PSI Center for Accelerator Science and Engineering

Superconducting Accelerator Magnets
An introduction in 60 min

CAS Mechanical & Materials Engineering for Particle Accelerators and Detectors
2-15 June 2024, Netherlands

Stéphane Sanfilippo Paul Scherrer Institute

Scope and limitations

Objective of the course: Magnets for accelerators

–Superconductivity: experimental facts- **Part I**

–Practical superconductors: From filament (tape) to cables- **Part II**

–Superconducting magnet issues- **Part III**

–Examples taken with CERN LHC magnets and PSI magnets **Part III**

Not in this course:

- Details on the conductor fabrication
- Description of MgB_2 and Bi2212 (Bi2223) properties
- Magnetic design methods
- Dynamic effects (decay and snap back of magnetization, AC losses)
- Field quality and Magnetic measurement techniques (refer to previous lecture)

For further reading, please consult the list of recommended readings
Glossary at the end of the talk

Recommended Reading-Courses

Superconducting Magnets

- CERN Accelerator School: Normal- and Superconducting Magnets, 2023, https://indico.cern.ch/event/1227234/contributions/
- “Lectures on Superconductivity and its applications”, C. Senatore, https://senatore.unige.ch/lectures/
- “Superconducting accelerator magnets”, S. Prestemon, E. Todesco, P. Ferracin, USPAS course 2015
- “From materials to applications”, M. Ainslie, 3rdESAS -IEEE CSC Summer School on numerical modeling for Applied Superconductivity
- “Magnets (SC)”, L. Bottura CAS Introduction to Accelerator Physics 2010
- “Superconducting accelerator magnets”, D. Schoerling CAS&EAS 2018
- “Superconducting Materials for High Field Applications”, A. Ballarino, Atomic Institut of Vienna, 2018
- “Superconducting Magnets”, G. de Rijk , CAS Introduction To Particle Physics, 2023

Recommended Reading-books

Superconducting Magnets

Books

- "100 years of superconductivity"; Rogalla and Kes, Springer
- "Vortices in High Temperature Superconductors"-G. Blatter et al., Review of Modern Physics, 66 (1994)
- Physical Properties of High-Temperature Superconductors

Rainer Wesche, Wiley

- "Superconducting Magnets", Martin N. Wilson Oxford Science Publication
- "Stability of Superconductors", L. Dresner, Plenum Publ. Corp
- "Case Studies in Superconducting Magnets", Y. Iwasa, Plenum Publ. Corp.
- "Nb_3Sn Accelerator Magnets"-Daniel Schörling Springer
- "Superconductivity-basic application to magnets"-R.G.Sharma Springer
- "Practical low temperature superconductors for electromagnets"-A.Devred CERN https://cds.cern.ch/record/796105

Acknowledgement

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- Special thanks to my colleagues A. Ballarino, L. Bottura, G. De Rijk, P. Ferracin, E. Todesco, H. Felice and C. Senatore for providing information, material and support during many years.

Superconductivity: experimental facts

commentary

Woodstock of physics revisited

Ten years have passed since the now famous American Physical Society meeting that heard the first breathless accounts of high-temperature superconductivity. Now, in calmer times, practical applications are emerging.

Paul M. Grant

Snap quiz: who can tell me the winner of the 1987 Super Bowl? Not most physicists, I suspect, for whom it was certainly eclipsed by two events of far greater consequence that shared the early months of that year. One, the discovery of Supernova 1987A, perhaps portended the other: the announcement of superconductivity above liquid-nitrogen temperature on planet Earth — a dream fulfilled for many condensed-matter physicists like myself, whose careers had orbited around this elusive star.

The successful sighting[1] fell to W. K. Wu and C. W. (Paul) Chu and their teams of students and postdocs at the Universities of Alabama and Houston, following only five months after the publication in autumn 1986 by Georg Bednorz and Alex Müller[2] at IBM Zürich of their discovery of superconductivity in a previously unexplored class of compounds, the layered copper-oxide perovskites.

The 'inside' story of the hectic interval between the first week in January 1987 — when an announcement of the confirmation of Bednorz and Müller's discovery first brought 'high-temperature superconductivity' to wide public attention — and the week of the American Physical Society's March meeting, remains to be told. Suffice it to say that this period, and the last three months of 1986, were replete with incredulity, credulity, excitement, secrecy and a sense of immedia… in competition with one's peers, all … resulted in, frankly, a substant… intrigue and suspicion. … surely came to un… done so before, th… ence but, perhap…

Rising stars: Müller and Chu with Shoji Tanaka (right), whose Tokyo … first confirmations of Bednorz and Müller's discovery.

intensely human pursuit — something they do not teach you in graduate school.

The programme of the March … held each year in a different … would concrete' early the … order of the thereafter, an … take part — and did ations prev… reaching a downpour in … before the meeting, as confir… of the Wu–Chu measurements were made. All in all, 51 presentations were to be given throughout the evening and early morning of Wednesday and Thursday, 18 and 19 March. That memorable and riotous session was to become our "Woodstock of physics", so named in honour of the village only 50 miles north where, in an obscure farmer's muddy field in 1969, the rock concert occurred that defined a generation of youth the world over.

… IBM … results that … prompted the … to take an unprecedent… …aple of the University of Cal-

Fever pitch: the room filled to overflowing with physicists eager for news of superconductivity.

Opening act

A few personal observations and anecdotes may help to convey the colour of that week in midtown Manhattan. Excitement was running high even before Wednesday night. On Monday, the opening day, the press were already beginning to catch some of us to be interviewed. That noon my colleague Ed Engler and I went to lunch at a nearby Brew 'n' Burger and found Alex Müller sitting by himself in a corner booth, attempting to escape the turmoil at the Hilton. At the time he was not yet widely recognizable to those attending the meeting or to the press — a situation that would soon change…

NATURE | VOL 386 | 13 MARCH 1997

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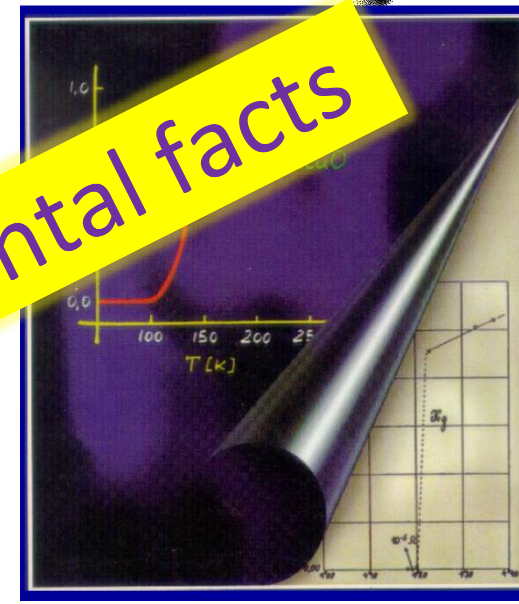
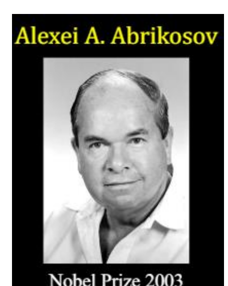
Woodstock of Physics NYC, 1987



H. Kamerlingh-Onnes (1911)



J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret

Bednorz and Müller, 1987

Superconductivity in two properties

Phenomena exhibited by some materials under certain conditions (T, B)

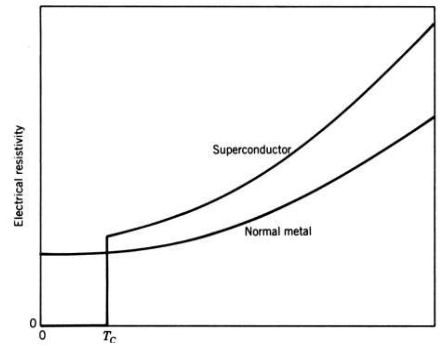
- R = 0 for $T<T_c$; No Joule heating losses
- **Meissner Effect** (perfect Diamagnetism, expel all magnetic fields from their interior when in the superconducting state)
- Strong magnetic field in a compact size
- Cryogenics required (Helium, Nitrogen….)
- Domain limitations : [Tc(K), Bc(T), Jc(A/mm²)]

– **T_c (B, Jc): Critical temperature**
– **Bc_2 (T, Jc): Upper critical field**
– **J_c (T, B): Critical Current density**

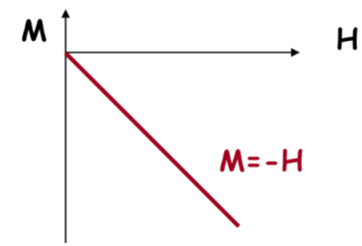
B_{C2} and temperature T_C of metallic superconductors are mutually related

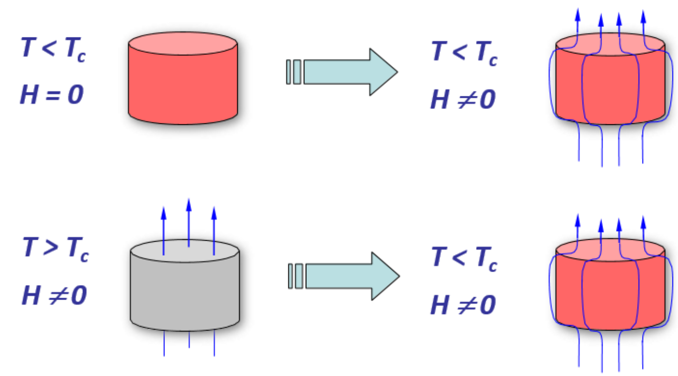
Both B_{C2} and T_C are determined by the chemistry of the material

ρ=0, T<Tc



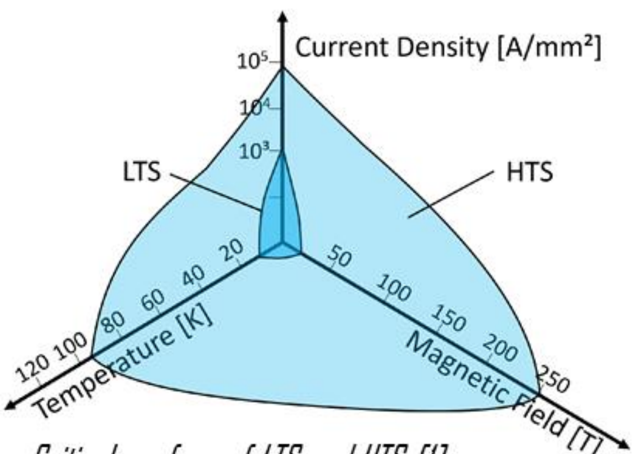
Meissner effect (field cooled)





Flux is excluded by persistent shielding currents flowing at the surface , T<Tc

Perfect conductor+perfect diamagnetism



Critical surface of LTS and HTS [1]

HTS accelerator magnets,
Thesis Jeroen van Nugteren (2016)

Critical surface: boundary between superconductivity and normal state

Inside the boundaries: superconductivity, R=0

Outside: normal state (R ≠ 0)

History and rise of critical temperatures T_c

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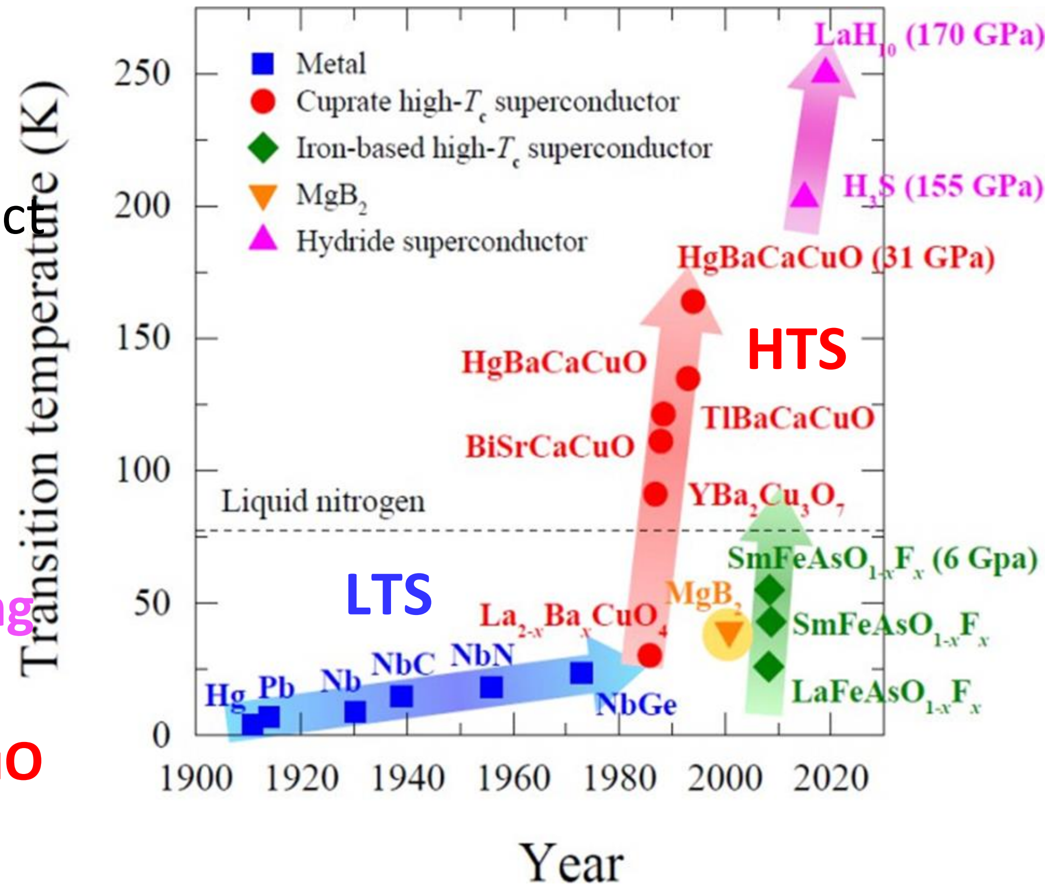
Discovery milestones:

- ✓ **1908** Onnes liquefies He
- ✓ **1911**: Superconductivity in Hg
- ✓ **1933**: Meissner-Ochsenfeld effect observed
- ✓ **1957** : BCS Theory
- ✓ ~ **1960:** {LTS} **Nb_3Sn** and **NbTi**, 1st practical wire and magnets

High Temperature Superconducting (HTS) era

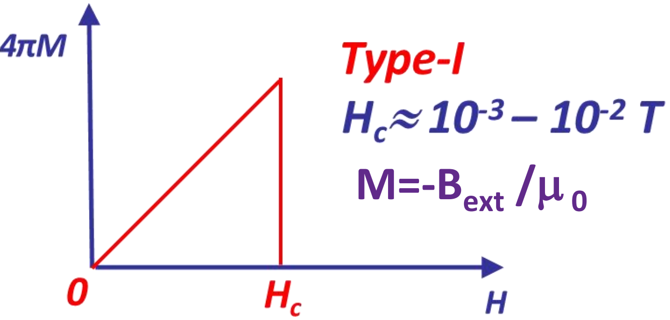
- ✓ ~ **1987:** {HTS} Cuprates, **BiSrCaCuO** and **YBaCuO (Tc~92 K > 77 K)**
- ✓ **90`s:** {HTS} **HgBaCaCuO**
- ✓ **2001:** {ITS} **MgB_2**
- ✓ **2008:** {HTS} Iron **FeAs-Based** Superconductors

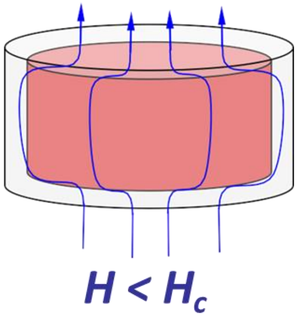


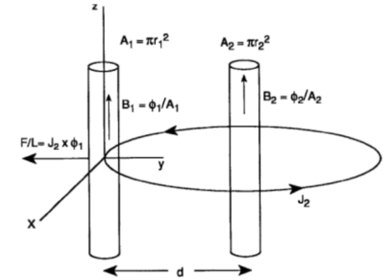
From Chao Yao and Yanwei Ma
iScience 24, 102541, June 25, 2021

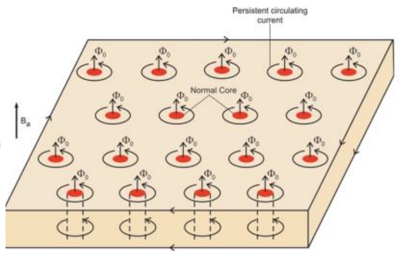
Slide from H. Ten Kate

Type I and II superconductors

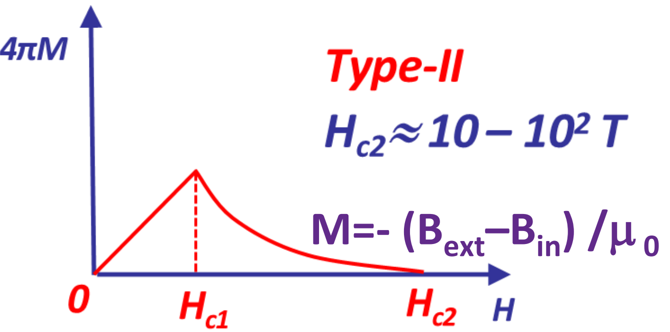


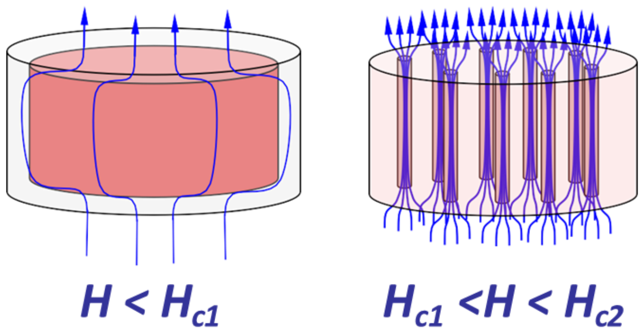


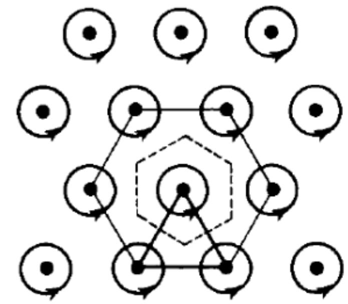




From R.G. Sharma







Type I/II superconductor characteristics

- **Type-I:** Meissner state B = 0 for H < Hc; normal state at H > Hc_1
- **Type-II:** Meissner state (H < Hc_1), partial flux penetration (Hc_1 < H < Hc_2), normal state (H > Hc_2)
- Hc_1<H<Hc_2 – **mixed state:** penetration of the field as quantum of flux called **fluxoids**, **the vortices**, i.e. **normal regions** of cylindrical magnetic tubes containing a magnetic flux quantum $\Phi o = h/2e$;The vortex core has $\Phi = 2\xi$
- **Vortex interaction : Hexagonal vortex lattice** to minimize the flux repulsion energy
- ***In a SC magnet : Transport current + shielding supercurrents due to vortices coexist !***

Practical superconductor: Pinning of the vortices

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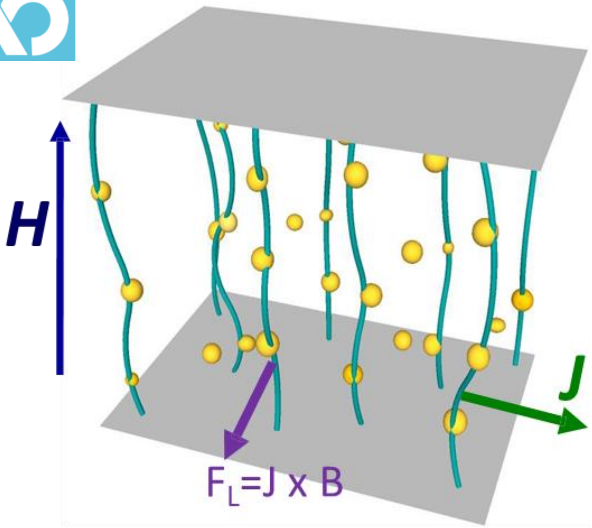
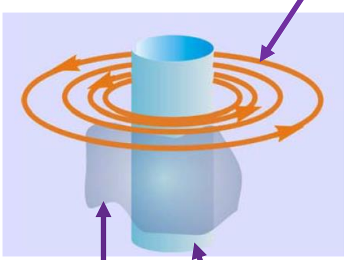
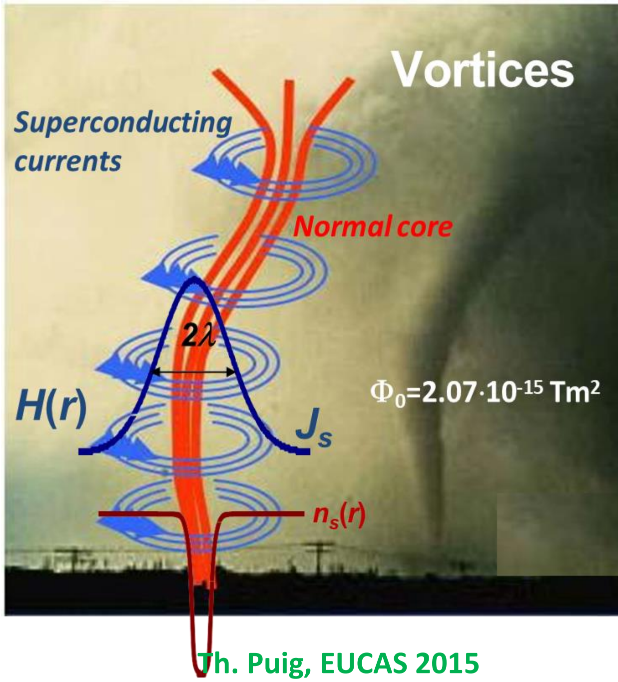


