Joint Universities Accelerator School

JUAS 2016

Archamps, France, 22nd – 26th February 2016

Normal-conducting accelerator magnets

Thomas Zickler,

CERN

Lecture 3: Magnet production

Magnetic materials

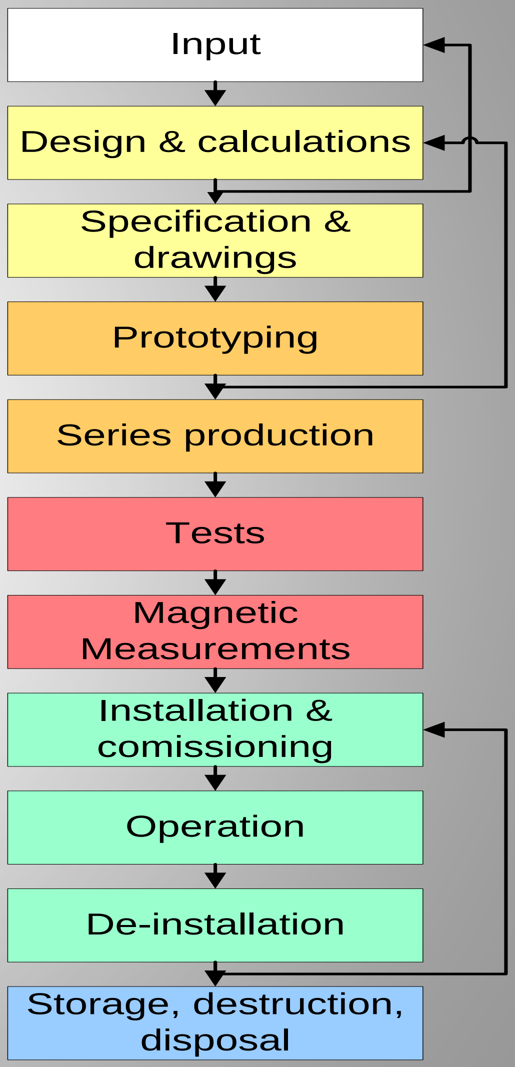
Manufacturing techniques

QA & Acceptance tests

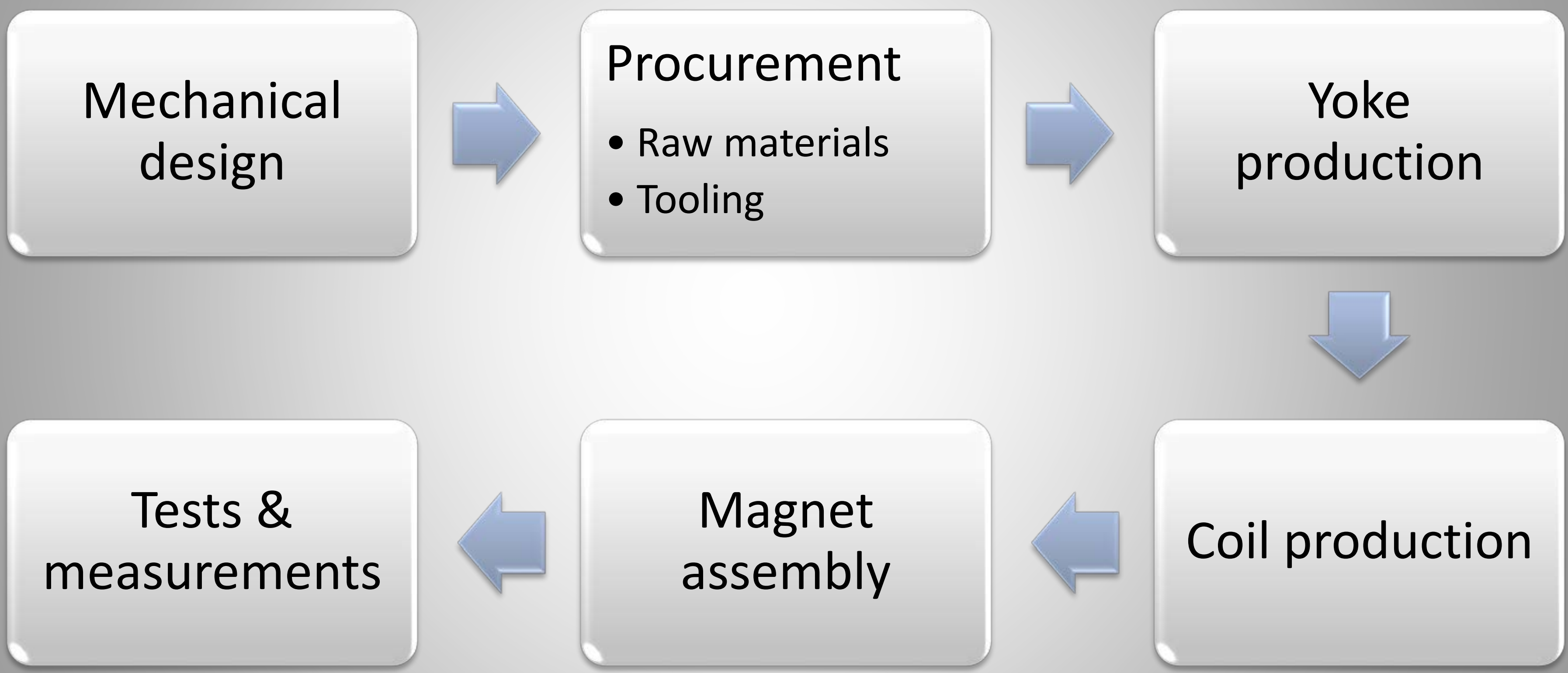
Recurrent issues

Magnetic measurements

