EPFL

Superconducting Magnets, part 1

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SWISS PLASMA CENTER

Superconducting Magnets

PART I

1. Basic introduction to superconductivity
2. Technical superconductors
3. Introduction to the superconducting magnet design

PART II

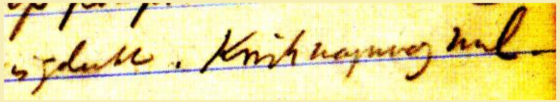
4. A stepped approach to superconducting magnet design
5. Lessons learned from fusion magnets from last century

PART III

4. The challenges of ITER magnets
5. Toward DEMO
6. HTS for fusion?

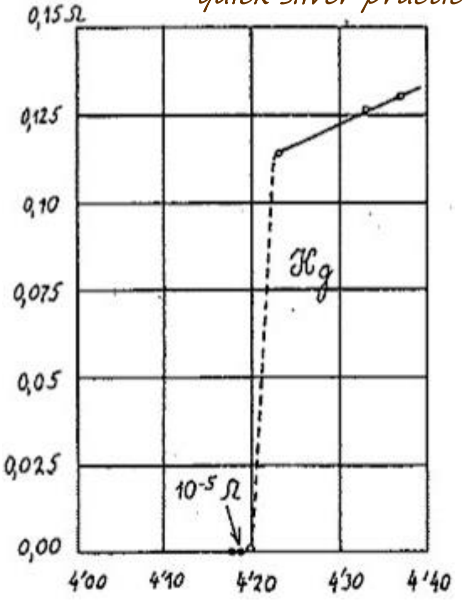
8th April 1911

Heike Kammerlingh Onnes Notebook #56



'Kwik nagenoeg nul'
quick silver practically zero

Resistance (Ω)



Temperature (K)

In 1913, H.K. Onnes obtained the Nobel price in Physics for his investigations on the properties of matter at low temperatures which led, among other things, to the production of liquid helium."

'Mercury at 4.2 has entered a new state which which on account of its extraordinary electrical properties can be called the superconductive state'

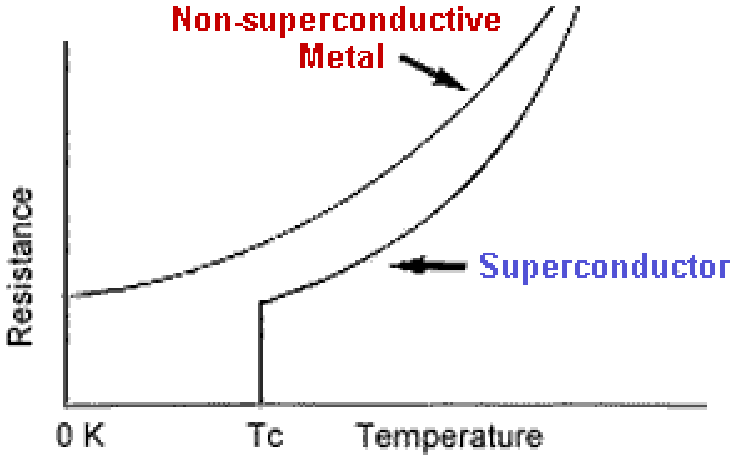
HKO Nobel Lecture in 1913

Resistivity of Metals at Low Temperature

Why was Onnes interested in measuring the resistivity of mercury at low temperature? Several hypothesis were predicted about the metal resistivity:

1. Lord Kelvin believed that electrons flowing through a conductor would come to a complete halt ➔ metal resistivity would become infinitely large at absolute zero.
2. Others, including Kamerlingh Onnes, felt that a conductor's electrical resistance would steadily decrease and drop to zero.

Reality Check (by experiments):

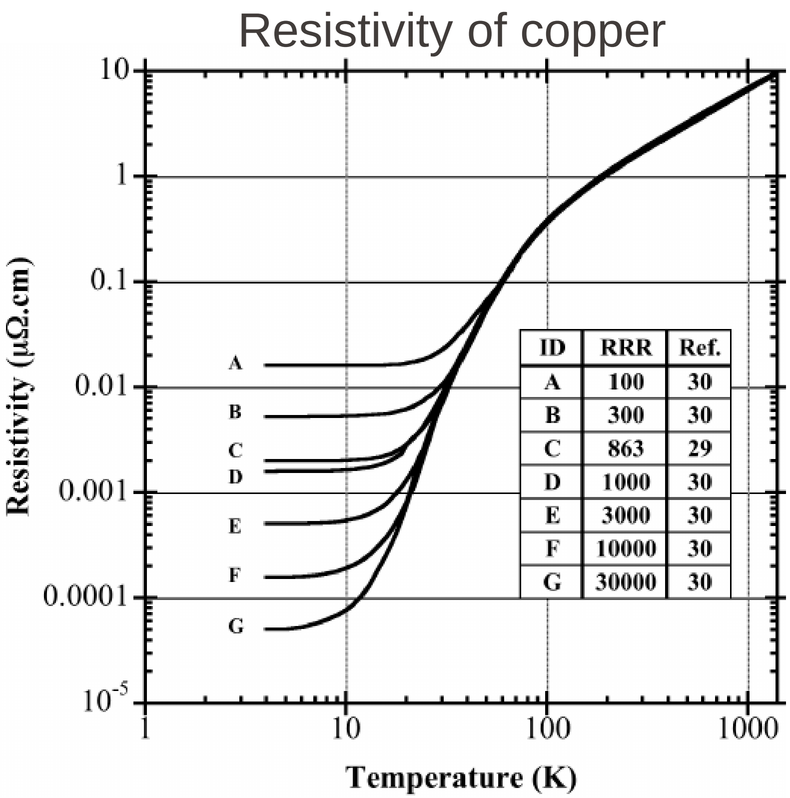


Resistivity of Copper at Low Temperature

The scattering of conduction electrons in metal is due to crystal lattice imperfections (vacancies, dislocations), impurities, grain boundaries, the metal surfaces or can be due to collisions with the phonons:

$$\rho_{tot}(T) = \rho_{phonons}(T) + \rho_{impurities} + \rho_{grain\ boundaries} + \ldots$$

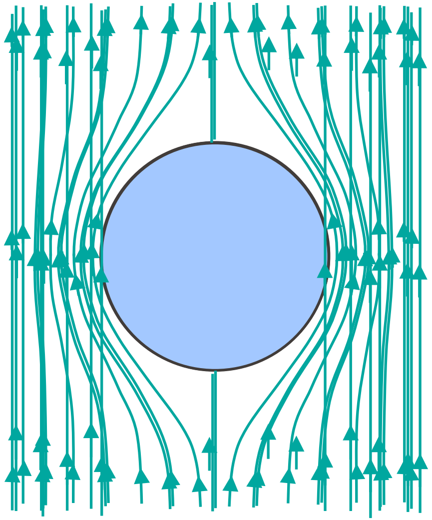
- Phonons are the quanta of the lattice thermal vibrations.
- Phonon-electron collisions have an intrinsic temperature dependence.
- All the other processes mentioned are essentially independent of temperature.



Superconductors of “Type 1”

In the following 50 years, the phenomenology of the superconductivity was investigated.

