Superconducting Magnets theory and design

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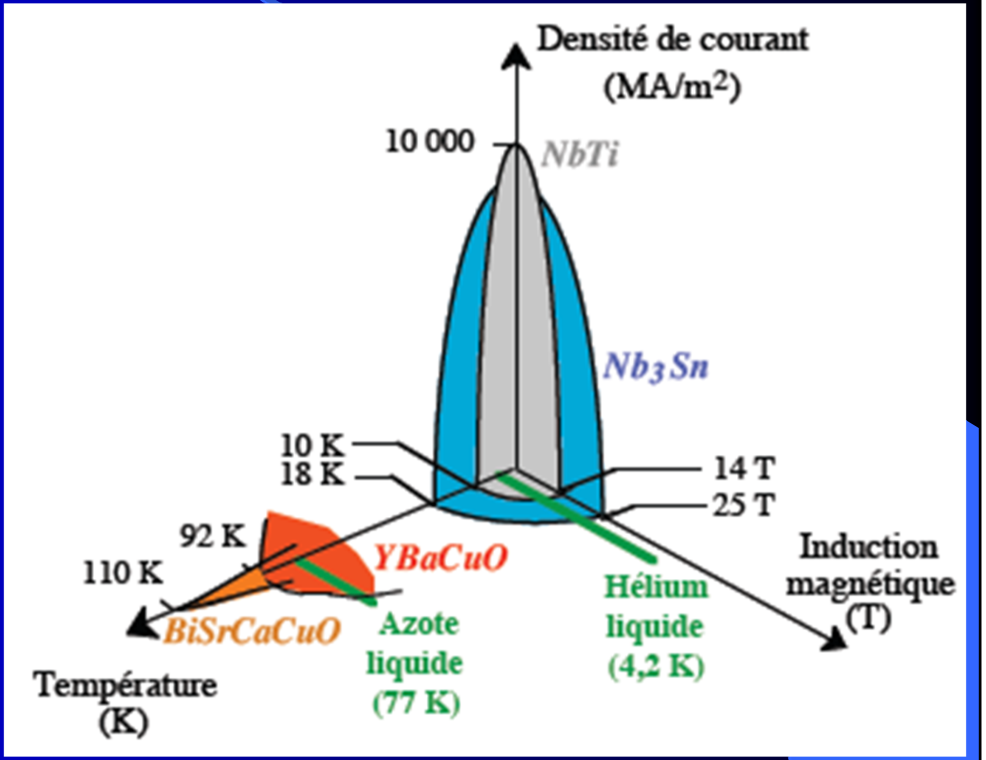
Superconducting wire
Critical parameters

- Critical temperature
- Critical magnetic field
- Critical current density



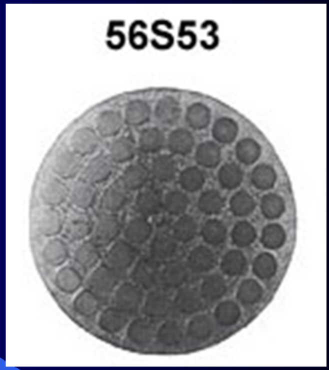
Critical surface for superconducting materials

Different type of superconducting wire

- LTC superconducting wire
  - NbTI
  - Nb_3Sn, Nb_3Al
- MTC superconducting wire
  - MgB_2
- HTC superconducting wire
  - Bismuth tape
  - YBCO tape

LTC superconducting wire

- NbTi conductors (many fine filaments of a niobium-titanium (NbTi) alloy embedded in a copper matrix)
  - The most commonly used (developed since the sixties)
    - *High performance*
    - *Tc (0T) = 9,5K ; Tc (11T) = 4,1K*
    - *Feasible industrially (Supercon, ASC..)* 2000 t/year
    - *Easy to provide*
    - *Competitive cost (around 300 $/km depend on wire diameter or 100 $/kg or* 1 €/kA/m*)*
    - *Guaranteed critical characteristic*
    - *Easy to handle and no special precautions for use (like copper wire)*
    - *Lot of choice (size, resistive matrix, copper proportion, multi or mono filamentary…)*
    - *Isotropic properties*
  - Operate at 4 K or lower temperature
    - *Helium cryogenic*
    - *High refrigeration cost 1W/700W*



Ø = 0.5 mm

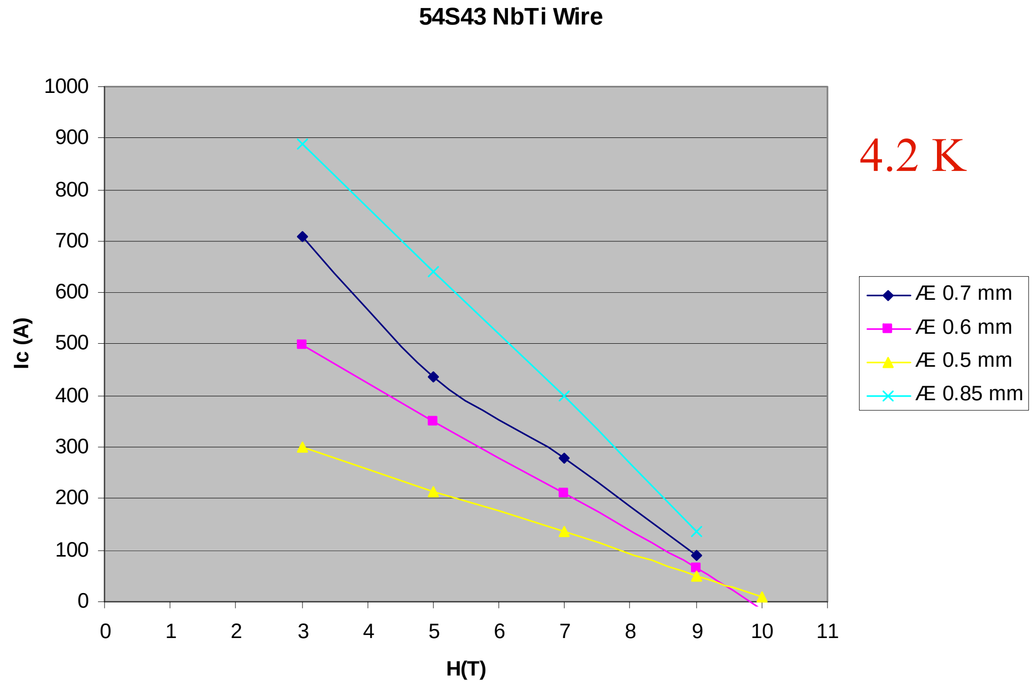
I_c = 500 A

J_e = 2500 A/mm^2

(4.2 K ; 0 T)

LTC superconducting wire

pe	No. of Filaments	Cu to SC Ratio	Diameter (mm)		Critical Currents (Amps @ 4.2K) at fields (Tesla,T)				Filament Diameter (µm)
			Bare	Insulated	3T	5T	7T	9T	
56S53	56	00.9:1	0.30	0.330	125	100	55	20	30
			0.40	0.430	270	190	120	45	39
			0.50	0.540	470	330	205	70	48
			0.60	0.643	620	440	270	100	58
			0.70	0.753	850	600	370	135	68
			0.85	0.896		790	490	175	83
54S43	54	1.3	0.30	0.330	100	80	45	16	25
			0.40	0.430	215	150	90	30	35
			0.50	0.540	300	215	135	50	45
			0.60	0.643	500	350	210	65	55
			0.70	0.753	710	435	280	90	60
			0.85	0.896	890	640	400	135	75
			0.95	1.000		780	480	165	85
			1.04	1.094		880	550	200	90
			1.25	1.300			750	240	110
54S33	54	2.0	0.40	0.430	150	110	70	23	31
			0.50	0.540	240	170	105	32	38
			0.60	0.643	360	240	160	50	46
			0.70	0.753	500	350	210	70	54
			0.85	0.896	730	500	300	100	65
			0.95	1.000		610	360	120	73
			1.04	1.094		700	400	155	80



For our NbTi Coil

- We used 54S43 multifilament wires from supercon company
- Good stability (1/3 of copper) and good performances
- Coil design limited under 9.5 T at 4.2 K

LTC superconducting wire

- In superfluid helium at 1.8 K we can reach up to 12 T
- BUT
  - When operated at reduced temperatures and higher fields, the energy in the magnet can be increased by 50% or more.
    - Consequently, the magnet might be irreparably damaged if a quench occurs and if the magnet is not sufficiently protected

LTC superconducting wire

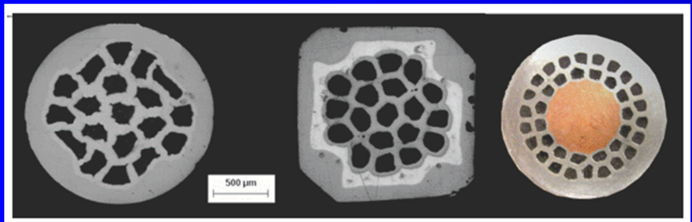
- Multifilamentary, Niobium-Tin (Nb_3Sn) conductors
  - Characteristics
    - Are used when the field on the conductor is in excess of about 9 Tesla (90 kilogauss)
    - Better critical characteristics than NbTi
      - (Tc (0T) = 18,3 K; Tc (11T) = 10,4K ; $Jc=10^6$ A/cm^2)
    - Allow to reach higher field (up to 18 T)
    - Used for fusion application (ITER) (fields of 13 T are needed)

LTC superconducting wire

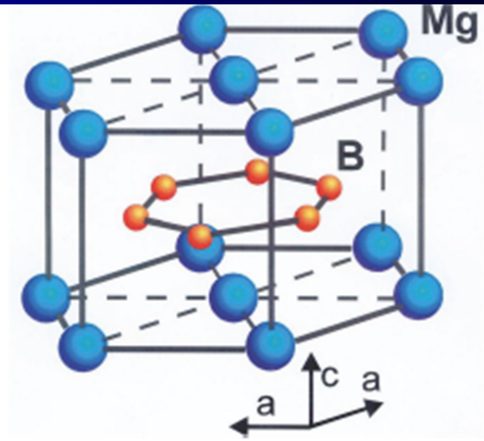
- Multifilamentary, Niobium-Tin (Nb3Sn) conductors
  - Difficult to wind
  - The coil must be realized before the heat treatment of the wire (lead to impregnation problem)
  - Very brittle after the heat treatment
  - expensive $2000/kg ; 10 €/kA/m ; only 20 t/year produced
  - Cost more than NbTi magnets.
  - Like for NbTi magnets, some improvement in performance can also be achieved by reducing the temperature of Nb3Sn magnets, but the increase in field is not as significant as it is in NbTi magnets
- Nb_3Al
  - Better mechanical properties in comparison with Nb_3Sn
  - Industrial development much less advance than for Nb_3Sn

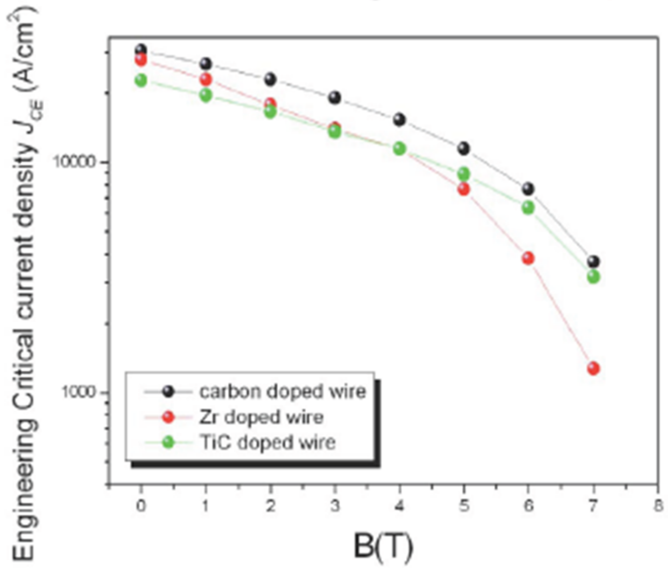
MTC superconducting wire

- MgB_2
  - Tc (0T) = 39K
  - $J_E = 3*10^4$ A/cm^2
  - Fabrication process : Powder in tube (PIT)
  - Long length available (several km) in Nb+Cu or Fe+Cu matrix
  - Marketable, development in progress:
  - Cost ≈ 100 €/kA/m



Different type of MgB2 wire
Diameter 1-2 mm
(Columbus Superconductors SpA)





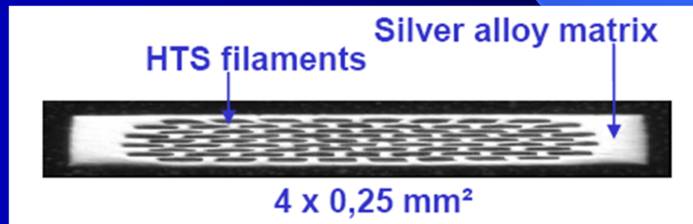
HTC superconducting wire

- Critical temperature around 100K
  - Liquid nitrogen 77K or cryocooler

- Bismuth PIT tape (powder in tube)

fil Bismuth PIT

fil



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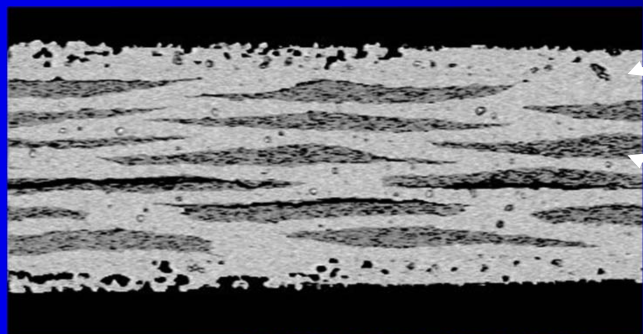
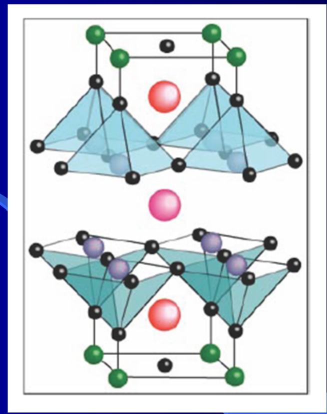


