q_{total}}{c_p v_{slab}} = \mu_o J_c \left| \frac{\partial J_c}{\partial T} \right| \Delta T_1 \frac{a^2}{3 c_p}$

Stability condition: $\Delta T_2 < \Delta T_1$

$$a < \sqrt{\frac{3 c_p}{\mu_o J_c \left| \frac{\partial J_c}{\partial T} \right|}}$$

=> Limited size for stability $<=$

Flux jump - adiabatic criterion

Max diameter for stable flux jump:

$$\emptyset_f < \frac{\pi}{2} \sqrt{\frac{c_p}{\mu_o J_c \left| \frac{\partial J_c}{\partial T} \right|}}$$

Adiabatic criterion

$$J_c(T, B) \approx J_c(T_o, B) \frac{T_c(B) - T}{T_c(B) - T_o}$$

$$\emptyset_f < \frac{\pi}{2} \sqrt{\frac{c_p (T_c(B) - T_o)}{\mu_o J_c^2(T_o, B)}}$$

Flux jump

Max diameter for stable flux jump:

$$\emptyset_f < \frac{\pi}{2} \sqrt{\frac{c_p (T_c(B) - T_o)}{\mu_o J_c^2(T_o, B)}}$$

$$c_p = 5000 \text{ J/m}^3/\text{K}$$

$$\text{NbTi} \quad J_c(4.2 \text{ K}; 5 \text{ T}) = 3000 \text{ MA/m}^2$$

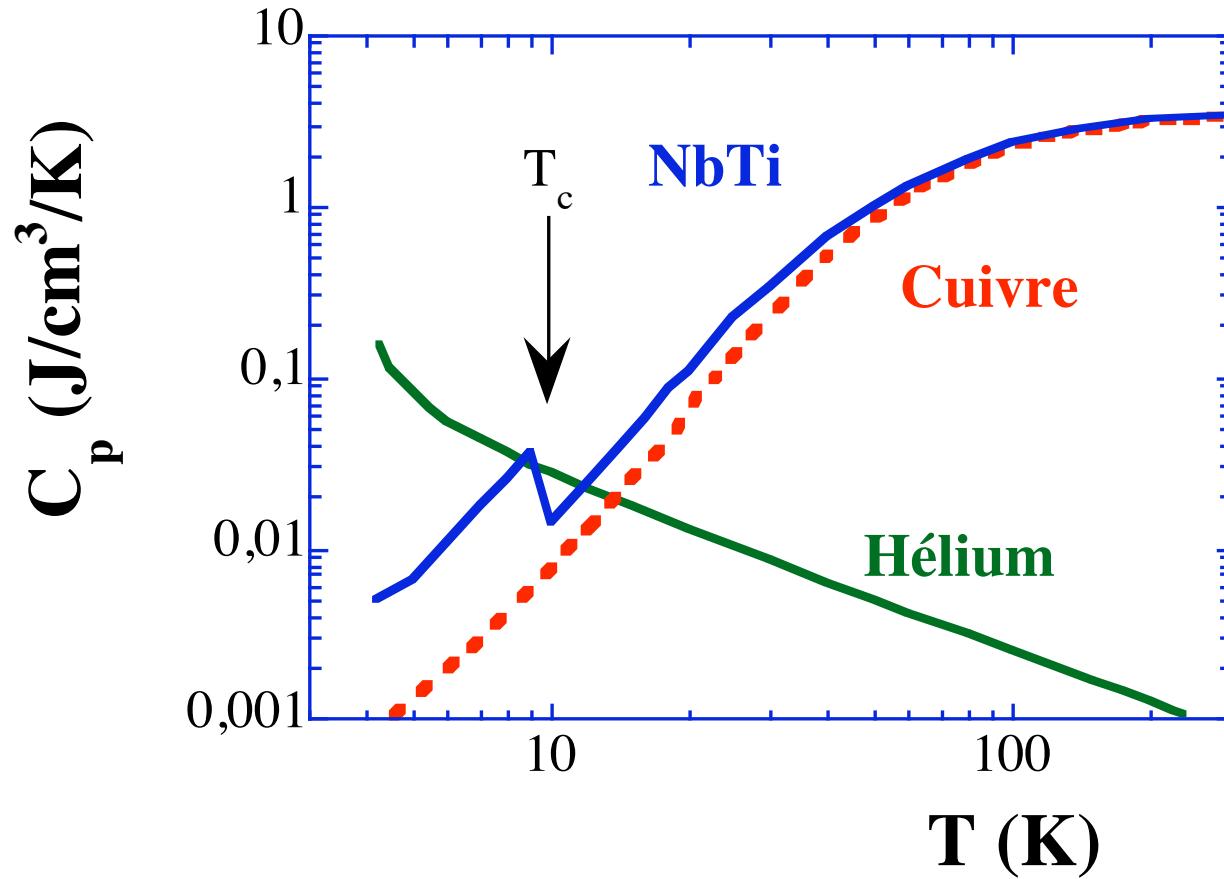
$$T_c(5 \text{ T}) = 8 \text{ K}$$

$$a < 64 \mu\text{m}$$

Experience shows that this value is pessimistic

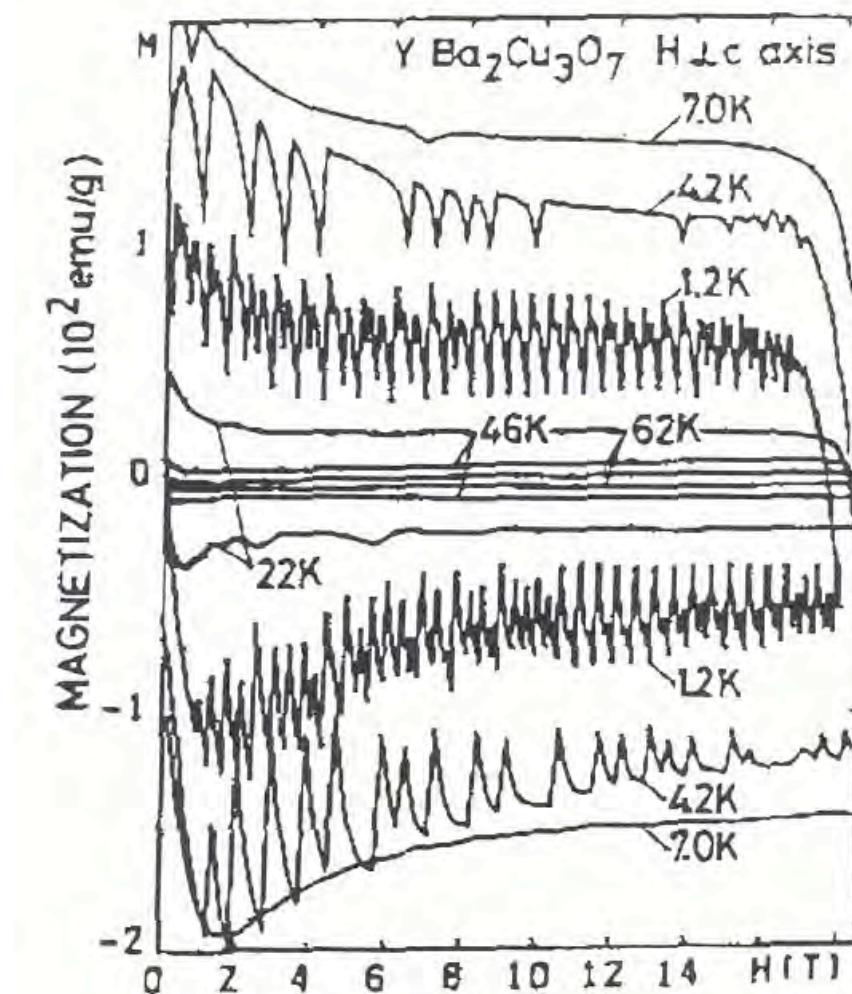
SC must be subdivised into μm size filaments
Between the filaments: Cu
Stability, protection

Temperature effect



Flux jump

Magnetization
experimental
curves



J.L. Tholence et al.
Solid State Com.,
Vol. 65, 1988

Mimimum propagation zone

Conclusion 1 (MPZ):

To embed the superconductor in a good thermal and electrical conductor (Cu)

Conclusion 2 (Flux jump):

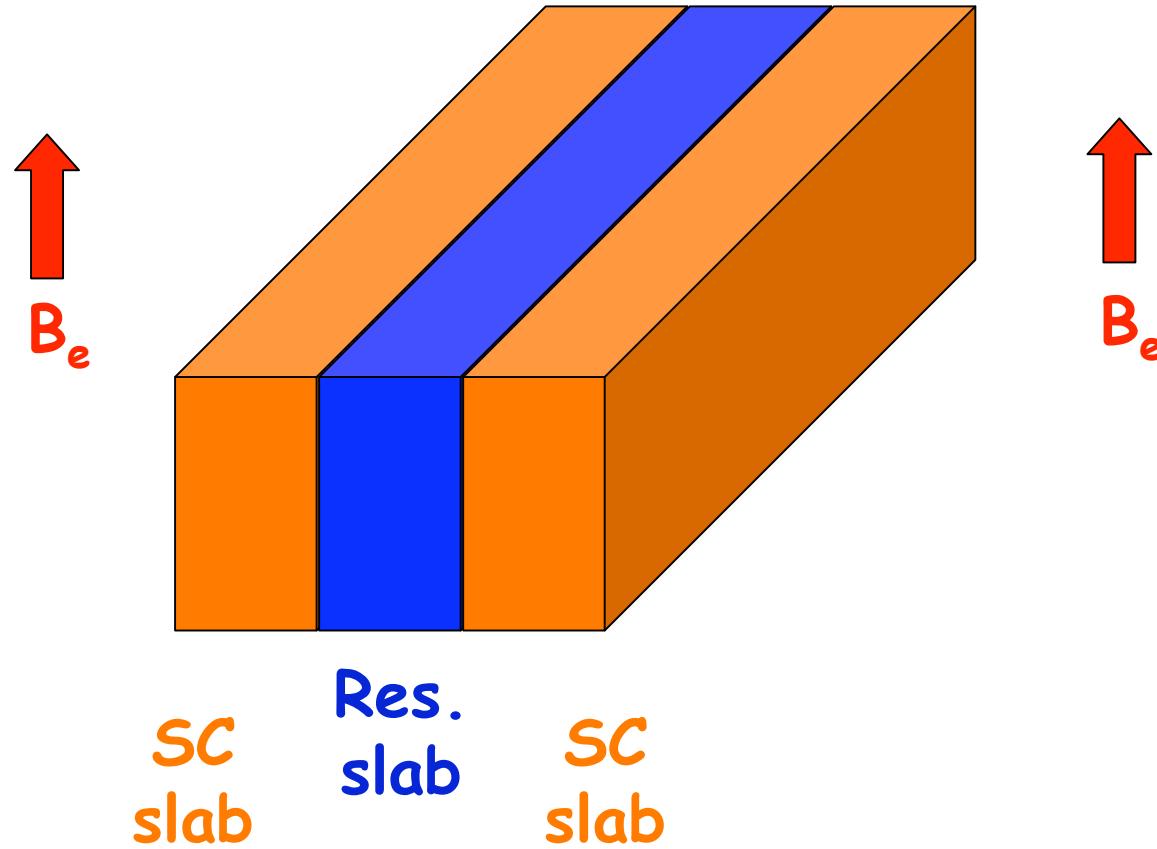
To subdivide the superconductor in μm size filaments

Filaments in a good thermal and electrical conducting matrix

Problem

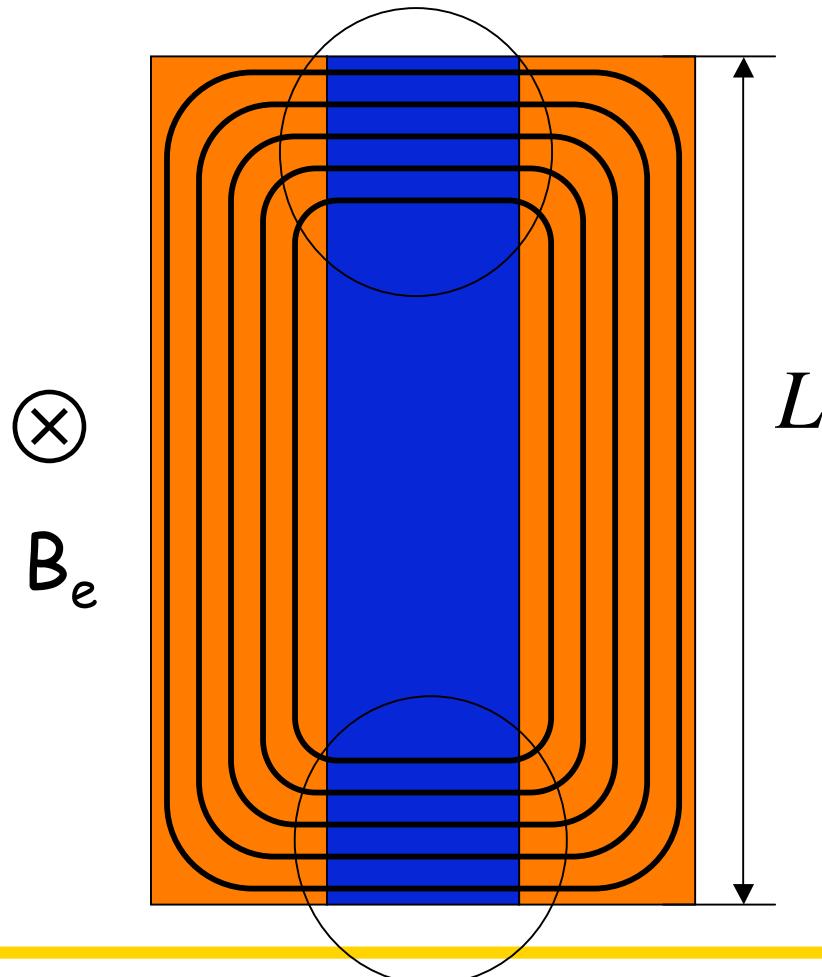
Electromagnetic coupling of the
filaments by the resistive matrix

Coupling



Coupling

Resistive areas : damping



Time constant of the damping currents:

$$\tau \propto \frac{1}{12} \mu_0 \frac{L^2}{\rho_t} \quad \text{Diffusion} \\ (\alpha_{\text{mag}} = \rho/\mu_0)$$

ρ_t : transverse matrix resistivity

A.N. : $L = 100 \text{ m}$, $\rho_t = 0.2 \text{ n}\Omega\text{m}$

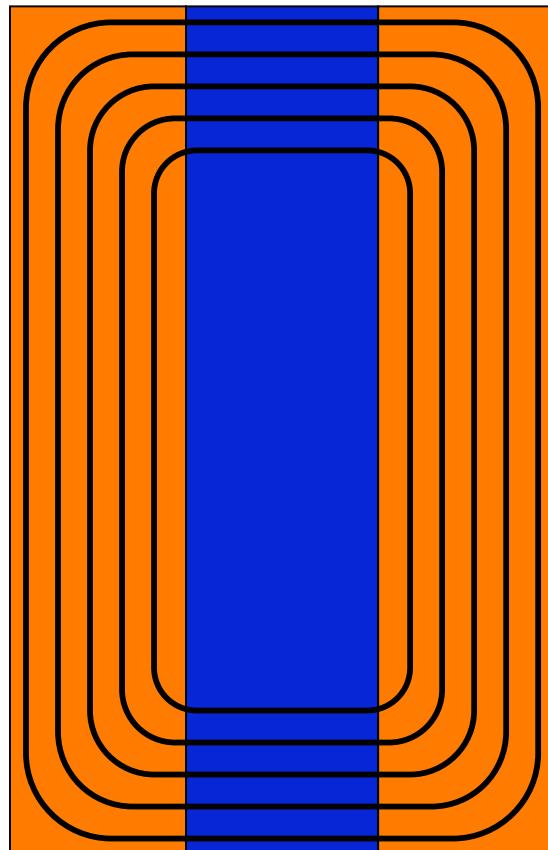
$\tau = 52 \cdot 10^6 \text{ s}$ (60 days)

+ other limit: L_c

Coupling

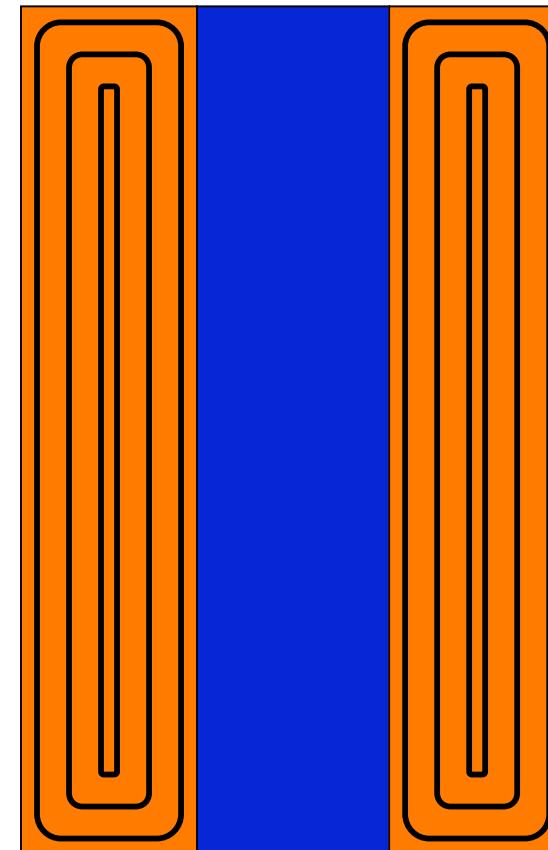
⊗

B_e



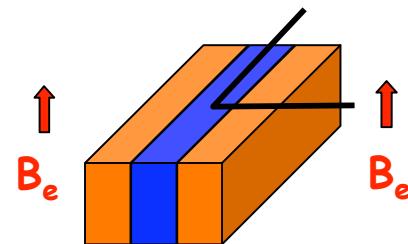
« Coupled » slabs

$$t \gg \tau$$

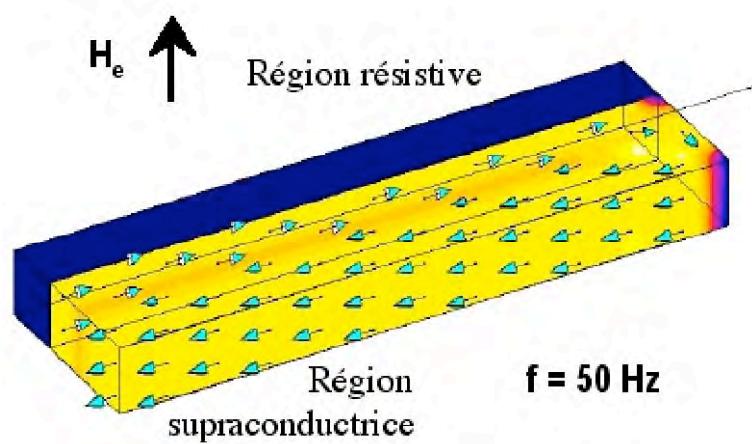


« Uncoupled » slabs

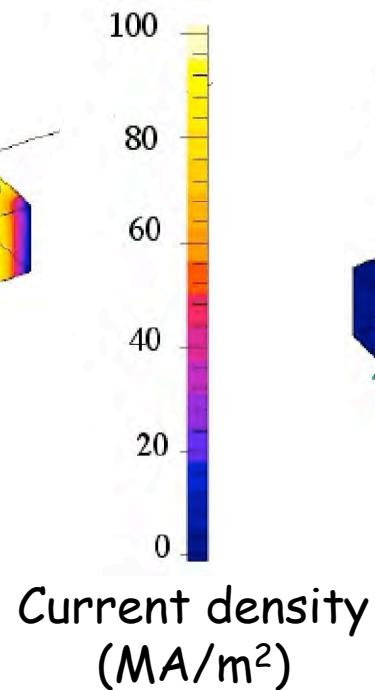
Coupling



$$B_e = B_{\max} \sin(2\pi f) t$$



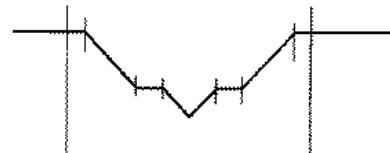
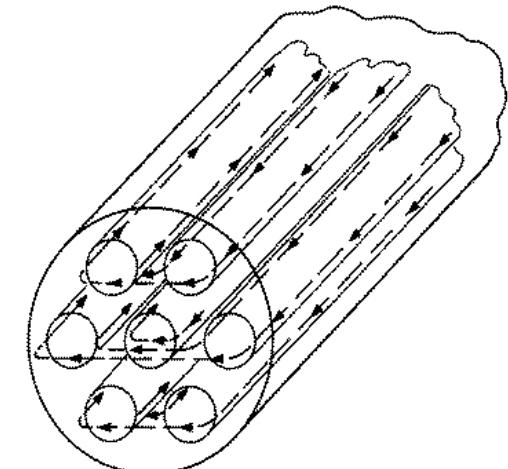
$$\frac{1}{f} \gg \frac{1}{12} \mu_o \frac{L^2}{\rho_t}$$



$$\frac{1}{f} \ll \frac{1}{12} \mu_o \frac{L^2}{\rho_t}$$

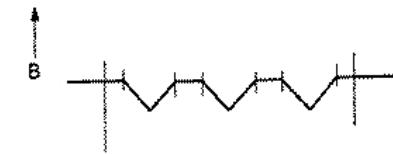
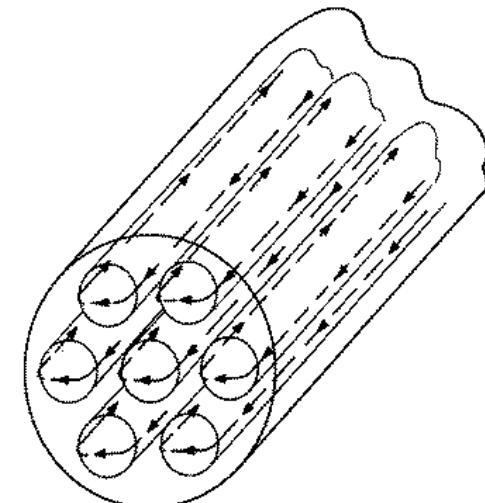
Coupling - decoupling filaments

Same phenomena for filaments



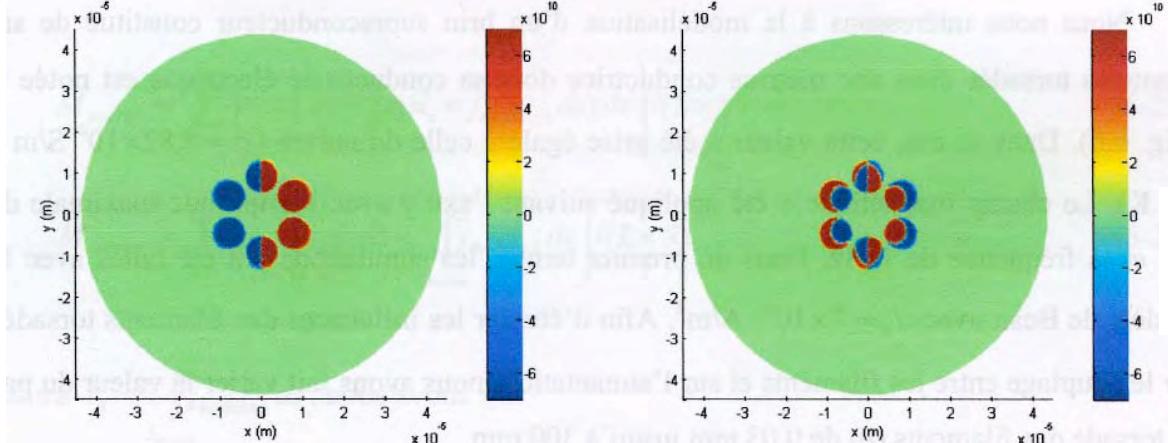
« Coupled » filaments, behave
as a single « big » filament
Unstable flux jump

M. N. Wilson
« SC magnets »

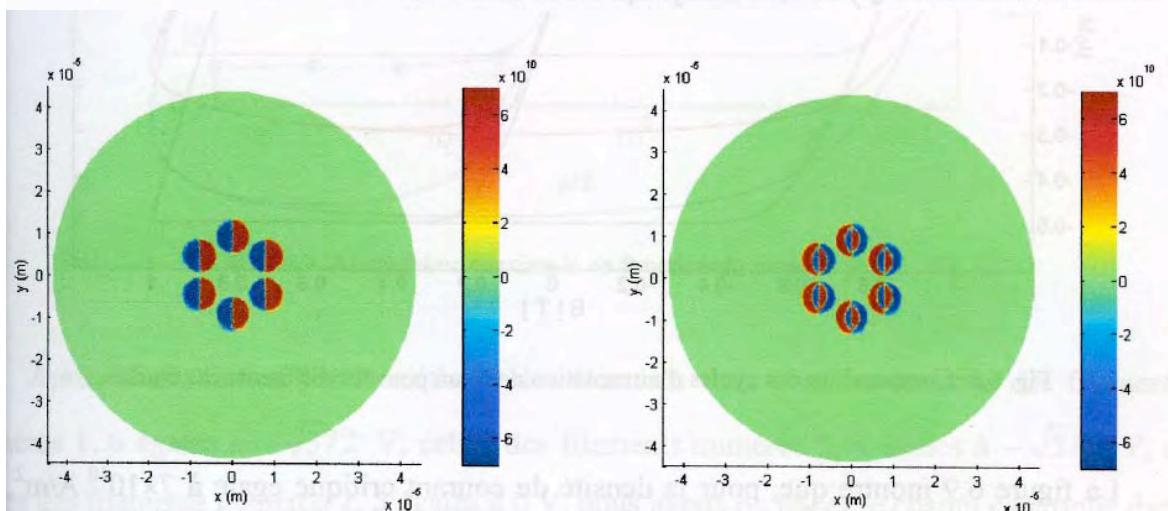


« Decoupled » filaments,
behave as independant
filaments
Stable flux jump

Coupling - decoupling filaments



Coupled filaments
(twist pitch = 300 mm)

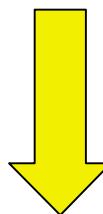


Decoupled filaments
(twist pitch = 0.03 mm)