1933: Meissner-Ochsenfeld effect



- cool down superconductor in magnetic field
- at the critical temperature T_c the field is pushed out
- increase the field - field is kept out
- increase the field even more - superconductivity is extinguished and the field jumps in
- decrease the field - it's pushed out again

The description of the Meissner effect

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1935: (Fritz & Heinz) London theory

- within a superconductor

$$\nabla^2 B = B / \lambda$$

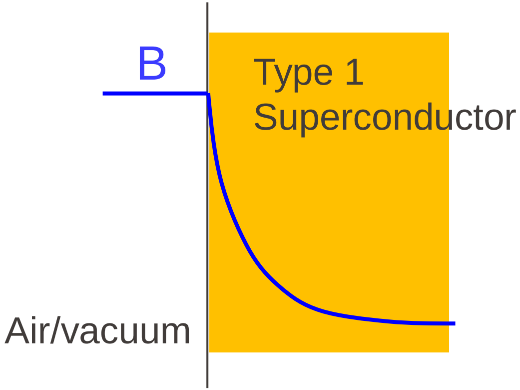
$$\lambda^2 = m / 2e^2 \mu_o n_c$$

where m = mass electron, e = charge electron,
n_c = density of carriers

➔ at the boundary

$$B = B_o \exp(-x/\lambda)$$

λ = London (magnetic field) penetration depth
(typical value = 100 nm)

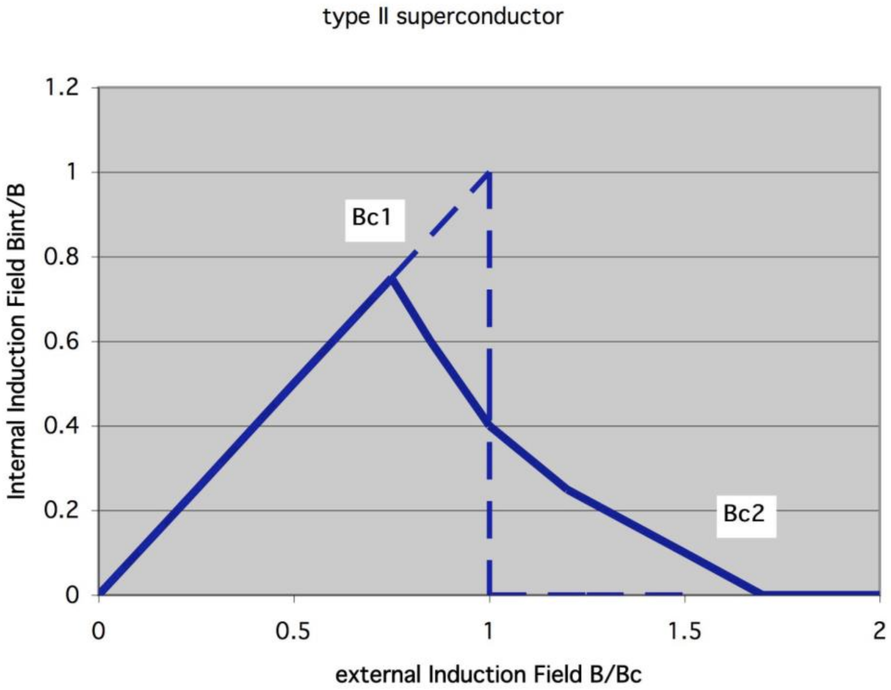


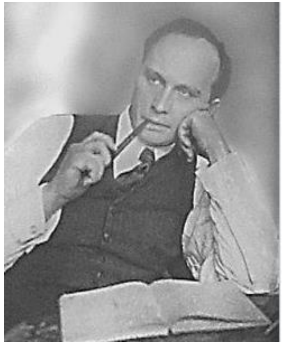
Another important milestone

1937: Type 2 superconductors

Type 1: diamagnetic up to B_c then resistive

Type 2: diamagnetic up to B_{c1} , then partially diamagnetic up to B_{c2} , then resistive ($B_{c2} >> B_{c1}$)





Instead of receiving the Nobel prize, Shubnikov was killed in the Stalin purge and his name is almost forgotten

Major contribution from the theory

1957 BCS: Bardeen Cooper & Schrieffer

An effective attraction between pairs of electrons (Cooper pairs) via the lattice promotes a condensed state in which the phases of all the individual wave functions are locked together. Opposite to electrons, the Cooper pairs obey Bose-Einstein statistic (composite boson). Therefore, unlike electrons, multiple Cooper pairs are allowed to be in the same quantum state.

1950 - 1959 GLAG: Ginzburg, Landau, Abrikosov & Gorkov

The behaviour of superconductors is determined by relationship between London penetration depth λ and coherence length ξ (distance over which superconducting state can change).

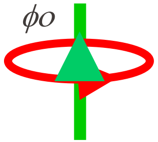
$\lambda < \xi / \sqrt{2}$ Type 1 behaviour $\Rightarrow$ Meissner effect

$\lambda > \xi / \sqrt{2}$ Type 2 behaviour $\Rightarrow$ Shubnikov state

λ … field penetration depth

ξ … coherence length (describes the "size" of a Cooper pair and the distance over which the superconducting properties can vary.

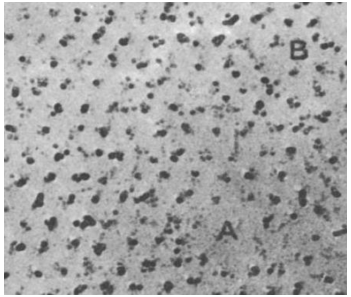
In type 2 superconductors, magnetic field enters the material as quantized “fluxoids”.



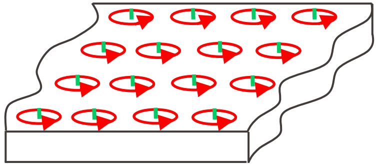
$$\phi_o = \frac{h}{2e} = 2\times10^{-15} Webers$$

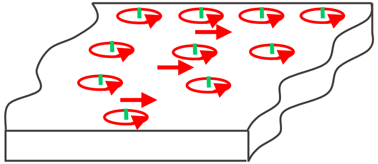
Flux Pinning

- Unlike type-I superconductors, which completely expel magnetic fields (Meissner effect), type-II superconductors allow magnetic fields to penetrate in the form of quantized flux lines or vortices.
- These vortices consist of a core of normal (non-superconducting) material surrounded by a circulating superconducting current.
- Flux pinning occurs when these flux vortices are "trapped" or "pinned" by lattice imperfections, i.e. defects, impurities, grain boundaries, or artificially introduced defects.
- Flux pinning stabilizes the superconducting state in the presence of magnetic fields, which is essential for many applications, such as high-field magnets.
- If flux vortices are free to move, they will do so when subjected to a Lorentz force (caused by an applied current, **F = J** x **B**). This motion dissipates energy, leading to “resistance” and the loss of superconductivity.
- Flux pinning prevents this motion, allowing the superconductor to carry a higher critical current (the maximum current it can carry without losing superconductivity).