Cost estimates and optimization



Magnet manufacturing



Massive vs. laminated yokes

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

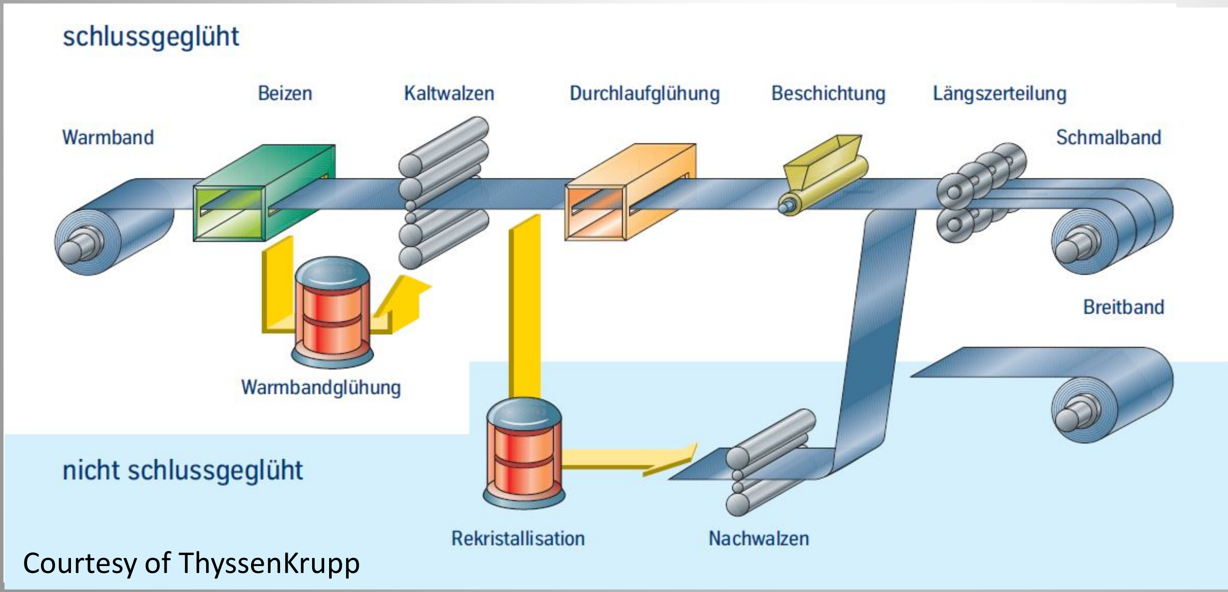
+ no stamping, no stacking
+ less expensive for prototypes and small series
- time consuming machining, in particular for complicated pole shapes
- difficult to reach similar magnetic performance between magnets

