Joint Universities Accelerator School

JUAS 2017

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# Normal-conducting accelerator magnets
# Lecture 3: Magnet production

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CERN

# Lecture 3: Magnet production

Magnetic materials

Manufacturing techniques

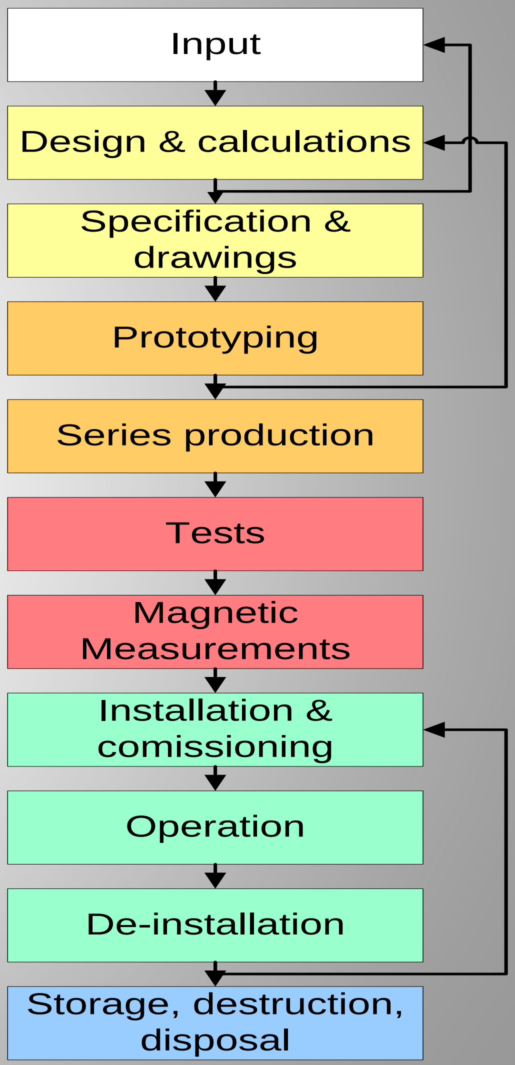
QA & Acceptance tests

Recurrent issues

~~Magnetic measurements~~

(see practical work @ CERN)

Cost estimates and optimization



# Magnet manufacturing

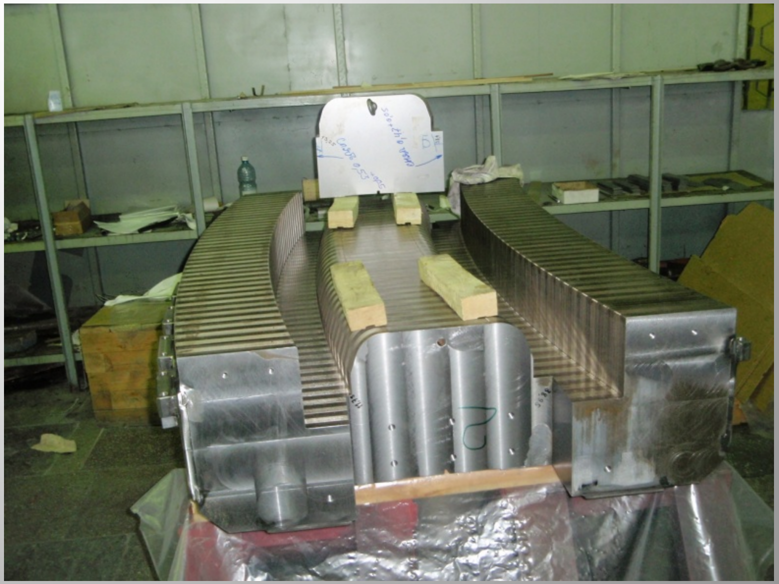
Mechanical design → Procurement (• Raw materials • Tooling) → Yoke production → Coil production → Magnet assembly → Tests & measurements

# Massive vs. laminated yokes

Historically, the primary choice was whether the magnet is operated in persistent mode or cycled (eddy currents)

+ no stamping, no stacking
+ less expensive for prototypes and small series
- time consuming machining, in particular for complicated pole shapes
- difficult to reach similar magnetic performance between magnets

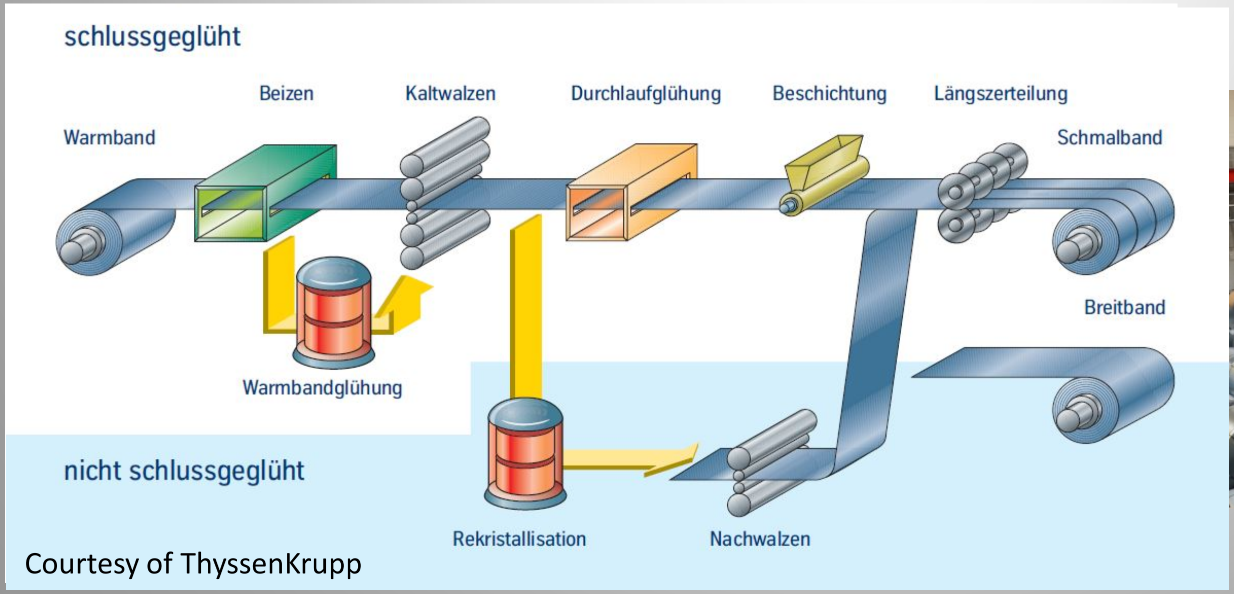
+ steel sheets less expensive than massive blocks (cast ingot)
+ less expensive for larger series
+ steel properties can be easily tailored
+ uniform magnetic properties over large series
- expensive tooling



# Magnetic steel

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

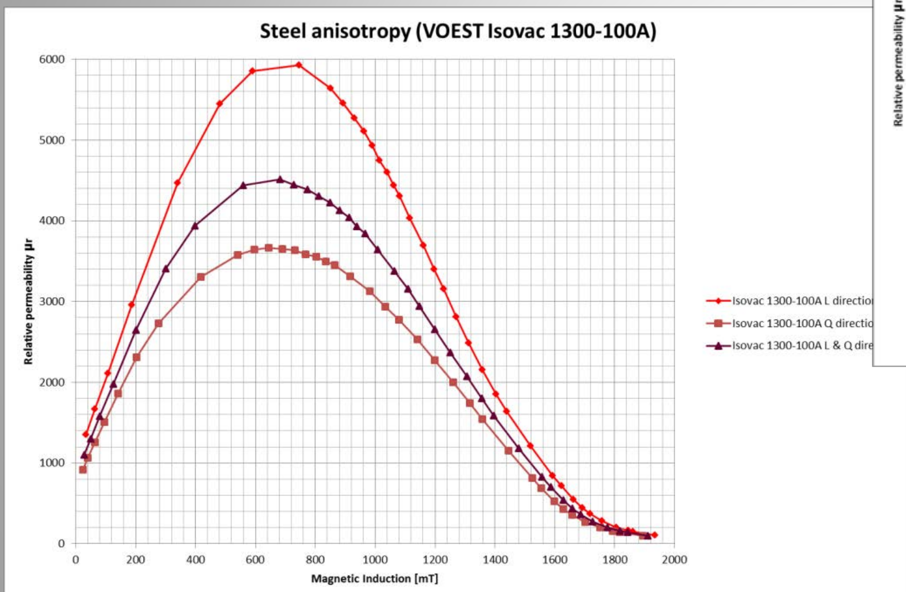
- Magnetic and mechanical properties can be adjusted by final annealing
- Reproducible steel quality even over large productions
- Magnetic properties (permeability, coercivity) within small tolerances
- Homogeneity and reproducibility among the magnets of a series can be enhanced by selecting, sorting or shuffling
- Material is usually cheaper, but laminated yokes are labour intensive and require more expensive tooling (fine blanking, stacking)

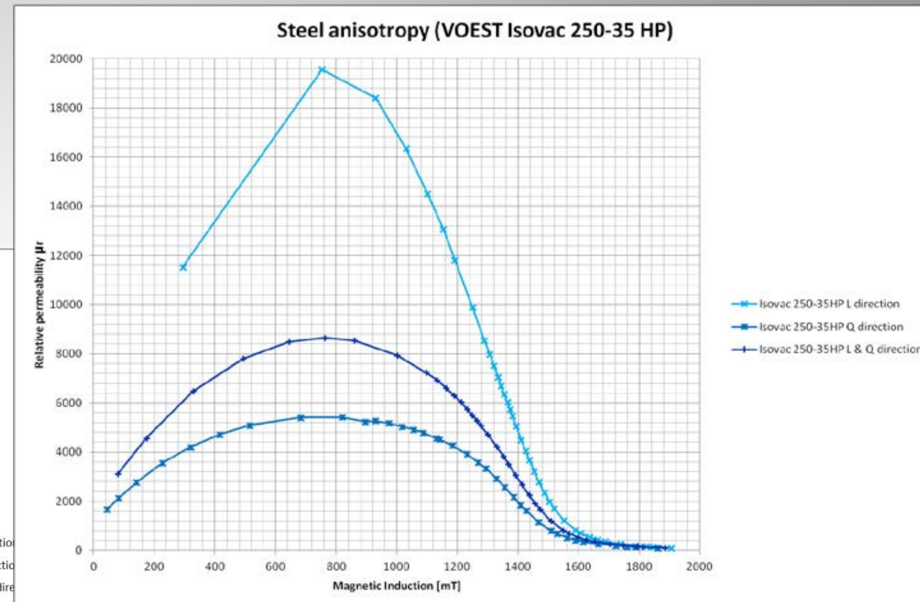



Courtesy of ThyssenKrupp

# NGO steel properties

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




ISOVAC 250-35HP: $H_c$ = 30 A/m

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

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

Electr. resistivity @20°C:
0.16 (low Si) $\le \rho$
$\le$ 0.61 µΩm (high Si)

# Sheet insulation

Surface coating:

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

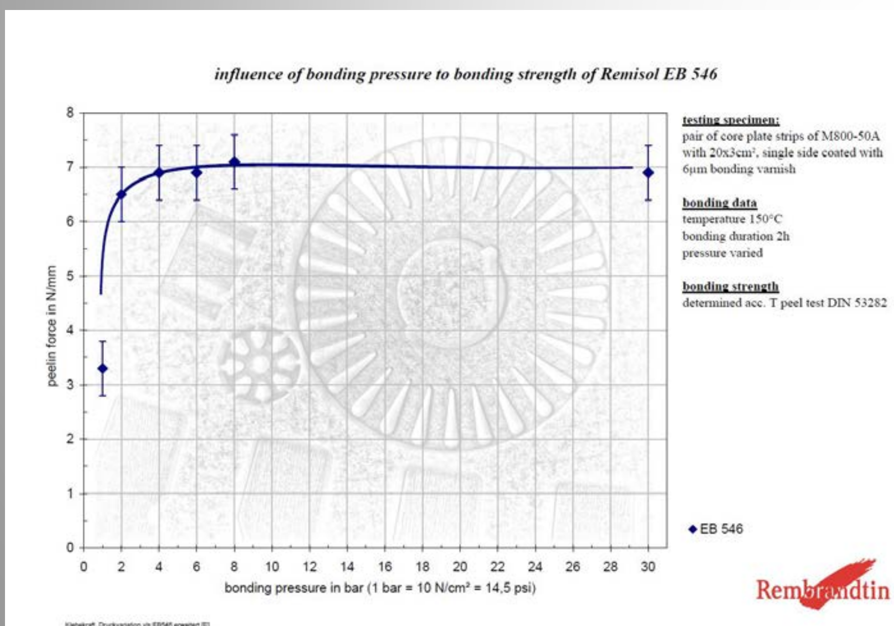
| **Insulation designation** IEC 60404-1-1 | **Insulation type** | **Color**[1)] | **Coating** | **Coating thickness each side** in µm | **Insulation resistance at room temperature** to ASTM A717/A717M-95 Ωm²/Lamelle |
|---|---|---|---|---|---|
| **STABOLIT 10** EC-3 by prior arrangement only | organic | 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<br>4.0 - 7.0<br>6.0 - 9.0 | > 90 |
| **STABOLIT 60** EC-5 | inorganic with organic components pigmented | grey | both sides | 0.3 - 1.0<br>1.0 - 2.0<br>2.0 - 3.5 | > 5<br>> 15<br>> 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<br>passive max. 1.5 | - |