U Essman & H Trauble





Flux Pinning

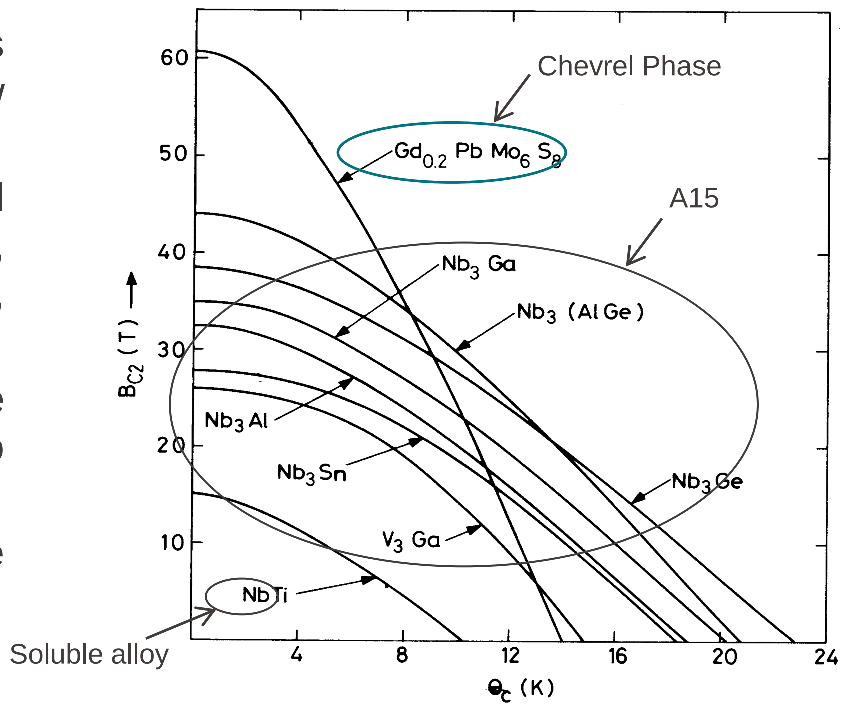
- Flux pinning is also the reason that some superconductors can stably levitate above a magnet. the flux lines remain pinned in the superconductor, locking it in place.
- In summary: Flux pinning is the mechanism that "anchors" magnetic flux lines within a type-II superconductor, preventing their movement and enabling the material to maintain its superconducting properties under high currents and magnetic fields.
- Consequence: Type 1 superconductors, in which magnetic flux is completely expelled from the superconductor, is unable to withstand high magnetic field → they turned out unsuitable for transporting high currents and for the manufacture of superconducting electromagnets. Only after the type 2 superconductors were discovered, strong superconducting electromagnets could be built.

(In the rest of the presentation, we use the term “magnet” for an electromagnet).

Major technology milestones

- The initial expectation to obtain high field magnets by winding high purity superconducting metals (Hg, Pb, Nb), was quickly disappointed, because of the low Bc of Type 1 superconductors.
- The first "superferric" magnet is reported in 1954 (0.6 T, Nb cw wire on copper), followed by small magnets with MoRe, Nb_3Sn, NbZr.
- From the sixties, NbTi became the undisputed work horse for solenoids up to 10T.
- Nb_3Sn magnets above 10T started in the mid 70', first as a tape, then as a wire.

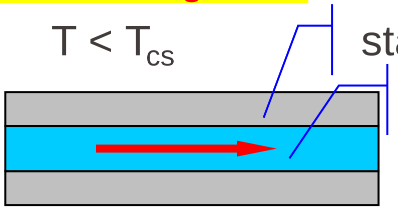
Superconducting materials till mid 80'

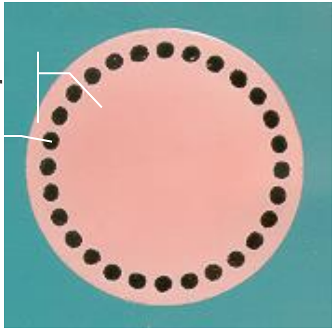


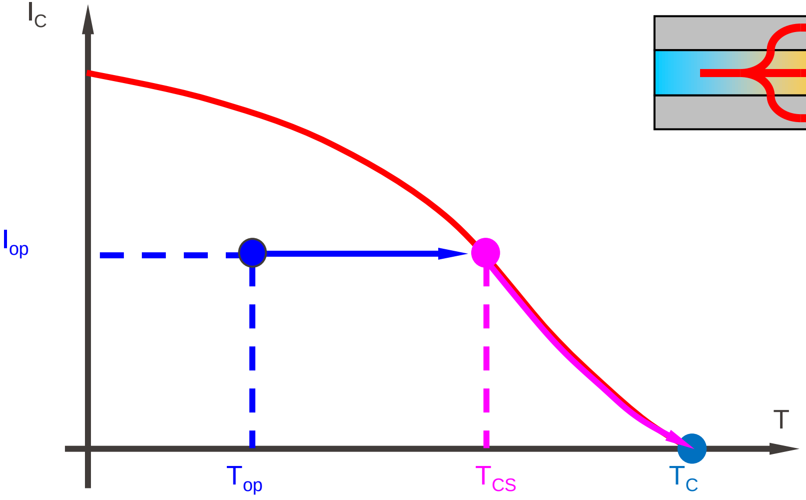
Current sharing

superconducting state

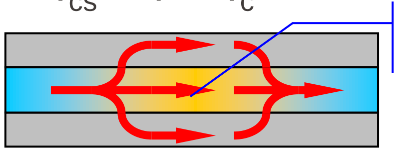
$T < T_{cs}$





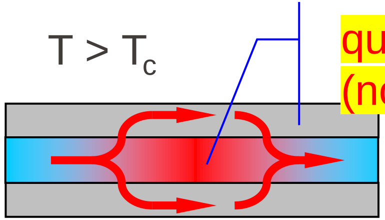


$T_{cs} < T < T_c$



current sharing

$T > T_c$



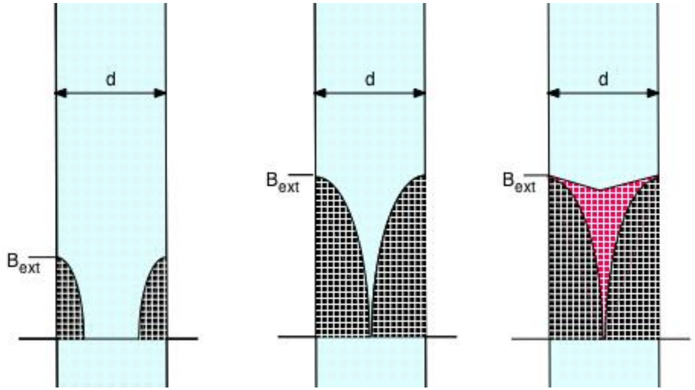
quenched state
(normal state)

The big engineering issue of the late sixties

– Flux jumps and stabilization

- The magnets of the sixties did not achieve the performance expected from the superconducting properties. At some point of the current ramp, the winding abruptly looses superconductivity ("quench") because of the *Flux Jumps*.
- At increasing field, the fluxoids start to penetrate the Type 2 superconductors. The pinning centers trap the fluxoids preventing further penetration till the density is too high and more fluxoids enter. At increasing field the pinning forces decrease and the fluxoids distribution collapses letting a large amount of flux entering the superconductor within less than 1µs.