When a superconductor carries a current J_T, $\mathbf{F_L = J_T \times B}$

Vortice motion → **Flux flow, energy dissipation, resistivity- no superconductivity**





Th. Puig, EUCAS 2015

- To avoid vortices motion, **vortices** are **pinned by microstructural defects**
- Force on an individual line: $F_L = J_T\Phi_0$
  Critical state : J_T=J_s
- Pinning on an individual line: $F_p = f_pV$ (strong pinning)
- **Flux will not move into SC as long as $F_L < F_p$**

The anchoring of vortices by defects occurs at the scale of the vortex core: Maximum efficiency being achieved for a volume on the order of ξ^3

Low T_c's ξ ~4-6 nm ; High T_c's ξ ~1-2 nm

Manufacturing processes of superconducting materials shall optimize "**flux pinning**" → Practical superconductor ($J_e \neq 0$): Material with pinning defects

Type of defects to pin the vortices

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•***Point defects - 0D*** (vacancies, grain boundaries, precipitates…)

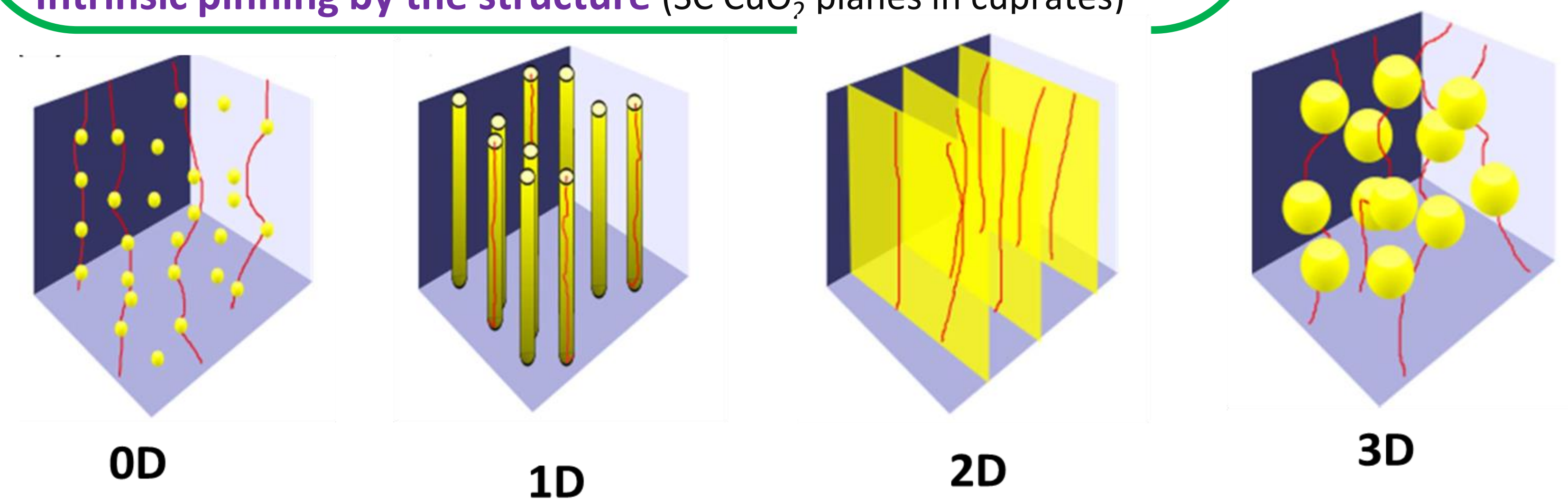
Artificially introduced defects, including:

– Green phase inclusions by the Melt Texturing method
– **Columnar defects (1D)** introduced by heavy ion irradiation
– Point like defects introduced by doping (Zr)
– large size defects, spherical pinning centers, e.g. modification of substrates by growing nano-particles to create interfacial defects

Core pinning

•**Extended defects 1 D & 2 D** (dislocations, twin planes)

•**Intrinsic pinning by the structure** (SC CuO_2 planes in cuprates)



To increase Jc and B: optimize the pinning centers distribution and morphology of pinning centers with the size ~ ξ*

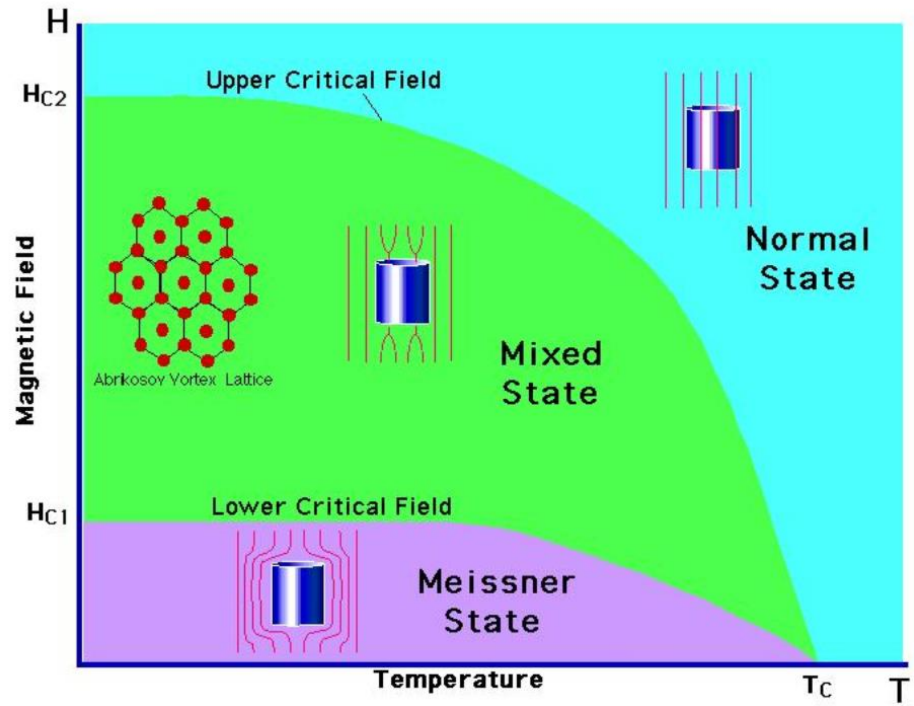
Extended defects: reduce the wandering of vortices due to thermal fluctuations (HTS)

(Simplified) magnetic phase diagrams of Type II superconductors

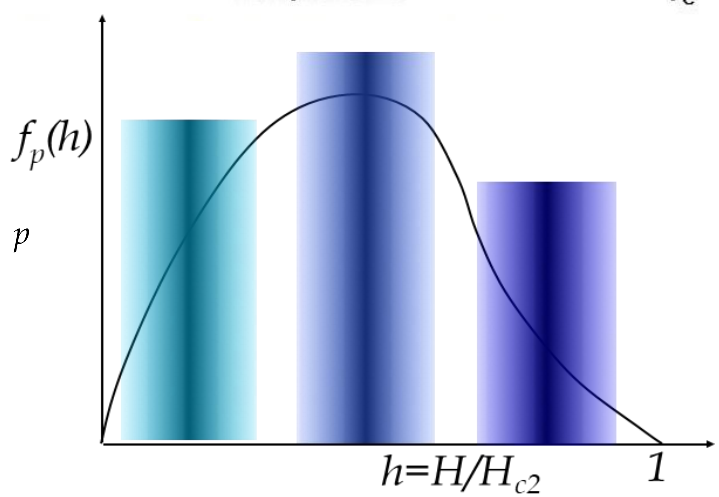
Competiting energies:

- Pinning energy $U_{pinning}$
- Vortex lattice rigidity $U_{elastic}$ (due to magnetic repulsion-Tends to keep vortices equidistant in absence of defects)
- Thermal effects $k_B T$ → Depinning, flux flow

Low Tc : $U_{pinning} \sim U_{elastic} << k_B T$



- At low fields (but>Hc_1) the distribution is governed by interaction between flux lines
- At intermediate fields, **the pinning force f_p is provided by the pinning sites**, capable of hindering flux flow by withstanding the Lorentz force acting on the fluxoids
- At high field < Hc_2, the number of fluxoids significantly exceeds the number of pinning sites



HTS: New vortex phases

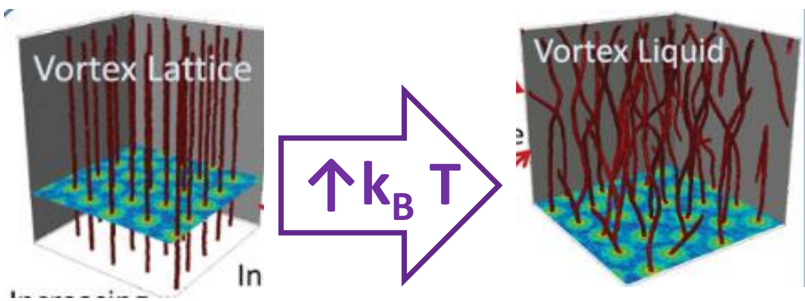
Thermal fluctuations → Melting line
Pinning centers → Irreversibility line

- High T_c
- High anisotropy
- Small coherence lengths

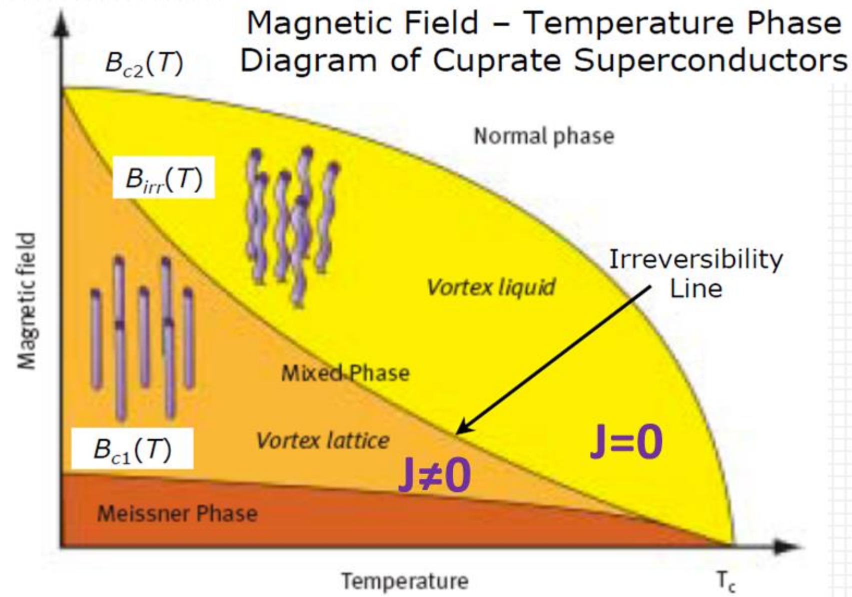
Thermal fluctuations: $\uparrow k_B T$

Pinning energy: $\downarrow U_{pinning}$

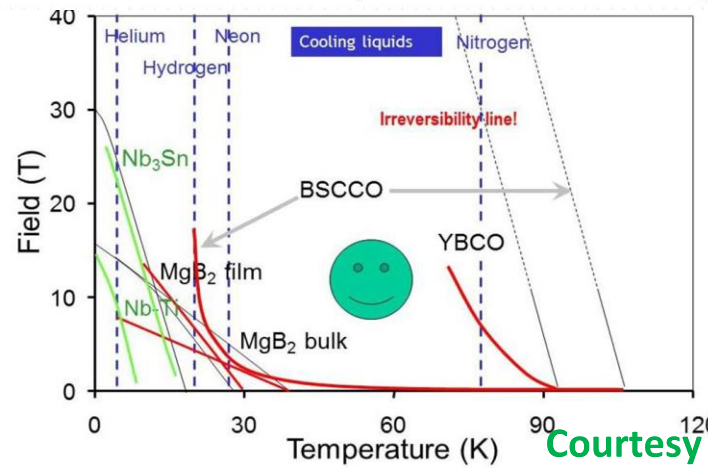
Elastic energy: $\downarrow \downarrow U_{elastic}$



Wai-Kwong Kwok et al, Re.Prog.Phys. (2016)



Vortex liquid, $T < T_{melting}$
Irreversibility line $B_{irr}(T) \ll Bc_2(T)$
Large part of the B (T) diagram for $J_c=0$



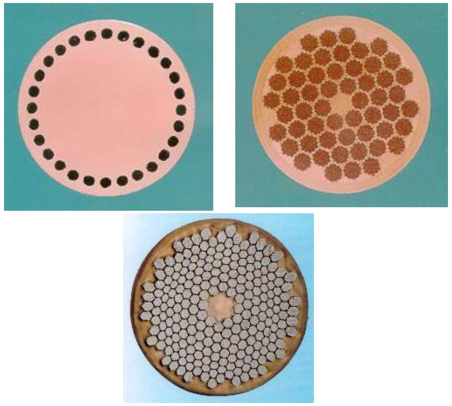
Courtesy H. Ten Kate)

- ***In HTS the Irreversibility Line limits the practical domain of use***
- ***Difficulty to use «practical HTS» at high temperatures (T>50 K)***

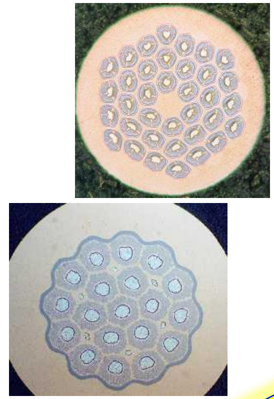
ReBCO is the only superconductor that allows us to generate high magnetic fields without using liquid helium in the temperature range 20-50 K

The practical superconductors

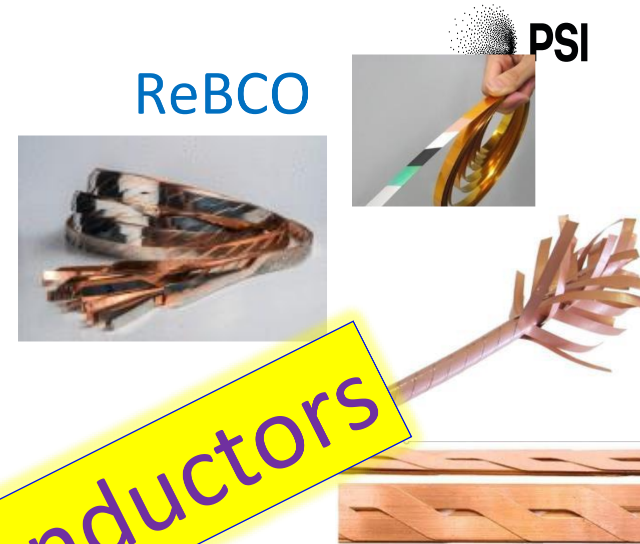
NbTi

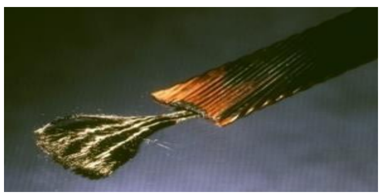


Nb_3Sn, Nb_3Al

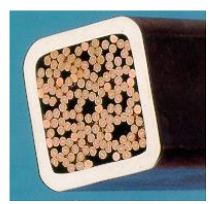


ReBCO





BSCCO



MgB_2

Strands, cables, CIC, tapes, Roebel, CORC®...

L. Quettier

Practical superconductors main properties

Compound	Year	T_c (K)	$B_{c2}(0)$ (T)	Field application (T) @4.2 K	Coherence length (nm)	
NbTi	1960	9.5	14.6	~ 10	4	LTS
Nb_3Sn	1953	18.3	24 - 28	~15-16	4	
$PbMo_6S_8$	1970	15	60			
Nb_3Ge	1972	23	38			
Nb_3Al	1975	19	33			
MgB_2	2001	39	39^a_{bulks}; 60^a_{film}	~3-4	~35/39	ITS
$Bi_2Sr_2Ca_1Cu_2O_8$	1989	94	> 100	>16T	~2/0.1	HTS
$Bi_2Sr_2Ca_2Cu_3O_{10}$	1989	110	> 100	>16T	~2.9/0.1	
$YBa_2Cu_3O_7$	1988	92	> 100	>16T	~1.6/0.2	
$(Ba_{0.6}K_{0.4})Fe_2As_2$	2007	38	70 - >135			

From René Flükiger-Spring School and Educational Courses (SSEC) 2014

Practical Superconductor: NbTi wire

Niobium and titanium combine in a ductile alloy :

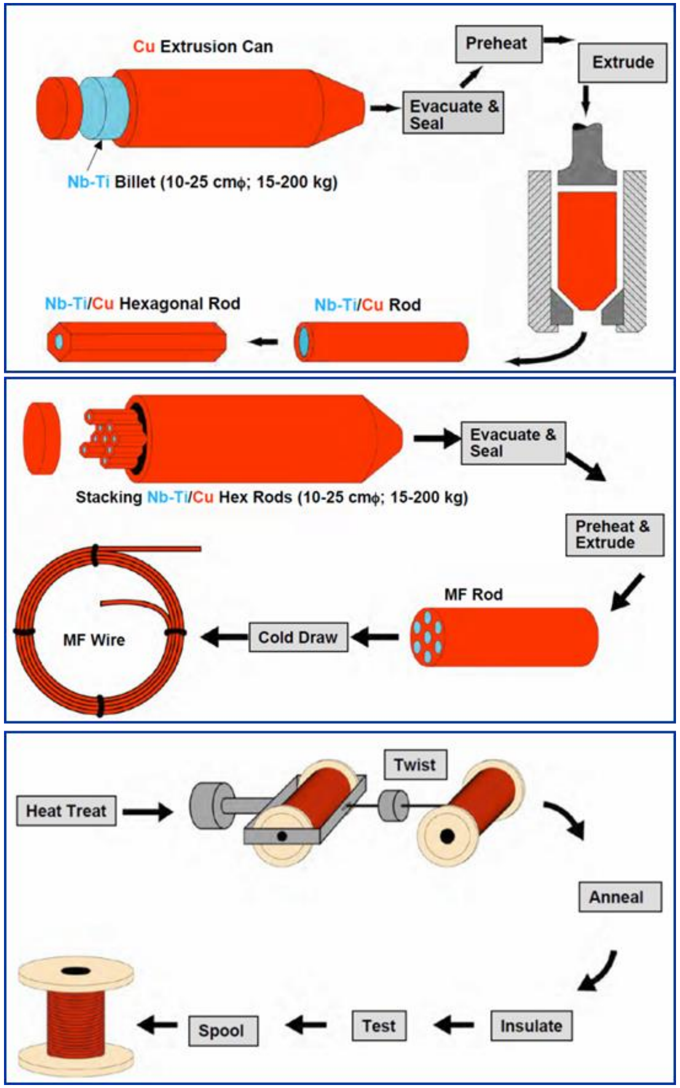
+Easy to produce (drawing)
+Good mechanical properties (flexible)
- Modest superconducting properties:
T_c is ~9.2 K at 0 T, B_{C2} is ~14.5 T at 0 K.