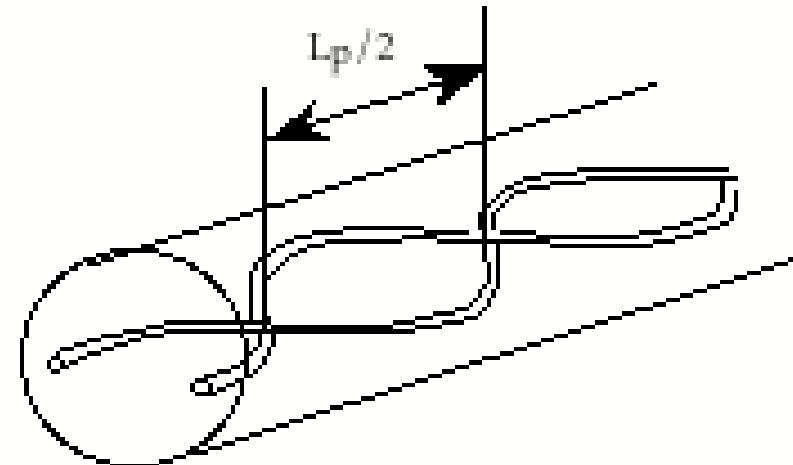
To avoid coupling: twisting

Filament decoupling to
avoid flux jump:

$$\tau \propto \frac{1}{12} \mu_o \frac{L^2}{\rho_t} \quad Low$$



Filament twisting

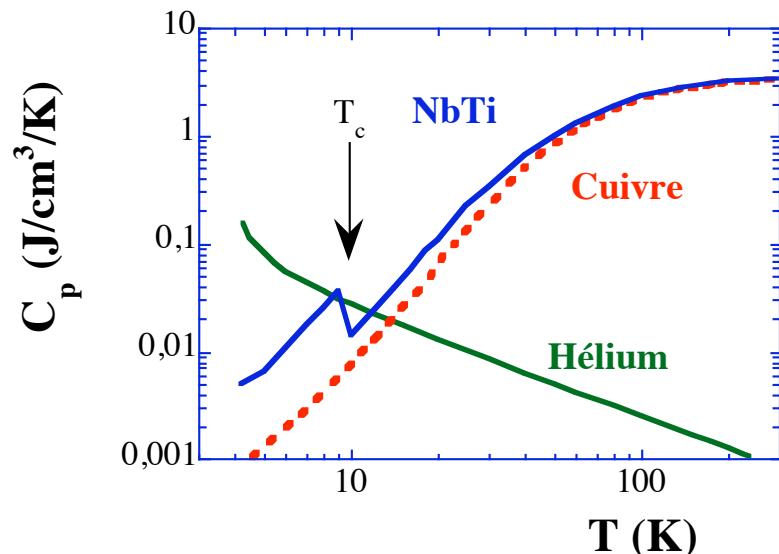


L_p : twist pitch

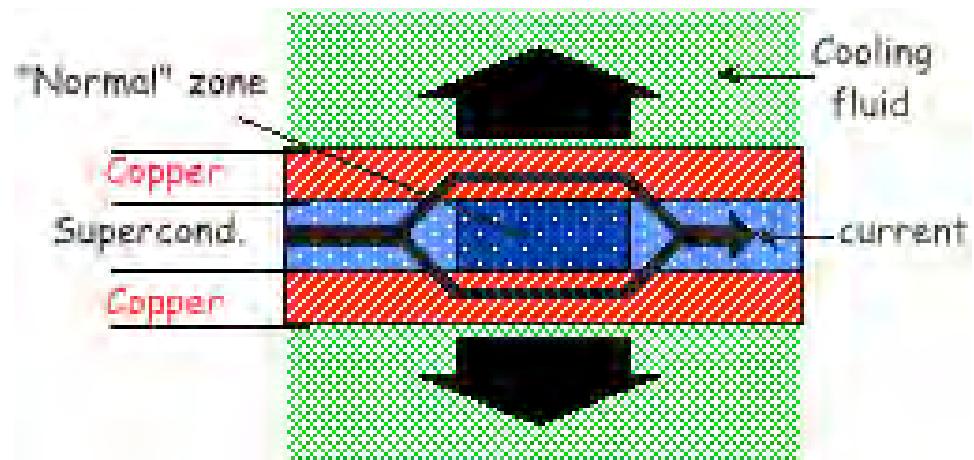
Limit for L_p : filament breaking ($L_p > 5 \varnothing_{brin}$)

Cryostabilization

The exchanges with the coolant have been neglected
(adiabatic conditions)
Coolant: important and favorable part



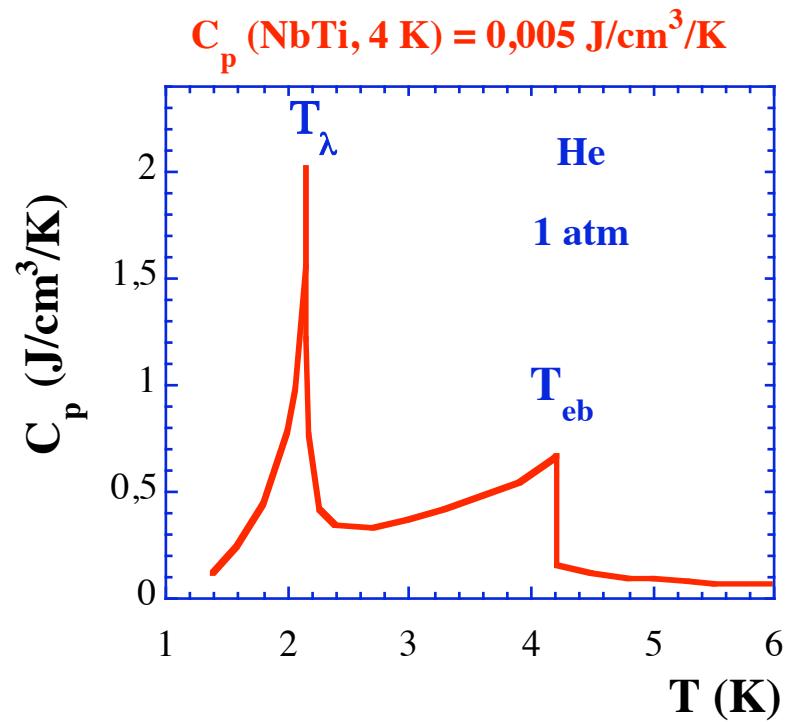
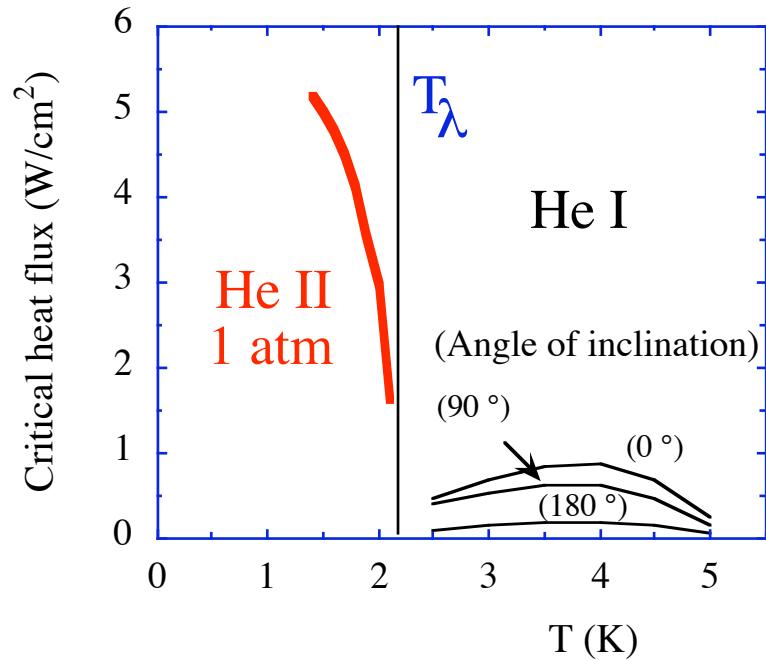
He : enthalpy tank



$$R I^2 < W_\lambda S_{\text{exc}}$$

Stekly cond.

Exchanges with He

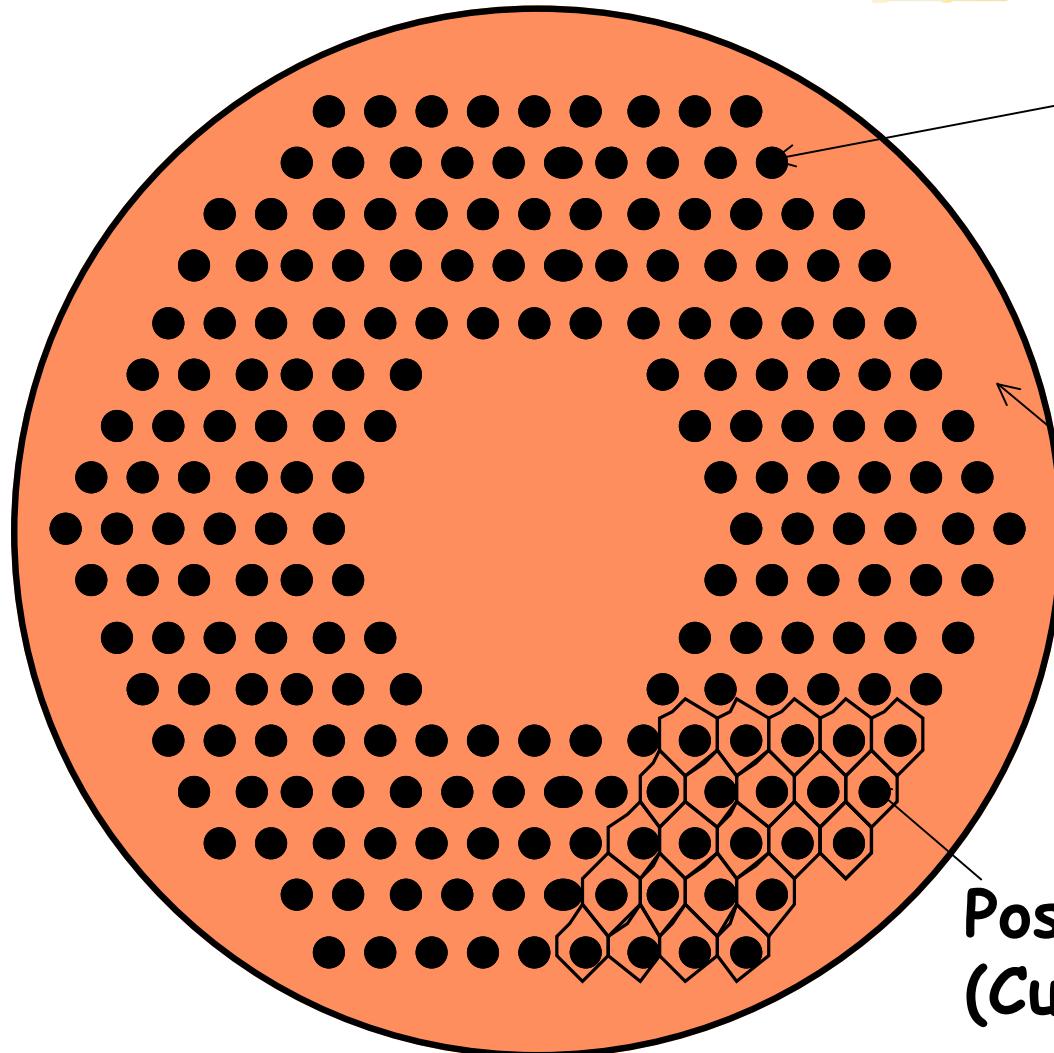


Conclusion : multifilament composite

Stabilization achieved by :

- SC embedded in a matrix with high electrical and thermal conductivity
 - Increases MPZ and limit temperature rise (quench)
- SC under the form of fine filaments
 - Avoid flux jump
- A very efficient cooling if possible (cryostabil.)
- An operation not to close the critical surf.
- Reduction of the perturbation on the SC
 - Very good mechanics and electromagnetic shields

Multifilament composite



Fine SC filaments
(tens of μm or lower)

Intrinsic stabilization

Stabilizing matrix (Cu)

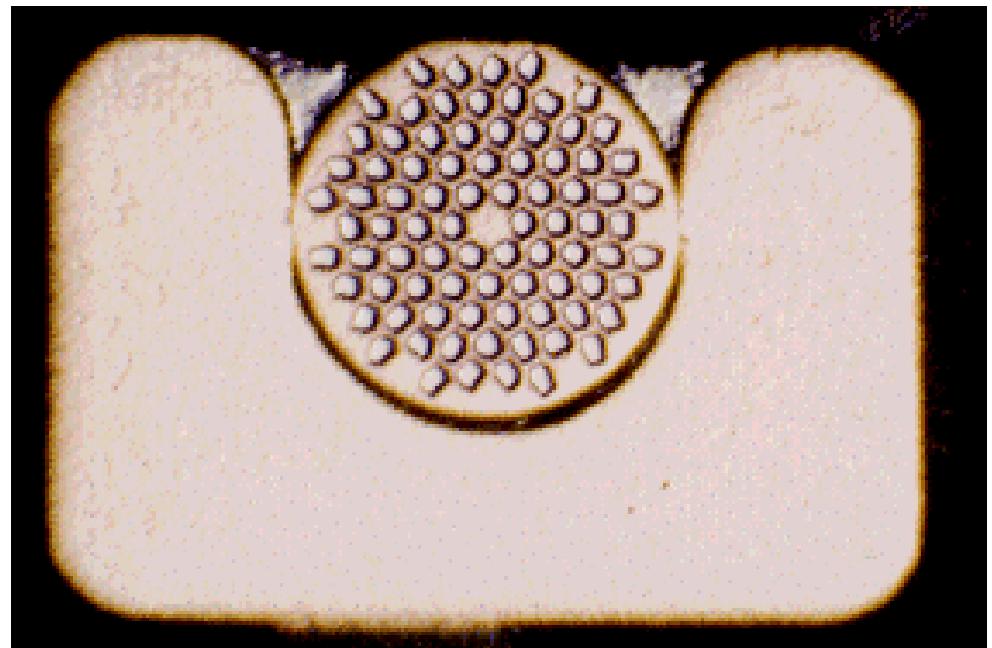
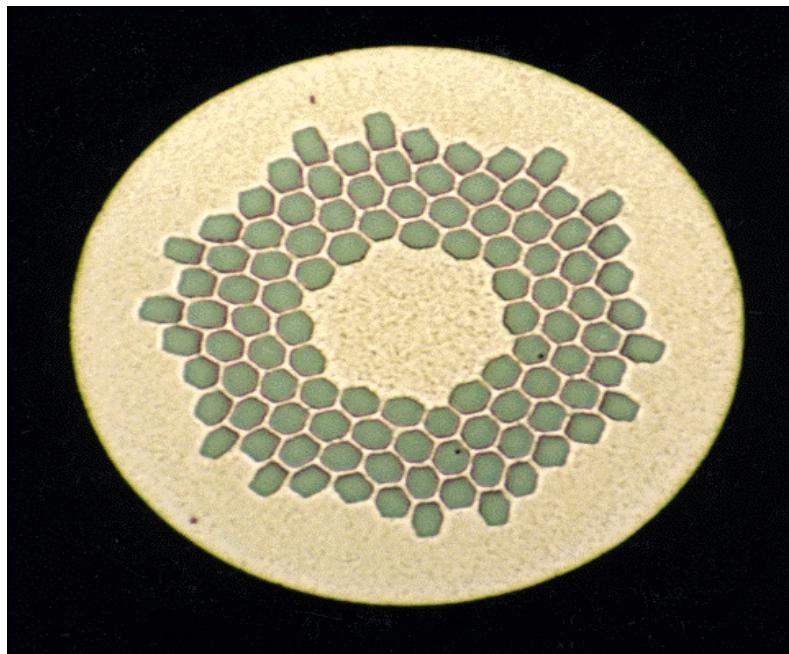
L_{MPZ}

Protection (quench)