The sudden flux motion causes energy release (magnetization) with very large power: the temperature increases much faster than the heat is removed. If the temperature exceeds T_c and there is transport current, the flux jumps leads to "quench" of the magnet.



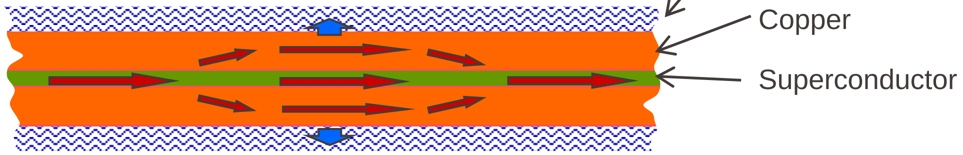
The cure for Flux Jumps

1. Cryostability. The superconductor with copper joined in parallel is well cooled by liquid helium. If the superconductor turns normal, the current diverts to copper and the heat is transferred to the liquid helium. If the heat removal rate is larger than the ohmic heating rate, the temperature falls and the current returns to the superconductor. The Stekly criterion, α, correlates the maximum stable current, I_{lim}, with the copper cross section A_{cu} and heat transfer coefficient, h.

$$\alpha_{Stekly} = \frac{\rho_{Cu} I^2}{A_{Cu}} \Big/ hP_w (T_c - T_{op})$$

Ohmic Heat

Removed Heat



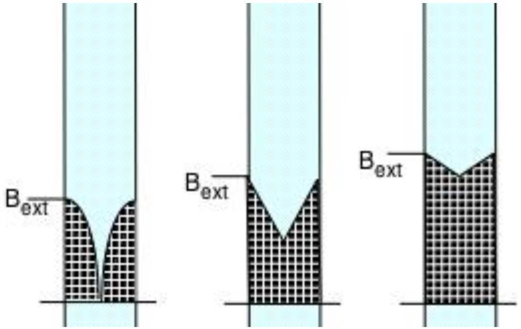
Cryostability does not prevent flux jumps, but makes its effect reversible.

Current ramp ➔ flux jump ➔ $T > T_c$ ➔ copper shunt ➔ cool-down ➔ recovery.

However, the large amount of copper for cryo-stability dilutes the current density, frustrating the high field applications.

The real cure for Flux Jumps

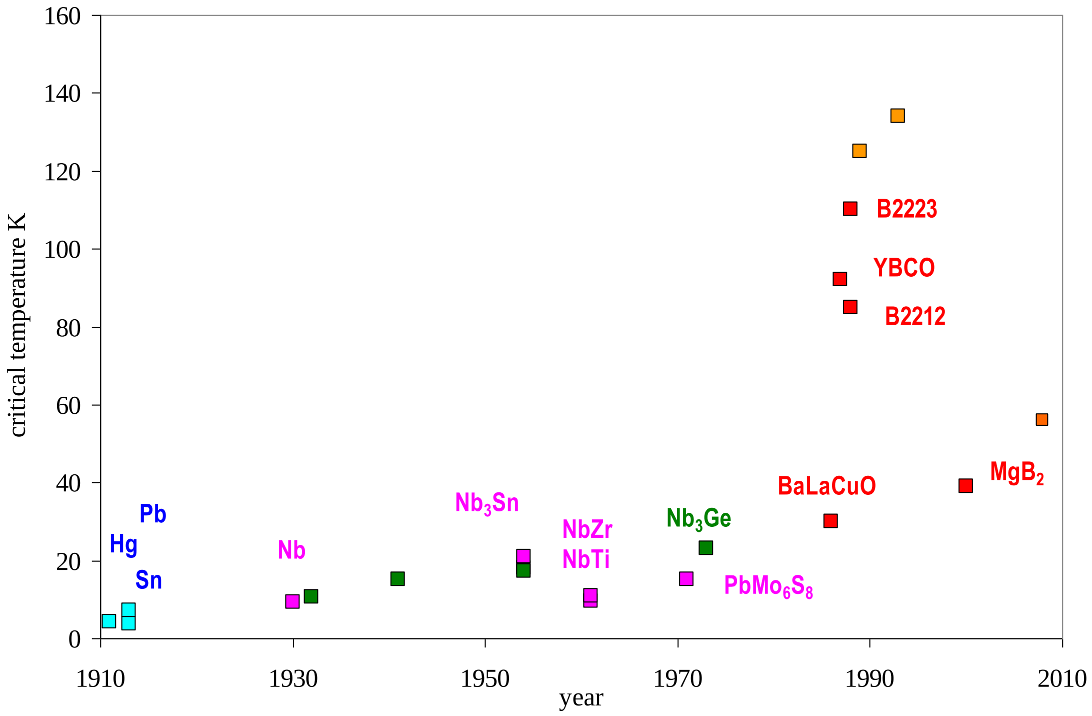
2. Thin Filaments. Reducing the filament size promotes quick full penetration of the fluxoids and prevents the condition for collapse of the flux profiles. Since the 70', the multifilament composites replaced the single core NbTi.



Today thin filaments are standard in all applications, not only because of the flux jumps, but also because of the low magnetization, which is highly appreciated because of low charging loss (helium free magnets) and the high field accuracy (accelerators, NMR).

HTS - The last 35 years

- After over 30 years of “stagnation”, new generations of superconducting materials were found starting 1986 / Müller –Bednorz.



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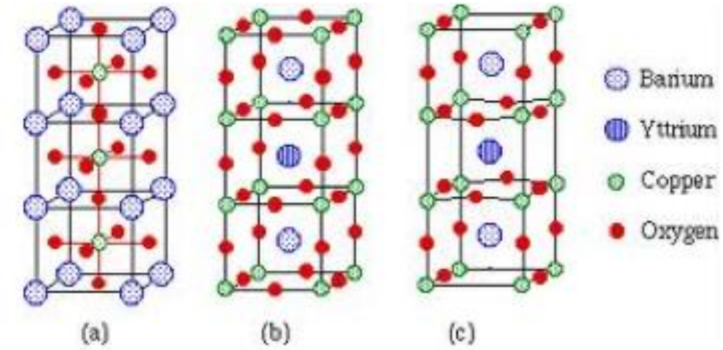
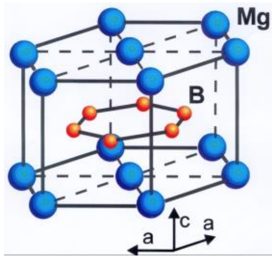
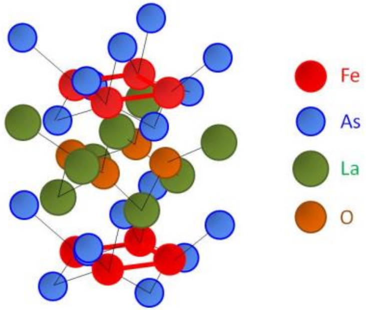
HTS – Materials



▪1986. The main family of HTS superconductors belongs to the perovskite, a kind of cuprates, with T_c up 120 K and B_{c0} up 50 T.