Silver

Bismuth

HTC superconducting wire

■ Bismuth PIT wire



- ◆ High anisotropy
- ◆ Available in kilometric length
- ◆ Tc = 110K (Bi_{2223}); Jc=5.10^4 A/cm^2 (77K);
- ◆ Very brittle wire
  - *Minimum bend radius*
  - *Problem with successive thermal cycling (ice in porosity which damage the wire during the following cooling)*
- ◆ Expensive (due to silver matrix 5€/m) Bi_{2223} ≈100 €/kA/m

HTC superconducting wire

- Bismuth PIT wire

  - Difficult to make solenoid coil due to rectangular cross section (critical current decreases rapidly when we applied a bend along the radial direction)

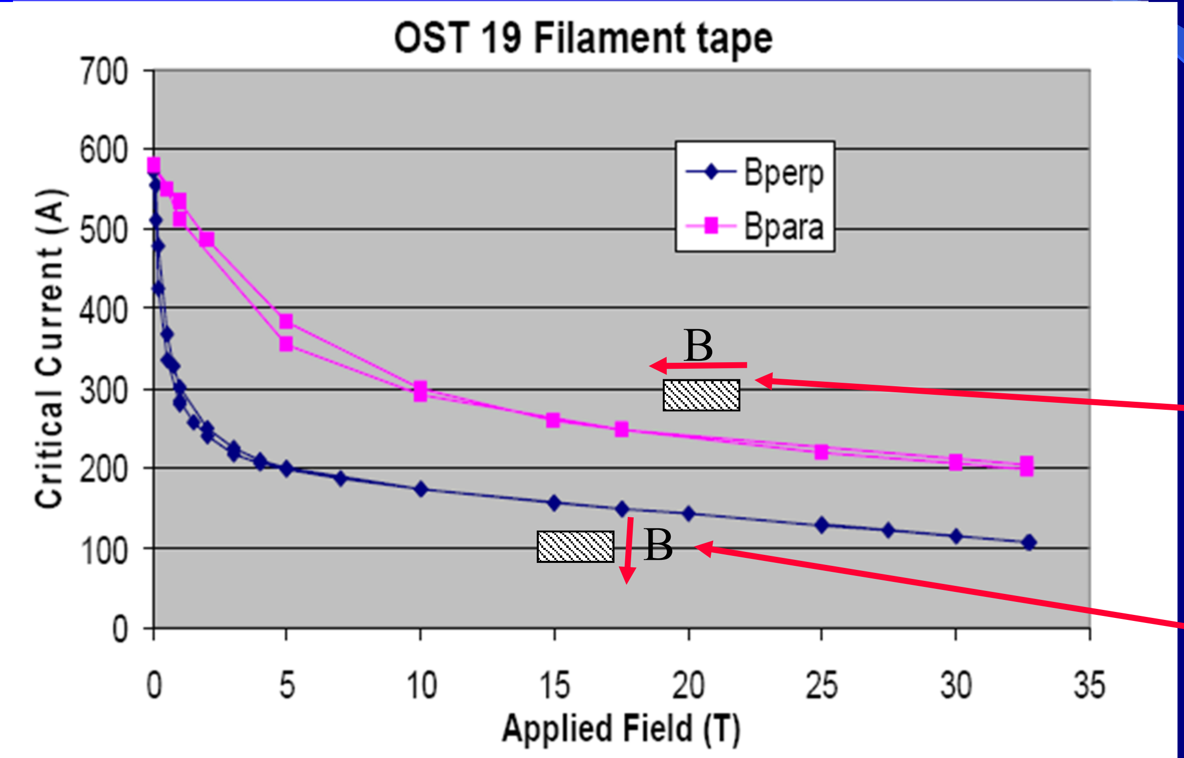
    - *Pancake coil*

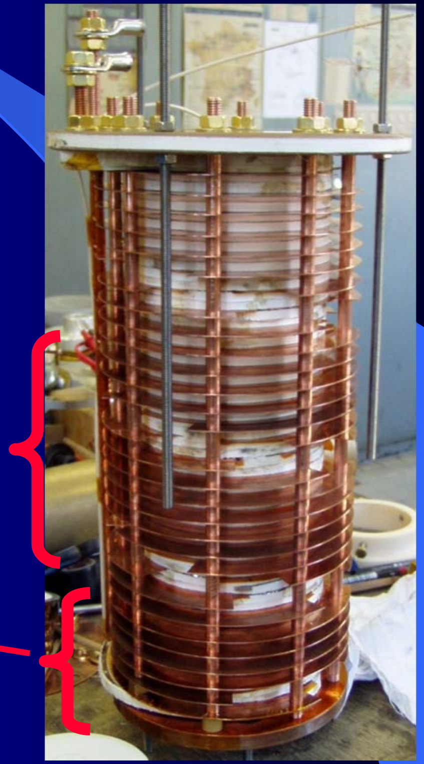
  - Low mechanical properties (alloys silver Mg for matrix or used of stainless steel tape in parallel to reinforced the structure)

  - Cryogenic cost less important than for superconducting LTC coil

HTC superconducting wire

- Bismuth PIT wire
  - High anisotropy

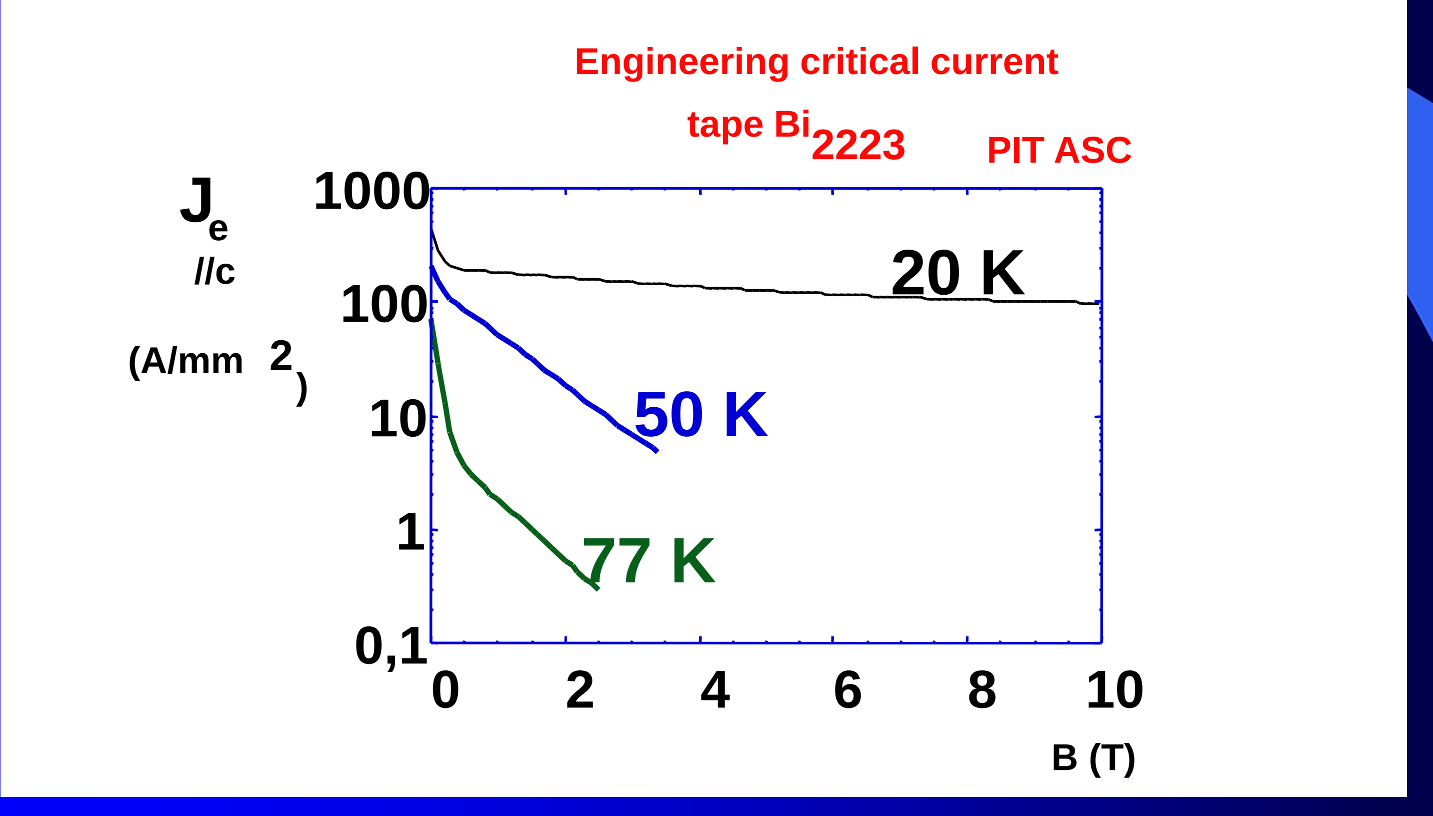




In comparison with LTC superconductors this tape have always a critical current at high field. It can be used to do insert inside high field coil

HTC superconducting wire

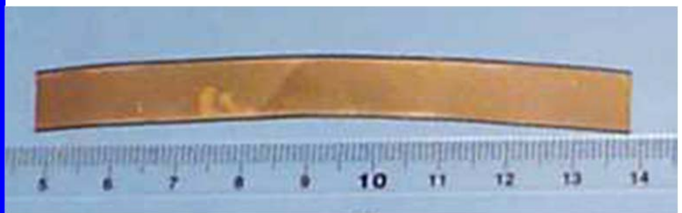
- Bismuth PIT wire
  - Critical current is very sensitive to the magnetic field at high temperature, at low temperature it is much better