Multi-steps fabrication process of a wire:

- **Extrusion**: Composite billet Nb core surrounded by a copper matrix is **heated and extruded** through a die to form a long, continuous rod
- **Stacking**: Multiple extruded rods are stacked in a copper tube to form a multifilament billet
- **Heat treatment**: The stacked assembly undergoes multiple heat treatments. Heat treatments are applied to produce **pinning centers (α-Ti precipitates).**
- **Cold drawing**: The conductor is drawn through a series of dies to reduce its diameter while elongating it (small filament diameter, better mechanical and electrical properties)
- **Twisting**: The wires are twisted to form and coated with an insulating layer

NbTi wire for LHC magnets

(alloy 46-48% Ti by weight)



Practical Superconductor : Nb_3Sn wire

Niobium and tin form Nb_3Sn

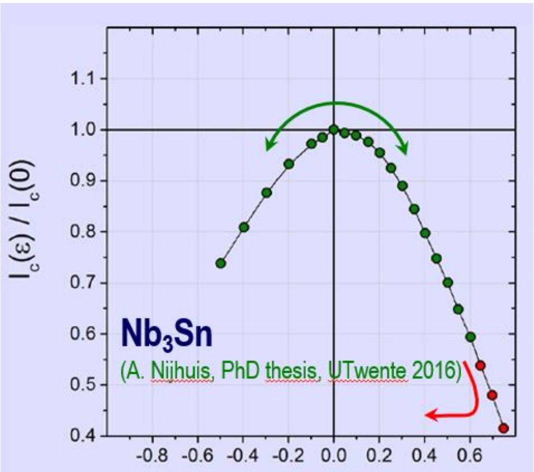
T_{C0} is ~18 K at 0 T and 0 strain.

B_{C20} is ~23-26 T at 4.2 K and 0 strain

For fields up to 15 T!

Brittle and strain sensitive, the (A15) Nb_3Sn phase is created during a heat treatment of 180 h at up to 660°C

Wind and React: the heat treatment is performed on a wound Nb_3Sn coil



Reversible strain dependence at low strain levels;
Irreversible('micro-structural') degradation at higher strain;

Ability to transport current is impacted by mechanical strain (limit of reversibility)

Nb_3Sn coil fabrication steps

1) Assembly multifilament billets from Nb_3Sn precursor
2) Fabrication of the wire through extrusion-drawing
3) Fabrication of the cable (NSc phase)
4) Fabrication of the coil (NSc phase)
5) *"reaction": the Cu, Sn and Nb are heated to 600-700 C and the Sn diffuses in Nb and reacts to form Nb_3Sn (Wind and React)*

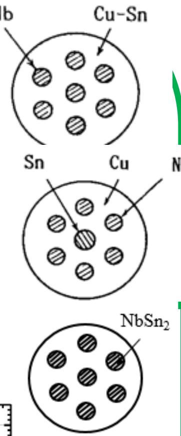
Pinning : Fine grain size of Nb_3Sn (150-200 nm)

Nb_3Sn strand fabrication routes

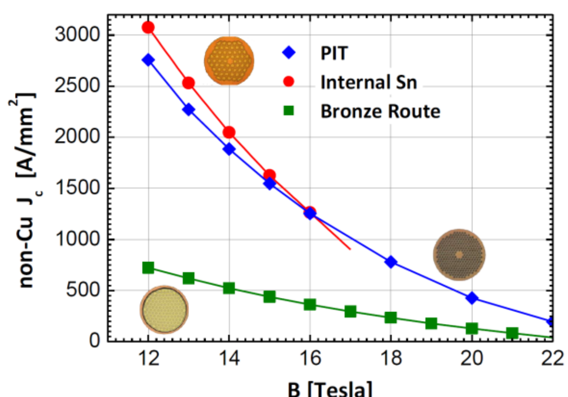
Bronze process (***Sn source = CuSn bronze)*** →fine filaments , high mechanical strength, lower Jc

Internal Tin (***Sn source = Sn rod)***→ very high Jc, large filament size

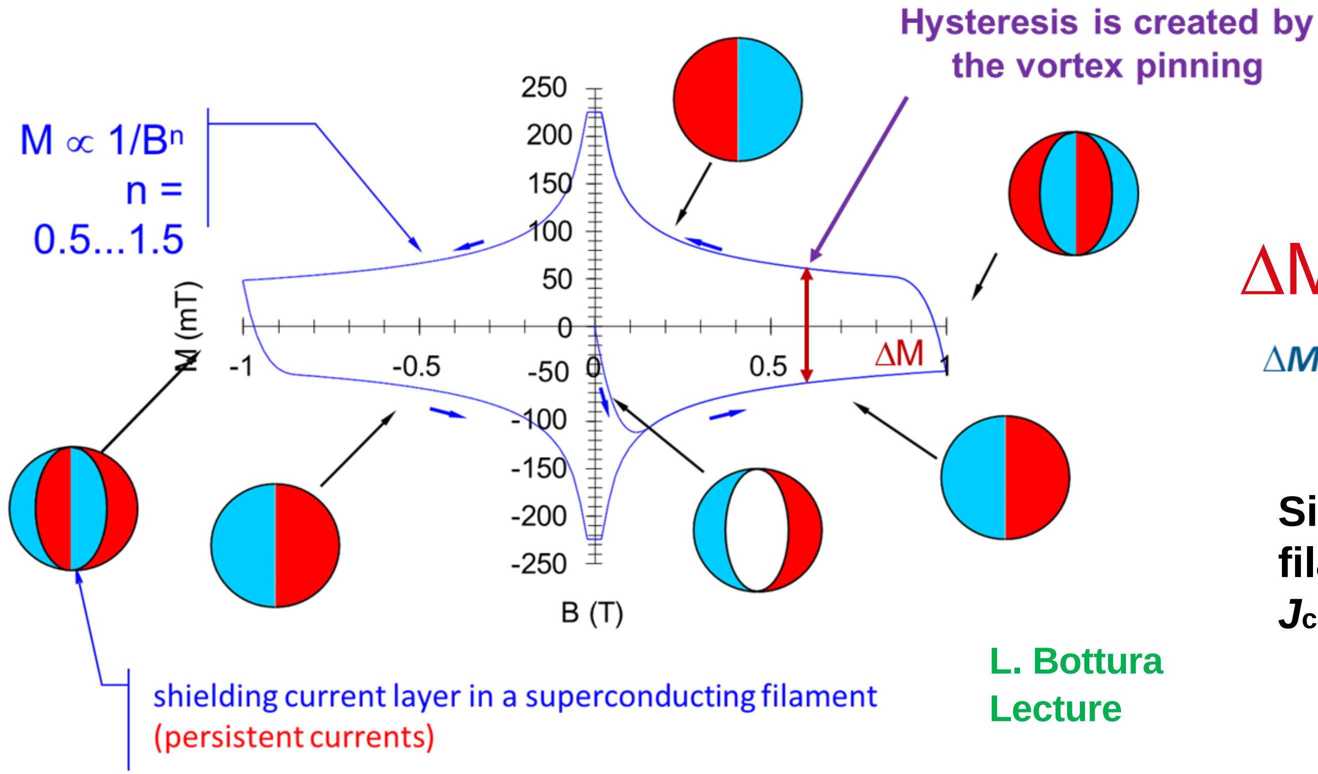
Power in tube (***Sn source = $NbSn_2$ powders)***→
High J_c but large filament size



C. Senatore Lecture



Hysteresis, J_c and filament size



L. Bottura Lecture

$$\Delta M \approx J_c d_{eff}$$

$$\Delta M = \Delta M(B) \Rightarrow J_c = J_c(B)$$

Simple model: SC filaments carries either J_c or no current

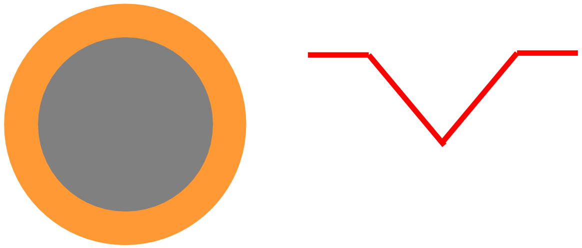
The persistent current creates a magnetization adding to the magnetic field !
The magnetization is proportional of the filament diameter

Large filament size
Large screening field

Large magnetic hysteresis →large loss (Q ≡ $\int MdH$)

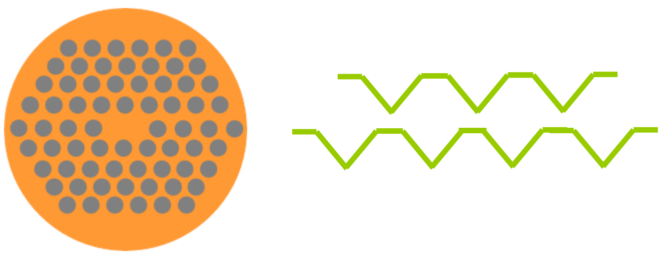
Field quality perturbation and flux jumps

Superconducting wires (strands) are multifilamentary



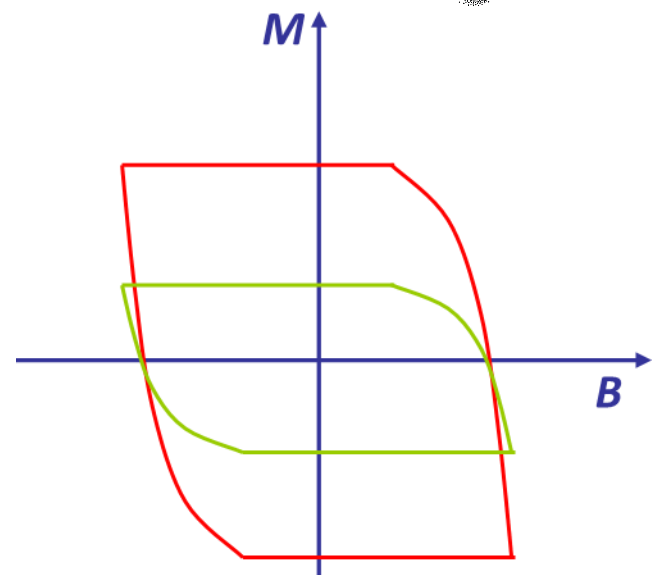
$$\Delta M \propto J_c d$$

d is the filament size



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

d is the filament size



$$W = \int \mu_o H dM = \int \mu_o M dH$$

Reduce filaments size to reduce magnetization

With the subdivision of the superconducting wire (strand) in filaments, hysteretic losses are reduced but the critical current density J_c is unchanged

- HERA filament diameter 14 µm
- LHC filament diameter 6-7 µm
- HL-LHC filament diameter 50 µm
- FCC target filament diameter 20 µm

$$d \leq \frac{2}{J_c}\sqrt{\left(\frac{3\gamma\, C\, (Tc - T)}{\mu_0}\right)}$$

γ= density

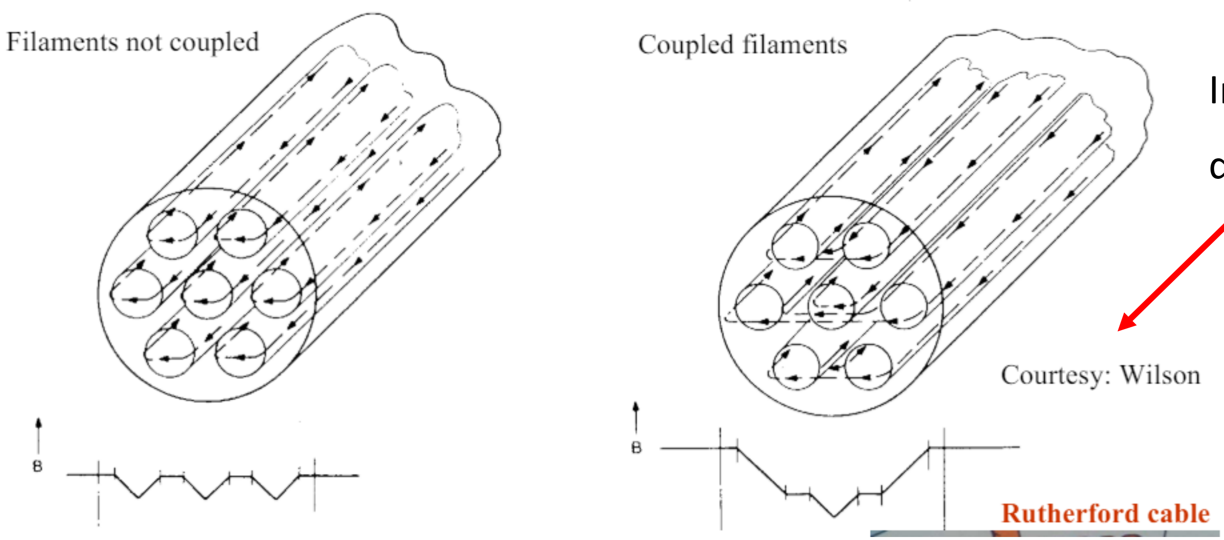
Tc = critical temperature

C = specific heat

From C. Senatore Lecture

Size of the filament (2)

But if d is too small: Coupling effect in filaments and an apparition of large coupled filaments with an increased effective diameter d_{eff}



Increase of Magnetisation

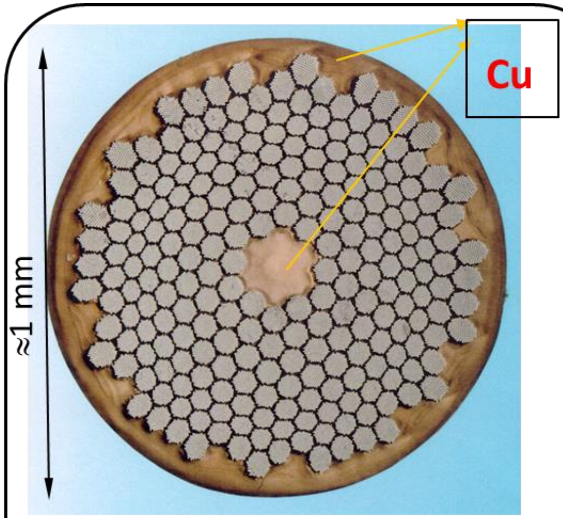
d_{eff}~1 mm

- When a multifilamentary wire is subjected to a time varying magnetic field, current loops are generated between filaments.
- Large loops are generated, with large currents
- High losses If the strands are magnetically (or physically) coupled the effective filament size is larger
- The effect is significantly reduced by twisting the filaments just prior to final draw: Twist pitch = 12 – 30 mm

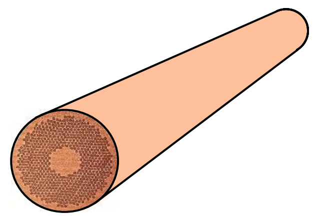
Stabilizer: Cooper or Aluminium

At $T > T_c$, in normal state

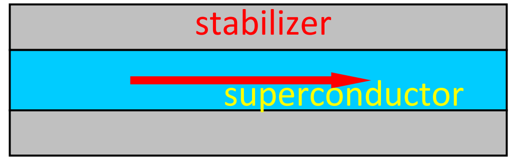
$\rho_{Nbti,n} \sim 5\ 10^{-7}$ W.m > $\rho_{Cu} \sim 1.7\ 10^{-8}$ W.m



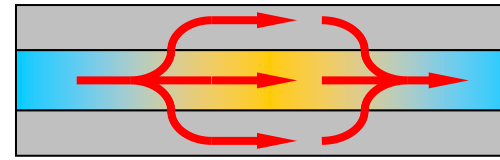
NbTi wire composed of very small filaments embeded in a copper matrix



Multifilament wire

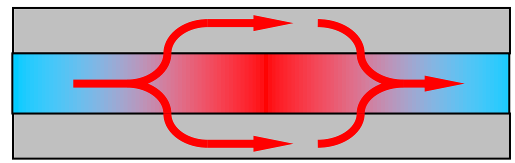


$T < T_{cs} < T_c$



$T_{cs} < T < T_c$

T_{cs}: current sharing temperature



$T > T_c$

Stabilizer role :

Improving Current Carrying Capacity: help in maintaining the current carrying capacity of the superconducting wire

Enhancing Mechanical Properties: enhance the mechanical properties and mechanical stability of the wire

Quench Protection and heat spread: providing an alternate pathway for the current and enhancing heat dissipation

How does it work?

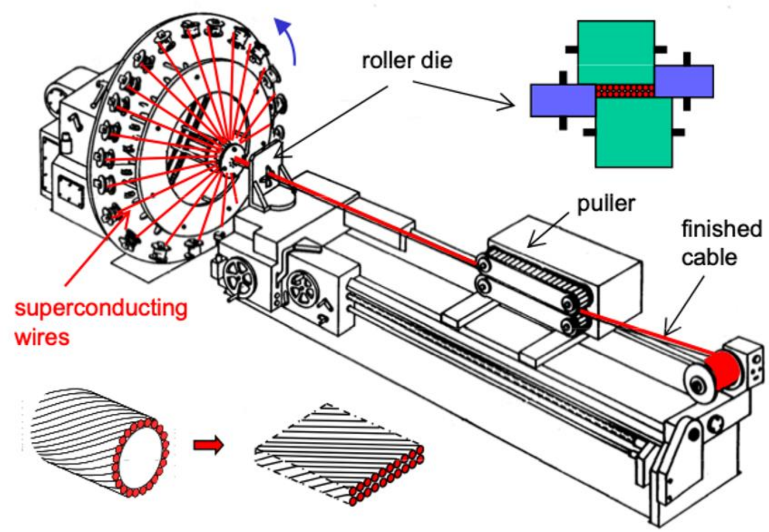
1. $T < T_{cs} < T_c$ Current flows in the superconductor
2. $T > T_{cs}$: the current starts to flow in the stabilizer
3. $T > T_c$: If the temperature keeps rising, the current will ONLY flow in the stabilizer – without sufficient cooling, the transition is irreversible: it is a quench

Cabling the strands into Rutherford cables

Superconducting coils wound from a multi-strand cable (Rutherford cable)-Why?:

- Reduce strand length (less expensive)
- Reduce number of turns
- Easy winding
- Smaller coil inductance
- Current redistribution in case of a quench in a strand
- High packing factor

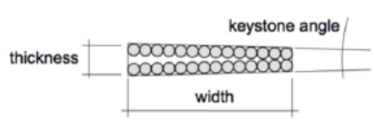
The most commonly used multi-strand cables are the **Rutherford cable** that can be rectangular or trapezoidal.



