Joint Universities Accelerator School

JUAS 2025

18. – 24. February 2025

Normal-conducting accelerator magnets
Lecture 4: Magnet construction

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CERN

Magnet construction

Magnetic steel

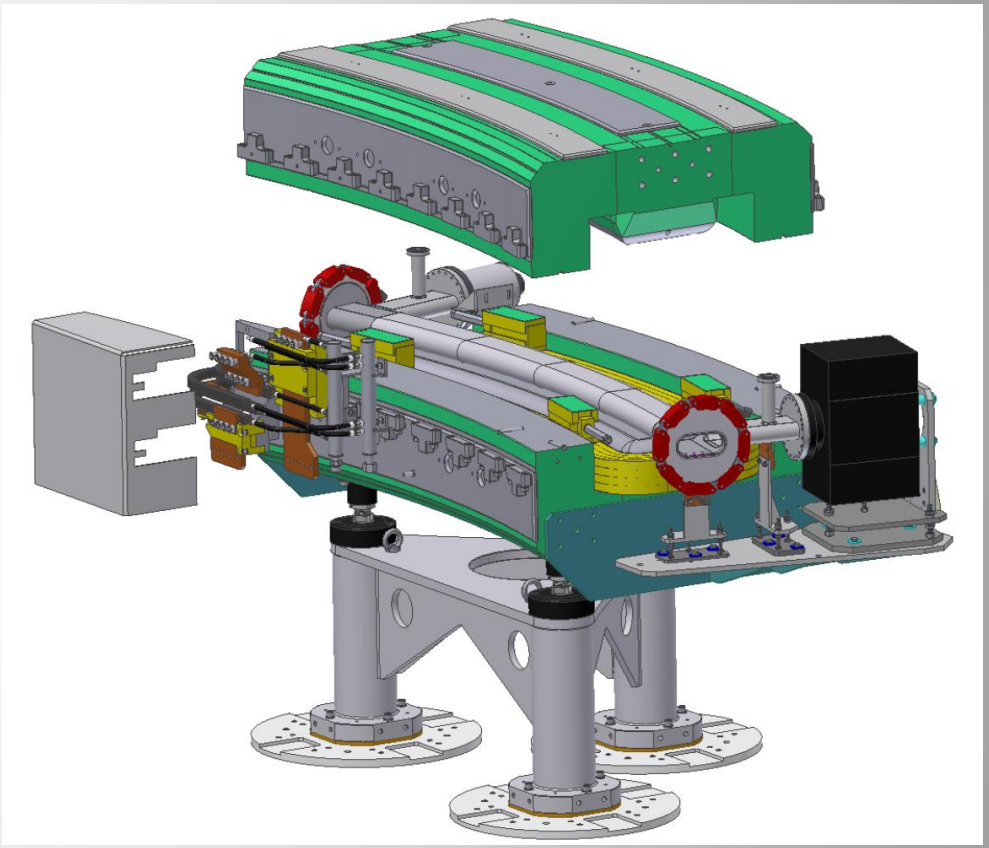
Yoke manufacturing techniques

Conductor materials and insulation

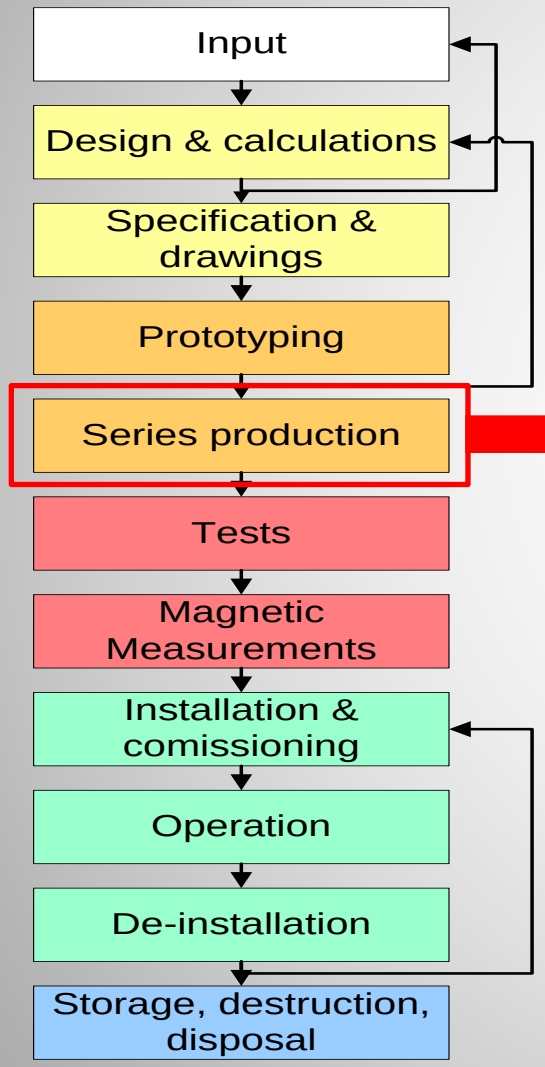
Coil manufacturing techniques

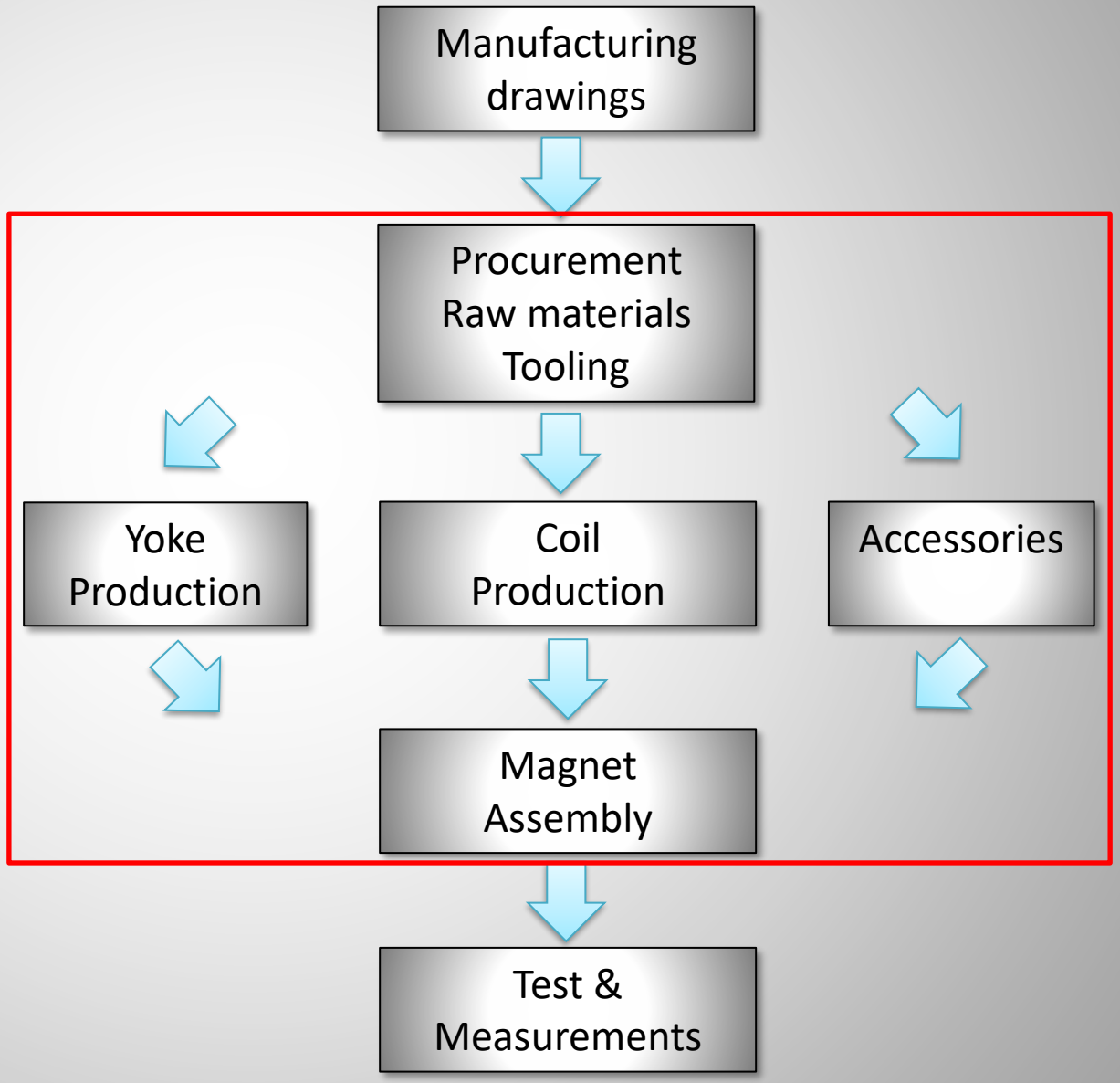
Auxiliary components

QA, tests & measurements



Magnet construction

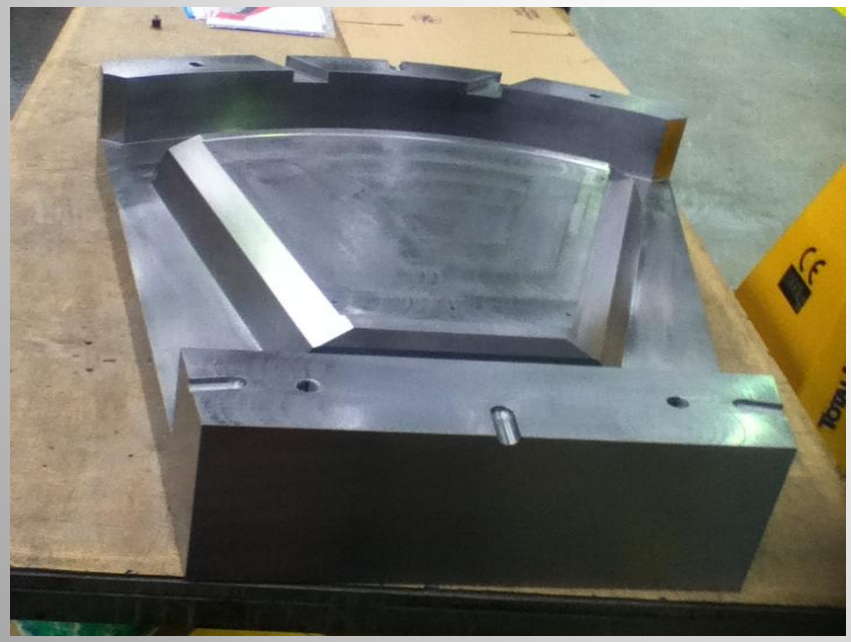




Massive vs. laminated yokes

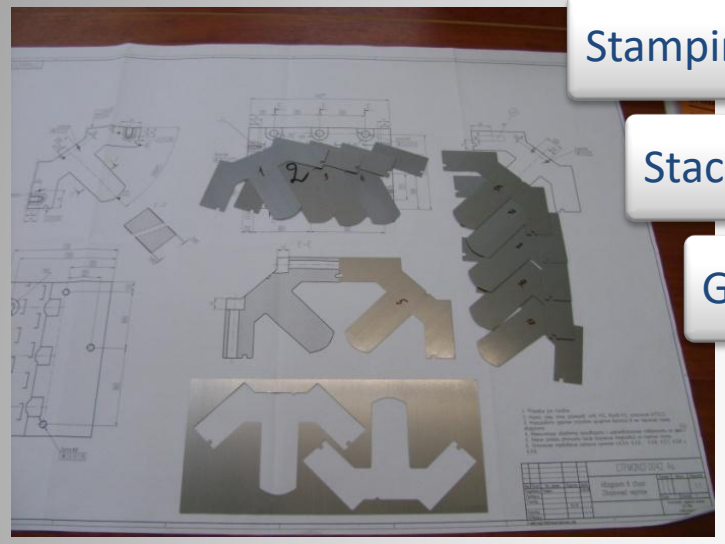
Solid yokes support eddy currents and hence cannot be pulsed or cycled rapidly
To reduce or avoid eddy currents in cycled operation the yoke has to be laminated