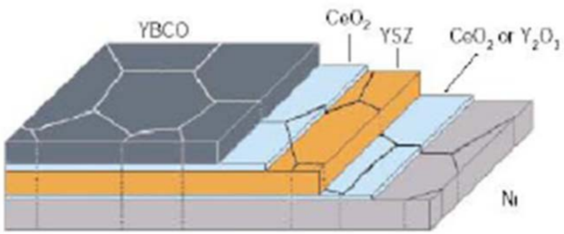


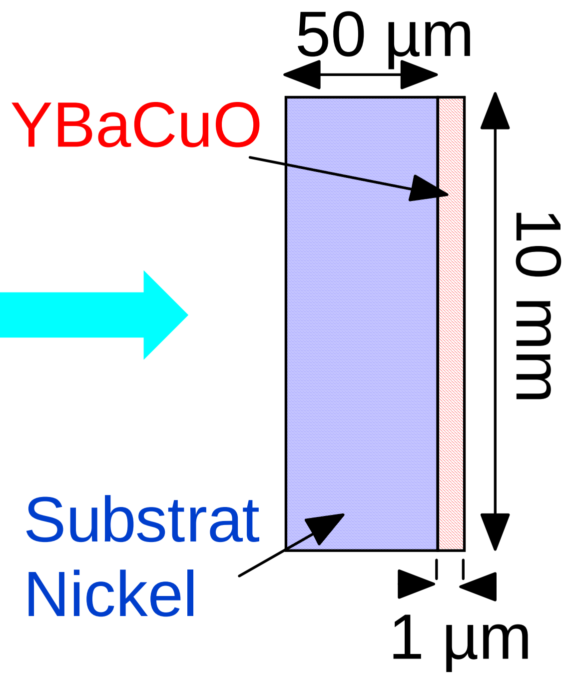
HTC superconducting wire

- Coated conductors YBaCuO

YBaCuO tape ; I_c = 200 A





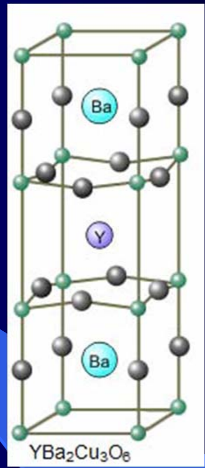


Nickel substrate textured by rolling

Buffer layers are deposited then YBCO is deposited

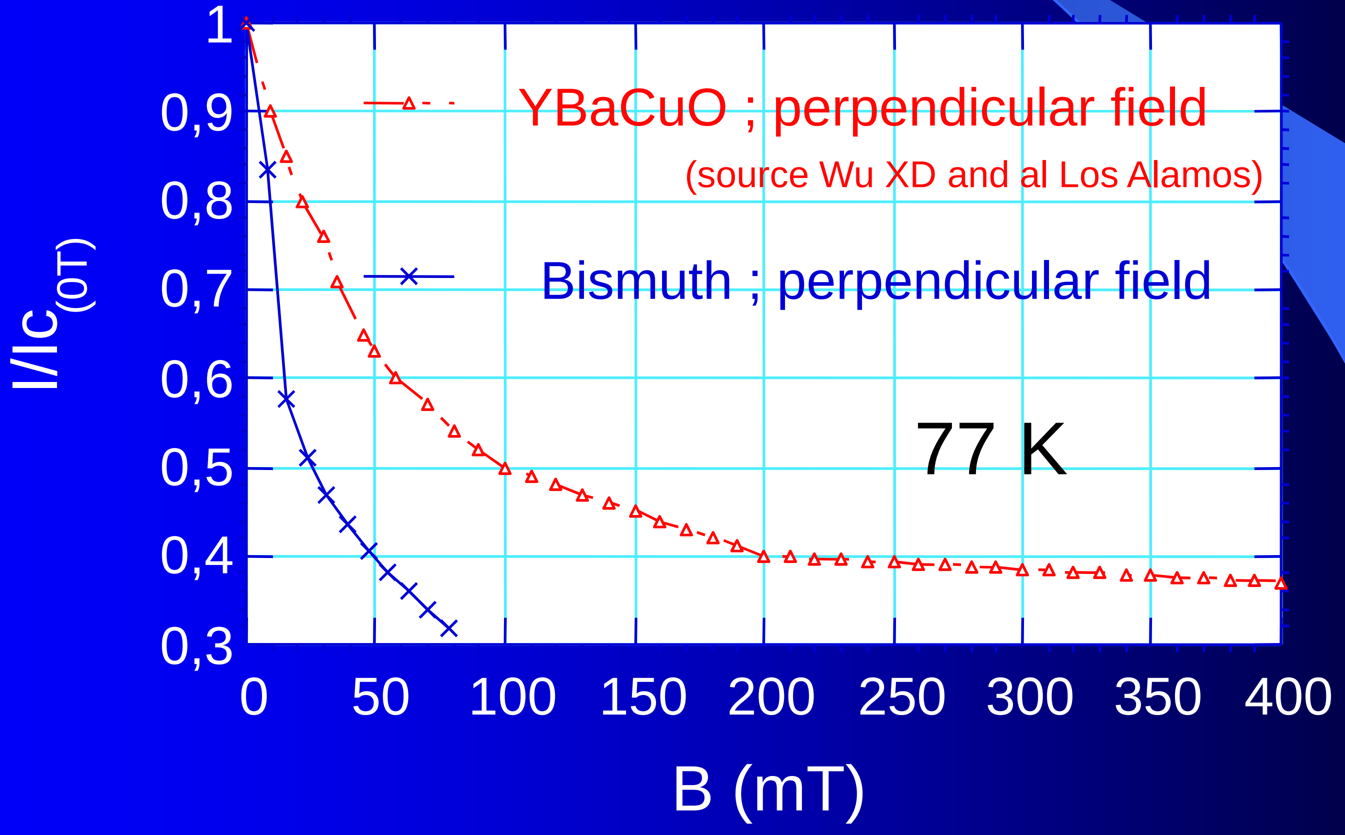
HTC superconducting wire

- Coated conductors YBaCuO
  - High anisotropy
  - High Tc and critical current density Tc=92K; Jc=5.10^{4} A/cm^{2} (77K) ; Jc=2.10^{6} A/cm^{2} (4.2K)
  - Difficult to do (epitaxial growth of YBCO layers)
  - For the moment, no real industrial process to do it in long length (100m) with constant critical properties
    - MOCVD, PLD,
  - No economical blocking (no silver like for PIT tape)
  - Interesting but expensive for the moment
    - > 200 €/kA/m

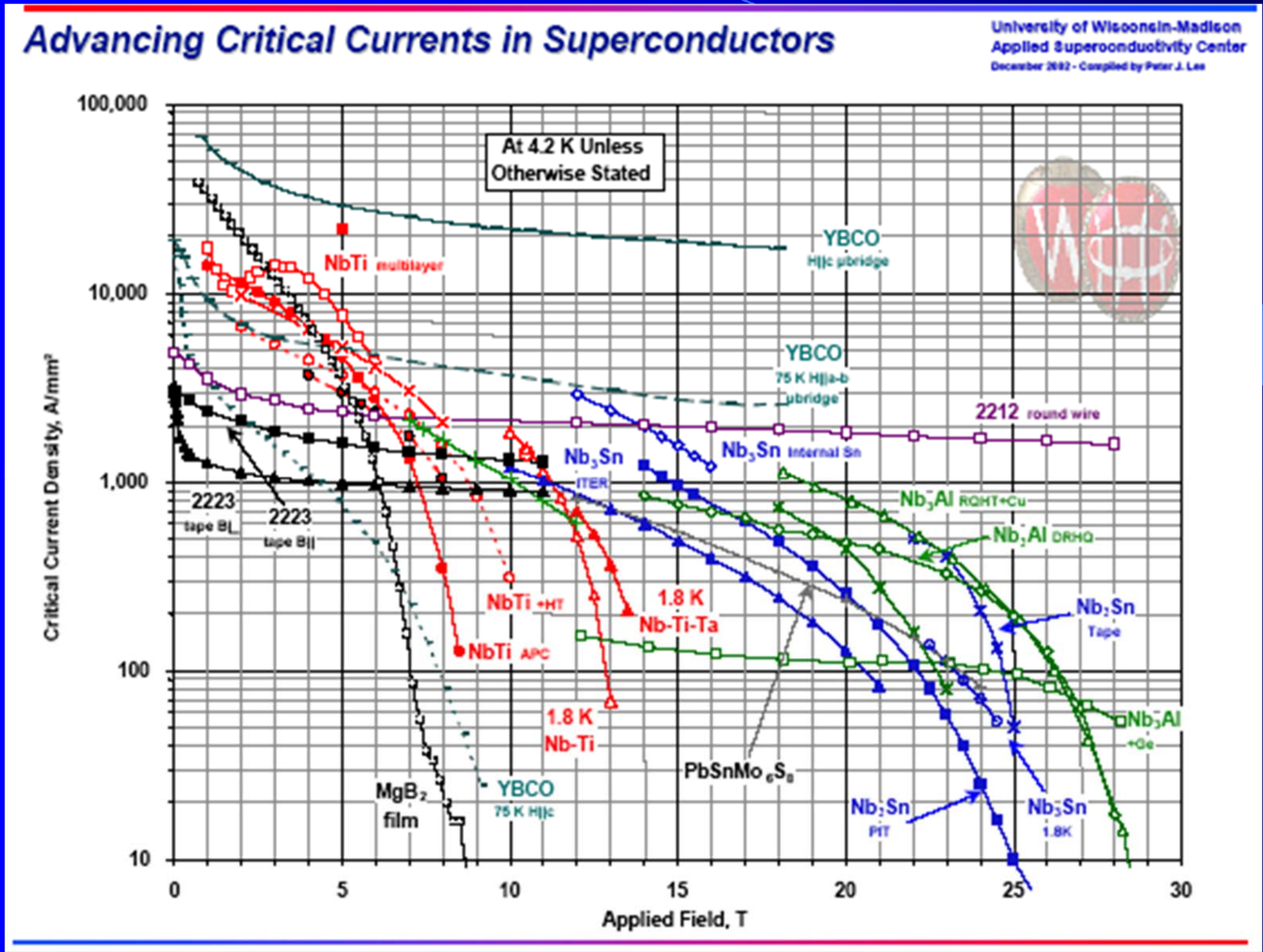


HTC superconducting wire

- Coated conductors YBaCuO



Comparison LTC and HTC



Cost today:

NbTi : 1 €/kA/m ;
Nb3Sn : 10€/kA/m
MgB2 : 100€/kA/m
Bisco : 200€/kA/m

YBCO : 300€/kA/m

Interest to do a superconducting magnet

- Compared to copper coil
  - Generate intense magnetic fields with low electrical power input
  - Current densities are high :
    - *superconducting magnet systems are quite compact, more light and occupy only a small amount of laboratory space*
- very high field stability (superconducting switch)
- No losses in DC application, low electrical power consumption

Superconducting magnet

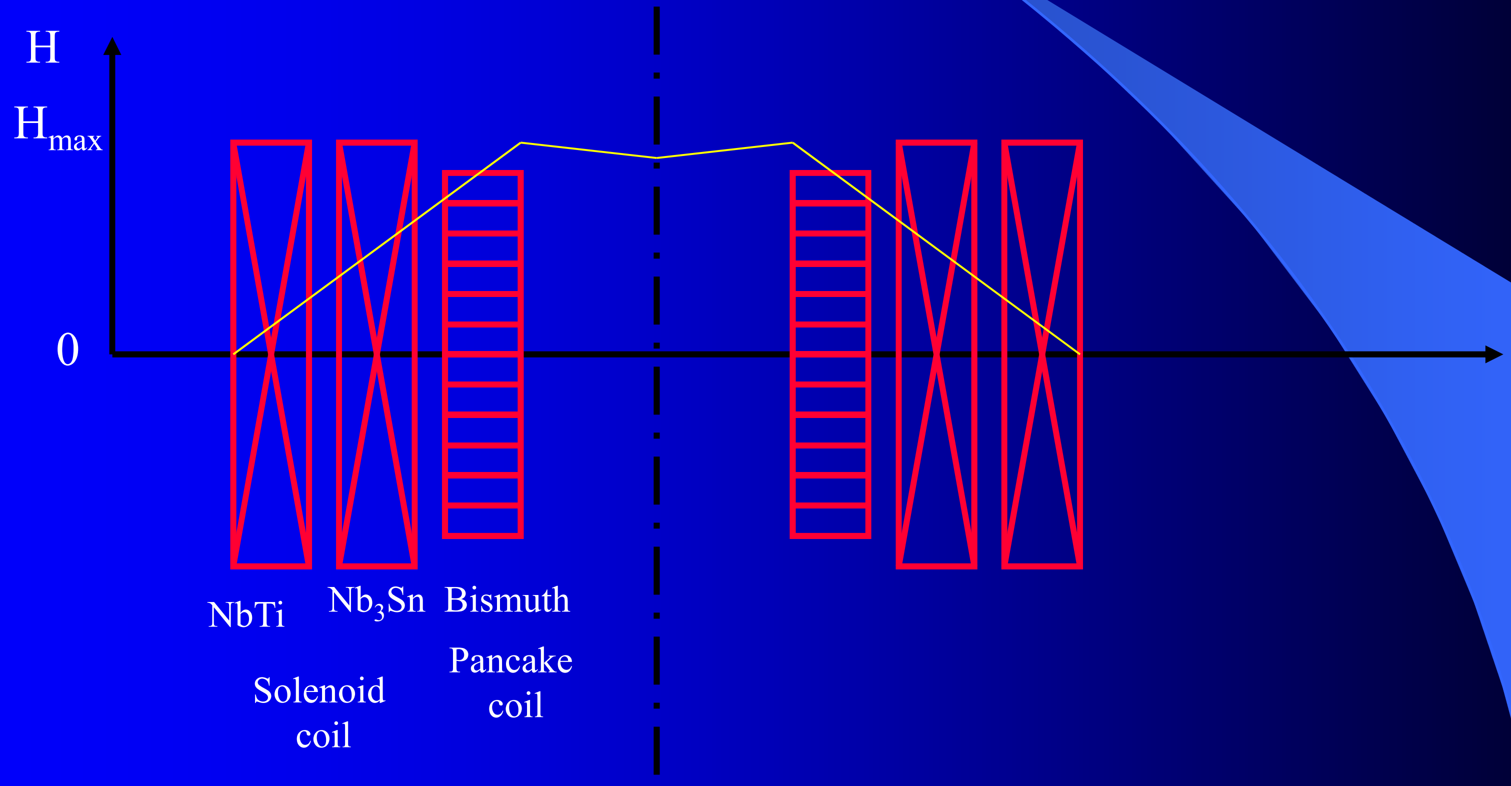
- Small superconducting magnets
  - are frequently used :
    - *to reach field intensities, stabilities or field shape that are not reachable with alternative magnets*
    - *cost less than conventional magnets offering comparable or inferior performance.*

- In large magnets
  - cost in favor of superconducting magnets (based on the relative costs of power for operating the magnets).
    - The cost becomes more favorable for superconducting magnets as the period of operation increases.

- For magnetic field intensities of 1 Tesla or less, without demanding stability requirements :
  - Frequently better generated with water cooled copper coils with or without iron.

Superconducting Magnet

- Geometry for high field coil >20 T



High field magnets could be wound with a combination of NbTi wires in the low field region followed with Nb3Sn wound in medium field region and using Bi2212 windings in the high field region.