2001. Another popular new material is MgB_2 a binary compound with T_c=39 K and B_{c0} < 10 T.



2008. The youngest family of HTS materials is iron based pnictides, with T_c in the range of 50 K.

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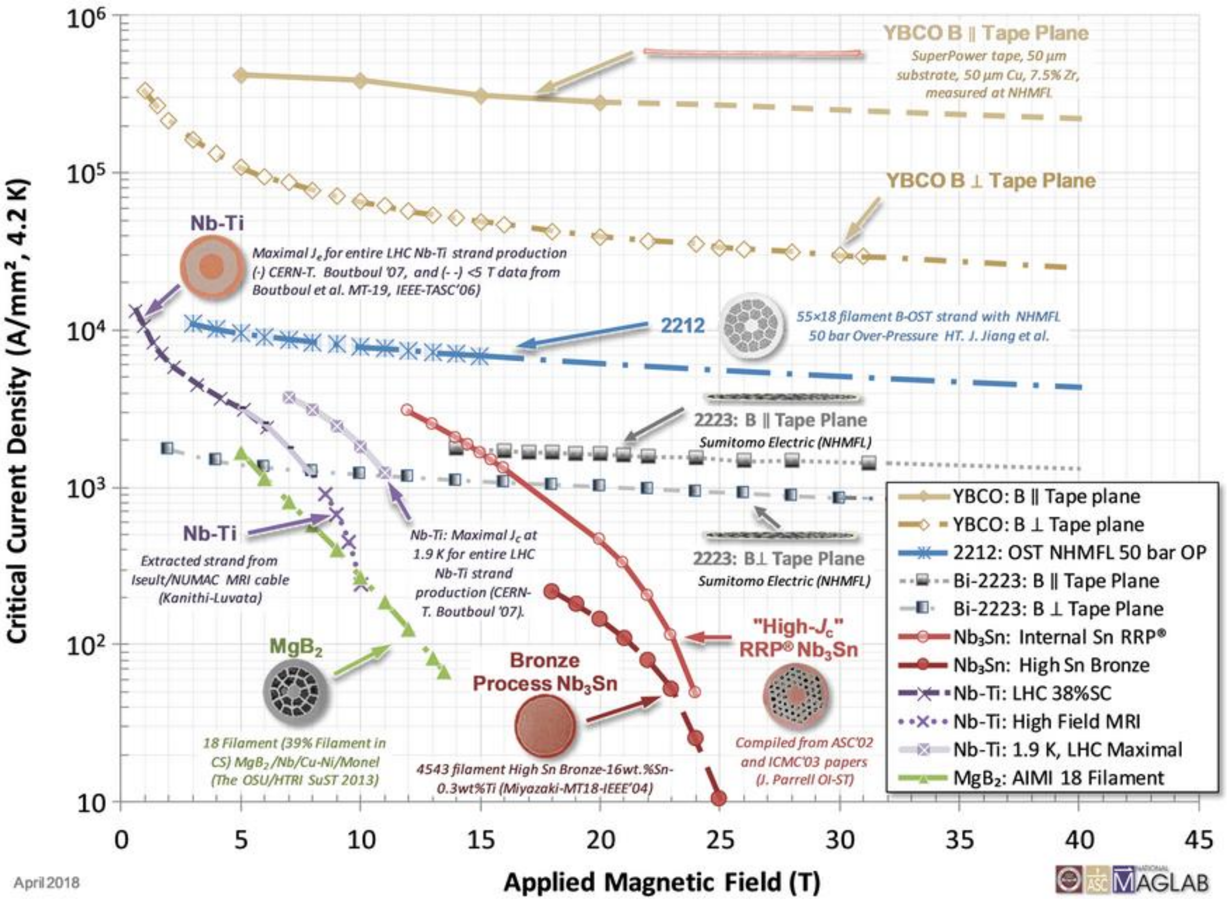
Why HTS?



- For transporting the current in the grid, high J_c is an advantage (cooling with LN_2 is much more efficient compared to LHe).
- In fusion magnets, high magnetic field together with operating temperature leads to low J_c, and thus to low performance.
- However, when HTS magnets are cooled down to 20 K or more, the J_c gets high again due to the high B_{c2} field at low temperature.
- HTS fusion magnets generate ~twice higher field than LTS magnets.

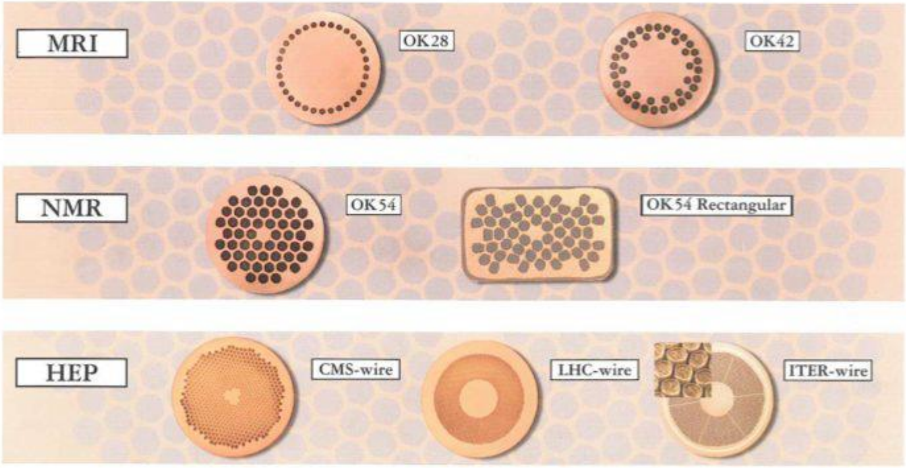
Technical superconductors today - NbTi

NbTi is the best superconducting soluble alloy. T_c = 9.2 K, used in superconducting magnets up to 8T (4.2K) or 11T (2K).

Very ductile, co-drawn with copper down to submicron filaments, produced since 50 years in thousands of tons.

Today the main market is MRI, followed at distance by NMR, High Energy Physics, Fusion, laboratory magnets, etc.

Price ≈ 150 €/kg
(≈20 times Cu)



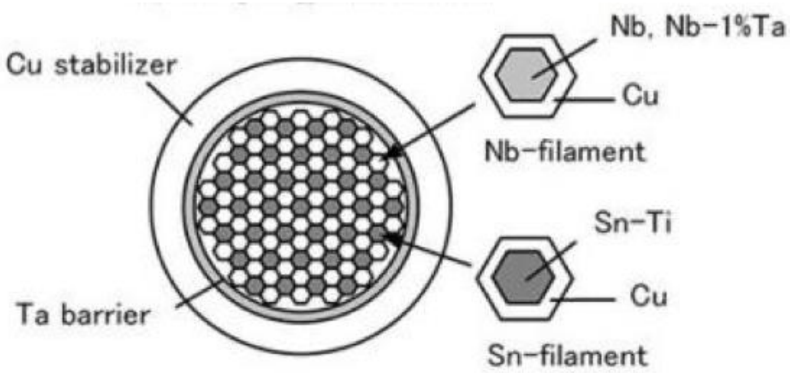
Technical superconductors today – Nb_3Sn

Nb_3Sn is a *brittle* intermetallic A15 compound (fixed stochiometry). Since the 60' it is obtained by solid state diffusion of Sn into Nb (600-700C / 50-200 hrs). The multifilamentary composite is a precursor containing Nb filaments and Sn. The precursor is ductile and can be wound or cabled to the final form. Eventually it must be heat treated to build the Nb_3Sn. After heat treatment, it is very brittle and must be handed with care, controlling bending and loading.

