Superconducting Magnets - 1

Pierluigi Bruzzone

EPFL-Swiss Plasma Center, Villigen, Switzerland

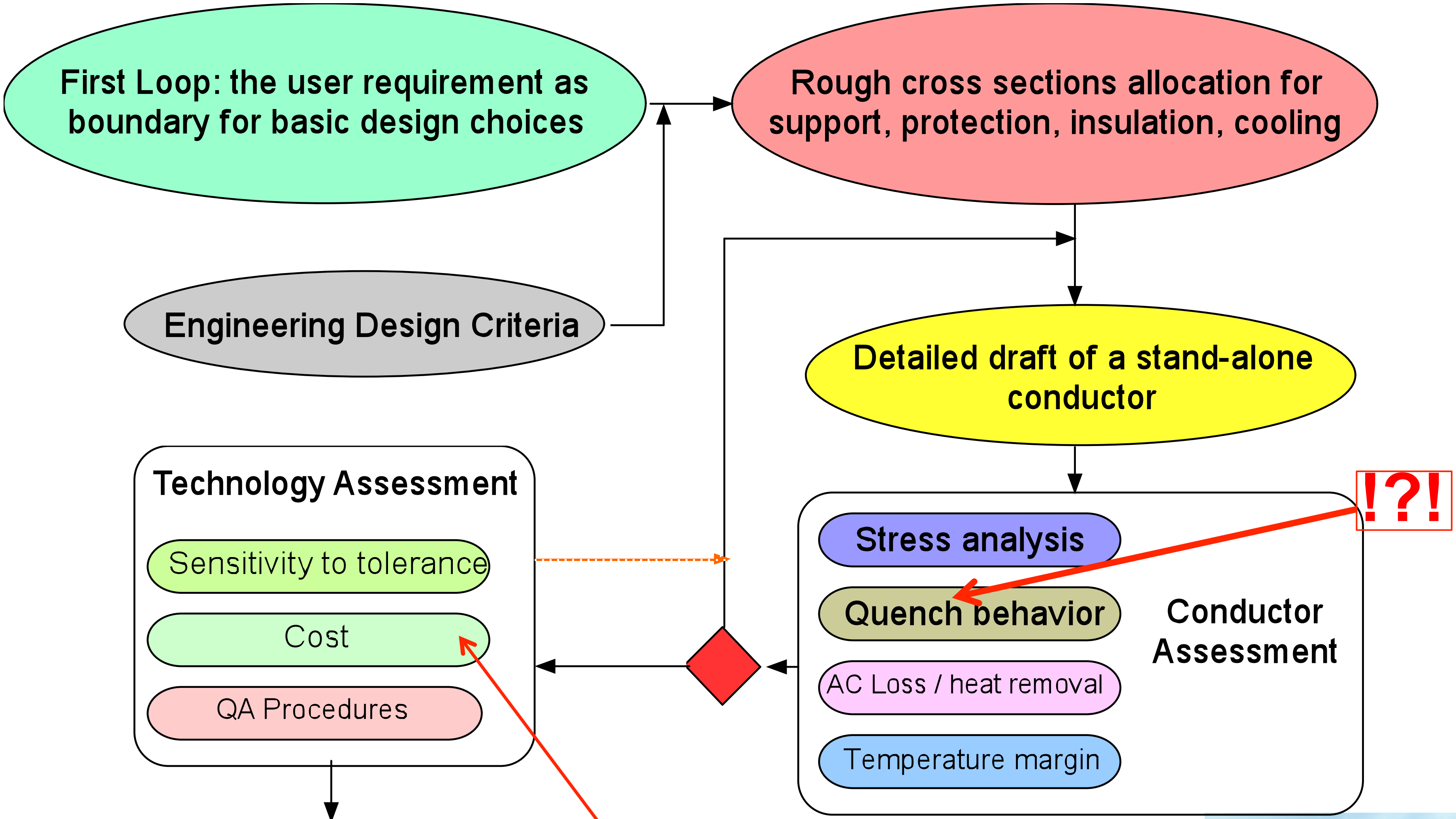
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER

Outline

1. Stepped Approach for the Design of large Conductors and Magnets
2. Examples of Superconducting Fusion Magnets from last Century
3. The ITER Conductors and Coils
4. Toward DEMO - HTS

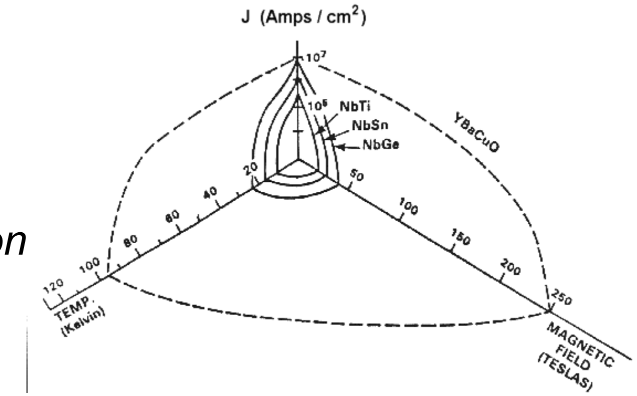
A stepped roadway for conductor/magnet design



“Quench” ?

(do not look in the dictionary, it has nothing to do with forging and tempering)

In a superconducting coil a quench event is the
***local, non-recovered loss of superconductivity**:*



The critical surface (B, T, I) is exceeded in a (short) section of the winding and the superconductor becomes resistive

The local ohmic power generation overcomes the heat removal capability

The temperature runaway may eventually lead to 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, i.e. avoid temperature runaway / preserve the integrity of the coil

Quench Protection Strategy

The interval between the start of the quench and the reliable detection with related action, is called "delay time", t_d, and can last up from few ms to few seconds, depending on the quench propagation rate, v_q. During t_d the power deposited at the quenched spot is in the range of few kW in large coils.

The most common quench detection method is based on voltage monitoring of the winding sections. The voltage threshold for quench detection ranges from 10 mV to 1 V, depending on the achievable rejection rate of noise and inductive voltage.

The very first obvious action as soon as a quench is detected is to stop powering the quenched winding.

However, placing the power supply in "freewheeling" (basically a short circuit), is not effective to stop the current in the winding, which is sustained by the stored energy. Even if the power supply is short circuited, the current decays very slowly, as L/R_{quench}, depositing most of the stored energy at the quenched section of the winding, which expands moderately slowly.

Quench Protection Strategy

Depending on the stored energy / mass of the winding, the amount of copper in the conductor, the heat diffusion in the winding, etc., various approaches can be taken to preserve the integrity of the coil in case of quench.

If all the stored energy is dissipated in the coil, the average final temperature, starting from ≈ 4 K, can be estimated comparing the conductor enthalpy with the density of the stored energy.