Cooling and shielding

Possible resistive barriers
(CuNi) *AC loss reduction*

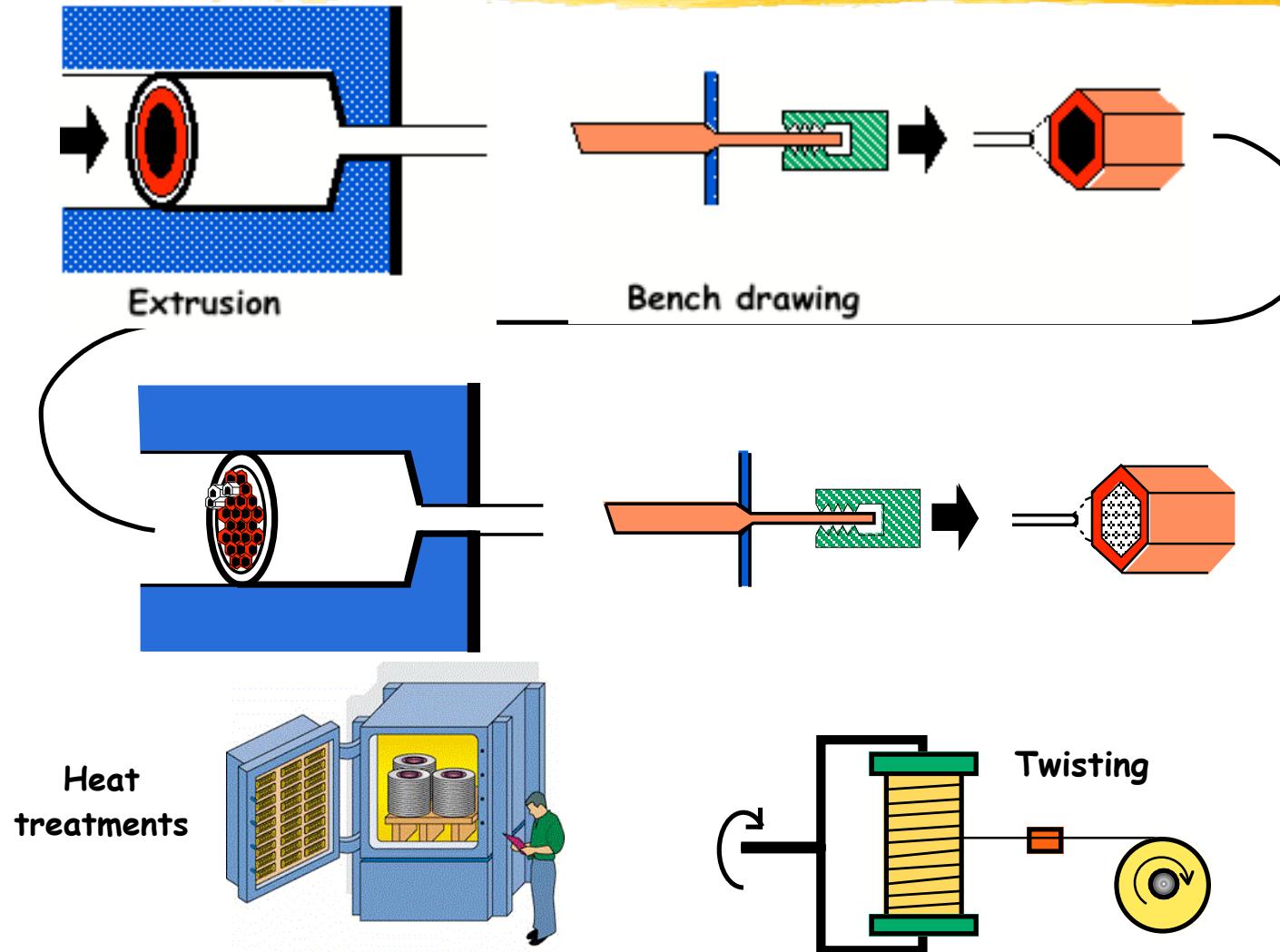
Multifilament composite - examples



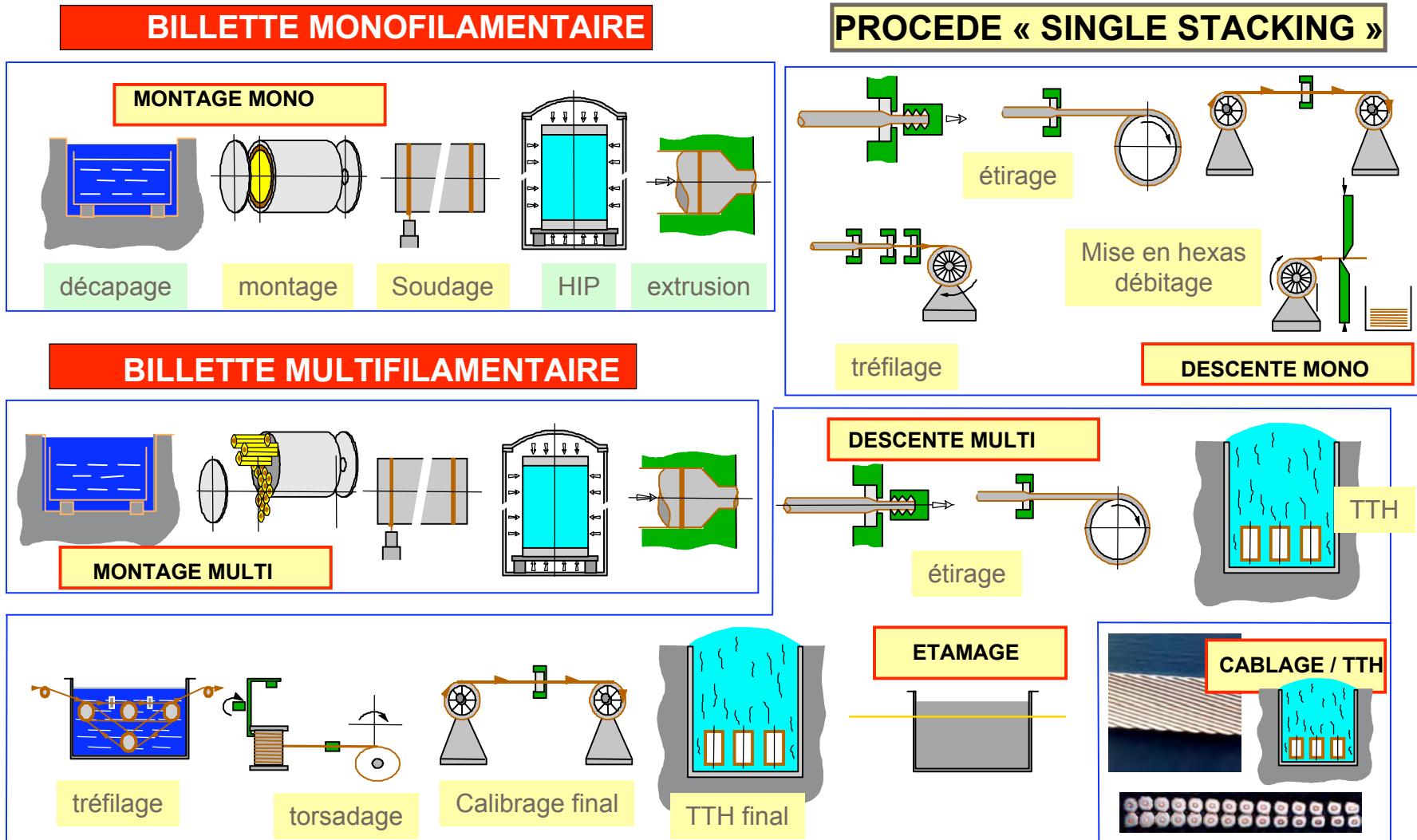
Multifilament composite - example



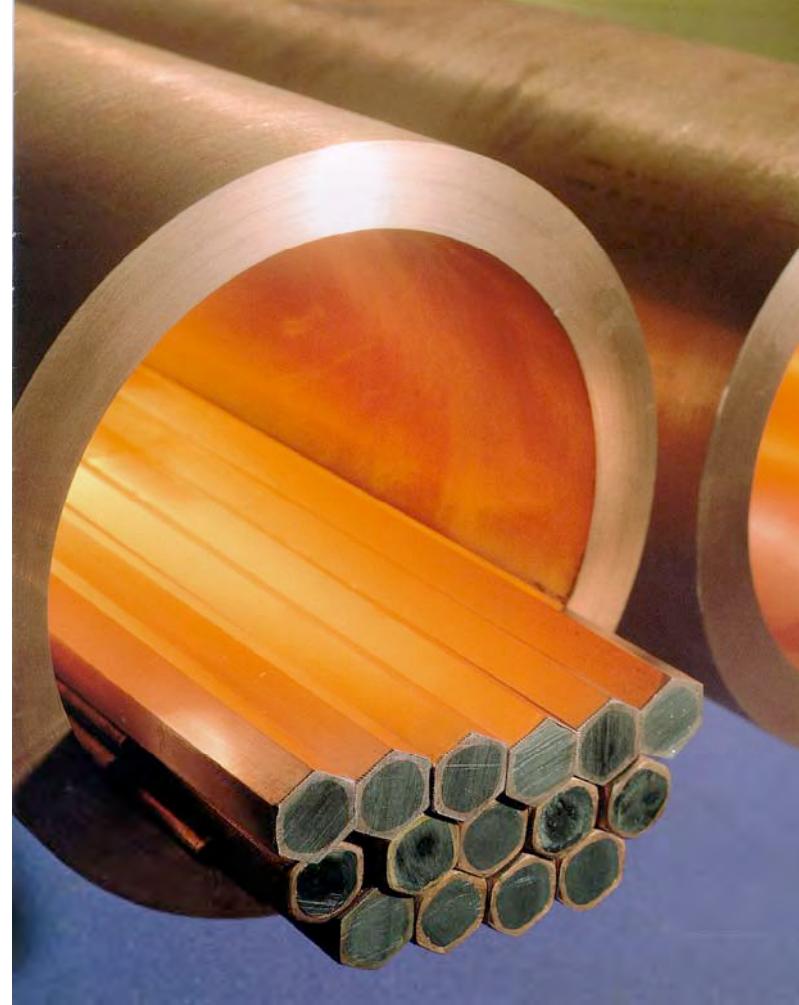
SC composite elaboration



Alstom MSA process

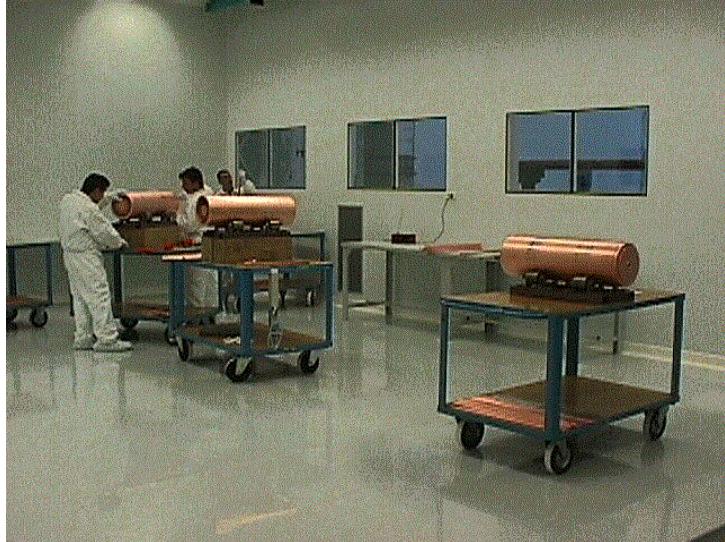


Billet



Furukawa Electric company

Billet



Photos Alstom

Drawing

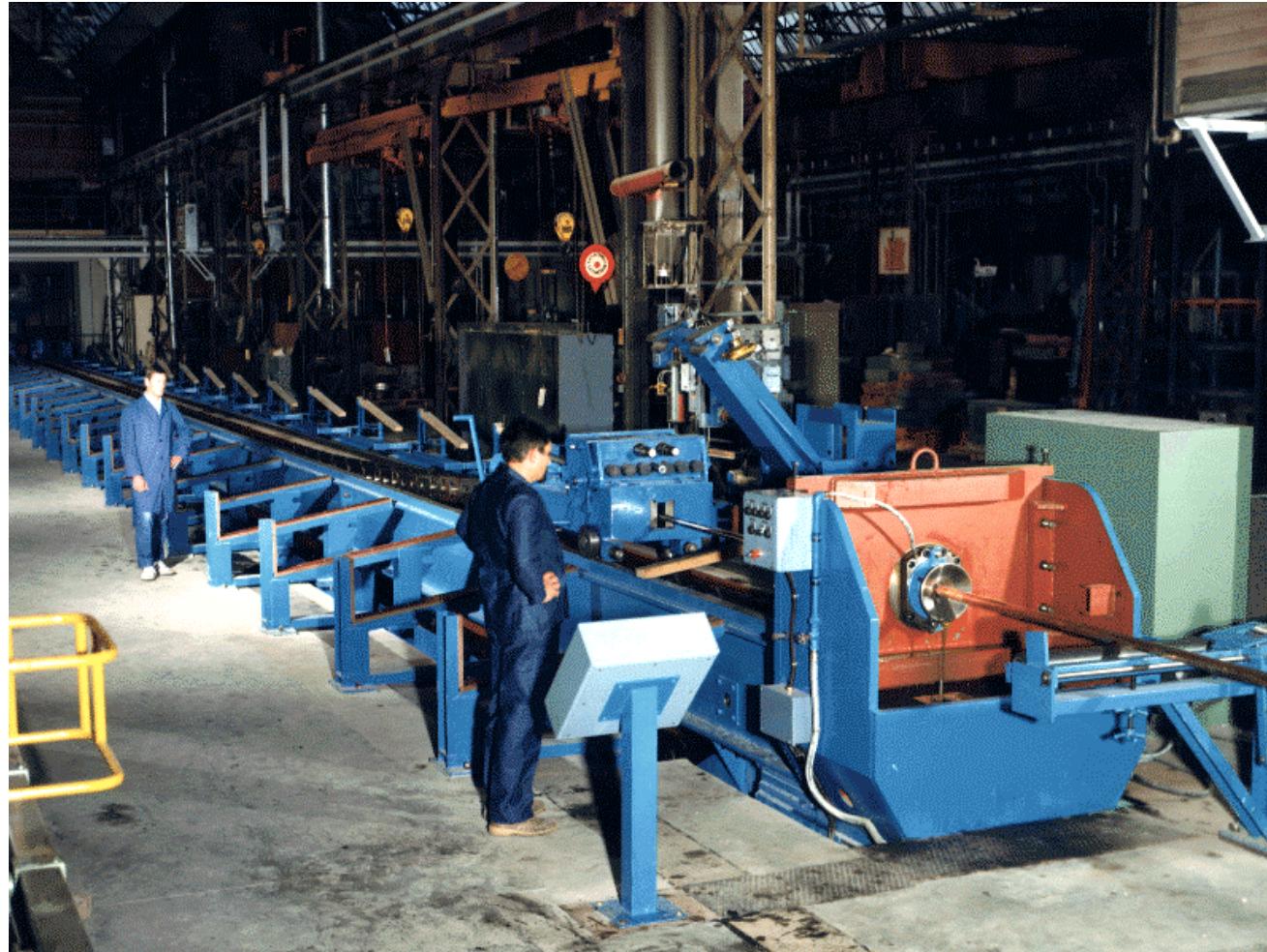


Photo Alstom

SC cables

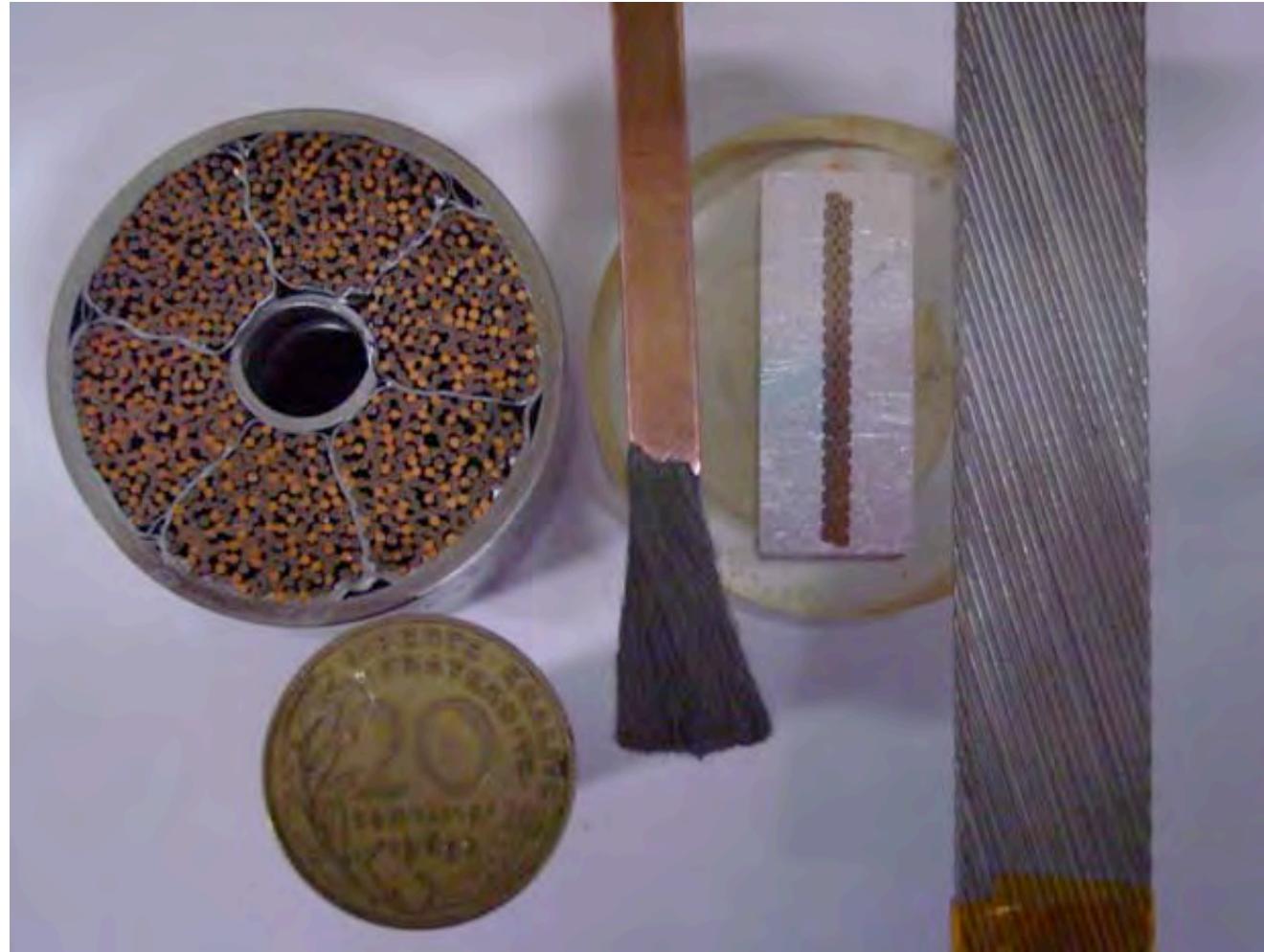
Strand current < 1000 A

\Rightarrow necessity for a multi strand cable

- Reduction on strand length ($1/N$)
- Current redistribution - higher stability
- Reduction of series turns (winding)
- Reduction of coil inductance

- High currents (10 -200 kA)
 - Large current supply and current leads

SC cable examples



Rutherford cables

Used for particle accelerator magnet coils

Flat two layer, slightly
keystoned cable with a
few tens of strands,
twisted together.



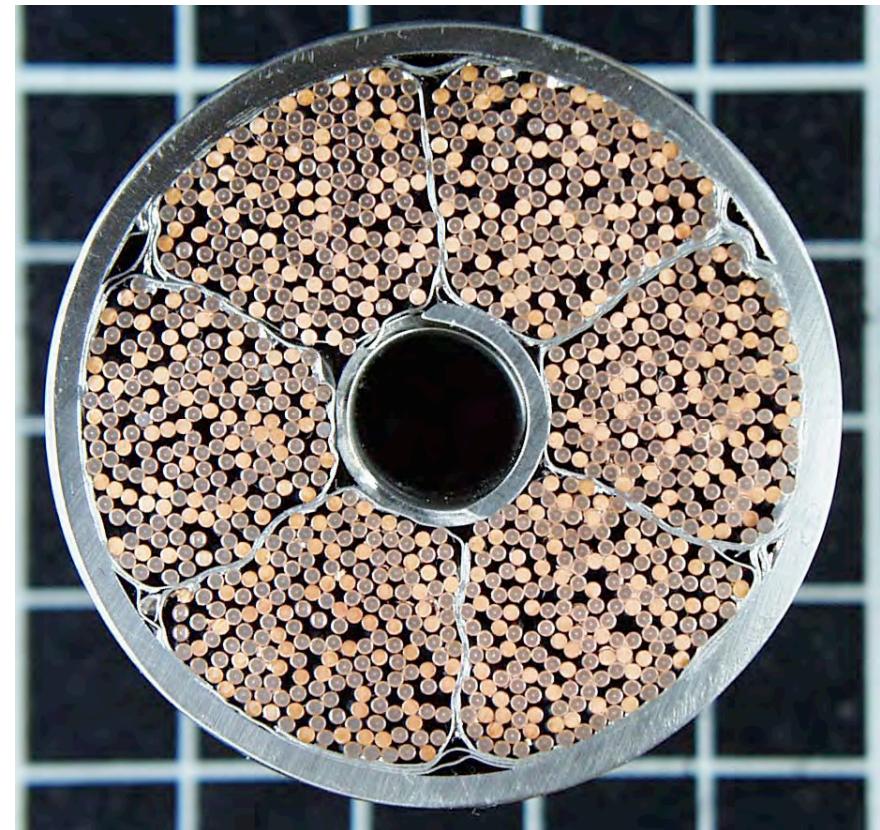
Cables in conduct (CICC)

Very high current cables used for fusion magnets

Cryostable cables

A large number of twisted SC strands inside a metallic jacket where helium flows.

Large capacity to accept losses

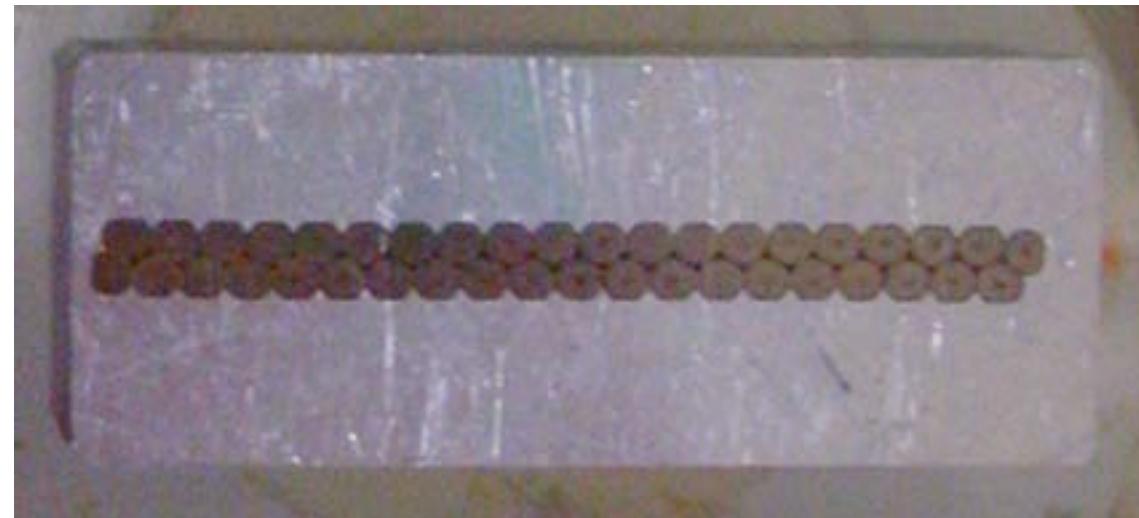


Nb_3Sn CICC

Cable embedded in Aluminum

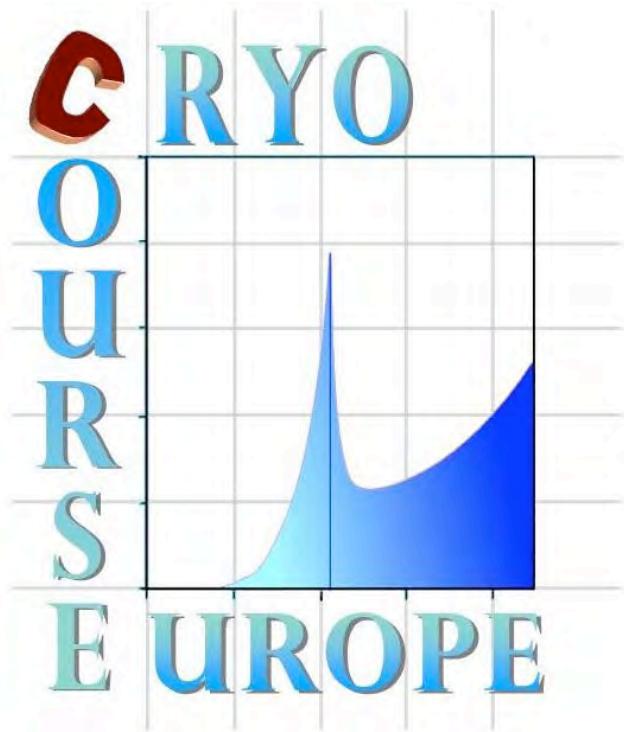
Cables for indirect cooling magnets
(detector magnets)

Large Al section for stabilization



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Applied
superconductivity

IV. AC losses

Losses in SC (under critical surface)

Depend on electromagnetic environment
(magnetic field or current)

- Time constant electromagnetic environment
 - No or very little losses
-  HTS with low "n" value : resistive losses under I_c
- Time varying electromagnetic environment
 - Losses, AC losses

AC losses

$$\text{Curl } \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t}$$

Maxwell-Faraday law

Time varying electromagnetic environment

B: external field or self field

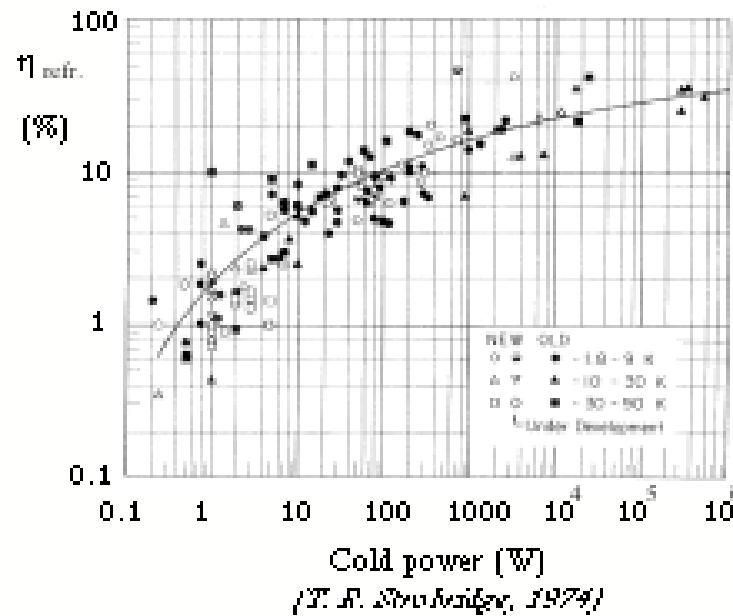
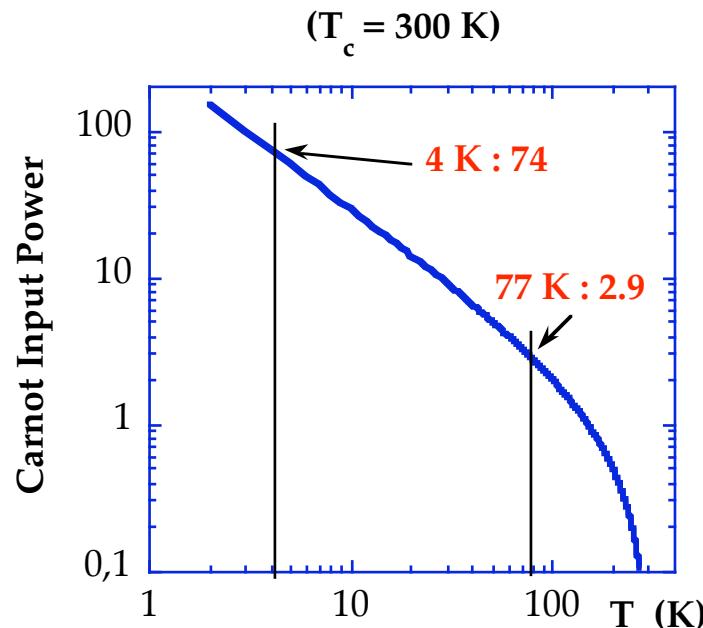
=> Electric field

=> Losses $E J_c$ - AC losses

AC loss consequences (1/2)

- SC operation
- Energetic cost

$$\frac{W_{\min}}{Q_f} = \frac{1}{\eta_f} \frac{T_o - T_c}{T_c}$$



AC loss consequences (2/2)

Investment cryocooler cost

	Running cost	Investment cost
Now	15-20 % carnot 18-24 W/W	100 - 200 \$/W
Objective	> 30 % carnot < 12 W/W	< 25 \$/W

65 K cryocooler costs

Self field losses 1/2

Self field: field created by the transport current

The conductor being alone or with little other conductors

Cable, single layer windings ...

One expression: Norris formula

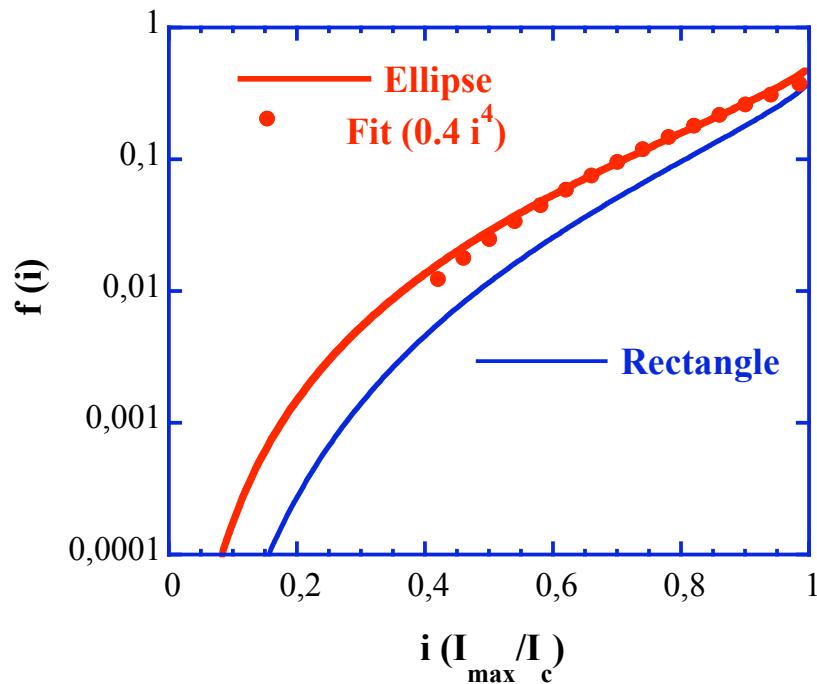
$$P_{\ell}^{cp} = \frac{\mu_o f I_c^2}{\pi} f(i) \quad [W/m] \quad \left(i = \frac{I_{\max}}{I_c} \right)$$

$$f(i) = (1-i) \ln(1-i) + (2-i) \frac{i}{2} \quad \text{Elliptical section}$$

$$f(i) = (1-i) \ln(1-i) + (1+i) \ln(1+i) - i^2 \quad \text{Rectangular section}$$

Self field losses 2/2

$$P_{\ell}^{cp} = \frac{\mu_0 f I_c^2}{\pi} f(i) \quad [W/m] \quad \left(i = \frac{I_{\max}}{I_c} \right)$$

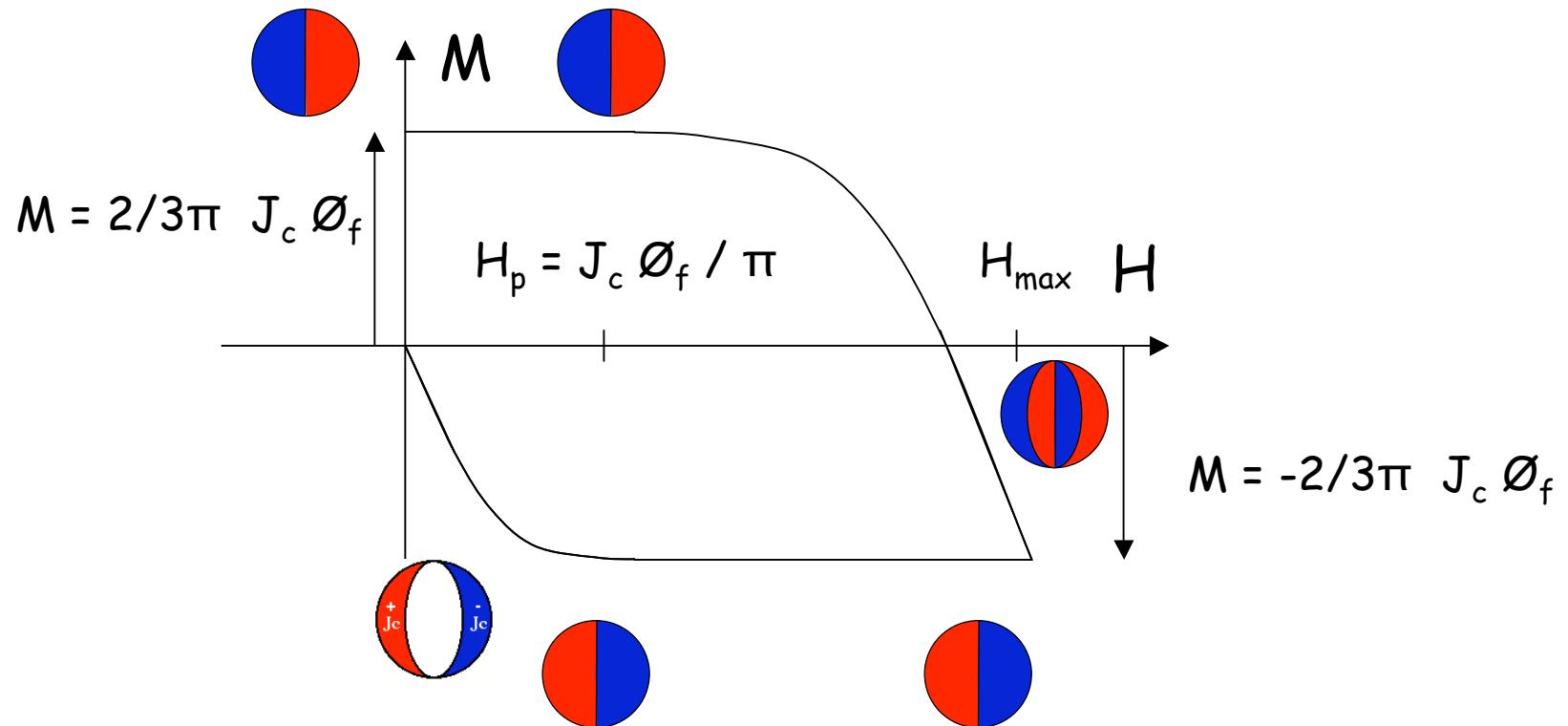
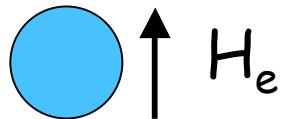


Reduction of self field losses:

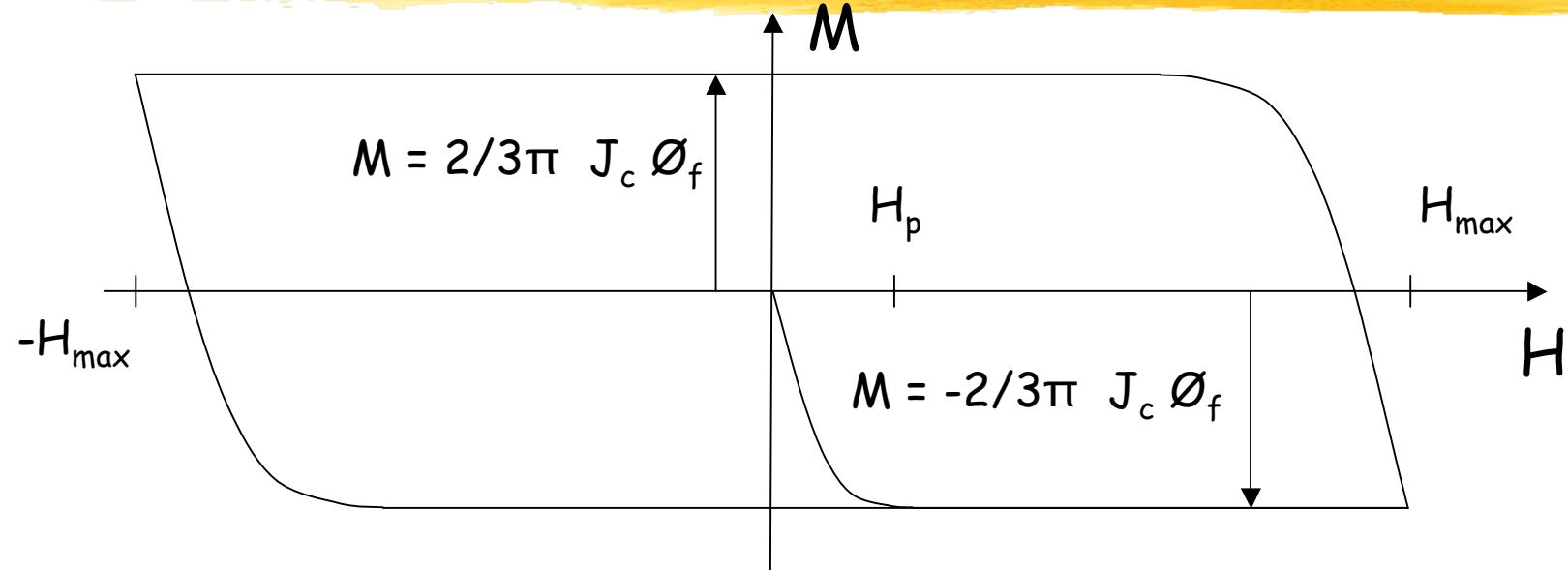
- Reduced conductor section
- Low operating factor

Hysteresis losses

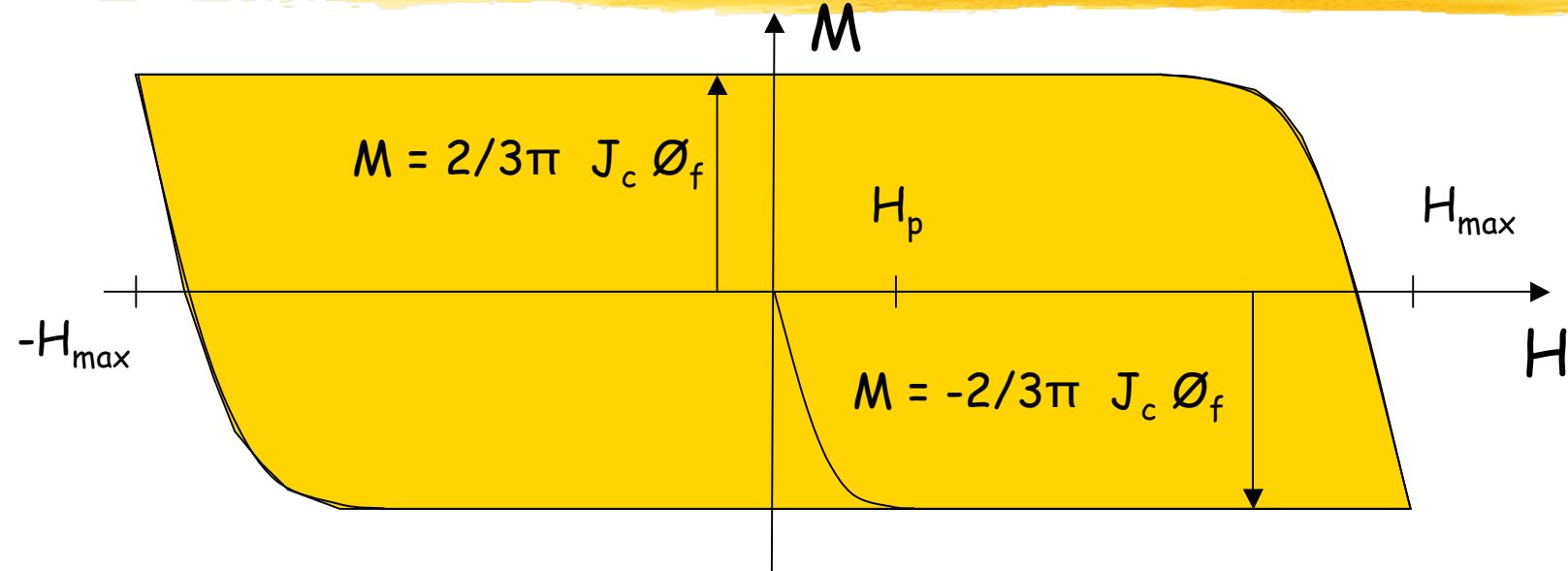
Losses in superconducting twisted filaments