+ 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)

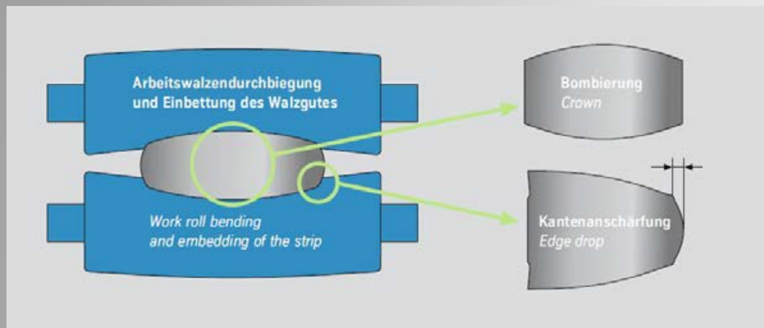
- Magnetic and mechanical properties can be adjusted by final annealing
- Reproducible steel quality even over large productions
- Magnetic properties (permeability, coercivity) within small tolerances
- Homogeneity and reproducibility among the magnets of a series can be enhanced by selection, sorting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

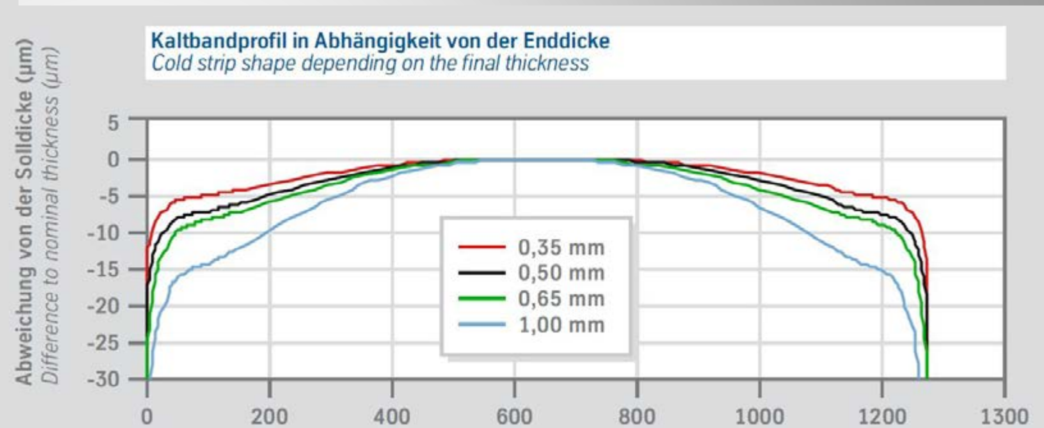


Courtesy of ThyssenKrupp

Profile of steel strips

The rolling process produces a thickness variation perpendicular to the rolling direction:





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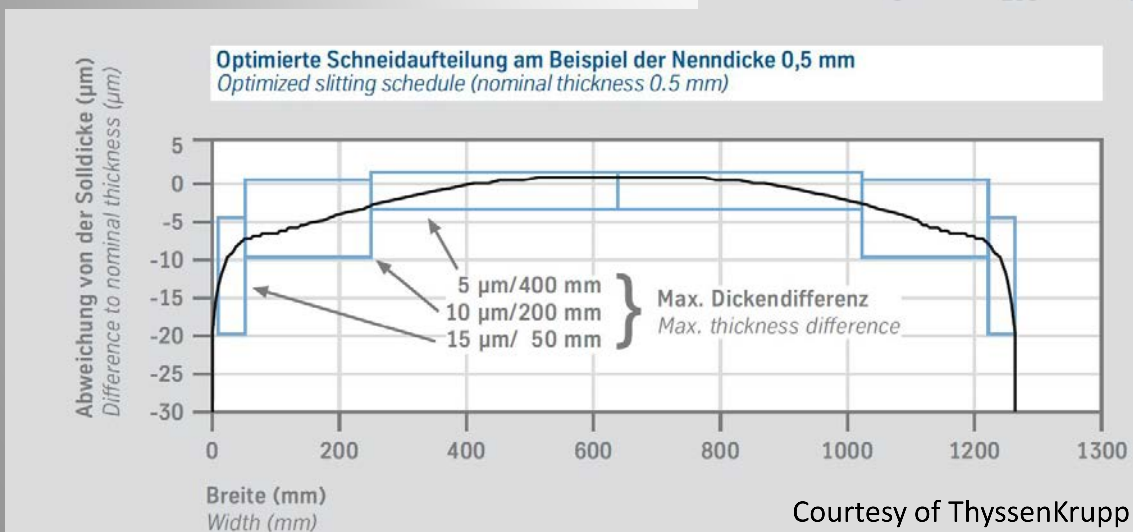

