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Superconducting Accelerator Magnets – Lecture 1: Fundamentals

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The lecture series

Goal: learn the **fundamentals & keywords** of a magnet test campaign. **Qualitative**, not quantitative.

1 Fundamentals

Superconductivity, practical conductors, first look at quench, training, degradation

2 Magnets & why we test

Anatomy of an accelerator magnet, test goals, a test campaign from installation to warm-up

3 The test stand

Power converters, current leads, busbars and splices, DAQ and interlocks

4 Electrical integrity

Insulation and hi-pot tests, electrical QA, failure diagnostics

5 Quench detection & protection

Voltage taps, thresholds, energy extraction, heaters, CLIQ, LTS vs HTS

6 Diagnostics & data analysis

Magnetic measurements, quench antennas, acoustic emission, strain and fibre sensors, training plots

Topics inspired by the CERN "TIDM² x SC Magnets" lecture series on test stands, protection and diagnostics (2023, 2025), CAS 2023 on Normal and SCs Magnets, USPAS 2024 SC Accelerator Magnets

Outline

1

Superconductivity in a nutshell

What it is, its limits, Type I vs Type II, pinning, the critical surface

2

Practical superconductors

From material to wire and cable: NbTi, Nb₃Sn, HTS

3

Pills: what happens in a real magnet

Operating margin, quench, training and degradation

Where superconducting magnets are used



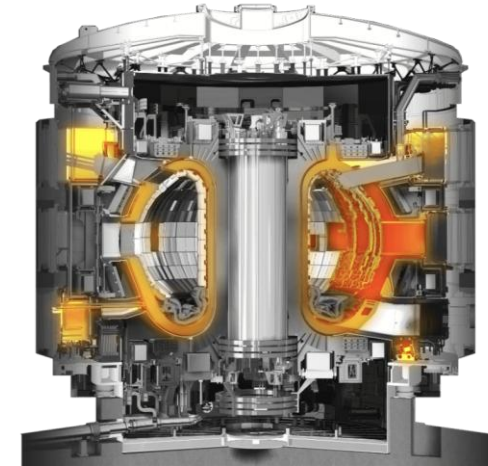
Medical imaging (MRI)

1.5 to 7 T, the largest market for superconducting wires



Particle accelerators

LHC: 1232 dipoles at 8.3 T, 7 TeV



Fusion

Confining plasma: power grows as B^4

Also: NMR spectrometers, detector magnets, gantries for particle therapy, power cables, fault current limiters, SMES, maglev.

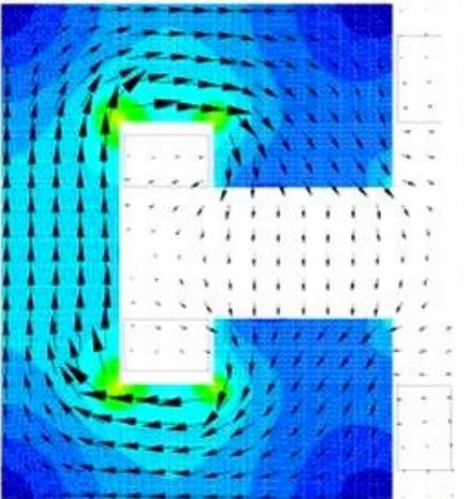
Common need: **high magnetic field** in a **compact** volume with **almost no power consumption** in the windings.

Images: P. Ferracin et al., USPAS 2025 (MRI, LHC tunnel); M. Marchevsky, USPAS 2024 (tokamak)

Why superconducting accelerator magnets?

To bend a beam: $p \text{ [GeV/c]} \approx 0.3 \cdot B \text{ [T]} \cdot \rho \text{ [m]}$ for a given radius, higher energy needs higher field

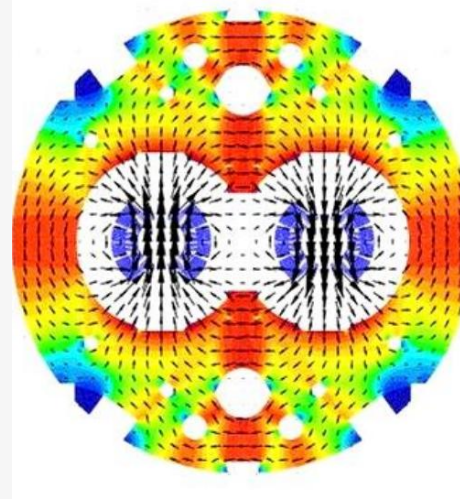
LEP (1989-2000): normal conducting



- Iron-dominated dipole, copper coil
- **0.13 T**, $\sim 4.5 \text{ kA} \cdot \text{turn}$
- Electrons up to $\sim 100 \text{ GeV}$

S. Russenschuck, "Overview: Design of accelerator magnets", CAS 2023

LHC (2008-): superconducting

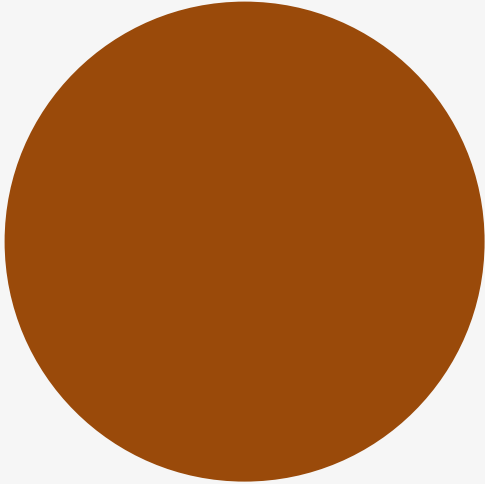


- Coil-dominated two-in-one Nb-Ti dipole at 1.9 K
- **8.3 T**, $\sim 1 \text{ MA} \cdot \text{turn}$ per aperture
- Protons at 7 TeV in the same 27 km tunnel

Copper vs superconductors: some numbers

0,85 mm

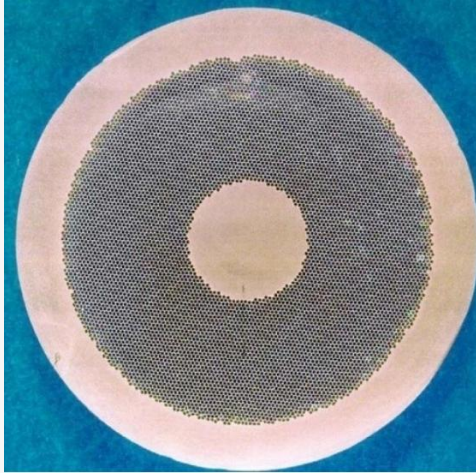
Copper



$J_e \sim 5 \text{ A/mm}^2$

$I \sim 3 \text{ A} \mid B \sim 2 \text{ T}$

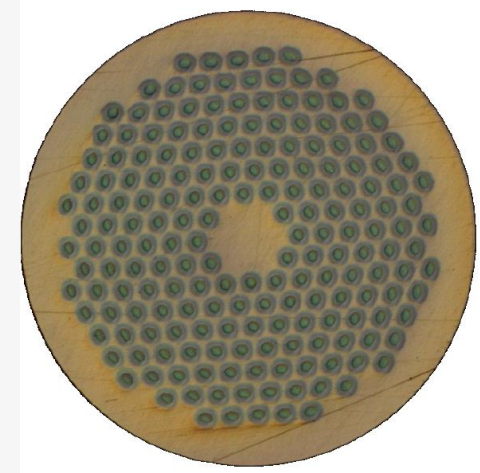
Nb-Ti



$J_e \text{ 600-700 A/mm}^2$

$I \text{ 300-400 A} \mid B \text{ 8-9 T}$

Nb₃Sn



$J_e \text{ 600-700 A/mm}^2$

$I \text{ 300-400 A} \mid B \text{ 12-13 T}$

A superconductor carries **$\sim 100\times$ more current**, with no resistive heating!!!