Laboratory superconducting magnet design

- User's specifications
  - Magnetic field configuration (maximum field, field shape, compensated zone, stray field)
  - Environmental constraints (geometrical, hole field size, weight, material used for mandrel, flange)
  - Operating mode (DC or AC or Pulsed, long term stability ➔superconducting switch)

Laboratory superconducting magnet design

- First design approach
  - Determine the winding configuration
    - Ampere-turns needed to produce the field
    - The stored energy
    - The peak field in the conductor region
    - An estimate of the magnetic forces and the needed mechanical structure
    - The dependence of these parameters on the average current density in the winding

Laboratory superconducting magnet design

- First design approach
  - Cooling mode
    - Pool boiling
      - *very efficient, ➔ direct contact with helium, we must used superfluid helium at 1.8 K*
      - *but we need a solid and lick-tight helium vessel*
    - Forced flow internal cooling
      - *very efficient, cooling directly inside the conductor*
      - *no helium vessel but difficult with internal joint*
    - Indirect cooling
      - *heat conduction through a compact winding from a restricted cooling loop or cryocooler*
      - *simplest scheme but sensibly lower efficiency*
      - *use for magnet operating in steady state regime*

Laboratory superconducting magnet design

- First design approach
  - Stability
    - Ability of a superconducting magnet to operate without accidental transition to the normal state under thermal disturbance
      - *Stability margin*
        - Cooling method
        - Conductor characteristics

Laboratory superconducting magnet design

- First design approach
  - Stability
    - Example : impregnated superconducting solenoid ; He pool boiling
      - *Maximum field on conductor : 9T*
      - *Nominal current : 90 A*

…e	No. of Filaments	Cu to SC Ratio	Diameter (mm)		Critical Currents (Amps @ 4.2K) at fields (Tesla,T)				Filament Diameter (µm)
			Bare	Insulated	3T	5T	7T	9T	
56S53	56	00.9:1	0.30	0.330	125	100	55	20	30
			0.40	0.430	270	190	120	45	39
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			0.85	0.896	730	500	300	100	65
			0.95	1.000		610	360	120	73
			1.04	1.094		700	400	155	80

Laboratory superconducting magnet design

- First design approach
  - Quench protection
    - Resistance or diode in parallel on the output of the coil
    - Quench detector for certain coil with high energy
    - Shut down the power supply in case of quench

Electrical insulation

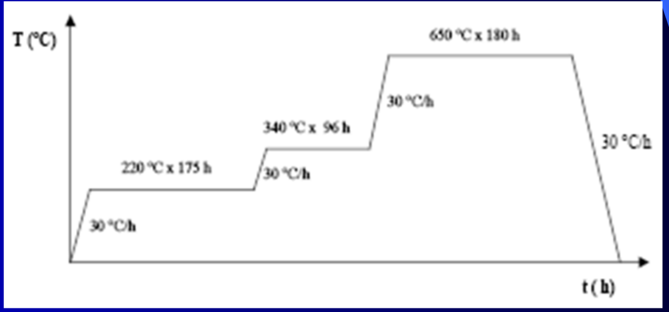
- In steady state there is no voltage across the coil
  - But
    - *during the quench ➔ fast dump of current*

      ➔high voltage can be created and can damage the magnet

- Special requirement for cryogenic insulation
  - Related to electrical, thermal and mechanical properties
  - We mainly used
    - *Fiber glass, glass-epoxy composite (G10 G11), Kapton (polyimide film), araldite for impregnation, Mylar (polyester films, "polyethylene terephthalate"), teflon ("Polytetrafluoroethylene (PTFE) "), nylon*

Electrical insulation

- For Nb_3Sn magnet, there is another difficulty :
  - Thermal cycle at high temperature (660- 700 °C) required to synthesize the superconducting phase
    - *Polymer insulation cannot be used before the thermal cycle*
    - *Usually fiberglass spacers are used during thermal cycle ➔ this step is followed by a impregnation under vacuum*
    - *Nb_3Sn superconducting phase and fiberglass are very brittle after the heat treatment➔ impregnation process needs special care*



Electrical insulation

- Table : Electrical and thermal properties for insulating materials (p 347 handbooks of cryogenic engineering)

Insulating materials	Thermal conductivity at 4.2 K (W/m · K)	C_p at 4.2 K (J/kg · K)	Integrated thermal contraction from 293 to 4.2 K (%)	Breakdown voltage DC condition (kV/mm)
Liquid helium	0.028	4500	–	30 at 4.2 K
Gas helium	0.008	7300	–	15 at 4.4 K 0.5 at 77 K 0.2 to 0.3 at RT
Glass–epoxy composite	0.07 ± 0.02	0.4 to 2	0.16 to 0.38 depending on fiber orientation	
• Unidirectional				
parallel to fiber	0.13 ± 0.05		0.1 to 0.55	
transverse to fiber			0.26 to 0.8	
• Woven 48% fiber				
longitudinal	0.07 ± 0.02		depending on fiber volumic fraction	
through thickness	0.06 to 0.075			
Glass fiber	0.12 ± 0.02			
Glass	0.1			
Phenolic resin (varnish)	0.6	3.2	0.9	118 at 300 K
Polyimide film	0.045	17	0.4 ± 0.1	301 at 4.2 K
Epoxy resin	0.04 to 1.1	1.4 ± 0.6	1.15 ± 0.06 rigid 1.1 flexible 1.5	
Polyethyleneterephtalate	0.008	0.96	0.42	543 at 4.2 K
Polytetrafluoroethylene	0.043 ± 0.003	2.96	2.1 ± 0.6	33 at 4.2 K
Polyethylene	0.012	0.8 crystalline 2 amorphous	1.5	360 at 4.2 K
Nylon	0.012		1.5	
Copper used in superconductor		0.09	0.29	

Impregnated NbTi superconducting solenoid

- Superconducting solenoid construction
  - Theoretical design
  - Mechanical part design, machining
  - Winding and impregnation
  - Protection
  - Superconducting switch
  - Magneto forming contact
  - Cryogenic tests, training, field card

8 T coil with 0 field zone

Impregnated NbTi superconducting solenoid

- Theoretical design
  - First approach
    - Choose the most appropriated wire to do the coil (wire diameter, critical current)
      - *Maximum current define by the user (power supply, experimental set up)*
      - *Maximum field and size of the hole field*
    - Estimation of number of turns to reach the user's specification
      - Max field, volume, compensated zone, field shape, field homogeneity at the maximum,
      - first estimation

Calculation of magnetic induction in the center of a solenoid with constant field density

$$B = \frac{\mu_0 NI}{H}$$

N : nb of turns, I current
, H solenoid length

$$B = 0.4.\pi.h.J.\lambda.\ln\frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}} \quad Gauss - cm - A$$

h = ½ length (cm)
J = current density in the superconducting wire (A/cm^2)
α = external radius / inner radius
β= half length / inner radius
λ = packing factor

Impregnated NbTi superconducting solenoid

- Estimation of energy

$$W = \frac{1}{2} L I^2$$

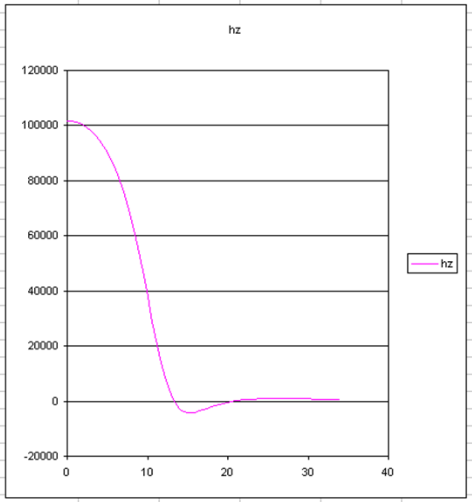
  - With L(μH)=2.2*N^2*D^2/(2.2*H+D)
    Solenoid length H(m) diameter D(m), avec N nb of turns
    - *For a solenoid having H/D>.2, with a degree of accuracy of 3%.*

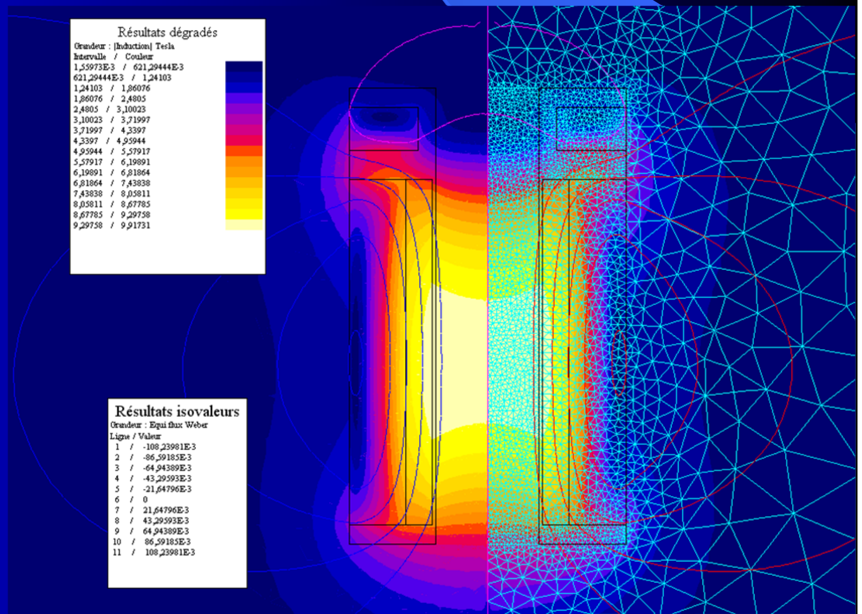
Impregnated NbTi superconducting solenoid

- more accurate work :
  - Thanks to a finite element software Flux2D, 3D (computation electromagnetic software) or FORTRAN programs
    - We can calculate precisely the magnetic field in all place of the space (axial, radial and total magnetic field)
    - Calculate inductance , energy
    - Calculate Lorentz force distribution in the winding for stress analysis σmax ≈ 270 MPa for NbTi and 240 MPa for Nb3Sn

a1	a2	b	densite
3,2025	4,8	10,025	9609,49
4,83	7,95	10,025	26741
4	8,32	14,175	-25938,89
4	8,32	11,675	25938,89

z	r	hz	hr	ht
0	0	101701,647	0	101701,647
0,5	0	101602,544	0	101602,544
1	0	101303,317	0	101303,317
1,5	0	100798,171	0	100798,171
2	0	100077,334	0	100077,334
2,5	0	99126,8894	0	99126,8894
3	0	97928,5644	0	97928,5644
3,5	0	96459,508	0	96459,508
4	0	94692,097	0	94692,097
4,5	0	92593,8523	0	92593,8523
5	0	90127,5813	0	90127,5813
5,5	0	87251,9248	0	87251,9248
6	0	83922,5685	0	83922,5685
6,5	0	80094,4871	0	80094,4871
7	0	75725,7061	0	75725,7061
7,5	0	70783,1655	0	70783,1655
8	0	65251,2331	0	65251,2331
8,5	0	59143,0212	0	59143,0212
9	0	52513,5272	0	52513,5272
9,5	0	45471,519	0	45471,519
10	0	38184,8012	0	38184,8012
10,5	0	30873,5093	0	30873,5093
11	0	23790,3896	0	23790,3896
11,5	0	17192,82	0	17192,82
12	0	11313,011	0	11313,011
12,5	0	6330,592	0	6330,592
13	0	2350,7899	0	2350,7899
13,5	0	-607,4315	0	607,4315
14	0	-2609,0877	0	2609,0877
14,5	0	-3785,9116	0	3785,9116
15	0	-4308,3483	0	4308,3483

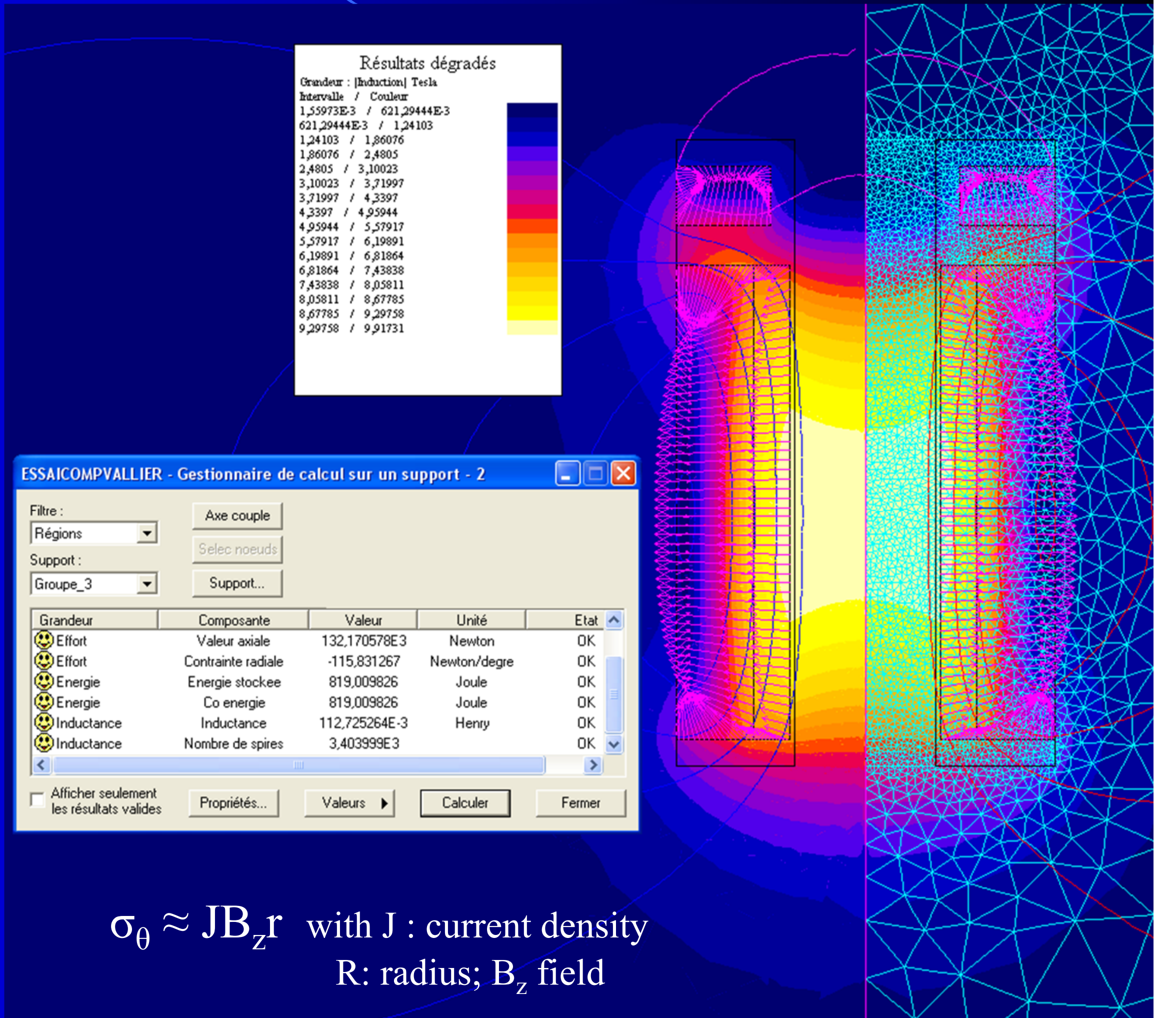




Induction shading

Impregnated NbTi superconducting solenoid

- Allows to choose the most appropriate superconducting wire
  - *bigger wire in the center of the coil where the field is maximum*
- Allows to design mandrel with material having the appropriate mechanical properties (define thickness)
  - *Aluminum, stainless steel or fiber glass mandrel*
- Make it possible to define the general shape of the coil to reach the specification (field homogeneity, maximum field, zero field zone etc ….)