It is produced by ten companies worldwide by either "bronze" route or "internal Sn" method. Best customer ever was ITER (700 t)

Price 700 - 1000 €/kg

Similar to bulk Ag



HTS superconductors today – Bi perovskite

Two perovskite superconductors are produced commercially on small scale:

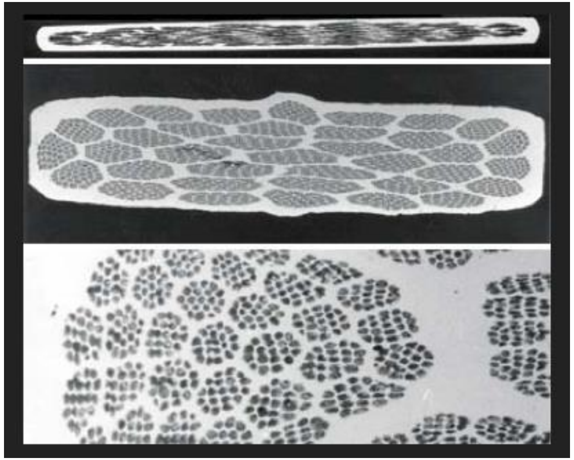
Bi - Sr *based cuprates,* $Bi_2Sr_2Ca_{n-1}CuO_{2n+4+x}$*, available as*

wire Bi2212 (precursor)

tape Bi2223 (heat treated)

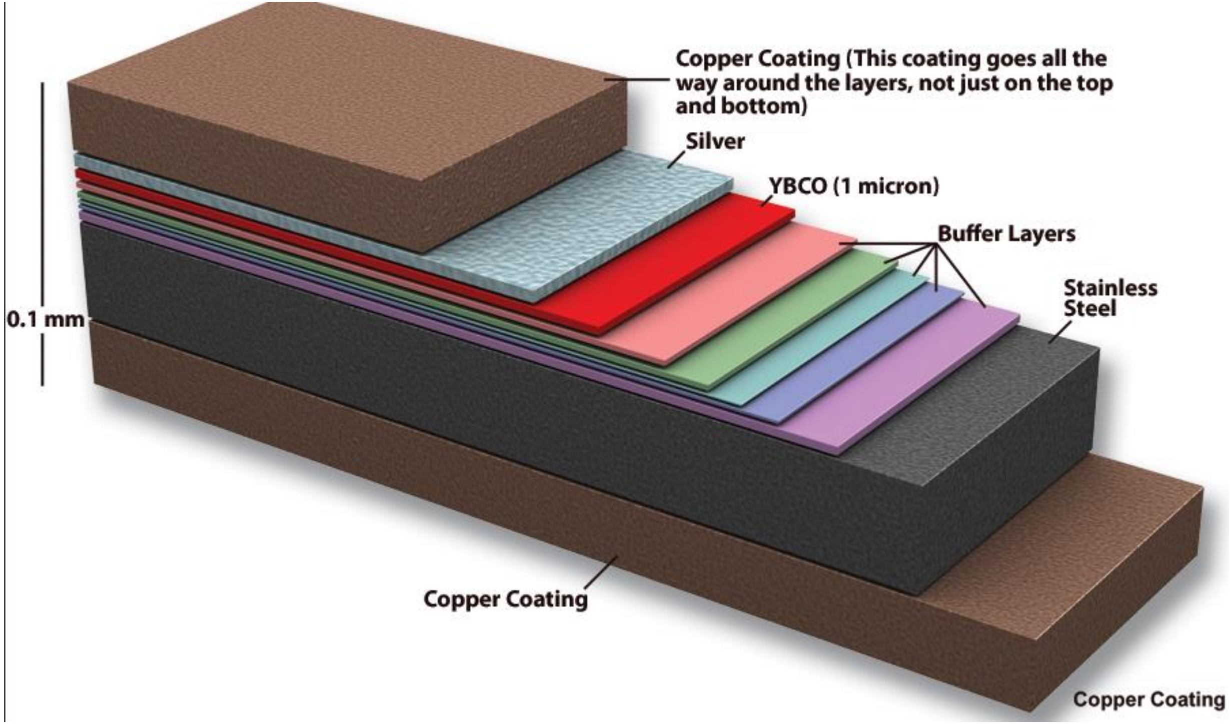
The matrix of both multifilament composites is Ag (transparent to Oxygen) The Bi2223 tape, with high anisotropy, is in use mostly for HTS hybrid current leads. The Bi2212 wire is a candidate for high field winding, but with technology challenges.

Price/kg close to Gold



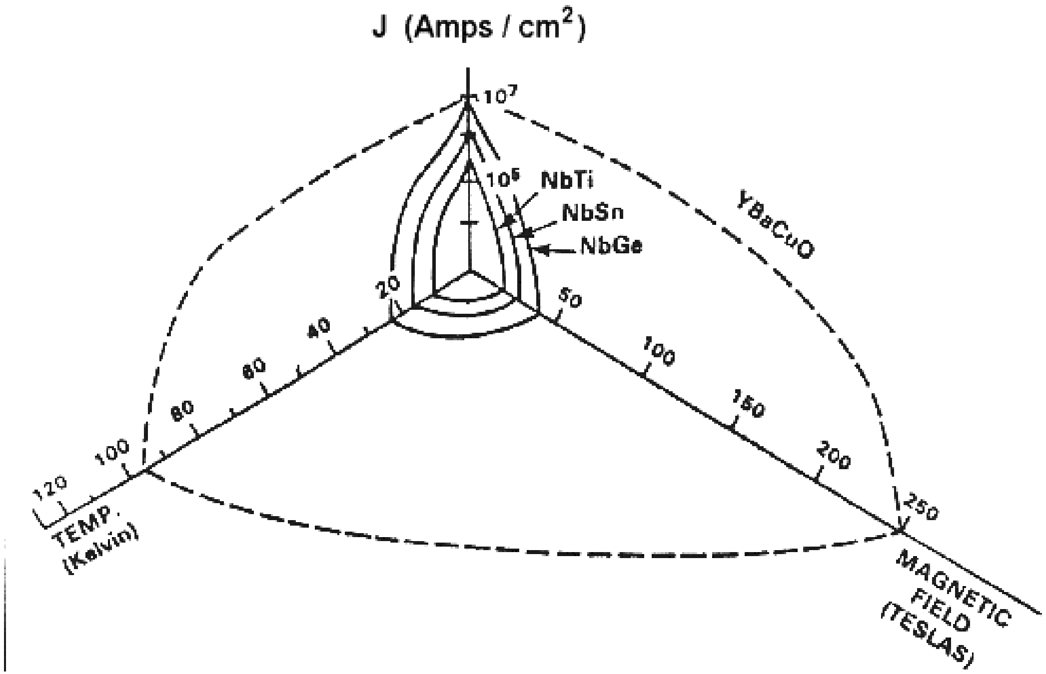
HTS superconductors today – Rare Earth perovskite

***REBCO** based cuprates ("coated conductors"), Y(or Ga)$Ba_2Cu_3O_{7-x}$ are thin tapes prepared by CVD or laser assisted PVD. Best candidate for high field insert coils.*



The critical surface for superconductors

For practical application, the range of operation for a superconductor is defined by the critical surface, a 3 D plot in the B-T-J space (more dimensions may include the mechanical strain and the irradiation dose). The distance from the operating point to the critical surface is a measure of the operating margin.