The cable design parameters are:

- Number of wires N_{wire}
- Wire diameter d_{wire}
- Cable mid-thickness t_{cable}
- Cable width w_{cable}
- Pitch length p_{cable}
- Pitch angle ψ_{cable} $(\tan\psi_{cable} = 2\, w_{cable} / p_{cable})$
- Cable compaction (or packing factor) k_{cable}

$$k_{cable} = \frac{N_{wire}\pi d_{wire}^2}{4 w_{cable} t_{cable} \cos\psi_{cable}}$$



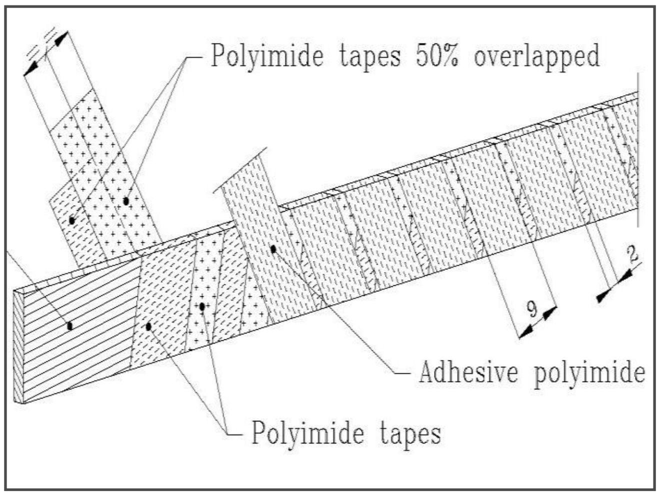
Typical compaction : 88-92 %

Last step: the cable insulation

PSI

Aim : To prevent electrical shorts

- Good **dielectric properties** to withstand turn-to-turn *V* after a quench
- Good **mechanical strength** to withstand high stress conditions
- Compactness: for efficient winding of the cables
- **Porosity** to allow penetration of helium (or epoxy)
- **Radiation hardness**



- In Nb-Ti magnets overlapped layers of **polyimide** (Kapton®)
- In Nb_3Sn magnets, **fiber-glass** braided
- Typical insulation thickness: 100 and 200 μm

Superconducting wires & cables summary

WIRE or Strand (= multi-filaments)

- High and uniform **Je** at operating field;
- Small **filaments size** to a) reduce magnetization and assure uniform field - mainly at injection, b) avoid flux jump;
- **Filaments twist** to minimize coupling effects during ramping (eddy currents);
- Appropriate **(Cu/non Cu) ratio** - minimum amount of copper needed for stability and protection, controlled within a strict tolerance (typically 1.5-2 ± 0.05 for accelerator magnets)
- Flexible, small bend radius (wound in coils)
- Low AC loss
- Long lengths
- Low costs

CABLES

- High-current cables (10 - 20 kA range)
- Minimum Jc degradation with respect to virgin strands;
- Uniform current density;
- High filling factor and ratio;
- Precise dimensions;
- Twisted wires to minimize coupling effect during ramping;
- Controlled inter-strand resistance between crossing strands in the cable

Typical wire configuration :

Strand: 1'000 -10'000 filaments

5 - 30 μm filament size

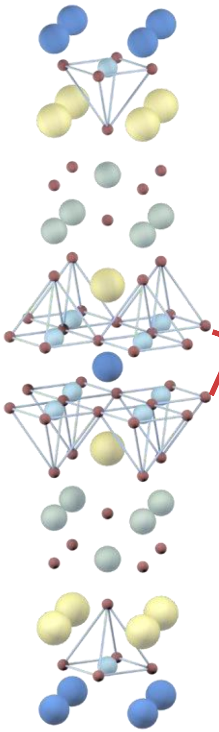
0.3 - 1.0 mm wire diameter

25 cm twist pitch

From A. Ballarino Lecture

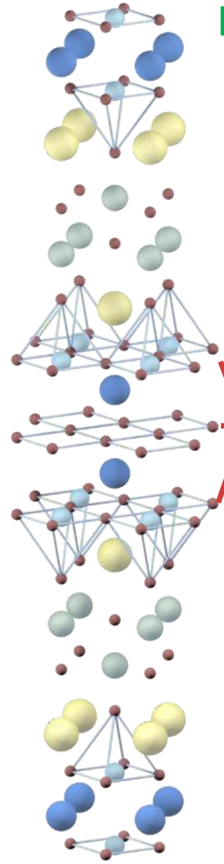
HTS materials for practical applications

From C. Senatore lectures



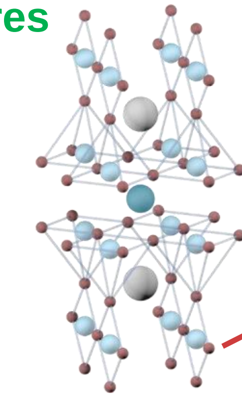
Bi2212

$Bi_2Sr_2CaCu_2O_{8+x}$



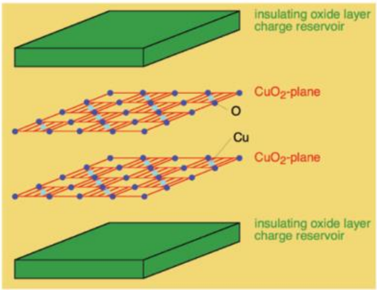
Bi2223

$Bi_2Sr_2Ca_2Cu_3O_{10+x}$

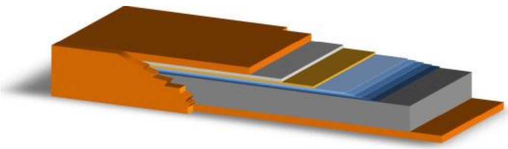


Y123

$YBa_2Cu_3O_{7-x}$

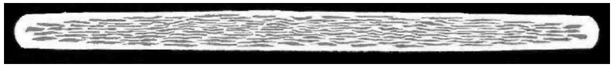


cuprate HTS :
layered structure



Coated Conductor

Bi2212 power in tube wire



Bi2223 power in tube tape

	Bi2212	Bi2223	Y123
a [Å]	5.415	5.413	3.8227
b [Å]	5.421	5.421	3.8872
c [Å]	30.880	37.010	11.680
# of adjacent CuO_2 planes	2	3	2
T_c [K]	91	110	92

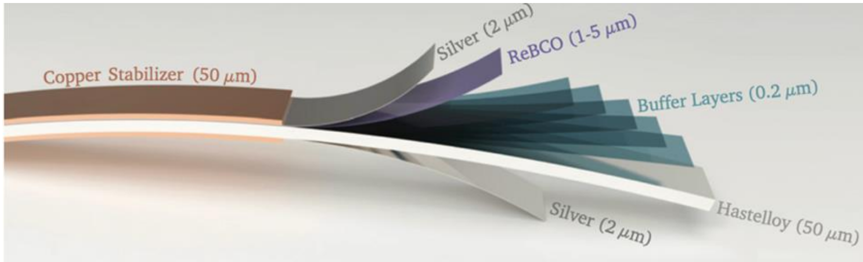
Perovskite structure:

Layered crystal structure consisting of one or more CuO_2 layers – called ab planes

Various layers are stacked together in the c-direction – called c axis

Anisotropic, CuO_2 superconducting planes, Tc increase with the number of planes CuO_2

RE-$Ba_2Cu_3O_{7-d}$ coated (ReBCO)
From tapes to multi-tapes and cables

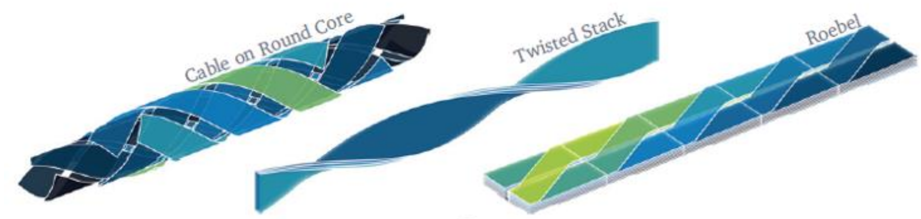


REBCO coated conductors

- ReBCO
- HTS film of 1-2 mm thickness deposited on one side of the substrate
- Produced in long lengths of 50-100 meter piece length

Goals

- Increasing the current and the current densities
- Allowing current sharing between tapes
- Reducing AC losses (transposition)
- Improving mechanical properties
- Reducing diameter bending capability



From HTS accelerator magnets,
Thesis Jeroen van Nugteren (2016)

First round, isotropic YBCO wire

Courtesy Danko van der Laan
(Advanced Conductor Technologies)

Roebel cable by KIT assembled from Bruker ReBCO tapes-
fiber glass rope inserted in the central channel

Twisted Stacked Tape Cable (TSTC)

J_e (A) vs B (T) for superconducting materials (2018)

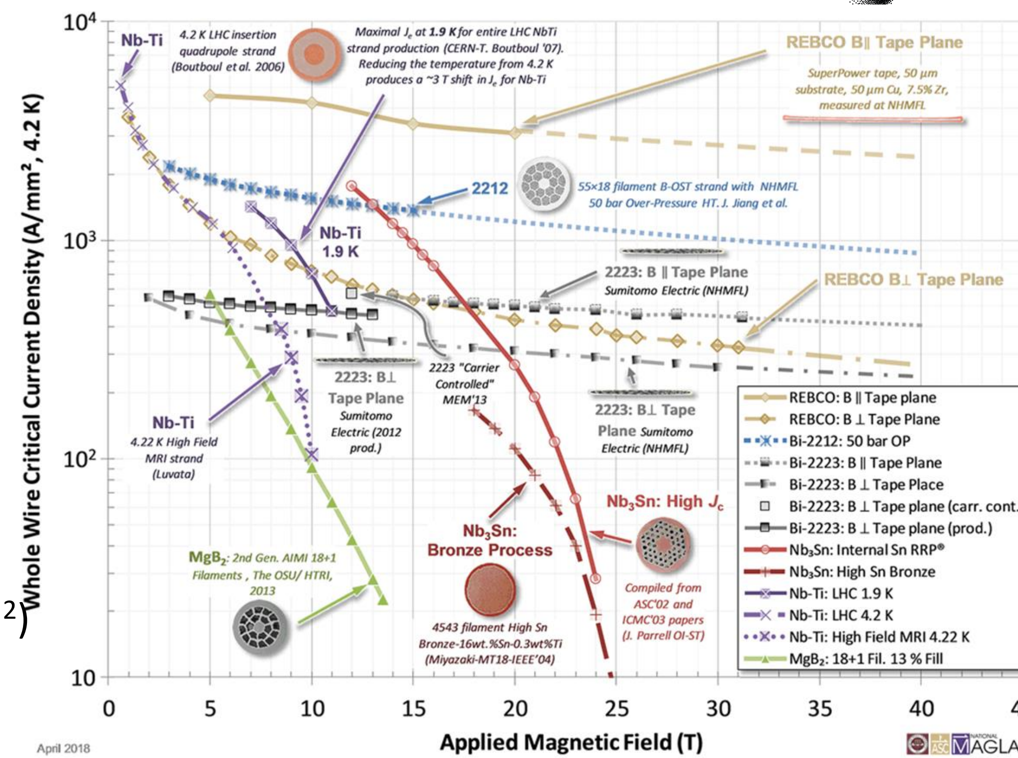
Nb-Ti: the workhorse for 4 to 10 T

- J_c up to ~2500 A/mm^2 at 6 T and 4.2K or at 9 T and 1.9 K
- Well known industrial process, good mechanical properties
- 10 T field in the coil is the practical limit at 1.9 K
- Reliable and well known. Thousands of accelerator magnets have been built

MgB_2 : Moderate Fields up to 5 T (J_c>300 A/mm^2)

Nb_3Sn: towards 20 T

– J_c up to ~3000 A/mm^2 at 12 T and 4.2 K
– Complex industrial process, **higher cost**, **brittle and strain sensitive**
– ~20 T field in the coil is the practical limit at 1.9 K, but above 16 T coils will get very large



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots/

HTS materials: >20T up to 40 T (Bi-2212, YBCO)

– Current density is low (at low field), but **well above 4.5 K and use of cryocoolers**
– Used in solenoids (20T range), used in power lines demonstrators of accelerator magnets – small racetracks have been built

Non-Insulated ReBCO multi tape coils at PSI

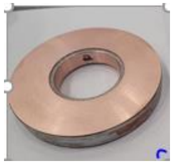
(Jaap Kosse, H. Rodriguez, M. Duda)

PSI

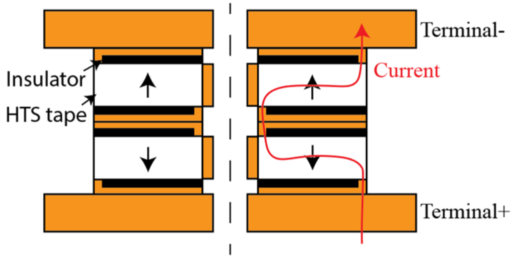
Non-insulated (multi) tapes

+ Larger superconductor volume - high J_c
+ transverse current path - better quench protection
+ High thermal conductivity, mechanical strength
- Very long time constant for current ramps (not adapted for AC application)

Diameter: 100 mm
Aperture: 50 mm
SC type: ReBCO
tapes: 2
turns: 2 x 170
SC length: 2 x 49 m

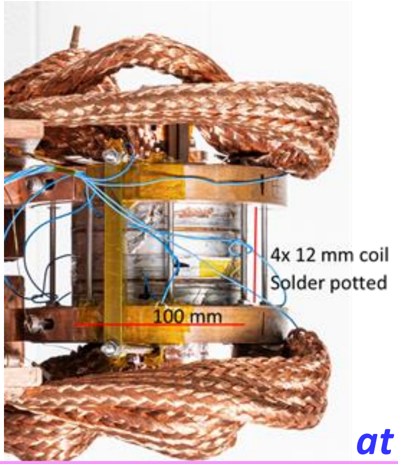


HTS Non-Insulated coils - Technology for High Field solenoid



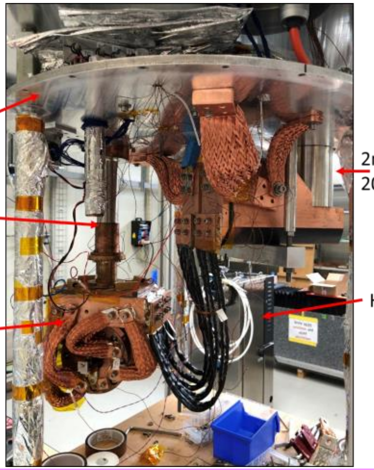
Licence agreement Tokamak Energy

tokamak energy — a faster way to fusion

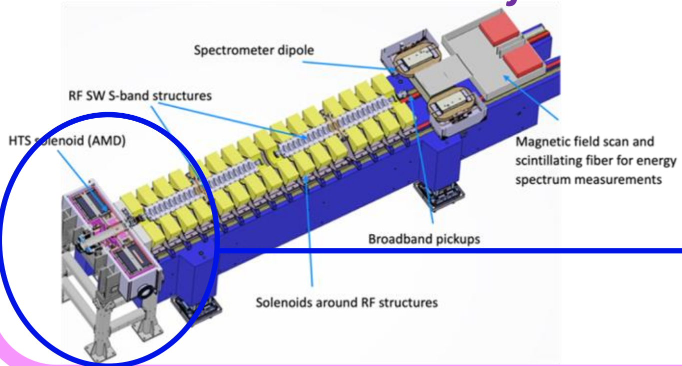


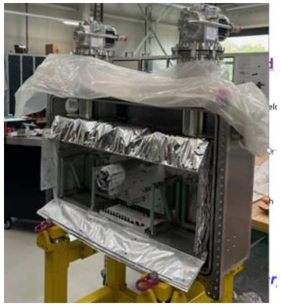
18 T (center)

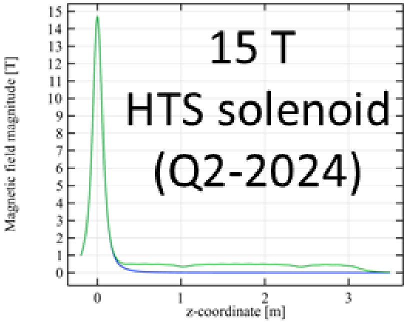
at 2 kA and 12 K !



FCCee Injector Study: P3 (PSI Positron Production)-2026







Superconducting magnets

Superconducting and room temperature magnets
Why they are different?

Superconducting magnets

- Performance limited by the selected conductor: you cannot exceed the wire performance- you only do worse !
- field defined by the current distribution (coil geometry) and not by the iron pole (except for the superferrics)
- high field capability but enormous electromagnetic forces
- quenches (transition to normal) need to be managed to avoid damage and ensure safety
- filaments magnetization results in hysteresis and field errors
- the field quality is changing with time at low temperatures and low magnetic fields - dynamic effects are very important at low fields
- careful handling of cryogenic fluids (not water)
- electrical interconnections in so-called cryo-lines + current leads
- more expensive to produce and operate due to the need for superconducting materials and cooling systems (cryostat, cryocoolers..)

What do we expect for a superconducting magnets ?

Excellent Material Properties: High ratios of irreversibility field (Hirr) to upper critical field (Hc_2), and critical current densities Jc(H,T) and J_E(H,T) at various magnetic fields and temperatures, along with a high critical temperature (Tc).

Advanced Fabrication: Capability to be fabricated into wires with flexible architectures.

Cost Efficiency: Favorable low cost-to-performance ratio.

Environmental Consideration: Minimal environmental footprint

Mechanical Robustness: High strength for enhanced durability.

Production Scale: Availability in long lengths suitable for large-scale applications

High-Performance Cables: Designed for high current applications.

Efficient Operation: Low ramping losses and enhanced magnet protection for reliable performance.

Applications are determined by high J_c, J_e and H_{irr} rather than by high T_c

What are the main technical problems to achieve these goals

PSI

Screening Currents

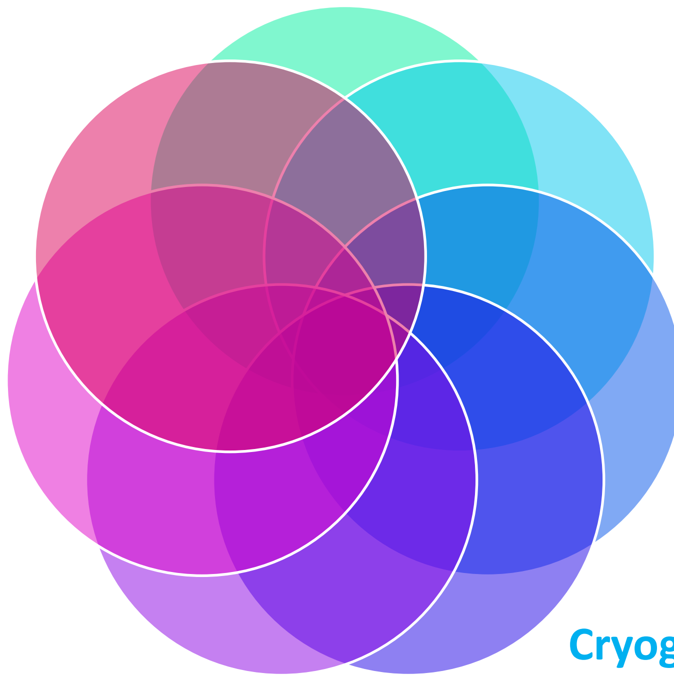
- Ramp losses
- Mechanics
- Field quality and beam-dynamics interface

Magnet Protection

- Detection
- Protection
- Major cost factor

Cabling, Insulation, Winding, Splicing

- Coil geometry / field orientation
- Requires transposition?
- In-line cable fabrication?



Circuit Protection, Powering, Electrical Integrity

- Busbar protection
- Extraction to grid
- Multiple parallel PCs,
- Equalization varistors
- Distributed or local powering (cryo PCs)

Cost

- Cable orientation in field
- Grading
- Protection for compact coils
- Market dilemma (what if compact-fusion fizzles?)

Mechanics

- React Lorentz forces
- Cope with screening currents
- Cope with shear
- Stress management?