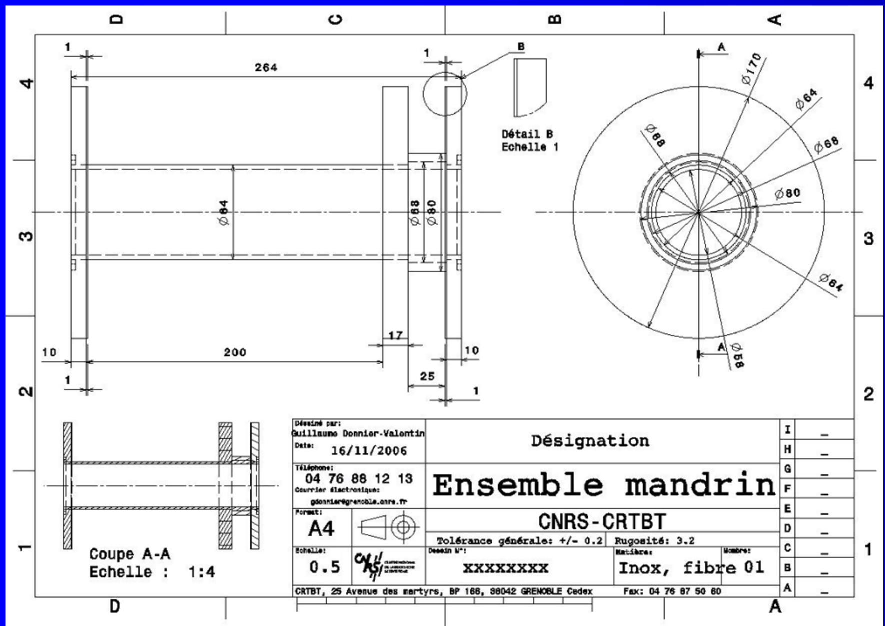


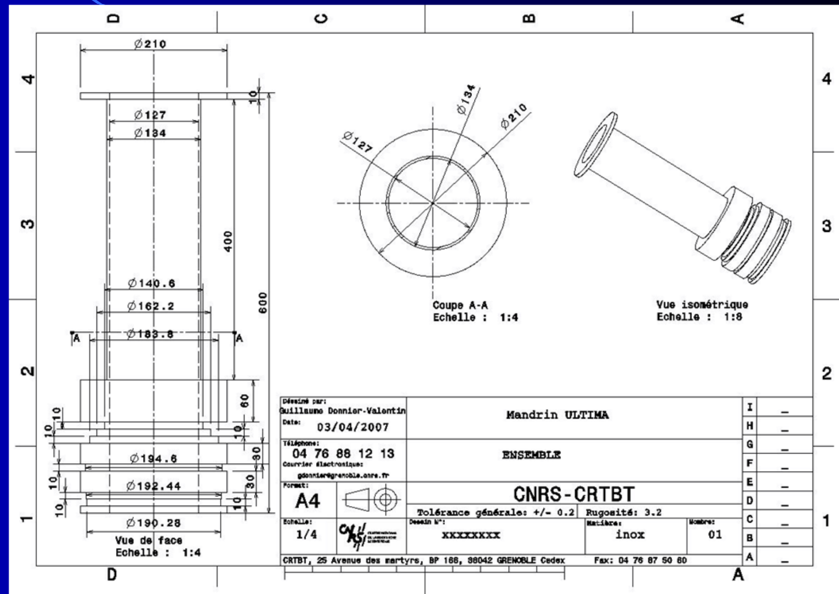
$\sigma_\theta \approx JB_z r$ with J : current density

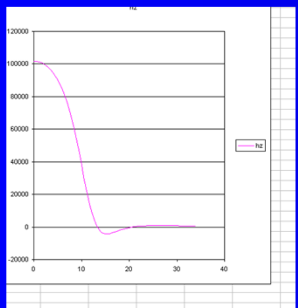
R: radius; B_z field

Impregnated NbTi superconducting solenoid

- Mechanical part design, machining
  - *Under 3D CAD Catia*

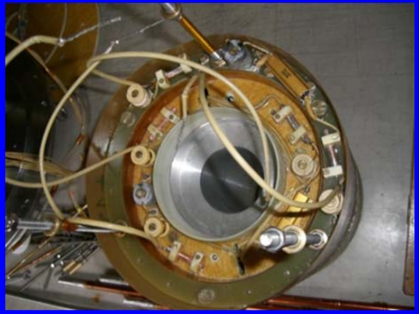


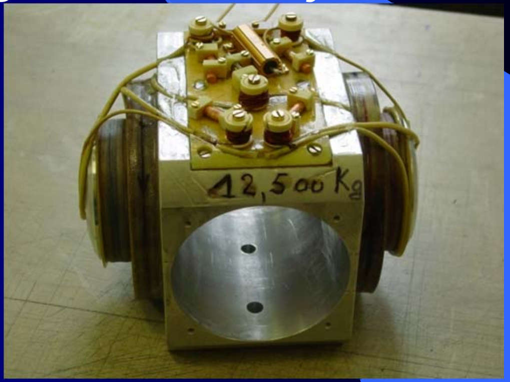




Impregnated NbTi superconducting solenoid

- Mandrel and flange insulation
  - The goal is to do electrical insulation between metallic mandrel, flange and the superconducting wire
    - *Use of kapton or mylar thin sheet around the mandrel*
    - *Use of thin fiber glass plate (0.5 - 1 mm) against extremity flange*





- Think about all wire entrances and outputs
  - Envisage all needed passage of wire before beginning the winding
  - Envisage all place and screwed hole you need to place contact, switch, resistance of protection, wire storage

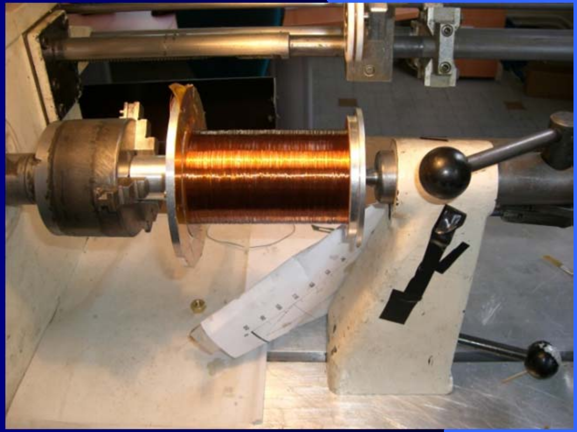
Impregnated NbTi superconducting solenoid

- Winding and impregnation
  - The winding
    - The goal is to make the most constant and homogeneous winding
      - *Determine the coil performance*
        - Field shape
        - Homogeneity
        - Superconducting wire stability

        - Control the wire tension

        - high tension :
        damage superconducting wire performance

        - not enough tension :
        low wire density, risk of wire movement during operation
          - due to high quantity of resin for impregnation, crack can easily appears



Impregnated NbTi superconducting solenoid

- The impregnation

  - To obtain a good insulation and a monolithic structure which cannot allow any movement of the conductor inside the coil

- Two techniques

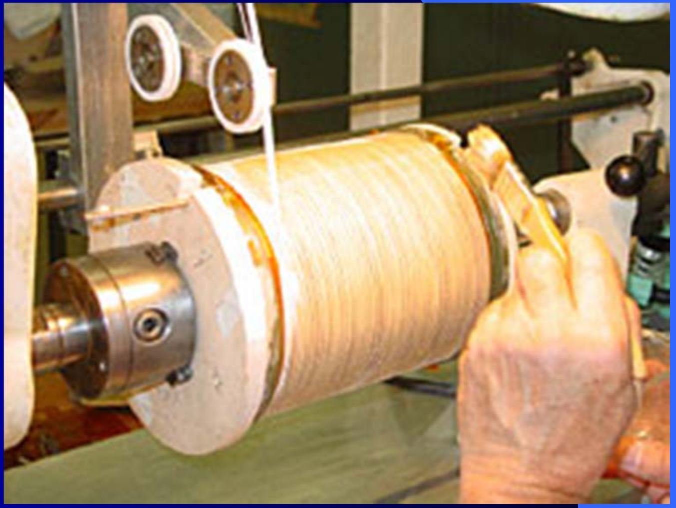
  - Vacuum Impregnation using epoxy resin
  - Direct impregnation layer per layer with a brush

Impregnated NbTi superconducting solenoid

- Vacuum Impregnation using epoxy resin
  - *Need of low viscosity resin (lower than 200 Mpa.S)*
    - ➔the resin flow through the different layers of the coil and through the glass fiber cloth
  - *There is always the risk of bubble formation*
    - Creates regions of reduced thermal conductivity
    - Risk of wire movement ➔ a risk of quench
  - *protect coil zones where we don't want resins after the process*
  - *Well cleaning the impregnation device after use*
  - *We must adapt the impregnation device for each different coil geometry ➔ expensive*
  - *Essentials for Nb_3Sn coil (because of heat treatment 600 - 700°C))*

Impregnated NbTi superconducting solenoid

- Direct impregnation layer per layer with a brush
  - *Difficult to obtain homogeneous impregnation*
    - Avoid to deposit high resins thickness ; risk of cracks
  - *More easier to control bubble formation*
  - *More easier to implement*
  - *Need handmade work*



- Good solution for laboratory coil which are all different the ones from the others

Impregnated NbTi superconducting solenoid

- Quench protection
  - to allow the magnet to quench safely
    - The quench
      - ➔ *conversion of the magnetic energy into heat inside the volume of the winding which has transited into the resistive state*
    - Protection techniques consist in :
      - *decreasing the current as fast as possible*
      - *without the appearance of over-voltages across or through the windings (max 500 - 1000 V)*
        - because of thin insulated layers and low helium voltage breakdown (300 V/mm at 300 K)

Impregnated NbTi superconducting solenoid

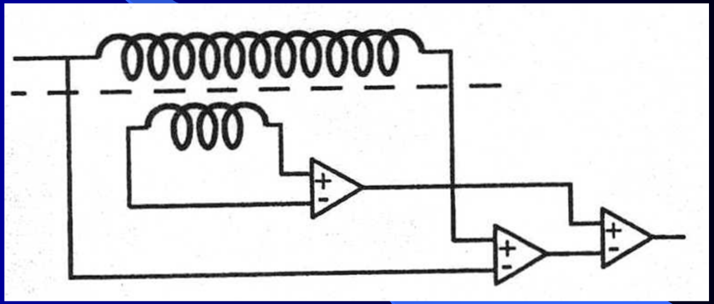
- Quench protection
  - *Discharge the energy into an external resistor*
  - *A significant part of energy is also dissipated inside the winding due to the Quench back effect*

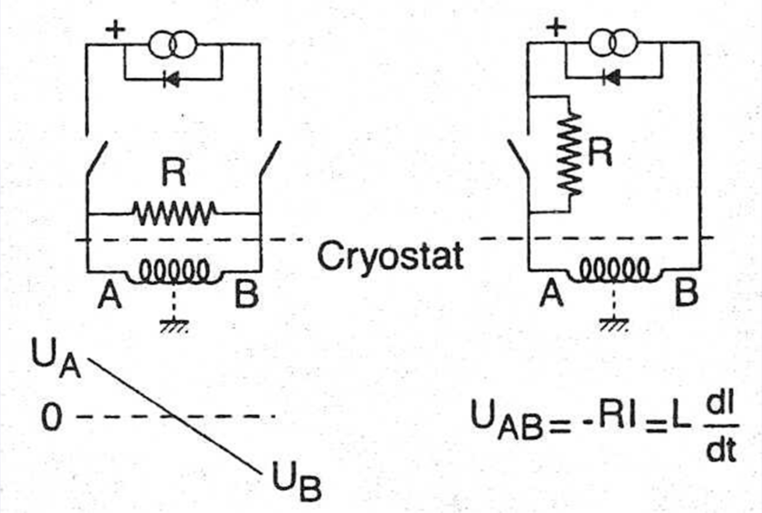
- Quench back effect
  - current decay → magnetic flux variation → eddy current in the coil mechanical structure →losses → heat → cause the quench of others coil parts still in the superconducting state

The result is a very fast growth of the coil resistance

Impregnated NbTi superconducting solenoid

- Quench detector
  - The device must detect a resistive voltage due to the quench which appear across the coil
    - One difficulty is that the inductive voltage is one or two order of magnitude greater
    - Electronic device allows to subtracting inductive voltage from the total magnet voltage
  - The stored energy is extracted outside the coil into an external resistor by opening of breaker triggered by the quench detector