Hysteresis losses

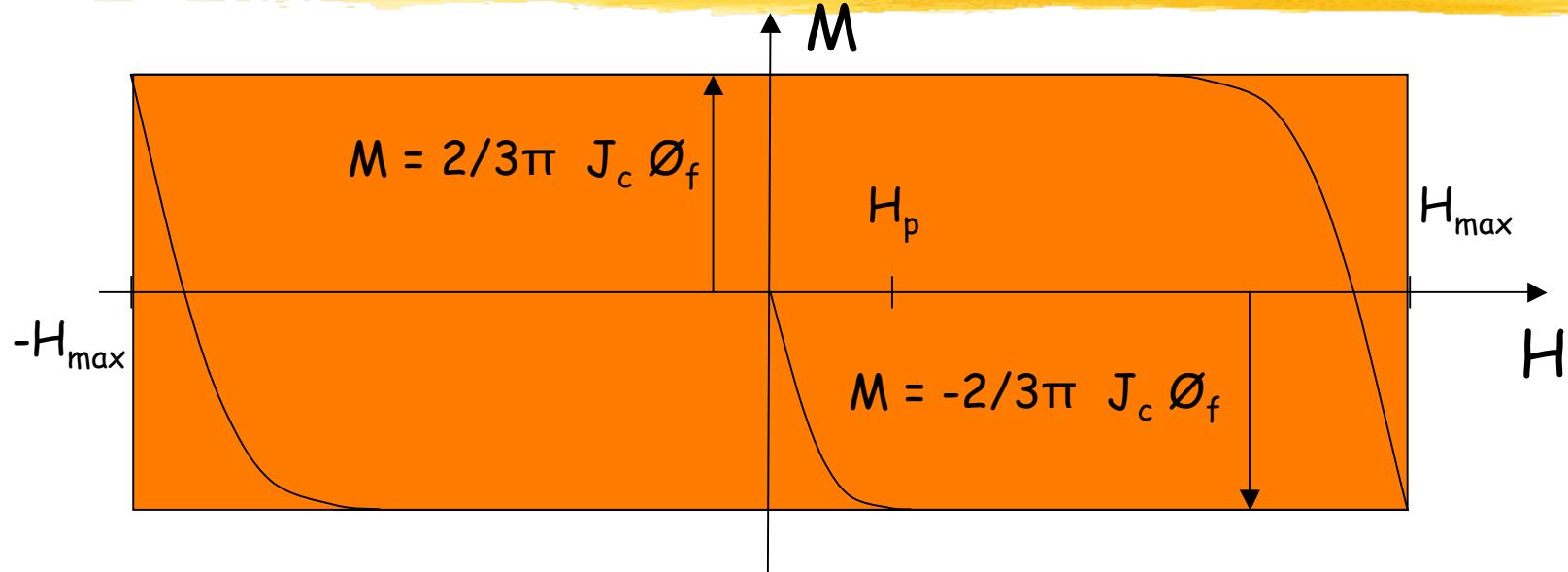


Hysteresis losses



Dissipated energy : **cycle area** $W_h = \oint \mu_o M dH$ $[J/m^3]$

Hysteresis losses

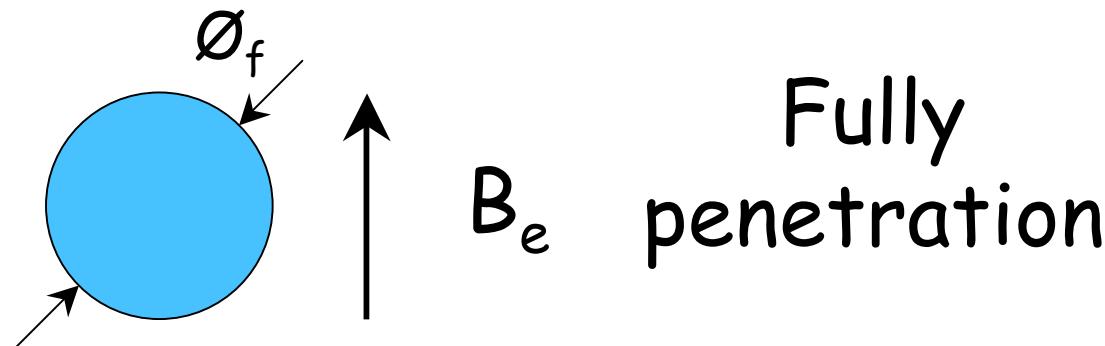


Dissipated energy : **cycle area** $W_h = \oint \mu_o M dH \quad [J/m^3]$

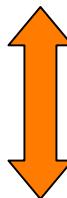
$$W \approx \mu_0 2 H_{max} \times 2 M_r = \mu_0 8/3\pi H_{max} J_c \emptyset_f$$

$$W_h = \frac{8}{3\pi} J_c \emptyset_f B_{max} \quad [J/m^3] \quad P_h = f W_h = \frac{8}{3\pi} J_c \emptyset_f f B_{max} \quad [W/m^3]$$

Hysteresis losses



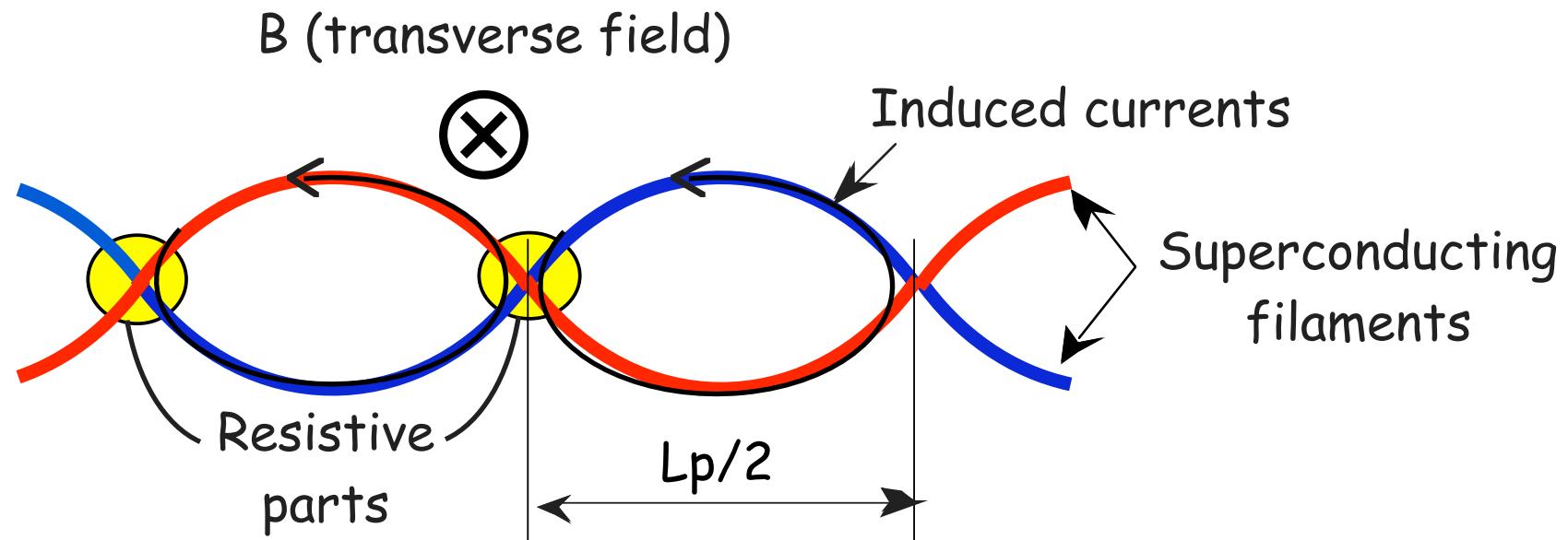
$$W_h = \frac{8}{3\pi} J_c \emptyset_f B_{\max} \quad [J/m^3]$$



$$P_h = f W_h = \frac{8}{3\pi} J_c \emptyset_f f B_{\max} \quad [W/m^3]$$

Coupling losses (1/2)

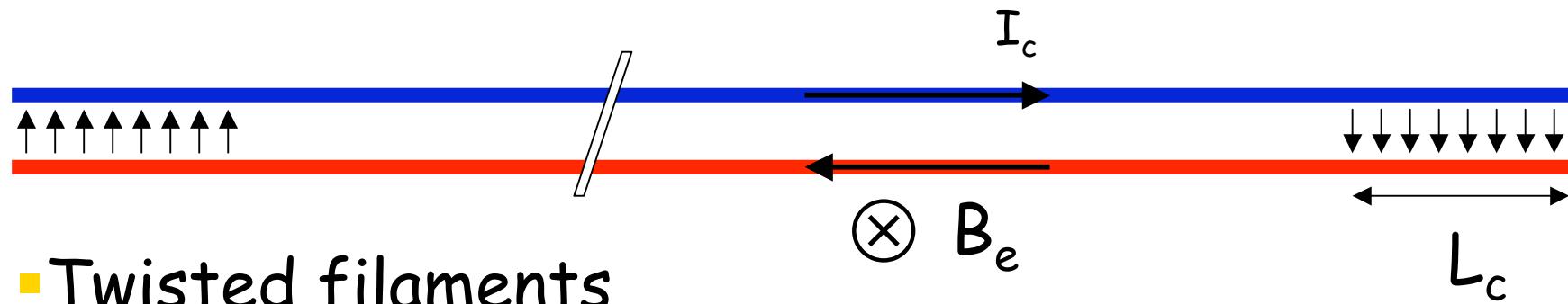
Losses in the matrix by coupling current induced between SC filaments



$$P_{cc} \propto L_p^2 \ (dB/dt)^2 / \rho_t$$

Coupling losses 2/2

- Non twisted filaments
 - Little coupling losses
 - low resistivity favourable



- Twisted filaments
 - High coupling losses
 - high resistivity favourable

Hysteresis loss reduction

Summary: AC loss reduction

- Self field losses
 - Conductor section reduction
 - Low operating factor
- Hysteresis losses (remanent field)
 - Transverse field reduction
 - Small SC twisted filaments
- Coupling current losses (if twisted)
 - High transverse resistivity matrix
 - Short twist pitch (strand Ø)

Conclusion: AC losses

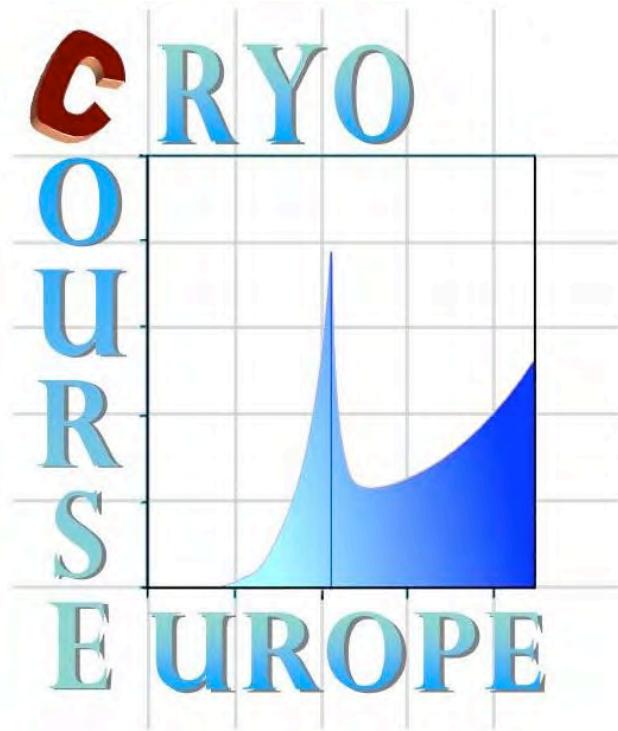
AC losses: an very important quantity

- o Thermal load for cryocooler
- o Interest itself of the SC device

- AC loss accurate calculation
 - Complex and hard task except in simple geometries
- Numerical computation
 - Useful tool but rapidly computing time problems

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Applied
superconductivity

V. Quench

Quench-transition: loss of SC state



A magnet is designed to avoid its quench
but it can always occur

■ Origins

- Mechanical perturbations
- Weak zone (strand, cable)
- Non equilibrated current distribution
- Rapid current variation (loading ...)
- Cooling fluid lack
- ...

Quench



- | To avoid quench
 - | Rigorous mechanical design
 - | Good cooling conditions: He_{II}, cryostabilization
 - | Important safety margins

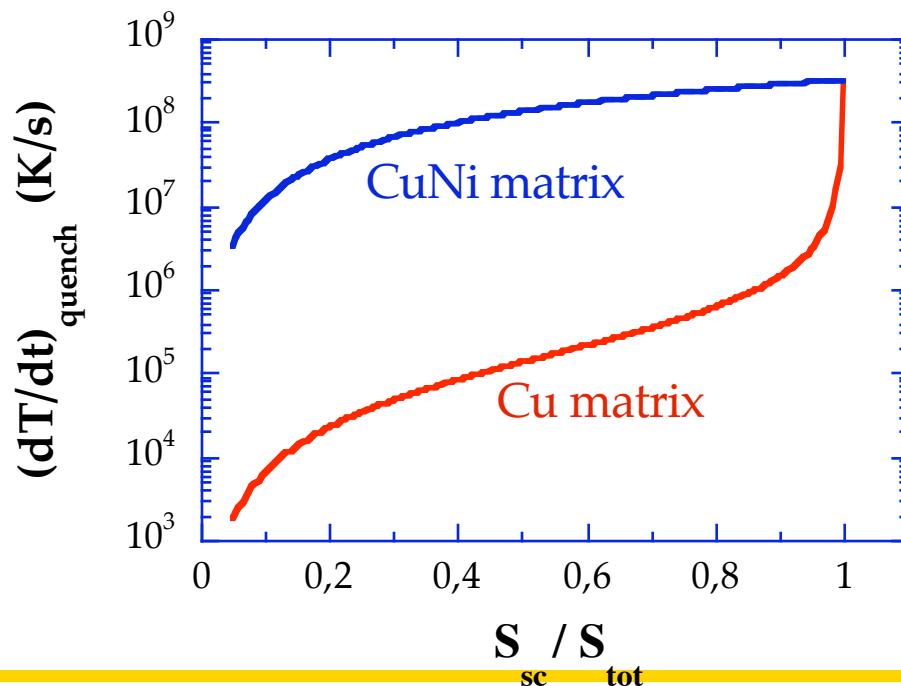
Quench

Equation in adiabatic conditions :

$$S \ell c_p \frac{dT}{dt} = R I^2 = \rho j^2 S \ell$$

$$\frac{dT}{dt} = \frac{\rho j^2}{c_p}$$

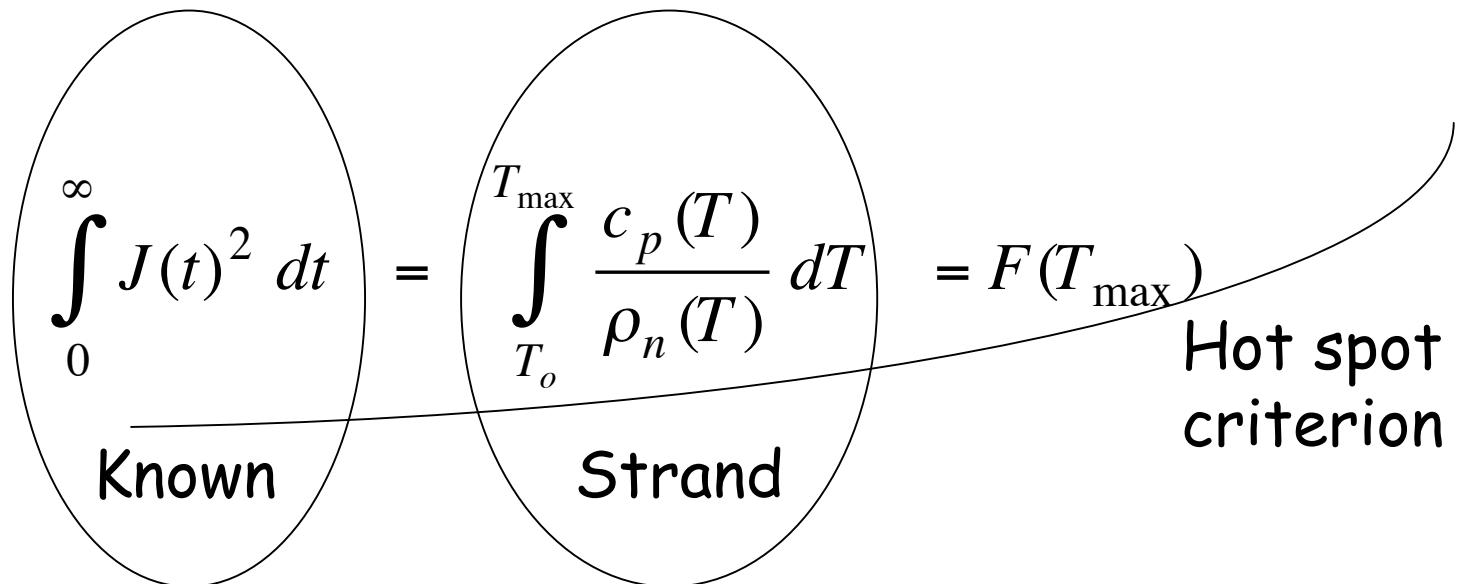
NbTi @ 4 K
 $J_c = 2000 \text{ A/mm}^2$
 $(dT/dt)_{t_0} \approx 300 \text{ K}/\mu\text{s}$



Quench

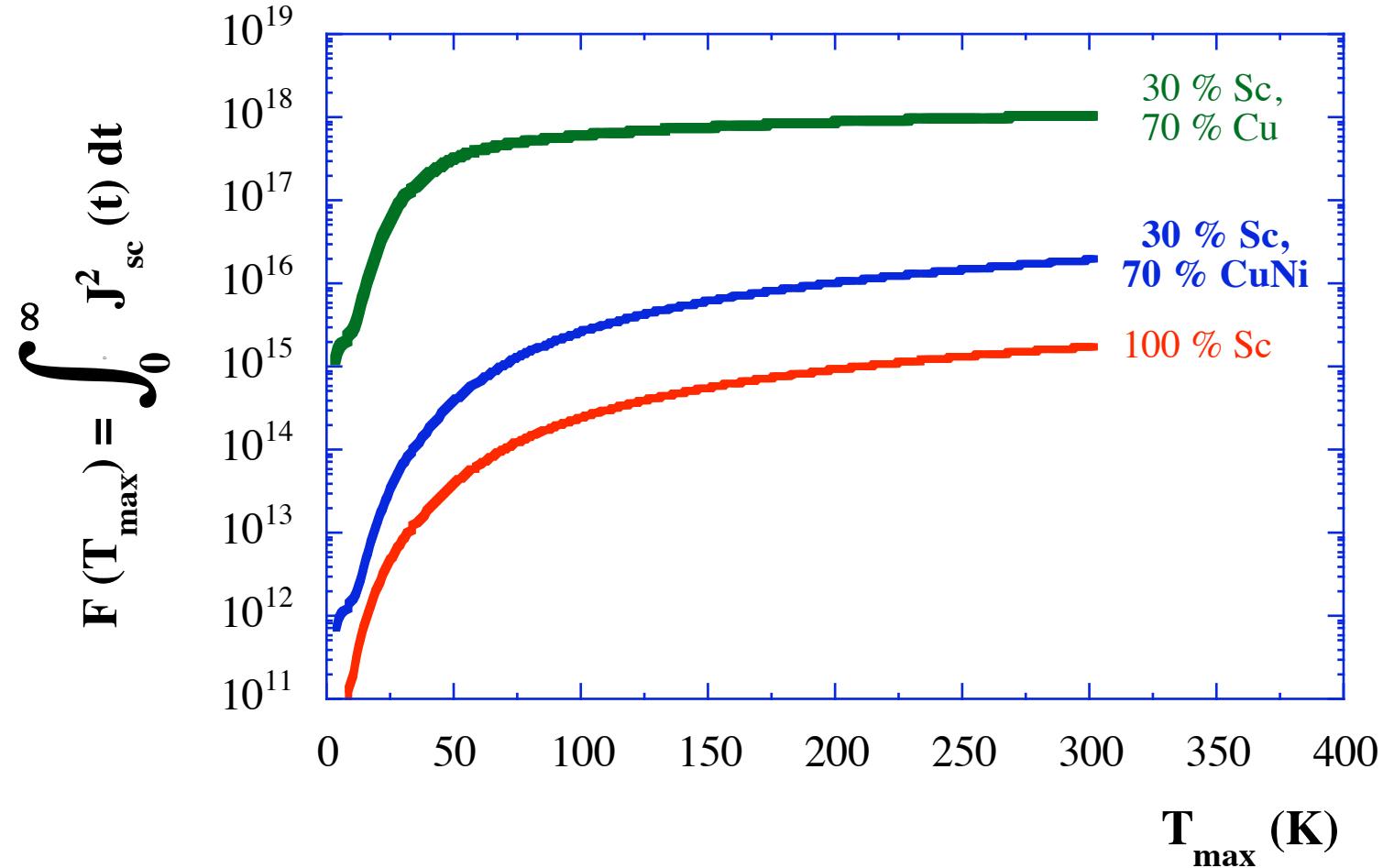


$$\frac{dT}{dt} = \rho_n(T) \frac{J(t)^2}{c_p(T)} \Rightarrow J(t)^2 dt = \frac{c_p(T)}{\rho_n(T)} dT$$



Calculation of the hot spot temperature

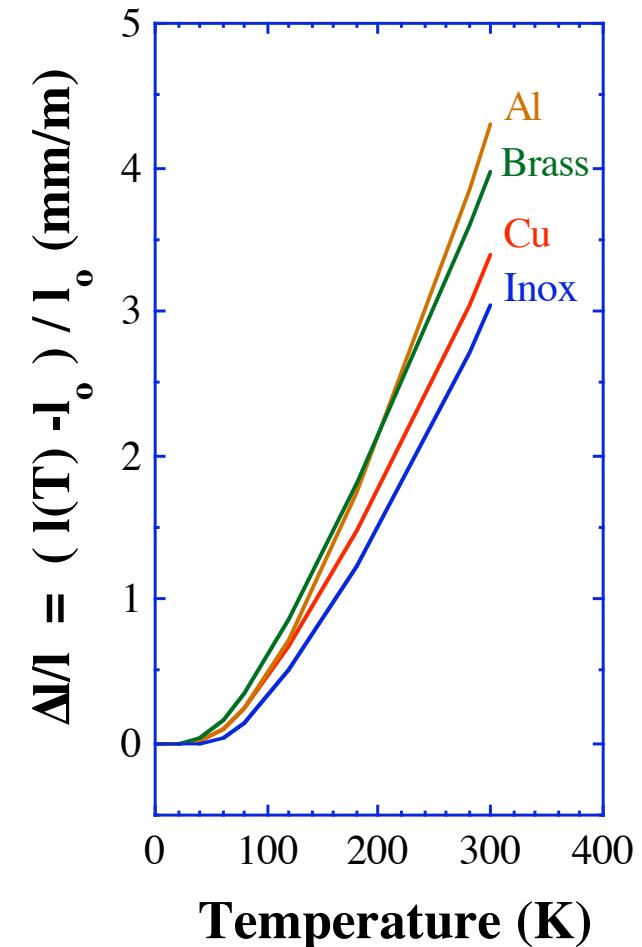
Quench



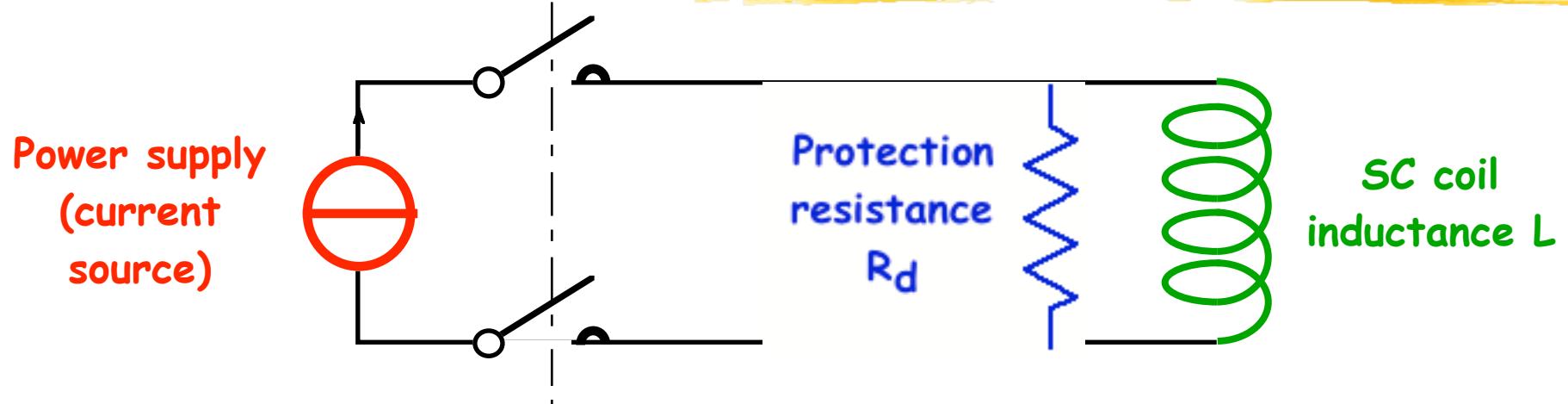
Quench

Maximum temperature

In general, the magnet is
designed not to overstep
80 K



Protection



Hypothesis: no propagation $\Rightarrow J = J_o \text{Exp}(-t/\tau)$

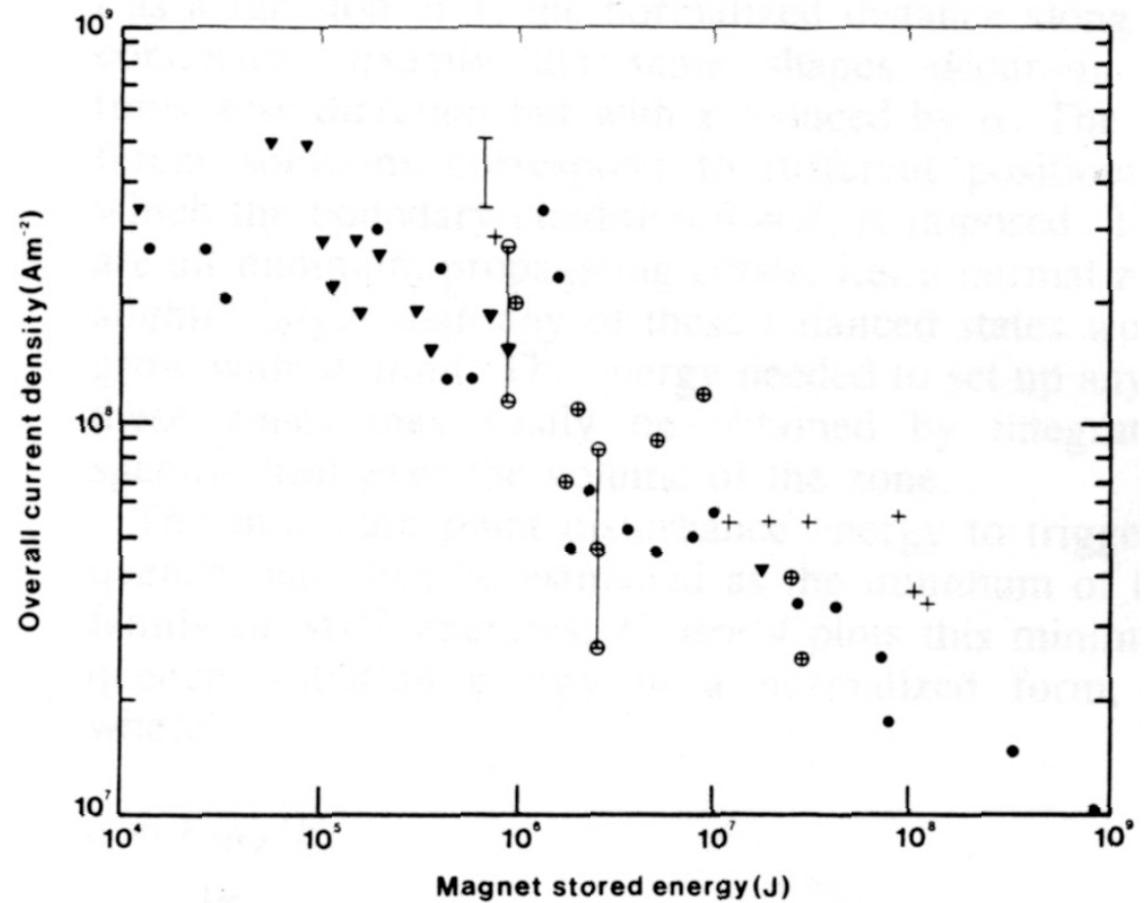
$$F(T_{\max}) = J_o^2 \left(\frac{W_{mag}}{V_{\max} I_o} + t_{det} \right)$$