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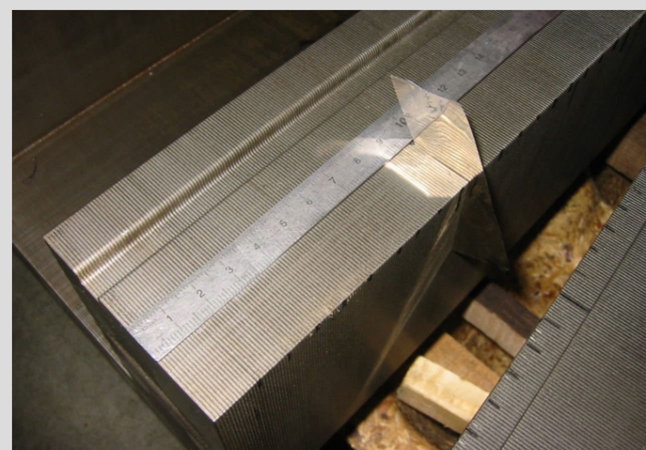
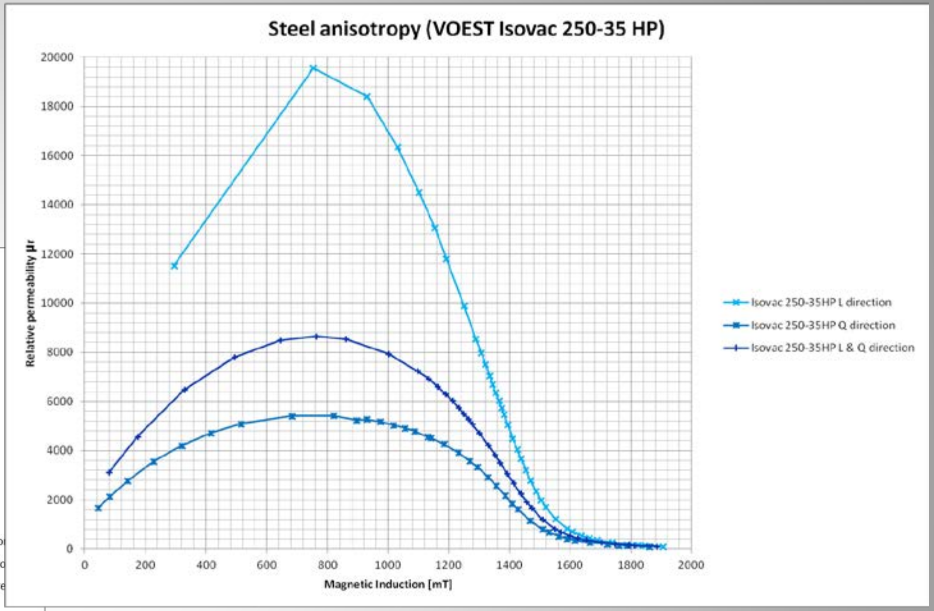
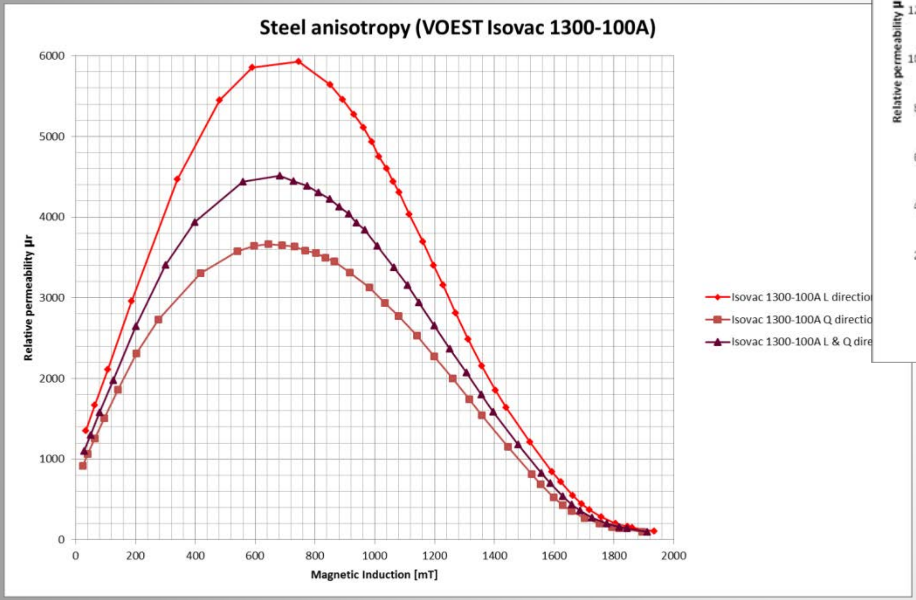