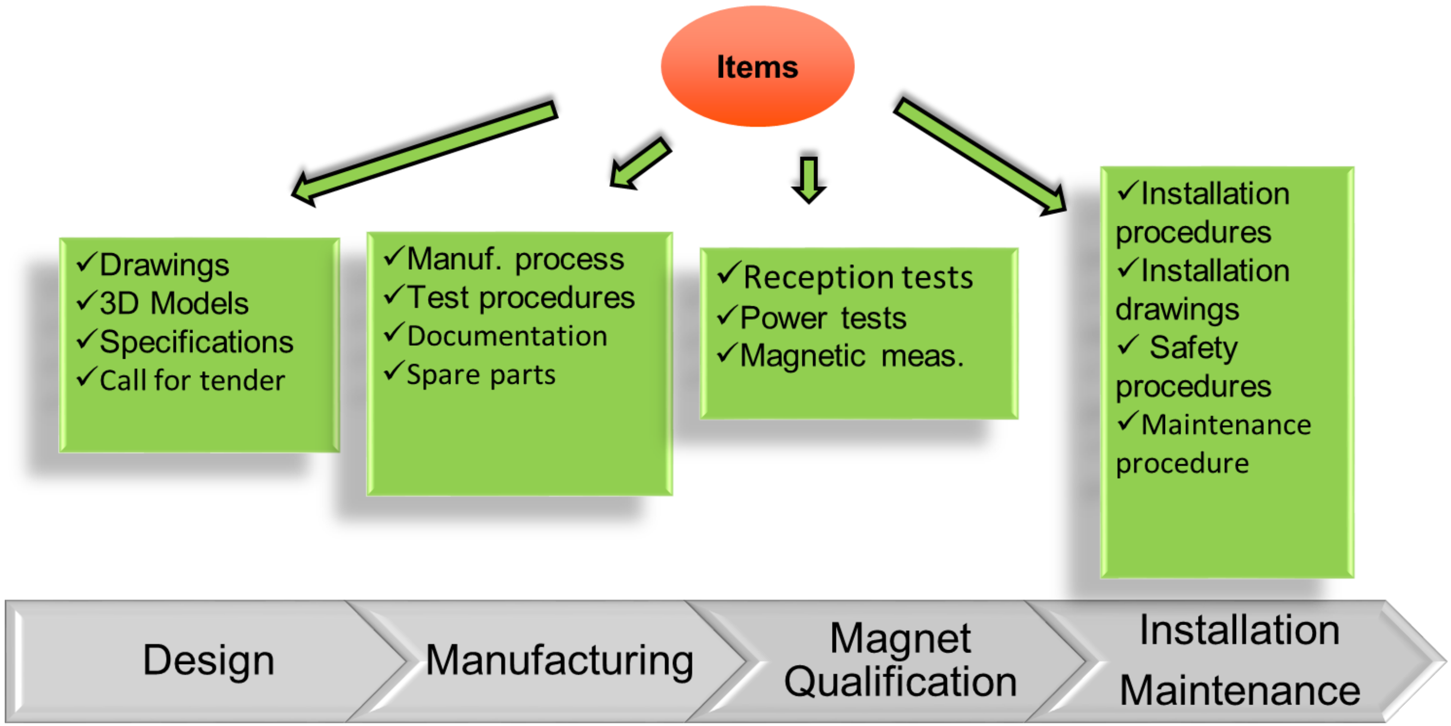
Cryogenics

- Operating temperature
- Low cryogen-inventory forced flow cooling
- Cryogen (GHe, H2?)
- T-Gradients along cryo circuit and in magnet x-section at end of ramp

Courtesy B. Auchmann

Superconducting magnets: life cycle

All the information through the production cycle has to be monitored



Multiphysics codes

- Performance (margin)
- field quality,
- Thermo-mechanics
- cooling,
- quench protection
- CAD design, specs,
- Tenders

Assembly control

- Conductor Quality
- Winding Process
- Heat Treatment
- impregnation
- Collaring and Yoking
- Cryostat, cooling system
- Protection
- Final integration

Cryogenic tests

- Electrical integrity
- Cryogenic integrity
- Power test
- Field quality,
- Quench protection

Installation

- Procedures
- Documentation
- Traceability

Magnet manufacturing process
Long and complex process

Multi-wire cable fabrication & Insulation wrapping

Coil winding, ends & transition manufacturing

Instrumentation (Voltage taps, sensors…)

Coil reaction (Wind & React for Nb_3Sn cables)

Impregnation:

–Vacuum-impregnated with epoxy resin or wax

–Curing: The epoxy is cured in a controlled environment to ensure optimal performance

Collaring process (stainless steel):

–Pre-collared coil assembly under a press, load the coil to the desired pre-stress (in the range of 50…100 MPa) to counteract the Lorentz forces

–Insert keys to "lock" the collars, provides the desired pre-load to the coil

Yoking process (mechanical stability, field enhancement):

–Insert the collared coils in an iron yoke

–Welding of the yoke using a press (max 19000 tons)

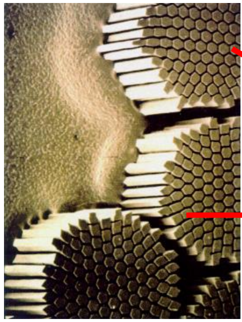
Cryostating: Inserting the cold mass in the cryostat

–Cryogenic enclosure: Vacuum enclosure, thermal shields

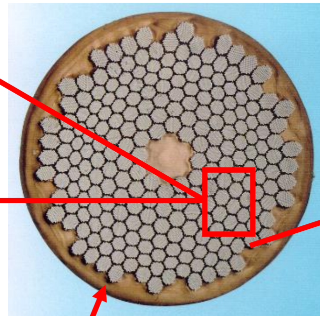
–Multilayer insulation (MLI) blankets

–Liquid helium pipes or cryocoolers

From conductor to magnets
Example CERN LHC magnets

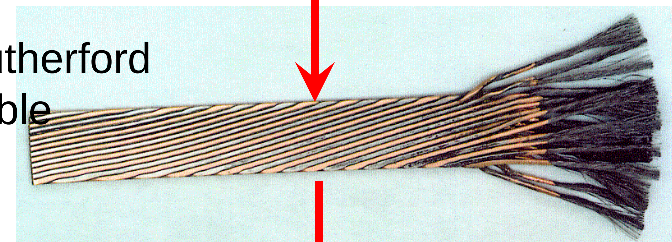


NbTi filaments

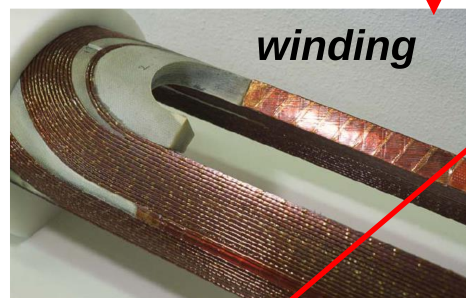


strands

copper

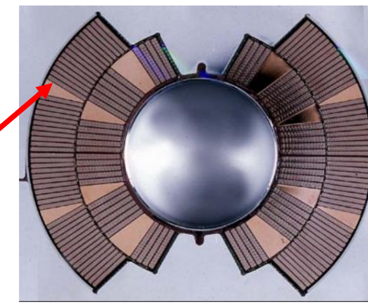


Rutherford cable



winding

Copper wedge



cross section
Cosine θ

Collaring process

Low c-steel collars

yoking process

Cold mass (cryostating)

Cooling (to remove the heat): many options

Heat removal requires direct or indirect cooling at cryogenic temperatures.

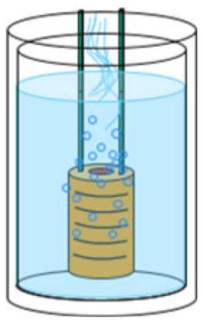
Typical examples:

Direct:

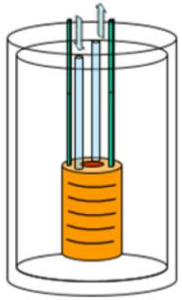
- Bath cooling: immersion in a pool of liquid helium
  - at atmospheric pressure and saturation temperature (4.2 K)
  - at sub-atmospheric pressure (superfluid helium He-II)
- Forced-flow cooling using supercritical or two-phase flow (inside the conductor)

Indirect (5 bars)

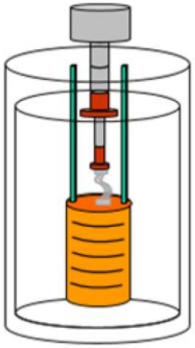
- Contact to a heat sink (e.g. to a cryocooler) through conduction



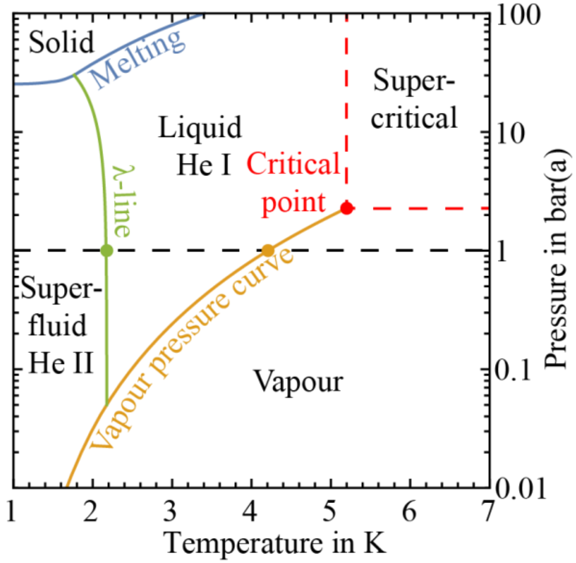
Direct cooling by bath



Direct cooling by internal forced flow



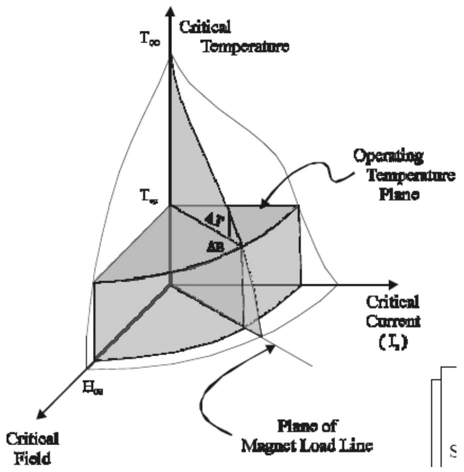
Indirect cooling by thermal link coupled with a cryocooler



Courtesy of B. Baudouy, CEA

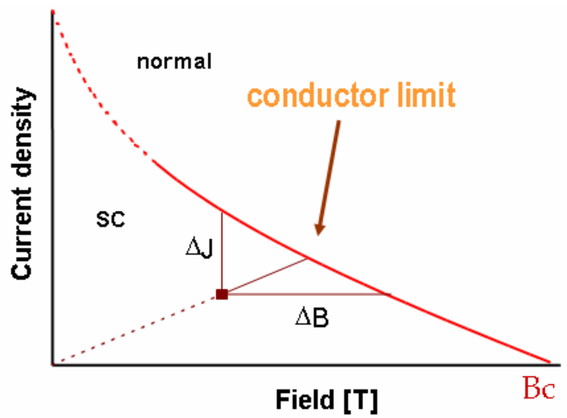
What is a quench?

Quench = irreversible instability with transition from superconducting to normal state
→apparition of voltage, temperature increase, thermal and electro-magnetic forces, and cryogen expulsion



Conductor limited quench :

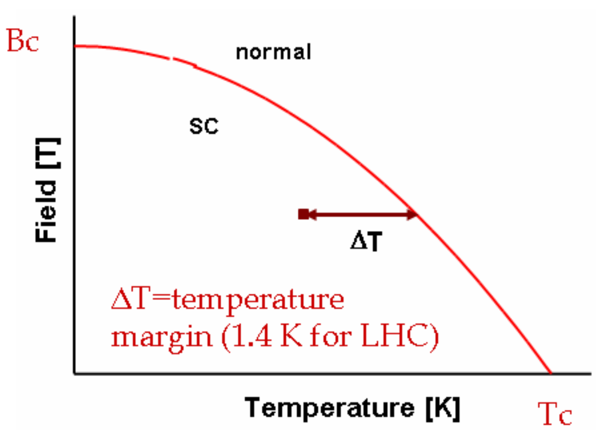
the critical surface J_c (B,T) is crossed because of an increase of *I* (and *B*)



or

Energy deposited quench :

the critical surface Bc (T) is crossed because of an increase of *T*



For LHC magnets at CERN:
Energy deposited quenches

$I_{quench} < I_{conductor\ limit}$

a local frictional displacement of the cable strand over **1μm** is sufficient to dissipate $2\cdot10^{-3}$ J and to drive the conductor volume normal

ΔQ ⇒ ΔT If ΔT > Tc(B,I) - Tbath ⇒Quench

$$\Delta T_{margin} = Tc\ (B,J) - Tbath$$

$$\Delta T_{margin} \sim 7\ K\ at\ B = 0.54T$$
$$\Delta T_{margin} \sim 1.4\ K\ at\ B{=}8.33\ T$$

Margins for stability: what does it mean?

PSI

Stability = Ability of a superconducting magnet to operate without accidental quench under thermal disturbance

- **Load Line margin** $= 1 - \frac{J_{op}}{J_c}$

operating current well below the $J_c\ (T_{op}, B_{op})$

- **Temperature margin**: T_{CS}-T_{op}

the difference between the operating temperature of a superconducting magnet and its current sharing temperature T_{CS}

Practical operation always requires margins:

Typical for NbTi conductor :

– Critical current margin:

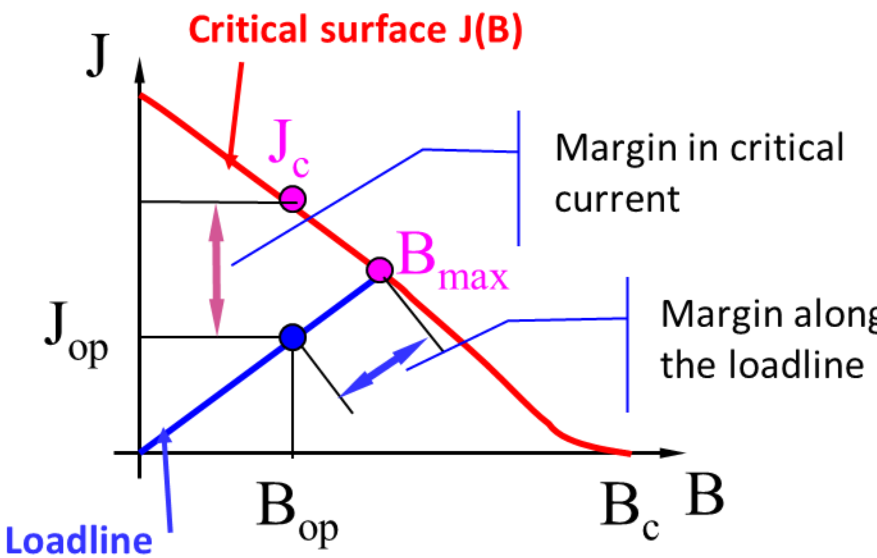
$J_{op} / J_c \approx 50\ \%$

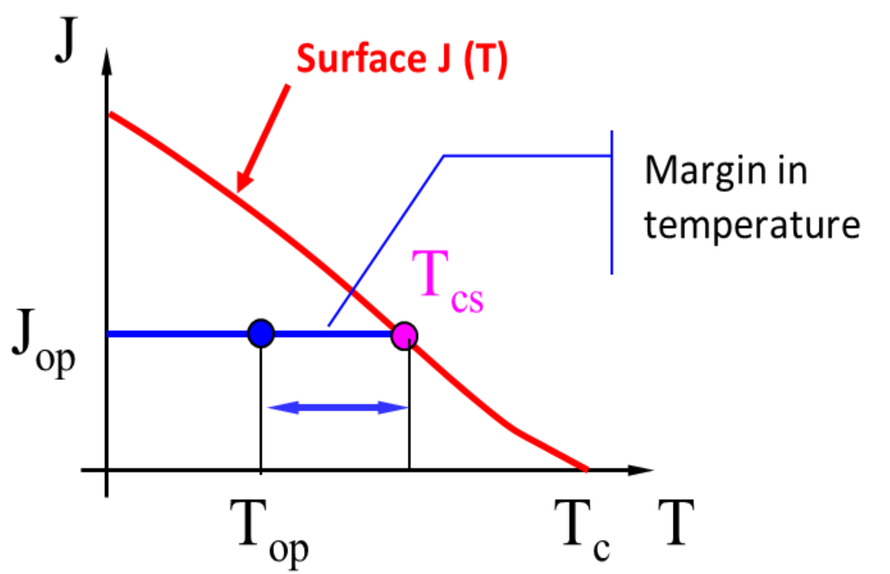
– Critical field margin:

$B_{op} / B_{max} \approx 75\ \%$

– Temperature margin:

$T_{cs} - T_{op} \approx 1...2\ K$



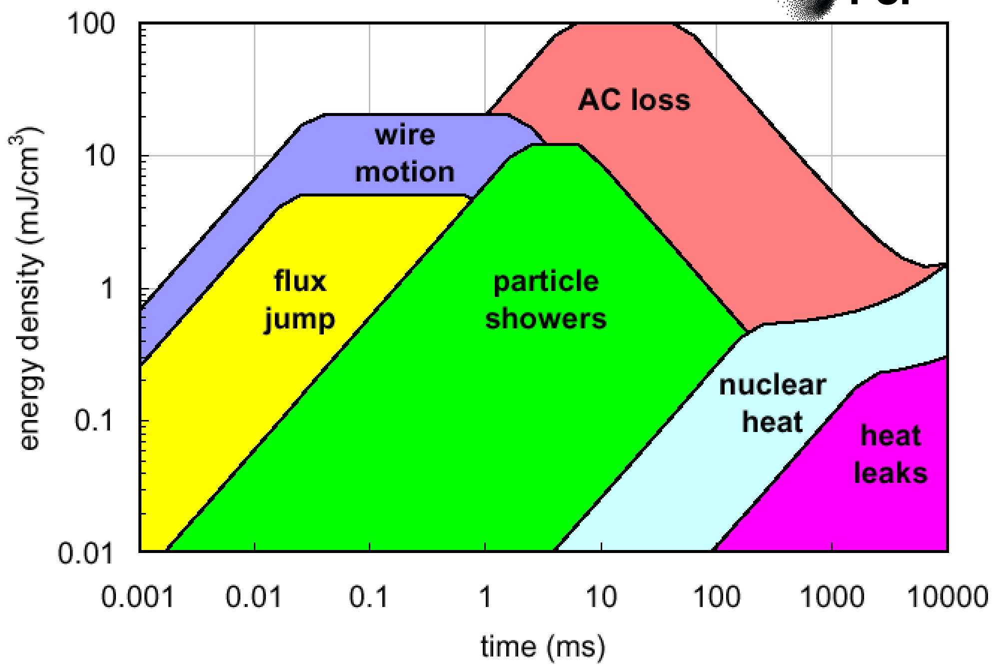


From Luca Bottura Lecture

Origin of quenches (conductor limited, premature)

- **Conductor limited**
  - Critical surface is passed by increasing the current
  - Part of current flows in the stabilizer
  - Power dissipation → Quench
- **Intrinsic**
  - Conductor instability (flux jumps)
  - Conductor damage / broken strands
  - AC losses
- **Mechanical**
  - Frictional motion of the conductor
  - Cracking of impregnation epoxy
- **Thermal**
  - Excess heating in splices or current leads
  - External heat leaks
  - Nuclear and beam radiation

} **deposited energy → local increase of temperature**



Disturbance spectra of accelerator magnets
(Y. Iwasa, "Case Studies in Superconducting magnets", Springer 2009)

$$\Delta Q_{quench} = \int_{T_{bath}=1.9K}^{T_c(B,J)} c_{eff}(T)\,dT$$

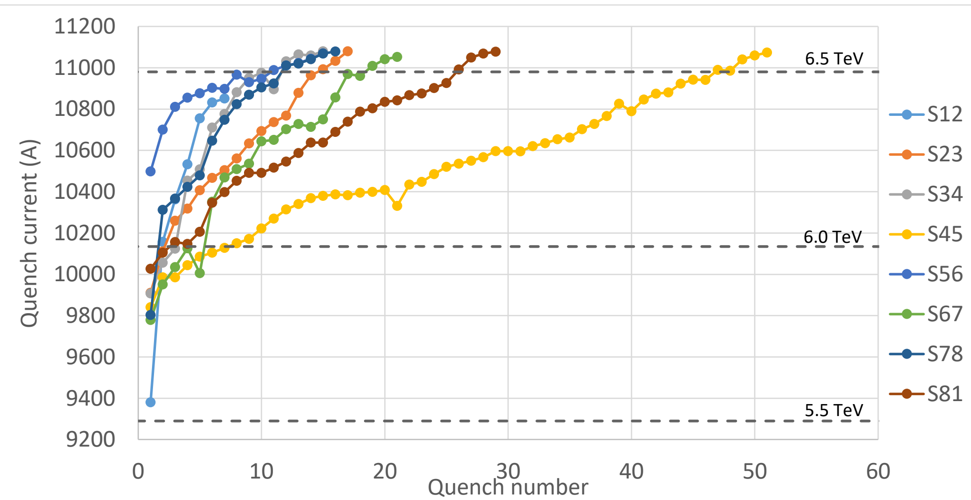
typical disturbances (~1ms) energy must entirely be absorbed by the enthalpy of the conductor

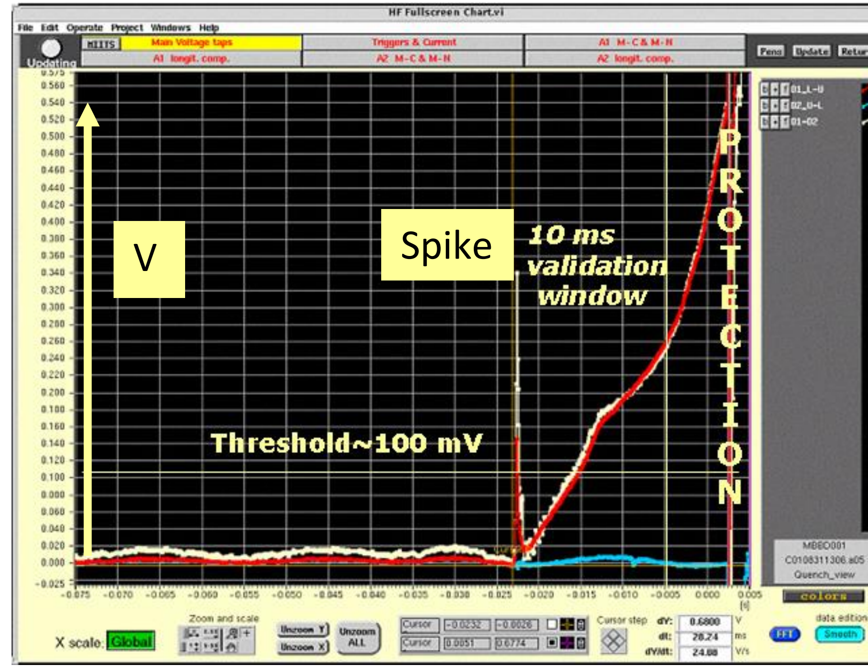
Quenching is therefore considered a natural part of the magnet operation, and magnet systems should be designed to handle it safely.