$$V_{\max} = R_d I_o \quad ; \quad W_{mag} = \frac{1}{2} L I_o^2$$

R_d : isolation - $R_d I_o = V_{\max} < 2 \text{ kV}$

Protection

$$F(T_{\max}) = J_o^2 \left(\frac{W_{mag}}{V_{\max} I_o} + t_{det} \right)$$



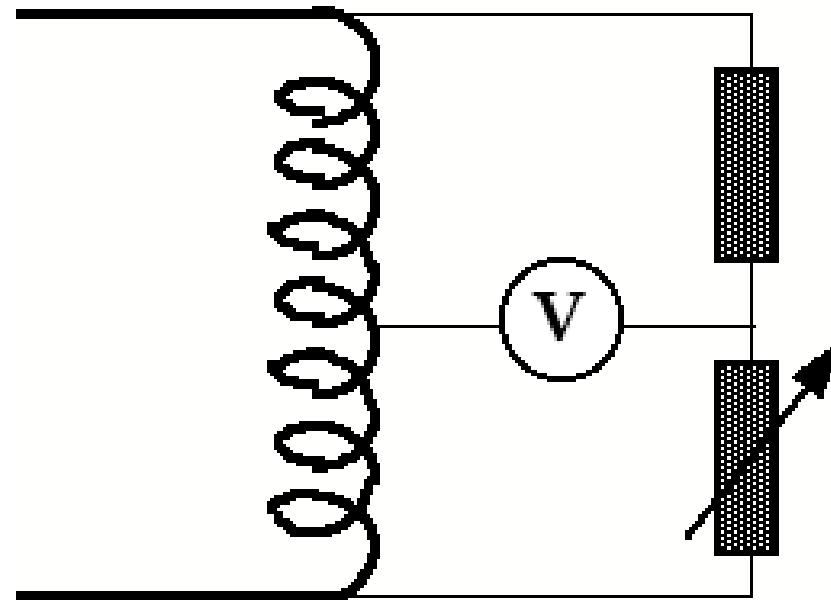
Wilson

Protection



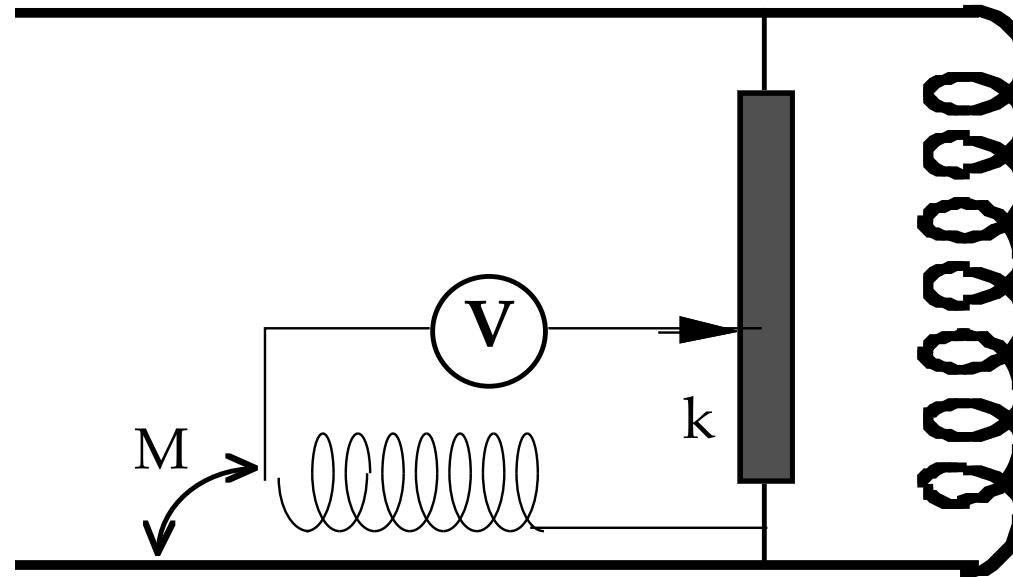
- Quench detection as soon as possible
- Switching off the power supply
- Triggering heater to distribute energy

Detection circuit 1/2



Bridge type
Equilibration at low current

Detection circuit 2/2

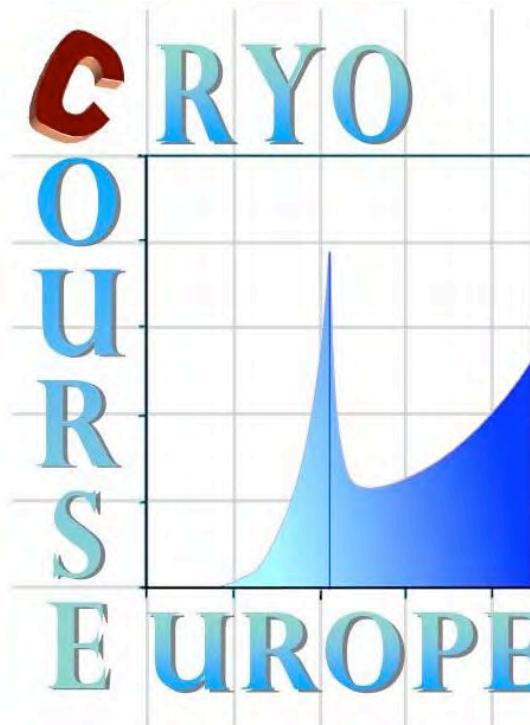


$$V = k R I + k L \frac{dI}{dt} - M \frac{dI}{dt}$$

$$k / kL = M \Rightarrow V = kRI$$

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Applied
superconductivity

VI. SC conventional
materials

NbTi & Nb₃Sn: critical parameters

	T _c (0T)	T _c (11T)	μ ₀ H _{c2} (1.8 K)	μ ₀ H _{c2} (4.2 K)
NbTi	9.5 K	4.2 K	14 T	11 T
Nb ₃ Sn	18 K	10.4 K	25.5 T	23.2 T

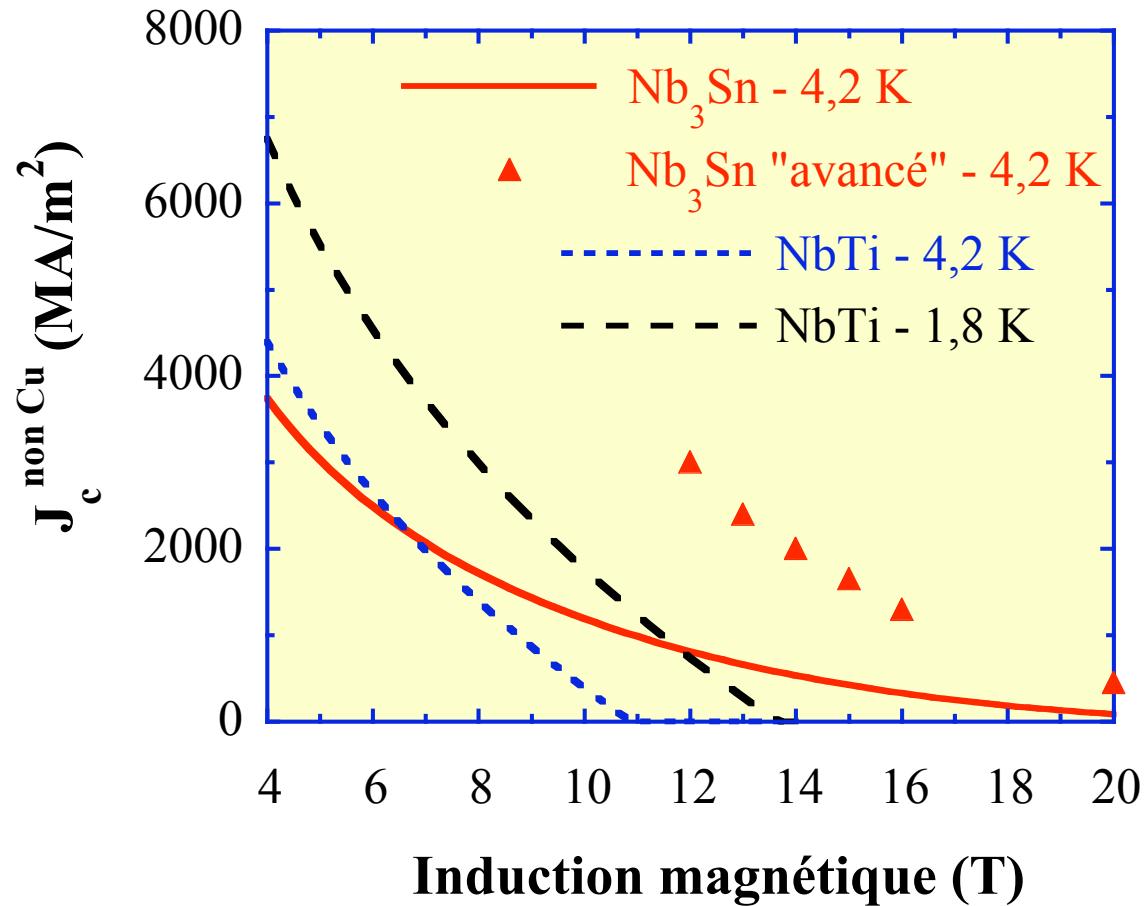
Cost

NbTi: 0.8-2 €/kA/m

Nb₃Sn: 8-10 €/kA/m

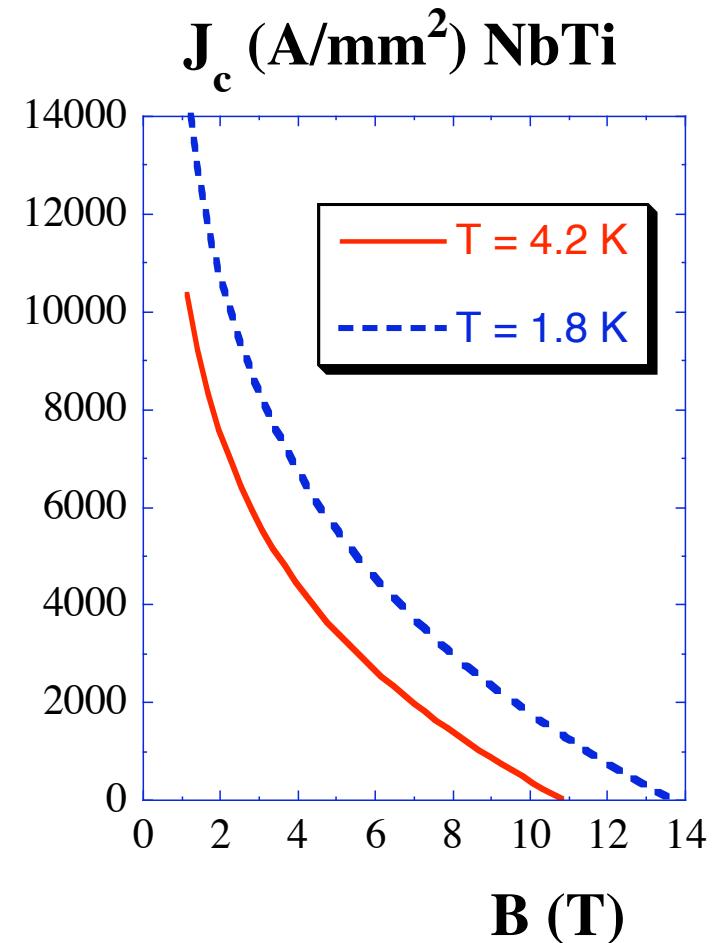
Winding complex ("wind & react")

NbTi & Nb₃Sn : critical characteristics



NbTi

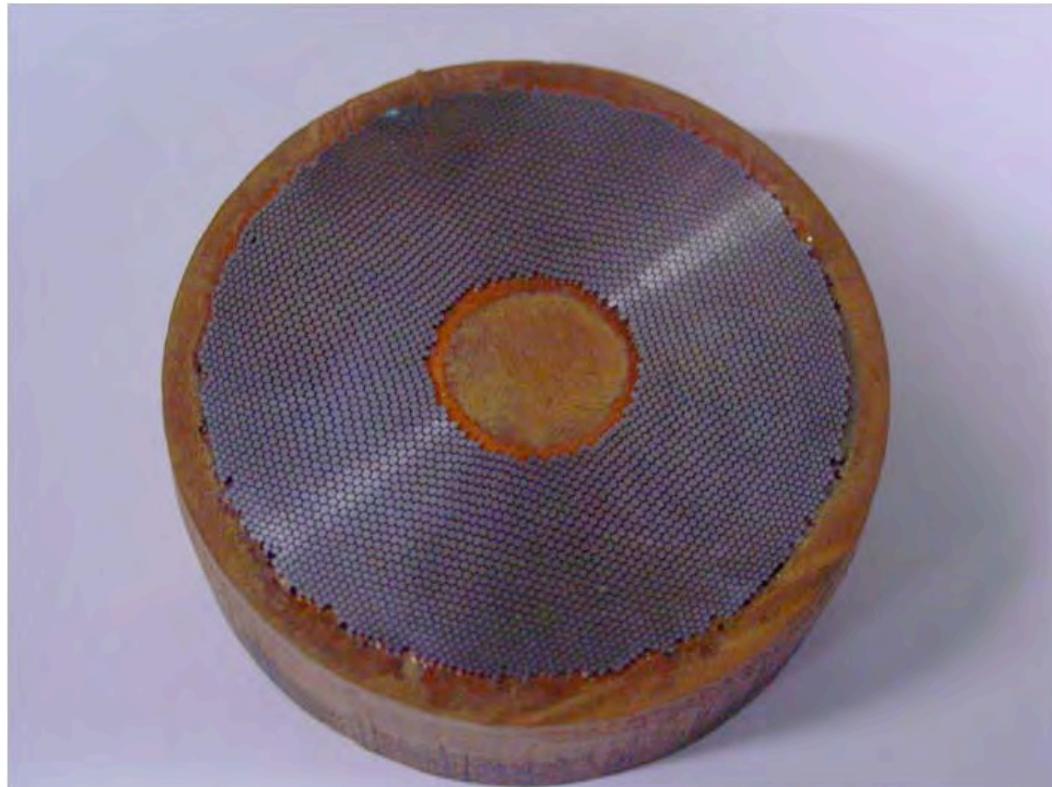
- Most widely SC used
 - 2000 tons/y (NbTi strand)
- Low cost ductile material
- Ti content : 45-50 % wt
 - Optimum in B_{C2}
- Very mature material
- Little advances now



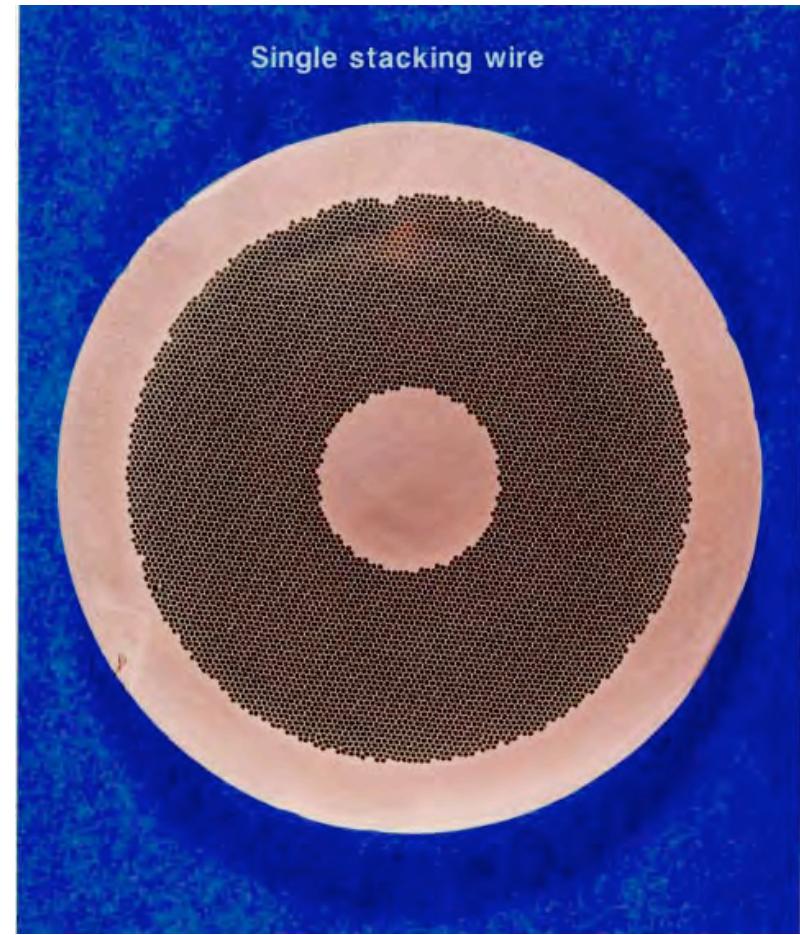
NbTi wire example: LHC strands

	Internal layer	External layer
Ø strand	1.065 mm	0.825 mm
Ø filaments	7 μ m	6 μ m
Number of filaments	8900	6500
Ratio Cu/Non Cu	1.6	1.9
Twist pitch	25 mm	25 mm
Critical current strand	515 A (10 T, 1.9 K)	380 A (9 T, 1.9 K)
Strand number of the cable	28	36
Critical current cable	13750 A (10 T, 1.9 K)	12950 A (9 T, 1.9 K)

LHC strand



Alstom strand



Single stacking wire

Nb_3Sn , A 15 material (15 tons/y)

$$T_c(0 \text{ T}) = 18 \text{ K} \quad T_c(11 \text{ T}) = 10.4 \text{ K}$$

$$\mu_0 H_{c2}(1.8 \text{ K}) = 25.5 \text{ T} \quad \mu_0 H_{c2}(4.2 \text{ K}) = 23 \text{ T}$$

$$J_c(4 \text{ K}, 10 \text{ T}) \approx 1200 \text{ A/mm}^2 \quad J_c(4 \text{ K}, 16 \text{ T}) \approx 300 \text{ A/mm}^2$$

\Rightarrow High magnetic field material

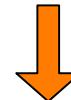
Nb_3Sn difficulties: strain sensitive, very brittle

"wind and react" technique

Winding when non brittle ($\text{Nb} + \text{Sn}$)
And after reaction $\text{Nb} + \text{Sn} \Rightarrow \text{Nb}_3\text{Sn}$

Nb_3Sn manufacturing

Brittleness of Nb_3Sn

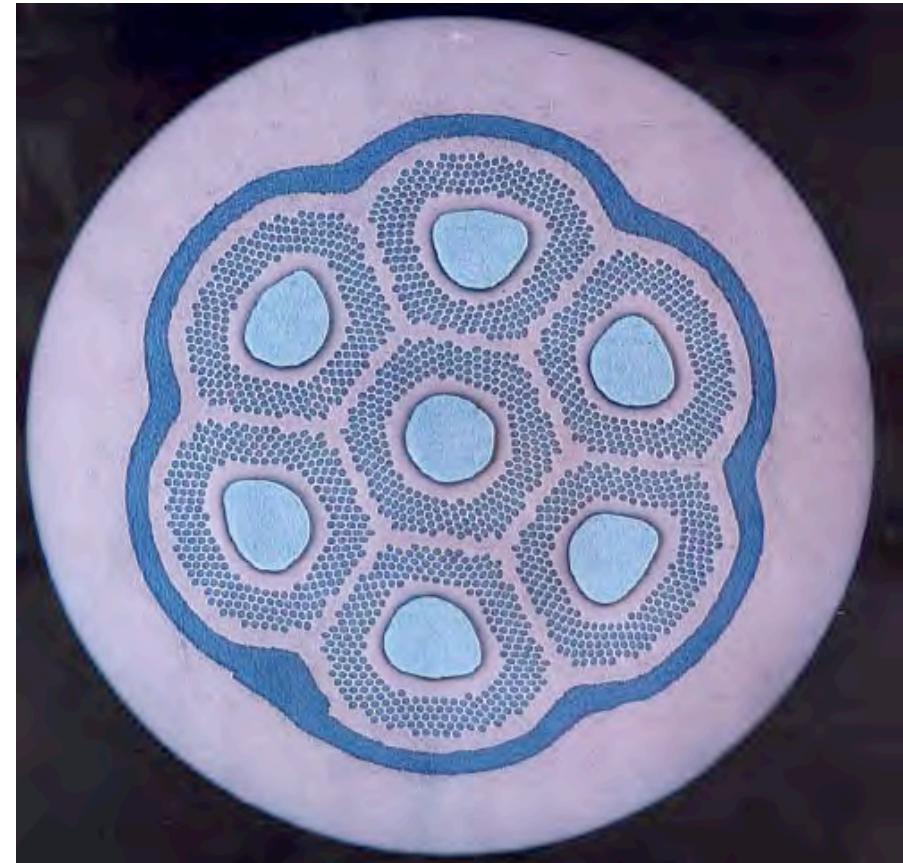
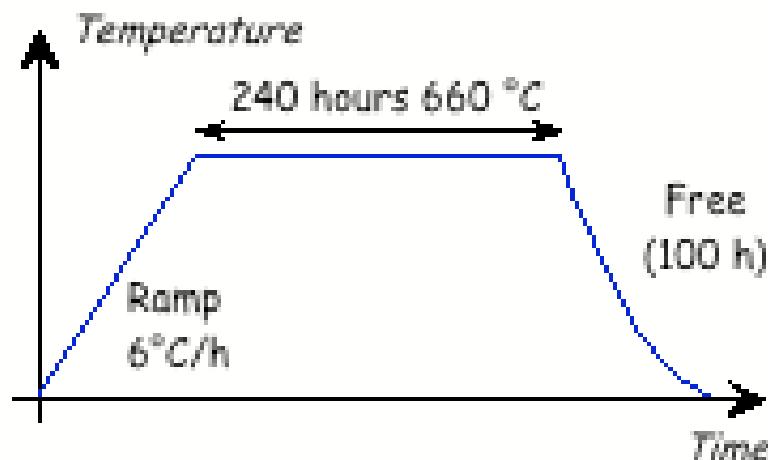


Formed *in situ* at final stage

- Four main methods of producing Nb_3Sn wires
 - Bronze
 - Internal tin
 - Modified Jelly Roll
 - Powder in Tube (PIT)

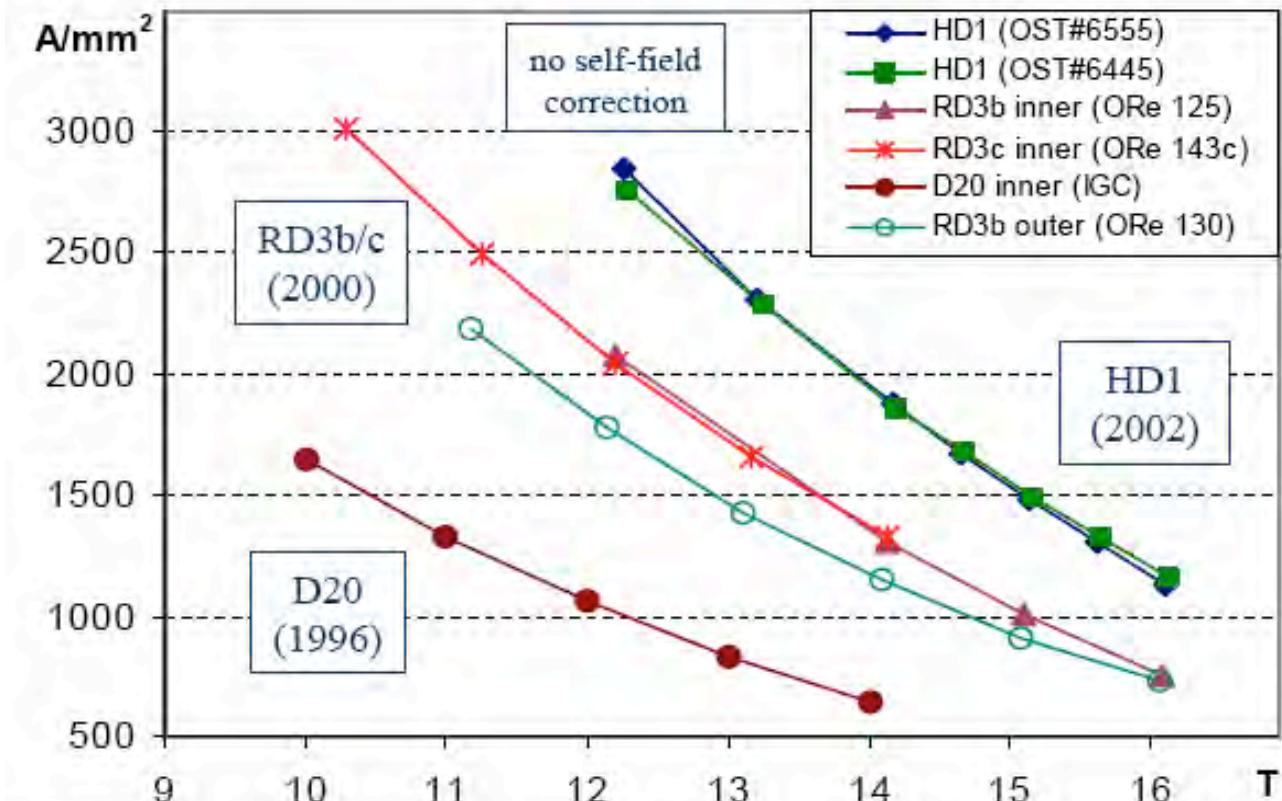
Internal tin Nb₃Sn wire

- Strand developed for ITER
- $\varnothing = 0.765 \text{ mm}$
- $J_c = 635 \text{ A/mm}^2 - 12 \text{ T @ 4,2 K}$
- Heat treatment: 19 days