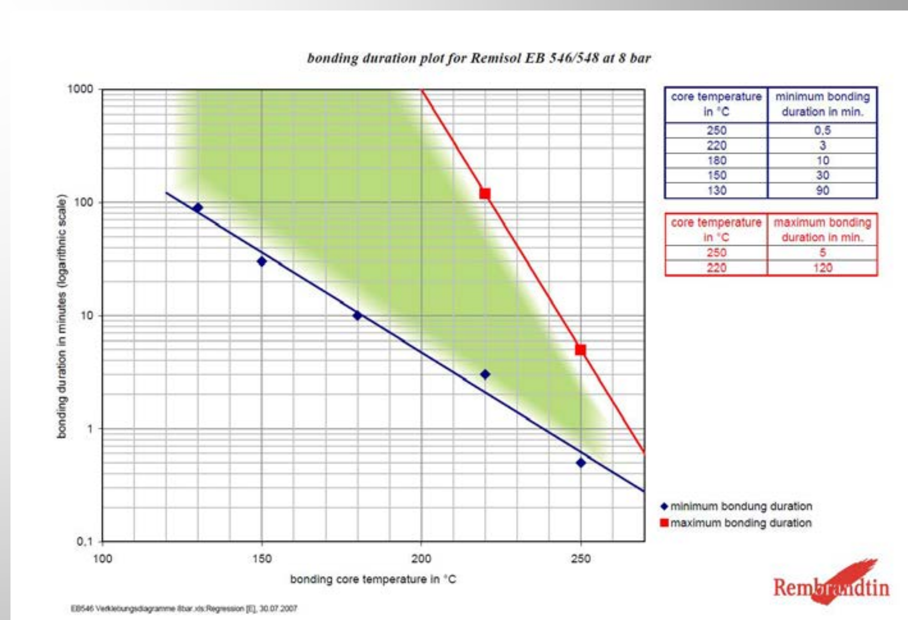
Source: ThyssenKrupp

# Bonding & insulation

Special coatings have been developed for the adhesive bonding of laminations:

- provide electrical insulation and mechanical bonding
- based on epoxy resins
- available in B-stage (partly cured) and C-stage (fully cured)
- Referred to as STABOLIT 70 by *ThyssenKrupp*




Courtesy of Rembrandtin

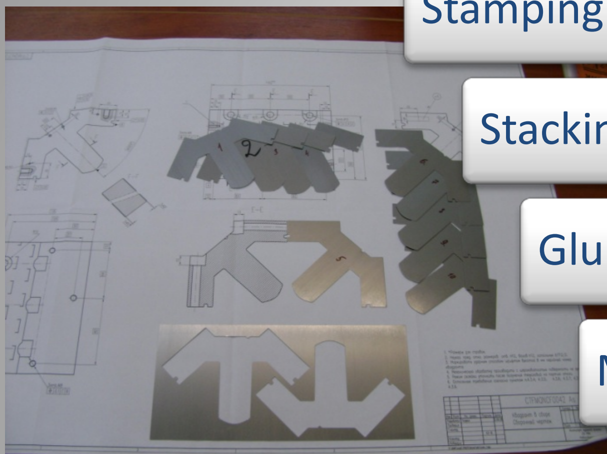
# Other magnetic materials

1. High purity irons
   - Iron referred to as "high purity" when total concentration of impurities (mainly C, N, O, P, S ,Si and Al) does not exceed a few hundred ppm
   - Otherwise Low Carbon Steel or Non-alloyed Steel
   - Very pure Fe: high electrical conductivity $\rightarrow$ not suitable for AC applications
   - For high permeability at $B$ > 1.2 T it is advisable to anneal at max. 800 °C and cool down slowly
2. Low-Carbon Steels
   - e.g. type 1010
   - Disadvantage: Magnetic ageing (increase of coercivity with time)
3. Non-grain oriented Silicon Steels (NGO)

   Advantages:
   - Increase in permeability
   - Decrease in hysteresis loss
   - Eddy current loss decrease due to higher resistivity (Al and Mn added as well)
   - No ageing
4. Grain-oriented Silicon Steels
5. Iron alloys
   a. Iron-Nickel
   b. Iron-Cobalt alloys with high magnetic saturation
6. Compressed powdered Iron and Iron alloys
7. Ferrites
8. Innovative materials and rare earths

Reference: S. Sgobba: Physics & Measurements of Magnetic Materials, CAS 2009, Brugges

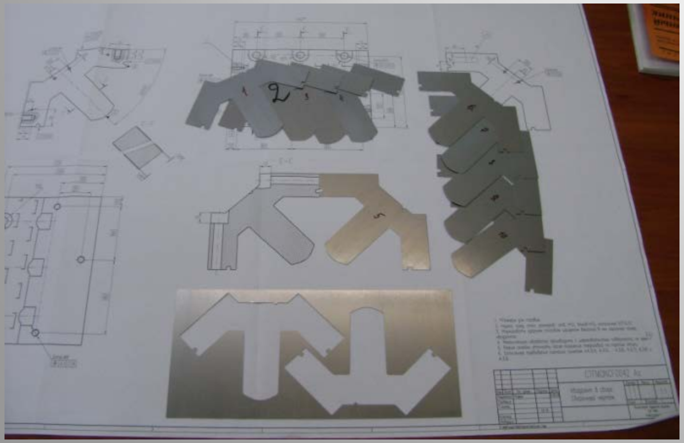
# Yoke manufacturing

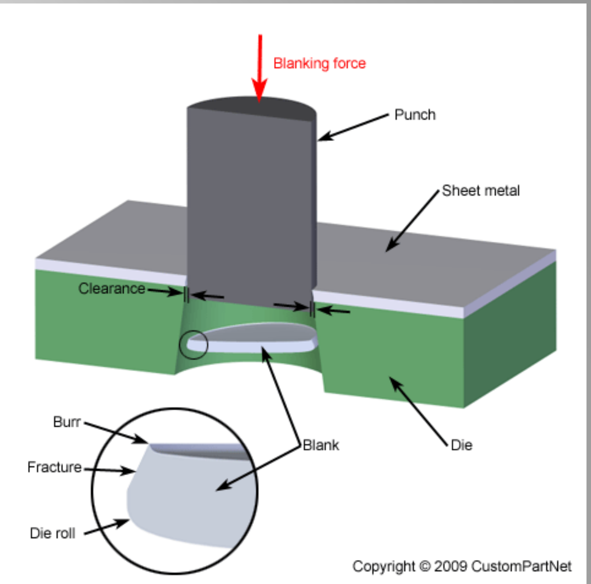


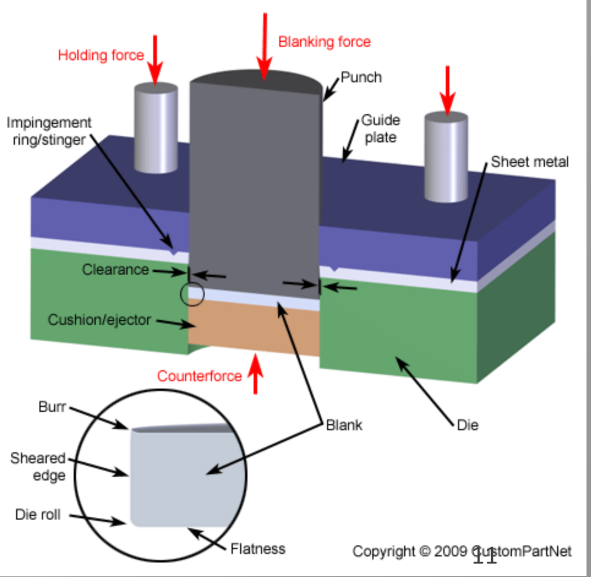
- Stamping laminations
- Stacking laminations into yokes
- Gluing and/or welding
- Machining
- Assembly (preliminary)

# Lamination punching

- Punching or fine blanking
- Fine blanking requires more expensive tooling
- Tolerances less than +/- 8 µm achievable
  (depending on thickness, material and layout)
- Material can be delivered in sheets or strips (coils)

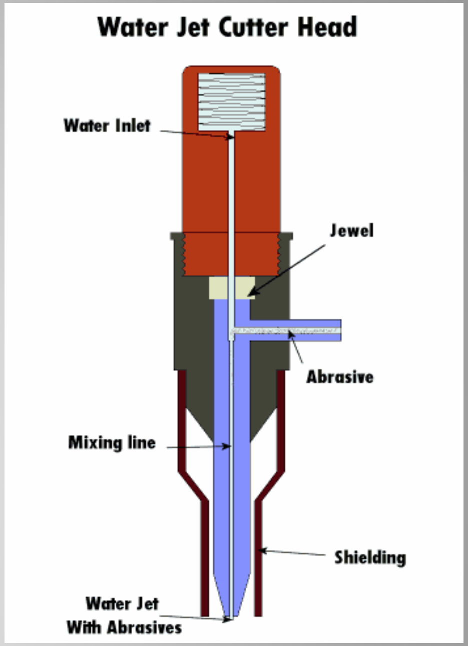




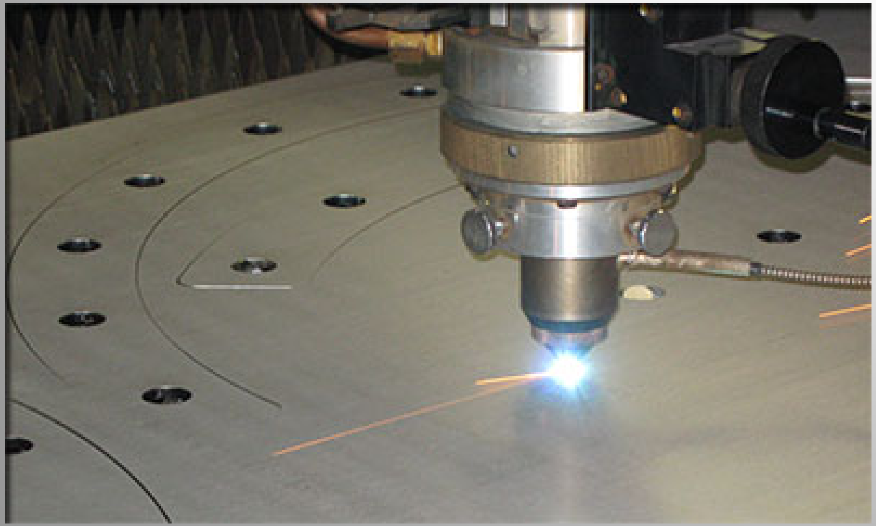



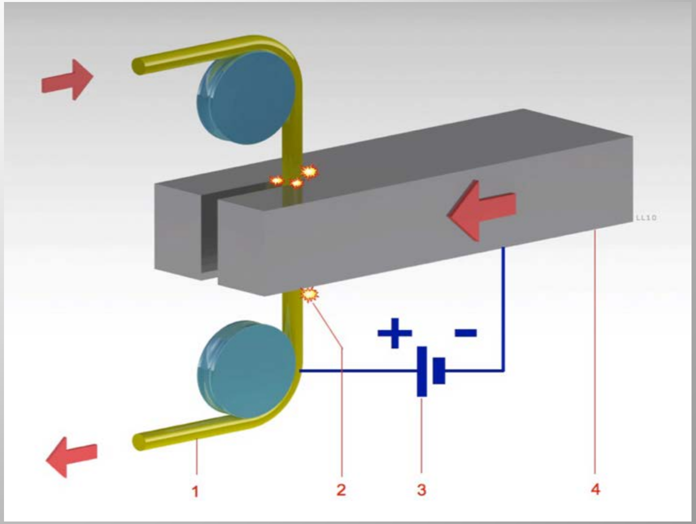
# Alternatives to punching

| Technique | Accuracy [mm] | Repeatability [mm] | Drawbacks |
|---|---|---|---|
| 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 | stacks only |
| Wire-cut EDM | > 0.002 | >0.001 | very slow, limited size |