Example	Stored Energy	Conductor mass, kg	Energy density	Average, final temperature
15 T Lab Solenoid	250 kJ	50 kg	5 J/g	≈ 70 K
LHC Dipole	8 MJ	800 kg	10 J/g	≈ 100 K
CMS Solenoid	2.6 GJ	220 t	11 J/g	≈ 80 K (Al)
ITER TF coil	2.28 GJ	43 t	53 J/g	≈ 300 K

At large, the conductor enthalpy (mix of copper, superconductor, steel) is:
≈ 2 J/g up to 50 K
≈10 J/g up to 100 K
≈ 60 J/g up to 300 K

Energy Management

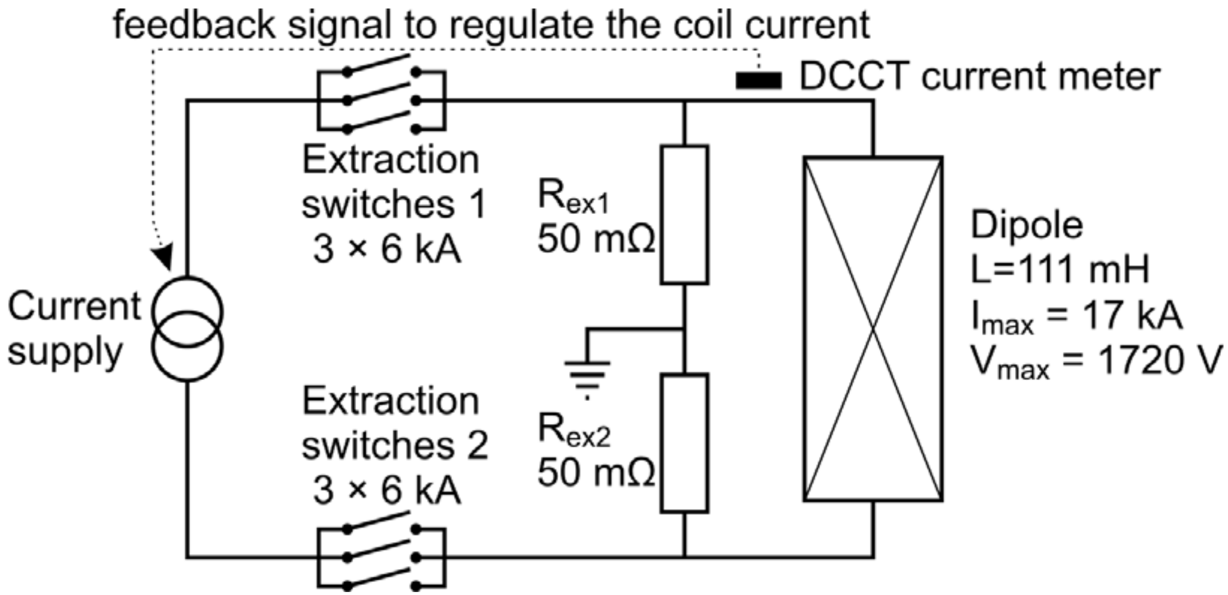
The energy is not dissipated homogeneously in the winding, with the largest fraction, and hence the largest temperature, at the spot where the quench initiated, also named "hot spot".

Large temperature gradients are dangerous because of thermal-mechanical induced stress, which can destroy the integrity of the winding. As a design criterion, the hot spot temperature is usually specified $T_{hot\ spot} \leq 150$ K in the rigid parts of the winding.

In superconducting magnets with stored energy density larger than few J/g, it is mandatory to extract the stored energy to limit the hot spot temperature.

Example	Measures in case of quench	
15 T Lab Solenoid	Passive: diodes and resistors in parallel with winding sections	
LHC Dipole	Active: fast heaters promote quench propagation + diodes	
CMS Solenoid	Active: current breakers and dump resistors in parallel	τ = 200 s, high λ, limited extraction
ITER TF coil		τ = 14 s, 90% energy extraction

Energy Extraction Scheme for Fusion Magnets

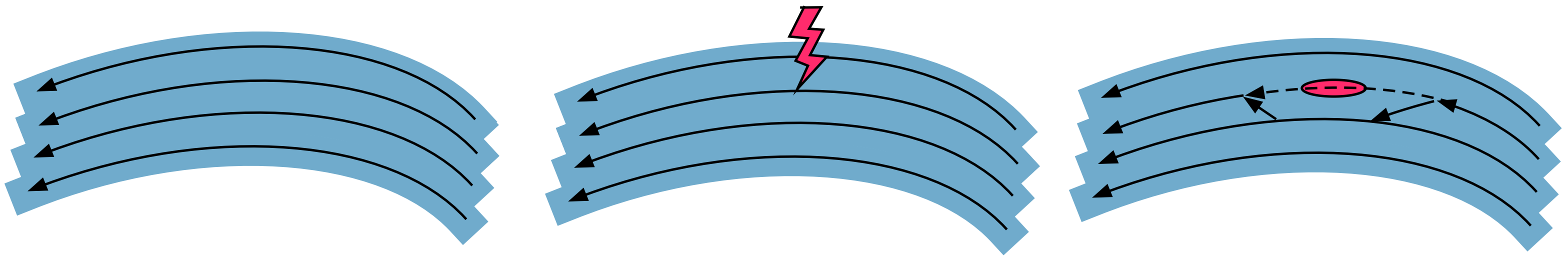


The key elements of a quench protection system are

- *The hot spot temperature in the coil, T_{max}*
- *The dump resistor outside the cryostat, R_{dump}*
- *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 quench detection time t_d*

Non – Insulated Coils: the ultimate cure for quench?

- As soon as some voltage builds up at the quench location, the current starts to transfer to the adjacent turns.
- The whole stored energy is dissipated in the winding.
- You must just slowly run down the current at the power converter.