Advances in Nb₃Sn wires

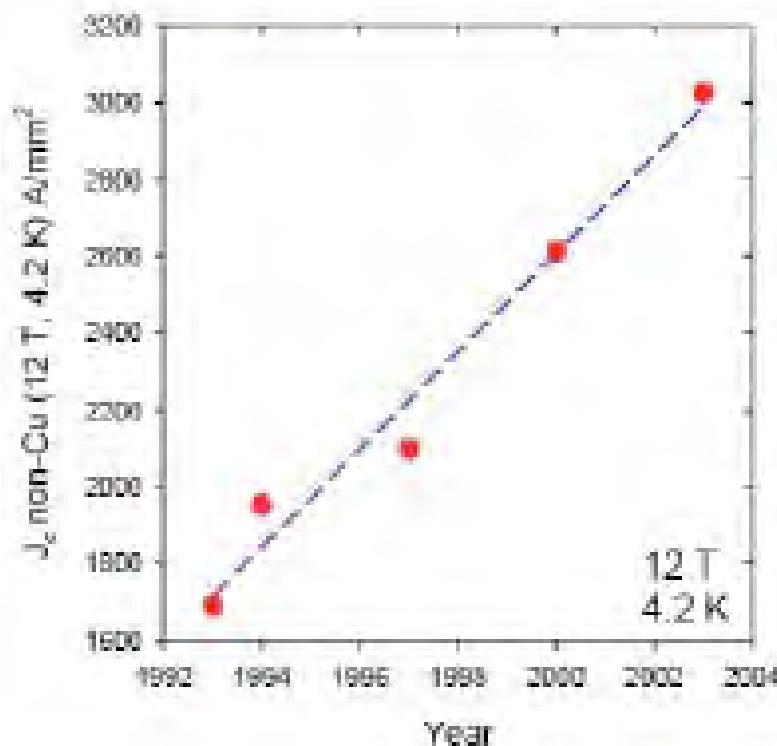
3000 A/mm² @ 12T, 4 K in Nb₃Sn strands



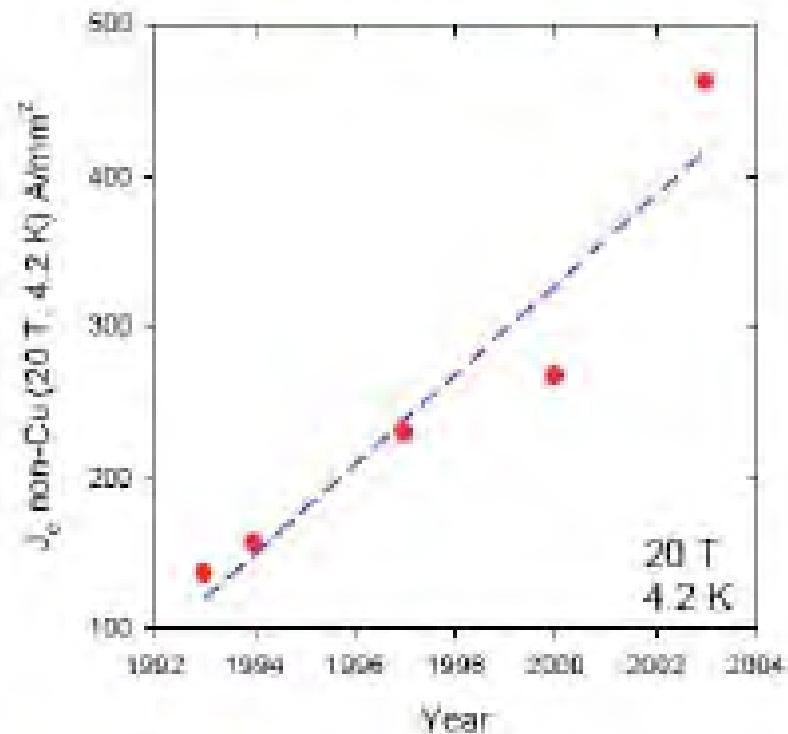
Courtesy A. Devred

Advances in Nb₃Sn wires

Doubled @ 12 T



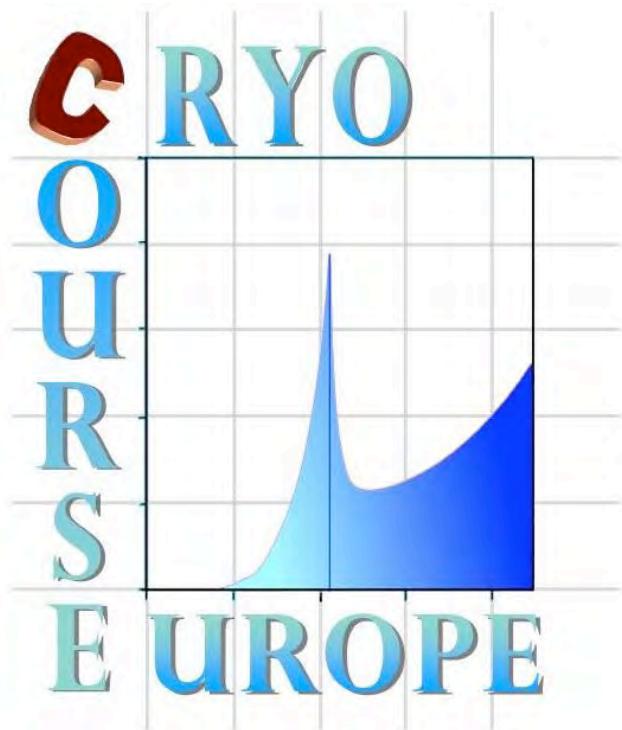
Tripled @ 20 T



(Courtesy S. Hong, OST)

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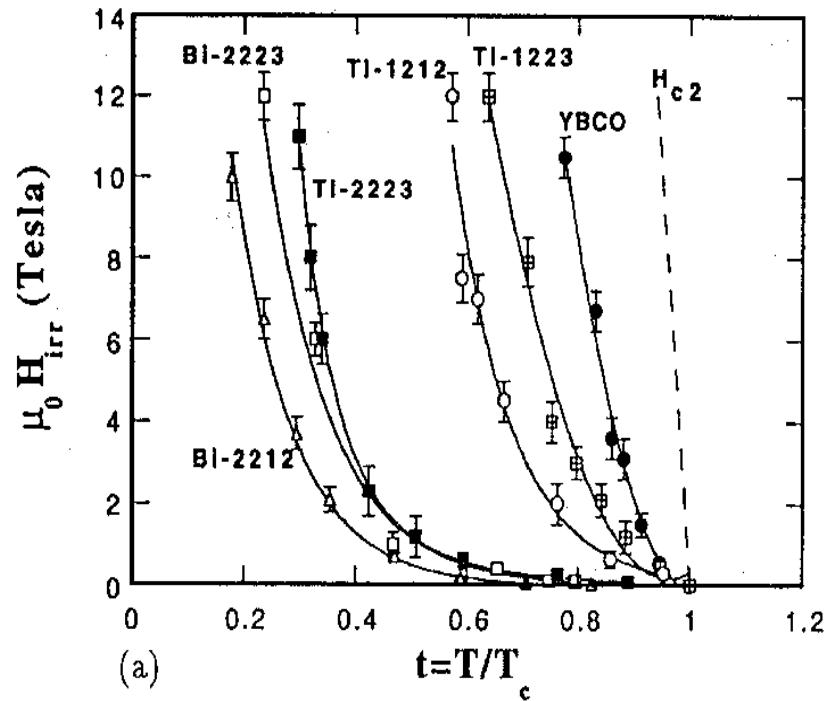


Applied
superconductivity

VIII. High T_c
superconductors

HTS specificities

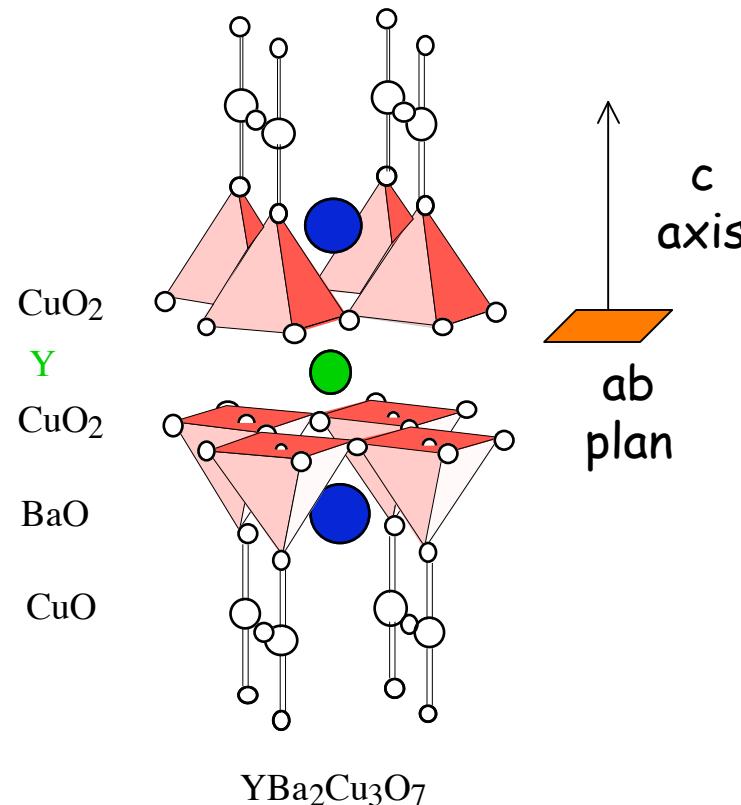
Relevant field for HTS:
irreversibility field H^* , not H_{c2}



HTS
materials:
-YBaCuO

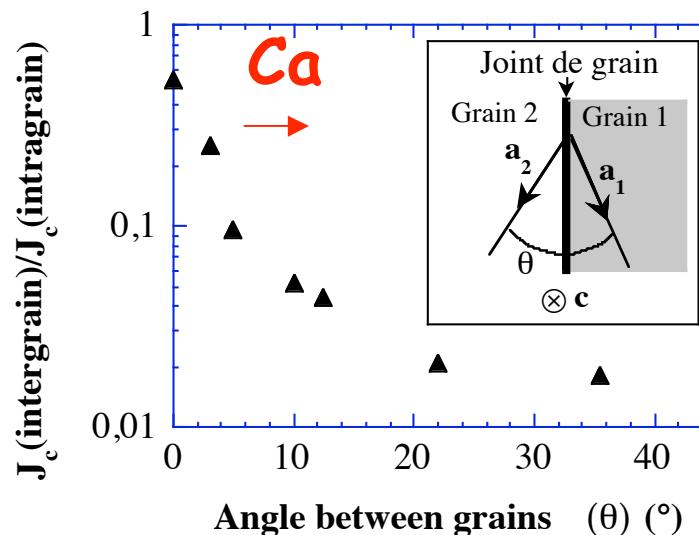
HTS specificities

High anisotropy



C. Bougerol - CNRS-LC

Orientation importance



D. Dimos et al., Physical Review Letter, Vol. 61, 1988)

HTS

- Ceramic type materials
- Very sensitive to defects (G.B.)



Sintered



Textured



Epitaxial

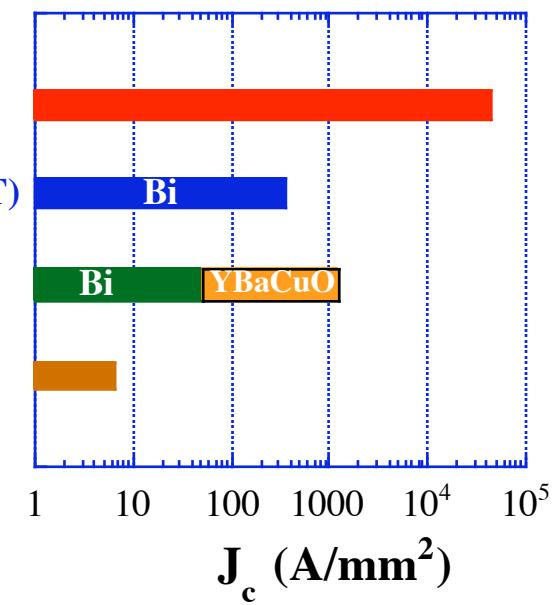
Epitaxial film

Textured tape (OPIT)

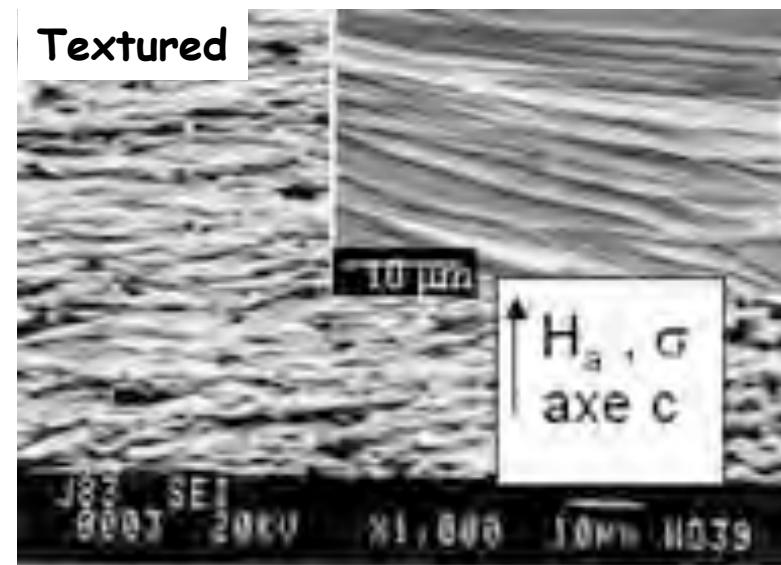
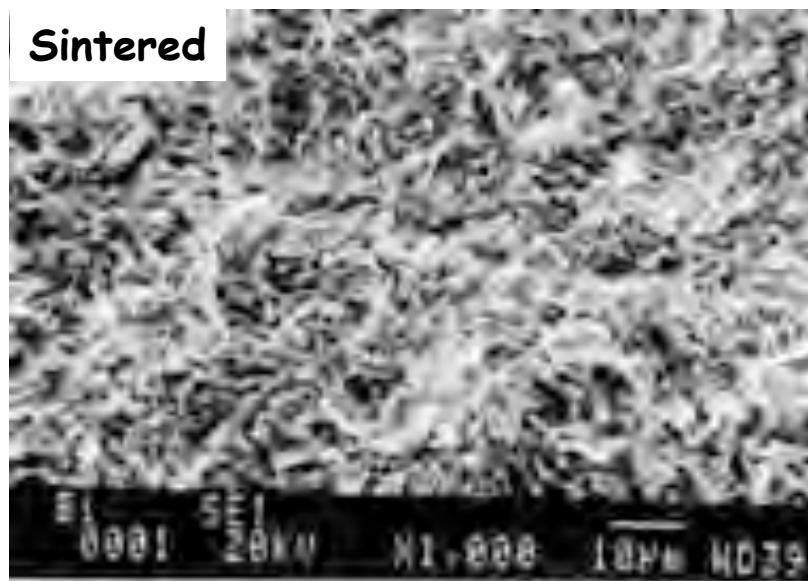
Textured bulk

Sintered bulk

J_c (77 K, 0T)



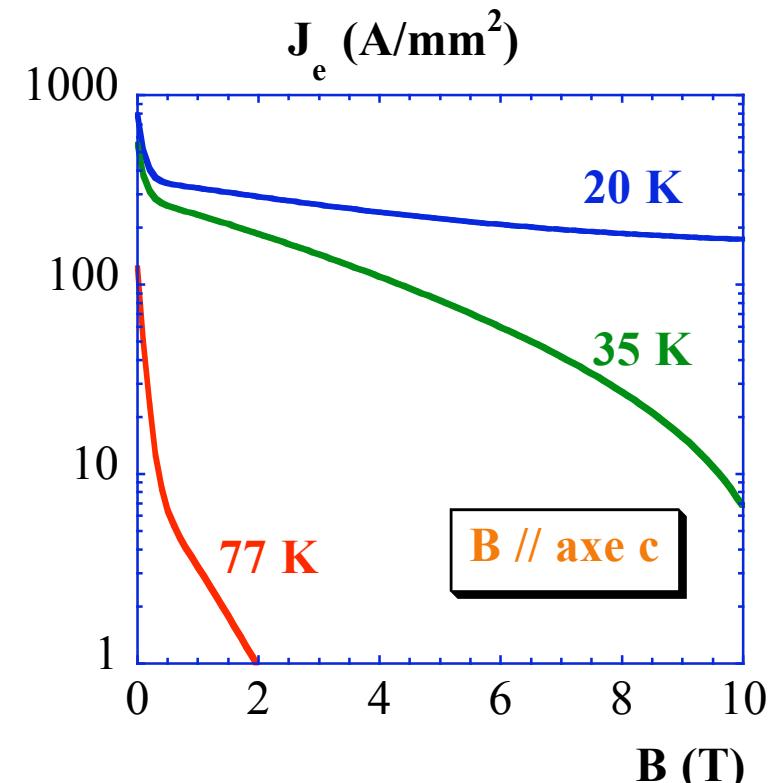
Texturation



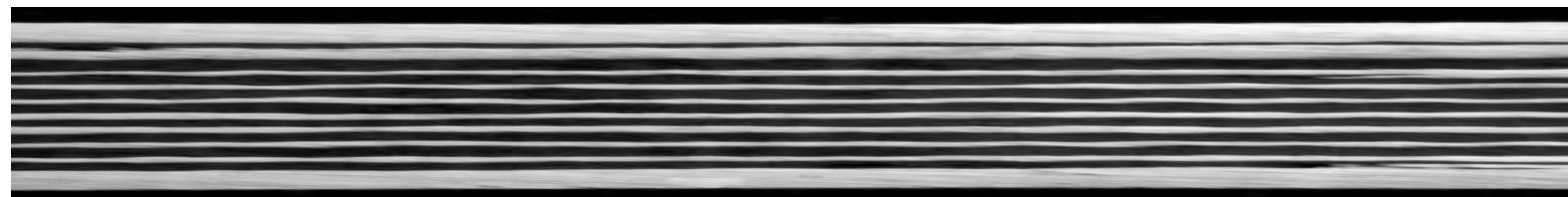
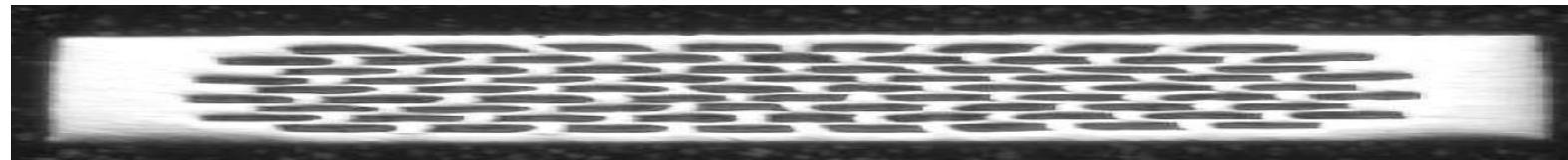
Powder In Tube Bi wire

- First generation of HTS wires
- Bi-2212 or Bi-2223
- Km length
 - EAS, Sumitomo, ...

$$J_e(77 \text{ K}, 0\text{T}) \approx 100 \text{ A/mm}^2$$

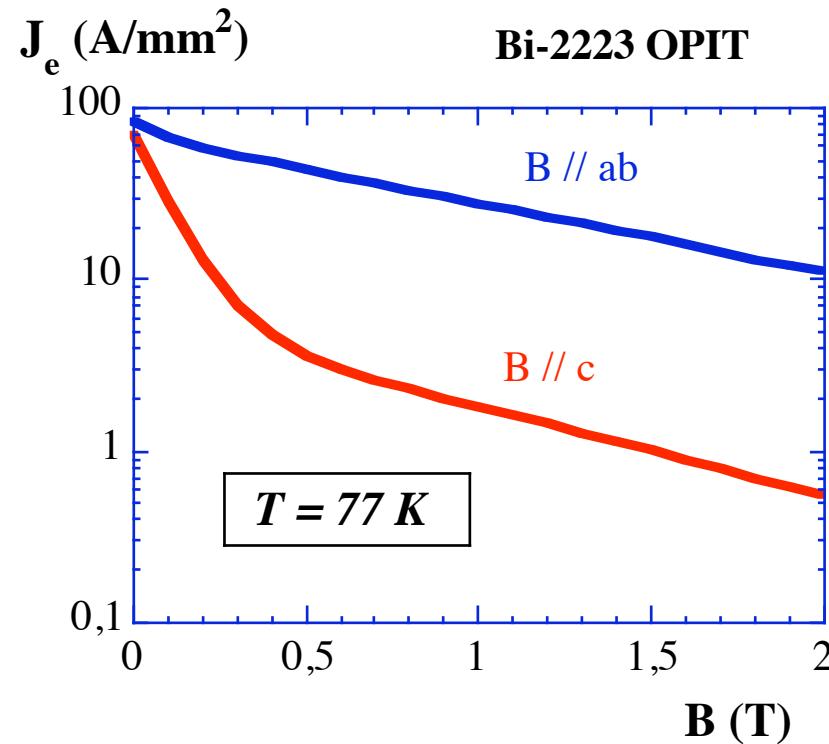


1G: PIT Bi wires



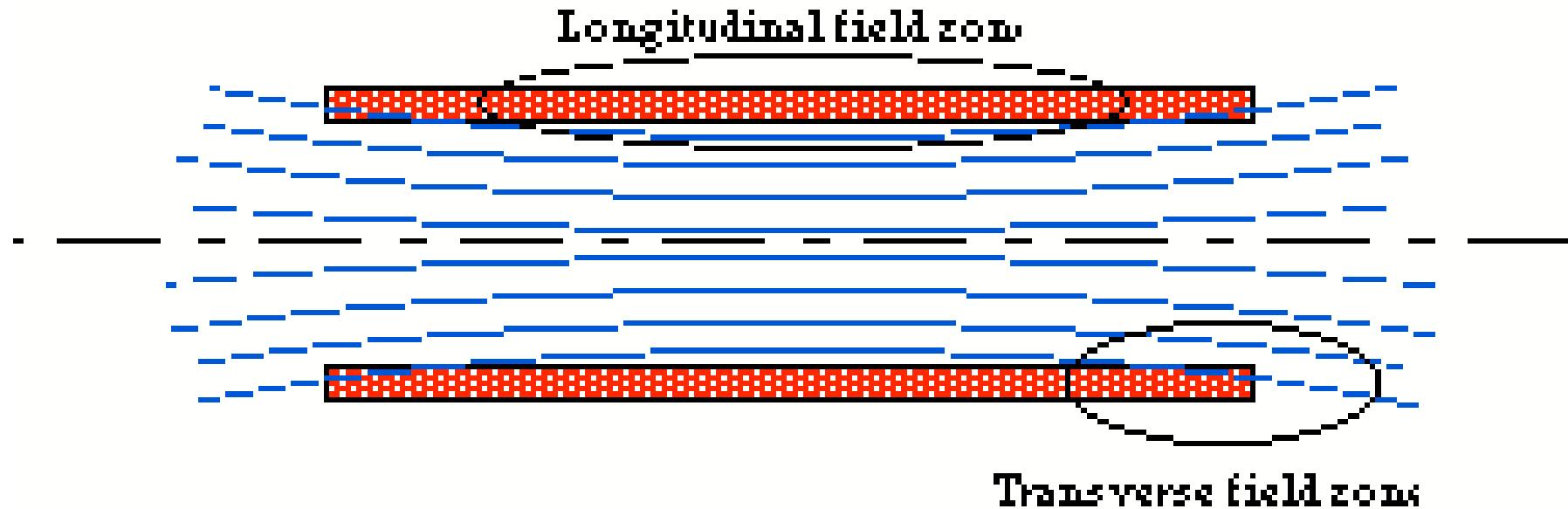
Nexans

Powder In Tube Bi wire

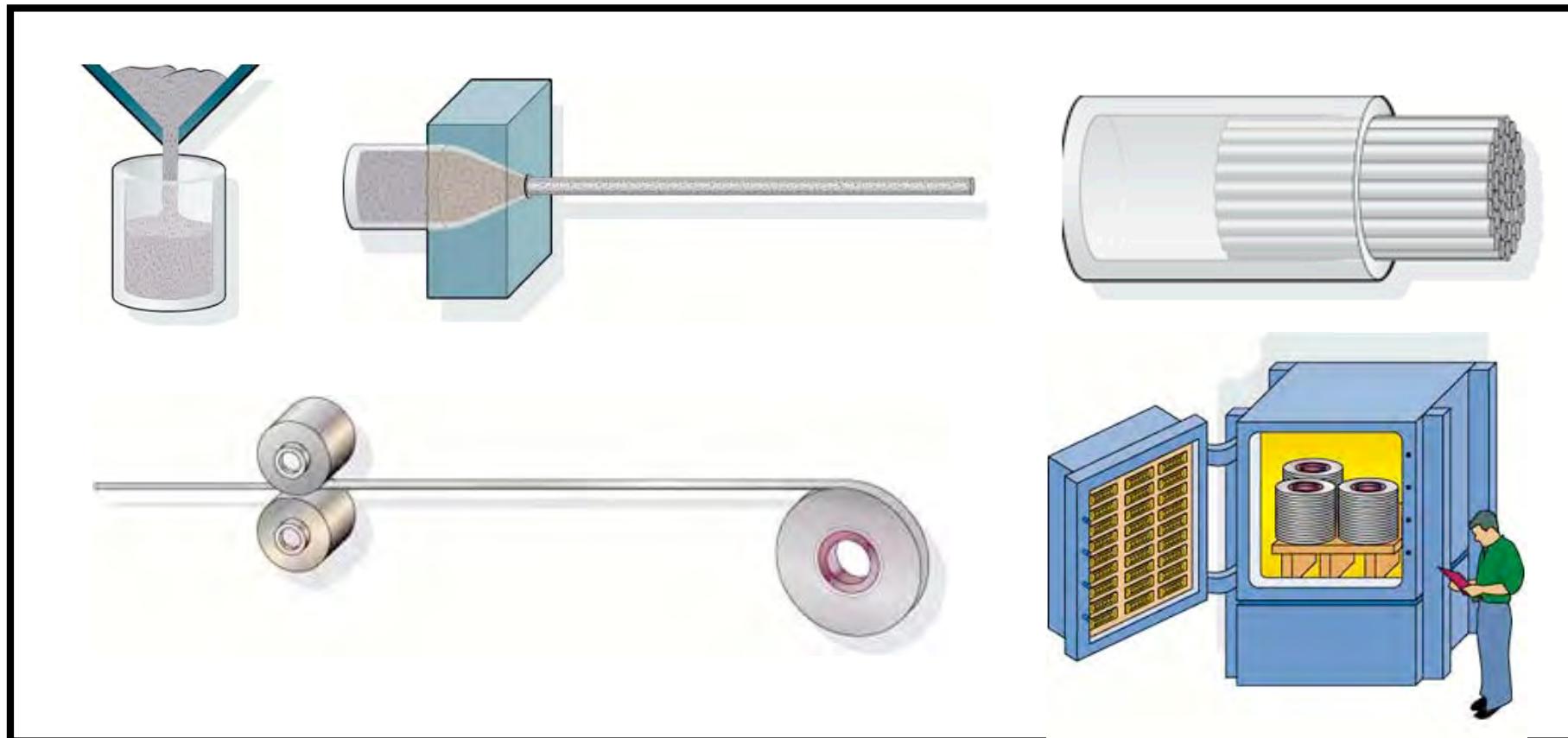


Magnet design should decrease
the transverse component

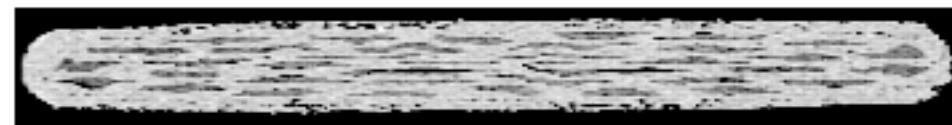
Longitudinal and transverse fields



PIT elaboration technique

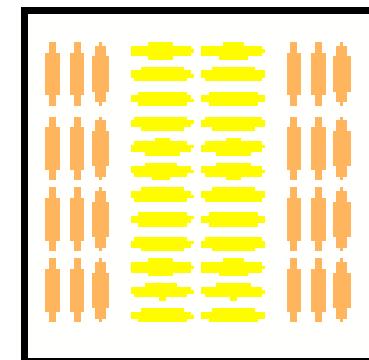
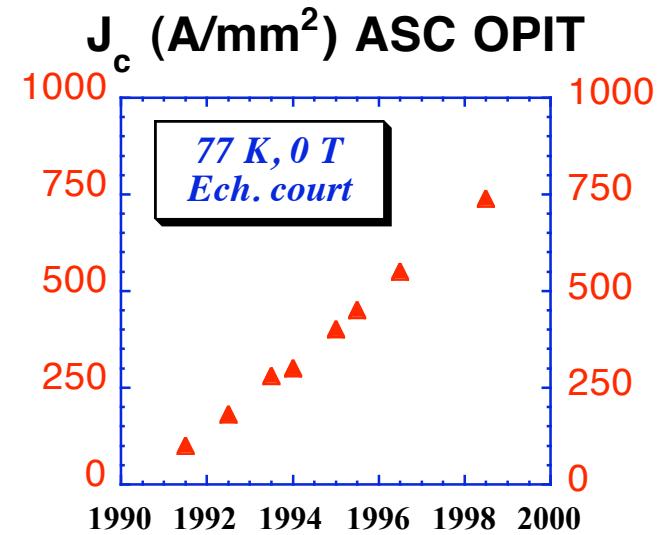