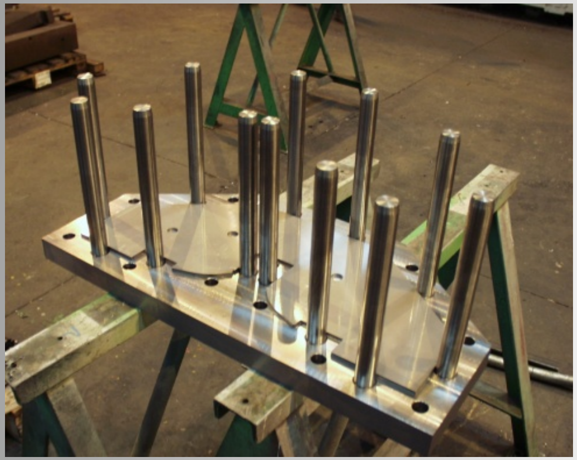

...or a combination of different techniques

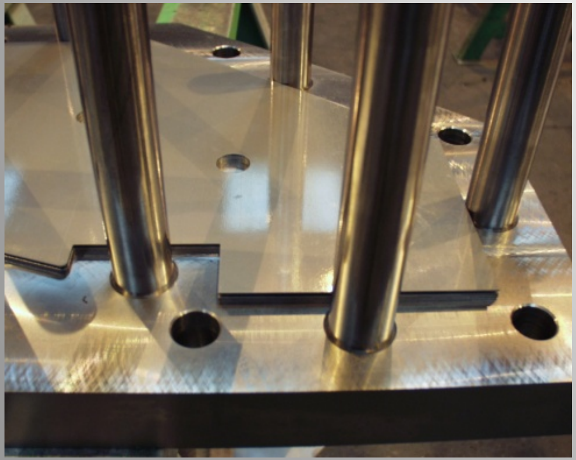
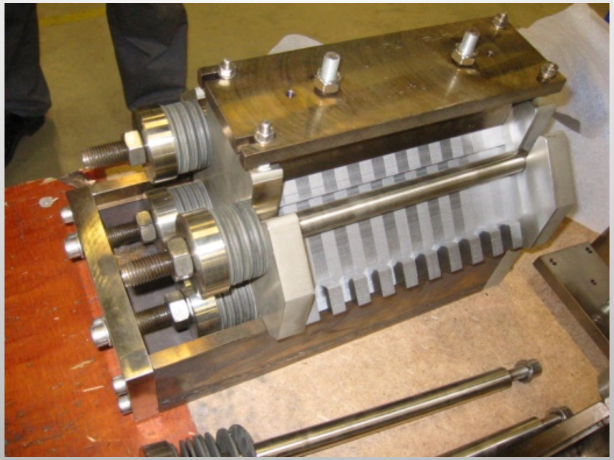




# Yoke stacking

Fixtures for stacking/baking/welding




# Glueing vs. Welding

## Welding

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

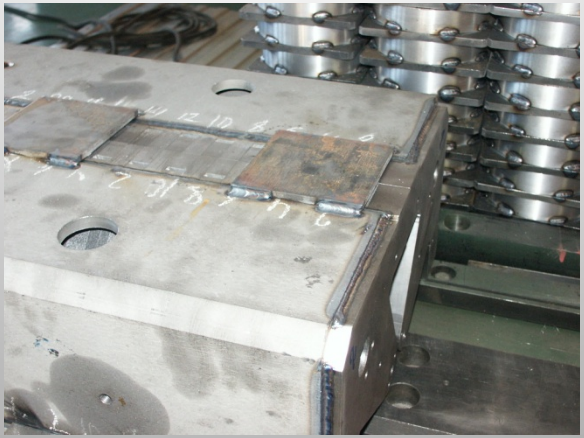
/ requires stacking fixture

## Glueing

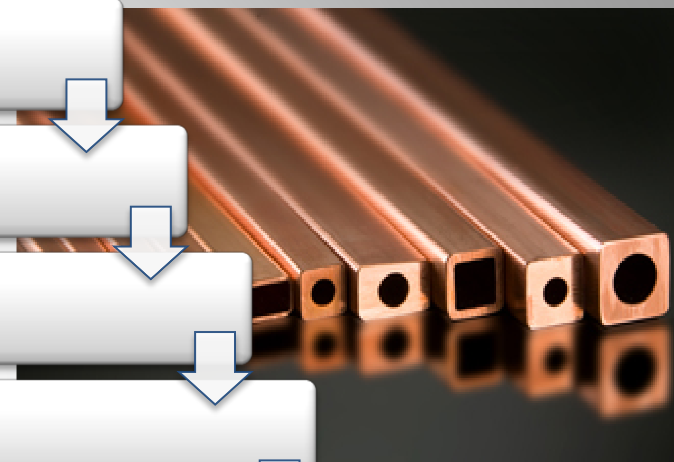
+ no stress, no distortions
+ no tension straps, no end plates (→ no eddy currents)
- glue sensitive to radiation and aging
- requires clean laminations and conditions
- requires baking oven

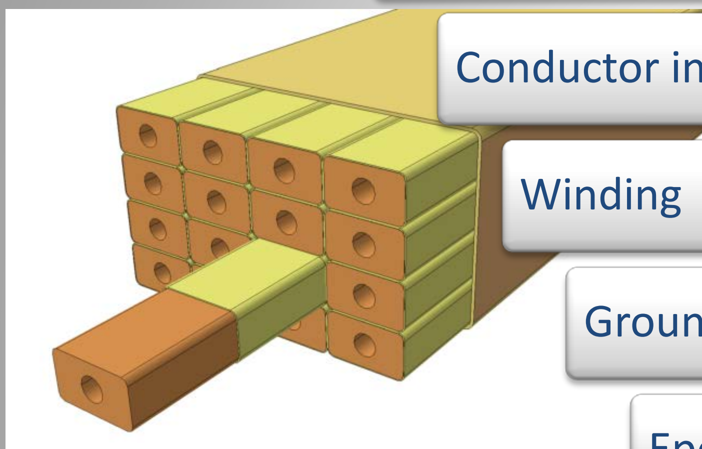
/ requires stacking fixture

Recommendation: combine gluing, welding & bolting

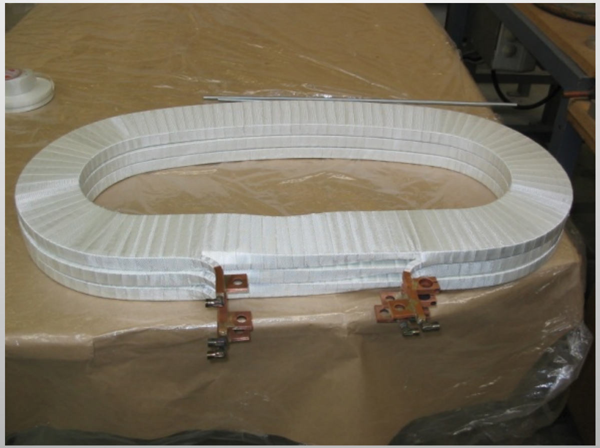


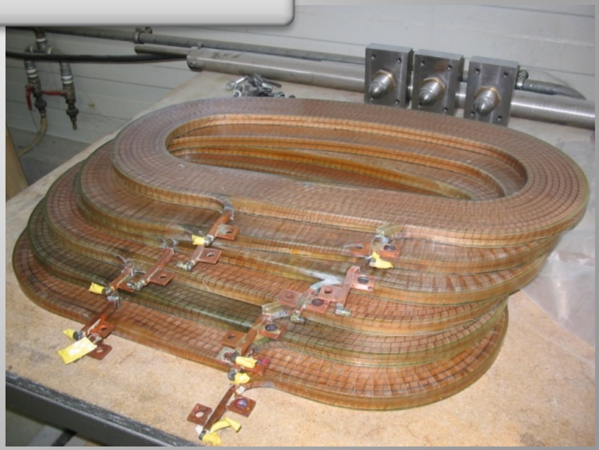
# Coil manufacturing





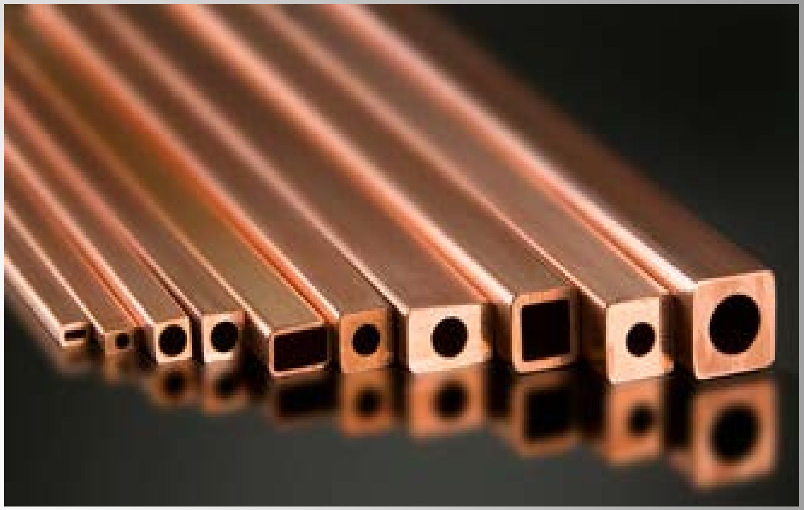
- Define conductor type and material
- Conductor insulation
- Winding
- Ground insulation
- Epoxy impregnation



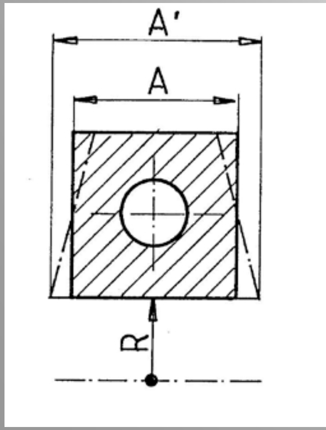


# Conductor materials

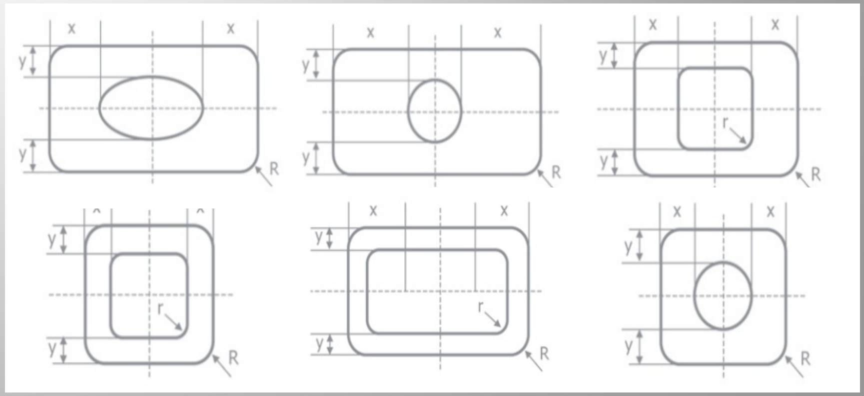
| | Al | Cu (OF) |
|---|---|---|
| Purity | 99.7 % | 99.95 % |
| Resistivity @ 20°C | 2.83 μΩ cm | 1.72 μΩ cm |
| Thermal resistivity coeff. | 0.004 $K^{-1}$ | 0.004 $K^{-1}$ |
| Specific weight | 2.70 $g/cm^3$ | 8.94 $g/cm^3$ |
| Thermal conductivity | 2.37 W/cm K | 3.91 W/cm K |



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

Dielectric materials can be distinguished in three main classes:

- inorganic materials: ceramics, glass, quartz, cements and minerals (e.g. mica)
- organic materials: thermoplastic: Rubber, PA (Nylon), PP, PS, PVC, PC, PTFE or
  thermosetting: Polyethylene, PI, PEEK, Epoxy, phenolic, silicon, polyester resins
- composites: fully organic (aramidic fibres-epoxy tapes) or mixed (epoxy-mica tapes)

A weak electrical insulation may produce:

- current leaks with local heating up to melting and possible fire
- progressive damage of the leakage path up to a short circuit
- unbalanced circulating currents ($\rightarrow$ magnetic field distortion)
- incorrect functioning of protections

The electrical insulation is stressed by several factors:

- electric
- thermal
- mechanical
- chemical (including oxidation)
- radiation

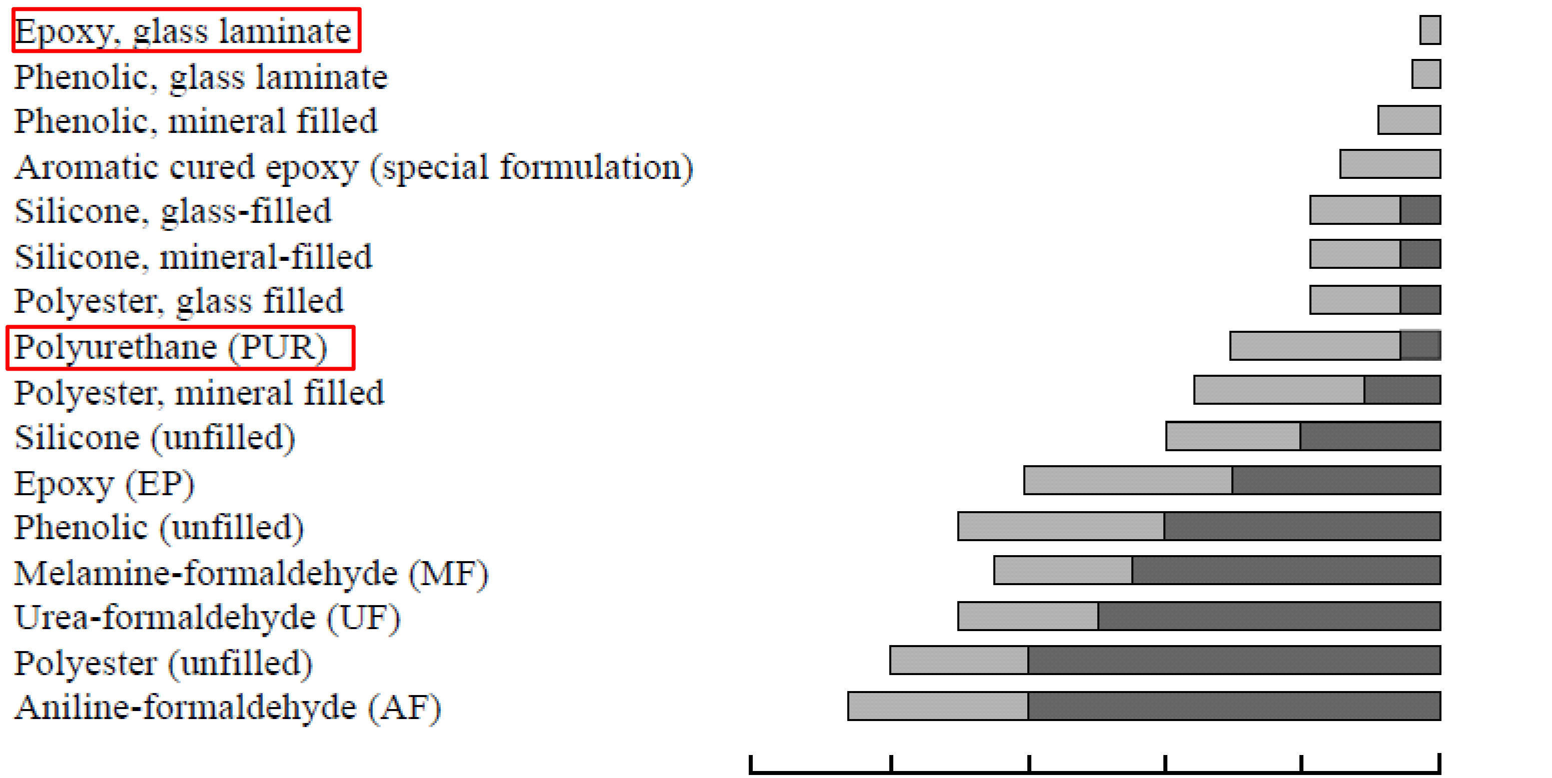
Montsinger's rule / Arrhenius equation: $L(T + 10\,K) \approx 0.5\; t(T)$

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

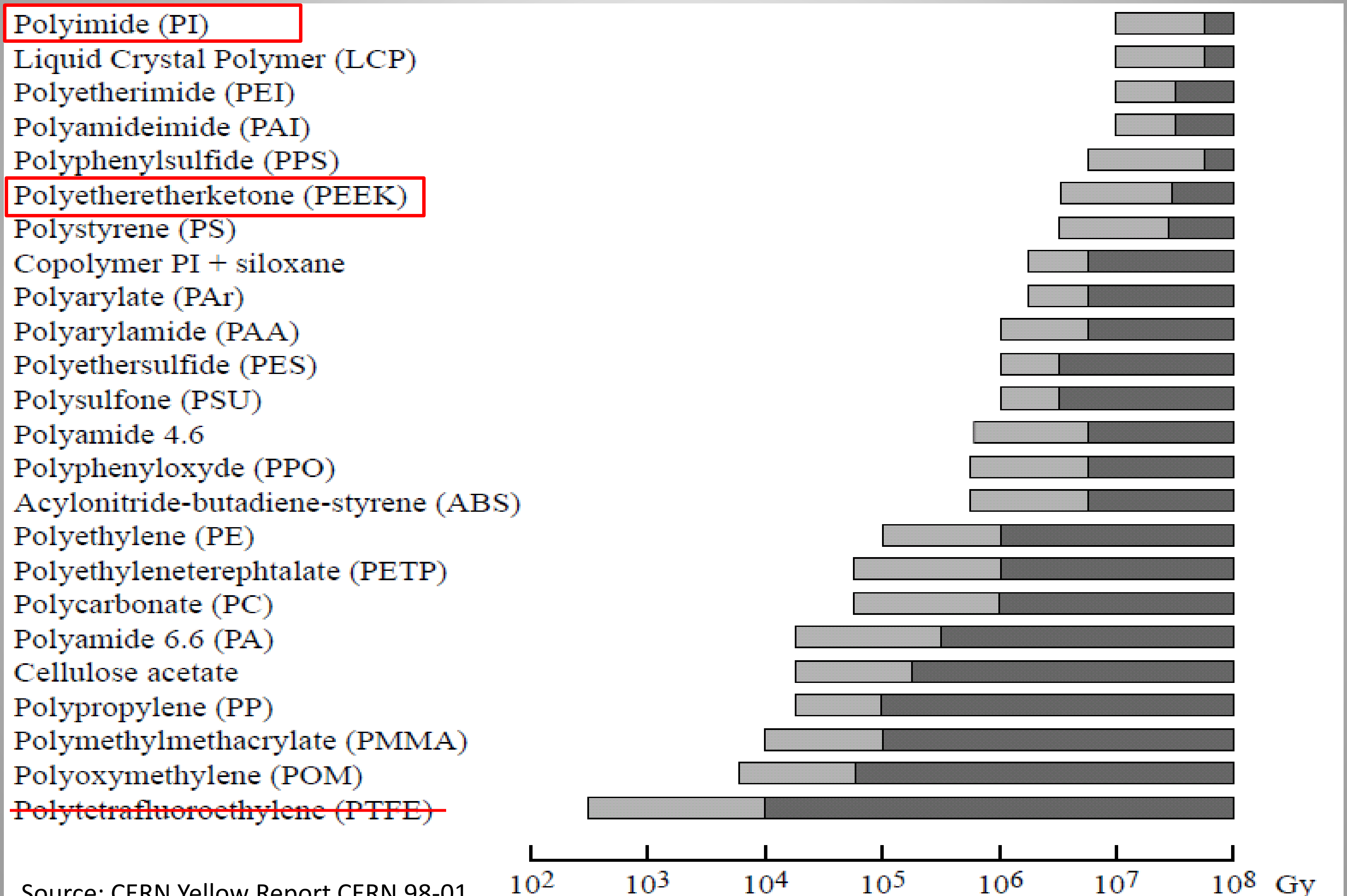
Radiation hardness is an important criterion for insulation materials used for accelerator applications




Source: CERN Yellow Report CERN 98-01

Above $10^8$ Gy special insulation techniques are required!

# Radiation hardness




Source: CERN Yellow Report CERN 98-01

# Coil insulation

Conductors with small cross-section:

straigthening → cleaning → conductor insulation → winding → ground insulation

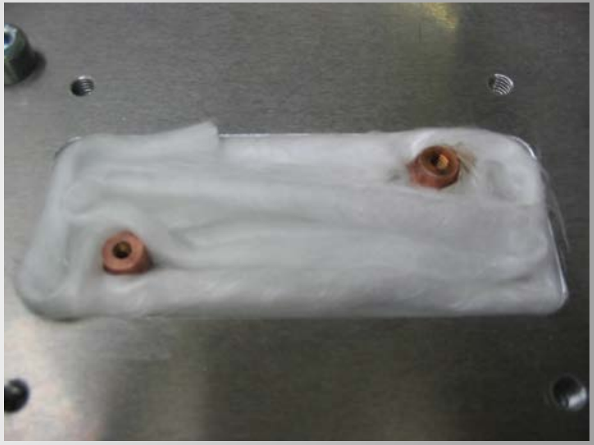
# Coil insulation

Conductors with large cross-section:

straigthening → winding → sand blasting → cleaning → conductor insulation → ground insulation

# Coil impregnation

heating and evacuating mold and coil (auto-clave or vacuum mold) → mixing resing → heating and degassing resin → injecting resin → curing cycle → cooling



# Coil impregnation

We can distinguish between two different impregnation techniques:

## Precise mold

+ very good surface finish
+ moderate resin consumption
- requires release agent
- difficult to avoid resin rich areas
- expensive tooling (mold)
- ejection more difficult

## Release tape

+ no excess of resin on the finished coil
+ inexpensive mold
+ easy de-molding
- poor surface finish
- higher resin consumption

# Magnet assembly

By hand....

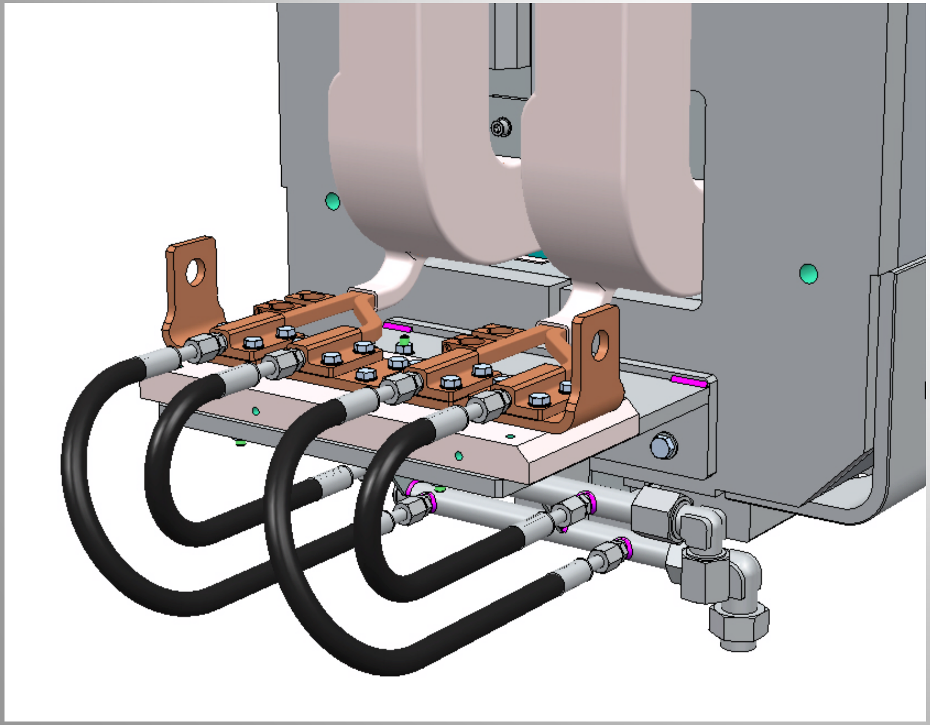


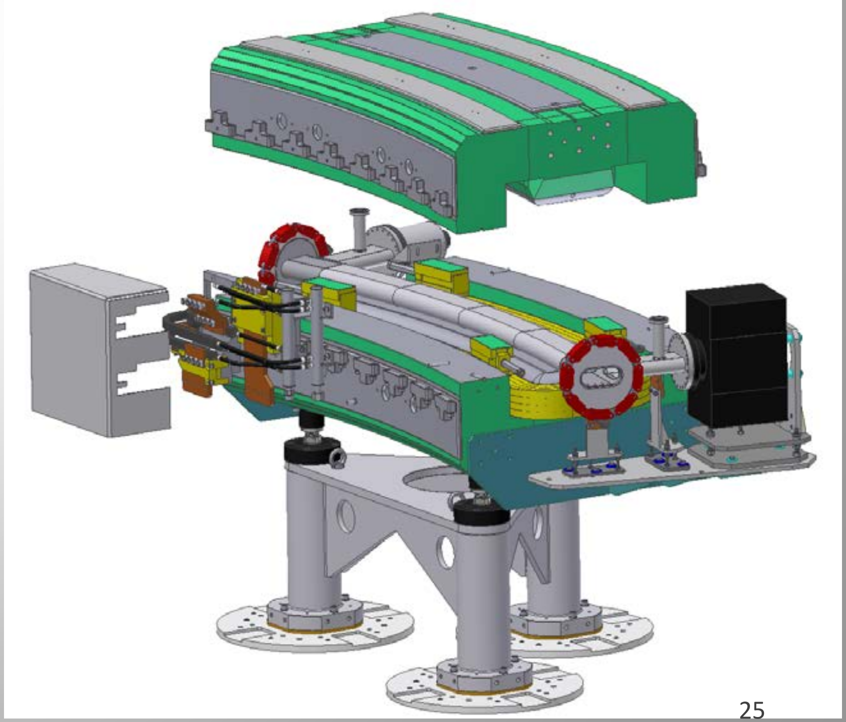

... or with the help of tooling




# Auxiliary components

- Electrical connections
- Hydraulic connections
- Interlock sytem (temperature, pressure, water flow)
- Alignment tragets, adjustment tables and support jacks
- Magnetic measurement devices (pick-up coils, hall probes)