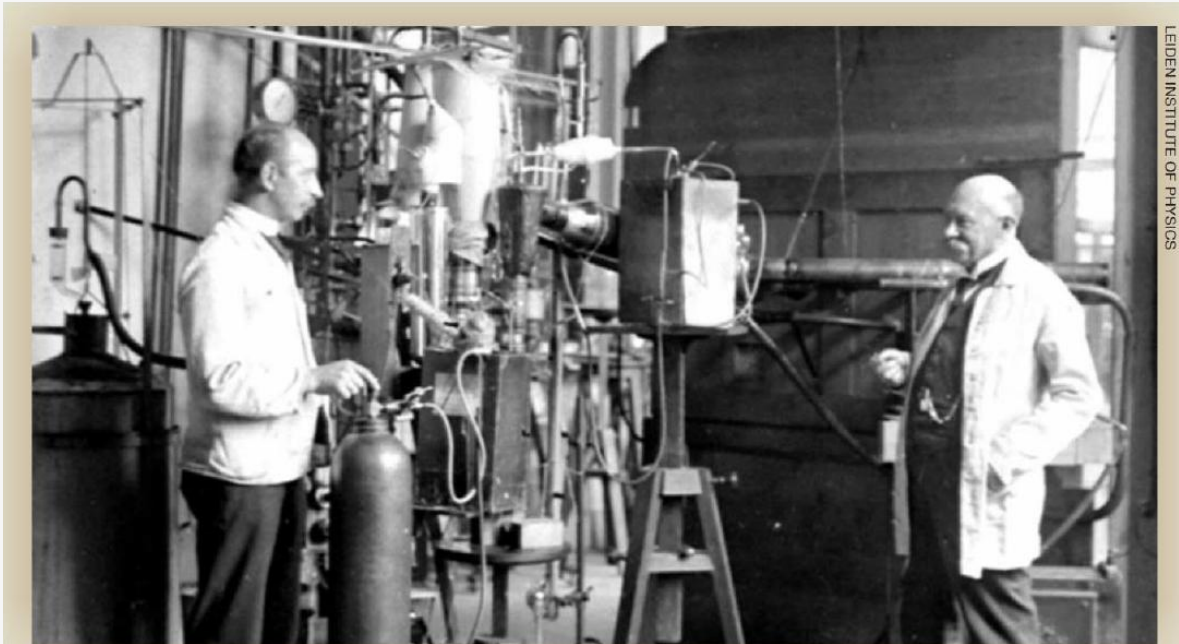
| Part 1



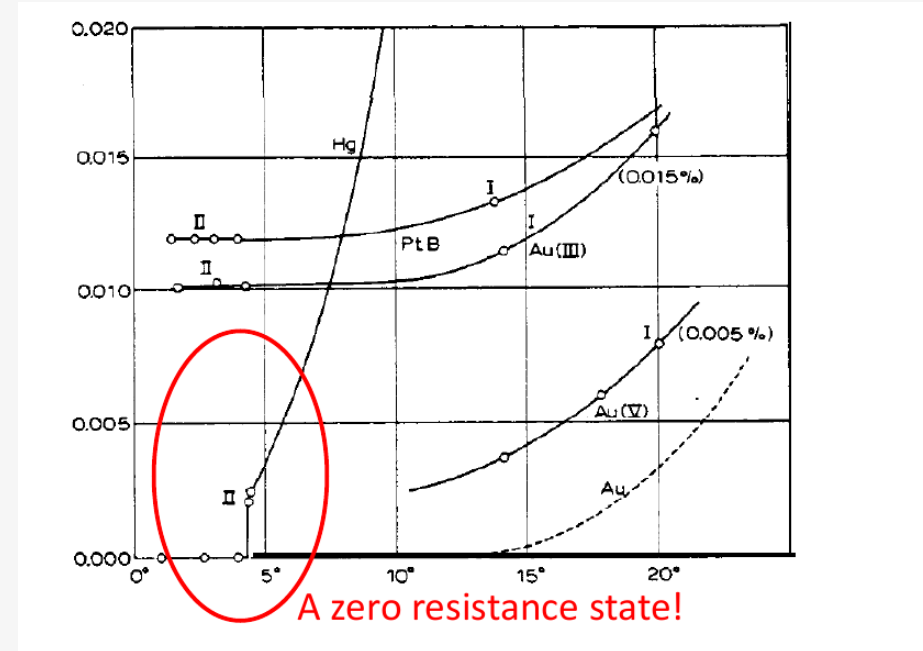
Superconductivity in a nutshell

What it is, its limits, Type I vs Type II, pinning, the critical surface

1911: the discovery



H. Kamerlingh Onnes (right) and G. Flim at the Leiden He liquefier, ~1911. M. Marchevsky, USPAS 2024



Resistance of mercury vs temperature (Onnes, 1911)

- Helium is liquefied in 1908 (**4.2 K**): for the first time metals can be studied close to absolute zero.
- Below ~4.2 K the resistance of mercury drops to **zero**, not just "very small": the superconducting state.
- The temperature of this transition is the **critical temperature T_c** .

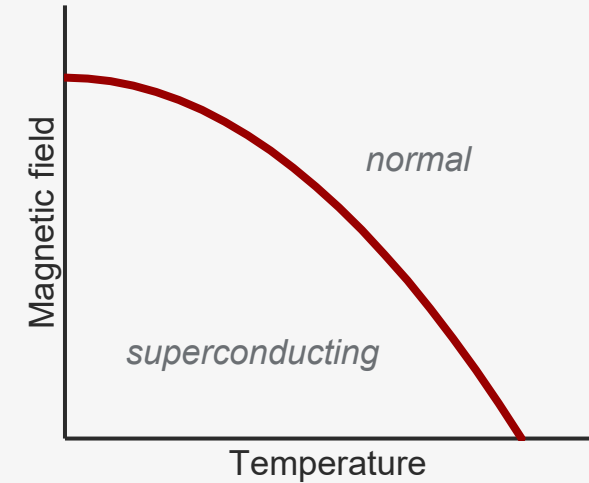
The magnetic field destroys superconductivity



Lead wire wound coil

Onnes' lead-wire coil, Leiden 1912. M. Marchevsky, USPAS 2024

- Onnes dreamed of a 10 T coil...
- ...but superconductivity vanished at **~0.06 T**.



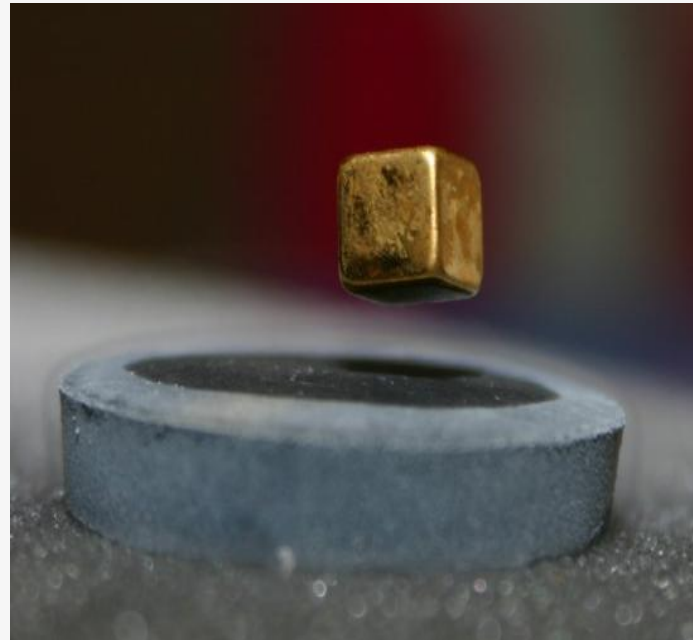
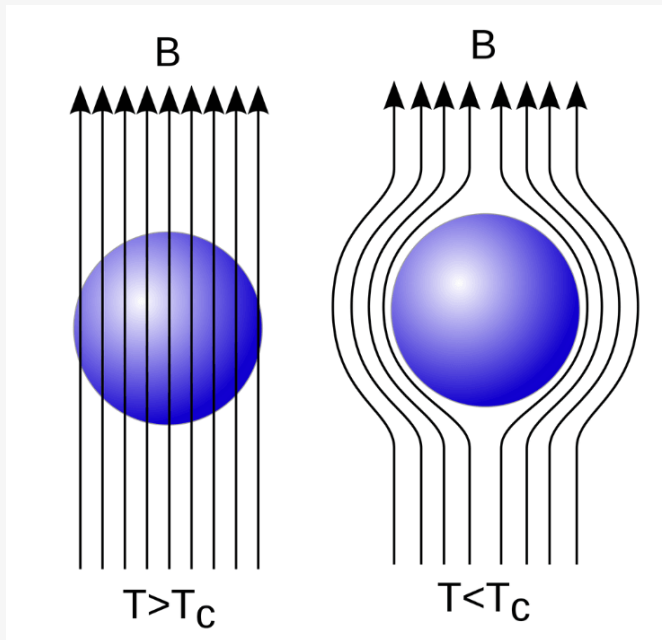
$$H_c(T) = H_c(0) [1 - (T/T_c)^2]$$

Three main limitations:

- **Temperature**
- **Magnetic field**
- **Current density**

Superconductivity survives only if all three stay below their **critical** values.

Meissner effect: a superconductor expels the field



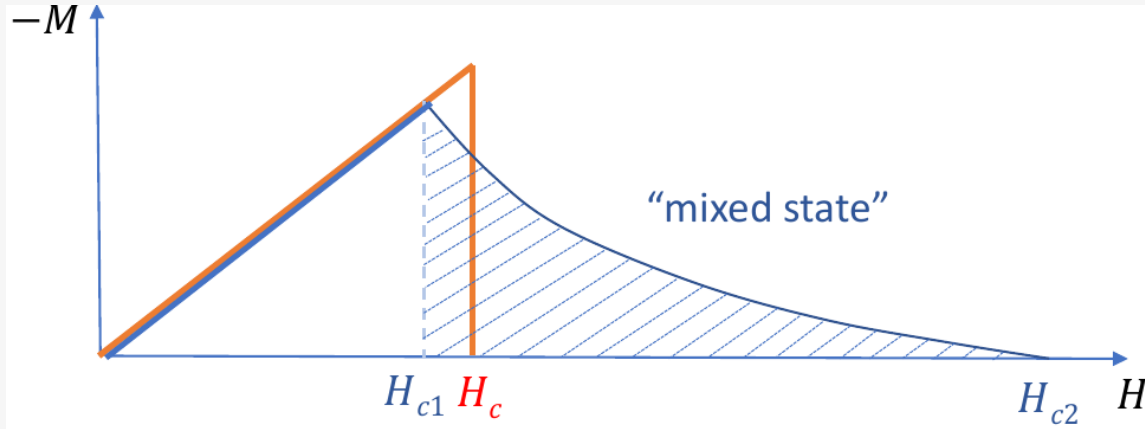
Type I superconductors

- Pure metals such as Pb, Hg, Sn, Al.
- Full Meissner state up to H_c , then normal everywhere.
- H_c is tiny: **below ~ 0.1 T**.

Useless for magnets.

- Cooled below T_c in a field, the material actively **pushes the field out** (1933).
- It is a **perfect diamagnet**: more than a "perfect conductor".
- Screening currents flow in a thin surface layer (the **penetration depth λ** , $\sim 0.1 \mu\text{m}$).

Type I vs type II superconductors



Magnetization vs applied field. M. Marchevsky, USPAS 2024

- **Type I** (orange): field expelled up to H_c , then superconductivity lost at once.
- **Type II** (blue): field starts entering at H_{c1} , superconductivity survives up to a much higher H_{c2} .
- In between: the **mixed state**.