ASC

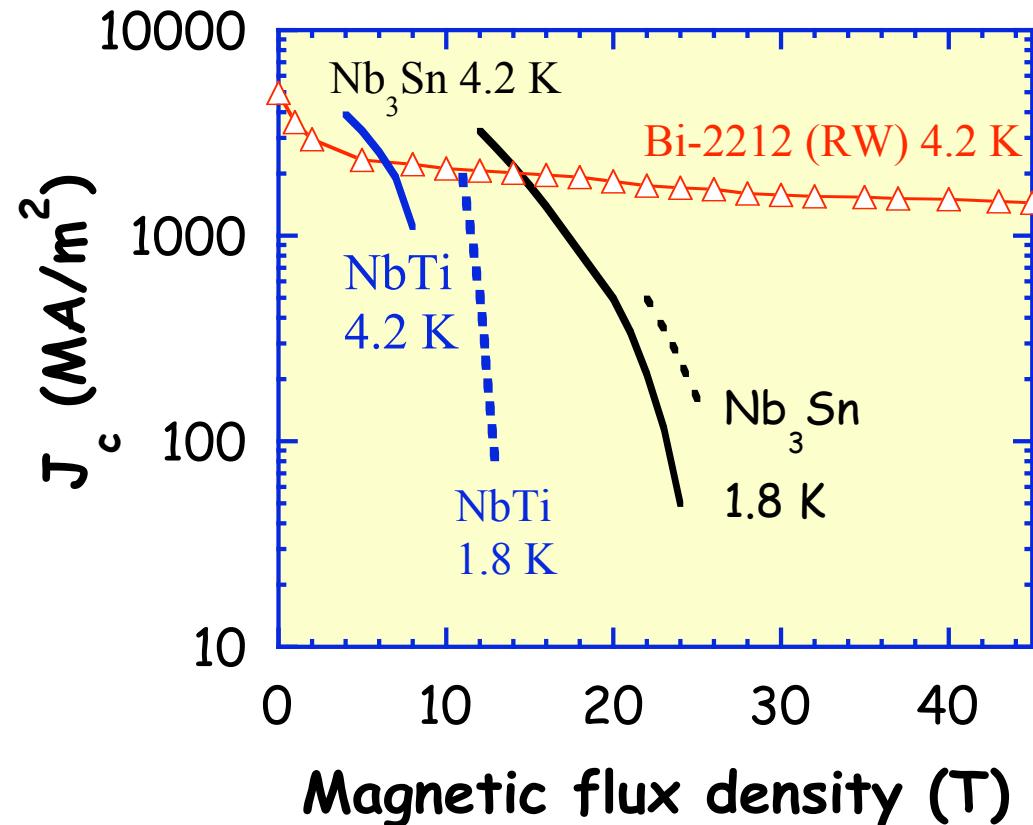


Bi PIT

- Low J_c under field @ 77 K
- Ac losses
- High cost
 - 300 €/kA/m (50 €/km/m)
- Complex, far from limits
- Increasing SC ratio
- Alloys, resistive barriers
- Anisotropy reduction



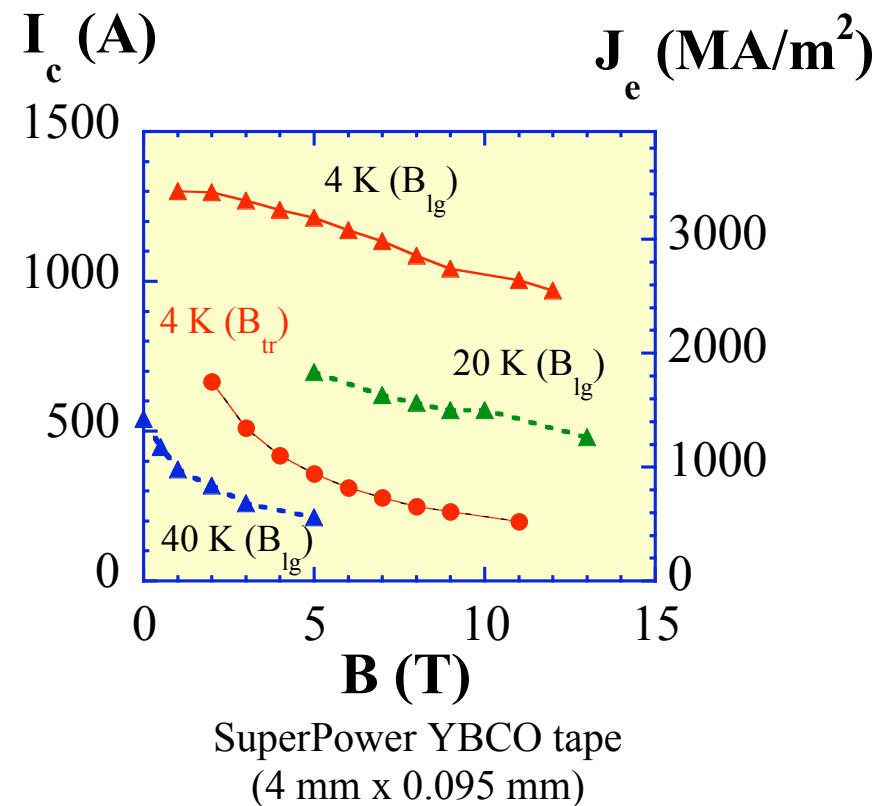
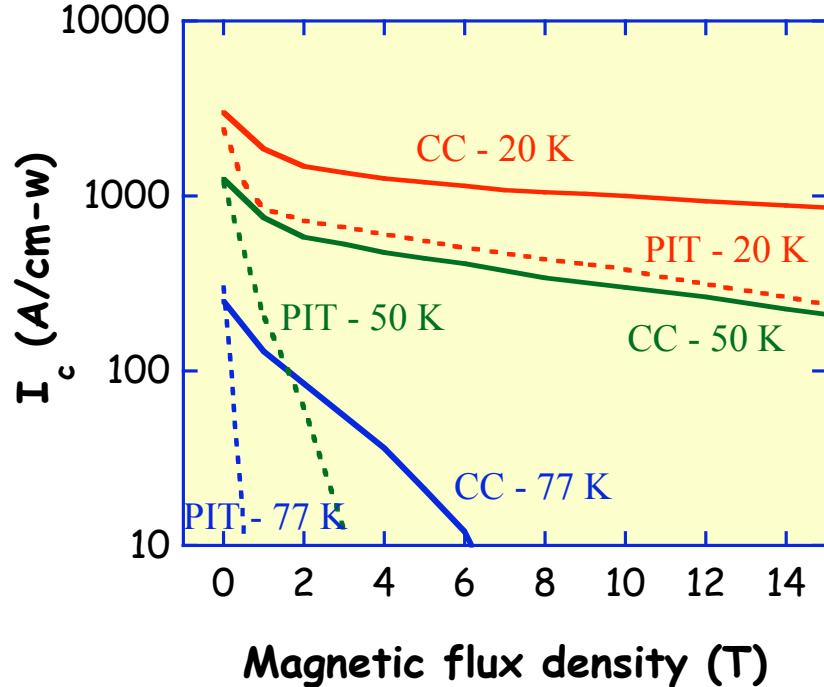
Bi PIT: niche application high field



Coated conductors

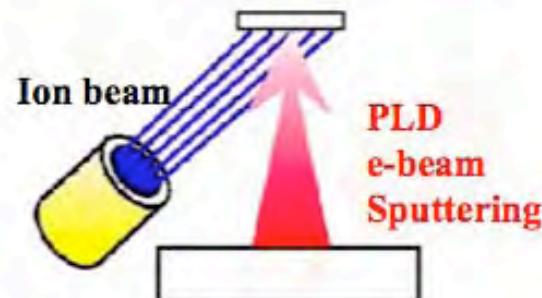
- 2nd generation of HTS wire
 - Y compound
 - 100 m length
-
- Great hopes
 - Moderate cost
 - High J under field @ 77 K
 - Large R & D programs

Coated conductors



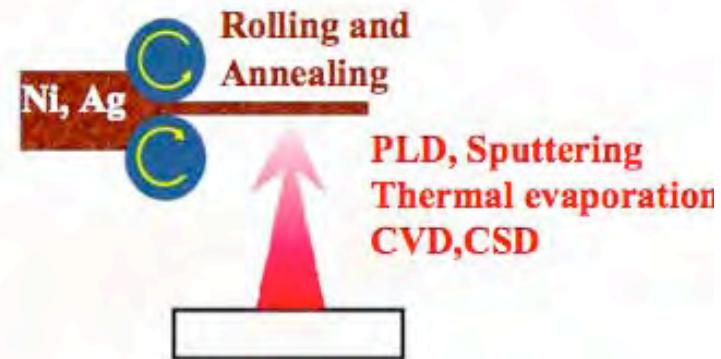
Coated conductors - two main techniques

Ion Beam Assisted Deposition (IBAD)



Biaxially textured buffer layers

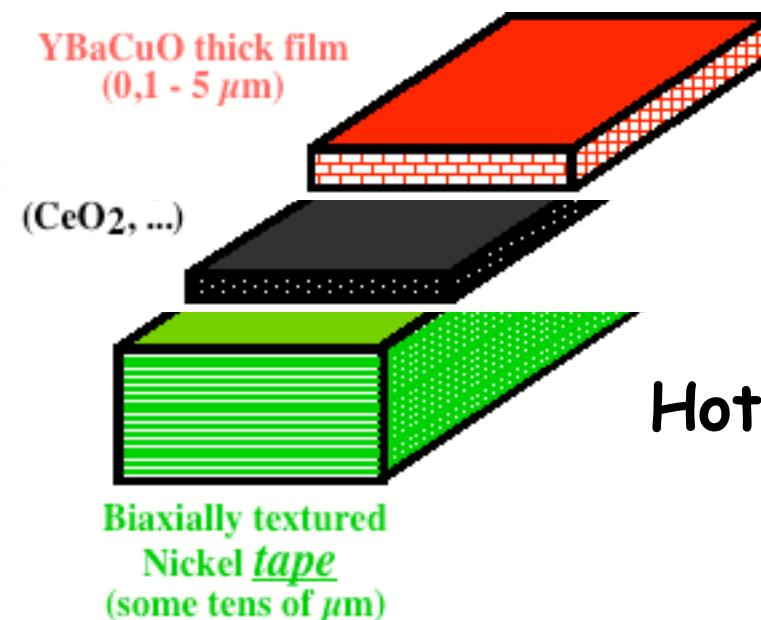
Rolling Assisted Biaxially Textured Substrates (RABiTS)



Biaxially textured substrates

RABiTS technique

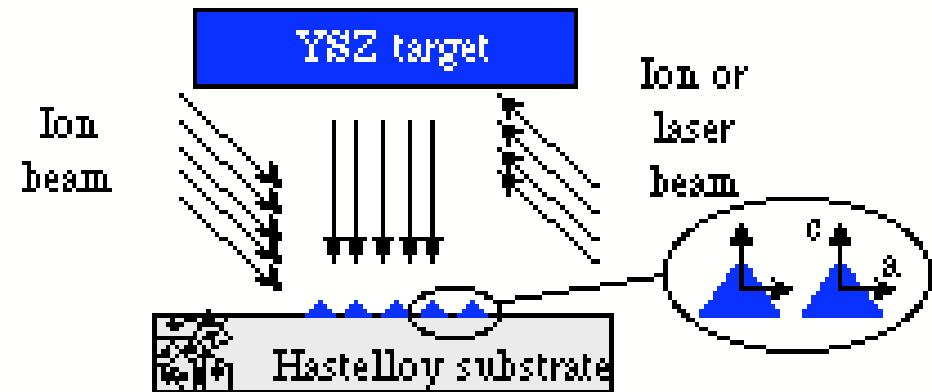
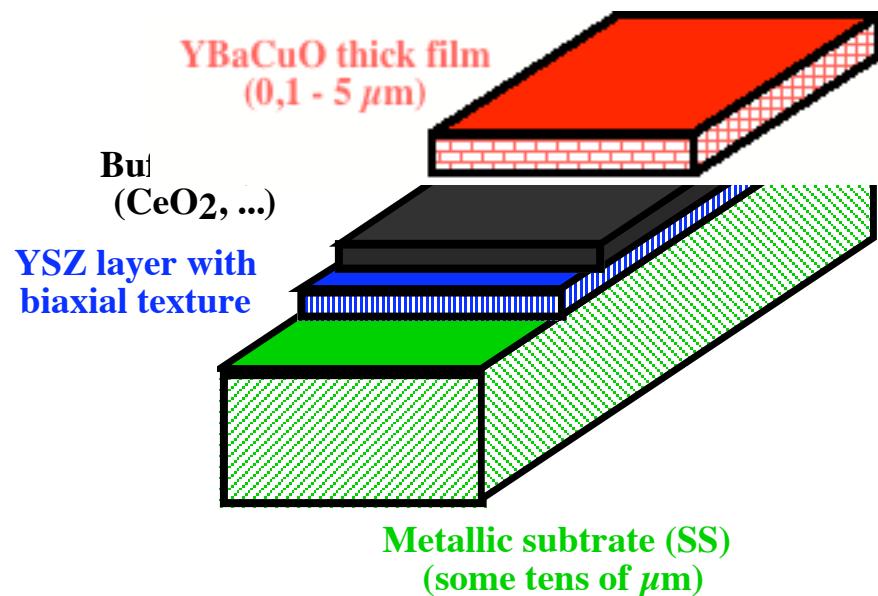
Rolling-Assisted Biaxially Textured Substrate



Hot-rolling operations
and annealing

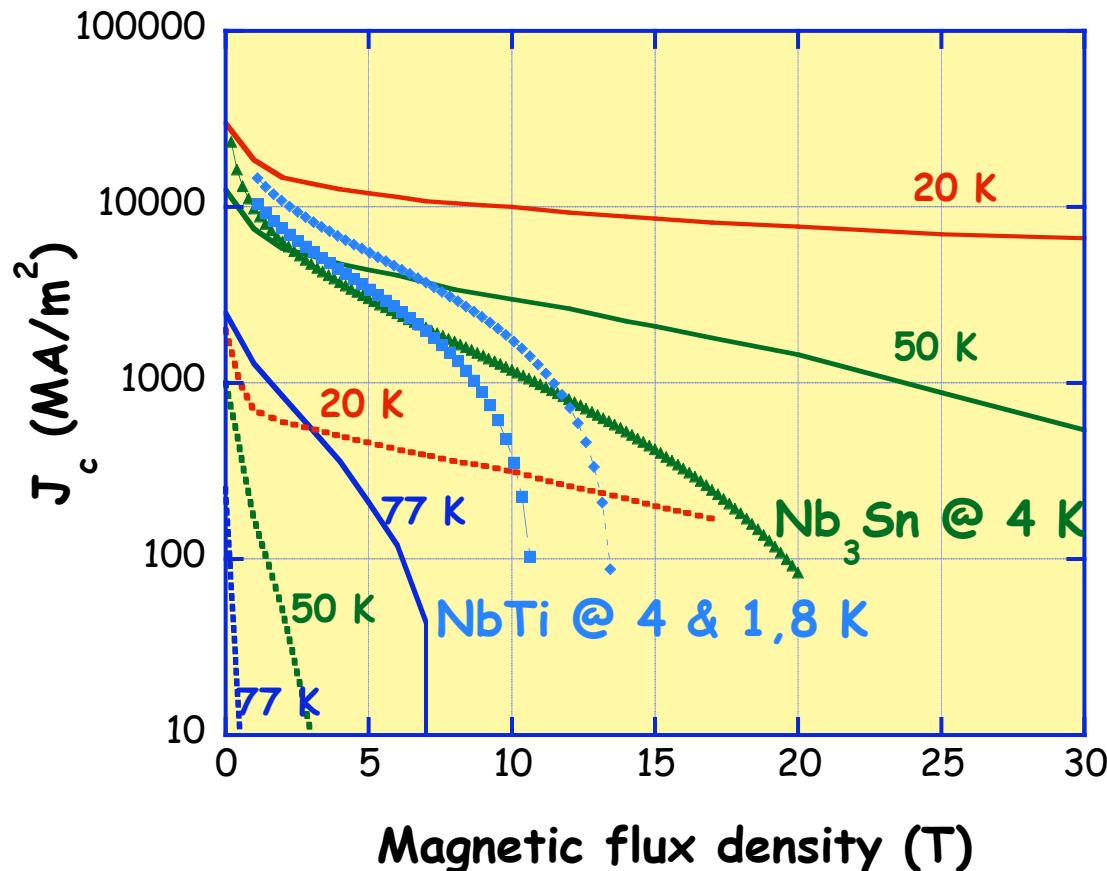
IBAD technique

Ion Beam Assisted Deposition

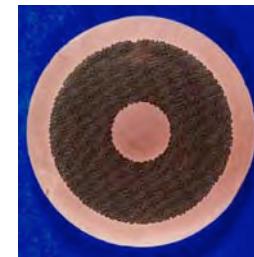


100-150 A/cm tens of meter

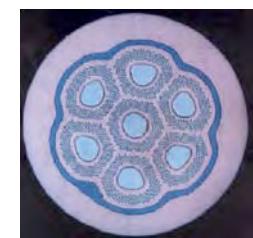
Superconducting materials



===== LTS =====



NbTi



Nb₃Sn

===== HTS =====



1G

PIT BiSrCaCuO
Bi-2212 & Bi-2223



Coated conductor
YBaCuO
2G

HTC materials summary

Cost, cost

PIT: niche applications

CC: large hopes

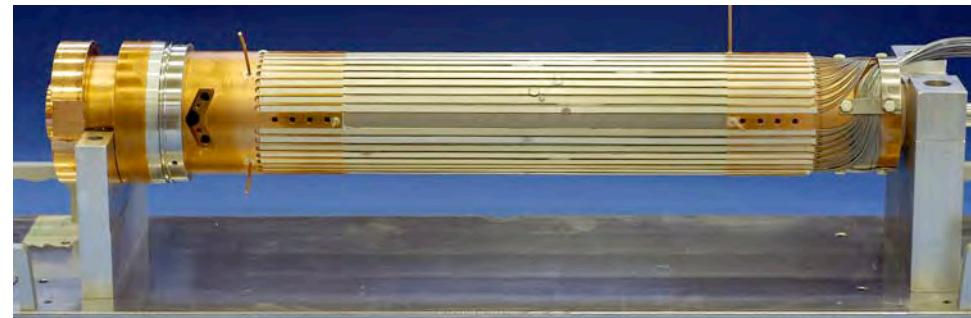
HTS current leads for the LHC

1720 electrical circuits, total current 1.7 MA

3286 current leads using Bi-2223 multi-filamentary tape



Number	Current rating (A)
64	13000
298	6000
820	600
2104	60-120



HTC applications

First application : HTC current leads

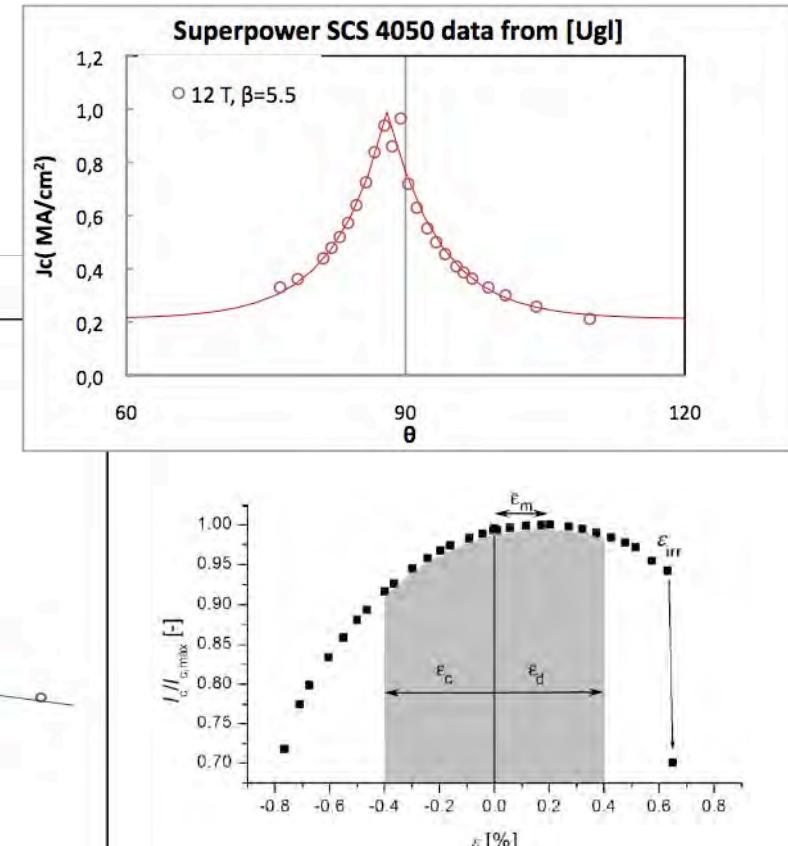
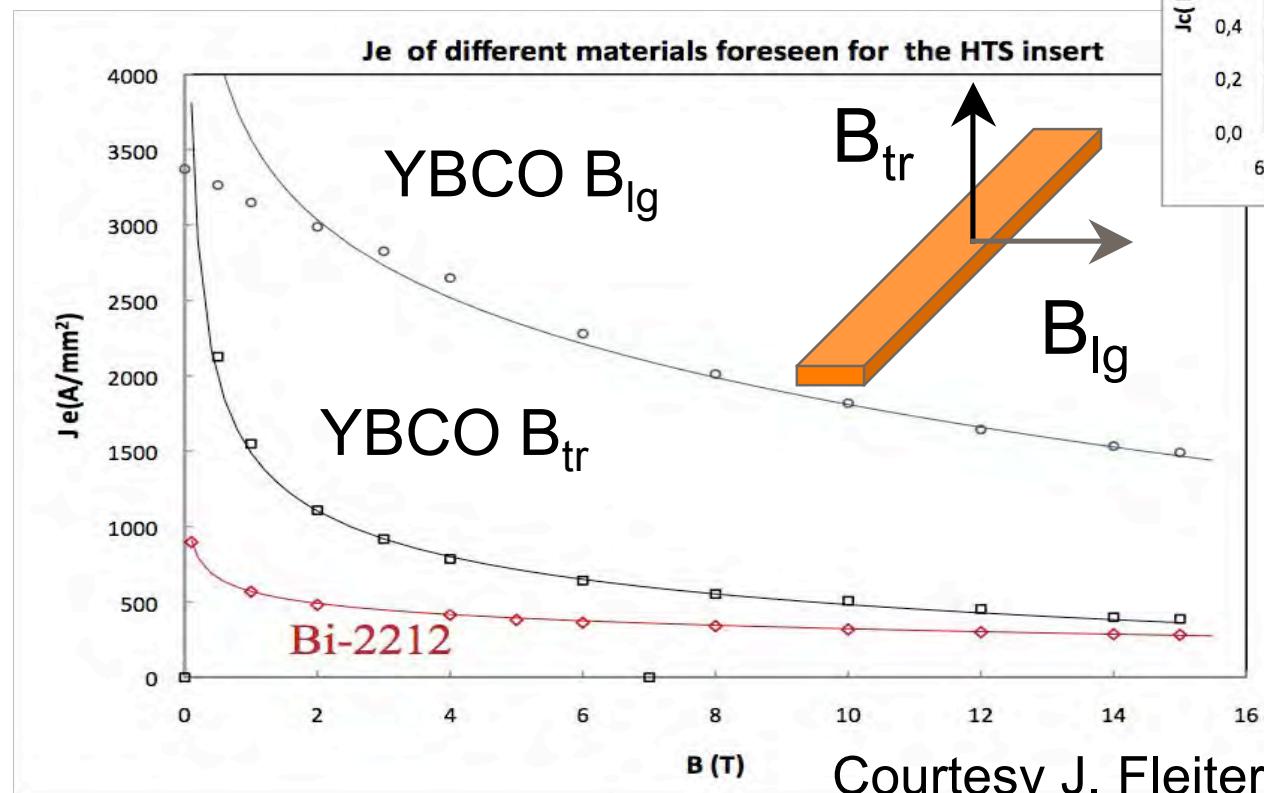
Second application : HTC high field insert

HTS insert Bi-2212 versus YBaCuO

	Bi-2212 (round wire)	YBaCuO (coated conductor)
	Round isotropic wire ($\varnothing = 0.8$ mm) High current cable (Rutherford) Bending radius (W & R)	Conductor of future Performances J_c & mechanics (700 MPa)
	Mechanical performances (100 MPa) Defect free lengths Niche conductor	Thin tape (4 x 0.1 mm ²) Lengths Large field anisotropy
	Thermal treatment Cost	High current cable