- time consuming machining, in particular for complicated pole shapes
- difficult to reach similar magnetic performance between magnets
+ less tooling
+ less expensive for prototypes and small series

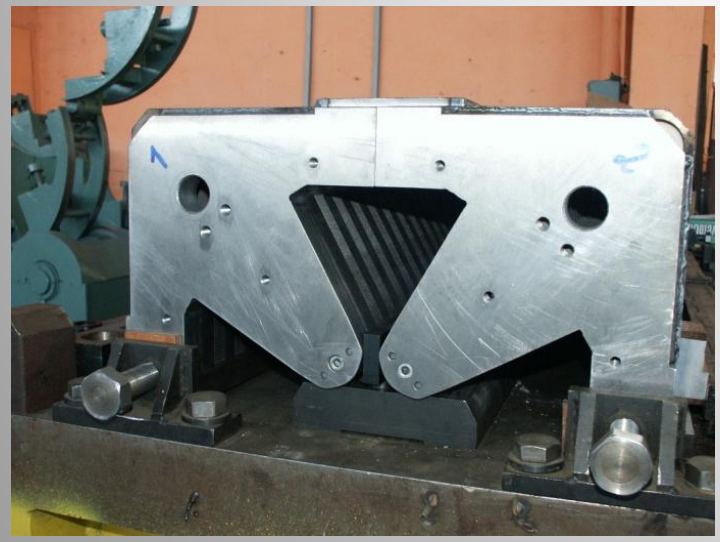


+ steel sheets less expensive than massive blocks
+ steel properties can be easily tailored
+ uniform magnetic properties over large series
- expensive tooling
+ less expensive for larger series

Yoke manufacturing



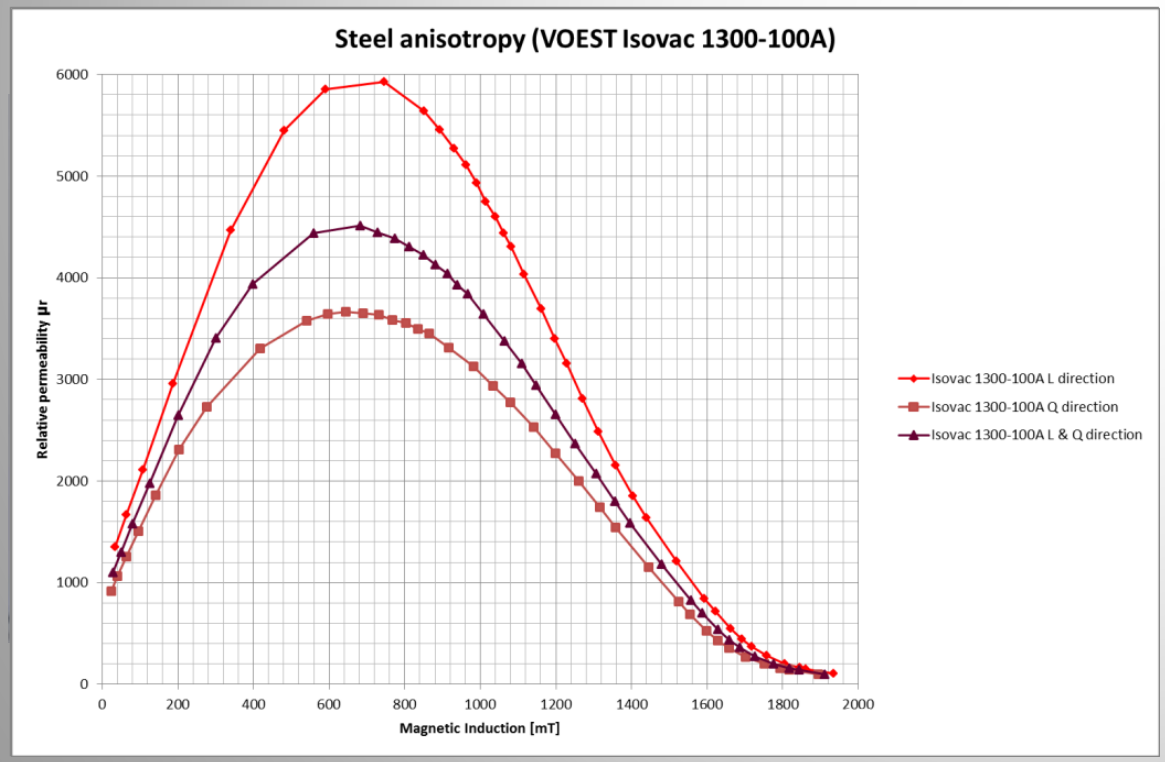
- Stamping laminations
- Stacking laminations into yokes
- Gluing and/or welding
- Machining
- Assembly (preliminary)



Magnetic steel

Today's standard: cold rolled, non-grain-oriented (NGO) electro-steel sheets (EN 10106)

- Magnetic and mechanical properties can be adjusted and controlled by final annealing
- Reproducible steel quality even over large productions
- Magnetic properties (permeability, coercivity) within small tolerances
- Material is usually cheaper, but laminated yokes are labour intensive and require more expensive tooling for stamping and stacking



Sheet thickness: $0.3 \leq t \leq 1.5$ mm

Specific weight: $7.60 \leq \delta \leq 7.85$ g/cm^3

Electrical resistivity @20°C:

0.16 (low Si) $\leq \rho \leq$ 0.61 μΩm (high Si)

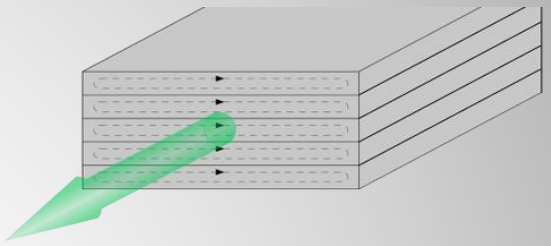
ISOVAC 1300-100A: H_c = 65 A/m

Take the anisotropy into account !

Sheet insulation

Surface coating:

- electrical insulation of several µm thickness
- one or both sides
- oxid layer, phosphate layer, organic or inorganic coating

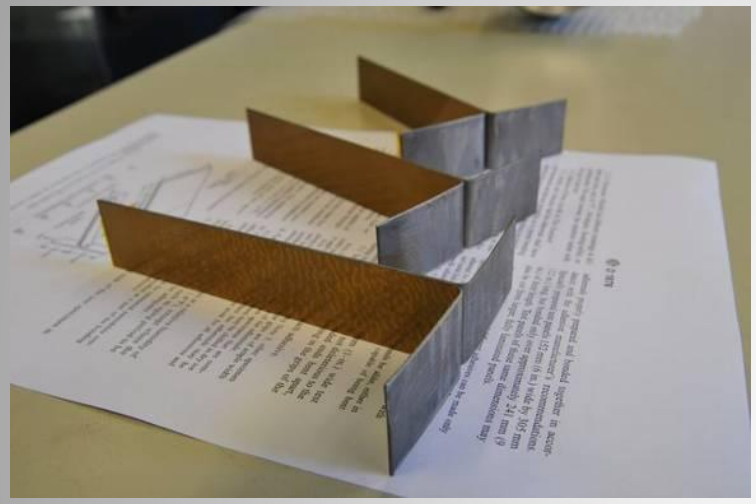


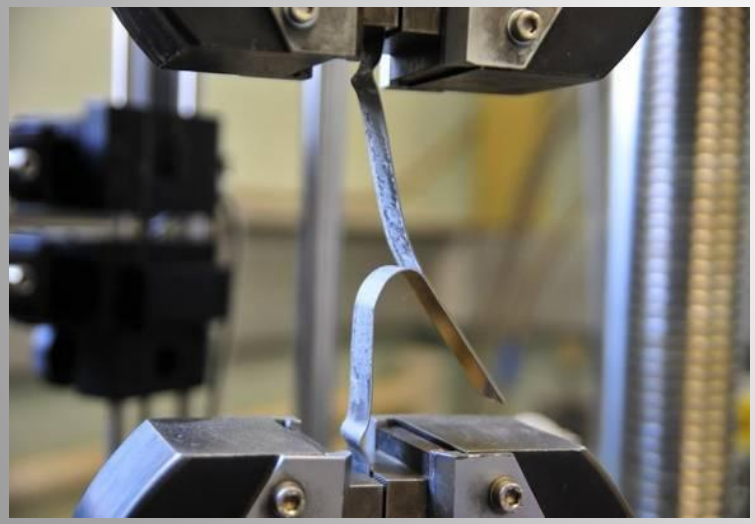
Insulation designation IEC 60404-1-1	**Insulation type**	**Color**[1)]	**Coating**	**Coating thickness each side** in µm	**Insulation resistance at room temperature** to ASTM A717/A717M-95 Ωm²/Lamelle
STABOLIT 10 EC-3 by prior arrangement only	organic	yellow-green	both sides	max. 1.5	> 15
STABOLIT 20 EC-5-P	inorganic with organic components	grey-green	both sides	0.5 – 1.5	> 5
STABOLIT 30 EC-5-P	inorganic with organic components	light grey	both sides	0.5 - 1.5	> 5
STABOLIT 40 EC-6	organic pigmented	grey	one or both sides	3.0 - 5.0 4.0 - 7.0 6.0 - 9.0	> 90
STABOLIT 60 EC-5	inorganic with organic components pigmented	grey	both sides	0.3 - 1.0 1.0 - 2.0 2.0 - 3.5	> 5 > 15 > 50
STABOLIT 70	organic bonding lacquer (active)	colorless	one or both sides	5.0 - 8.0	-
Combined insulation	organic bonding lacquer with one side heat treatment (passive)	colorless	both sides	active 5.0 - 8.0 passive max. 1.5	-