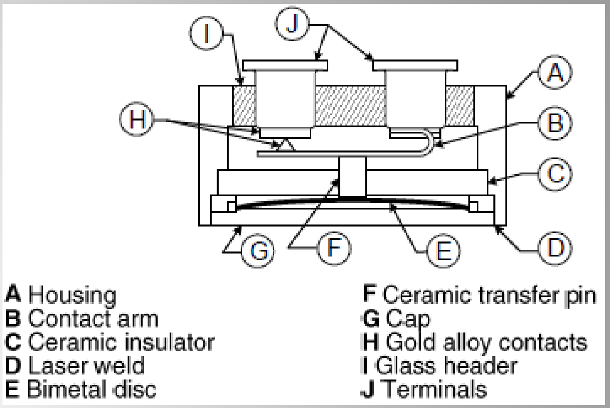
# Hydraulic circuits

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

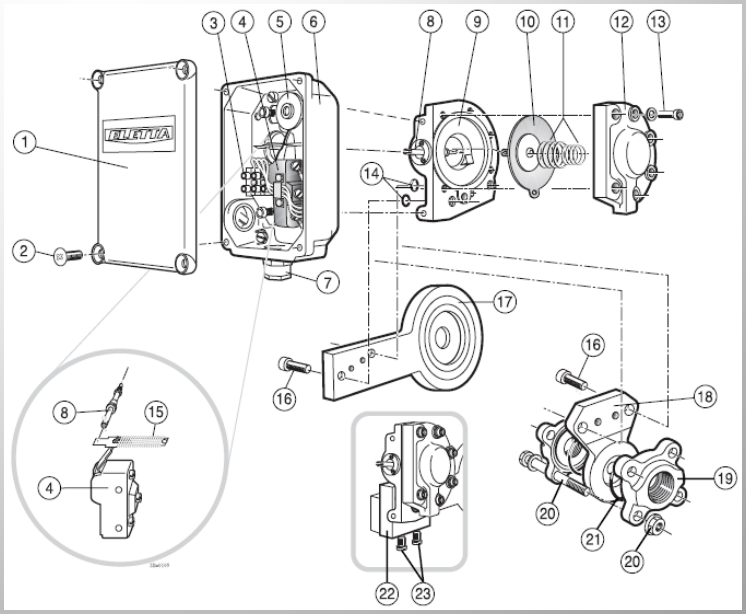
- Leaks can be detected and repaired during magnet acceptance tests and commissioning...
- ... but, many leaks occur only after years in operation
- Often not monitored $\rightarrow$ magnet damage (short cicuits, corrosion of iron yoke) <u>and</u> collateral damages on other equipment

# Interlock Sensors

Thermo-switch:



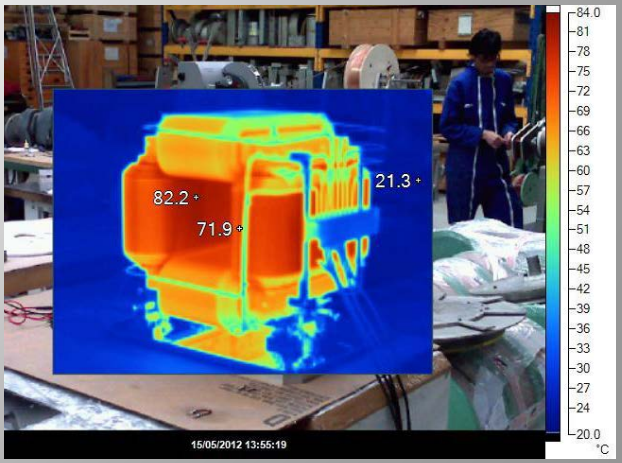

Flow-switch:



# QA & Acceptance tests

QA is important at each production stage

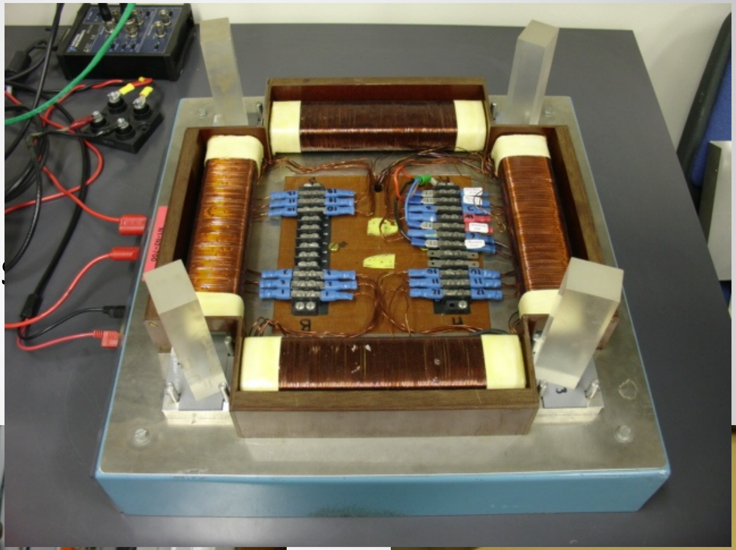
- Constant monitoring of critical items from the raw material, to semi-finished parts, to sub-components to the final product
- Sample testing (destructive or non-destructive) to qualify materials, manufacturing techniques and processes
- Acceptance test can include electrical, hydraulic, mechanical, thermal, and magnetic measurements
- Tests/measurements can be systematically (entire series) or on specific/random samples
- Complete recording and documentation indispensible (back-tracing in case of doubts or failures)

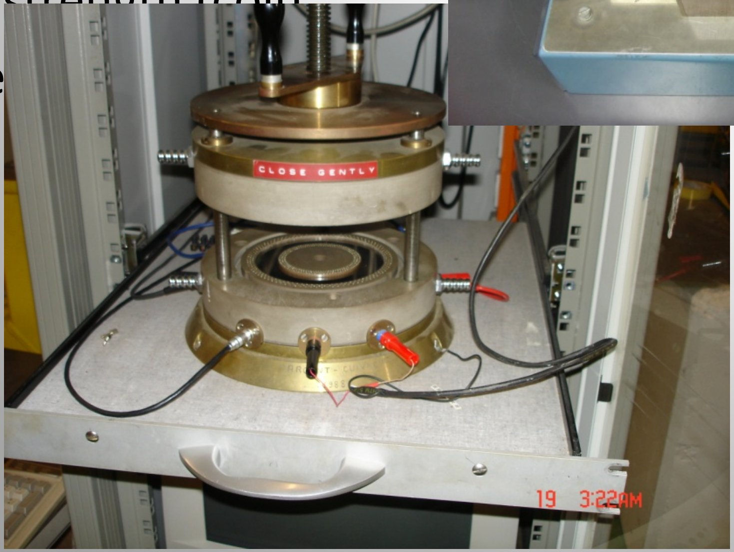


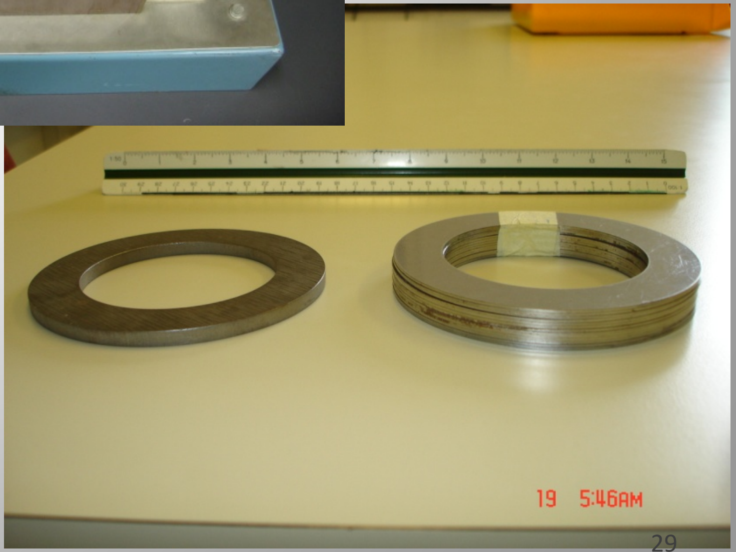
# Sample testing

Typically the following samples are tested to validate material performance and production processes:

- Magnetic steel
- Laminations
- Bond strenght (lamination
- Brazing / Welding
- Bond strength (coil)
- Impre





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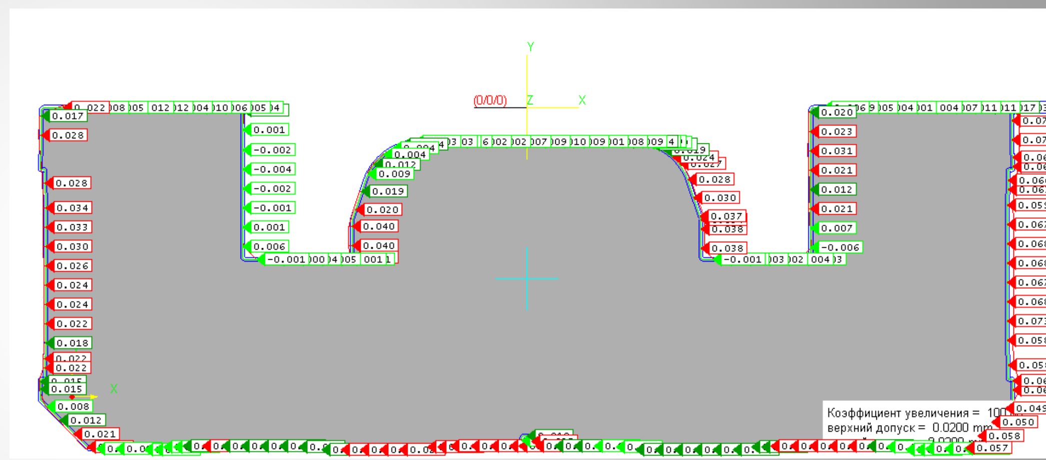


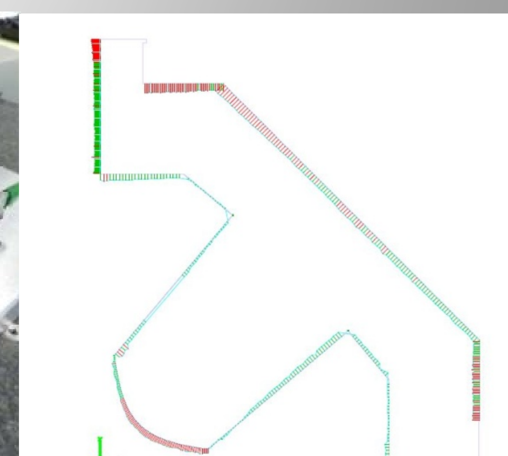

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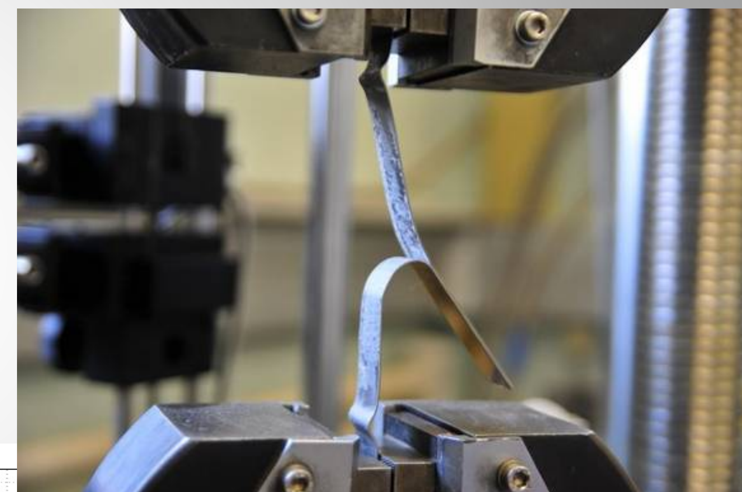