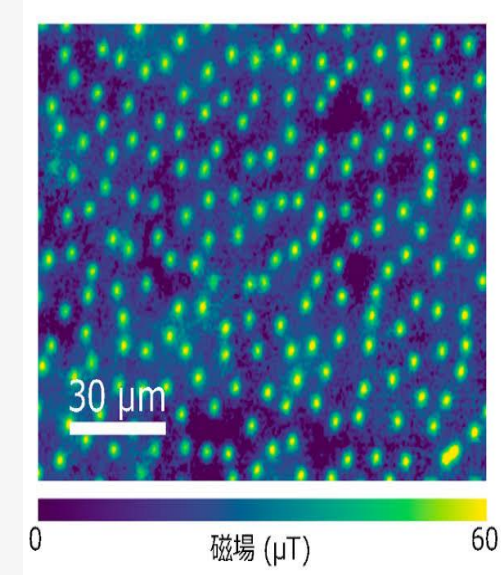
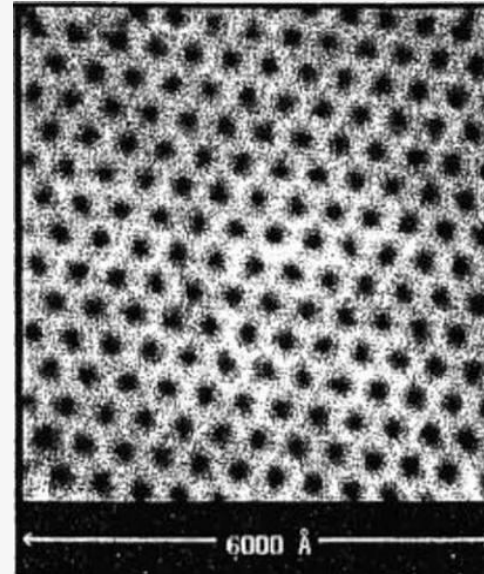
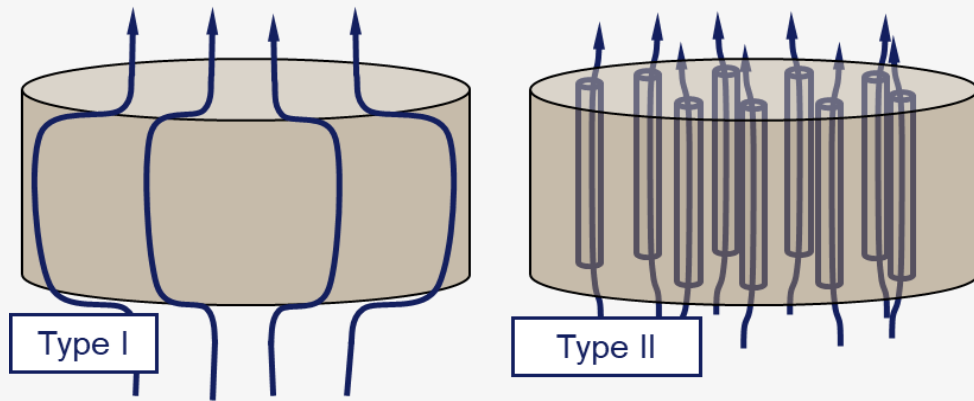
Every practical magnet conductor is type II.

Superconductor	T_c (K)	ξ_0 (nm)	λ_0 (nm)	GL parameter $\kappa = \lambda/\xi$	$\mu_0 H_c$ (or B_{c2}), (T)
Pb	7.19	83	37	0.445	0.08
In	3.14	70	40	0.57	0.03
Sn	3.72	230	14	0.06	0.03
Nb	9.26	38	39	1.026	0.82
NbTi	10	4	240	60	15
Nb ₃ Sn	18.3	3	65	21.7	30
MgB ₂	39	6	140	23.3	74
YBCO	92	1.5	150	100	~100
Bi ₂ Sr ₂ Cu ₂ O _{8+δ}	85	1.5	200	117.6	~120

Type I in red, type II in black. M. Marchevsky, USPAS 2024

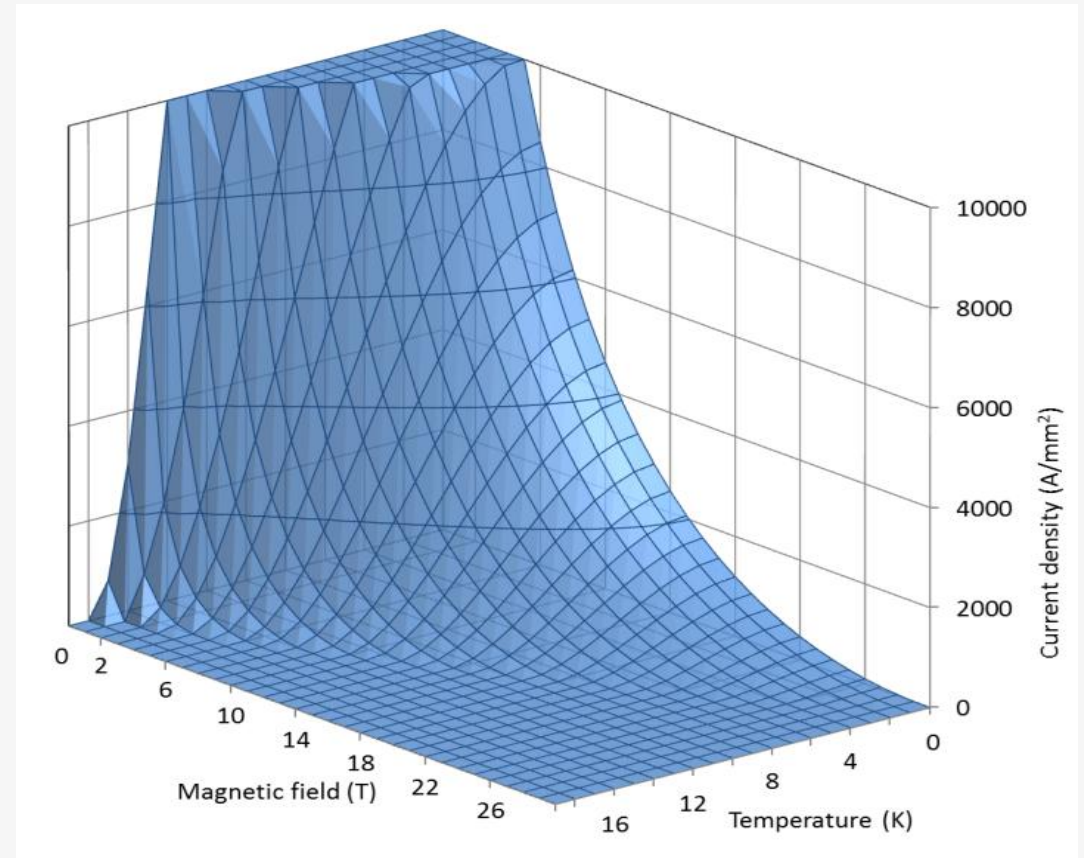
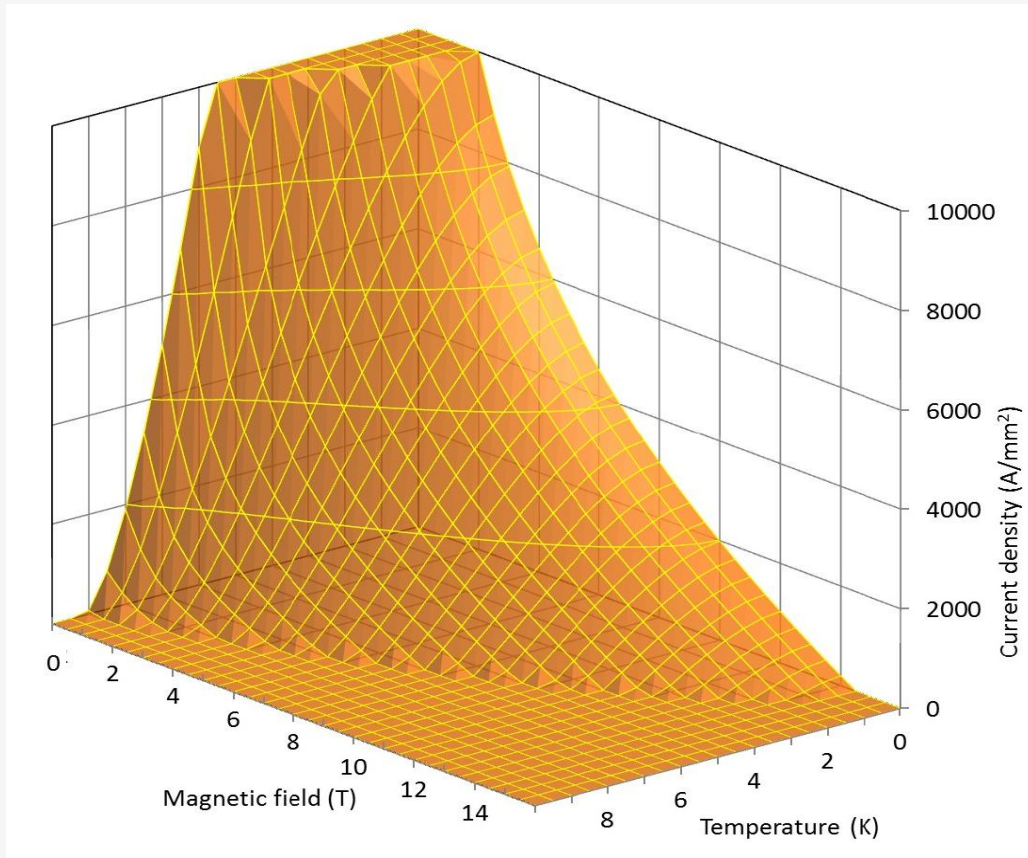
Look at the last column: from **0.03 T** (Sn) to **~100 T** (YBCO).

Fluxoids and pinning: where J_c comes from



- In the mixed state the field enters as tiny tubes, each carrying one flux quantum: **fluxoids** (or vortices).
- A transport current pushes them sideways (**Lorentz force**). Moving fluxoids dissipate energy: voltage appears.
- Defects in the material **pin** the fluxoids. The current at which they break free is the **critical current density J_c** .
- J_c is not given by nature: it is **engineered** by the wire manufacturer.

The critical surface

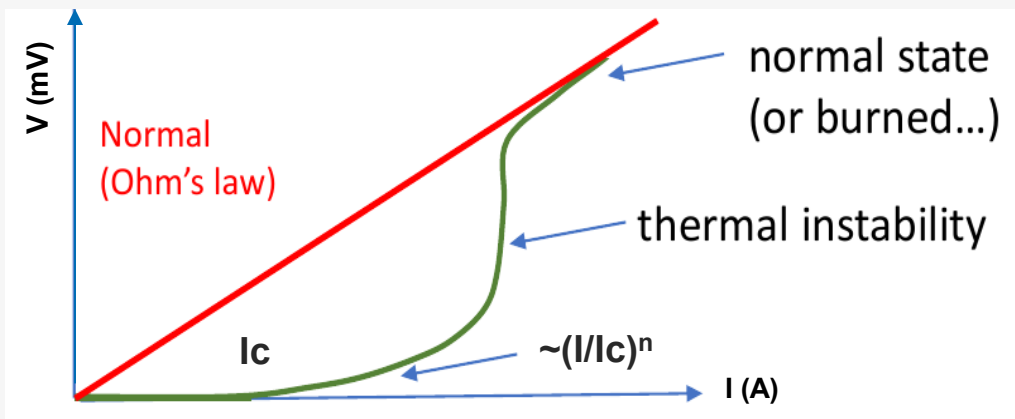


Critical surface of Nb-Ti (left) and Nb₃Sn (right). P. Ferracin et al., USPAS 2025

- The magnet operating point must sit **below** the surface.
- The distance from the critical surface it is the so-called **margin**.