Source: ThyssenKrupp

Sample testing

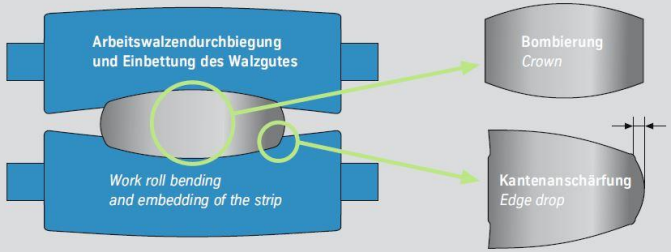
Bond strength tests

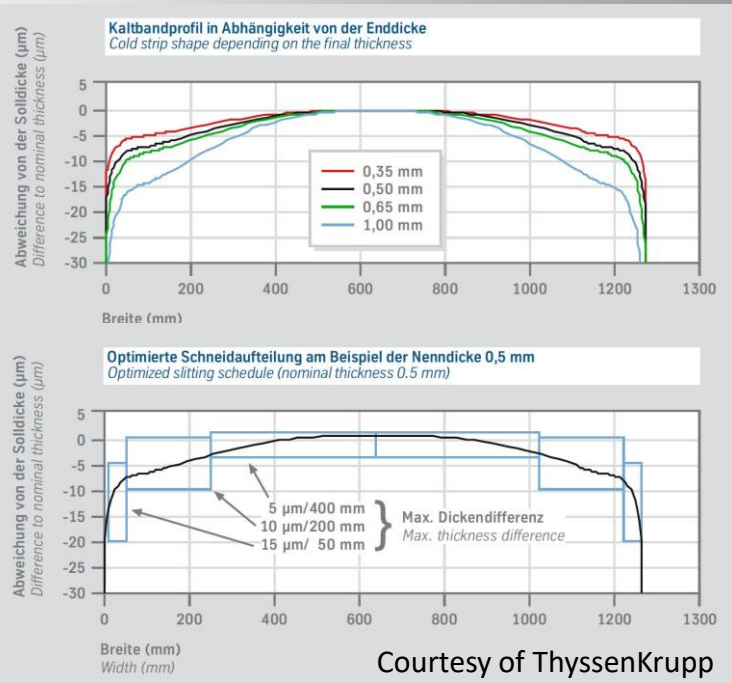




Verifying the magnetic properties

Sheet thickness control



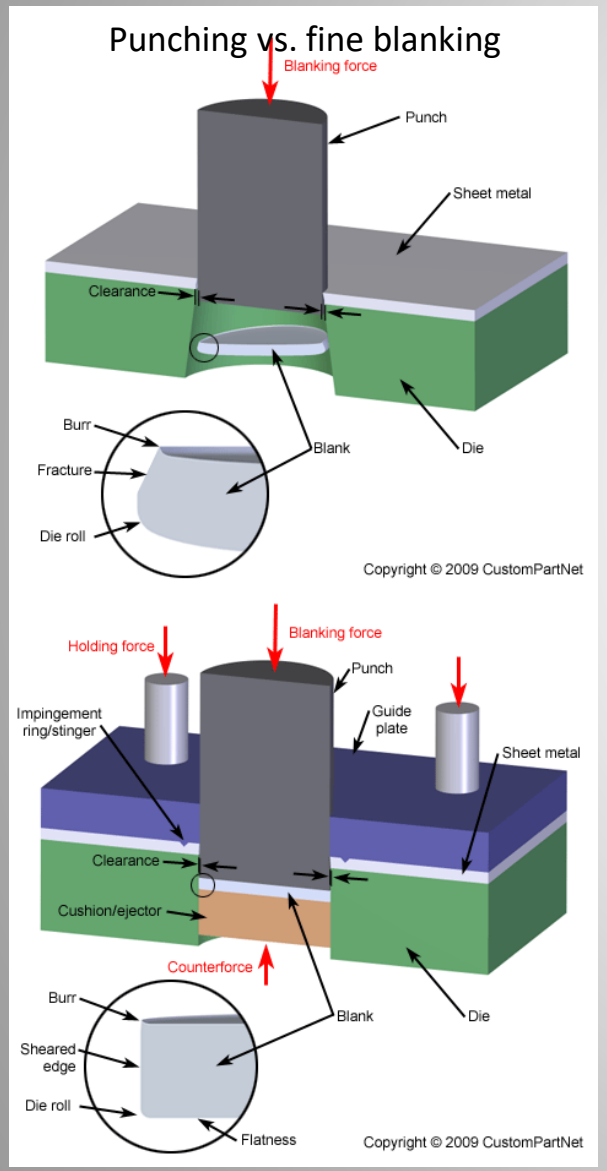


Courtesy of ThyssenKrupp

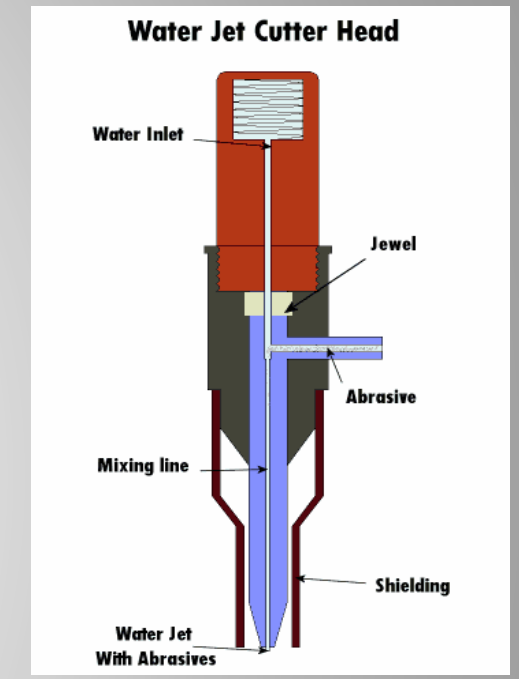
Other tests: chemical analysis, mechanical properties, electrical characteristics…

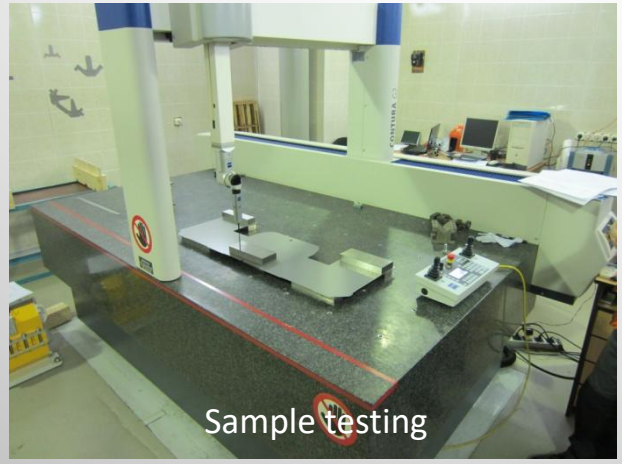
Lamination production

Punching vs. fine blanking

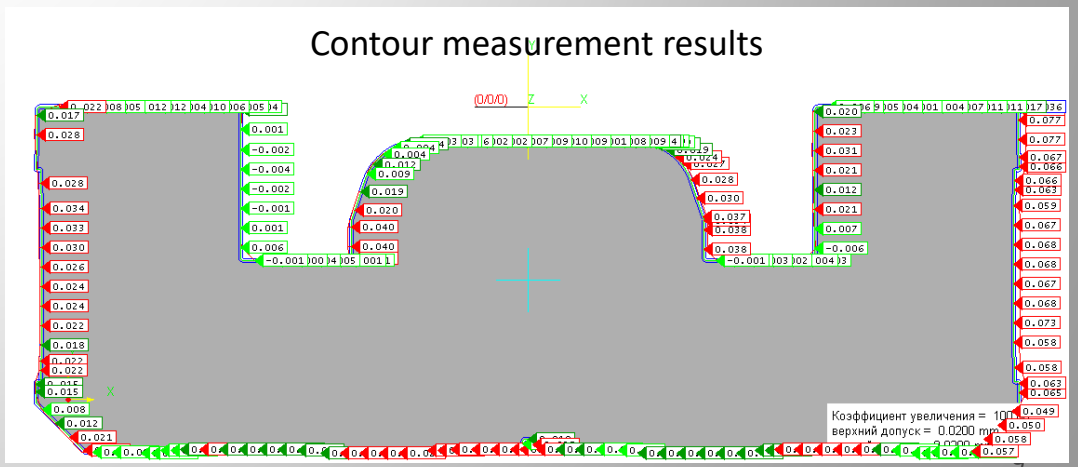


Technique	Accuracy [mm]	Repeatability [mm]	Drawbacks
Fine blanking	> 0.008	> 0.005	expensive tooling, only for large series
Water jet cutting	> 0.13	> 0.025	rough cutting edge, relatively slow
Laser cutting	> 0.01	> 0.005	cutting edge ‚burnt', relatively slow
CNC machining	0.01-0.001	0.01-0.001	for stacks only
Wire-cut EDM	> 0.002	> 0.001	very slow, limited size



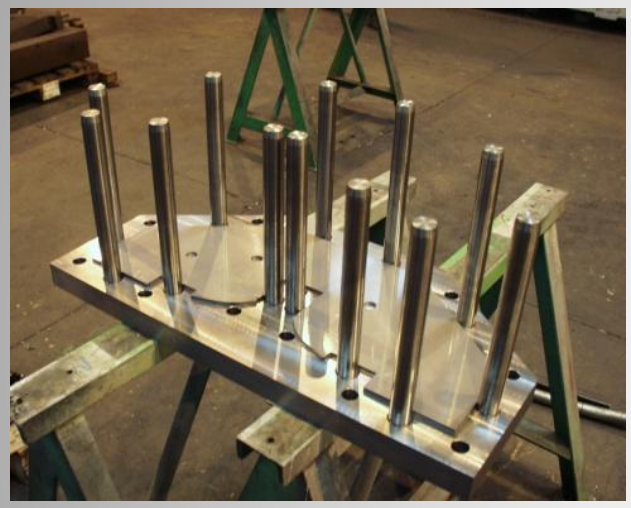


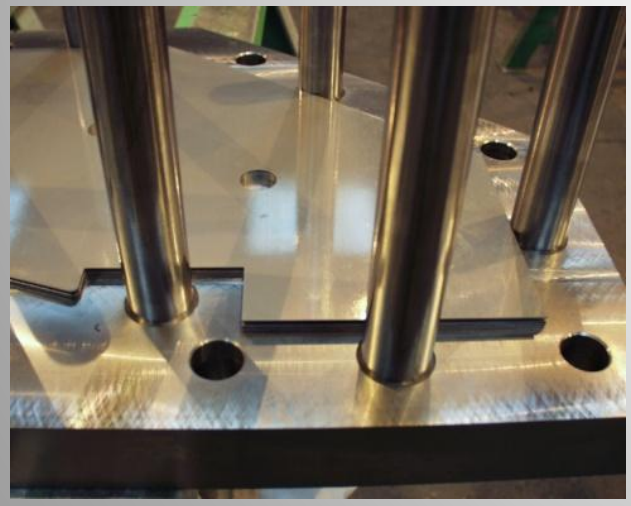
Contour measurement results



Yoke stacking

Rigid fixtures are needed for stacking laminations into yokes and subsequent baking/welding