No temperature runaway, no high voltage, no breakers, no transient, no fast quench detection, no critical instrumentation

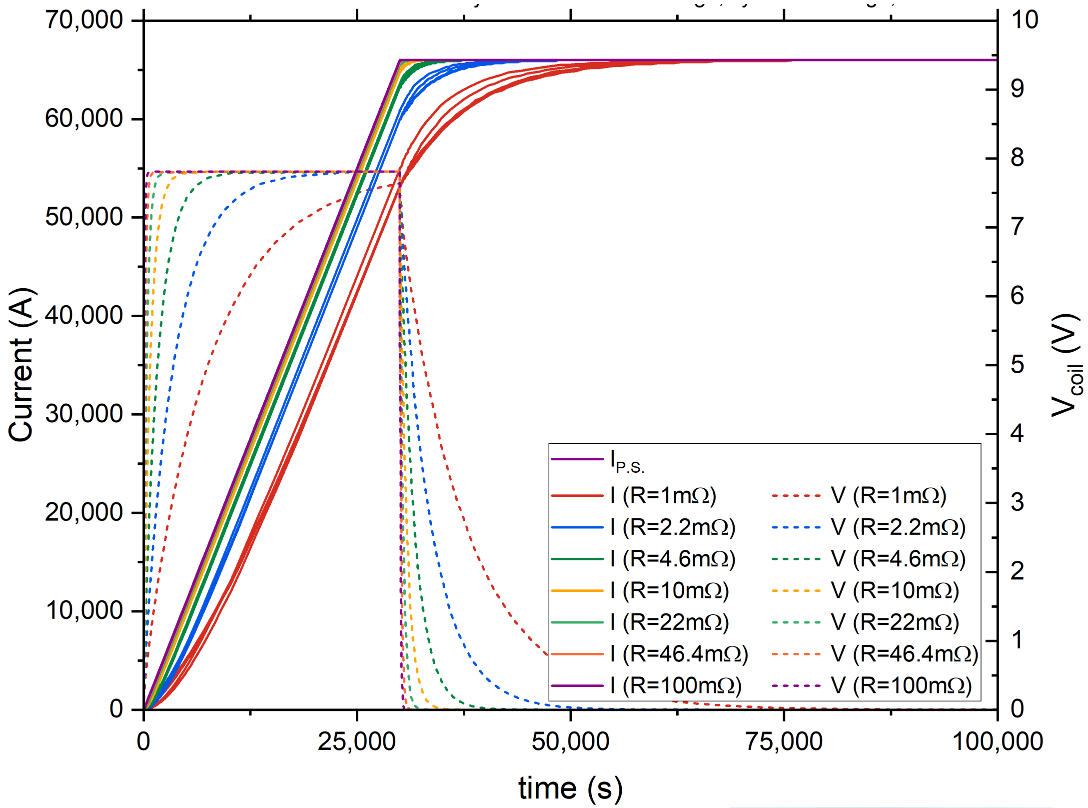
But…

The ability to control the coil current from the power converter is very poor. During the charge, the current in the superconducting turns is smaller than the output of the converter. The leakage current dies out slowly.

Only DC coil with long charge time can be “non-insulated”.

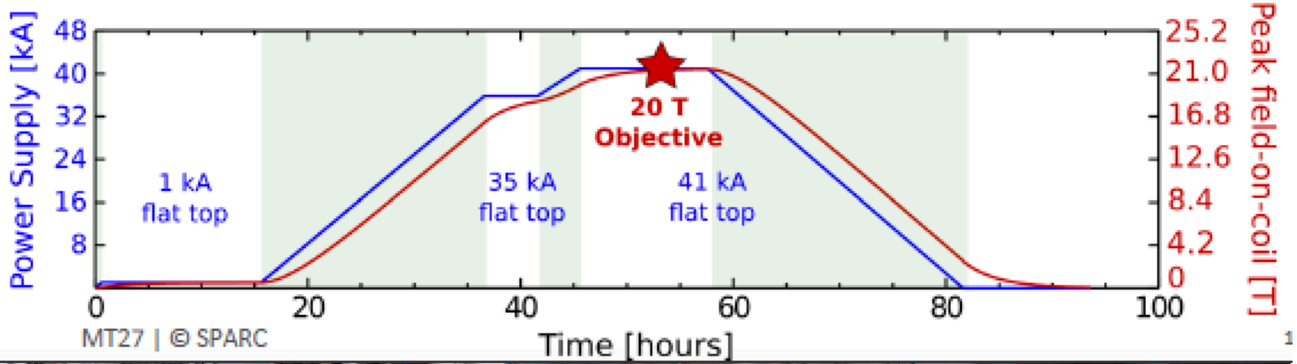
Even in case of emergency, no fast discharge is possible.

As all the stored energy is dissipated in the coil, the re-cooling is time consuming.



Example of non-insulated DEMO TF coil

The SPARC TFMC



And…

- To avoid hot spots in the winding, the heat must diffuse "fast" through the turns, in axial and transverse direction. If the heat diffusion time is longer than the current decay time, large temperature gradients occur.
- The heat diffusion time is also a function of the coil size: in the large TF coils of DEMO, the diffusion path is several ten meters…
- In the non-insulated TFMC of SPARC, the heat diffusion was slow and a region of the coil burnt upon a quench while the other regions remained cold.

In summary, the non-insulated coils are…

Good:

- Passive quench protection (safe and cheap)

- High current density (no need of large copper cross section)

Bad:

- No active control for field (only for certain DC coil)

- Long re-cooling time after quench (100% of stored energy “in the coil”)

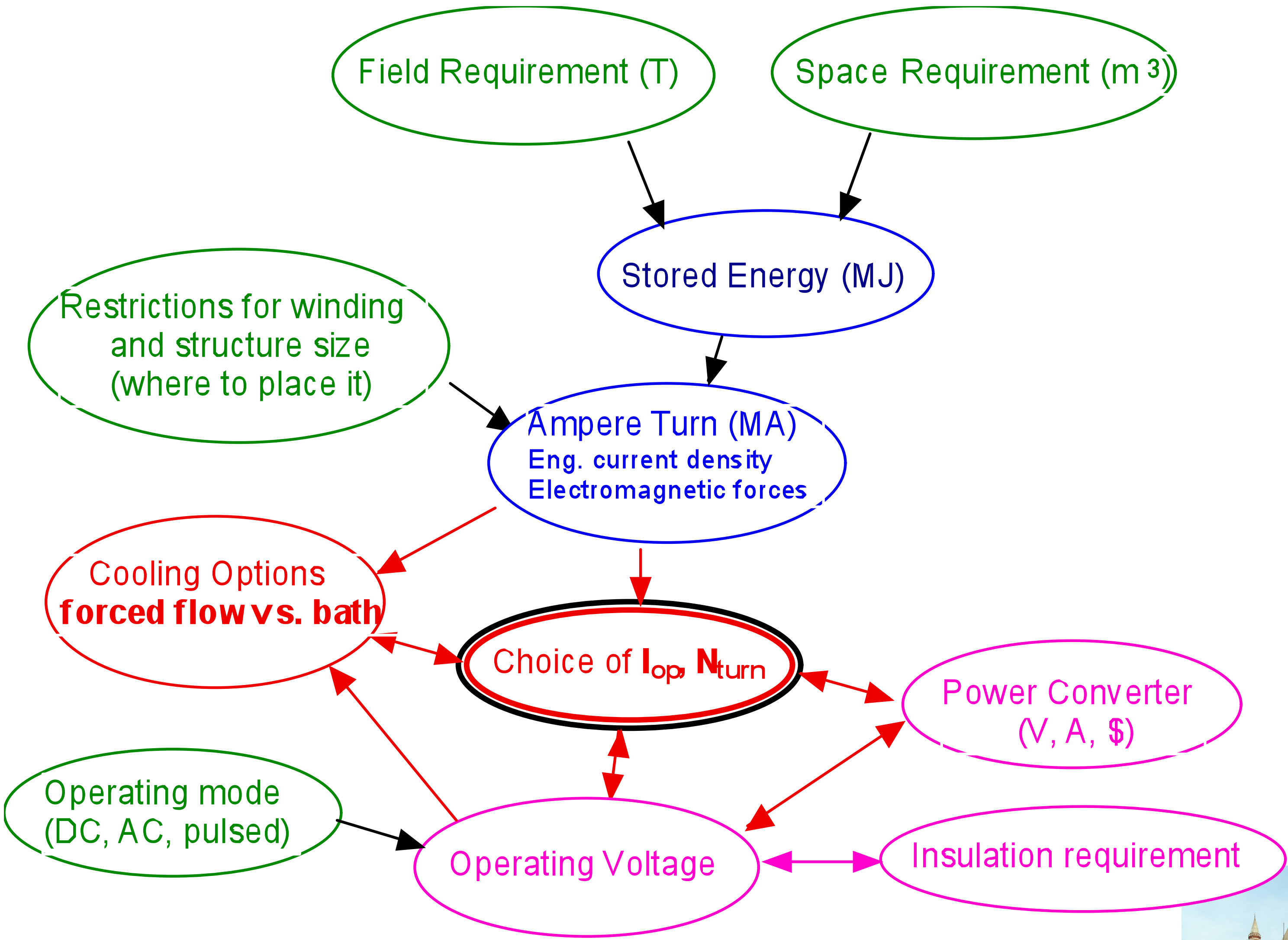
So far non-insulated coils are in use for small, high field insert solenoid.