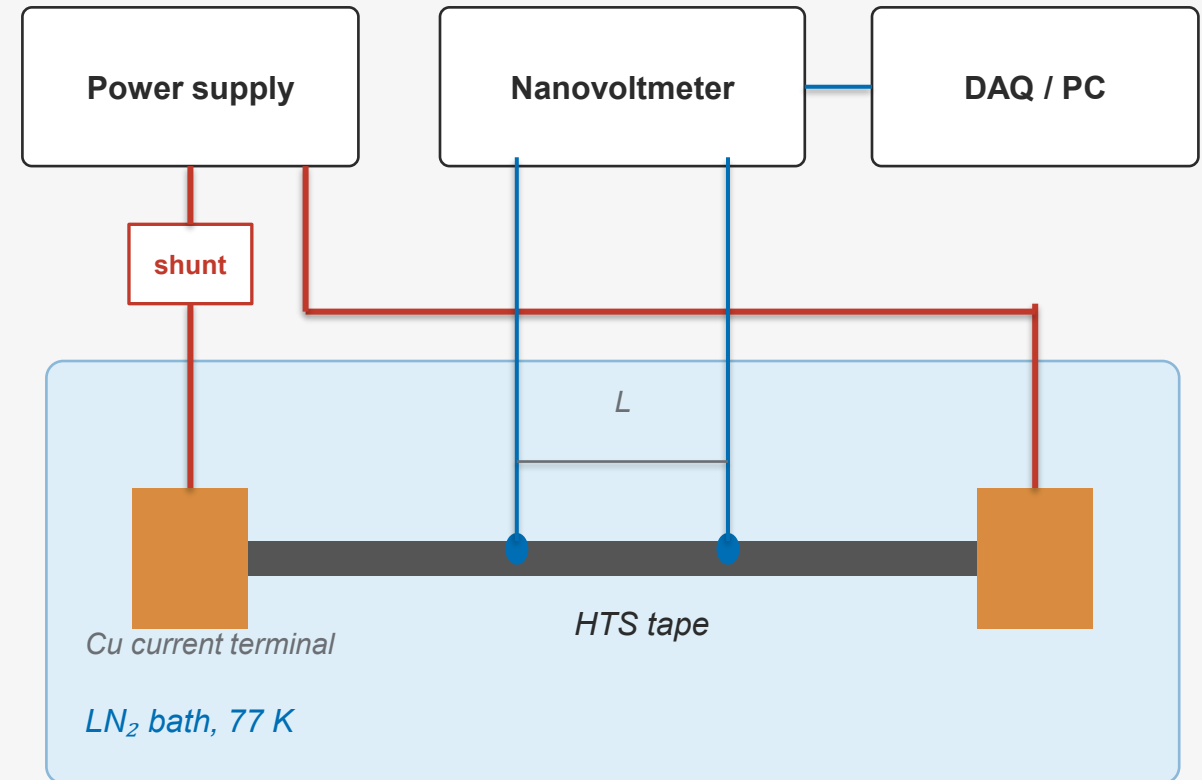
How we measure the critical current

Power Law: $E(I) = E_c (I/I_c)^n$ or $V(I) = V_c (I/I_c)^n$



Schematic of a voltage-current characteristic. M. Marchevsky, USPAS 2024

- The SC to resistive transition is **not sharp**: voltage rises smoothly, then a thermal runaway follows.
- I_c is defined by a **criterion**: voltage or electric field
- Historically, for LTS, the $E_c = 1 \mu\text{V}/\text{cm}$ (sometimes 0.1) is used.
- the **n-value** tells how sharp the transition is. For HTS a single n-value is not enough to define the characteristic.



Schematic. In-field tests add a background magnet and a variable temperature.



Practical superconductors

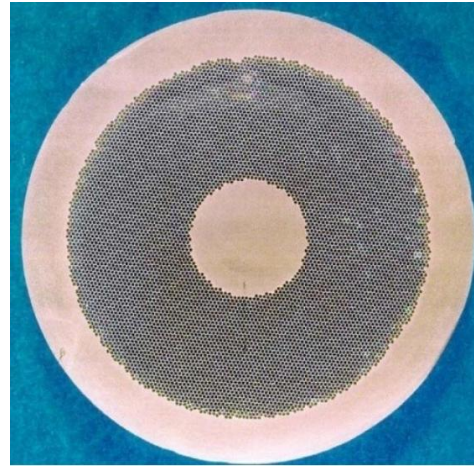
How a superconducting material becomes a wire you can wind into a magnet.

Anatomy of a conductor: from filament to coil



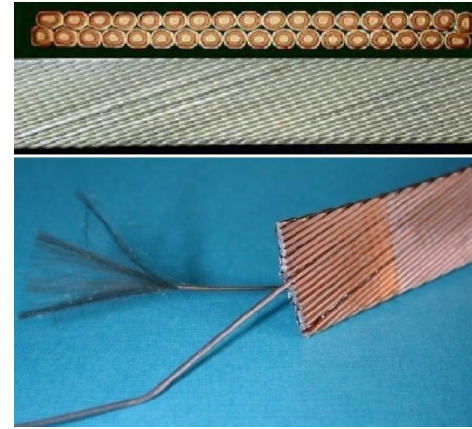
Filaments

Superconductor split in thousands of filaments, $\sim 1\text{-}50\text{ }\mu\text{m}$ (zoom)



Strand (wire)

Filaments embedded in a copper matrix, $\sim 0.5\text{-}1.5\text{ mm}$



Cable

Tens of strands twisted together, $\sim 10\text{-}20\text{ mm}$ wide

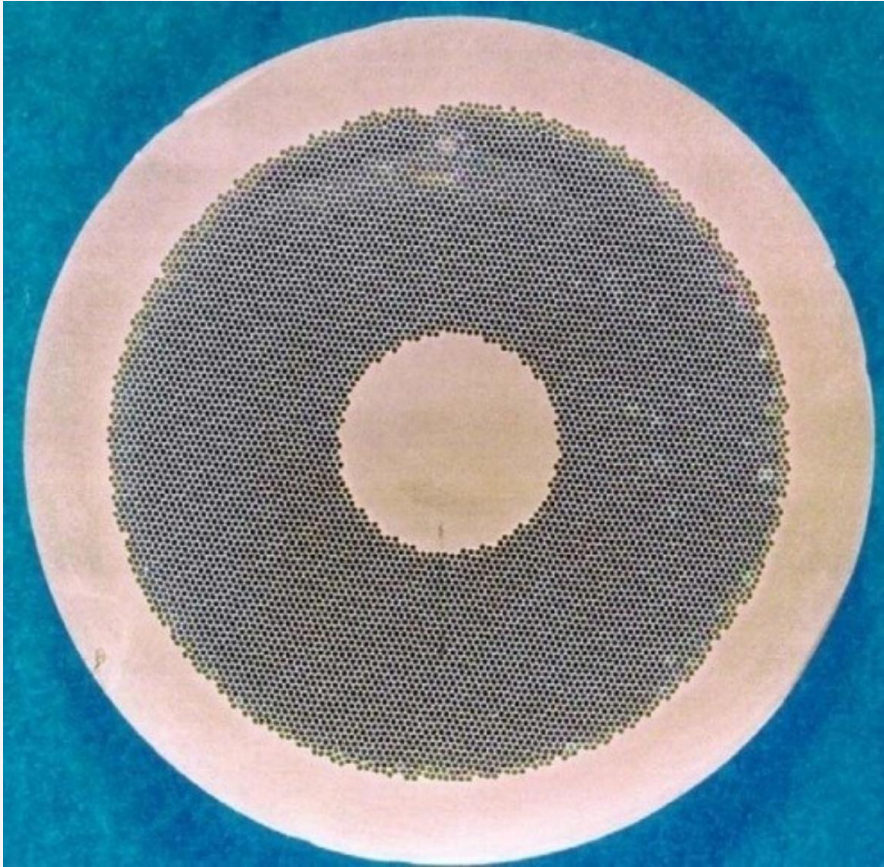


Coil

Insulated cable wound and impregnated

Images: P. Ferracin et al., USPAS 2025

Why filaments, twist and copper?



Nb-Ti strand cross-section. P. Ferracin et al., USPAS 2025

1

Small filaments

Avoid **flux jumps** (magneto-thermal instabilities), reduce **magnetization** (field errors) and **AC losses** during ramps.

2

Twisted filaments

The filaments are twisted along the wire (**twist pitch**) so they do not behave as one big filament in a changing field.

3

Copper matrix

The **stabilizer**: if the superconductor goes normal, the current flows in the copper instead. Essential for **quench protection**.

4

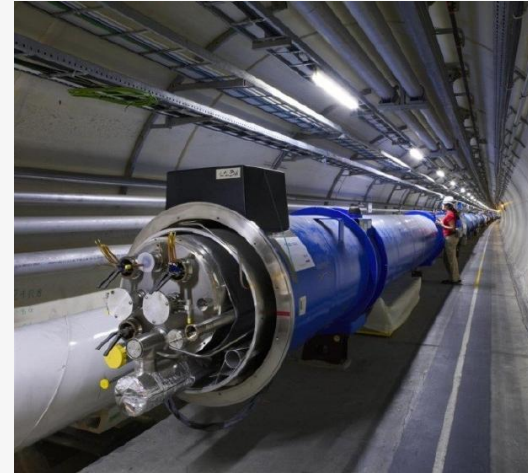
Copper quality

Cu/SC ratio (how much copper) and **RRR** (how pure the copper is at low T) are key wire specs.