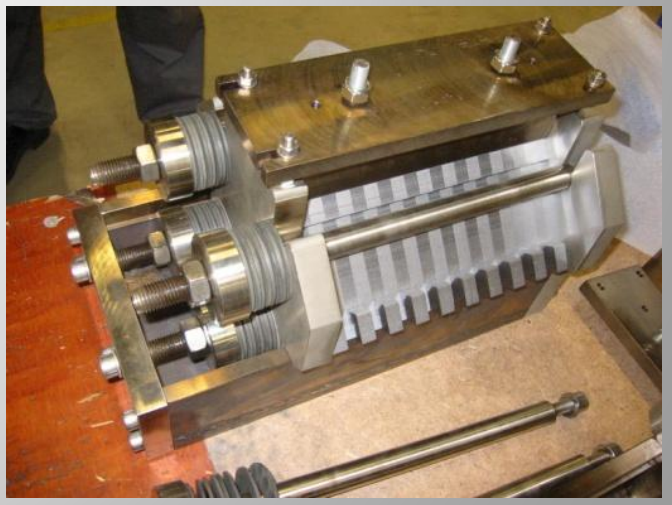


Precisely machined alignment rods are in contact with the pole and the mating surfaces assuring the correct position of the laminations in the stack

The lamination stack has to be compressed in regular intervals to achieve a good filling factor

To compensate for thermal expansion during baking spring washers apply the necessary pressure

Experienced manufacturers can obtain tolerances (planarity, straightness) on the pole contour of a few ten micro-meter (0.01 mm)



Gluing vs. Welding

Gluing

+ no stress, no distortions
+ no tension straps, no end plates (no eddy currents)
- glue sensitive to radiation and aging
- requires clean laminations free of lubricants
- requires baking oven

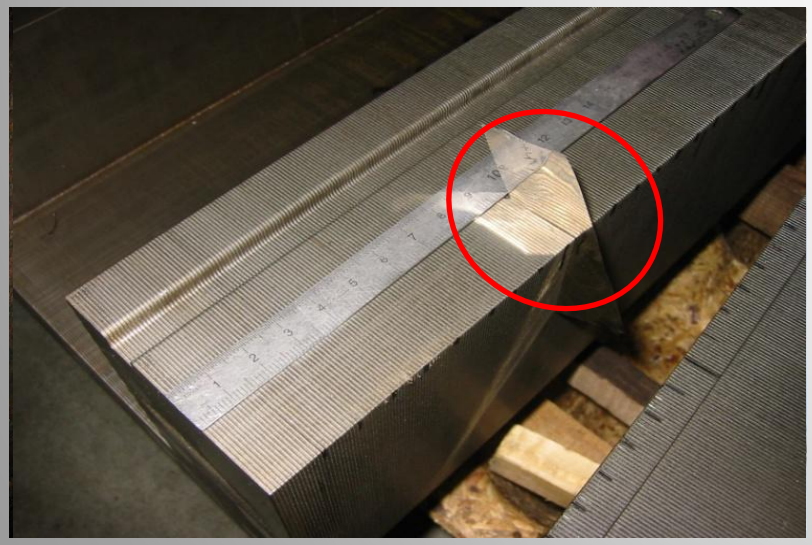
/ requires stacking fixture

Welding

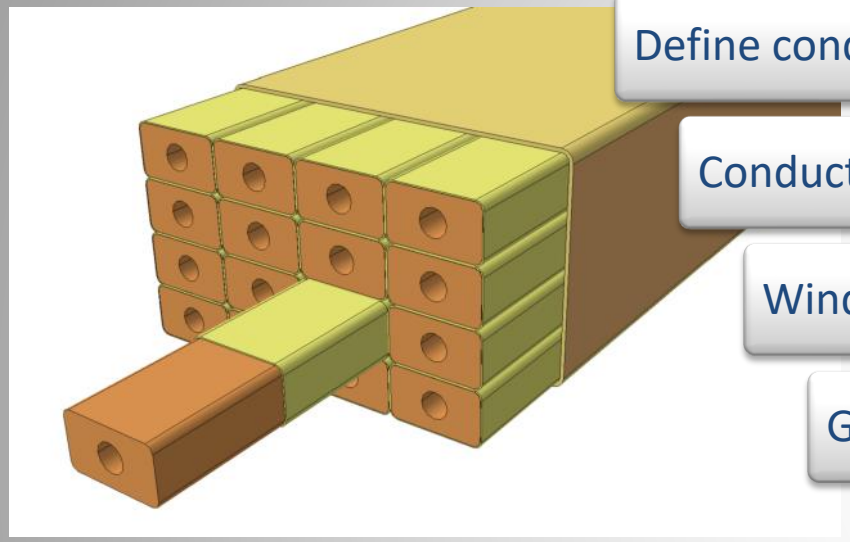
+ mechanically more ridgig
+ no aging
- massive end plates/tension straps needed
- continous welding introduces stress and deformation
- sophisticated welding procedure

/ requires stacking fixture

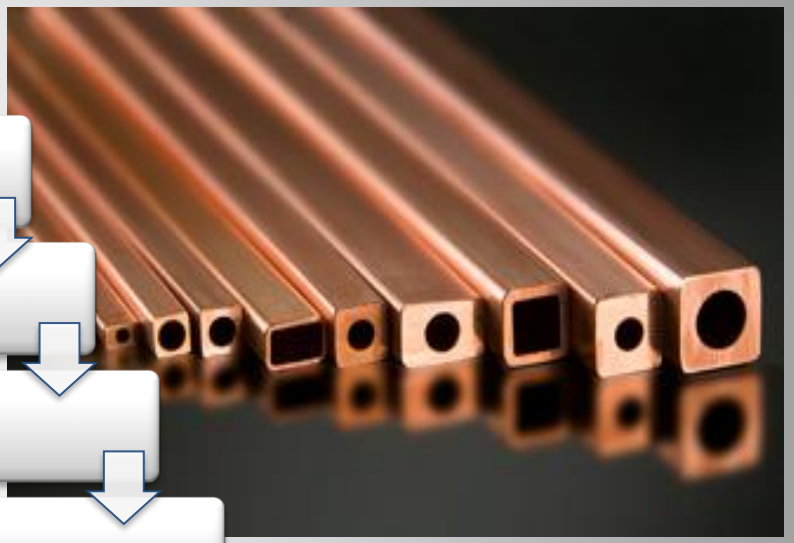
Recommendation: Combine gluing, welding & bolting

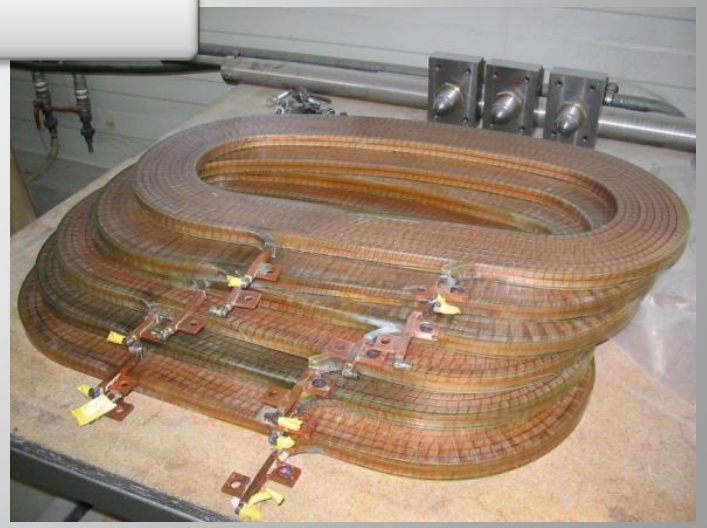


Coil manufacturing



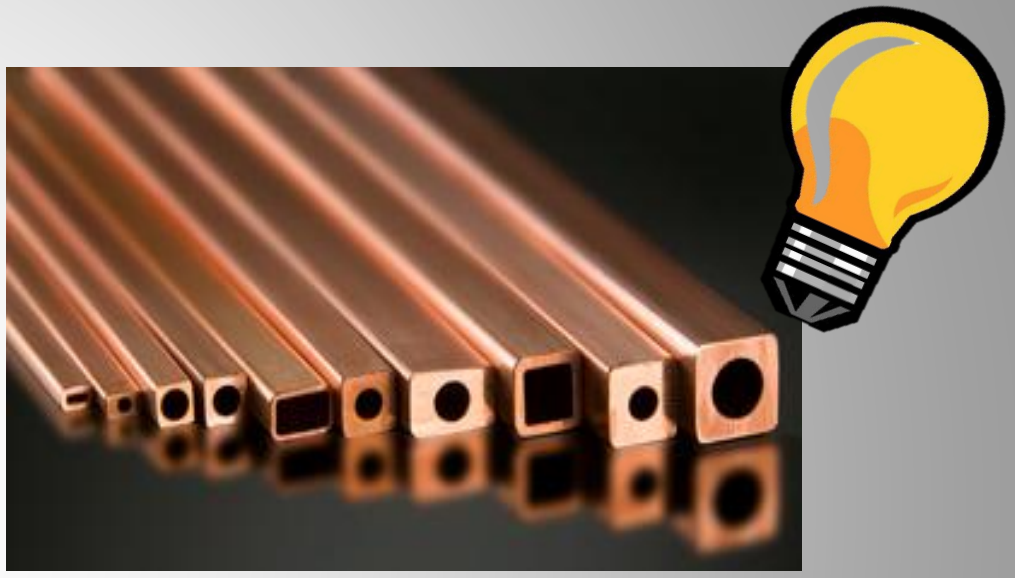
- Define conductor type and material
- Conductor insulation
- Winding
- Ground insulation
- Epoxy impregnation



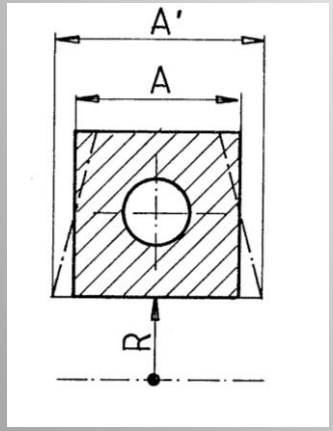


Conductor materials

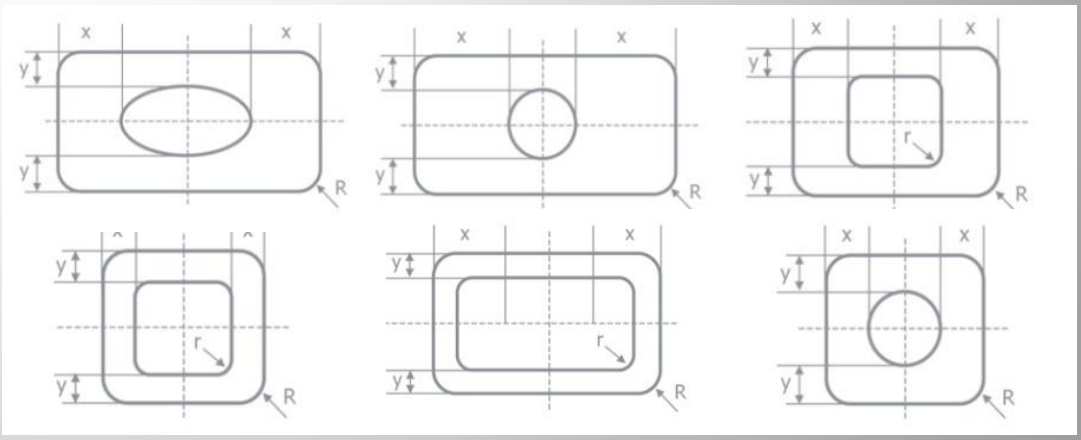
	Al	Cu (OF)
Purity	99.7 %	99.95 %
Resistivity @ 20°C	2.83 µΩ cm	1.72 µΩ cm
Thermal resistivity coeff.	0.004 K^{-1}	0.004 K^{-1}
Specific weight	2.70 g/cm^3	8.94 g/cm^3
Thermal conductivity	2.37 W/cm K	3.91 W/cm K