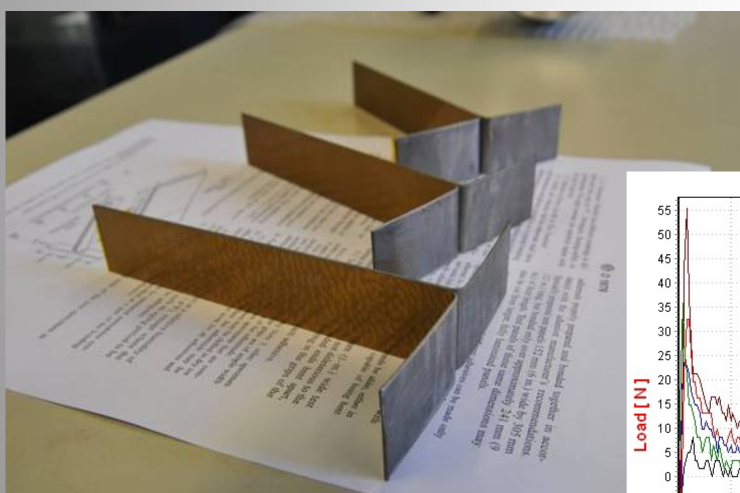

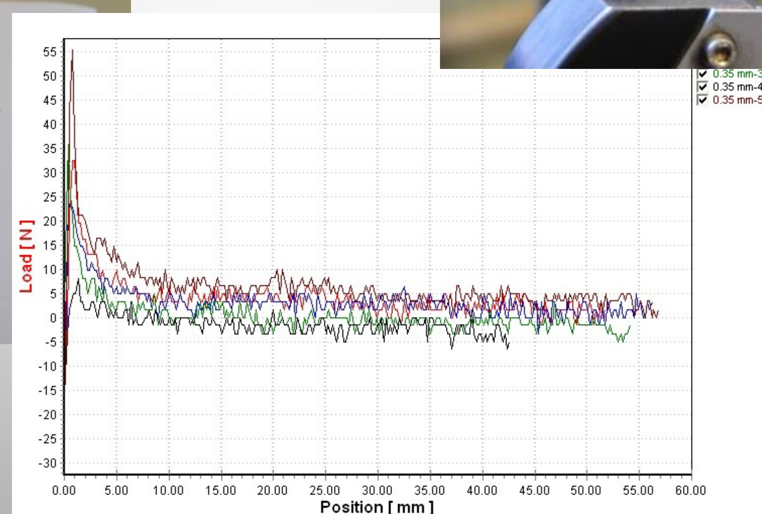

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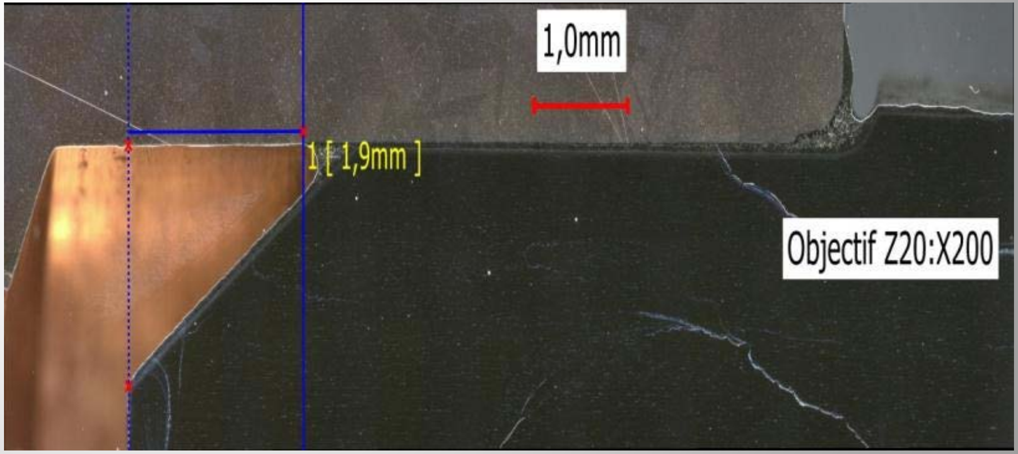

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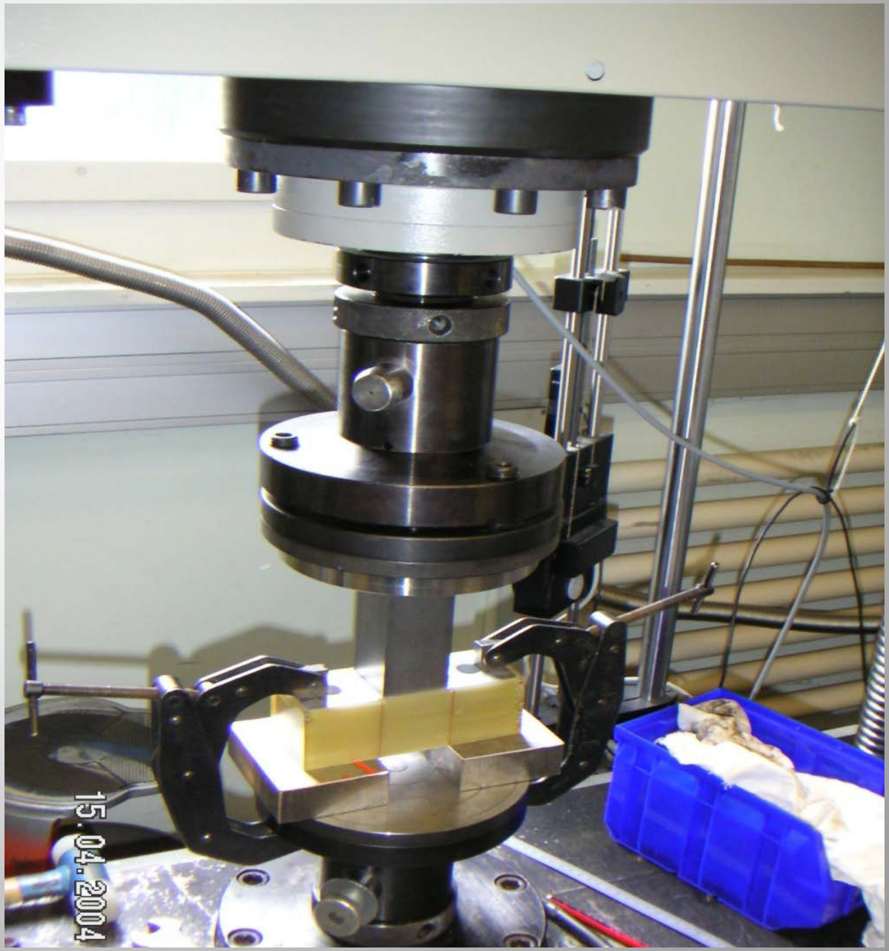

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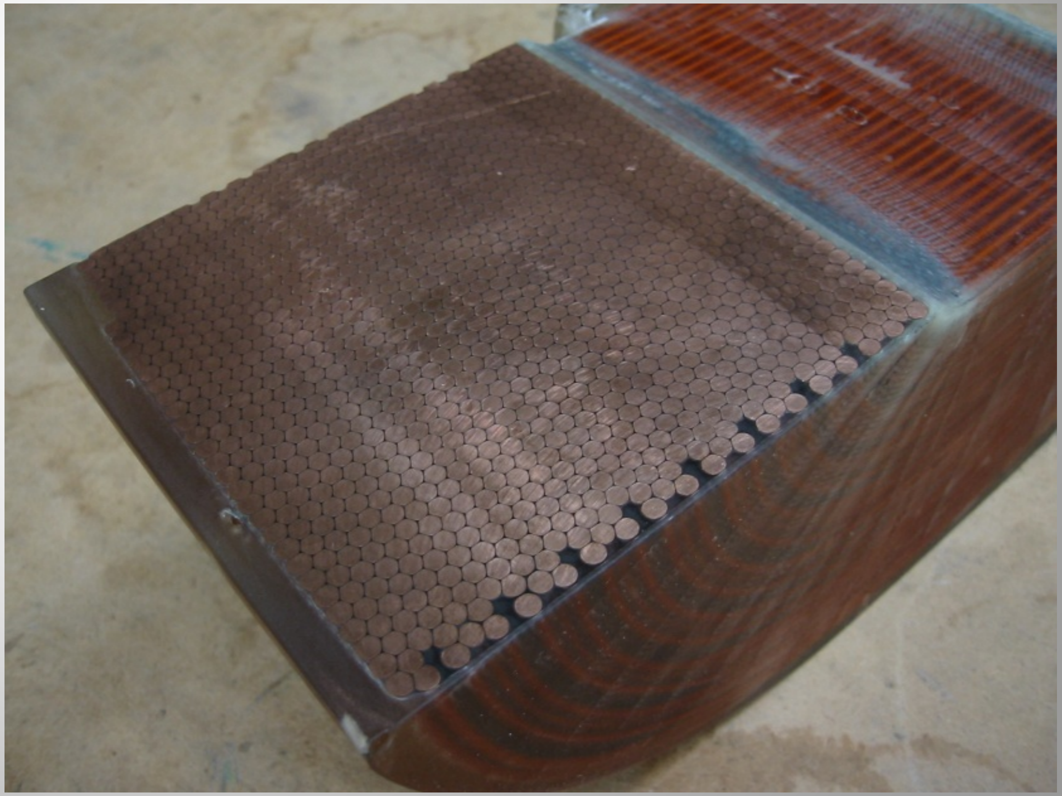


# Mechanical measurements

Yoke shape and dimensional accuracy is essential for magnetic field quality in iron-dominated magnets

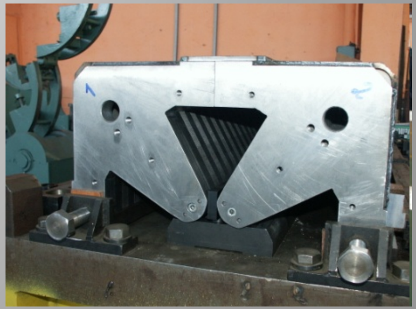
Mechanical errors can significantly influence the magnetic performance

We distinguish between:

- Systematic errors (lamination contour) ,
  can be relativley easy determined and corrected
- Random errors (stacking, machining, assembly),
  difficult to predicted, in general known only after series production, can be partly minimized by imposing low mechanical tolerances (expensive), enlarged design margins (also expensive), strict quality assurance and close follow-up of production processes

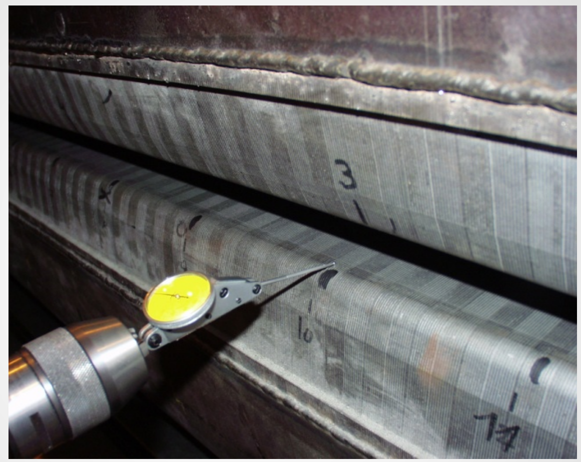
Mechanical measurements are required after each manufacturing step:

- Lamination punching
- Yoke pieces (half-yoke, quadrants) manufacture
- Yoke assembly
- Reproducability: after disassembling and re-assembling (dowel pins)
- Stability: no deformation due to handling, lifting, transport (lifting test)

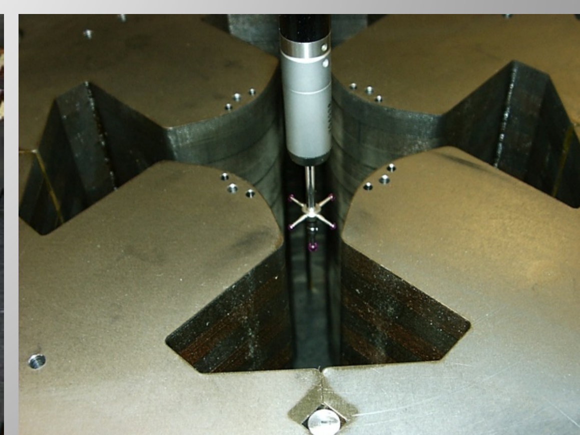


# Mechanical measurements

Various optical and mechanical techniques with different accuracy, precision and resolution are available for mechanical measurements