From M. Marchevsky lecture – USPAS 2017

Training quenches curve for LHC magnets

Training of CERN superconducting magnets in the LHC sectors





Quench induced by a mechanical movement (spike in V)

- Quench current **gradually** increases with every quench until "plateau" is reached
- "Memory" of a previous quench current (= **local** strain state)!
- Training is usually explained as gradual "compaction" of the winding under Lorentz forces, accompanied by a series of slip-stick or cracking/delamination events (causing a quench).
- Training is costly! Eliminating magnet training is a challenging and important problem

Magnet quench effects

There are dangerous failures in the magnet coil that can be induced during a magnet quench:

- overheating
  - insulation degradation, conductor degradation
  - meltdown of the splices and/or conductor
- high-voltages
  - arcing
  - short circuits
- overstressing
  - large thermal expansion stresses and structural failures
  - strain-induced conductor damage

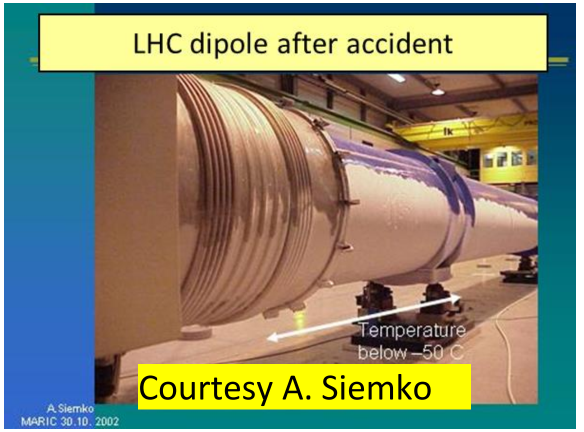
$E_{stored} = \frac{1}{2} L I^2$

At 11850 A : **7.1 MJ** (melting of 13 Kg of Cu)

Local deposition of all the energy!

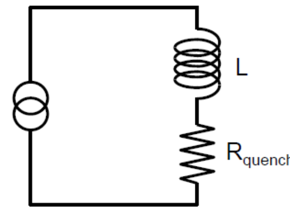
Failure in one LHC magnet after a quench (2003) :

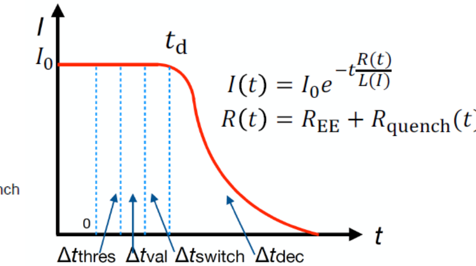
- How it happened
  - **Inter-turn short circuit** after first quench
  - Next quench above the critical current level in the coil
- What happened
  - Loss of the electrical integrity of the magnet
  - Damage of the coil preventing powering the MB circuit
  - Break of the electrical integrity of proximity electronics due to uncontrollable HV oscillations
  - Break of the vacuum and cryogenic integrity



Magnet protection against quenches

The magnet can be seen as a L/R circuit : $I(t) = I_0 e^{-t\frac{R(t)}{L}}$.





When the quench starts, a resistive voltage starts to grow →
Maximize *R* to decrease *I* : ↘ Joule losses

- Detection of that voltage (threshold at about 100 mV)
- Cut of the power supply and triggering of the protection
- Increase the speed of current decay (in L/R) the quicker the decay the lower the temperature in the coil (0.1 to 0.5 s)

$$\int_{T_{op}}^{T_{max}} \frac{\bar{C}}{\bar{\eta}}\, dT = \int_0^{\infty} J^2\, dt$$

total volumetric heat capacity

stabilizer resistivity

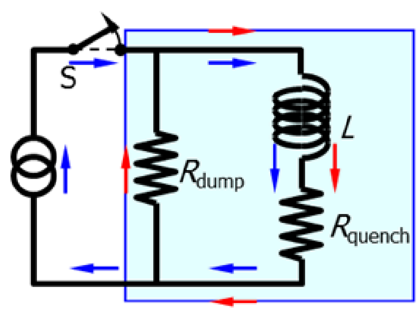
cable operati current densi

$T_{max} = T_{hot\ spot}$

How to speed up the decrease of current ?

Passive

By adding an external resistor in series with the magnet: dump resistor



$R_{dump} \gg R_{quench}$

← normal operation

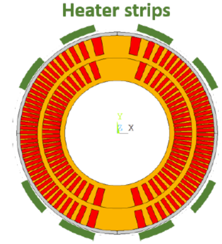
← quench

Part of the energy is extracted, dissipated outside the magnet

Active

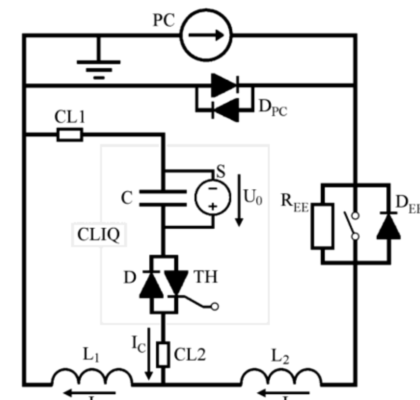
By heating up the coil, using heating elements on top of the coils called quench heaters

Heater strips



Coupling-Loss Induced Quench (CLIQ)*

I changes → *B* changes → Coupling losses (heat)→ *T* rises → Quench

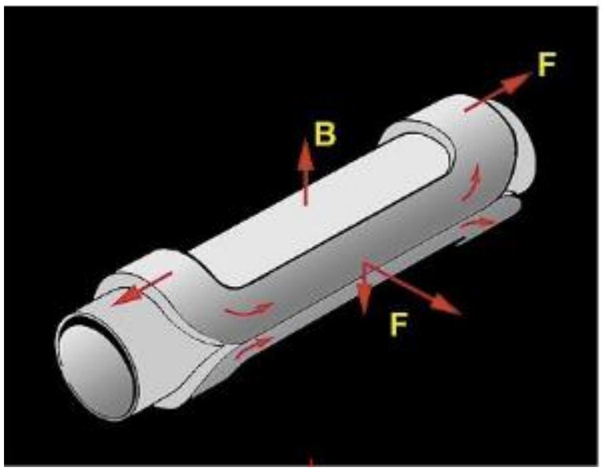


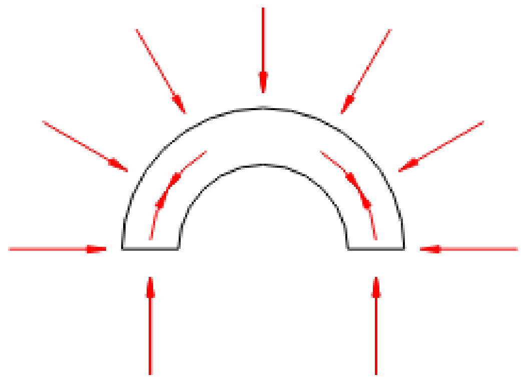
**E. Ravaioli- CLIQ. A new quench protection technology for superconducting magnets, PhD : Twente U. : 2015*

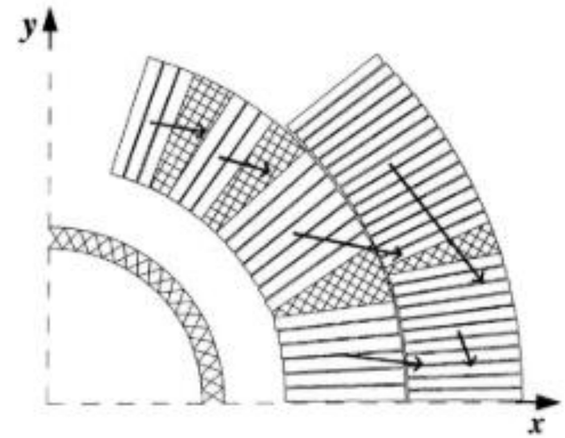
Lorentz forces on a superconducting magnet : LHC dipole example

The electromagnetic forces are enormous and in a dipole magnet tend:

- To push the coils towards the mid-plane in the vertical–azimutal direction (F_y, $F_\theta < 0$)
- To push the coils outwards in the radial–horizontal direction (F_x, $F_r > 0$)







From L. Rossi Lecture – CAS 2009 (Divonne)
"Superconducting Magnets
for the LHC"

Nb-Ti LHC MB

Values for a central field of 8.33 T

- F_x= 340 t per meter: ~300 compact cars/m
- Precision of coil positioning: 20-50 μm
- F_z= 27 t: ~weight of the cold mass

How to contain them?

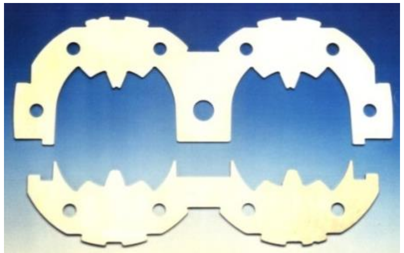
How to counteract the Lorentz Forces ?

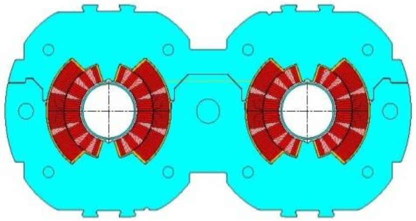
1. **Reinforcement with Mechanical Structures**: Adding mechanical supports or structures that can withstand the mechanical stress induced by Lorentz forces. Distribute distributes the forces evenly across the structure.

2. **Material Choices**: Selecting materials that can endure high mechanical stress without deforming. For instance, in superconducting magnets, using materials like reinforced composites can help maintain structural integrity under high Lorentz forces.

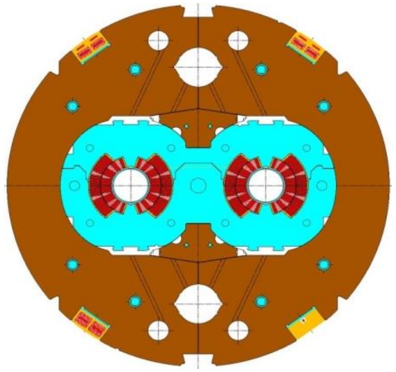
3. **Pre-stressing Techniques**: Applying pre-stress to materials or components can counteract the stresses induced by Lorentz forces during operation. This can be particularly effective in superconducting magnets, where wires or tapes can be pre-stressed to offset the expansive forces at work when in use.

Reinforcement of mechanical structure and pre-stressing



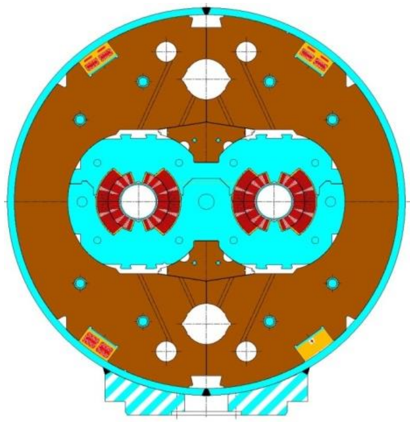


1. **Collaring**: By clamping the coils, the collars provide
   - coil **pre-stressing** to the coil after **cool down** in order to reduce conductor motion;
   - **Withstanding the electro magnetic forces**



2. **Yoking:** Ferromagnetic yoke around the collared coil provide
   - Magnetic function (~15 % increase LHC magnets)
   - Mechanical function (increase the rigidity of the coil support structure and limit radial displacement)

3. **Shell welding**: two half shells welded around the coil to provide
   - Helium container
   - Additional rigidity



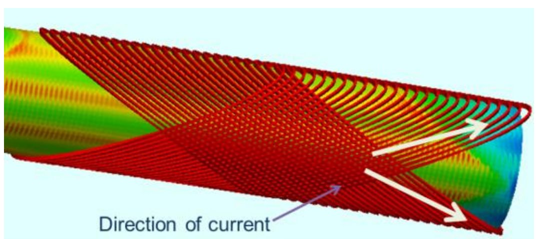
From P. Ferracin Lecture

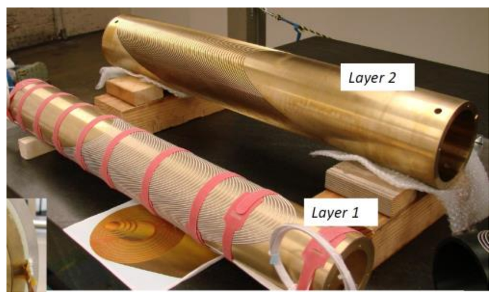
Stress management (interception) structure

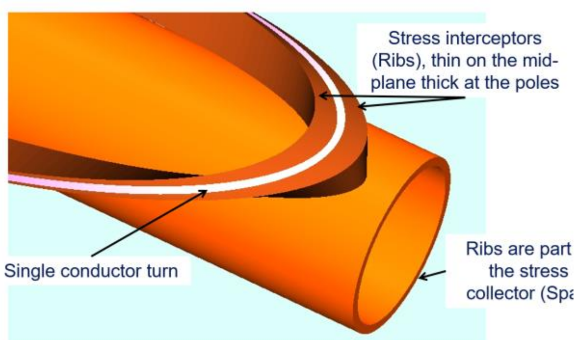
Selected structure gives a distribution of the current density and reduces the Lorentz force effect accumulation on coils

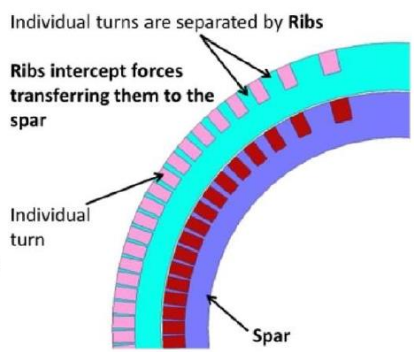
Canted cosine theta geometry (CCT)

- 2 layers of inclined solenoids: powered such that the axial B components compensate and the transverse B components add up.
- Each turn is individually supported with force interception at every single turn
- Mandrel (ribs + spar) : No collars, end parts, spacers…





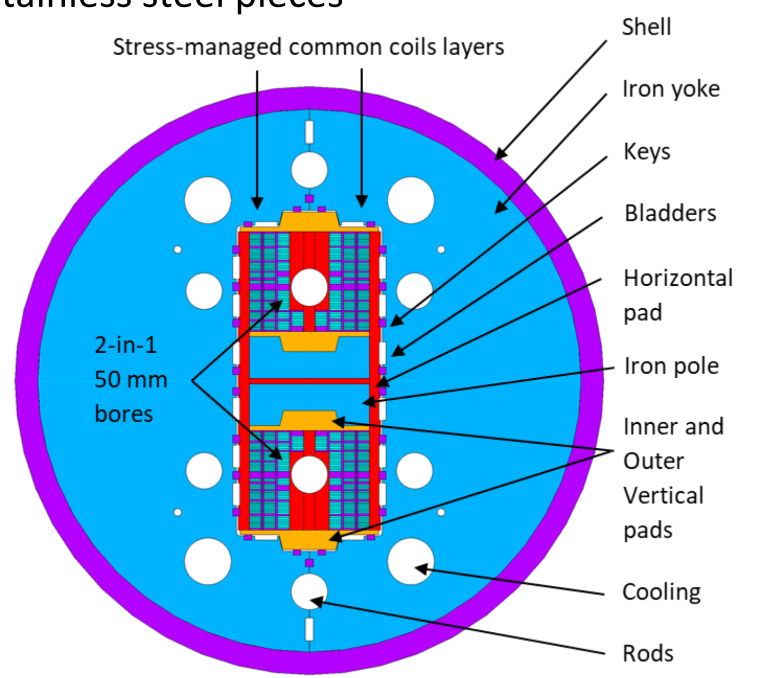


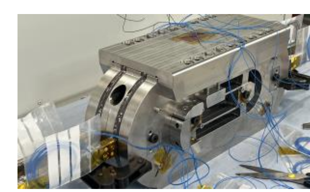


Courtesy: Shlomo Caspi (LBNL)

Stress managed coil geometry

- Stress interception of coil blocks by the structure (formers, rods)
- E.M. force exerted on multiple coil blocks does not accumulate
- Forces transmitted to the magnet frame by stainless steel pieces



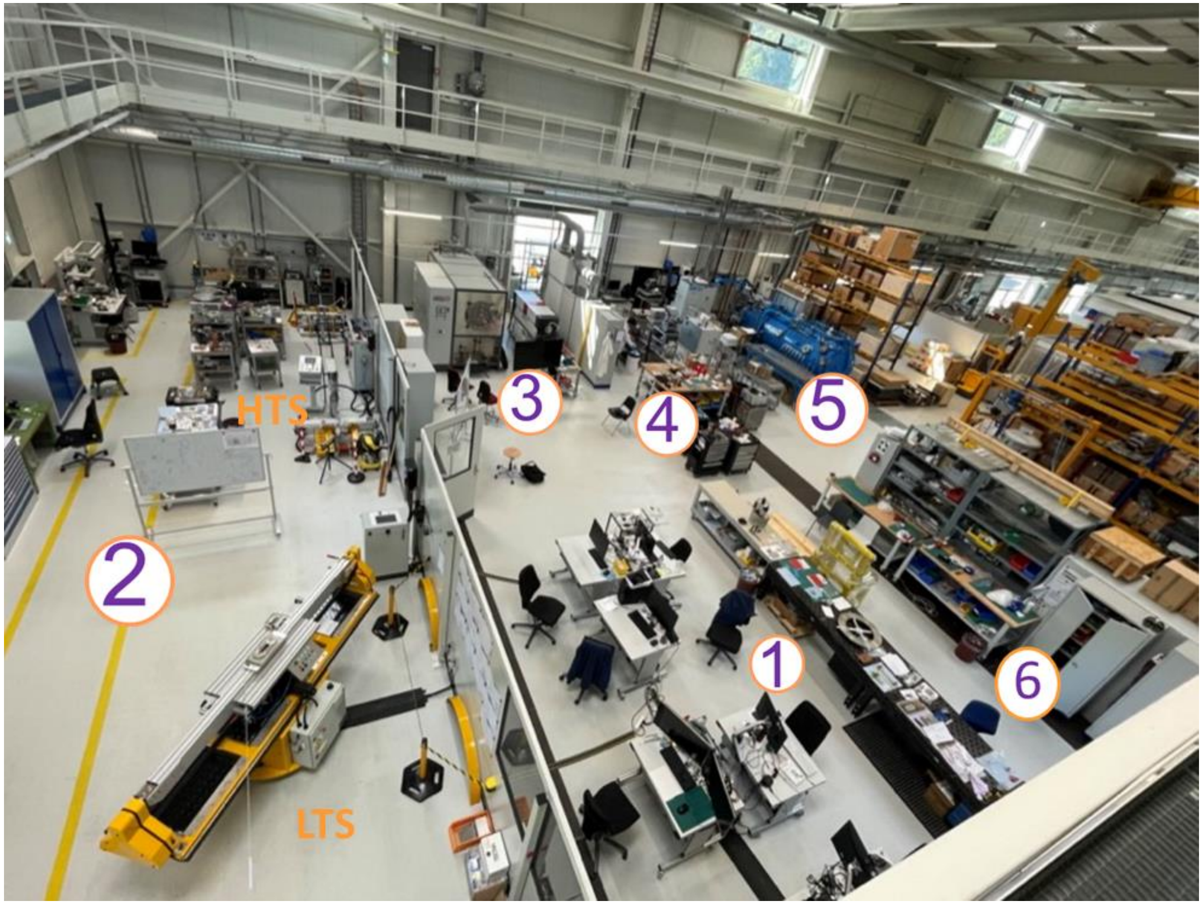


Courtesy: D. Martins Araujo

Example of magnet fabrication at CERN :
An overview of the infrastructure (bldg. 180)

From Daniel Schoerling Lecture, CAS 2018

Example of PSI: MagDev Lab for LTS/HTS coils and 1 m long magnets



1: Magn. & Mech & CAD Design

2: Coil manufacturing workplace

HTS automatic winder unit: tensioning table, vacuum solder vessel, argon glove box for solder…

LTS winding machine (Coll. with Ridgway Machines Ltd)

- Winder unit (2m40) with electrical connections.
- 3 positioner + tensioner units.
- Manual and programmable semi-automatic control