Key-stoning: risk of insulation damage & decrease of cooling duct cross-section

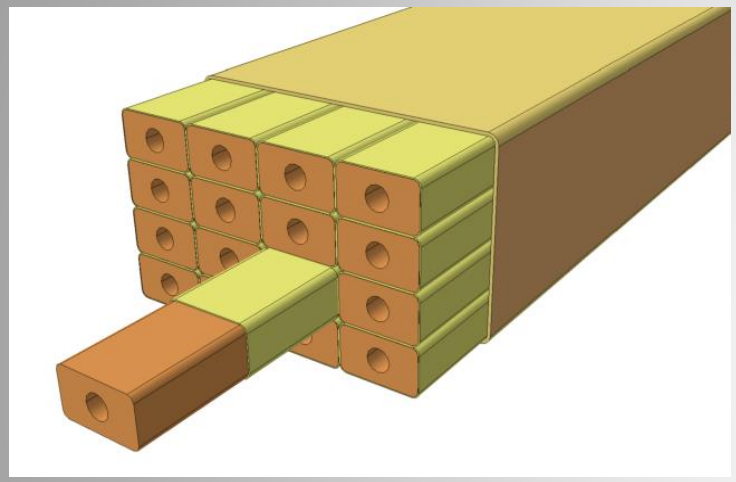


$$R = 3 \cdot A \Rightarrow \frac{\Delta A}{A} = 3.6\%$$



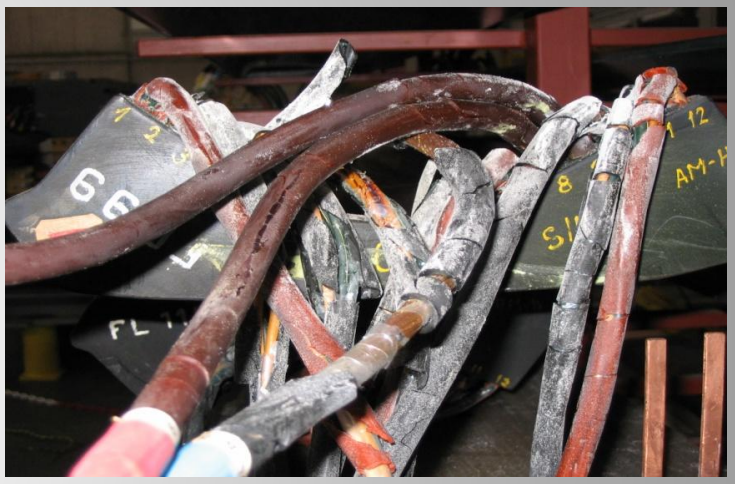
Coil insulation

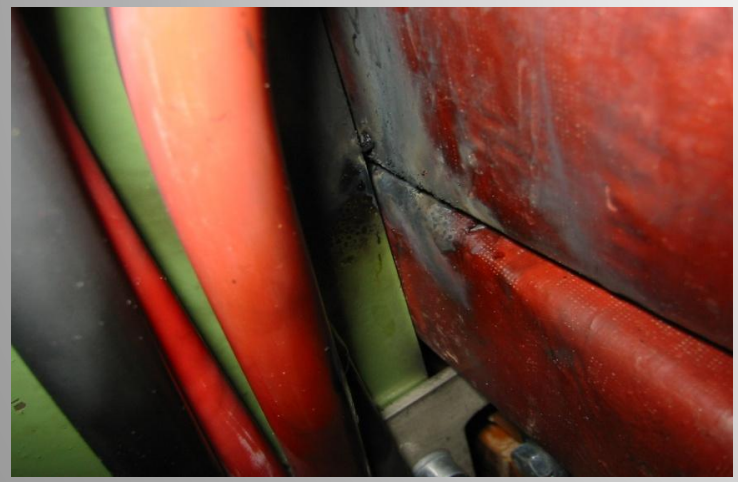
In a magnet coil, the electrical insulation ensures that current flows only along the conductors and not between individual conductors or between the conductors and other parts of the magnet



A weak electrical insulation may produce:

- current leaks with local heating
  → melting or fire
- progressive damage of the leakage
  → complete short circuit
- unbalanced circulating currents
  → magnetic field distortion





Montsinger's rule / Arrhenius equation:

$$L(T+10\,K) \approx 0.5\; t(T)$$

A temperature rise of 10 K halves the expected live time of an insulation system

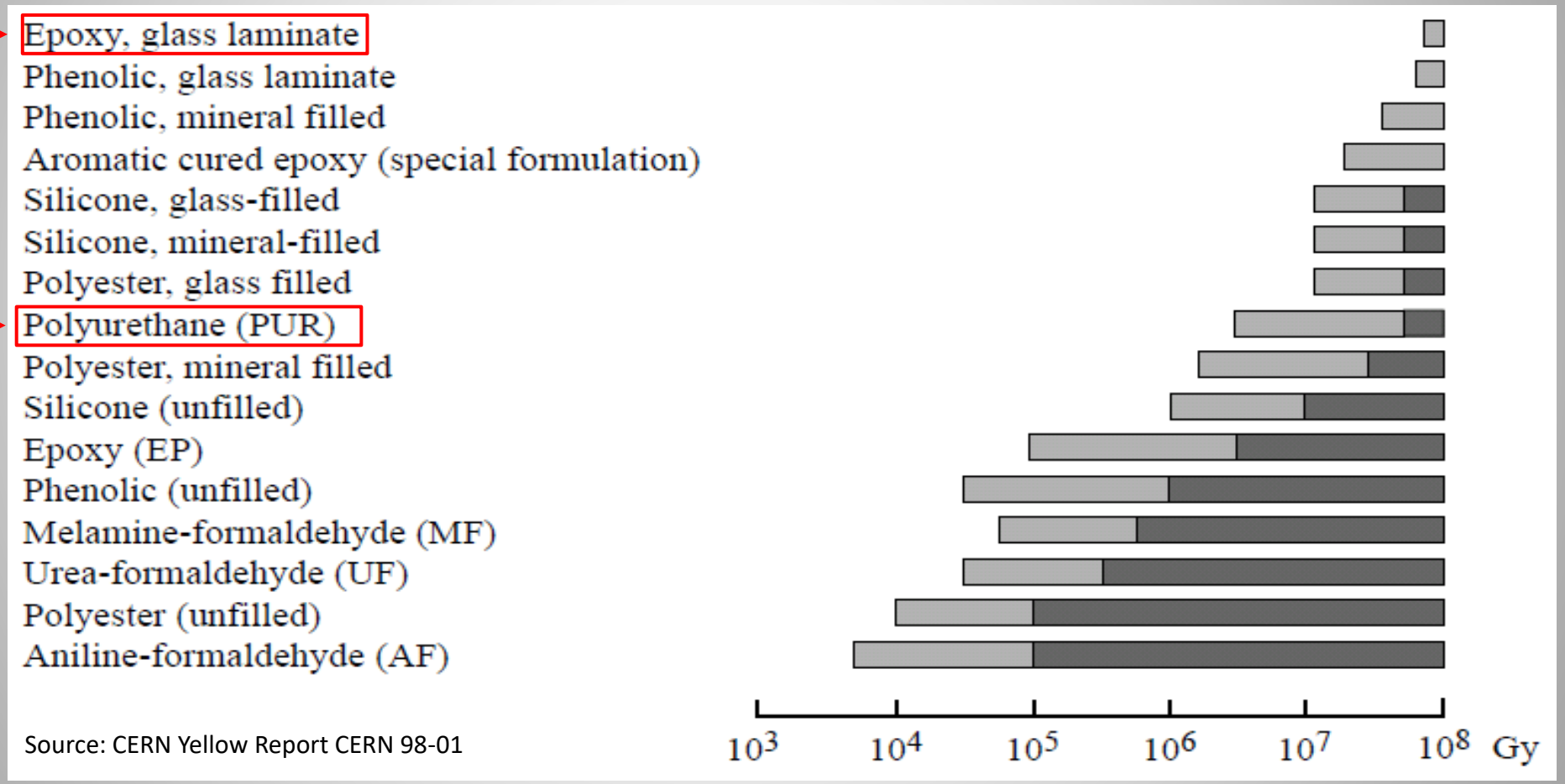
Reference: D. Tommasini: Dielectric insulation and high-voltage issues, CAS 2009, Brugges

Radiation hardness

Radiation hardness is an important criterion for insulation materials used for accelerator applications

Coil insulation →

(Flexible) cable insulation →



Source: CERN Yellow Report CERN 98-01

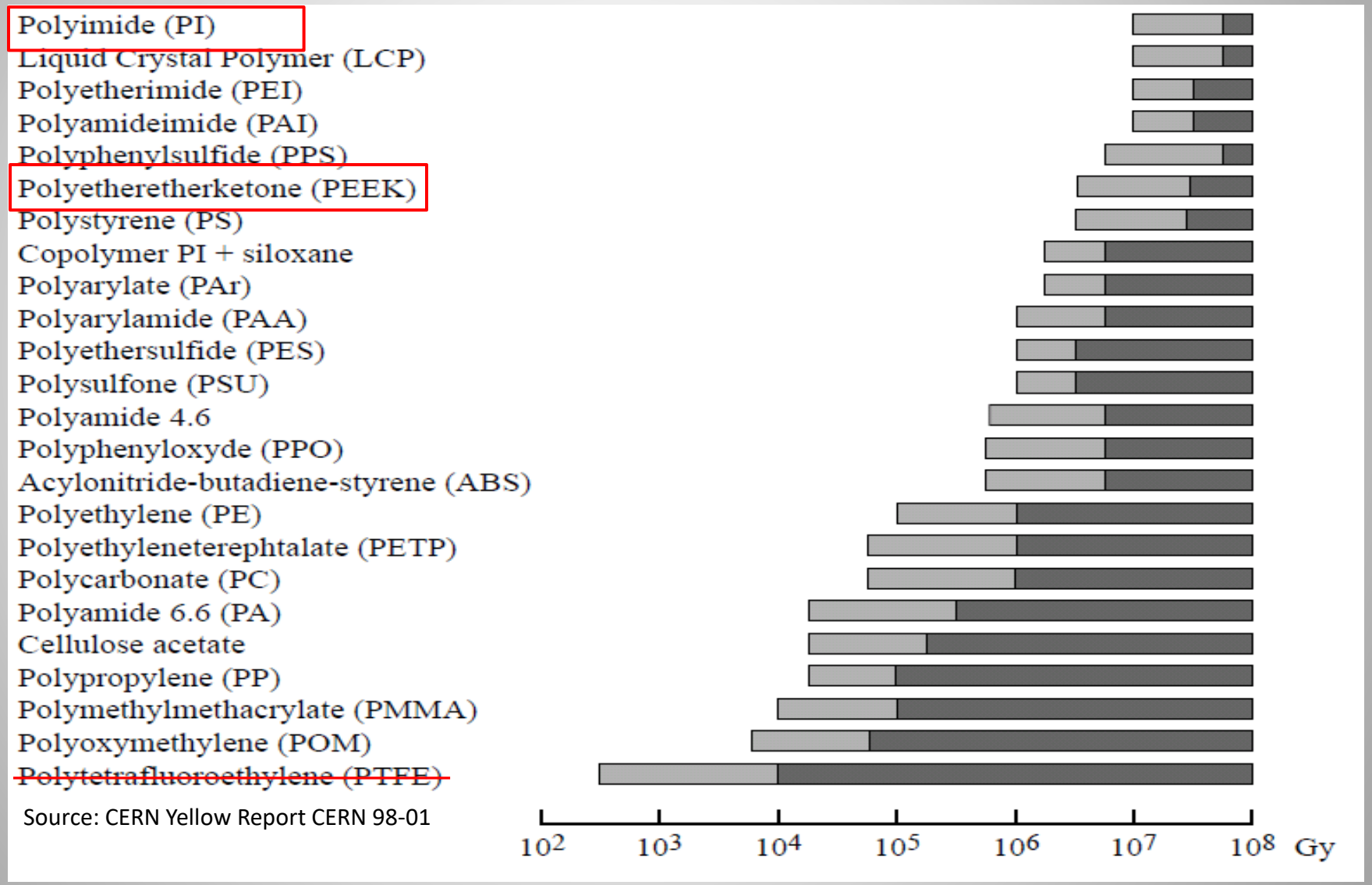
Above 10^8 Gy special insulation techniques are required!