NGO steel properties



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



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

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

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

Electr. resistivity @20°C:
0.16 (low Si) $\leq \rho$
$\leq$ 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 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

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

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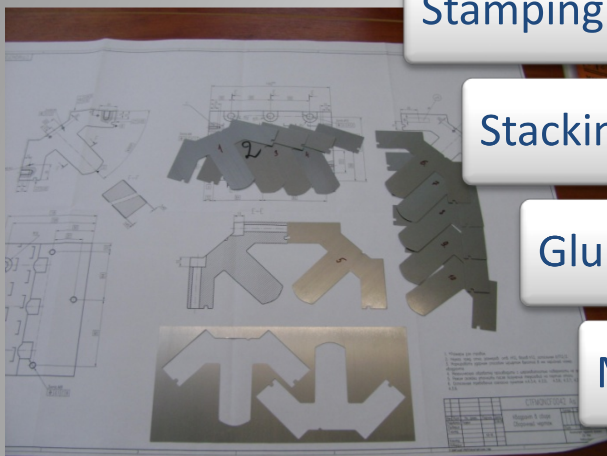
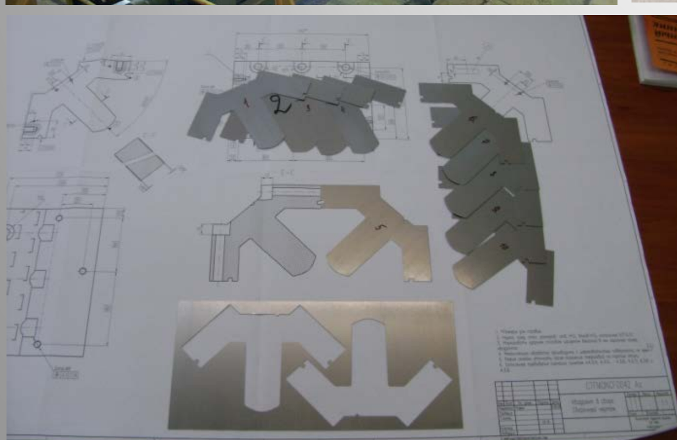
Yoke manufacturing