The use in very large winding is problematic because of heat diffusion issues.

In case of coil systems, e.g. TF coils, it may be not acceptable that one coil is “hot” while the others remain cold.

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

The first loop



“Tools” for the first 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

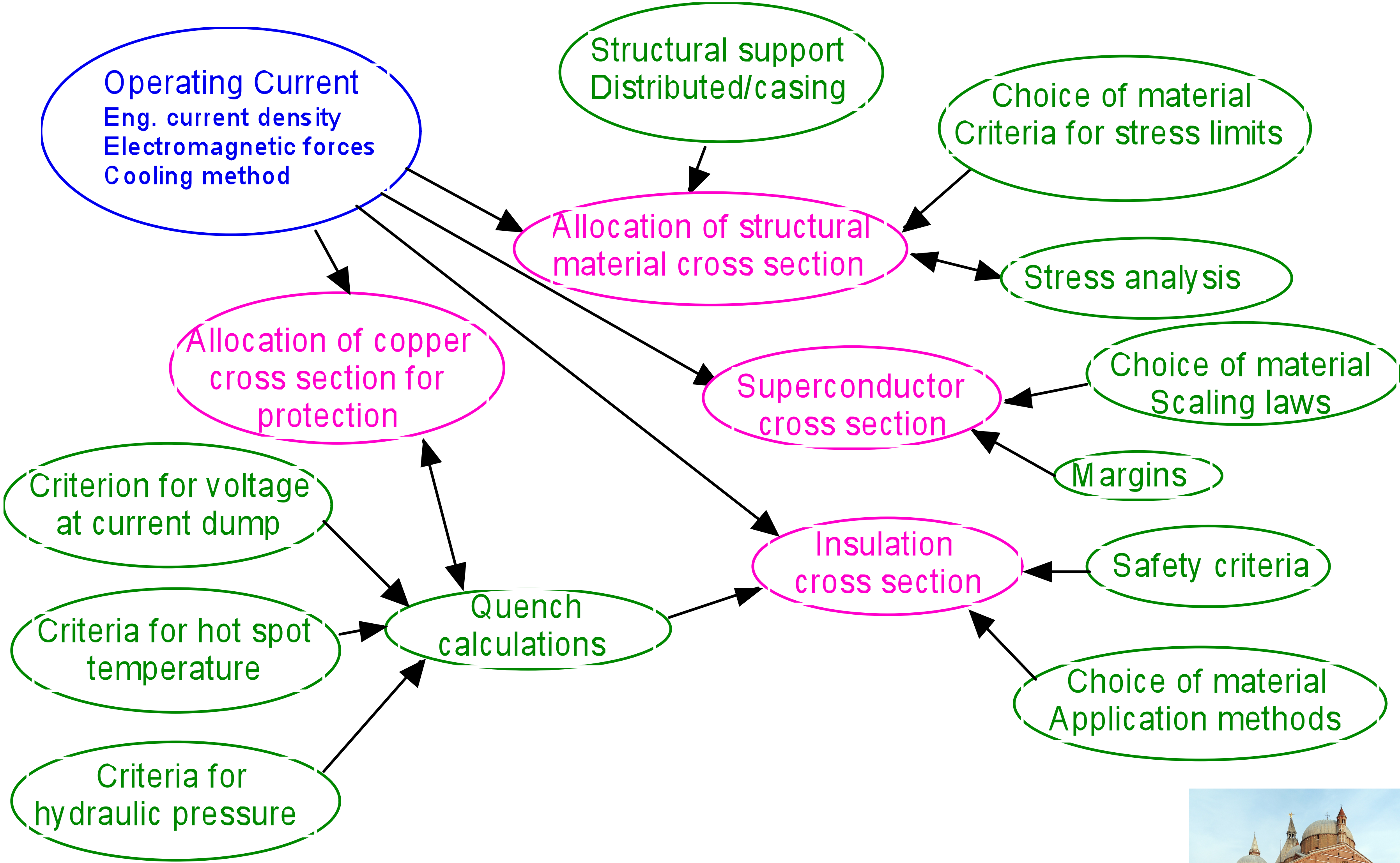
$$F = \int j \times B\, dV = IB \int d\ell$$

Faraday-Henry law
(Inductive Voltage)