Nb-Ti: the workhorse

A ductile alloy, easy to make and to wind

- Niobium-titanium alloy: extruded and drawn into long multifilament wires.
- Most widely used superconductor: **MRI**, Tevatron, HERA, **LHC**, detector magnets.
- LHC dipoles: **8.3 T at 1.9 K**, the practical limit of the technology.
- Cheap, robust, little sensitivity to strain.
- We use it in the current leads (**Rutherford cable**)



LHC tunnel with Nb-Ti magnets. P. Ferracin et al., USPAS 2025



MRI scanner. P. Ferracin et al., USPAS 2025

9.2 K

T_c

~14.5 T

B_{c2} at 0 K

≤ 9 T

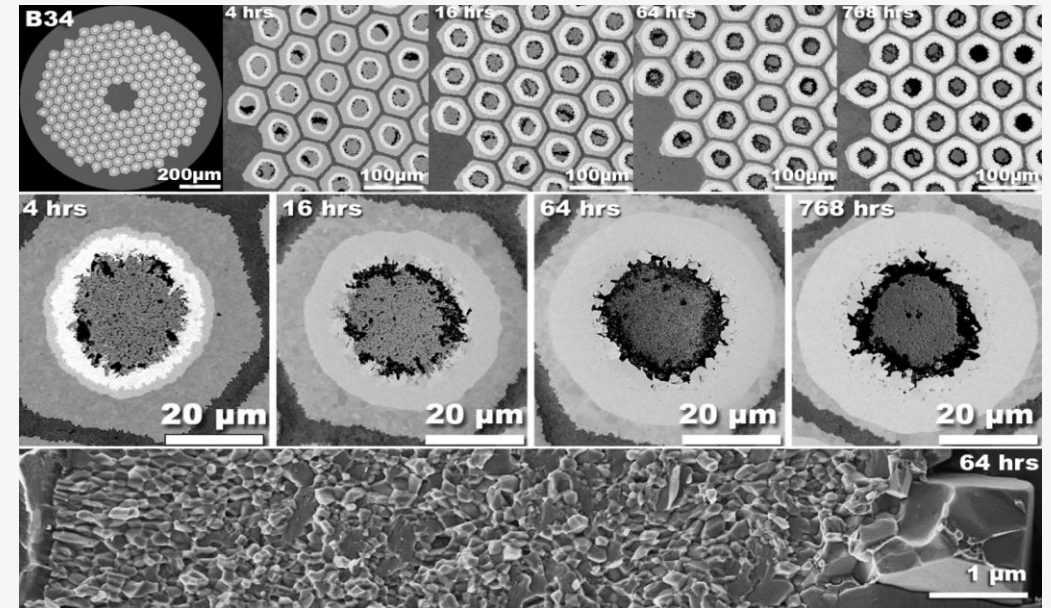
practical field

4.2 / 1.9 K

operating T

Nb₃Sn: higher field, but fragile

- **Brittle**: cannot be drawn once formed. **Wind & react**: wind the coil with the precursors, then heat treat at ~650 °C for days.
- **Strain sensitive**: I_c drops under stress, sometimes permanently.
- Main wire types: **RRP** (Rod Restack Process) and **PIT** (Powder In Tube).
- Used in HL-LHC, ITER, NMR, high-field R&D (FCC).



Nb₃Sn formation during heat treatment (PIT wire). P. Ferracin et al., USPAS 2025

18 K

T_c

~28 T

B_{c2} at 0 K

≤ 16 T

practical field

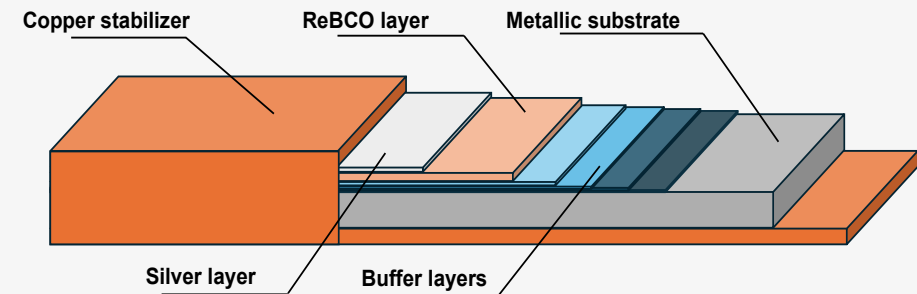
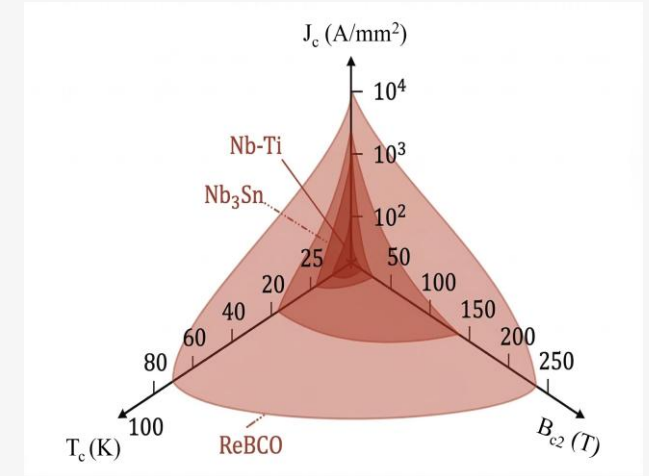
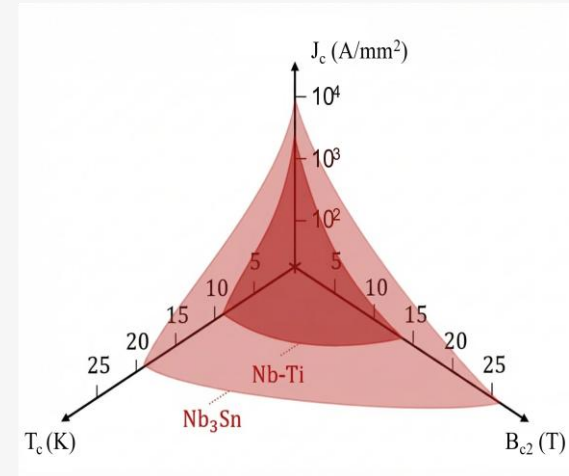
4.2 / 1.9 K

operating T

HTS and MgB₂ conductors

The only alternative to break 20 T barrier

- **REBCO tape**: thin superconducting layer (~1-2 μm) on a metal substrate. Very anisotropic and brittle!!
- **Bi-2212**: the only round-wire HTS, heat treated under high-pressure oxygen.
- **Bi-2223** tape: current leads and power cables (not very popular).
- **MgB₂**: $T_c = 39\text{ K}$, cheap, low field (MRI, links). Being used a lot lately!



~92 K

T_c (REBCO)

> 100 T

B_{c2}

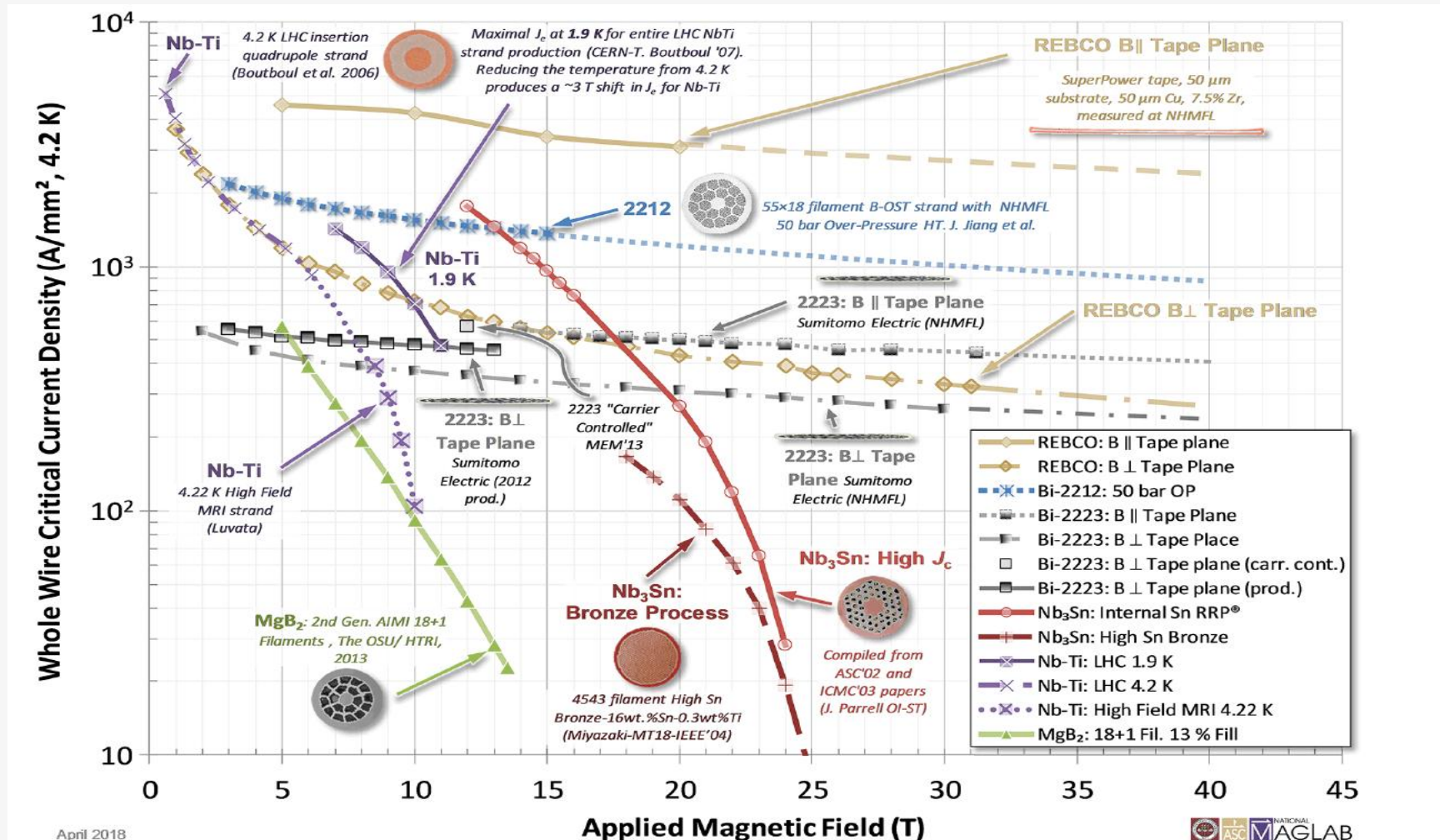
> 20 T

inserts, fusion

4-77 K

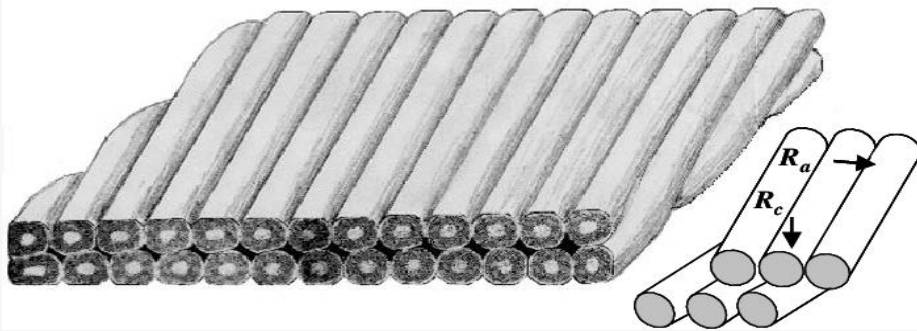
operating T

Which conductor for which field?