© 2009 General Cable Superconductors

HTS insert Bi-2212 versus YBaCuO



MgB_2

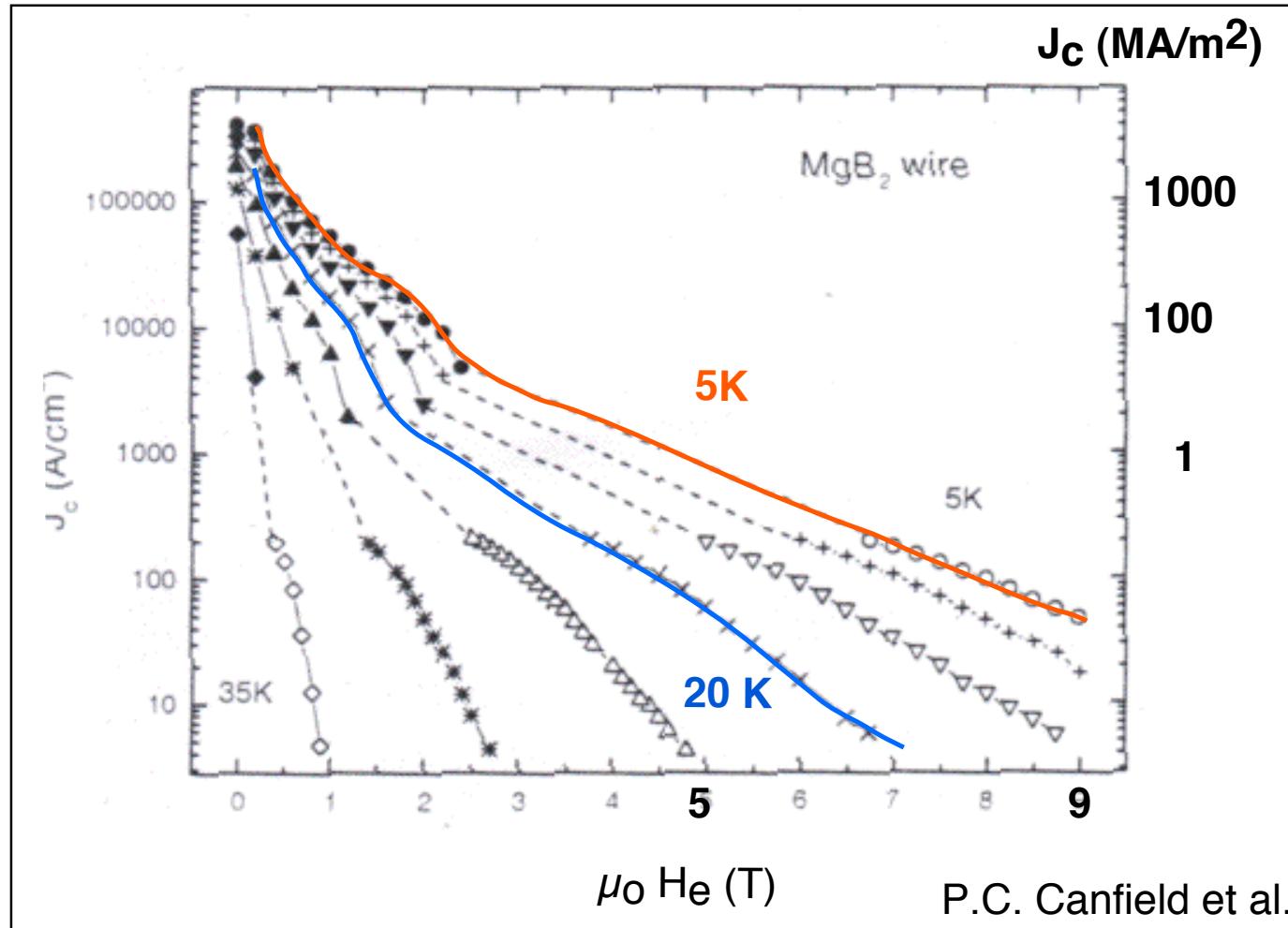


- Superconductivity under 39 K discovered in 2001 by J. Akimitsu (Tokyo)
 - Material known since 1953
 - Material used in chemist
 - Non expensive material
- 

MgB₂

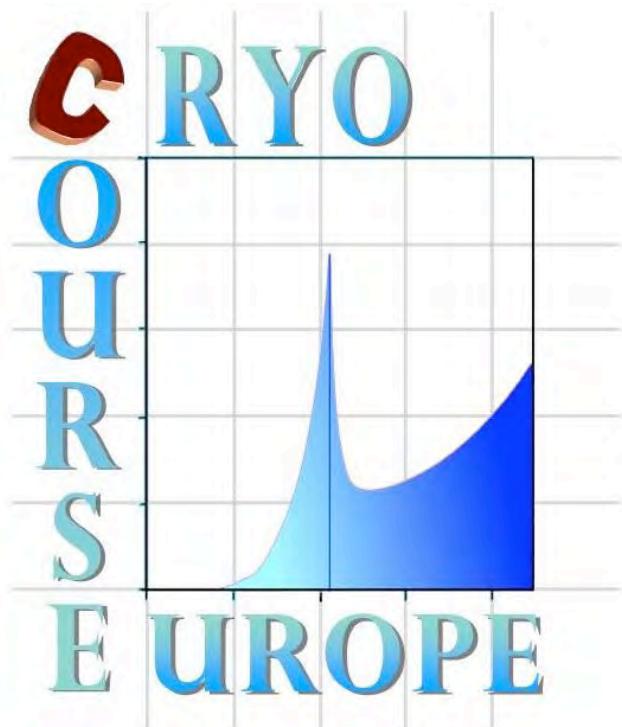
- Light (2.4) & little resistive ($\rho(40\text{ K}) = 4 \text{ n}\Omega\text{m}$)
- Very brittle material (A15)
- $\mu_0 H_{c2}(0\text{ K}) \approx 15 \text{ T} ; \mu_0 H^*(4,2\text{ T}) > 14 \text{ T}$

Critical current density (MgB_2 filaments)



Cryocourse 2011

Grenoble September 2011



Applied
superconductivity

VIII.
SC MAGNETS

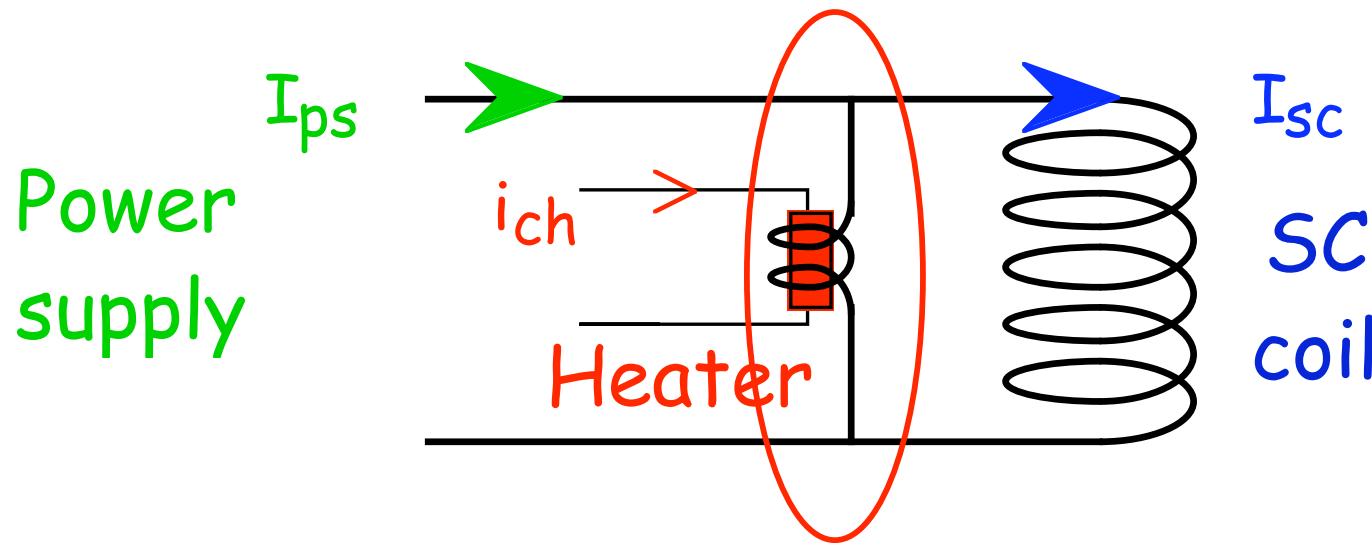
SC strand-cable choice 1/2

- Superconductor - NbTi - Nb_3Sn - HTS
 - Field level
 - Cryogenics (4 K - 1.8 K - 30 K)
- Conductor - assembled - CICC ...
 - Mechanical stresses
 - Cooling technique

SC strand-cable choice 2/2

- | Filament diameter
 - | Stability
 - | Hysteresis losses
 - | Permanent currents (remanent field)
 - | Operating mode (continuous, pulsed)
- | Matrix
 - | Protection
 - | Coupling losses
 - | Cryostabilization

Constant current operation



SC shunt with thermal (or magnetic) control

- Ultra constant current
- No power supply in normal operation
- No current lead losses (current leads removed)
(cold discharge resistances for protection)

Electromagnetic design - example

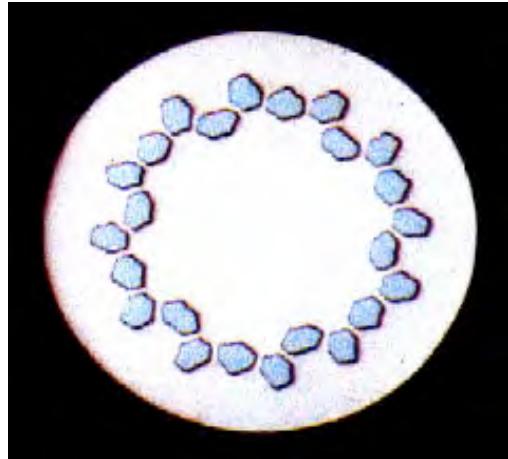
Need for 5 T in a bore of \emptyset 60 mm - h = 100 mm
No special requirements

5 T ==> Simplest solution :
NbTi @ 4.2 K (Helium bath)

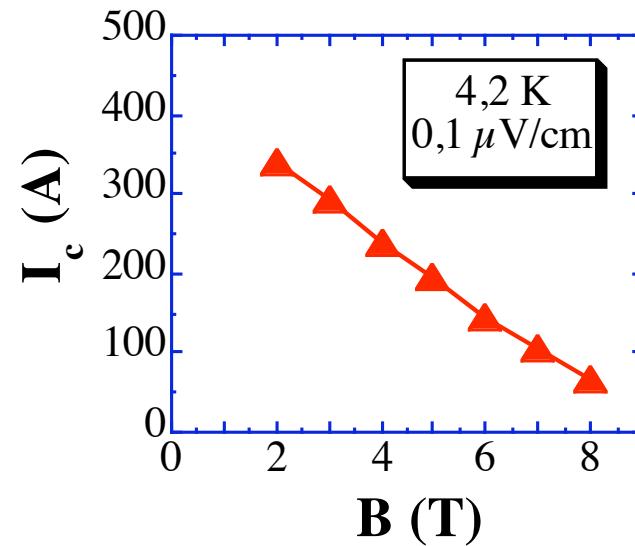
Small coil : single strand

Value of current ?

- Section
 - flexibility (winding difficulties)
 - number of turns
- Power supply
- Current lead
 - Realization
 - Losses (prop. to the current)



Alstom wire (0.8 mm)
24 NbTi filaments



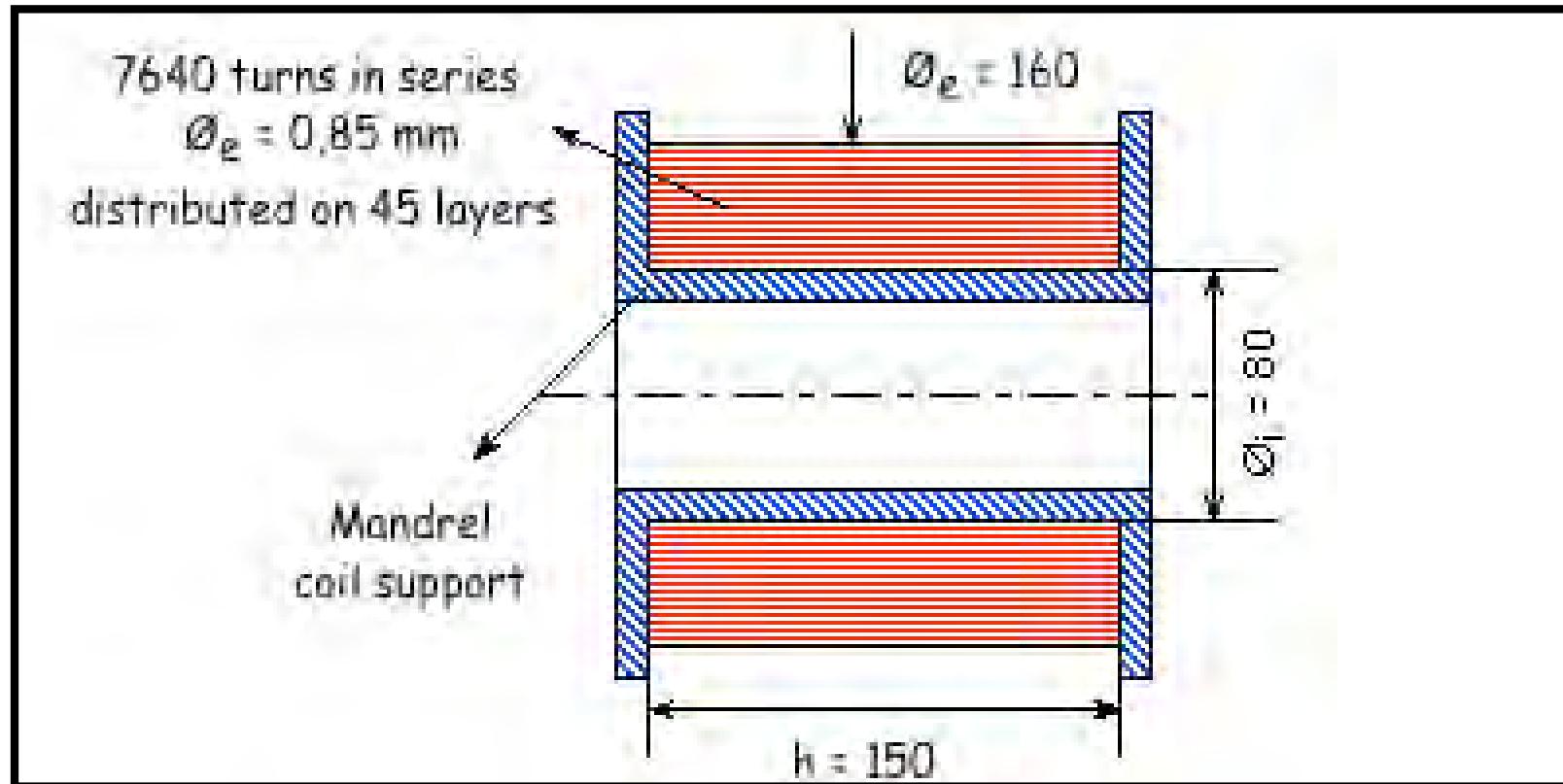
5 T
fl
 $I_c = 190 \text{ A}$
fl
 $I_e = 100 \text{ A}$

Coil design

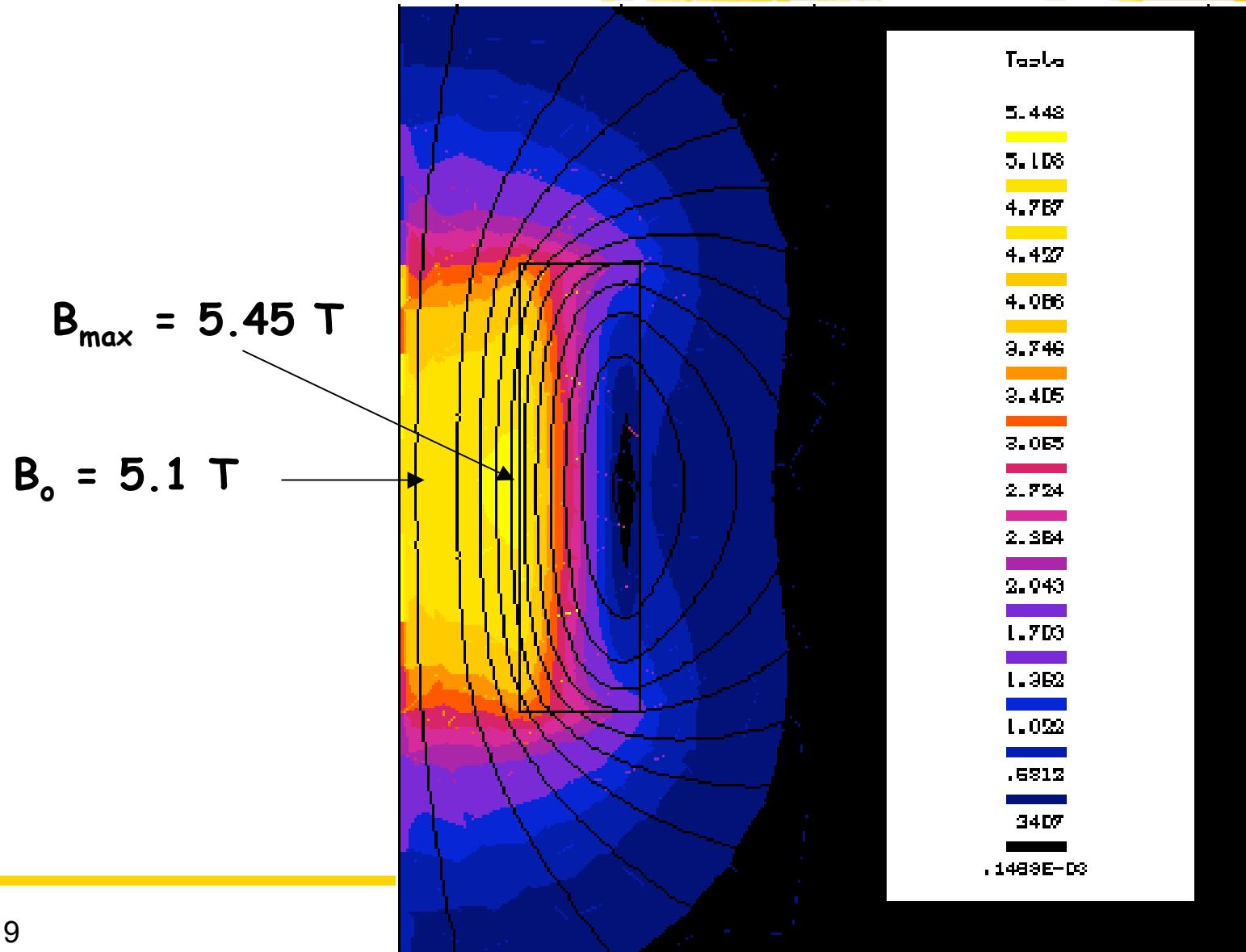
$$B_o = \frac{\mu_o N_s I}{\sqrt{h^2 + D^2}}$$

$$B_o = 5 \text{ T} ; I = 100 \text{ A}$$

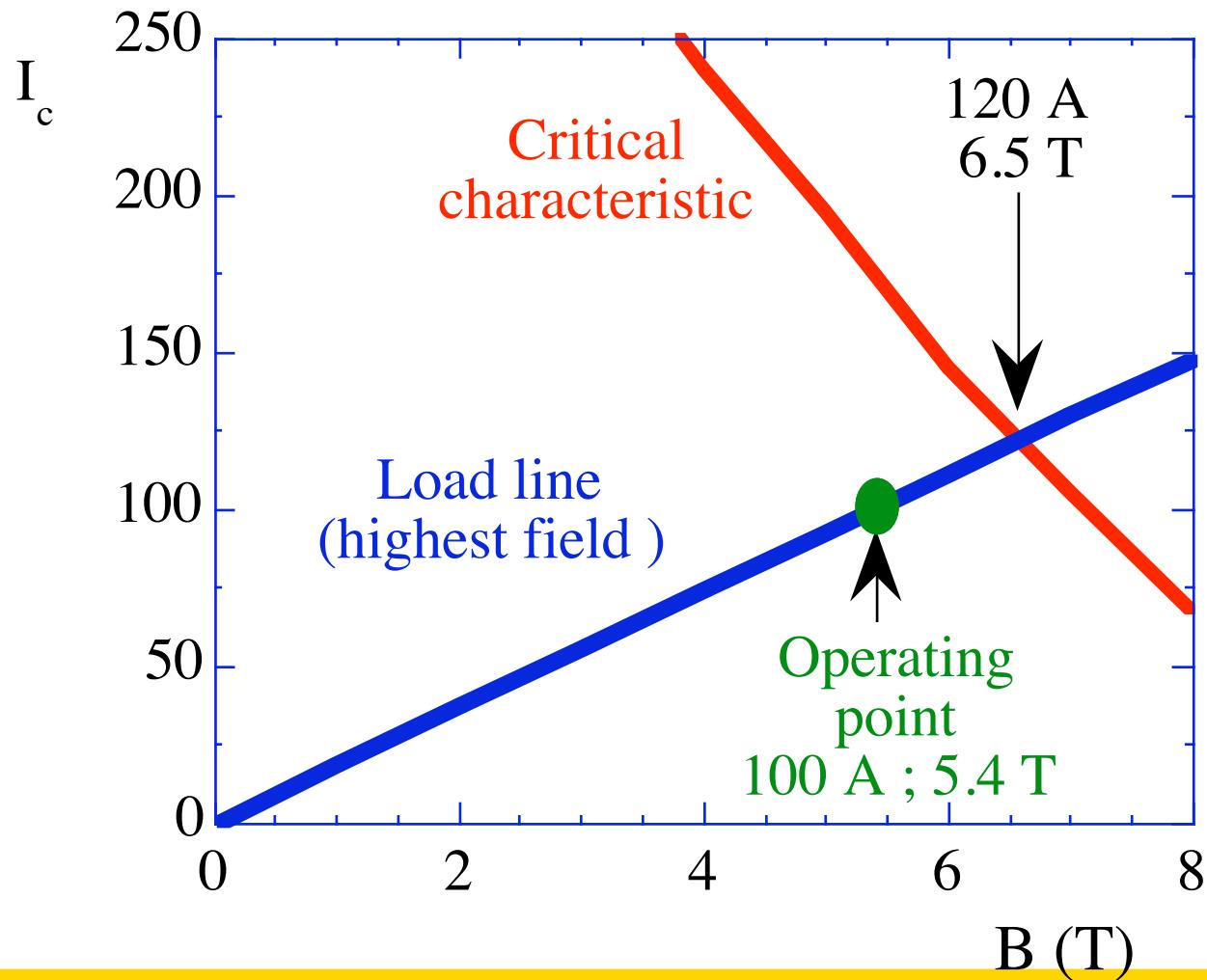
After some iterations :



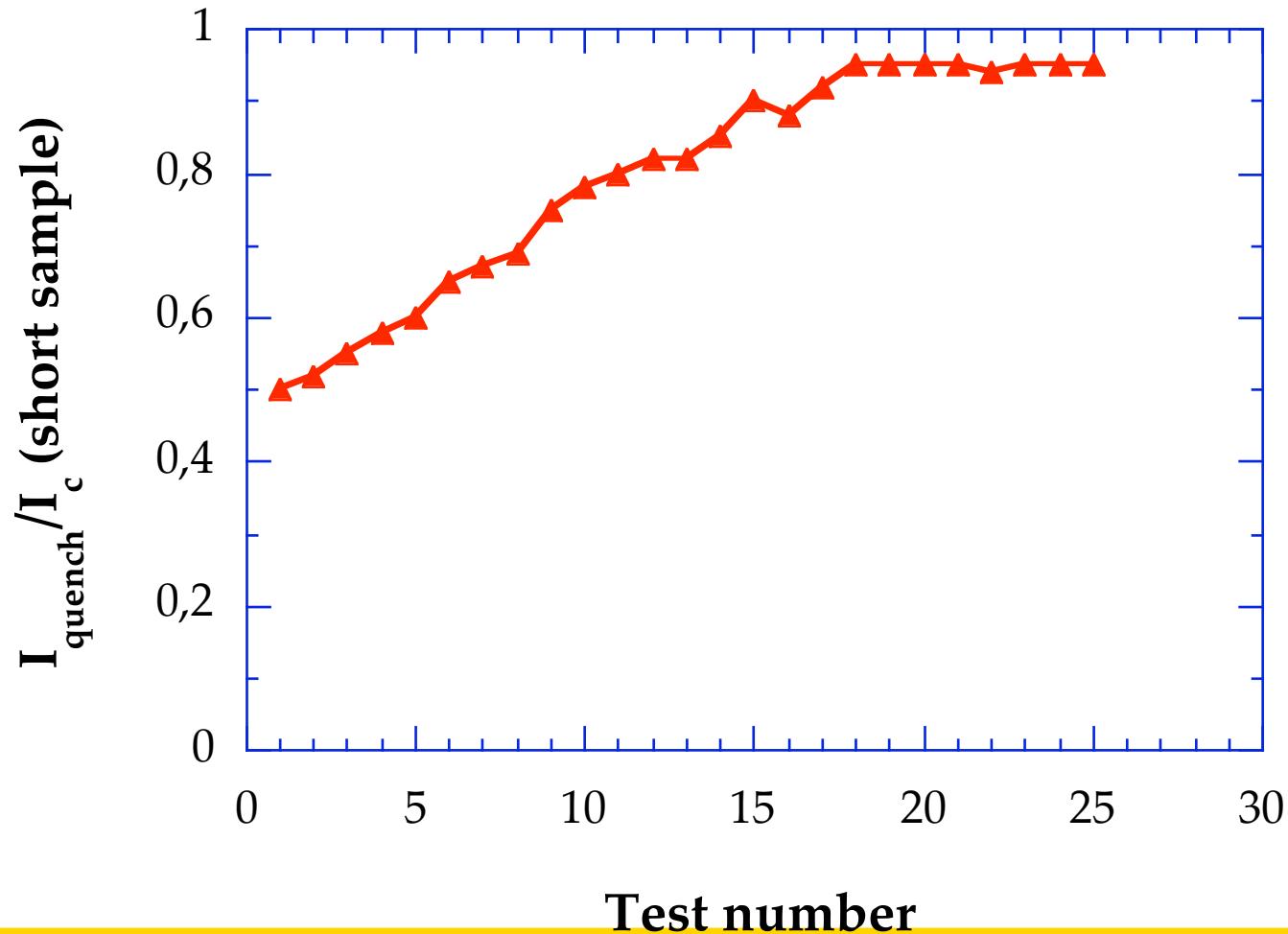
Field distribution



Load line



Training



Cooled magnets

- Possibility to extract losses by cooling fluid
- Possible operation even with perturbations
- SC state recovery

Very stable magnets but
large and expensive magnets

Cryostable magnets

- | Steckly criterion
 - | High matrix/SC ratio
 - | Low using factor I_o/I_c
 - | Large cooling surfaces
 - | Efficient cooling
 - | He I, 4.2 K - 1 atm
 - | He II, 1.8 K - 1 atm (*Claudet bath*)

Non cooled magnets

- Little possibility to extract losses
- Reduction of the perturbations
- Very stable conductor
 - Fine filaments, high Cu/SC ratio, low I_o/I_c
- Very good mechanical design
 - Rigorous holding, shrinkage, impregnation
- Protection from varying fields
 - Electromagnetic shields

Field quality

- Geometry
- Magnetic circuit magnetization
- SC filament magnetization
- Coupling losses
- Current non equilibrated distribution

Mechanics

Fundamental for SC magnets

Viriel theorem => very simple relation
between magnetic energy and magnet mass

$$W_{\text{mag}} = (M_t - M_c) \sigma_u / d$$

Steel 30 kJ/kg ; Carbon fibers 150 kJ/Kg (ultimate data)

Classical value \approx 10 kJ/kg (Record 13.4 kJ/kg)