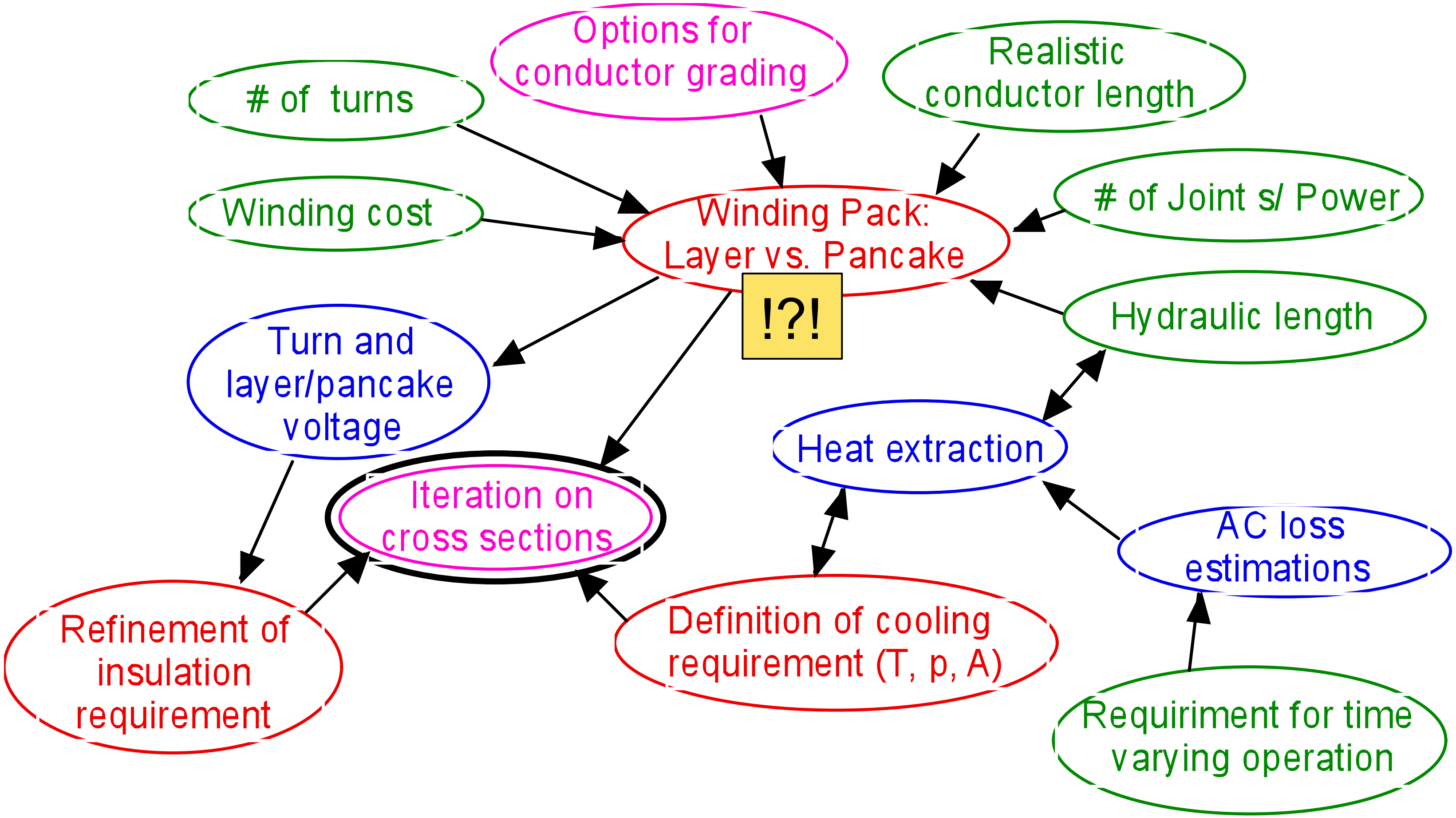
$$V = -L \frac{dI_{op}}{dt}$$

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SWISS PLASMA CENTER

The second loop - Cross sections management



Cooling and Winding pack impact on cross sections

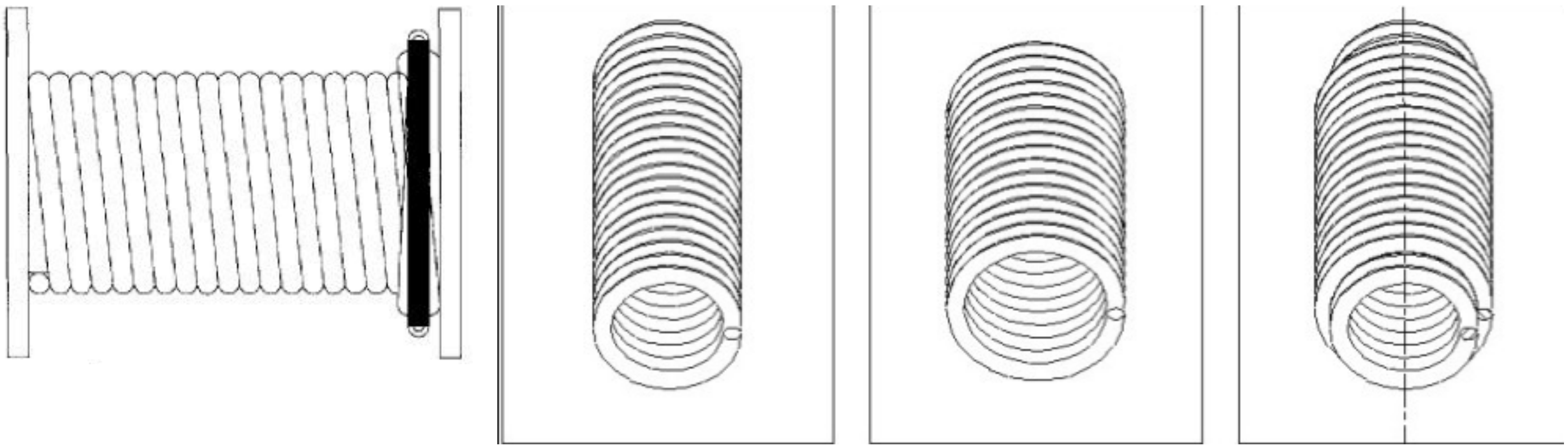


ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

Layer Winding

A winding pack, e.g. a solenoid, can be wound as

Layers: *start winding at the inner radius,*
build the innermost layer by turns at the same radius
wind next layer on top of the former one
continuous winding, joints/terminations at top and bottom