Engineering current density vs field at 4.2 K. P. Lee, NHMFL, from M. Marchevsky, USPAS 2024

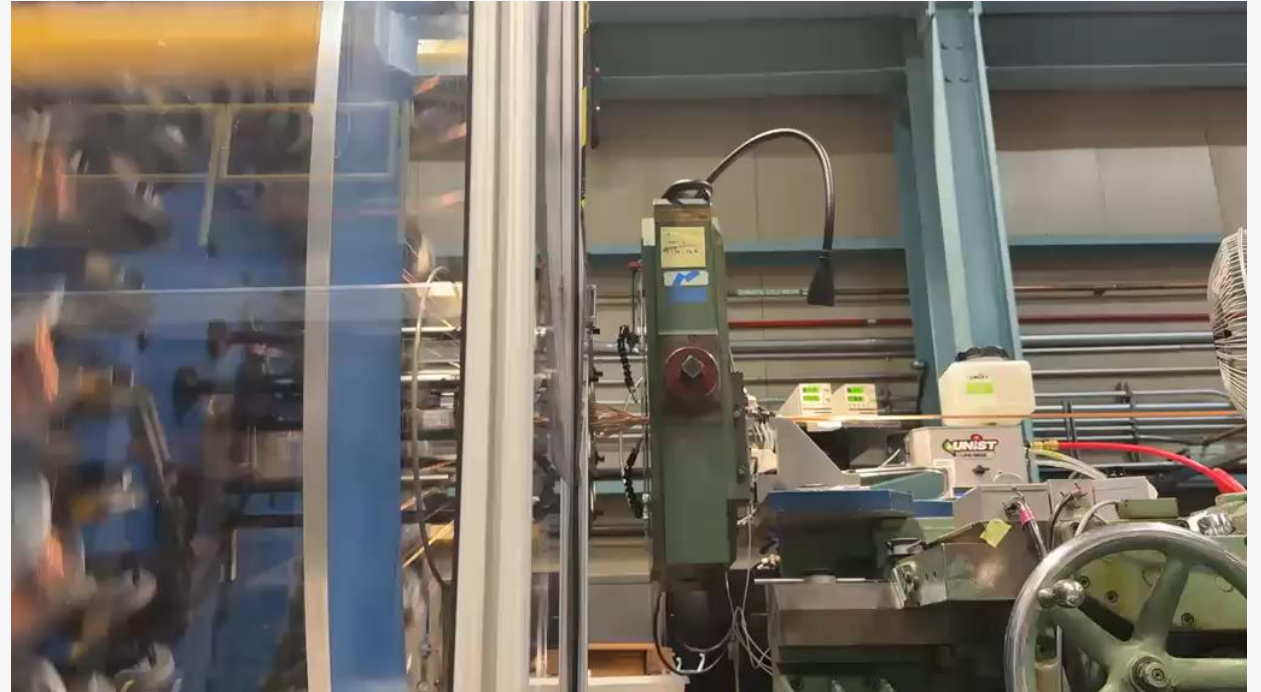
From wires to cables



- Magnets need kA currents: one wire carries only ~hundreds of A.
- **Rutherford cable**: tens of strands twisted and flattened into a two-layer cable. Standard for accelerator magnets.
- Cable insulation: polyimide (Nb-Ti), **fiberglass** (Nb₃Sn, survives the reaction).
- Cabling deforms the strands: if overdone, I_c is **degraded**.

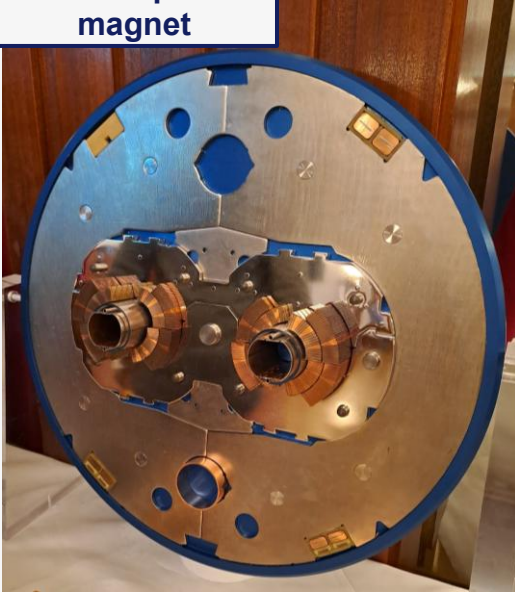


Rutherford cabling machine. P. Ferracin et al., USPAS 2025



From cable to magnet

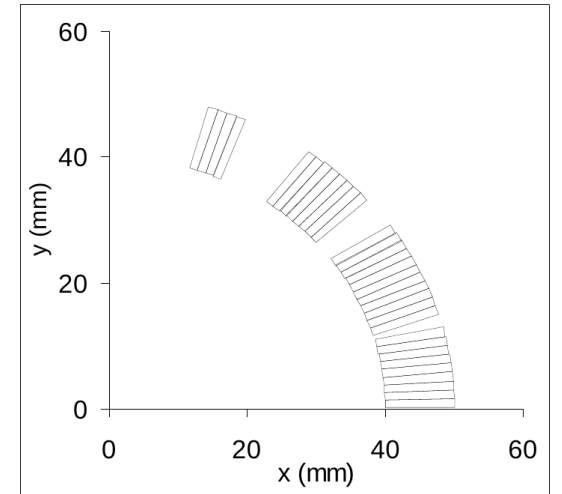
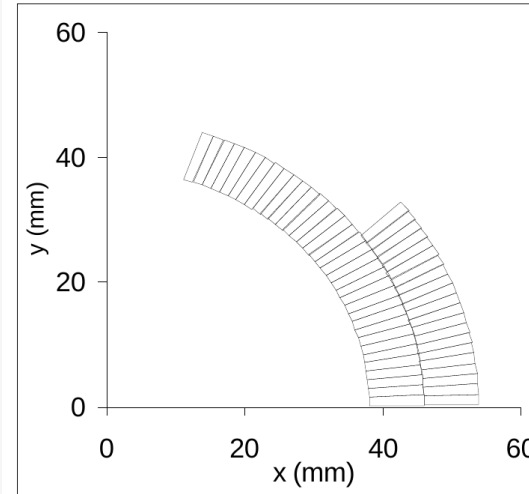
LHC dipole magnet



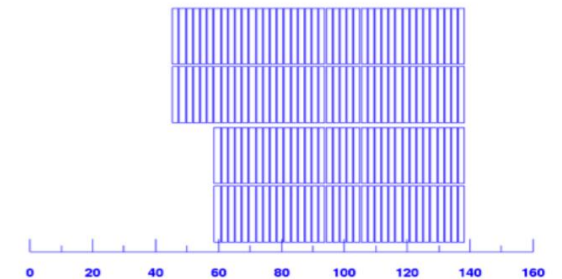
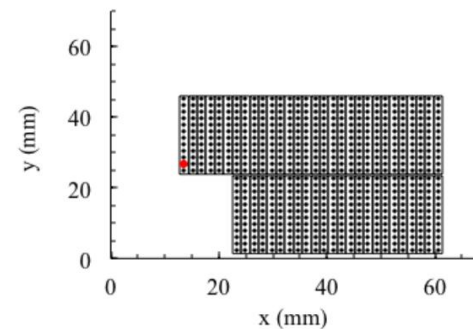
LHC quadrupole magnet (IR)



- Ideal: current density varying as $\cos \theta$ around the aperture gives a perfectly **uniform field**.
- Real coils approximate it with stacks of cable: $\cos \theta$ coils with copper **wedges** (LHC), or **block** coils, simpler with brittle Nb_3Sn and HTS.
- Field $\approx$ current density $\times$ **coil width**: more field means more J or a thicker coil.



Cos θ (sector) coils: Tevatron 1980 (left), RHIC 1995 (right). E. Todesco, USPAS 2025



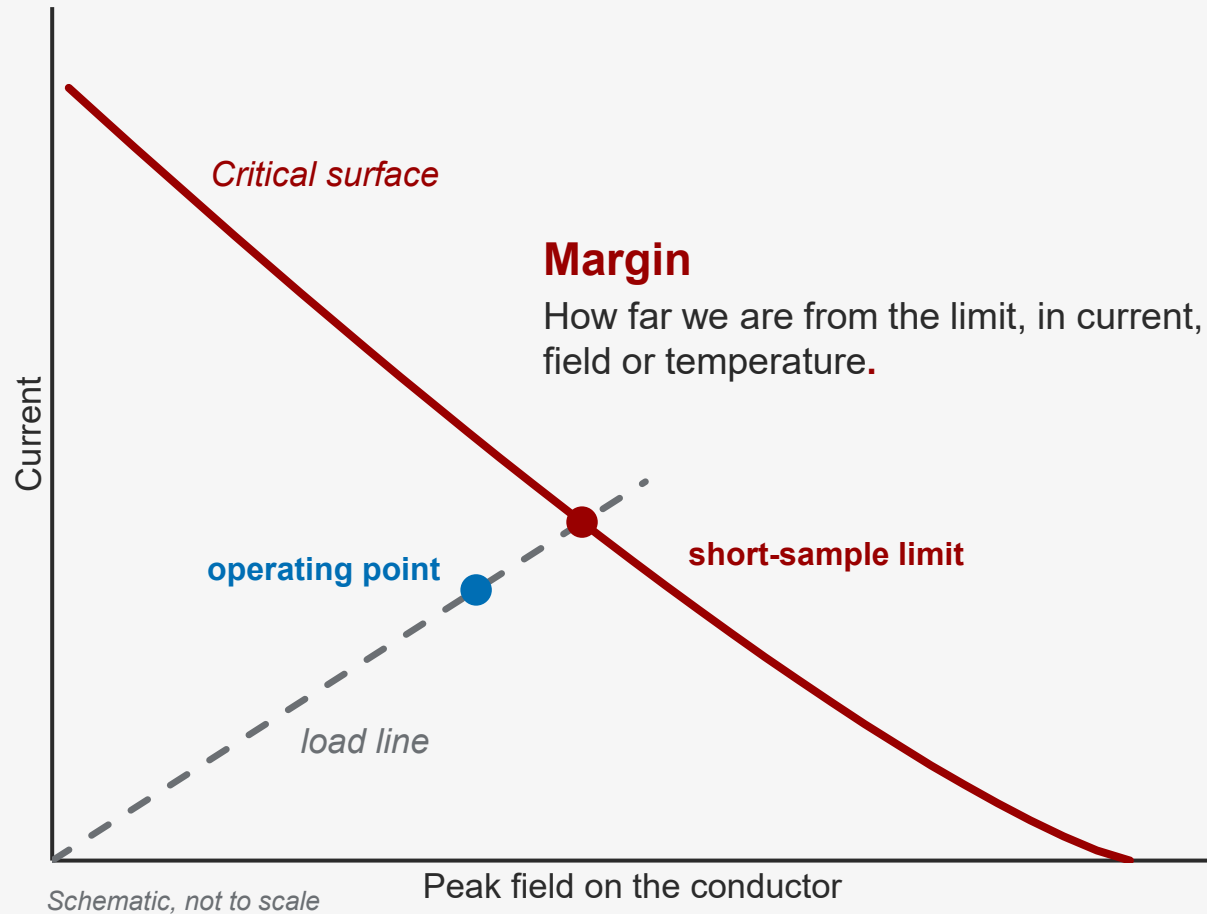
Block coils: HD2 (left), FRESKA2 (right), quarter cross-sections. E. Todesco, USPAS 2025