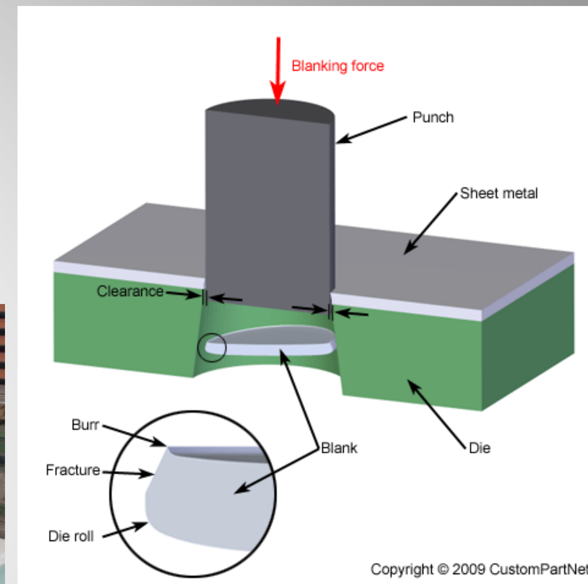
- Stamping laminations
- Stacking laminations into yokes
- Gluing and/or welding
- Machining
- Assembly (preliminary)

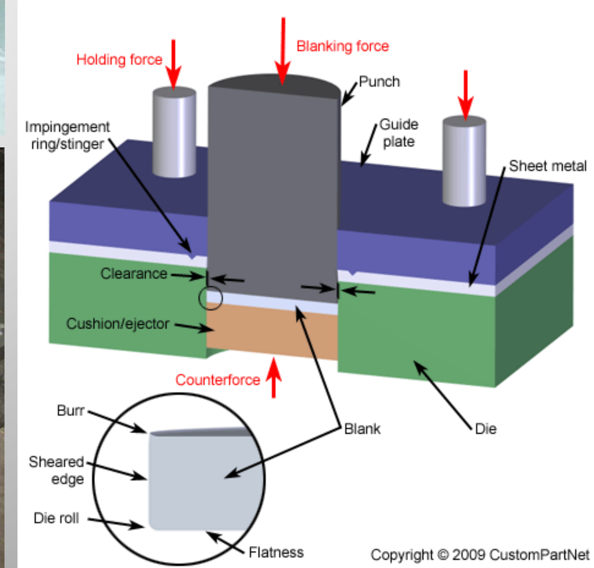


Lamination punching

- 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)