Pancake Winding

A winding pack, e.g. a solenoid, can be wound as

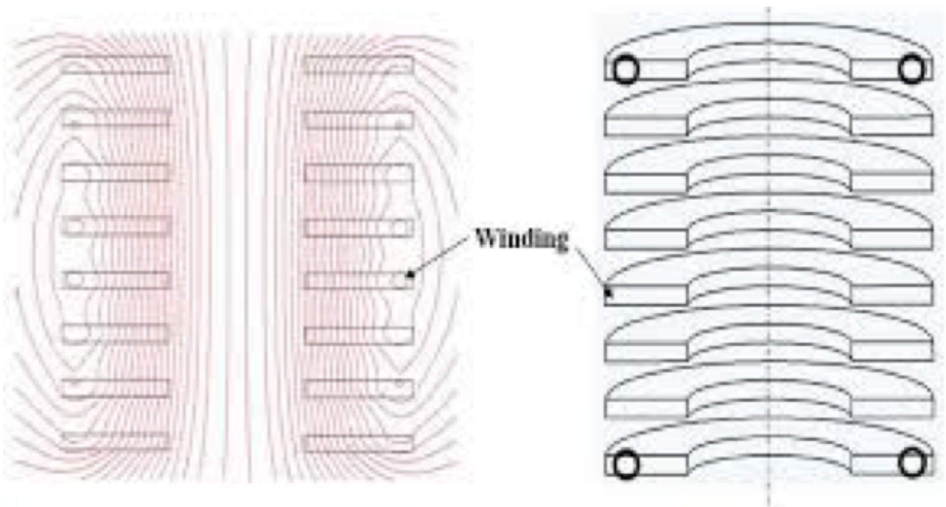
Pancakes: start at the inner radius

wind the turns at same high and increasing radius

separately wind next pancakes

stack all the pancakes on top of each other

joints at inner and outer radius



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

Pancake / Layer : Does it matter?

Layer

☺ *As each layer has a different peak field, the amount of superconductor can be adjusted in each layer, leading to cost and space saving (graded winding).*

☹ *In case of large and heavy winding, all the mass must be handed at the same time -> larger tools.*

☺ *Double layer windings and two-in-hand windings pose no problem.*

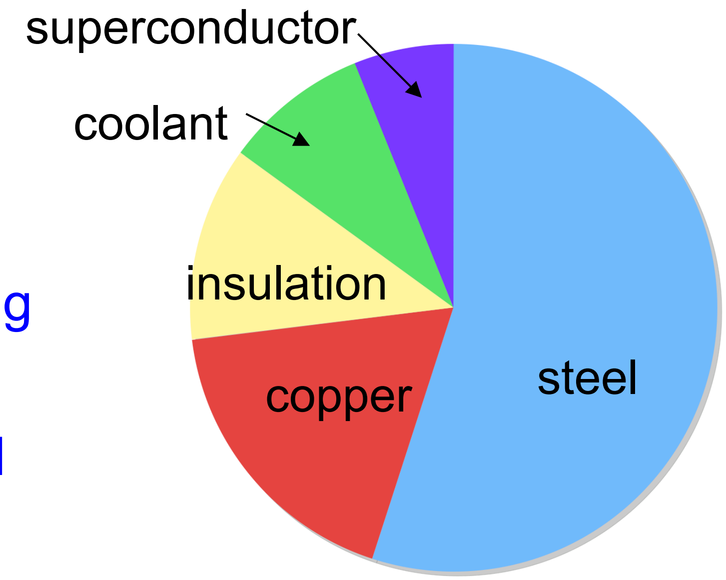
Pancake

☺ *The winding is fully modular, i.e. each pancake is wound separately and eventually stacked together -> lighter tooling for large coils.*

☹ *No grading is possible -> larger cost and space requirement.*

☹ *To avoid joints at the inner radius, double pancake is necessary, with complex handling.*

Conductor Layout



Once the cross sections and the operating requirement are roughly assessed, the stand-alone conductor can be drafted accounting for:

!?!

Superconducting strands available on the market

Transposition / current distribution

Cable layout consistent with ac loss and mechanical constraints

Local heat removal / stability

Sensitivity to manufacturing tolerance

Applicable quality control procedures

Procurement time and cost

Strand…

(not a city district of London!)

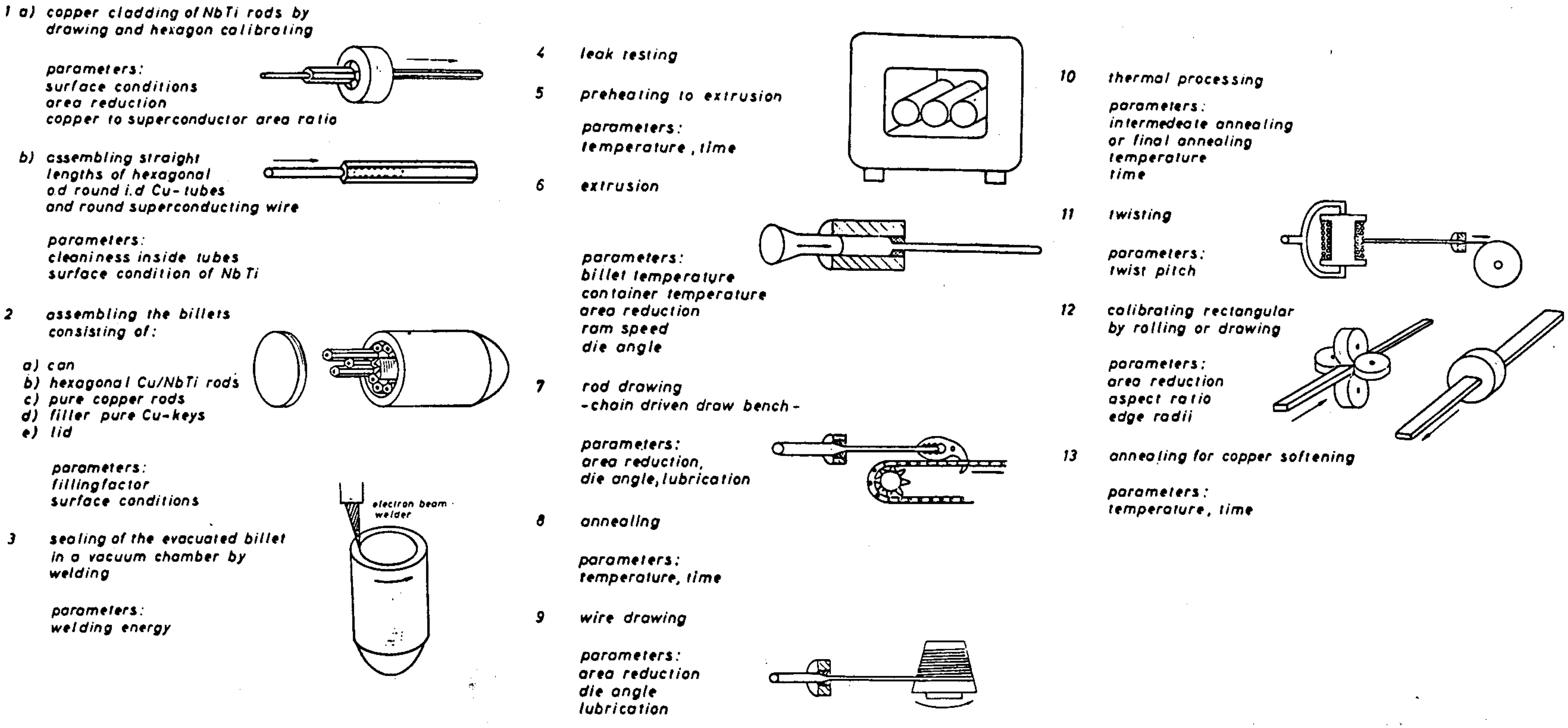
A “strand” is a multifilament composite wire, where the matrix is made of copper and/or copper alloys (for stability and quench protection) and the filaments are made of superconductor, typically NbTi or Nb_3Sn. A strand includes hundreds to thousands filaments. The need for thin filaments is driven by the flux jumps (sudden collapse of field profiles inside the filament).