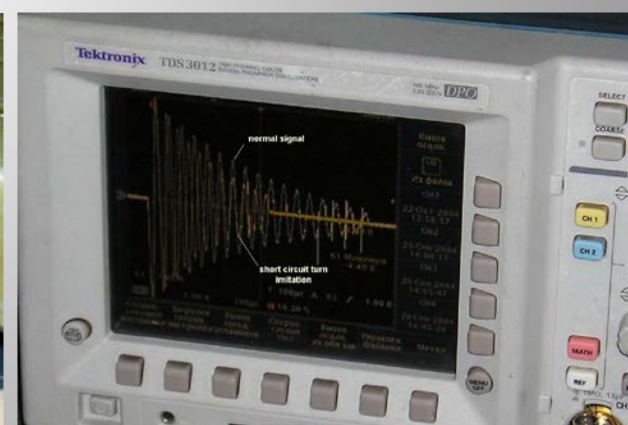







# Insulation testing

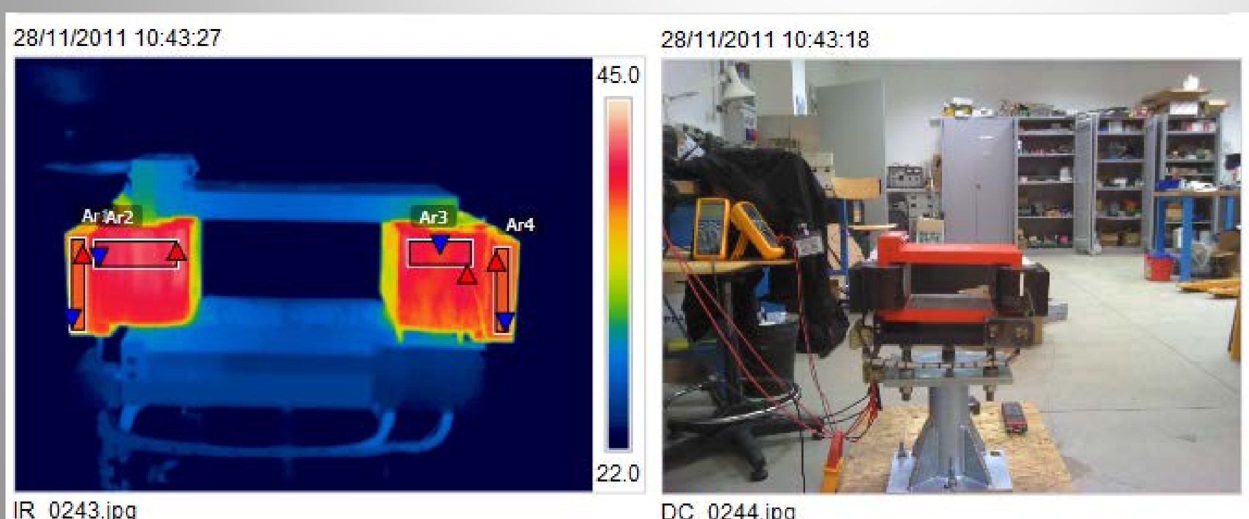
- Insulation tests are an integral part of the electrical testing in addition to the measurements of the electrical coil resistance and inductance
- An electrical insulation shall be tested to ensure its ability to provide the required insulation levels for specified operation and fault conditions and during a specified time → tests shall reveal manufacturing deficiencies
- In most cases, this means specifying test levels much beyond the real operational conditions
- For acceptance testing we typically perform two types of tests:
  - High voltage test of a conductor to ground
  - Capacitor discharge test for inter-turn insulation

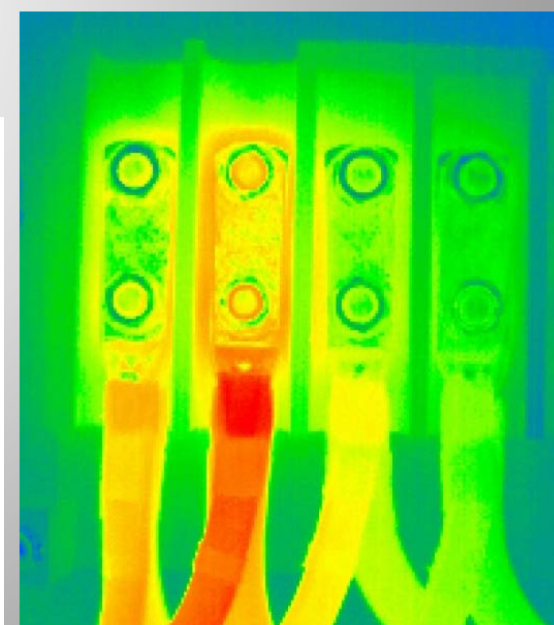


# Power and heating tests

Power test are performed to verify:

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



# Recurrent quality issues

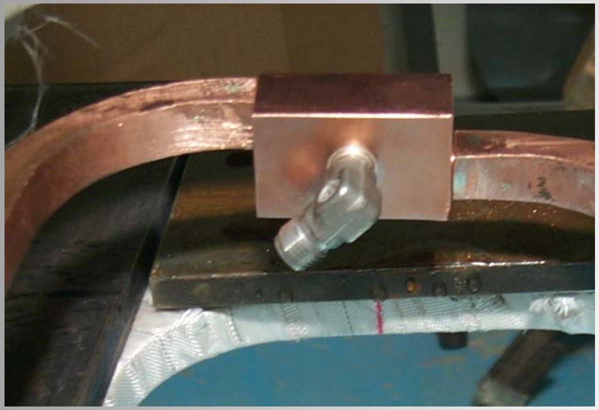
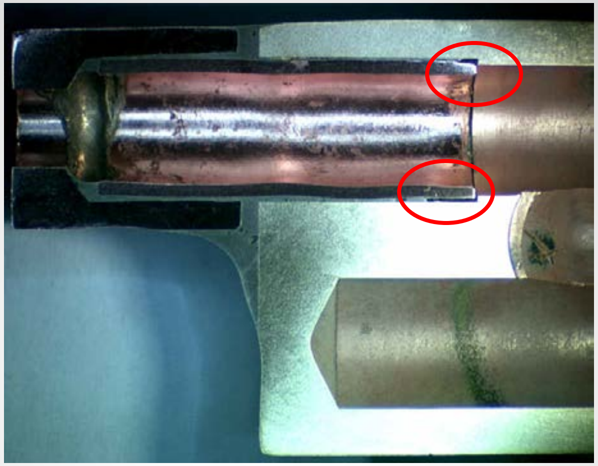
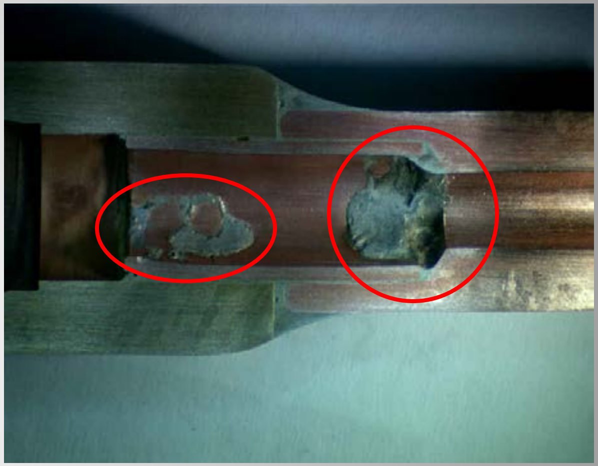
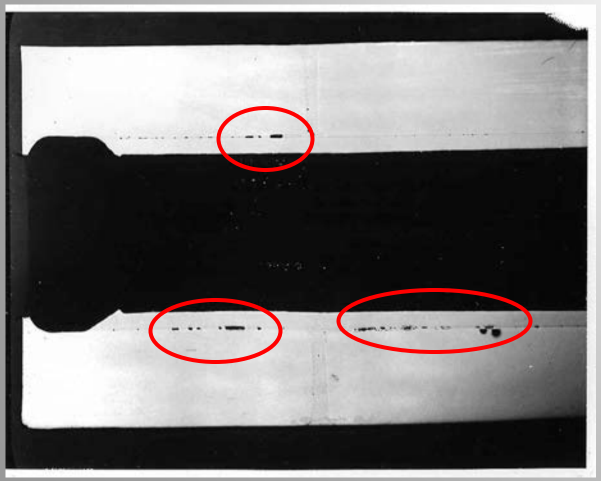
Despite a severe quality control by the manufacturer, we often find quality deficiencies during the acceptance tests and certification at CERN

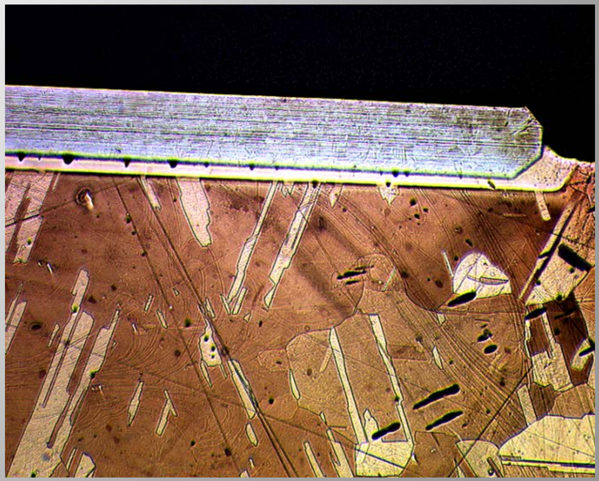
Amongst several other recurrent issues, the following are the most frequent and most serious:

- Poor brazing quality
- Poor bonding stength
- Poor coil insulation/impregantion
- Insufficient rust protection
- Loose or moving parts
- Covers not respecting IP2X
- Insufficient cable cross-section
- Obstructed cooling circuits
- Transport damages due to inadequate packaging

# Recurrent quality issues

## Lack/excess of brazing filler

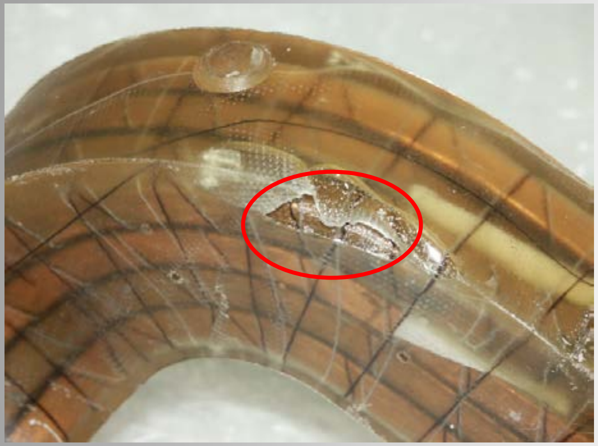







# Recurrent quality issues

Lack of resin: bubbles, voids, fissures, cracks, poor penetration, poor wetting

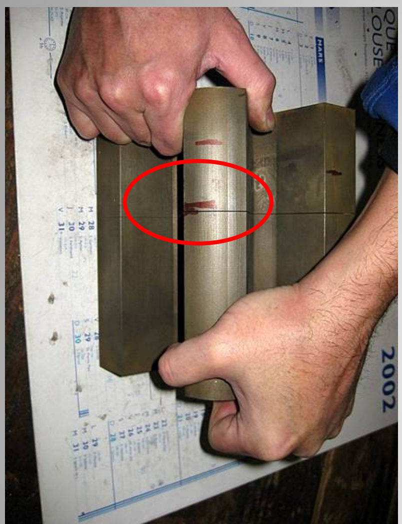
Excess of resin: volumes of pure resin






# Recurrent quality issues

## Poor lamination bonding stength




# Cost estimate

## Production specific tooling:

5 to 15 k€/tooling

## Material:

Steel sheets: 1.0 - 1.5 € /kg

Copper conductor: 10 to 20 € /kg

## Yoke manufacturing:

Dipoles: 6 to 10 € /kg (> 1000 kg)

Quads/Sextupoles: 50 to 80 € /kg (> 200 kg)

Small magnets: up to 300 € /kg

## Coil manufacturing:

Dipoles: 30 to 50 € /kg (> 200 kg)

Quads/Sextupoles: 65 to 80 € /kg (> 30 kg)

Small magnets: up to 300 € /kg

## Contingency:

10 to 20 %

| | | |
|---|---|---|
| Magnet | ***Magnet type*** | ***Dipole*** |
| | Number of magnets (incl. spares) | 18 |
| | Total mass/magnet | 8330 kg |
| Fixed costs | Design | 14 kEuros |
| | Punching die | 12 kEuros |
| | Stacking tool | 15 kEuros |
| | Winding/molding tool | 30 kEuros |
| Yoke | Yoke mass/magnet | 7600 kg |
| | Used steel (incl. blends)/magnet | 10000 kg |
| | Yoke manufacturing costs | 8 Euros/kg |
| | Steel costs | 1.5 Euros/kg |
| Coil | Coil mass/magnet | 730 kg |
| | Coil manufacturing costs | 50 Euros/kg |
| | Cooper costs (incl. insulation) | 12 Euros/kg |
| Total costs | Total order mass | 150 Tonnes |
| | Total fixed costs | 71 kEuros |
| | Total Material costs | 428 kEuros |
| | Total manufacturing costs | 1751 kEuros |
| | Total magnet costs | 2250 kEuros |
| | Contingency | 20 % |
| | **Total overall costs** | **2700 kEuros** |