3: Thermal Treatment

- **Argon-furnace** (2-m-long coils)
- **Research tubular furnace**

1-m-long, 14 cm diam.
Quartz tube, vacuum or gas atmosphere up to 1100ºC

6: Assembly

- Loading
- Instrumentation
- Metrology

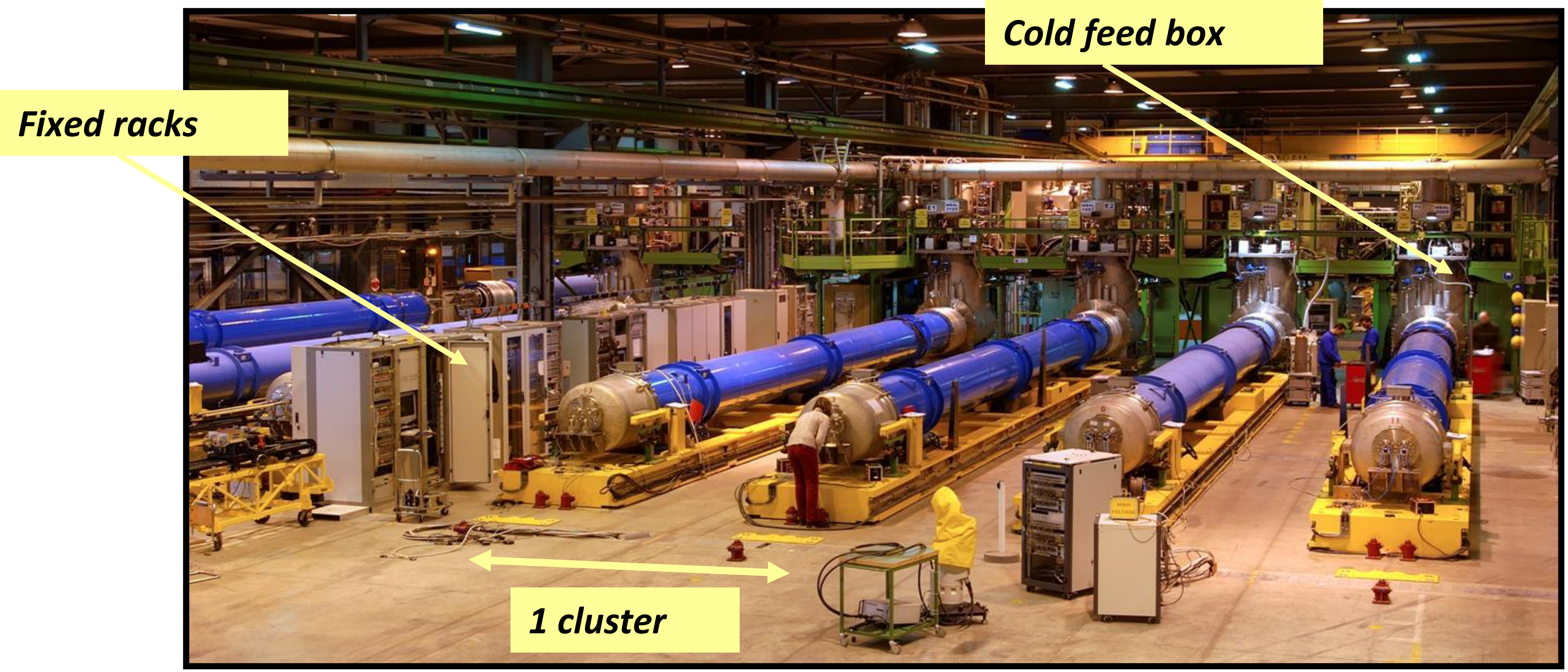
5: Impregnation

- **Vacuum-impregnation vessel** for 1-m-long coils, vertical impregnation.
- **Autoclave** for 2-m-long coils, horizontal impregnation, 250ºC, 10 bar.
- **Mixing, degassing set-up**
- **Box oven** for wax crystallization / epoxy curing

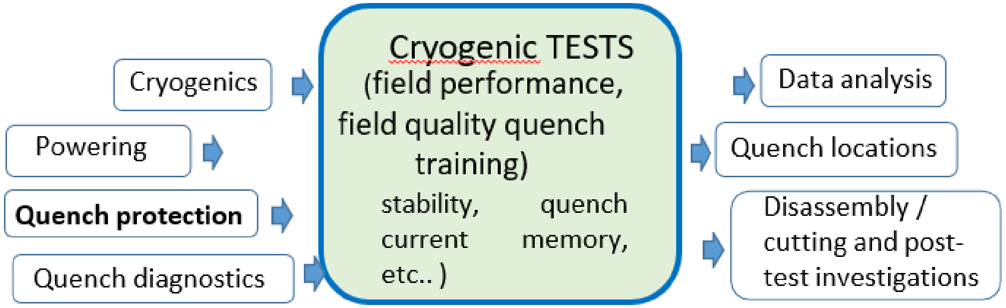
4: Chemistery workplace

- Spray-coating equipment.
- Ultrasonic cleaning
- Diamond wire saw.
- Polishing equipment.
- Optical microscope

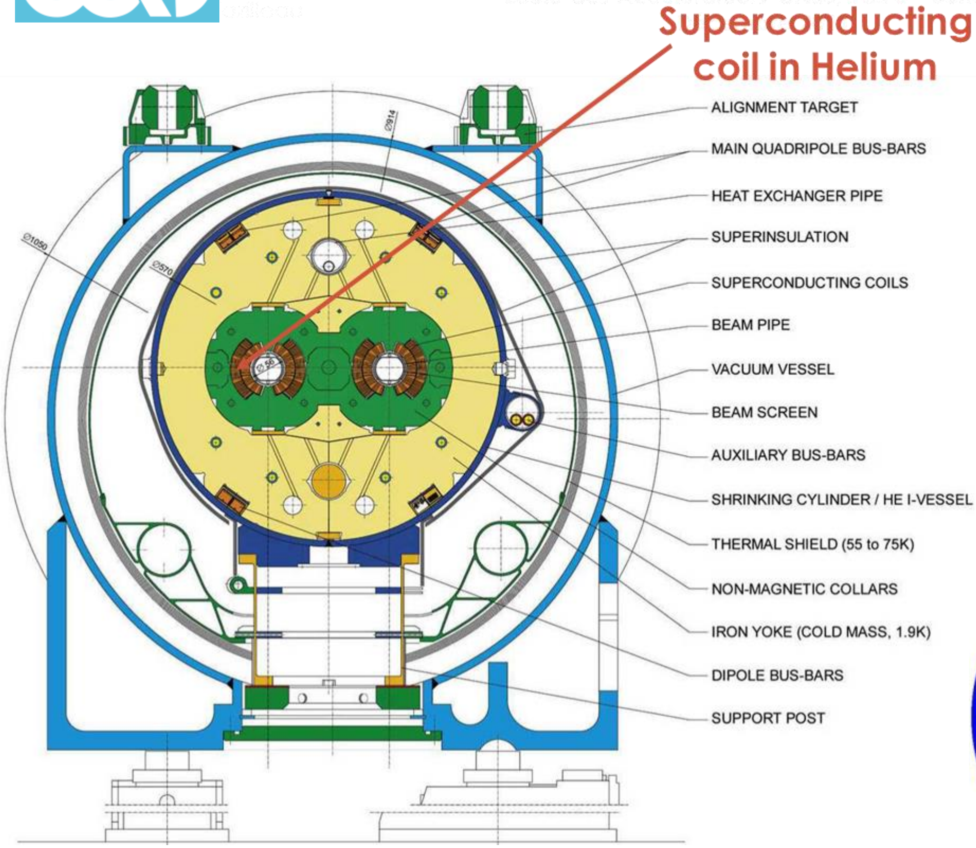
CERN test facility for LHC superconducting magnets



- The test facility: **12 fully equipped test benches** arranged in 6 clusters
- All test benches are capable **to operate, both at 1.9 K and 4.5K**
- ***Powering***: Per cluster 1 main PCs (14 kA, 15V), two 600 A P.Cs, two 60 A PCs
- Tests at 1.9 K (power tests and magnetic measurements) of 1232 dipoles and 392 quadrupoles arcs



Example 1: LHC dipole cross section



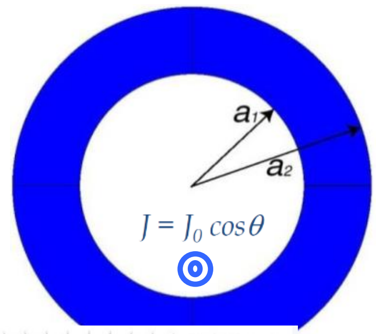
Cos(Θ) coil geometry

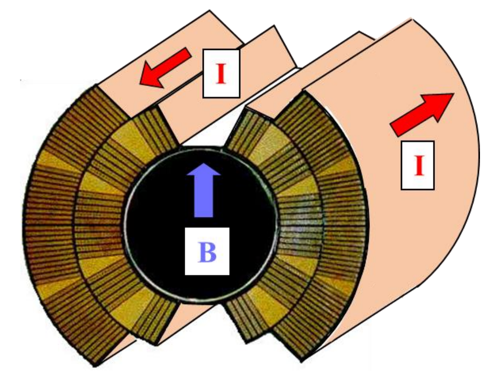
+ Allows a very good field quality
+ Is very efficient w.r.t the quantity of superconductor used

⊖ The EM forces cause a stress buildup at the mid-plane where also high fields are located

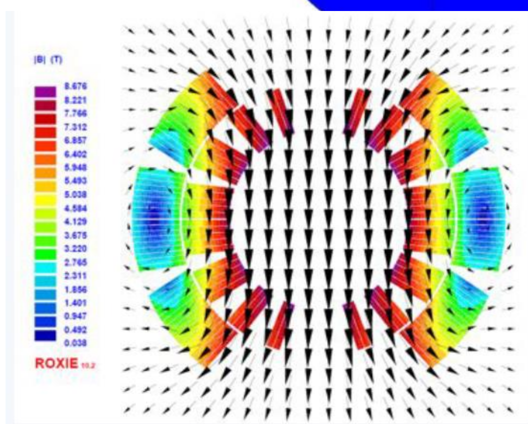
⊖ Coil ends should carefully be designed

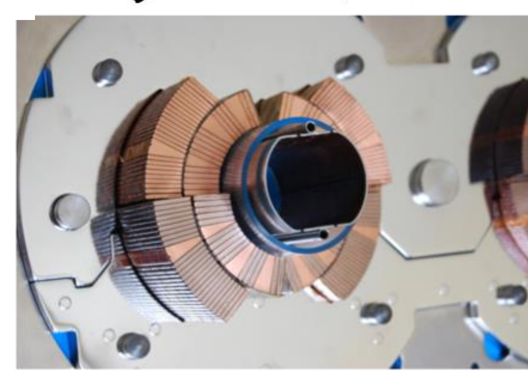
$$B_y = -\frac{\mu_0 J_0}{2}(a_2 - a_1)$$





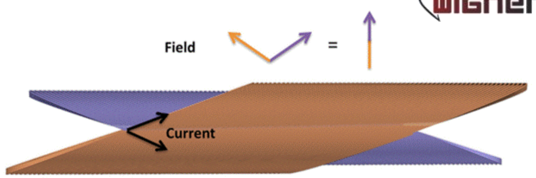
	Main Parameters
56 mm	Bore diameter
~16.5 m	Total length
1.9 K	Operating temp.
8.3 T	Magnetic field
11850 A	Nominal current
~ 30 t	Mass



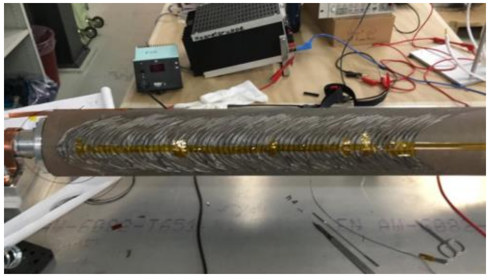


Example 2: Nb_3Sn Superconducting Accelerator Magnet designed and built at PSI

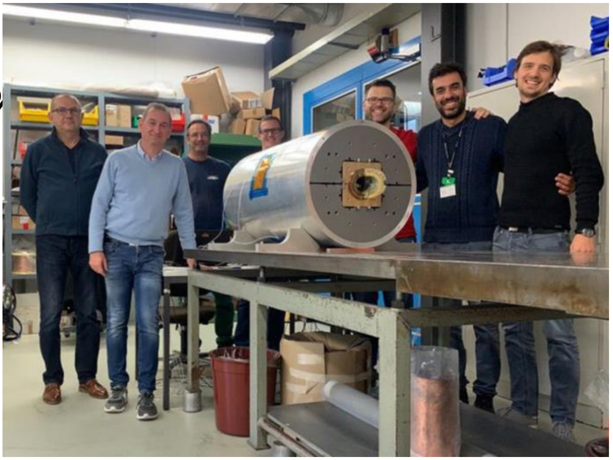
- Magnet construction from 02/2017 to 10/2019 Canted Dipole 1 (CD1) was tested at CERN in Q1'23
- Long training but….
- It reached a **record 10.1 T in the bore** at 1.9 K and 9.9 T or **100% of maximum field at 4.5 K**

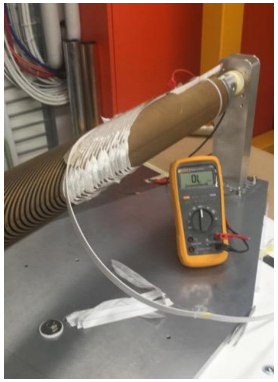


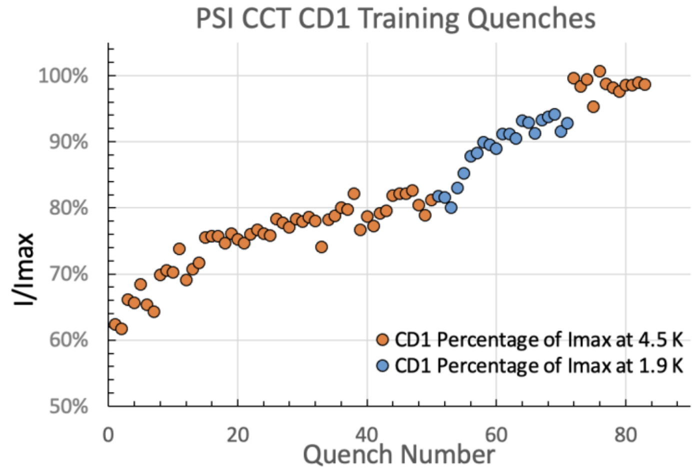
Two oppositely canted solenoids, producing a pure dipole field.



Swiss Accelerator Research and Technology







CD1 magnet training at CERN.
Courtesy F. Mangiarotti (CERN) and M. Daly (PSI).

"Coil Manufacturing Process of the First 1-m-Long Canted-Cosine-Theta (CCT) Model Magnet at PSI", G. Montenero et al., IEEE Trans. on App. SC., Vol 29(5), 2019

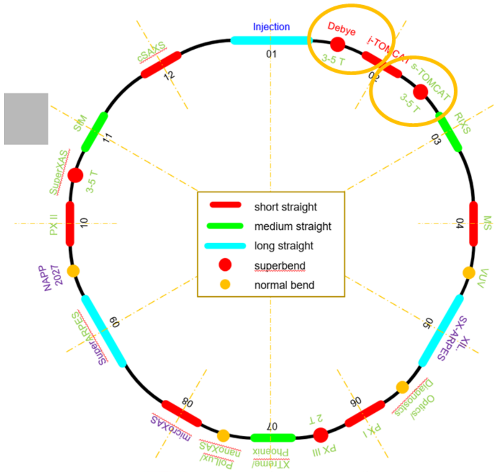
"Test Results From CD1 Short CCT Nb Sn Dipole Demonstrator and Considerations About CCT Technology for the FCC-Hh Main Dipole" B. Auchmann et al, IEEE Transactions on Applied Superconductivity, https://ieeexplore.ieee.org/document/10365505

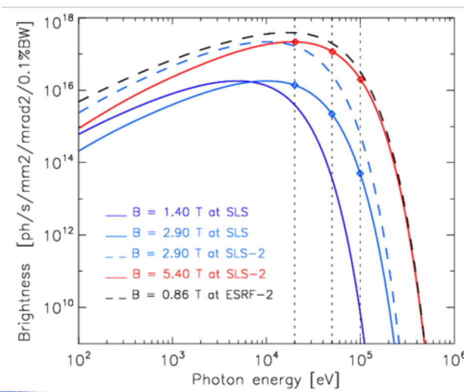
Example 3: 5 T superbends for SLS2.0

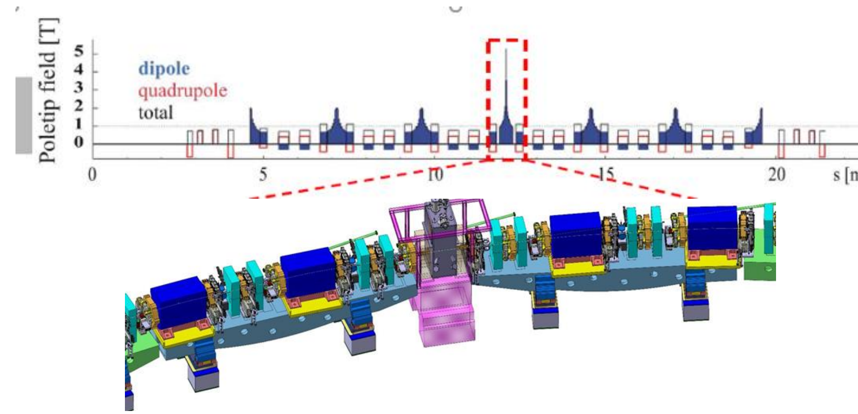
(ciro.calzolaio@psi.ch)

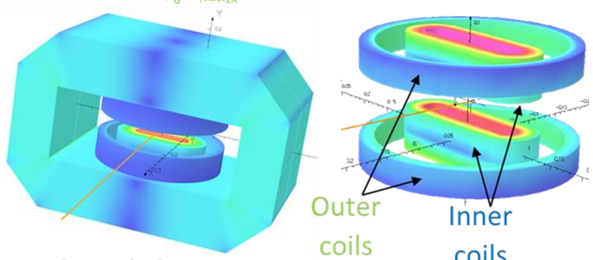
Upgrade of the PSI Swiss Light Source (SLS)

2 superconducting dipoles (3-5 T) to provide hard X-rays at two beam lines

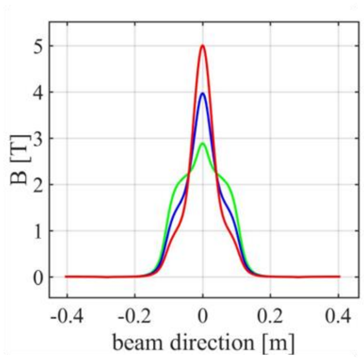


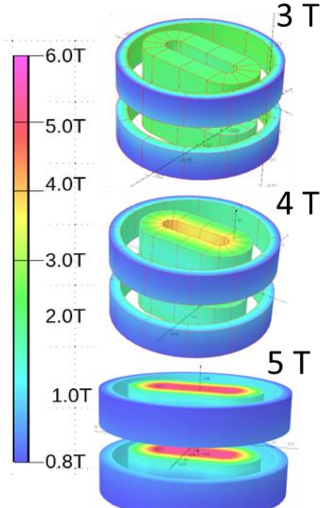




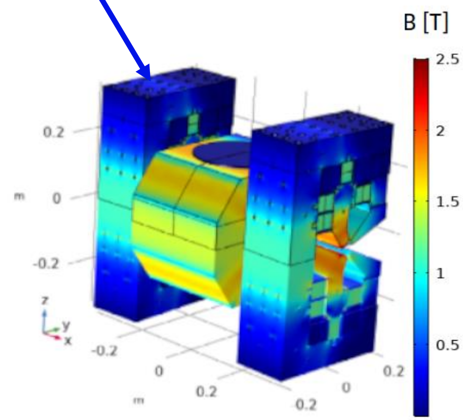


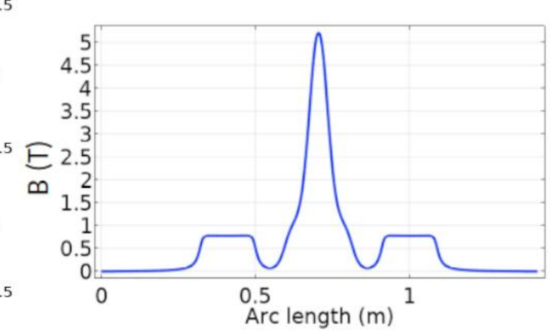
- Unique type for the 2 SC superbends
- Operating fields between 3 T and 5 T
- 2 pairs of Nb-Ti coils (racetrack, solenoid)
- 2 power supplies (200 A), 2 current leads
- ***Close yoke with remote vacuum chamber***