Radiation hardness

Kapton ® →

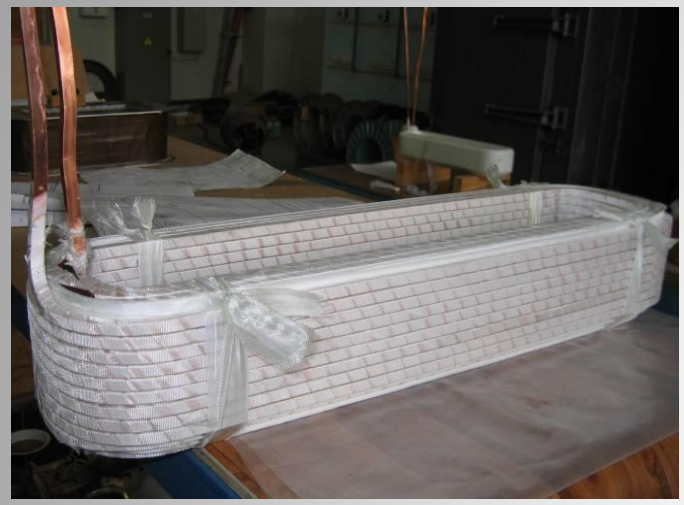
For isolating mechanical parts →

Never use in accelerator magnets →



Source: CERN Yellow Report CERN 98-01

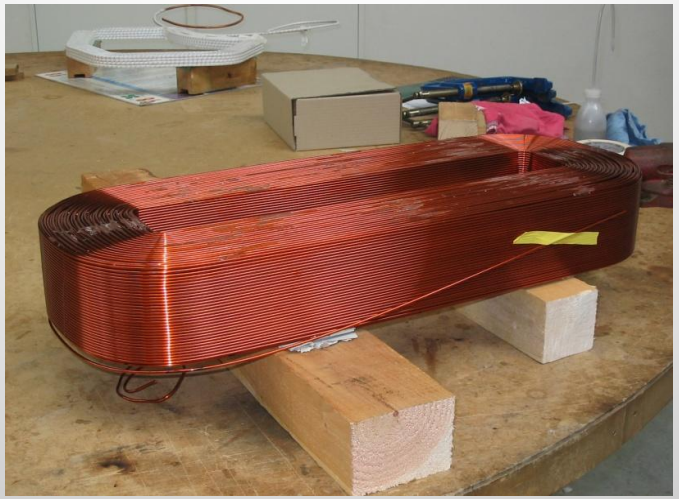
Coil insulation



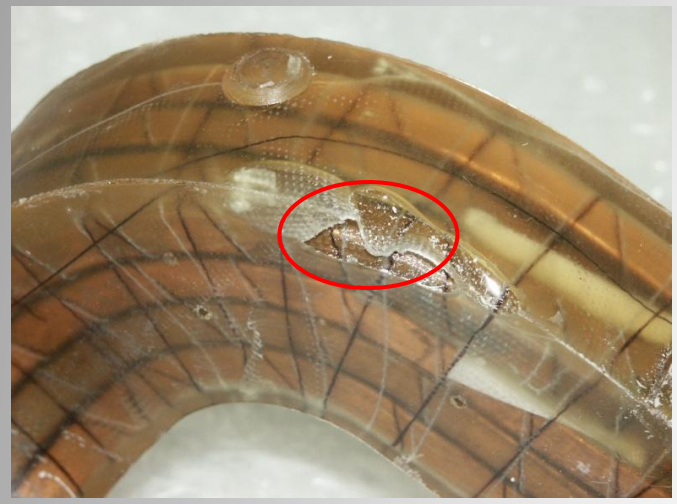
Interturn and mass insulation by several layers of glass-fibre tape

Alternative: Pre-impregnated conductor (Kapton® tape or varnish)

Vacuum impregnation with epoxy resin in auto-clave or vacuum mold



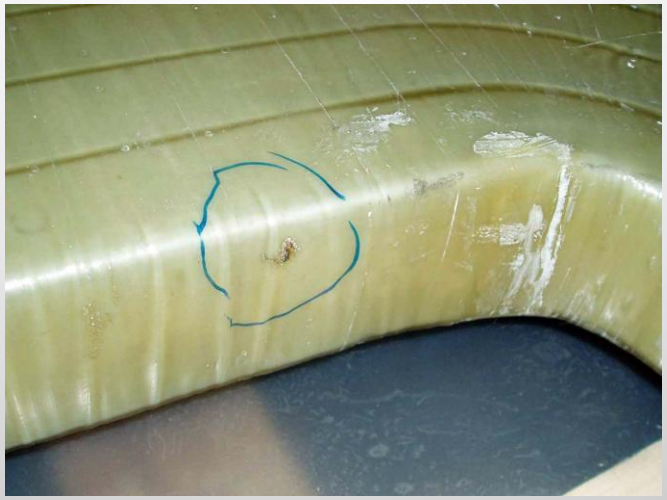
Recurrent quality issues

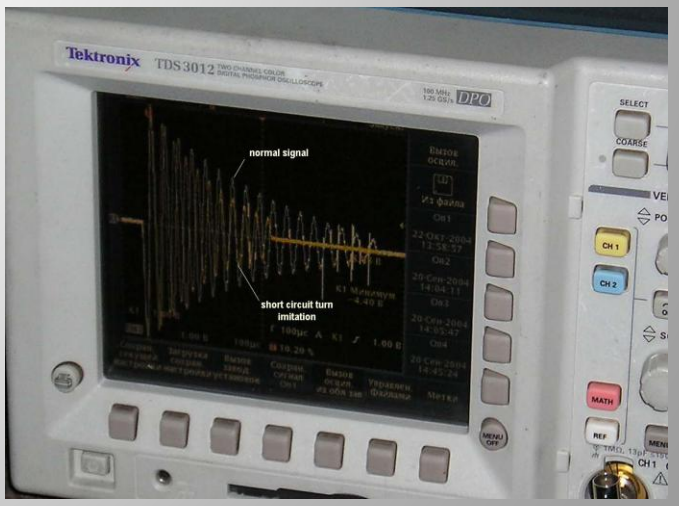


Obvious defects, like lack of resin bubbles, voids, fissures, cracks

Poor penetration or wetting can lead to defects during operation

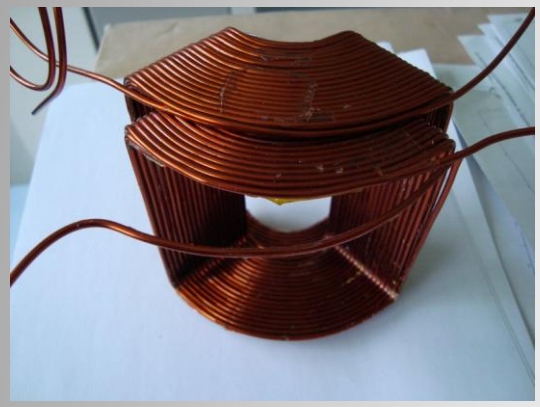
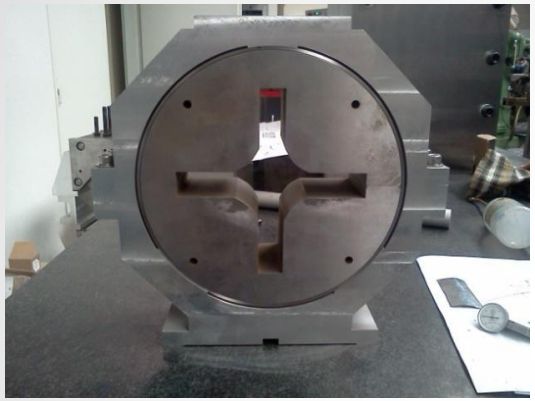
Electrical HV insulation test shall reveal ‘hidden’ defects





Magnet assembly

By hand....