Multifilamentary strands are manufactured by either single or multiple extrusion of billets and cold drawing with intermediate annealing steps.

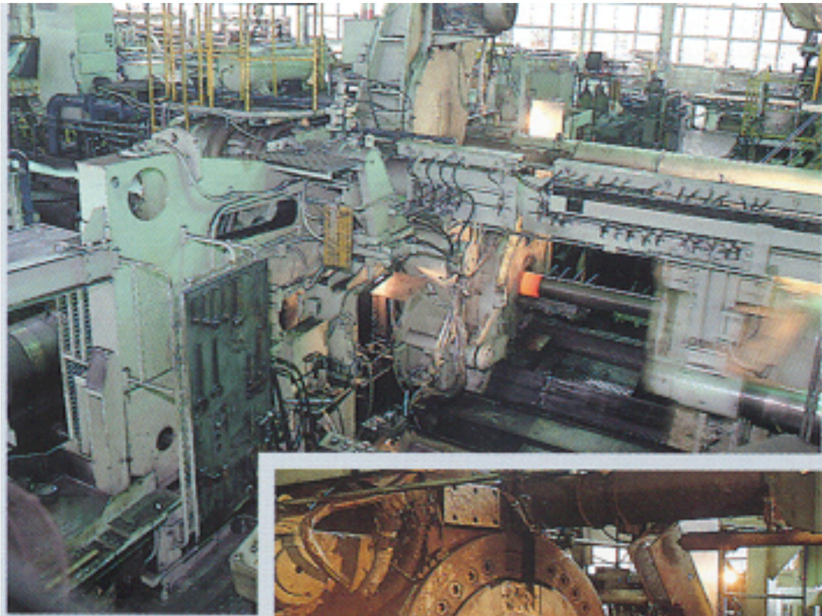
Typical manufacturing batches (billet size) range from 50 kg to 200 kg

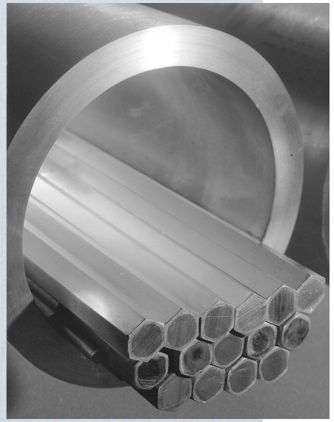
Typical diameter for strands in fusion magnets is 0.5 mm – 1.0 mm

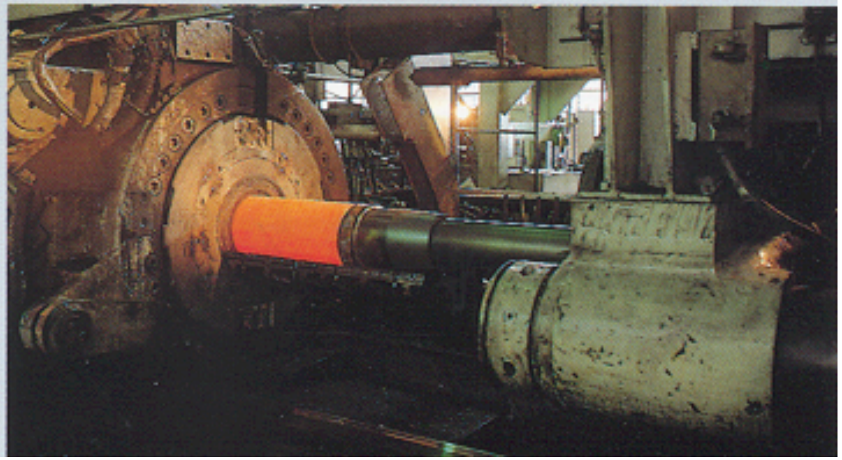
Typical Manufacturing Route for NbTi Strand