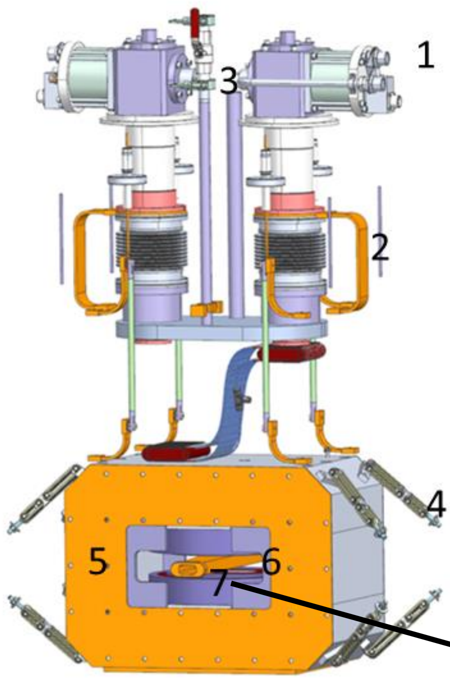
Permanent quadrupole



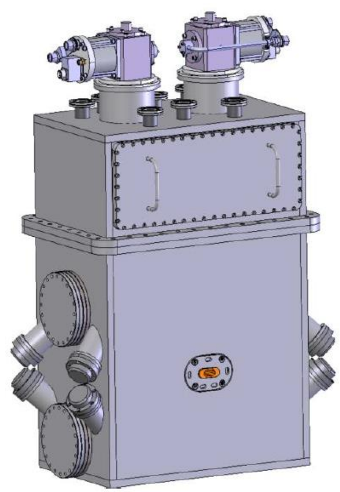


5 T superbends- main components

	Main magnet components
1	2 cryocolers RDK-415D
2	Thermal connections
3	Current leads (Cu+HTS)
4	Suspension straps
5	Armco Yoke
6	Vacuum chamber
7	Pair of NbTi coils inside the Al precompression ring



Cold mass



Nb-Ti coils and
aluminum pre-compression structure

Courtesy SIGMAPHI

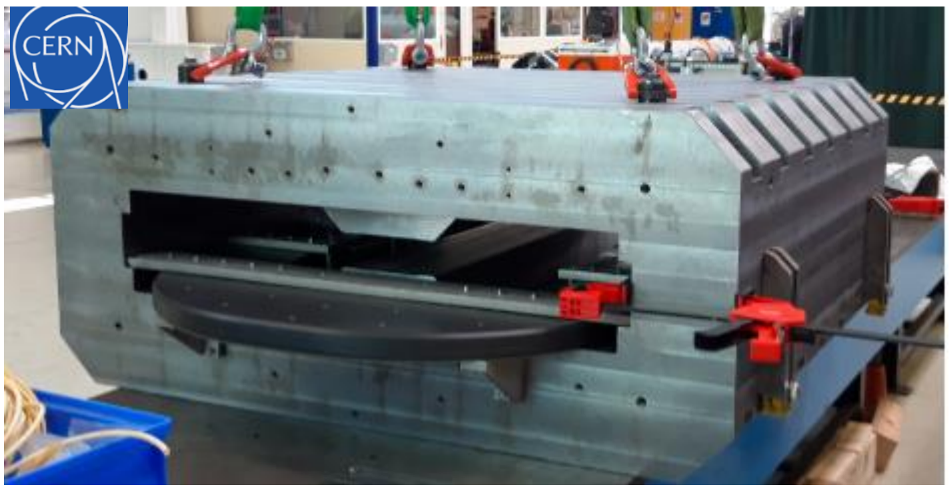
Last word on....superferric magnets

Superconducting coils but iron geometry strongly affects the field shape (field quality)

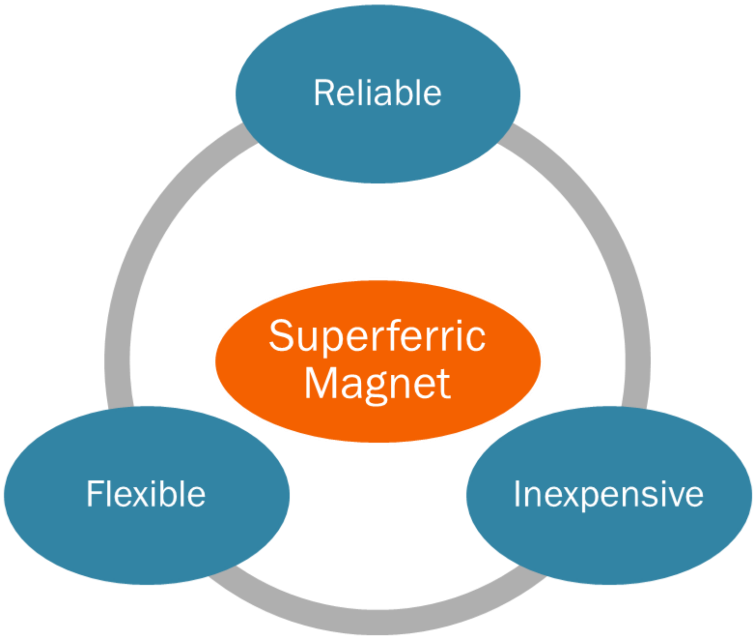
The design is characterized by a close coupling of the superconducting coil to the iron flux return of the magnet

Alternative to resistive magnets (B ~2T) to reduce energy consumption +minimize the cross section (dimensions and weight)

From Marco Statera CAS Magnets 2023



Energy Efficient Superferric Dipole demonstrator with MgB_2 coils (CERN - A. Devred, A. Ballarino)



Superconductor	T	I	B
3 kA MgB_2 cable	4.2 K	5 kA	1.95 T

CERN accelerating science: *https://home.cern/news/news/engineering/new-generation-iron-dominated-electromagnets-has-been-successfully-tested*

General conclusion

- Magnet technology has an interdisciplinary nature requiring expertise in material science, mechanical & electrical engineering, cryogenics, particle physics and electromagnetism….
- Some technologies are more advanced than others in achieving compact, flexible designs for high-field magnets that are both robust and reproducible
- Advanced simulation tools to better predict and optimize magnet performance are needed for designing next-generation accelerator magnets
- Developing radiation-hard materials and components is essential for ensuring the longevity and reliability of these magnets
- Cost reduction and sustainability are new upcoming challenges
- The magnet community will need to be creative and pragmatic

We need your contribution !

The scientific process has two motives: one is to understand the natural world, the other is to control it.

Charles P. Snow (1905-1980)

English novelist and physical chemist

Promoting a "third culture" based on a multi-disciplinary approach

Thank you

for your attention

Glossary: parameters in superconductivity

Critical Temperature, **Tc**, temperature at which superconductivity is suppressed;

Lower critical field, **Bc_1**, magnetic field at which the magnetic flux starts to penetrate the superconductor

Upper critical field, **Bc_2**, magnetic field at which superconductivity is suppressed

Irreversible field B*, magnetic field above which there is not flux pinning and energy is the critical current goes to zero, $B^* < Bc_2$

Coherence length, ξ (a few nm): spatial dimension of a superconducting pair, i.e., the minimum length over which superconductivity can vary until it disappears

Penetration depth, λ (10-100 nm): length over which an applied field penetrates in a superconductor

Critical current density, **J_C** : Current density below which transport current is carried without any resistance, and above which flux-flow resistivity sets in : $I_{op} = A_{sc} * J_C$. Only the superconducting volume fraction is considered

Engineering current density, **J_e** : Current density **in the unit cell area** including the copper and the insulation surface contribution :

(typically J_e is only 15% to 30% of J_c in HTS) $J_e = (N_{wire}\ A_{sc})/A_{ins\_cable} * J_c$

Vortex: magnetic flux quantum that penetrates the superconductor- Inside the vortex the superconductivity is destroyed

Screening or persistent currents: Currents flowing inside the superconductor and producing the flux expulsion

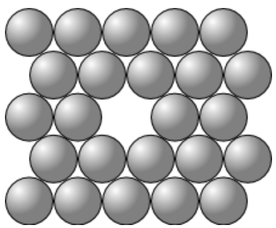
Annexes

Examples of Crystalline defects

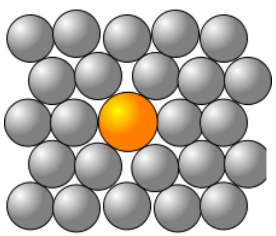
PSI

Punctual:

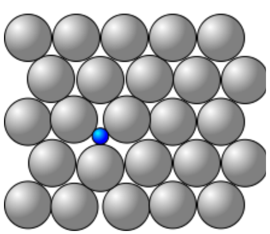
Vacancy



Substitutional atom

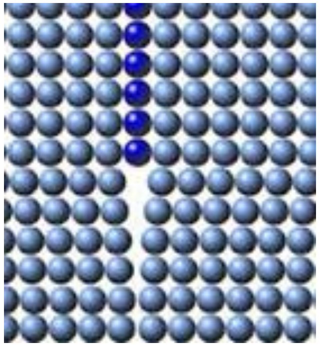


Interstitial atom

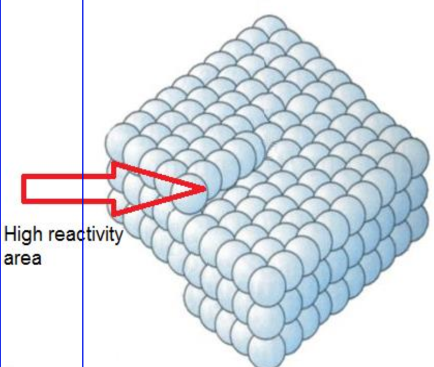


1D:

Edge dislocation

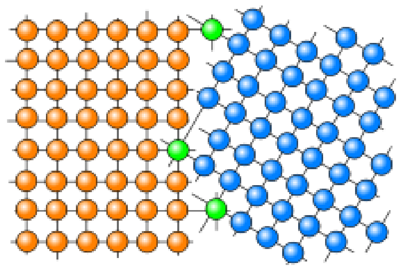


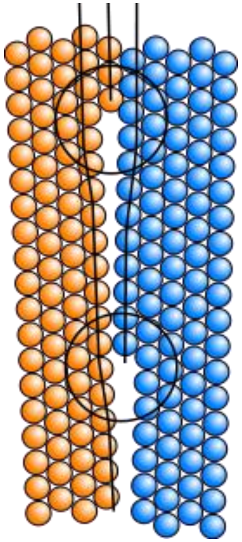
Screw dislocation



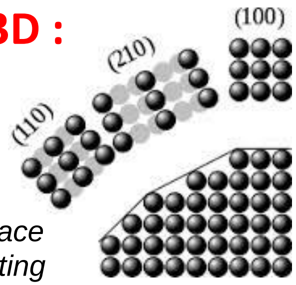
2D :

Surfaces, interfaces (GB)



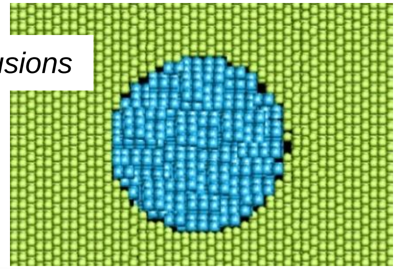


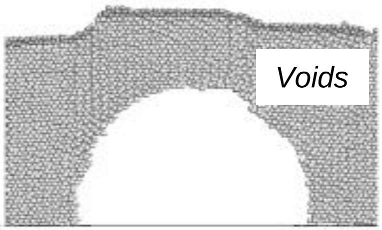
3D :



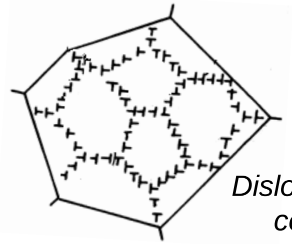
Surface faceting

Inclusions





Voids

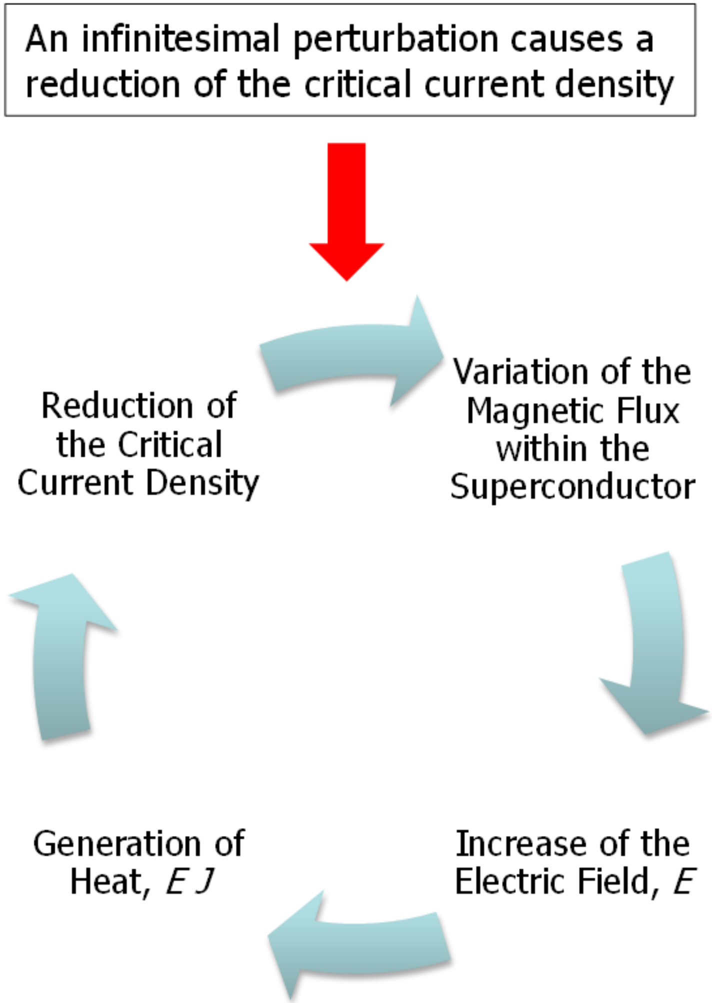


Dislocation cells

Filament size and flux jump

PSI

From A. Ballarino



$$d \le \frac{2}{J_c}\sqrt{\left(\frac{3\gamma\, C\,(Tc - T)}{\mu_0}\right)}$$

Maximum stable diameter of a filament in as metal matrix:

γ= density

Tc = critical temperature

C = specific heat

- **HERA filament diameter 14 µm**
- **LHC filament diameter 6-7 µm**
- **HL-LHC filament diameter 50 µm**
- **FCC target filament diameter 20 µm**

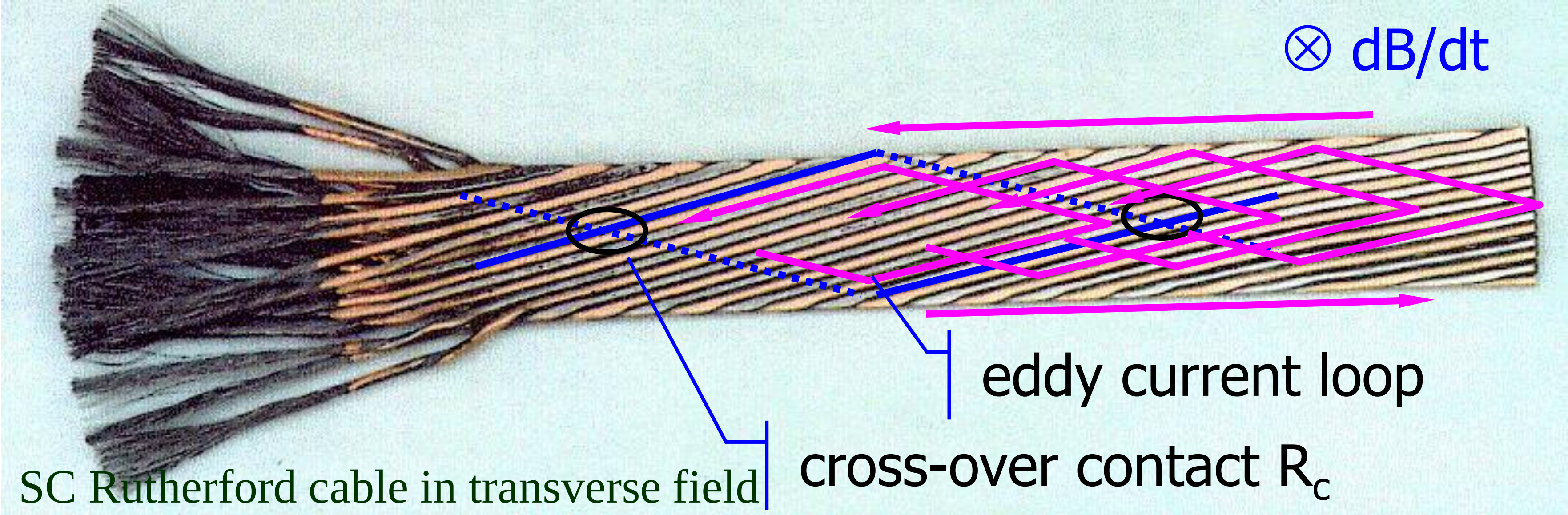
A small filament diameter is important for : increasing stability & reducing persistent currents

Redistribution of the current in the SC cables

PSI

Cable production quality is of very high importance: R_c interstrand resistance

If R_c is too low :



- Heat loss $P_{eddy} \propto$ dB/dt and $1/R_c$
- Advance in field $\Delta b_1 \propto$ dB/dt and $1/R_c$
- Magnetic field errors: Allowed and non-allowed multipole errors

But if R_c too high (>> 100 μΩ): Premature quench.

R_c specified for LHC: above 15 μΩ

Technical challenges for the superconducting coils and magnets

PSI

- **Conductor ultimately determines magnet performance**: Mostly **Rutherford like cables** with SC filaments and strands in a copper matrix (stabilizer)
  - Conductors are not stable against perturbation albeit very small
  - Energy release of the order of mJ are sufficient to drive superconductor normal= ***it quenches***
- The superconducting magnets are submitted **to training** (progressive increase of I_{quench} due irreversible change in the coil's mechanical status)
- Drawbacks coming from the **superconductivity** phenomena:
  - **Flux Jumps** (filaments of small diameter, LHC~6 mm) → Quench
  - **Hysteresis of the magnetization** → field quality and AC loss
  - **Decay of the magnetization** →Field quality control
- **Containment of large Lorentz forces due to High current and high field** and **energy** (**7MJ**)
  - a displacement (mm) of the conductor → potential release of frictional energy
  - Nb3Sn magnets: possible conductor degradation at about 150-200 MPa.
  - All the components must be below stress limits
  - Magnet protection issues ; The magnets are not self protected: protection (passive or active) is needed
- **Low temperatures** : Cooling using cryogenics (1.9 K, 4.2 K, 10 K…..)

MgB_2: the LTS with the highest T_c

PSI

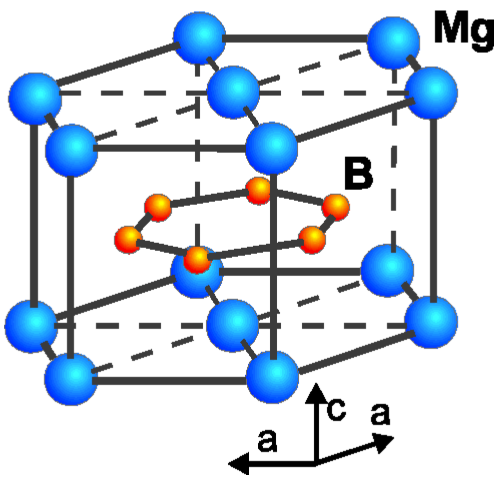


Table 9.2 Basic physical properties of the superconductor MgB_2. Some parameters are anisotropic, with only average values listed here.

Superconducting transition temperature T_c	39K*
Coherence length ξ_0	5 nm*
Penetration depth λ	140 nm*
Ginzburg-Landau parameter κ	$\cong$ 25
electron mean free path ℓ	$\cong$ 60 nm*
Residual resistivity ratio RRR $= \rho(300K)/\rho(42K)$	$\cong$ 20
Debye temperature Θ_D	340K
Fermi surface electron velocity V_F	4.8×10^5 m/sec*
Isotope effect constant α	0.32
Upper critical field B_{c2}, clean sample ($\ell \gg \xi_0$)	16T*
dirty sample ($\ell \ll \xi_0$)	30T*
Irreversibility field B_{irr}, clean sample	7T*
dirty sample	15T*
Thermodynamic critical field B_c	0.43T
Lower critical field B_{c1}	30mT

Akimitsu et al., Nature 410 (2001)63

- ***Superconductivity unespectedly discovered in 2001***
- ***Intermetallic compound with very high T_c (39 K)***
- ***Layered structure: alternate layers of Mg and B***
- ***Anisotropic properties: B_{c2} // (18 T) a is different from B_{c2} // c (3.8 T)***