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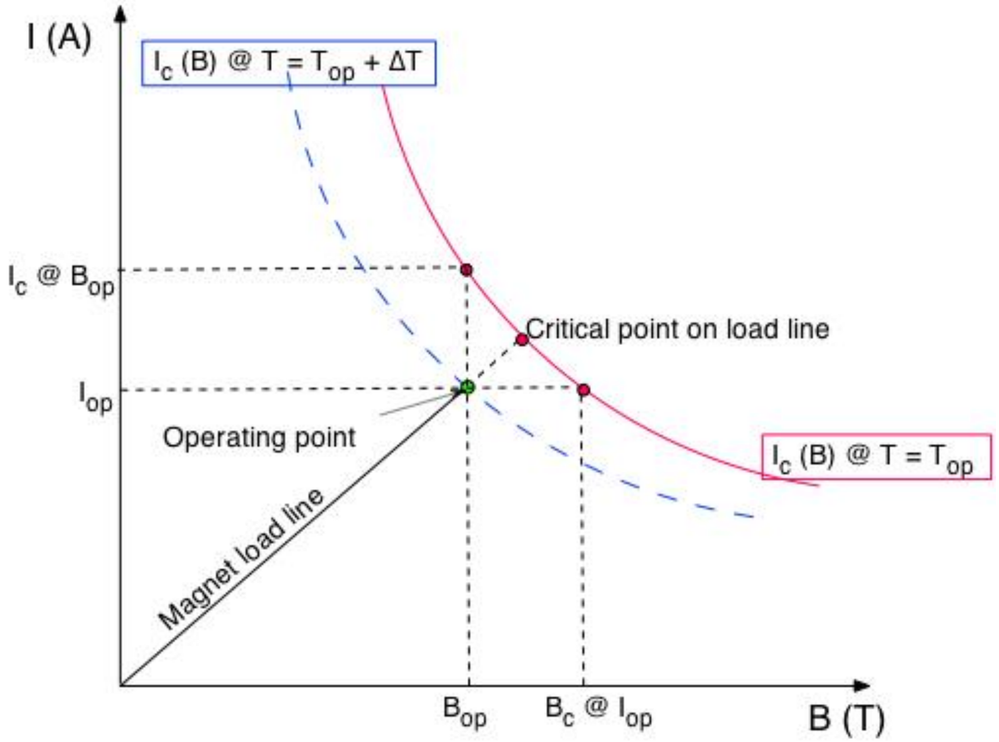
Definition of Margin

Practically, the "distance from the critical surface" can be defined in terms of:

- I_{op}/ I_c
- ΔT (T_{cs}-T_{op})
- % on load line
- B_{op}/B_c (seldom)



Scaling law for superconductors - NbTi

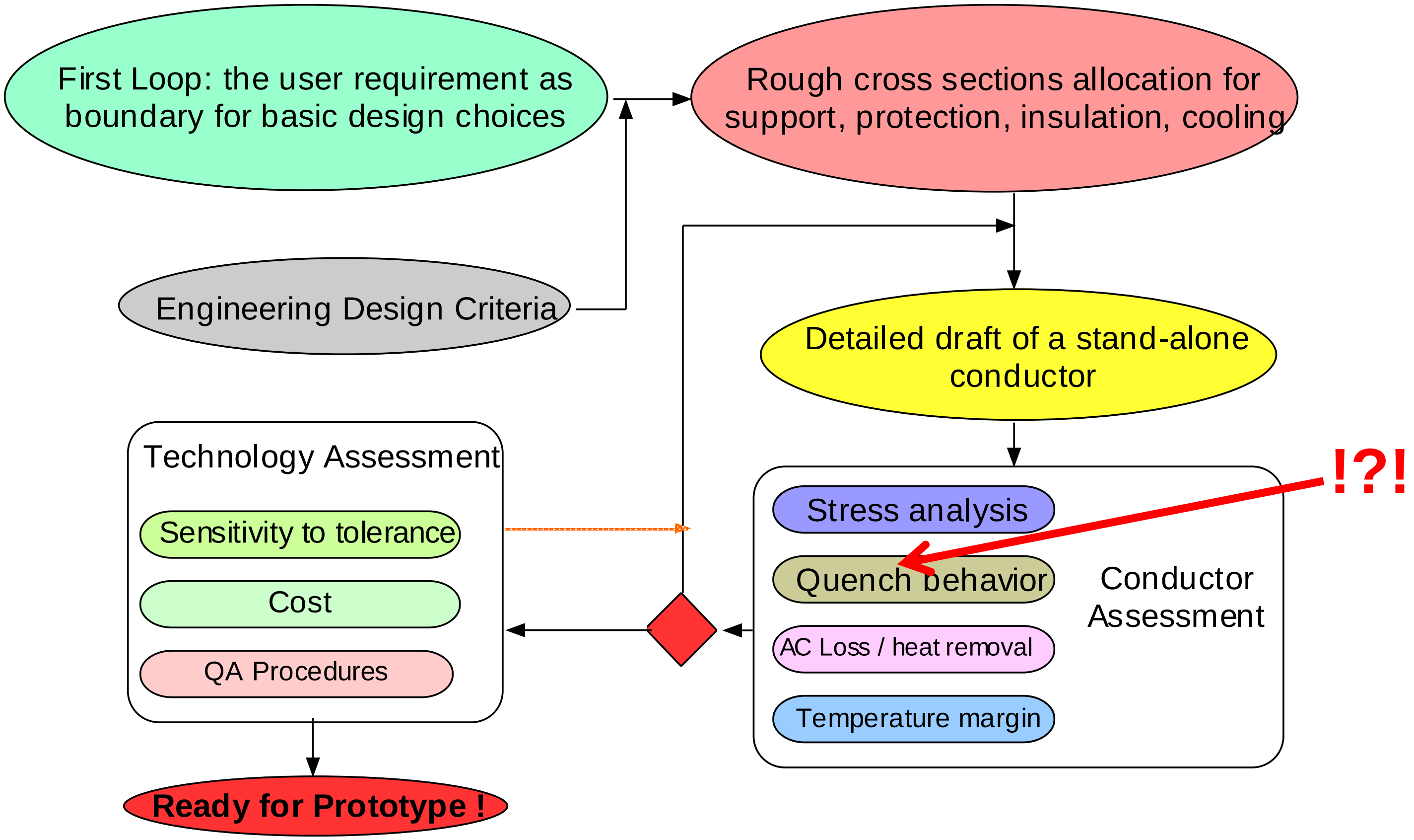
The key instrument for the designer is the scaling law, an empirical, interpolative formula for the critical current density, J_c, as a function of operating field B, operating temperature T (and if applicable, operating strain, irradiation dose, etc.).