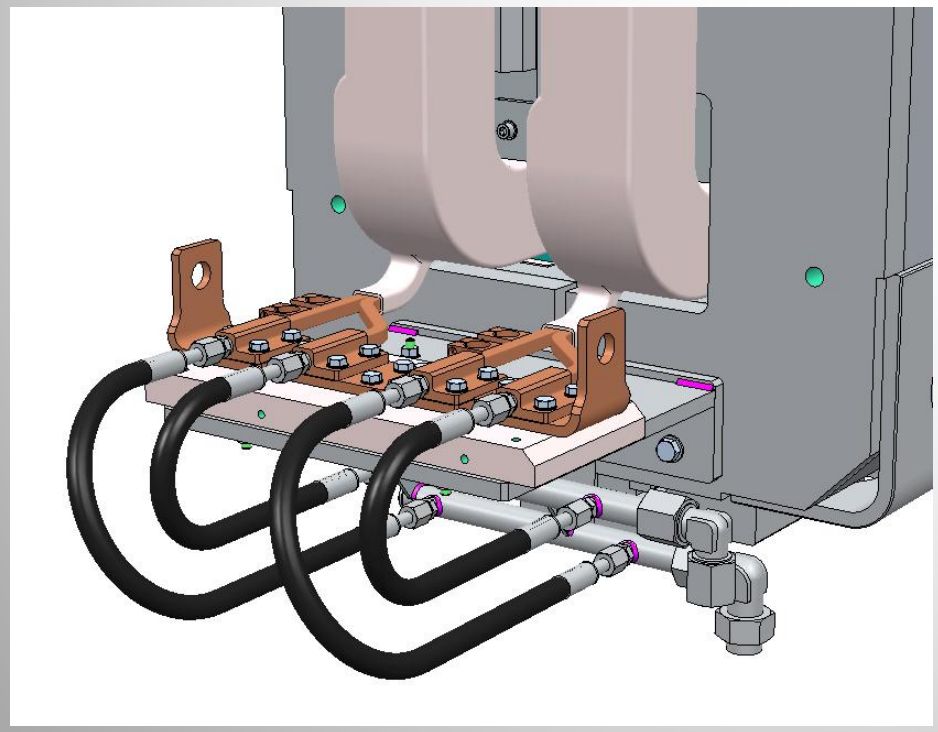



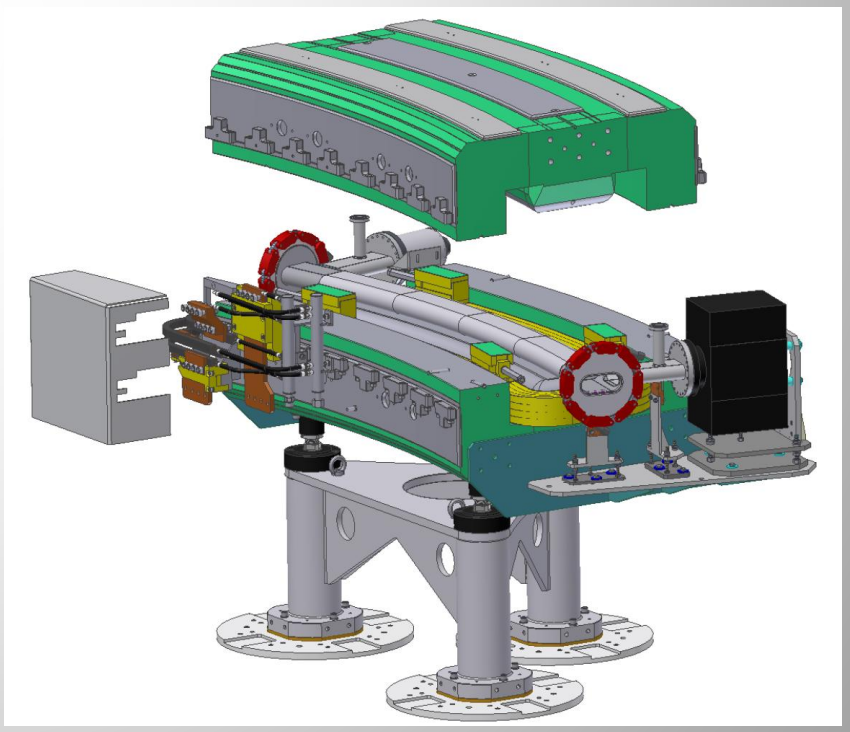
... or with the help of tooling




Auxiliary components

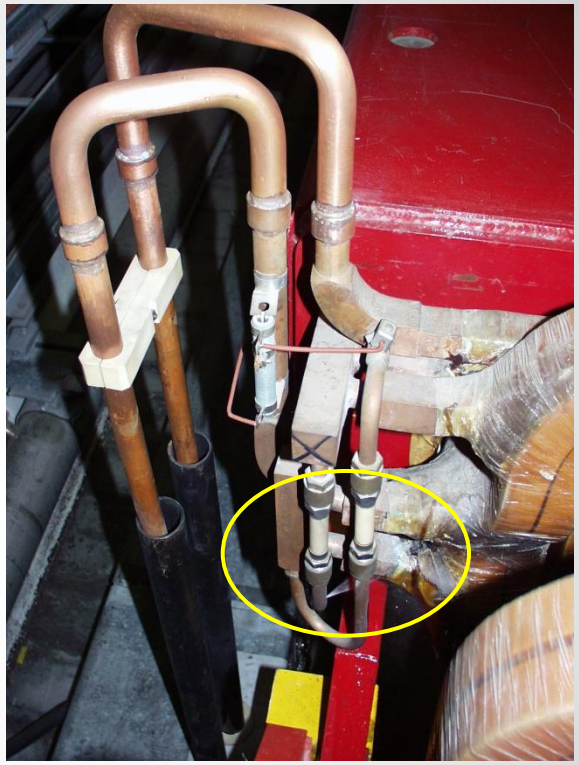
- Electrical connections
- Hydraulic connections
- Interlock system = magnet protection devices (temperature, pressure, water flow)
- Alignment targets, adjustment tables and support jacks
- Field measurement devices (pick-up coils, hall probes)

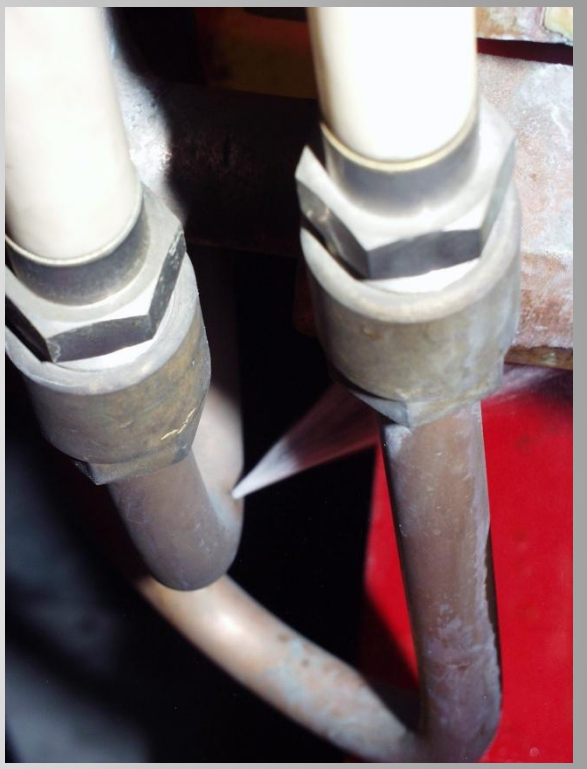




Hydraulic circuits

- Water circuits are most critical items
- 95% of all magnet failures are due to water leaks stemming from:
  - Corrosion/erosion
  - Poor brazing/welding quality
  - Failure or aging of joints
  - Inadequate materials
  - Incorrect assembly
  - Radiation damage
  - Inadequate design



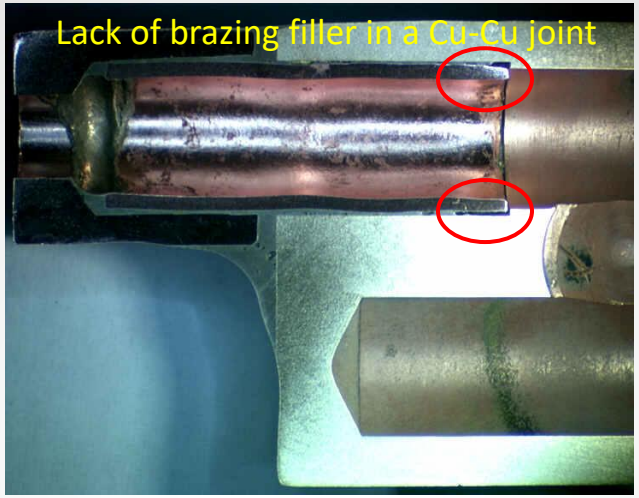


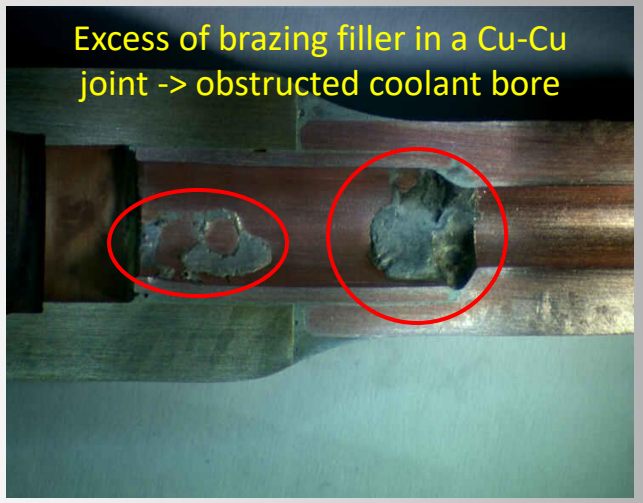
- Leaks can be detected and repaired during magnet acceptance tests or commissioning...
- ... but, many leaks occur only after years in operation
- Often not monitored → magnet damage (short circuits, corrosion of iron yoke) and collateral damages on other equipment

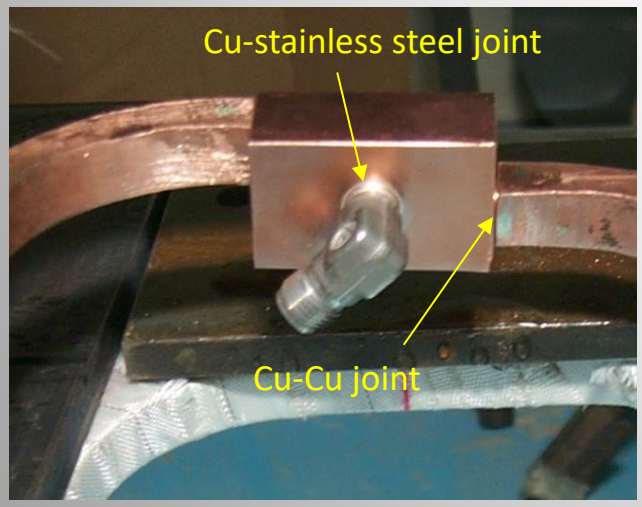
Recurrent quality issues

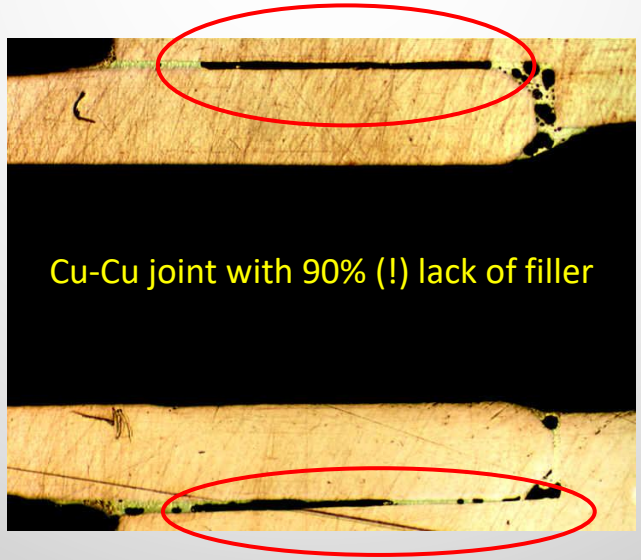
Cooling circuits have brazed or welded joints as transition from one part to the other (change of cross-section or different material)

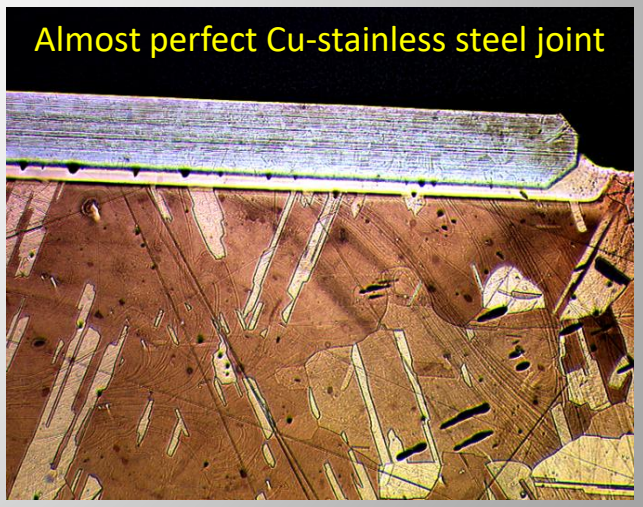
These joints are often vulnerable to water leaks if not carried out professionally with great care