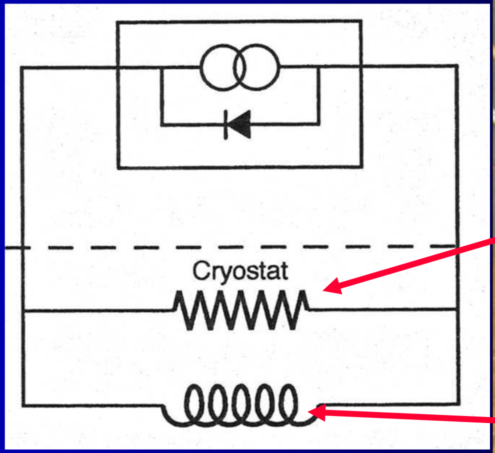


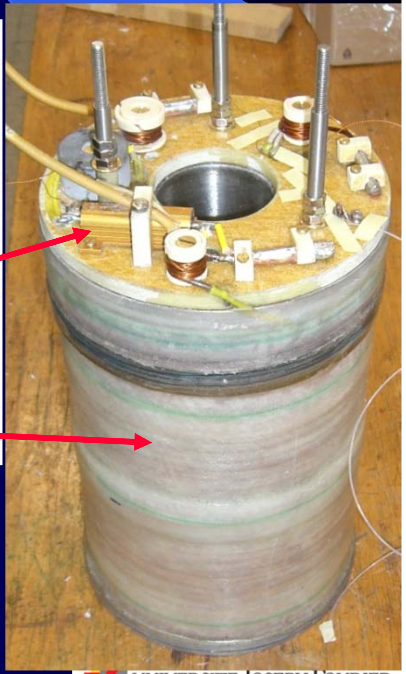


Impregnated NbTi superconducting solenoid

- For impregnated NbTi laboratory magnet
  - Not necessary to have quench detector
    - *Relatively low energy (hundred of kilojoules)*
    - *High current densities (hundred of amperes per square millimeters)*
      - internal resistance increase rapidly

  - The power source has its proper protective system against overvoltage
    - *If quench*
      - the power source is switched of
      - The current is discharged through the free-wheel diode of the source
      - A protective resistor must be mounted in parallel between the current lead terminals to prevent destructive damage in case of electrical line rupture





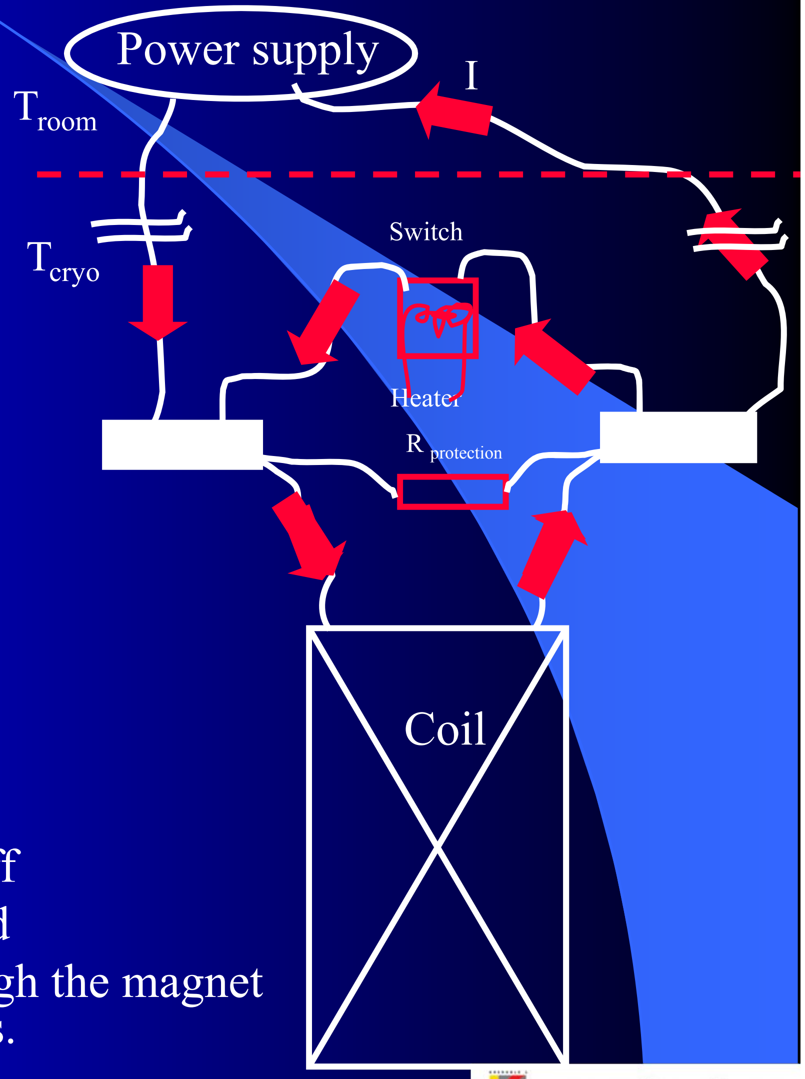
Impregnated NbTi superconducting solenoid

- Superconducting persistent switch
  - Used in order to increase magnet stability over long periods of time
    - (L/R time constant is extremely long → magnet can be operated for days or even months at a nearly constant field)
  - to reduce the rate of helium boil-off → no need of continually supplying current to the magnet.

- Description
  - persistent switch is comprised of
    - *a short section of superconducting wire connected across the input terminals of a magnet*
    - *Special superconducting wires with resistive CuNi matrix (multifilament NbTi wires)*
    - *an heater used to drive the wire into the resistive, normal state.*

Impregnated NbTi superconducting solenoid

- Superconducting persistent switch
  - Operation description
    - the heater is turned on (wire is resistive)
      - *a voltage can be established across the terminals of the magnet ➔magnet can be energized.*
    - the heater is turned off (wire becomes superconducting
      - *changes in the magnet current cannot be made.*

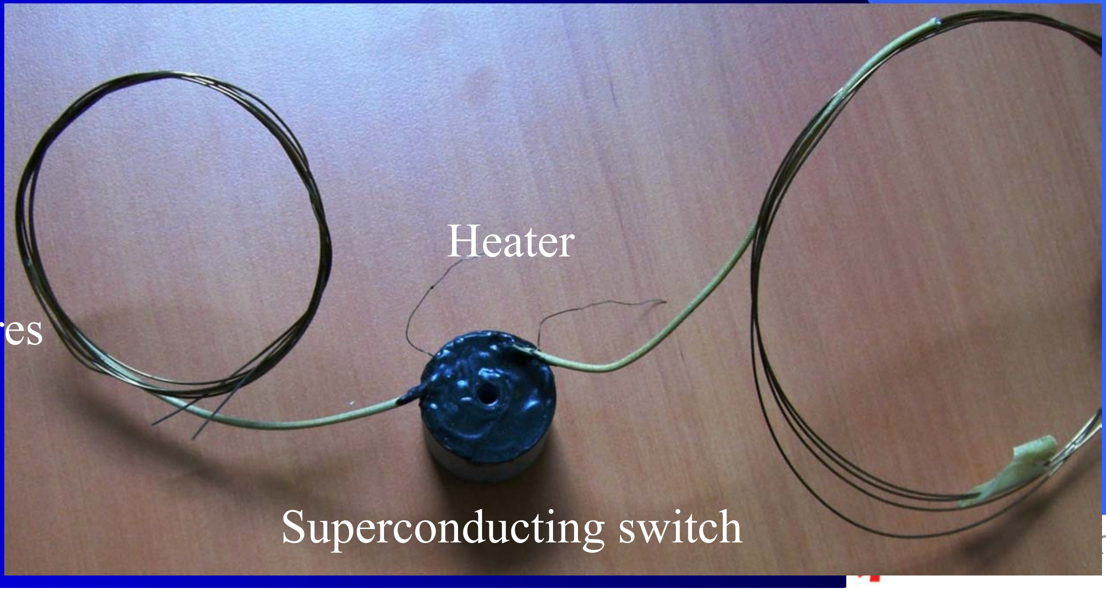


- In this persistent mode of operation,
  - the external power supply can be turned off
  - the heat input to the helium bath is reduced
  - the current will continue to circulate through the magnet and the persistent switch without losses.

Impregnated NbTi superconducting solenoid

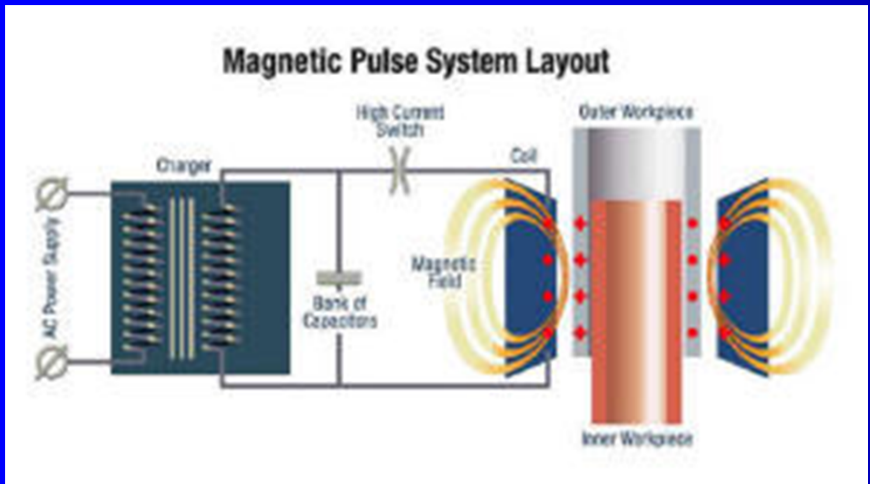
- Superconducting persistent switch
  - For a typical switch, the electrical heater in the persistent switch requires 300mW to drive the superconductor into the resistive state. The superconductive wire typically has 3 to 4 Ohms of resistance in the normal state
  - special care must be taken in making the joints between the switch and the magnet leads. (To avoid current dissipation and then magnetic field decreasing). ➔Magneto forming contact

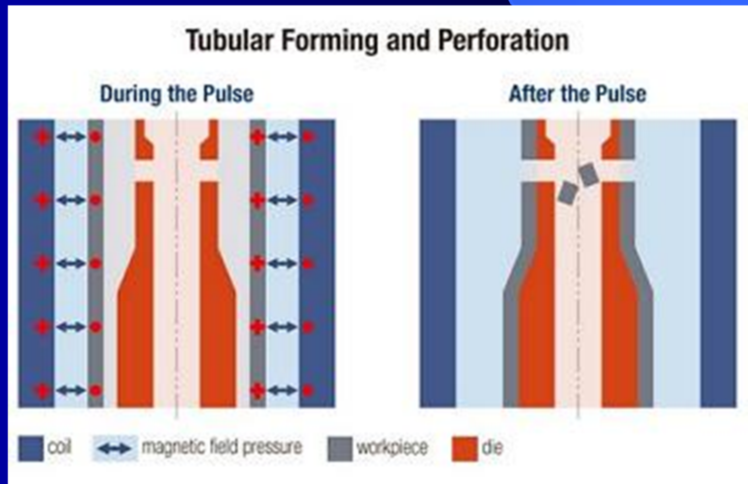
resistive CuNi matrix
multifilament NbTi wires



Impregnated NbTi superconducting solenoid

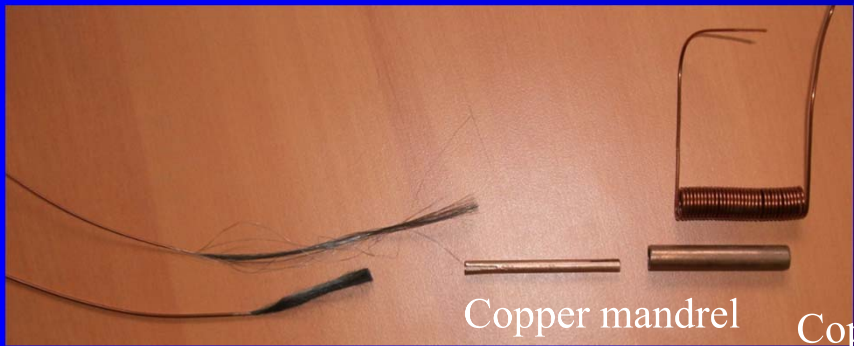
- Magneto forming contact (Magnetic Pulse Forming and welding)
  - The goal is to do an electrical contact with very low resistivity
    - A large current is discharged through a coil.
    - The discharging current creates a magnetic field. In the nearby sheet of metal an opposing magnetic field is induced. The result is that the two magnetic fields oppose and a force moves the sheet away from the coil.
    - Over a period of time the part is deformed, often to the shape of a mandrel
    - The method generates pressures up to 50 Kpsi creating velocities up to 900 fps