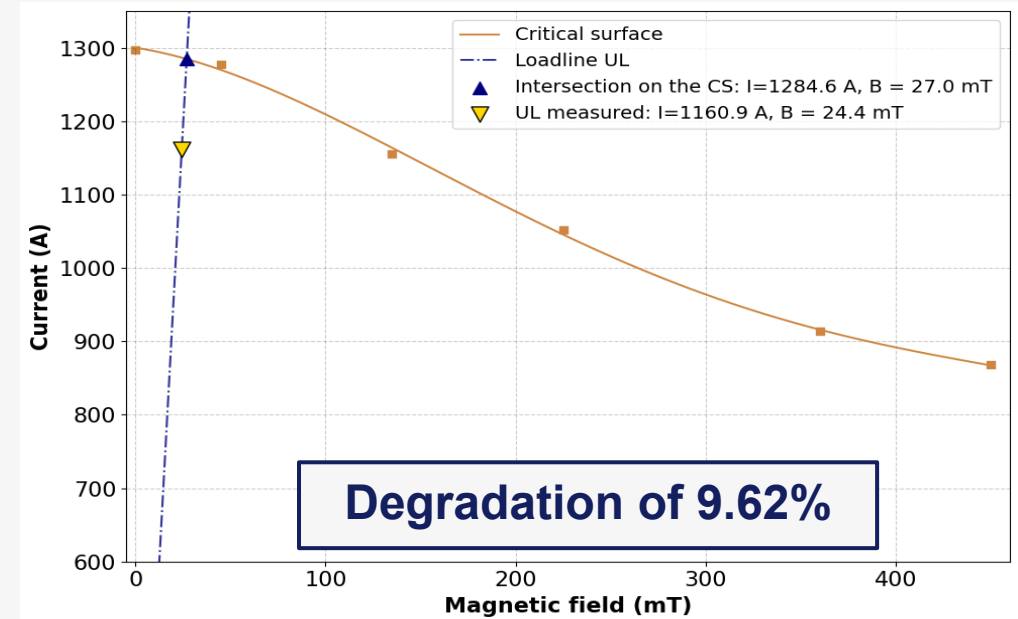
Pills: what happens in a real magnet

Short previews of what we will meet on the test station. Each one gets its own lecture later.

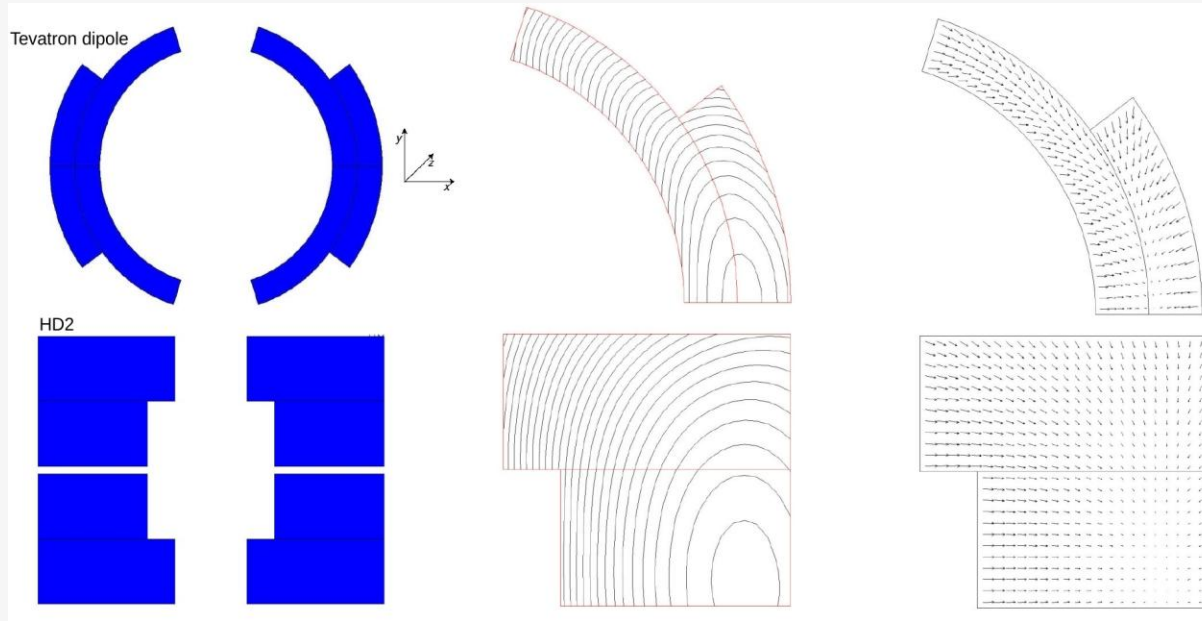
Operating point, load line and margin



- The peak field grows **linearly** with the current: the magnet **load line**.
- Where it meets the conductor $I_c(B)$: the **short-sample limit**, the best the magnet could ever do.
- We operate below it, e.g. at **~80% of the load line**.



Electromagnetic forces: why mechanics matters



Coil, field lines and Lorentz forces: Tevatron ($\cos \theta$) and HD2 (block). P. Ferracin, USPAS 2025

- The coil sits in its own field: forces push it **towards the midplane** and **outwards**; the ends are pulled **axially**.
- Forces grow with B^2 : doubling the field means four times the force.

340 t

per metre, horizontal force on one LHC dipole aperture (Nb-Ti)

500 t

per metre in the HD2 Nb₃Sn dipole

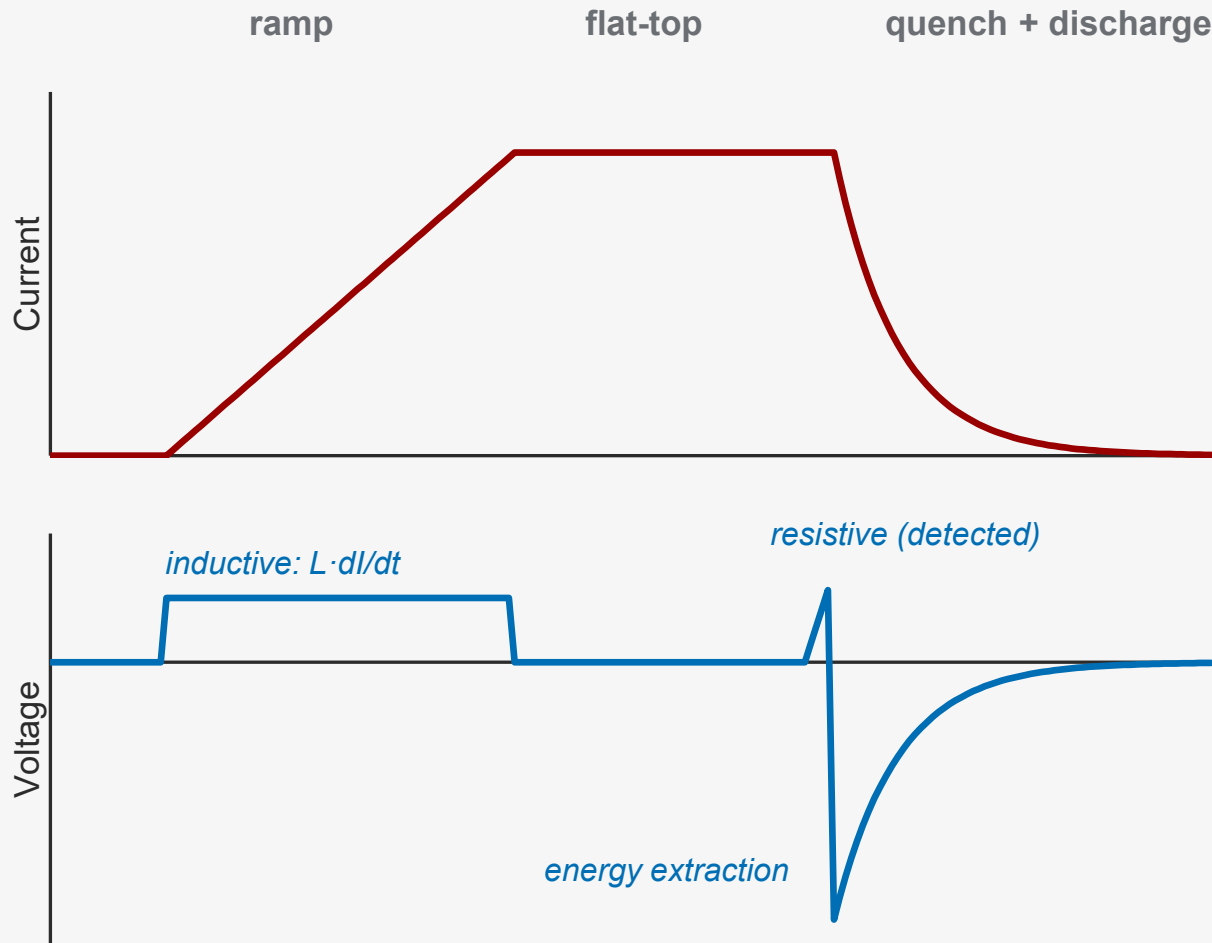
~400 atm

magnetic pressure on the coil at 10 T

- **Answer: pre-stress**

Collars, yoke, shell, keys and bladders squeeze the coil so that it cannot move. A few μm of motion can release enough heat to quench (**training**).