Reduced field $b=B/B_{c20}$ and reduced temperature $t=T/T_{c0}$ are used. *For **NbTi:***

$$J_c = \frac{C_0}{B}\left(1-t^{1.7}\right)^{\gamma} b^{\alpha}\left(1-b\right)^{\beta}$$

C_0 [A/T/mm^2]	B_{c20} [T]	T_{c0} [K]	α	β	γ
168512	14.61	9.03	1	1.54	2.1

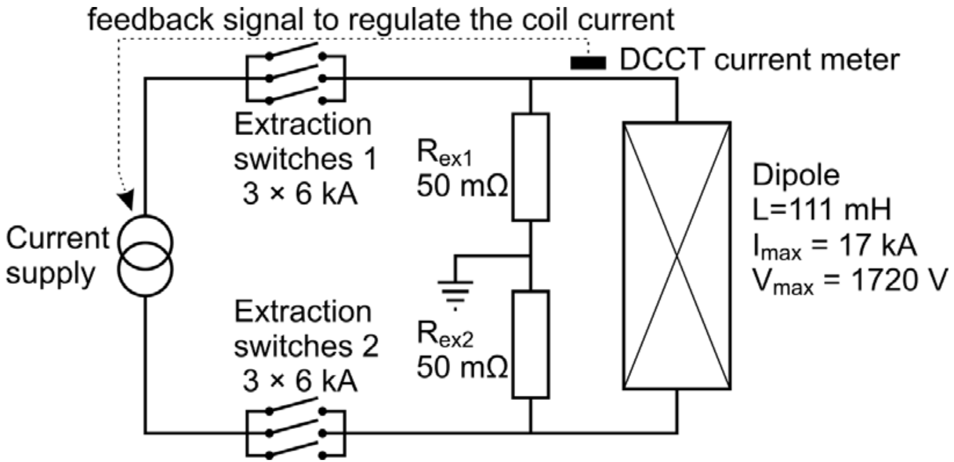
A stepped roadway for conductor design



"Quench" ?

- *In a superconducting coil a quench event is the punctual, irreversible loss of superconductivity:*
  - The critical surface (B, T, I) is accidentally exceeded, e.g. by loss of T or I control, and the superconductor becomes resistive
  - The ohmic power generation overcomes the heat removal capability
  - The temperature runaway leads to fatal thermal mechanical stress and/or melting of the coil
- *A quench event is a serious safety issue for superconducting coils. Even if a quench event should never happen according to the design, countermeasures must be planned to face a quench event*
  - Quench Detection, e.g. by accurate, fast voltage monitoring
  - Quench Protection = avoid temperature runaway / preserve the integrity of the coil
- Superconducting coils are always designed to withstand a quench (without a damage)

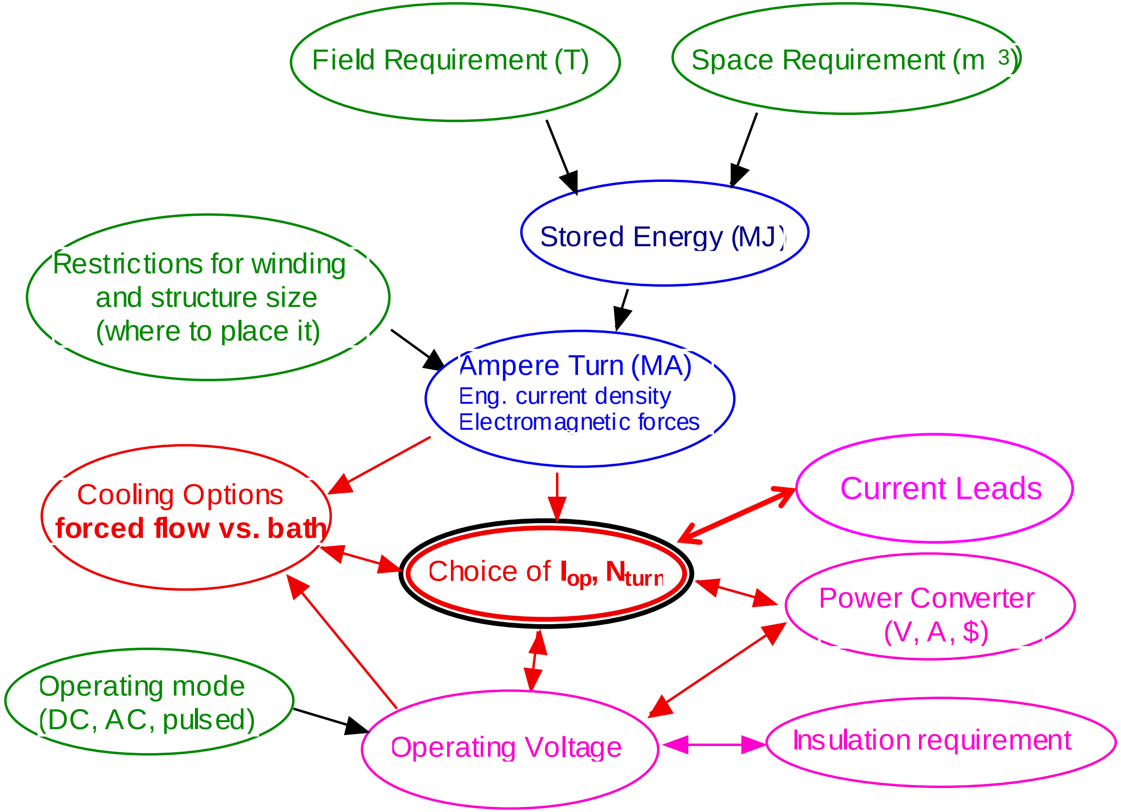
How to protect a coil in case of Quench?



- Low field and/or smaller size coils may dissipate the stored energy within the coil winding without a catastrophic increase of temperature.
- Large superconducting coils need extraction of the stored energy.

- *The key elements of a quench protection system:*
  - The quench detection system with a quench detection time t_d
  - The hot spot temperature in the coil
  - The dump resistor outside the cryostat
  - The fast current breakers to open the circuit
  - The maximum voltage at the terminal $V_{max} = I_{op} \cdot R_{dump}$
  - The time constant of the current dump $\tau = L / R_{dump}$

The first loop



"Tools" for the first design loop

- Stored Energy
  - (Volume integral of magnetic field)

$$E = \frac{1}{2\mu_0}\int B^2\, dV \equiv \frac{1}{2} L I_{op}^2$$

- Ampère law
  - (Field to current relation)

$$\oint B \cdot d\ell = \mu_0 I$$

- Lorentz force

$$F = \int j \times B\, dV = IB \int d\ell$$

- Faraday-Henry law
  - (Inductive Voltage)

$$V = -L \frac{dI_{op}}{dt}$$

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