Impregnated NbTi superconducting solenoid

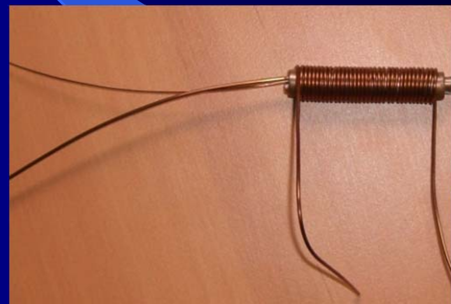
- Magneto forming contact



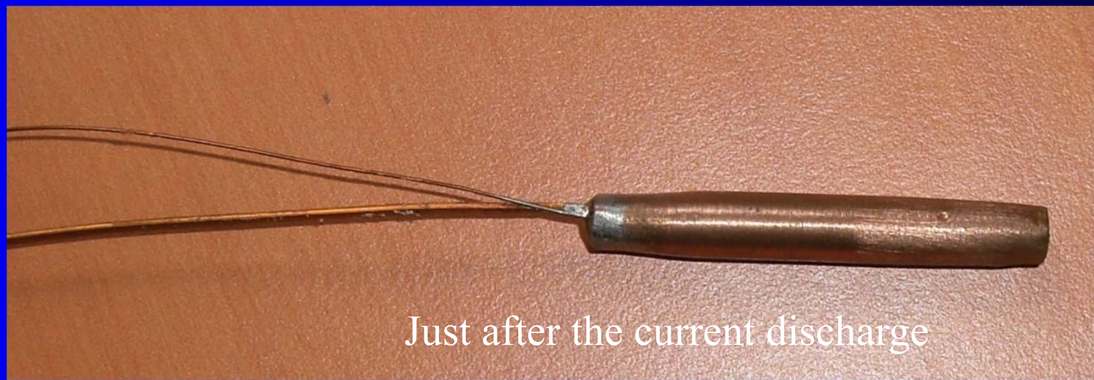
Copper coil

Copper tube

NbTi wire without copper matrix
(NbTi filaments)



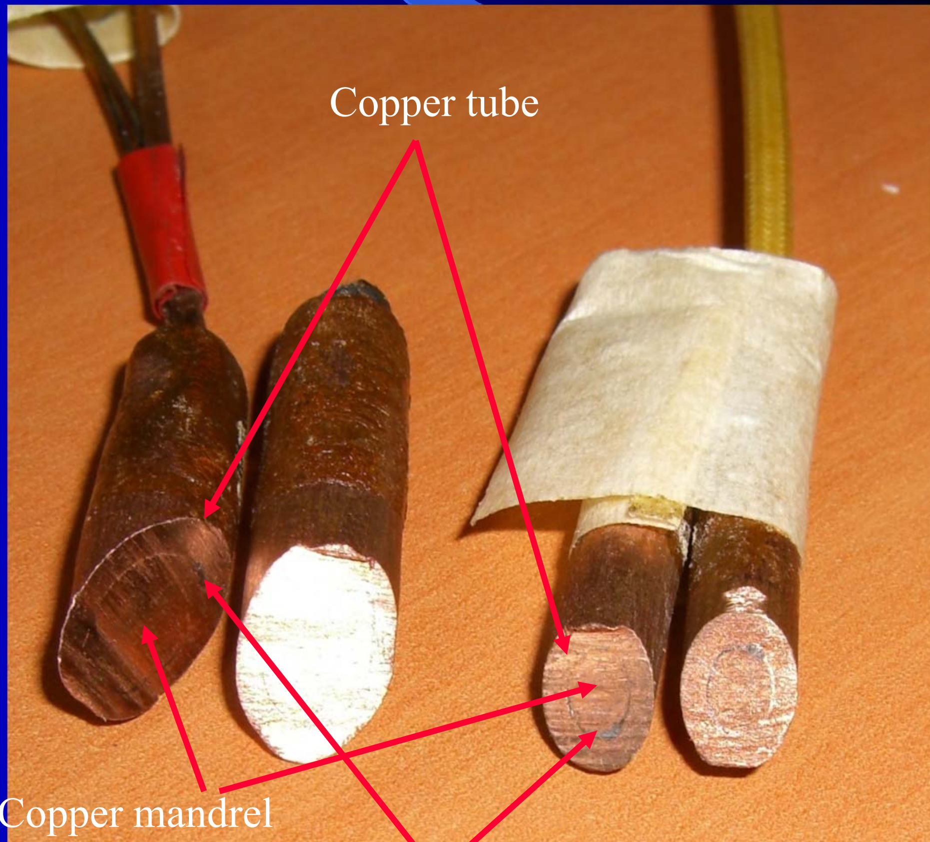
Just before the current discharge



Impregnated NbTi superconducting solenoid

- Magneto forming contact

$$R \approx 10^{-17}\ \Omega$$

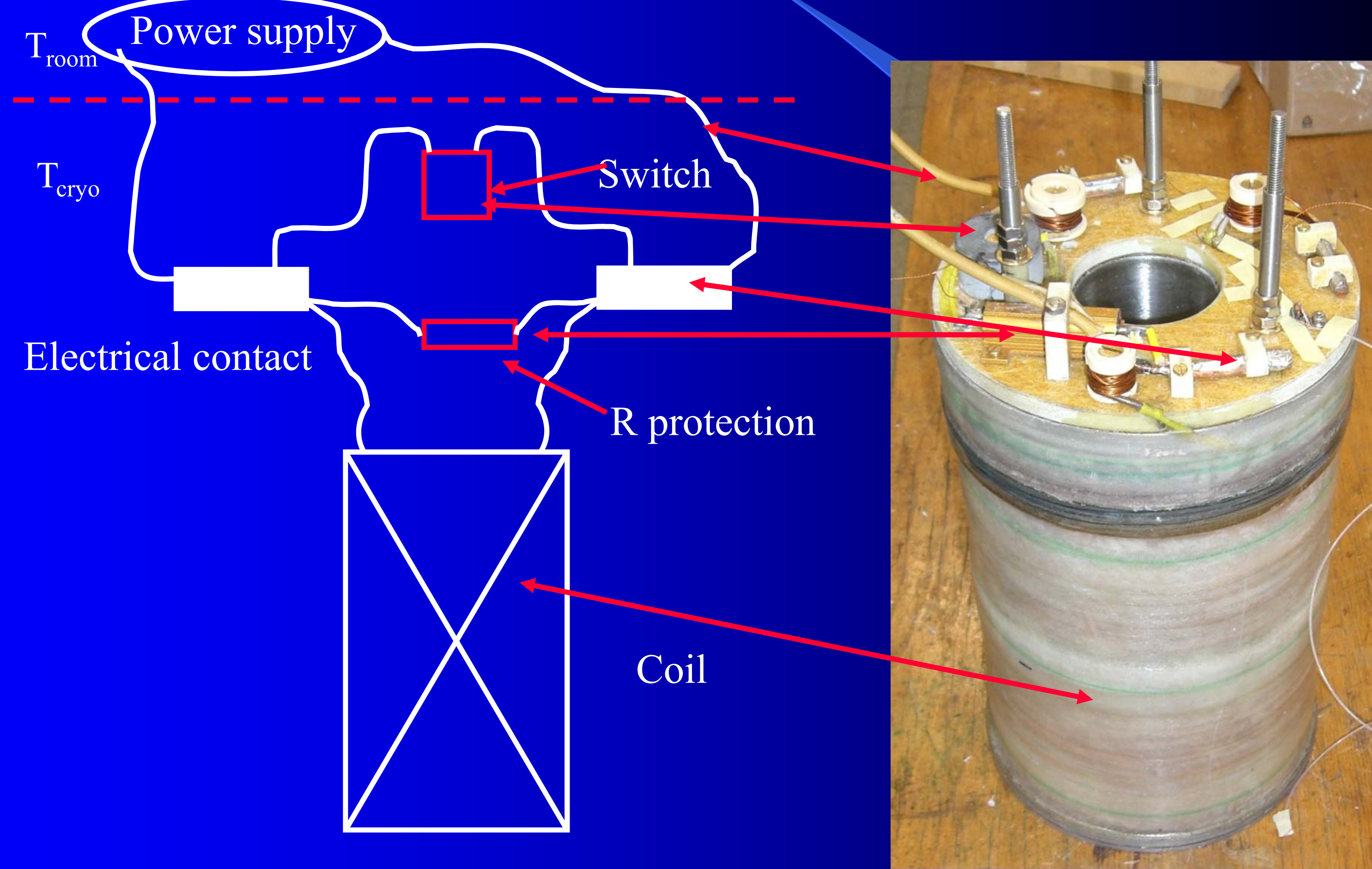


Impregnated NbTi superconducting solenoid

- Magneto forming contact
  - Advantages,
    - easy to control
    - Process is repeatable
    - no tool wear
    - very strong joints
    - Permanently joins dissimilar metals
    - Heat-free welding process (No heat inherent in the process to degrade materials)
    - Process is instantaneous
    - Very low electrical contact resistance for us

Impregnated NbTi superconducting solenoid

- Total system description



Impregnated NbTi superconducting solenoid

- Cryogenic tests, training, field card
  - The last step consist in
    - *Coil training*
    - *Coil characterization*
  - The means we need
    - *Liquid He cryostat with high section current leads*
    - *High capacity helium recovery line to minimize pressure inside the cryostat during a quench*
    - *Superconducting coil power supply (which automatically shut down in case of quench)*
    - *Hall sensor to do the field card of the coil*
    - *Helium level sensors to control helium consumption inside cryostat (particularly in case of quench)*
    - *Current source to drive the superconducting switch*

Impregnated NbTi superconducting solenoid

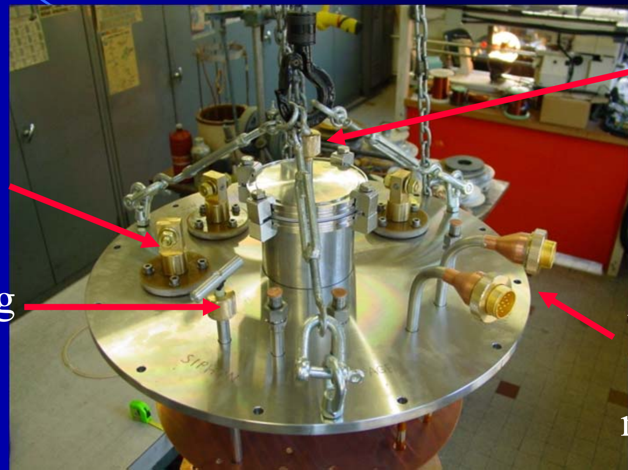
- Equipments for cryogenic tests

Current leads

Helium filling

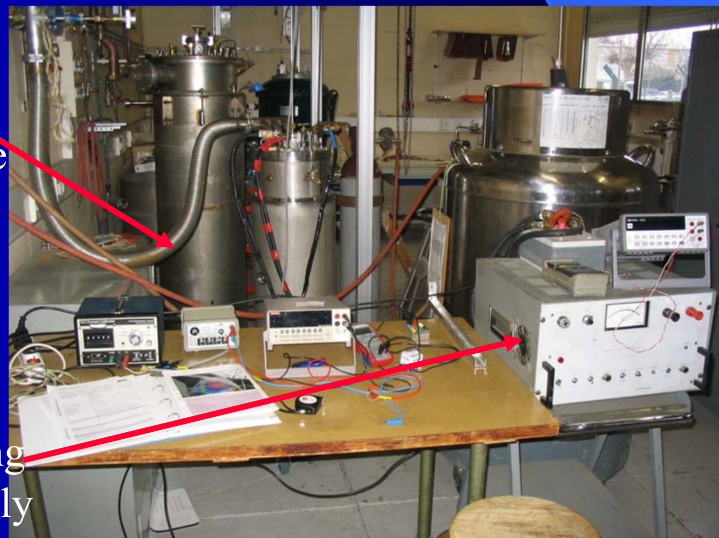
Thermal shields

Coil fiber glass support plate



Hole for field measure (Stuffing box)

Level, temperature, voltage measurement

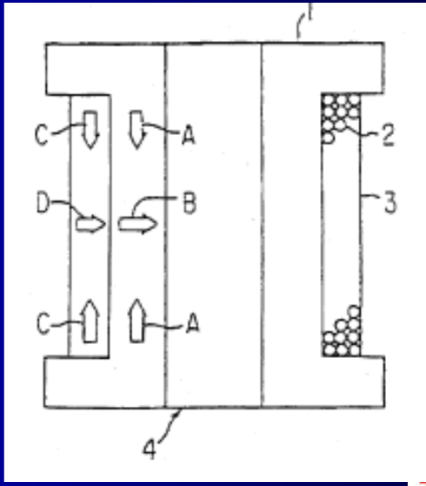


Helium recovery line

Superconducting coil power supply

Impregnated NbTi superconducting solenoid

- Training
  - When we immerse a superconducting coil device in a cryogenic liquid
    - Due to thermal expansion for both superconducting wire and mandrel
      - *contraction appears in the axial and in the radial direction, (thick arrows A and B, C and D)*
    - In theory, no looseness can occur in the combination of these elements

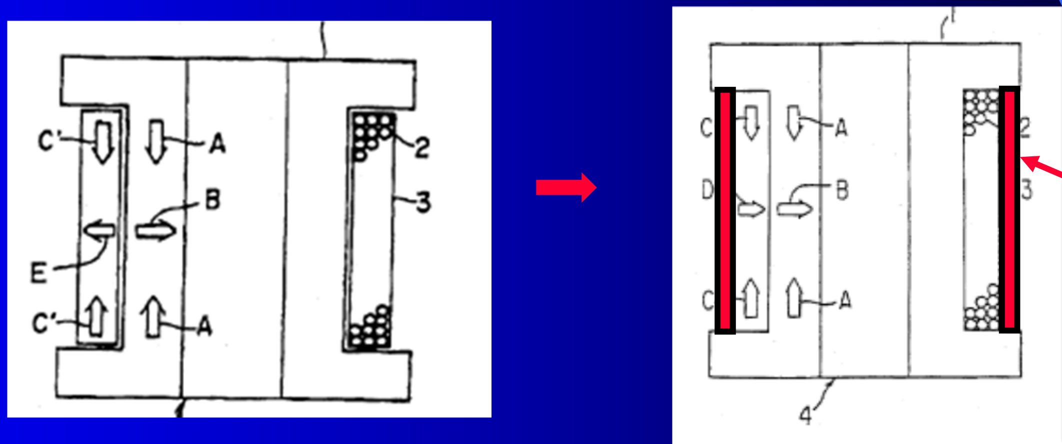


Impregnated NbTi superconducting solenoid

- BUT
  - During the first cooling cracks appears in the epoxy impregnation
    - *energy is released which cause disturbance that can affect the conductor stability.*
  - Consequence
    - *We must applied to a new superconducting coil several thermal and electrical cycles before to obtain the optimal performances*
    - *It is the training of the coil*