The magnet as an electrical circuit



Schematic, not real data

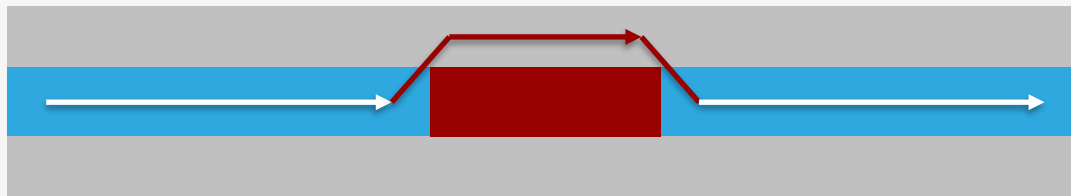
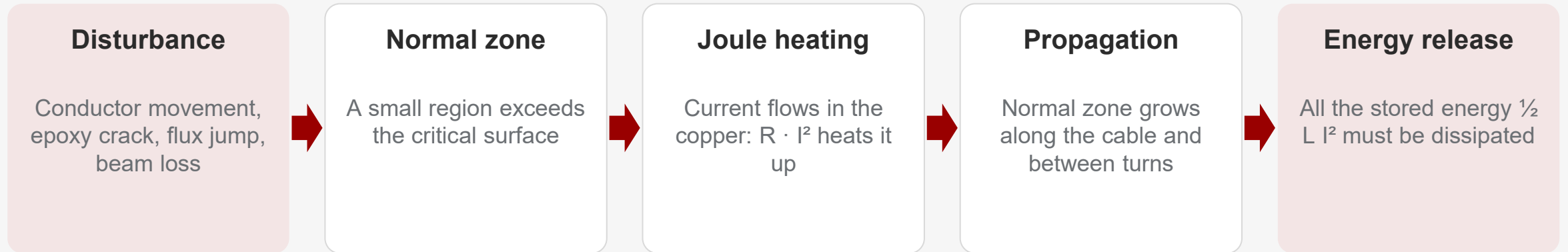
- A magnet is a large **inductance L** : ramping the current needs a voltage **$L \cdot di/dt$** , even with zero resistance.
- It stores the energy **$E = \frac{1}{2} L I^2$** : about **7 MJ** in one LHC dipole at nominal current.
- A quench appears as a small **resistive voltage** hidden under the inductive one: quench detection compares coil halves or subtracts $L \cdot di/dt$.

Energy extraction

A switch sends the current into a **dump resistor**: the energy leaves the cryostat, with hundreds of volts on the circuit.

Different protection mechanisms exist...

Quench: losing superconductivity in operation



grey: copper | blue: superconductor | red: normal zone. The current bypasses the normal zone through the copper.

Current-sharing sketch adapted from L. Bottura

- A quench is **not a failure** by itself: it is normal in testing, especially during training.
- Danger: the energy concentrates where the quench started, the **hot spot**.
- A good magnet lets the normal zone spread fast, so the energy is shared over a large volume.

Quench detection and protection

1 Detect

- **Voltage taps** across coils and splices
- Resistive voltage above a **threshold** (e.g. 100 mV)
- Hold for a **validation time** (ms) to reject noise



2 Act

- Switch off the **power supply**
- **Energy extraction**: open a switch, current goes into a **dump resistor**
- **Quench heaters** or **CLIQ**: quench the whole coil on purpose

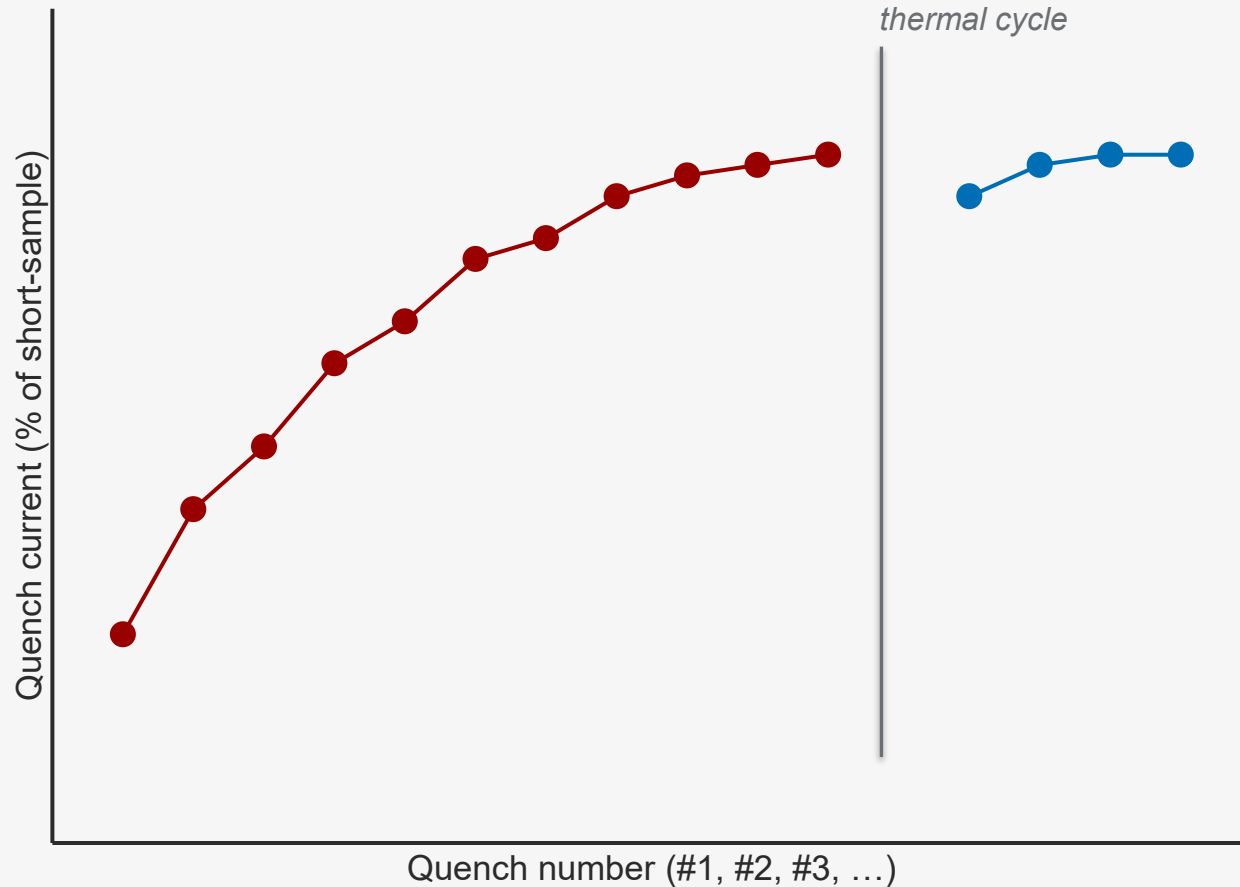


3 Goal

- Keep the **hot-spot temperature** low (typically < 200-300 K)
- Keep **voltages** to ground and between turns safe
- Whole sequence: a few **milliseconds** to a few seconds

- The **quench protection system** (QPS) does this automatically. It is the most important safety system of a test station.
- Our protection system is composed of the PotAim cards + SafetyMatrix + EEs.
- uQDS is the new version used to monitor symmetric quenches too

Training: the magnet learns



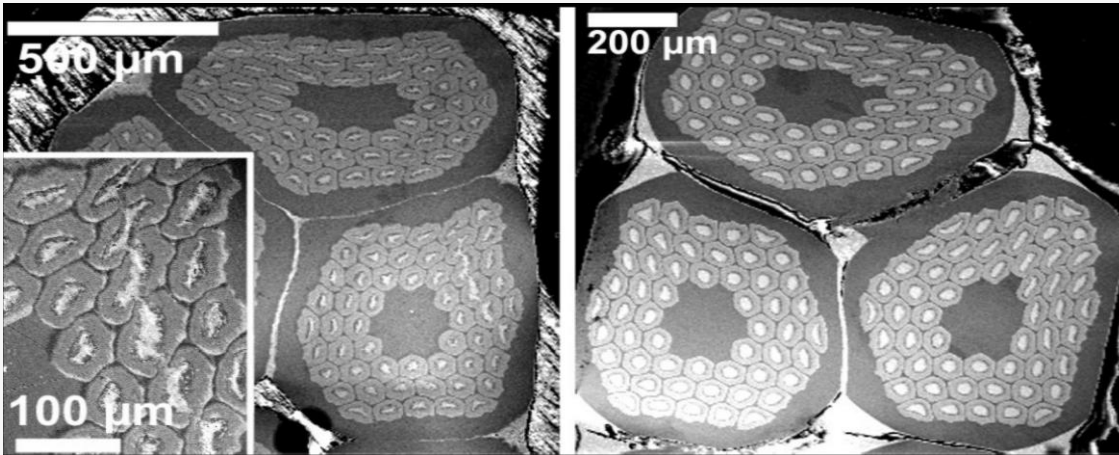
Schematic, not real data

- A new magnet often quenches **below** its expected limit. Each quench raises the next one: **training**.
- **Cause**: small mechanical events under the electromagnetic forces (conductor slips, epoxy cracks) release heat.
- After warm-up and cool-down, a good magnet remembers (**memory**). Losing it is **detraining**.
- It seems that magnets impregnated with wax train way less!
- Training is not a bad phenomenon! It is expected!

Training curves are one of the first plots you will make after a test.

Degradation: when performance is lost for good

- A **permanent** reduction of the critical current, unlike training.
- Typical causes:
 - too much **strain** or stress (Nb_3Sn , HTS)
 - damage during **cabling**, winding or handling
 - **overheating** at the hot spot during a quench
 - HTS: **delamination** of the tape layers



Damaged vs good strands. D. Dietderich, from P. Ferracin et al., USPAS 2025

	Training	Degradation
What	Premature quenches	Lower I_c
Reversible?	Yes, improves	No, permanent
Origin	Mechanical settling	Conductor damage

How we spot it: compare the magnet with the **short-sample** prediction and with previous tests.

Glossary of today's keywords

Tc, Bc2, Jc	Critical temperature, field, current density	Rutherford cable	Flat cable of twisted strands
Critical surface	Tc-Bc2-Jc limit in 3D	Wind & react	Nb ₃ Sn heat treated after winding
Type II	Superconductor letting field in as fluxoids	Load line	Peak field vs current of a magnet
Pinning	Defects holding fluxoids: gives Jc	Short-sample limit	Max current from conductor data
n-value	Sharpness of the transition	Margin	Distance from the critical surface
LTS / HTS	Low / high critical temperature SC	Quench	Loss of SC in operation
Strand	Multifilament wire, Cu + SC	Hot spot	Hottest point after a quench
Cu/SC, RRR	Copper amount and purity	Training	Quench current rising quench by quench
Je	Current over whole wire area	Degradation	Permanent loss of Ic

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Thank you! Questions?

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Next: Lecture 2, magnets and why we test them