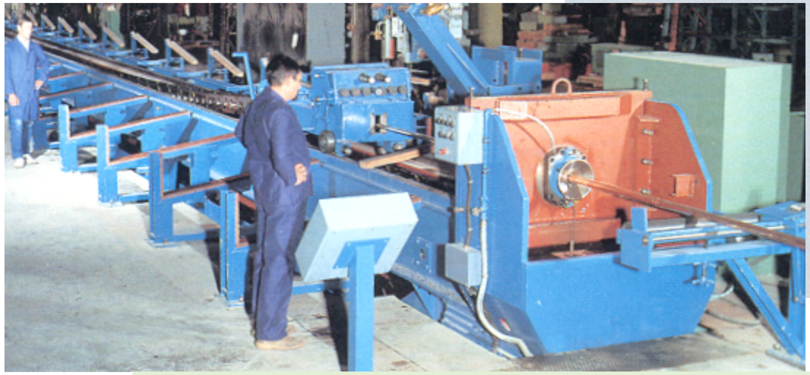
Hot extrusion

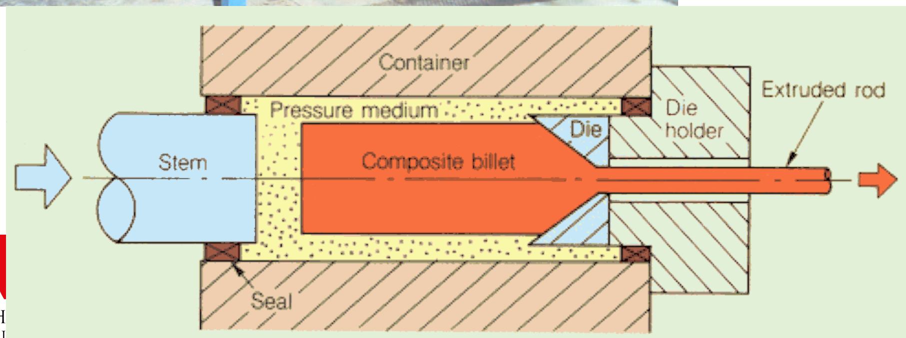






Cold drawing





Hidrostatic extrusion

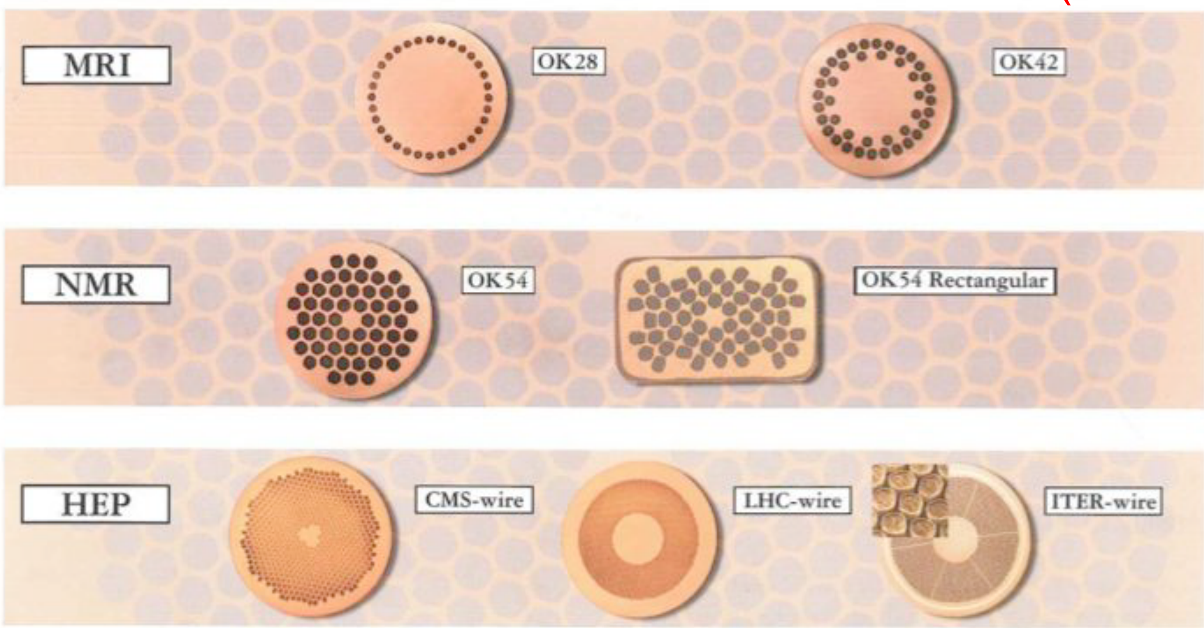
Technical superconductors today - NbTi

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.

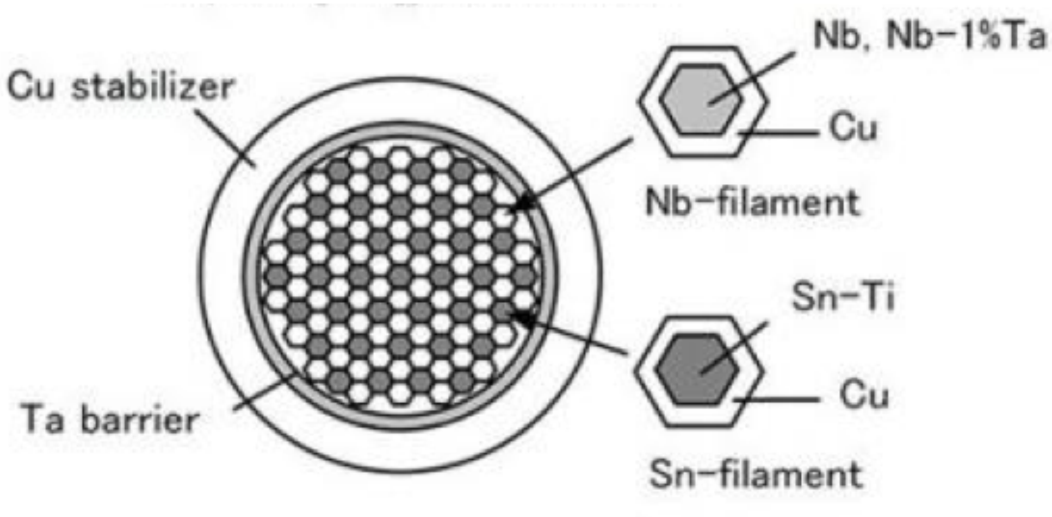
Price ≈ 150 €/kg
(≈30 times bulk copper)



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 half dozen of companies worldwide by either “bronze” route or “internal Sn” method. Best customer today is ITER (500 t)



Price ≈ 650-1000 €/kg
More than bulk Ag

ÉCOLE POLYTEC
FÉDÉRALE DE LA

Conductor-Coil Performance Assessment

Detailed conductor layout

Structural Assessment

In-plane load
Out of plane load
Stress in structural support
Shear stress / tension in insulation
Load on superconductor (Nb_3Sn)

Electrical Assessment

Local Field map
Peak operating conditions (B, T, ε)
Temperature margin (scaling law)
Estimate of ac loss

Thermal-Hydraulic Assessment

Stability (energy margin)
Steady state heat removal
Cool-down analysis
Cryogenic load

Safety Analysis

Quench (V, T, p)
Failure (insulation, q detection)

Assessment results vs. design criteria

Conductor Technology Assessment

When the magnet technology is well established, e.g. similar magnets have been already built, the assessment is done at industrial level, including

- Tolerance (minimum need, cost, impact of non-conformity)
- Tooling and methods (prefer low tech, affordable investment)
- Logistic and Interface (geographic and contractual split, transport)
- Quality control (where must it apply, recovery/repair measures)
- Acceptance and certification (what is the minimum to be covered)
- Warranty (strategy and cost for warranty, effectiveness of penalty)

In some cases, e.g. HTS coils, the technology is **not** well established. Crucial steps of R&D must be identified to bring to maturity the magnet technology before starting an actual project, e.g. “proof-of-principle”, “demonstrators”, “reduced scale models”, etc.

Non-mature technologies may be considered in the *conceptual phase* of a project. In the engineering phase, no doubts should remain about the **readiness** of the technology.

Functional vs. blue-print Specification

In the functional specification, the supplier is thought to know better than the user about design, technology, layout, computations, etc.

-> The supplier guarantees for the performance

Lab Solenoid

Fusion magnet

In the blue print specification, the supplier makes anything the user says with his best manufacturing experience.

-> The supplier guarantees for the methods, the user takes responsibility for the overall performance

Depending on the maturity of the technology, it may be convenient the one or the other way.

Blue print is cheaper for exceptional items and non-existing products, e.g. an ITER TF coil, but can be inconvenient or even more expensive if you want to re-invent products which are already on the market, e.g. a vacuum pump.

Moving from ITER to DEMO and Fusion Power Plants, the design responsibility should drift to the suppliers, i.e. “functional specification”