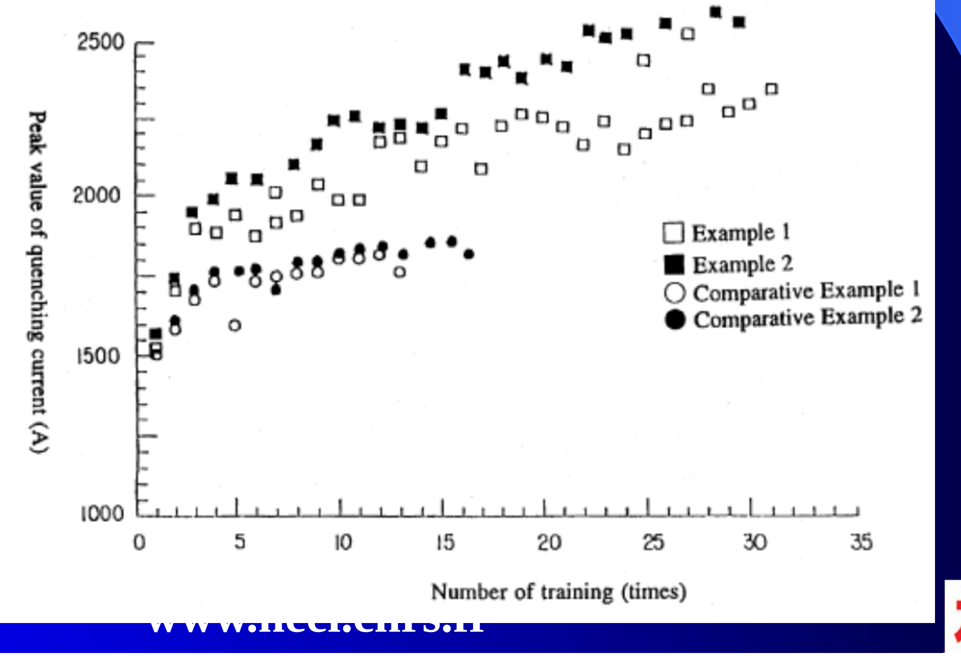
Impregnated NbTi superconducting solenoid

- Training :
  - Electrical current pass through the superconducting coil ➔ electromagnetic force appears ➔ superconducting coil exhibits an increased degree of contraction in the axial direction, but expansion in the radial direction (thick arrows C' and E)
  - looseness occurs in the combination of mandrel and superconducting coil
  - to reduce this problem ➔ fiber glass binding band (to shrink) around the last layer of superconducting tape
  - cracks in epoxy impregnation ➔ some wire can slightly "move" ➔ generation of frictional heat which can causes a quench.



Impregnated NbTi superconducting solenoid

- Training
  - By doing several quench, the superconducting wire of the coil move toward the most stable position
    - *the consequence is a direct improvement in the coil characteristic*
      - Thermal and electromechanical cycles

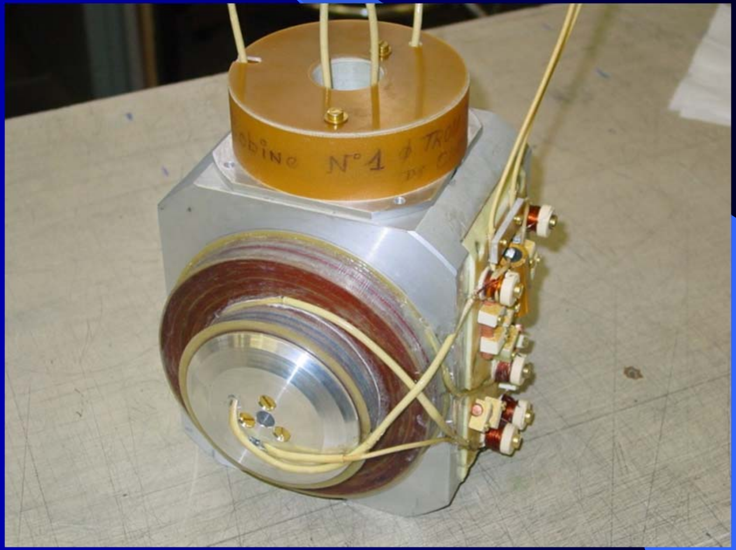


Impregnated NbTi superconducting solenoid

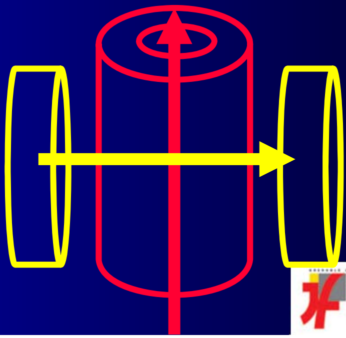
- cryogenic tests
  - Superconducting switch tests
    - To validate persistent mode
    - To see if there is no defective magneto forming contact
      - *In case of defective contact, we observe a decrease of magnetic field (L/R)*
  - Field card
    - To compared with user's specifications
    - To validate the coil

Others type of superconducting coils

- NbTi coils
  - Two axis system (X, Y)
    - High field main solenoid + helmoltz coil



8.6 T (Z) ; 1.5T (X) at 4.2K
Stainless steel and aluminum mandrel



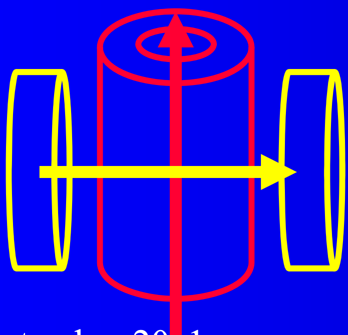
Zone of field homogeneity in the center of the coil by playing with winding shape

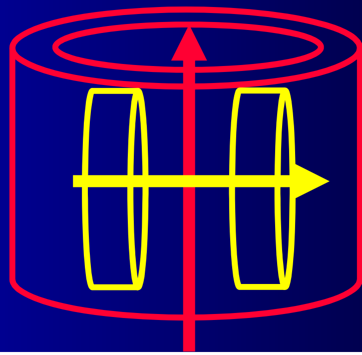
Others type of superconducting coils

- NbTi coils Two axis system (X, Y) High field main solenoid + helmoltz coil

5T (Z) ; 0.5T (X)
Without metallic part
only use of fiberglass (G11)

3T (Z) ; 2T (X)





Others type of superconducting coils

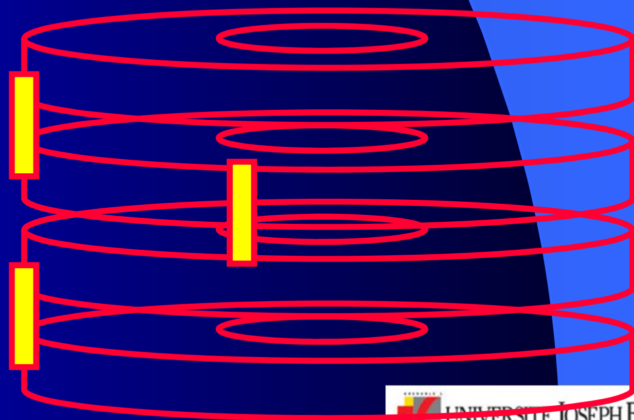
- HTC superconducting coils
  - With bismuth tape
    - Very brittle
    - Difficult to do helical coil : brittleness of the superconducting phase → very difficult to keep the same length of tape between each layers

      (the tape "don't like" to be bend in the transverse direction)

◆Solution

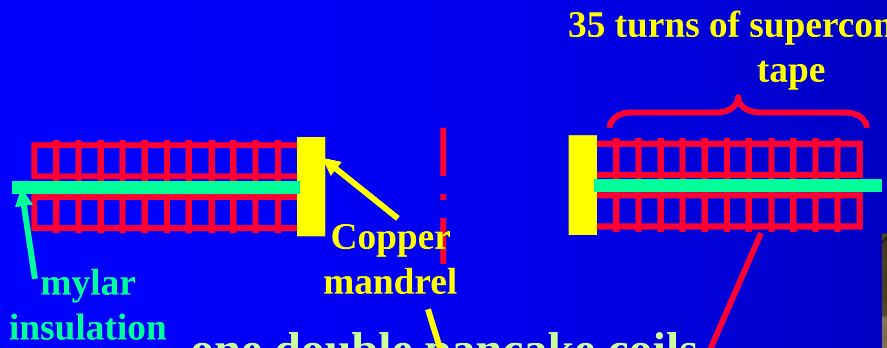
- Wind and react techniques : heat treatment to obtain the superconducting phase after windings
- To do pancake coil

With superconducting strap to do electrical connection between each pancake coils

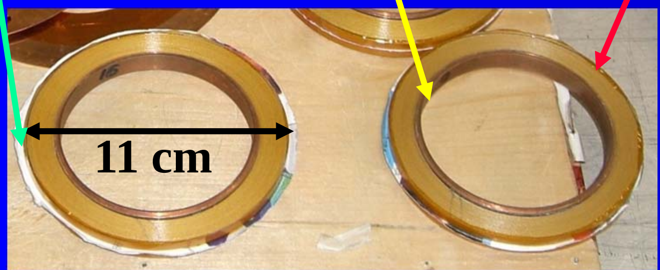


HTC BISCO 32 double Pancake coils

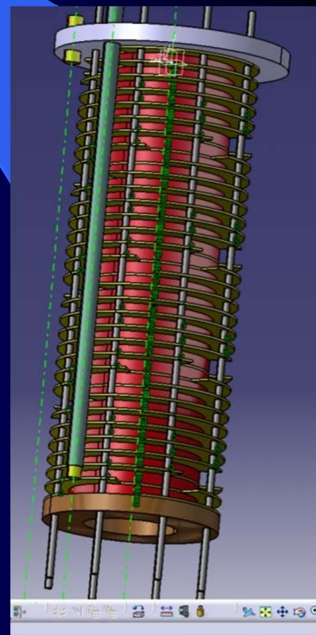
- Operate at 20 K in vacuum
- Cooling by conduction along the copper mandrel thanks to cryocooler
- Operating field 1.5 T operating current 210 A (tape section 0.33*4.5 mm^2)
- homogeneity of 0.3% on 16 cm along the central axis of the coil



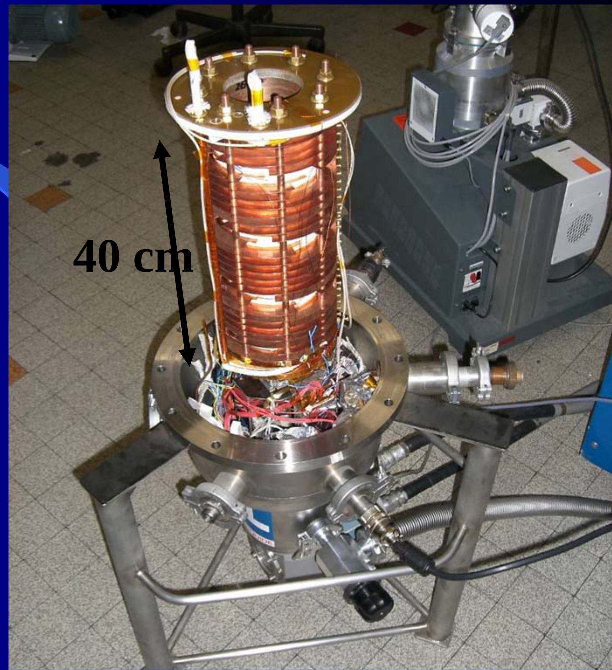
one double pancake coils



Two double pancake coils



Others type of superconducting coils



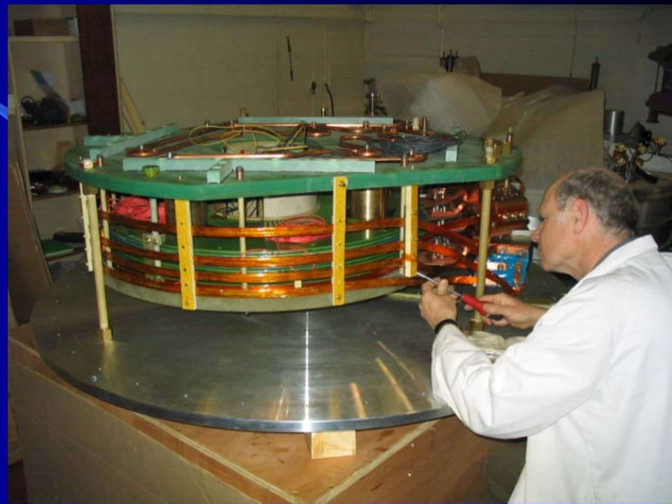
Thermal copper plates

32 double pancake coils

Tests with gifford macmahon cryocooler

Others type of superconducting coils

- SMES 26 pancake coils
  - For electrical energy storage (800kJ)
  - Operate in vacuum at 20 K
  - Cooled with two cryocooler
  - Superconducting tape "glued" on thermal copper plate



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