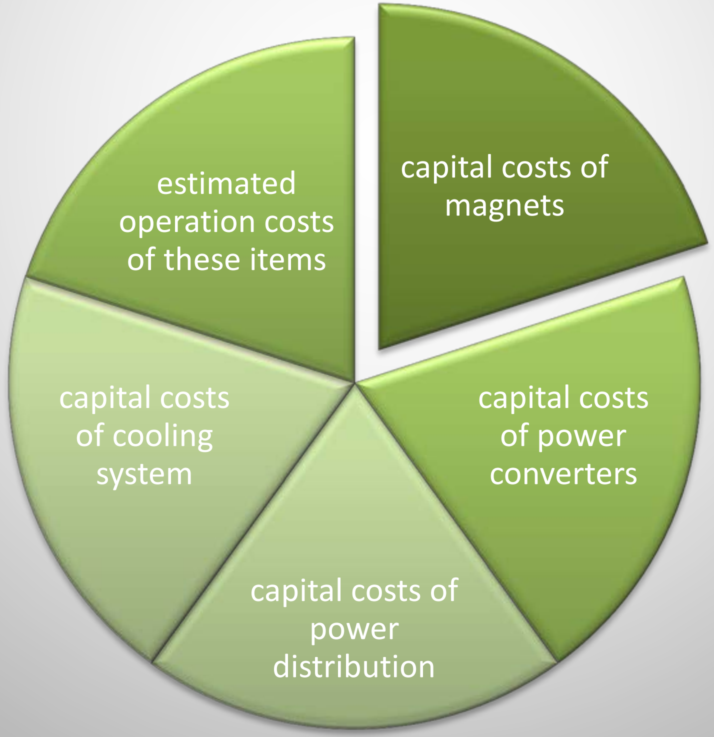
NOT included: magnetic design, supports, cables, water connections, alignment equipment, magnetic measurements, transport, installation
Prices for 2011

# Cost optimization

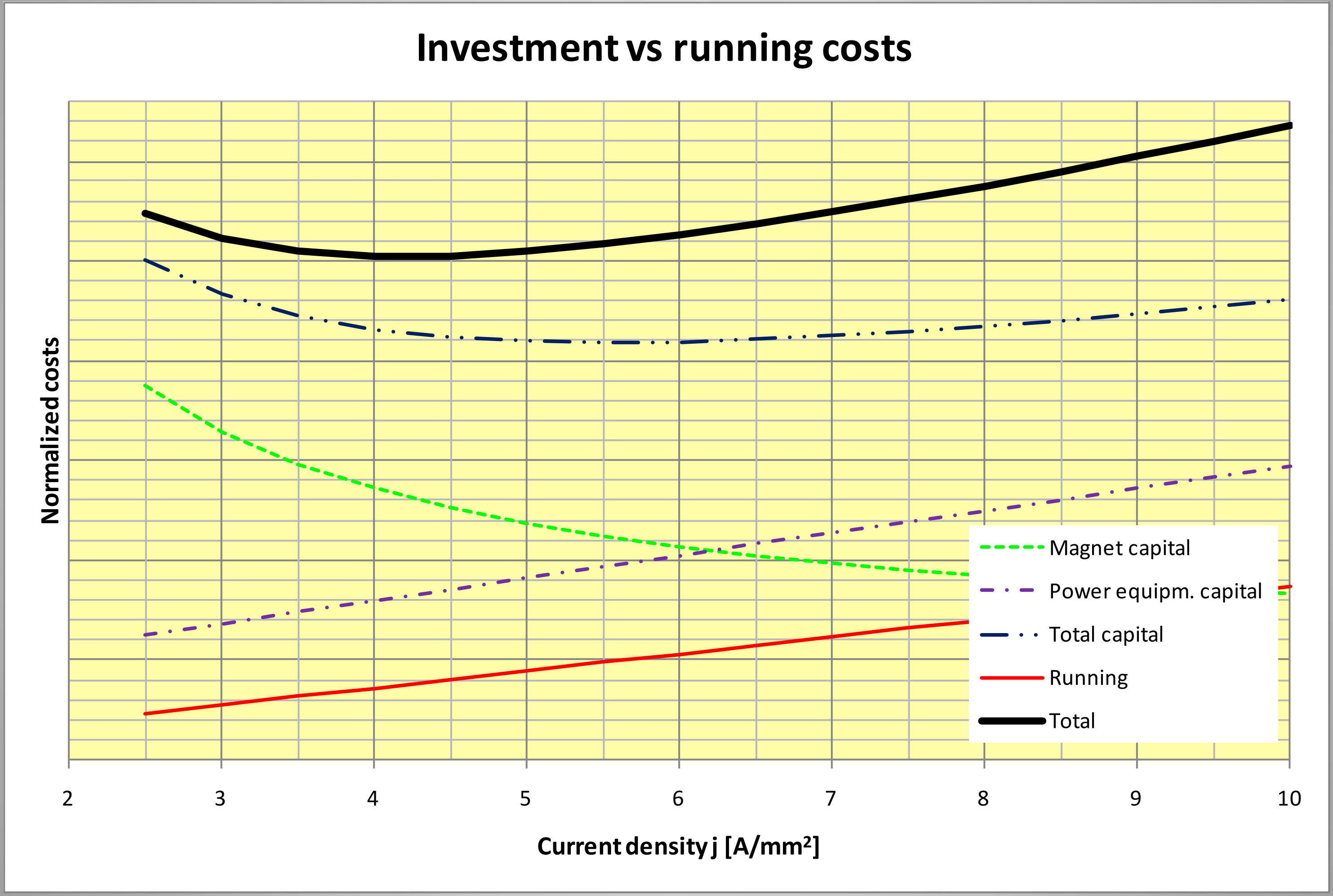
*Focus on economic design!*

Design goal: Minimum total costs over projected magnet life time by optimization of capital (investment) costs against running costs (power consumption)

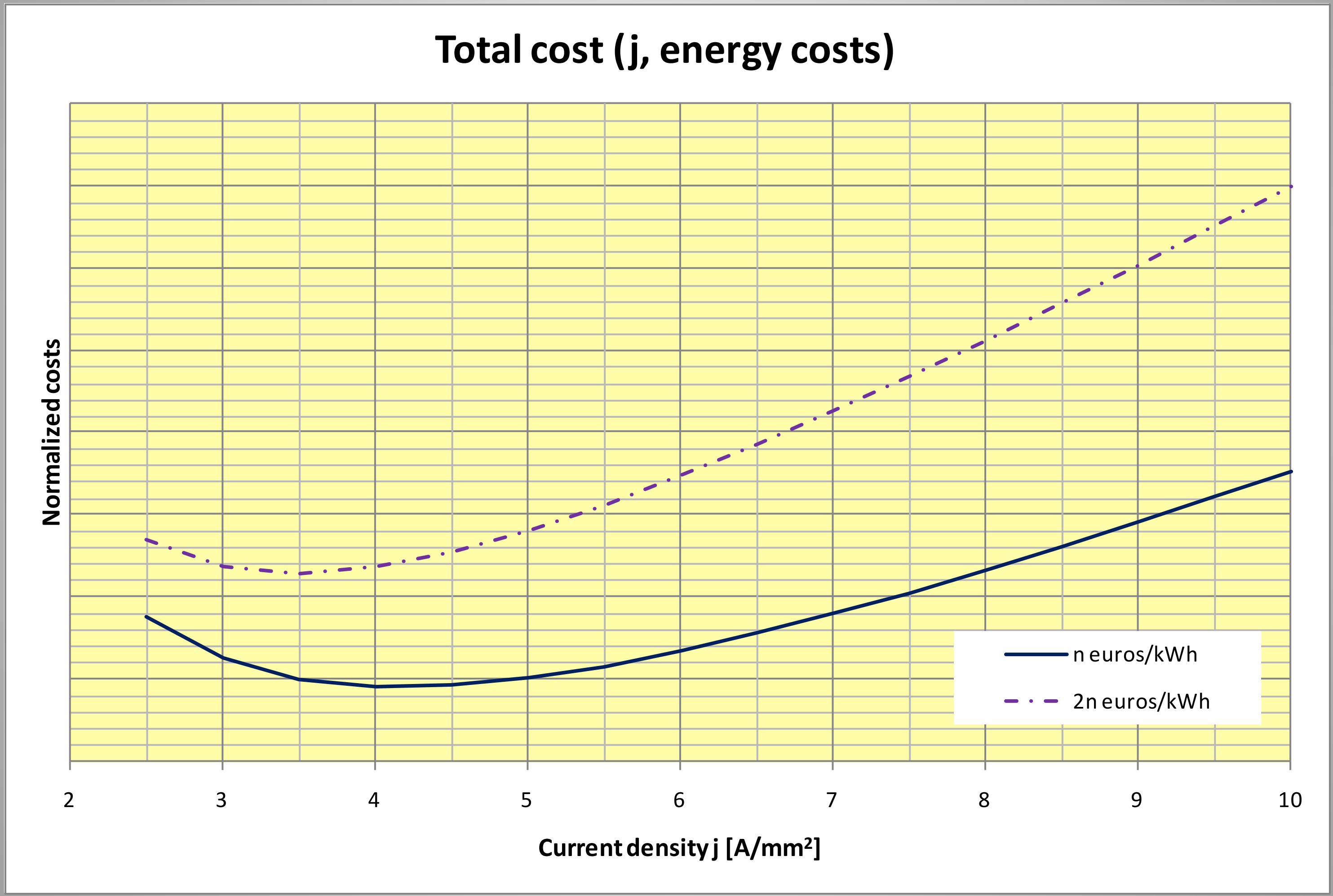
Total costs include:



# Cost optimization



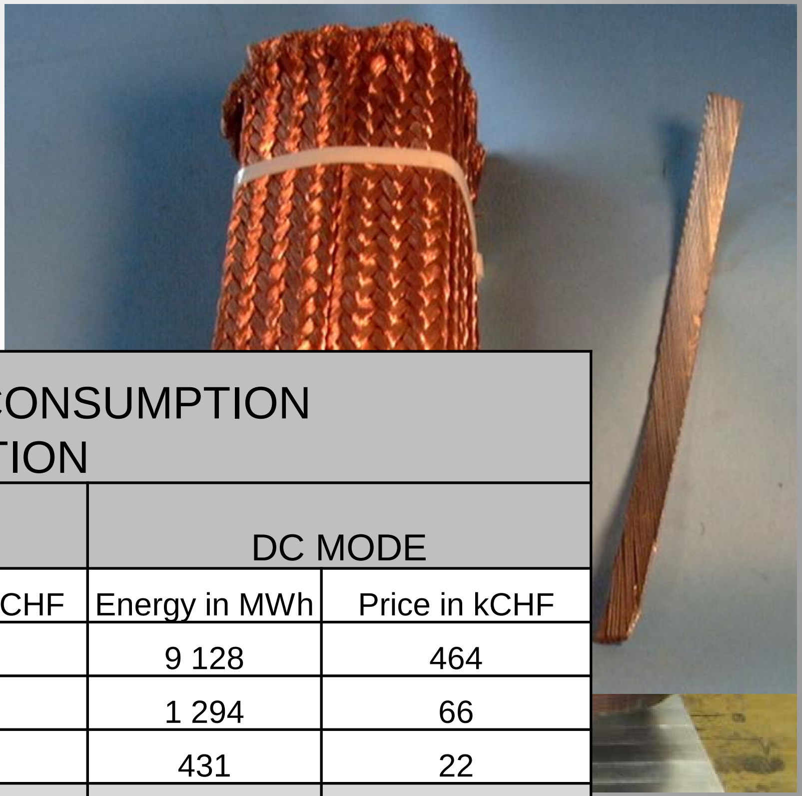
# Cost optimization



# Consider alternatives!

So far we have discussed only normal-conducting, iron-dominated magnets operated in dc… but this might not always be the best choice!

- Permanent magnets (Sm2Co17)
- Hybrid magnets
- Use of high-saturation materials
- Superconducting / super-ferric magnets
- Pulsed operation



| EAST AREA ANNUAL POWER CONSUMPTION AFTER CONSOLIDATION | | | | |
|---|---|---|---|---|
| | PULSED MODE | | DC MODE | |
| | Energy in MWh | Price in kCHF | Energy in MWh | Price in kCHF |
| Total magnet electrical consumption | 557 | 28.3 | 9 128 | 464 |
| Water cooling electrical consumption | 79 | 4.0 | 1 294 | 66 |
| Air cooling electrical consumption | 26 | 1.3 | 431 | 22 |
| **Total electricity consumption** | **662** | **33.7** | **10 853** | **551.8** |
| Total cooling fluid | | 6.2 | | 101.5 |
| **TOTAL energy cost** | | **40 kCHF** | | **653 kCHF** |

# Summary

- Magnet design has a direct impact on manufactruing (and vice versa)
- The yoke shape and dimensional accuracy is essential for magnetic field quality in iron-dominated magnets
- The manufacturing techniques shall be adapted to meet the specified requirements of the finial product in all respects
- Tight QA is the key for success and important at each production stage
  - Sample testing to qualify materials, manufacturing techniques and processes
  - Acceptance tests to verify the correct performance of the final product
  - Magnetic measurements are an essential part of the qualification process
- Cost optimization is an important design aspect, in particular in view of future energy costs