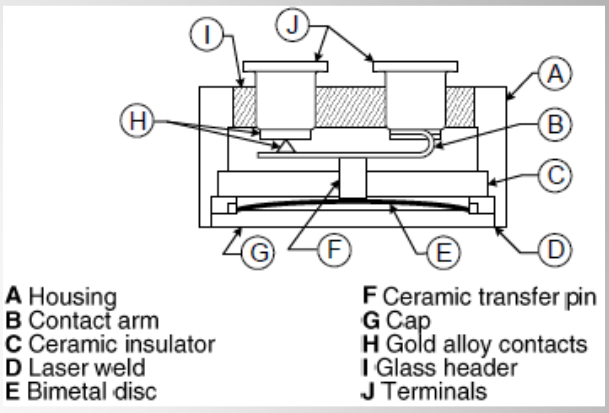




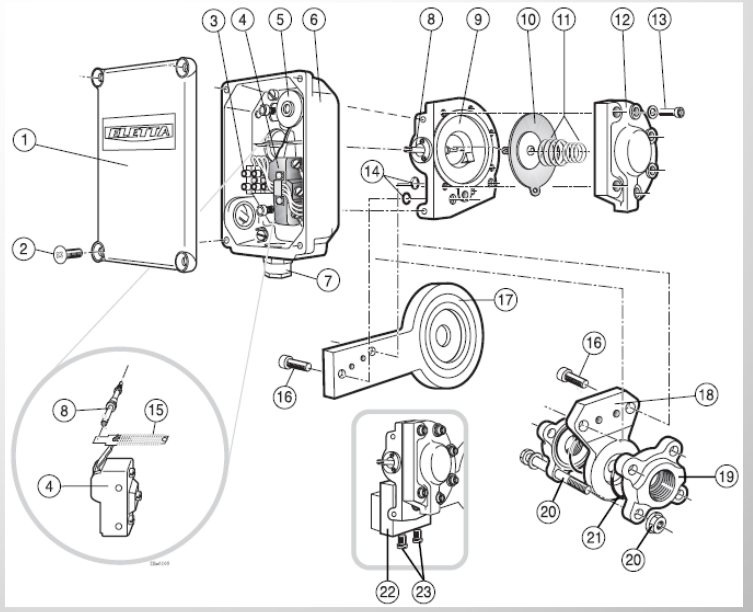


Magnet protection devices

Thermo-switch:



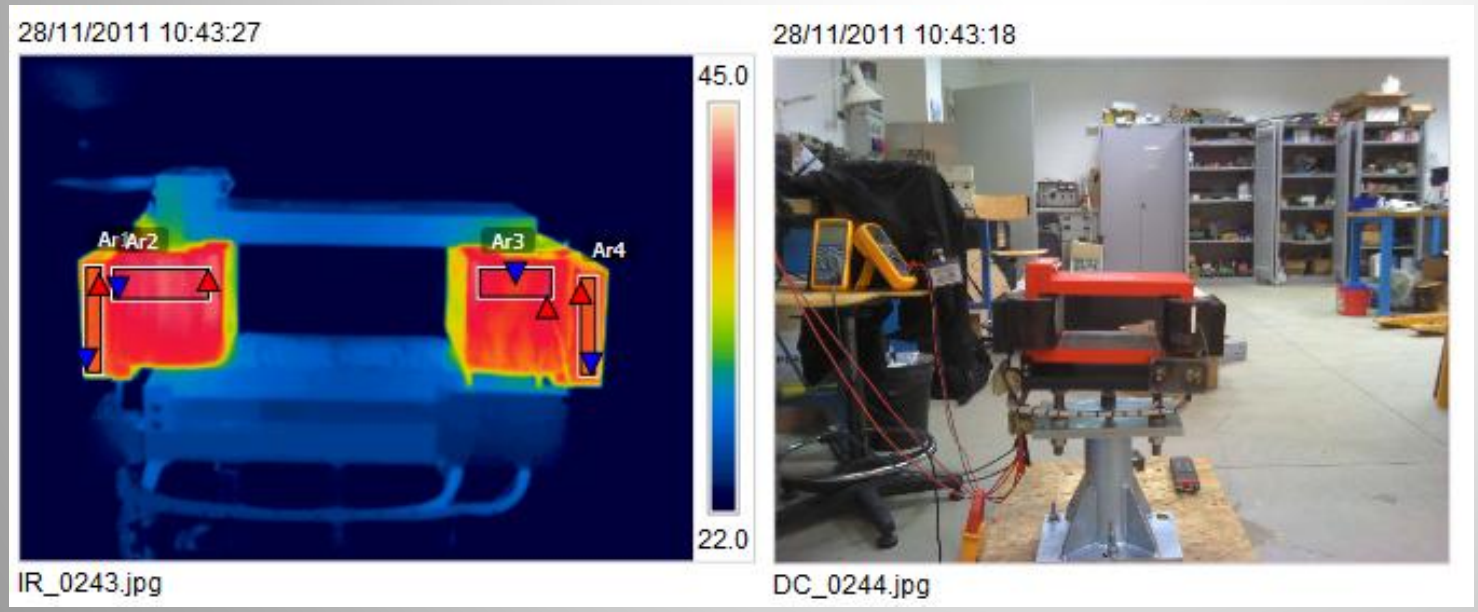
Flow-switch:

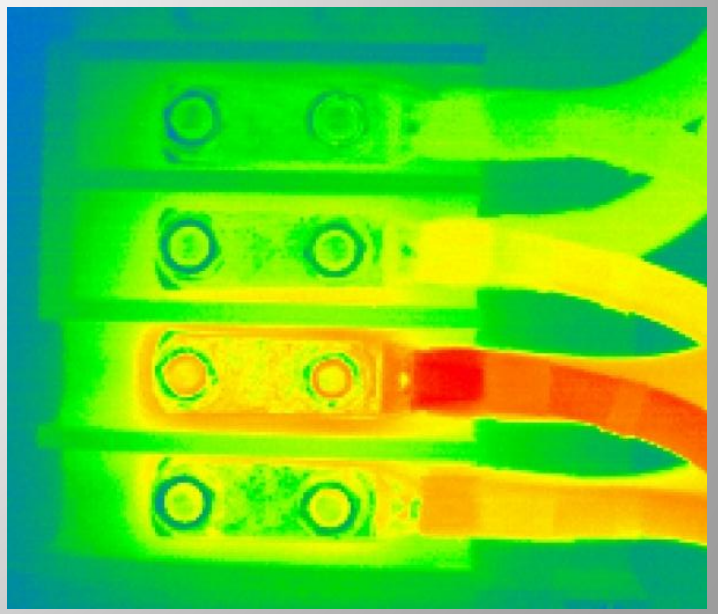


Power and heating tests

Power and heating tests are performed to verify:

- no accidental over-heating
- correct cooling performance
- absence of poor electrical contacts
- interlock system performance
- absence of moving parts (pulse test)

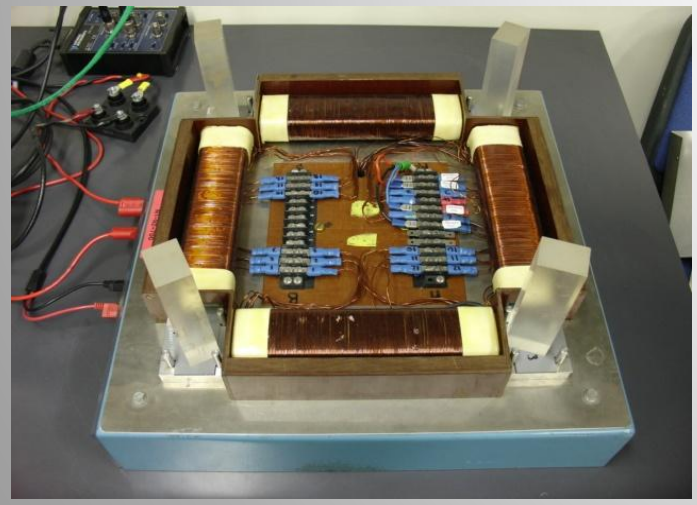


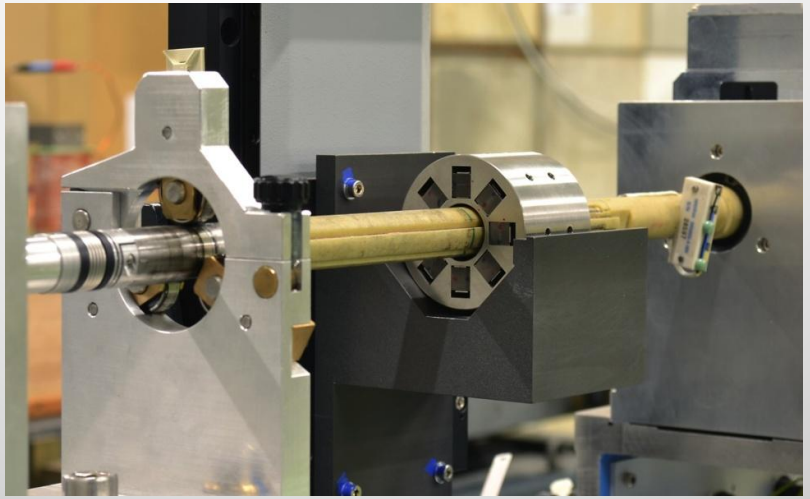


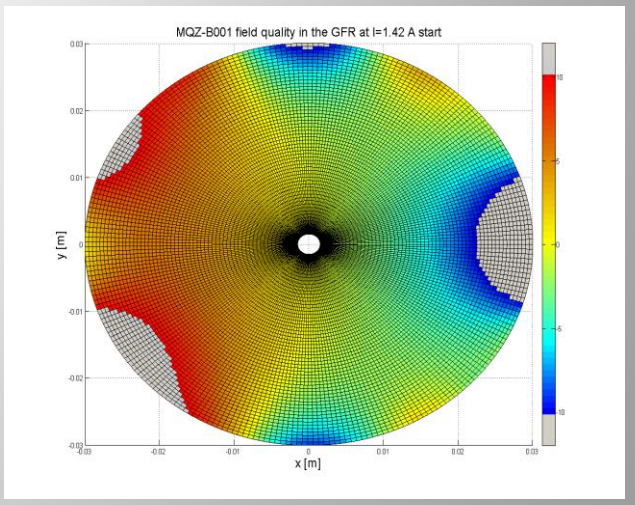
Magnetic measurements

Magnetic measurements are performed to:

- characterize soft (iron) and hard (permanent magnets) ferromagnetic materials
- prove that the electro-magnetic design is correct
- monitor production quality and steer manufacturing
- collect information and data for operation: polarity, transfer function, field uniformity, magnetic axis, dynamic effects (eddy currents) and magnetic cycling effects (hysteresis)
- characterize magnets after repairs or to use in different operational ranges







Thanks for your attention…