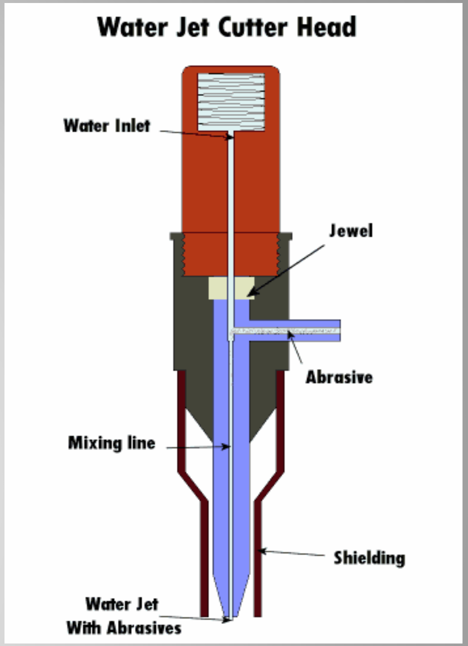




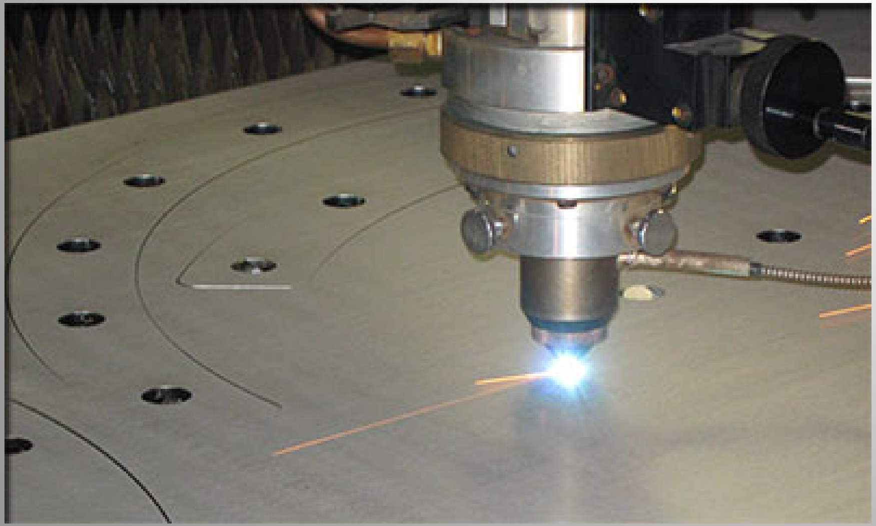


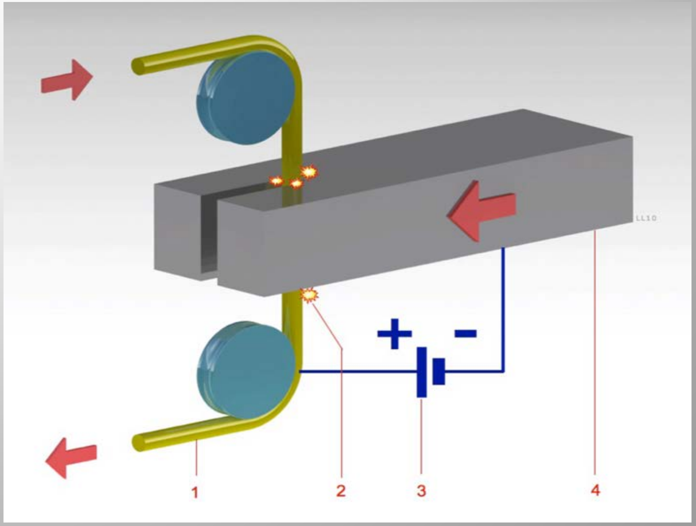
Alternatives to punching

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

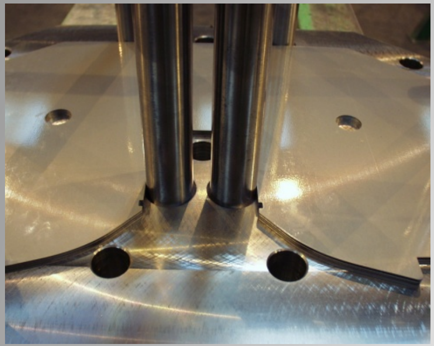


...or a combination of different techniques



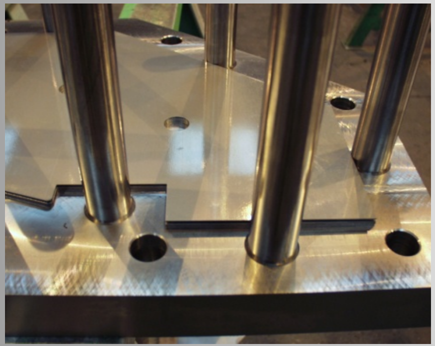


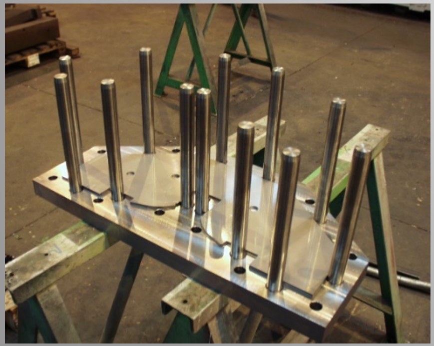
Yoke stacking

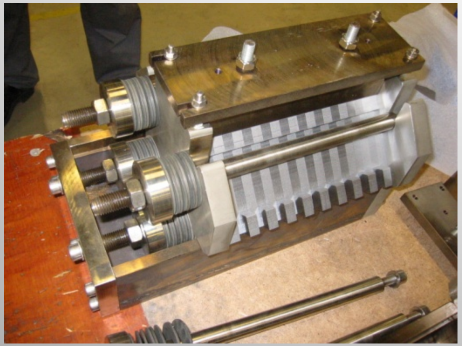


Tooling for:

- stacking
- baking
- welding



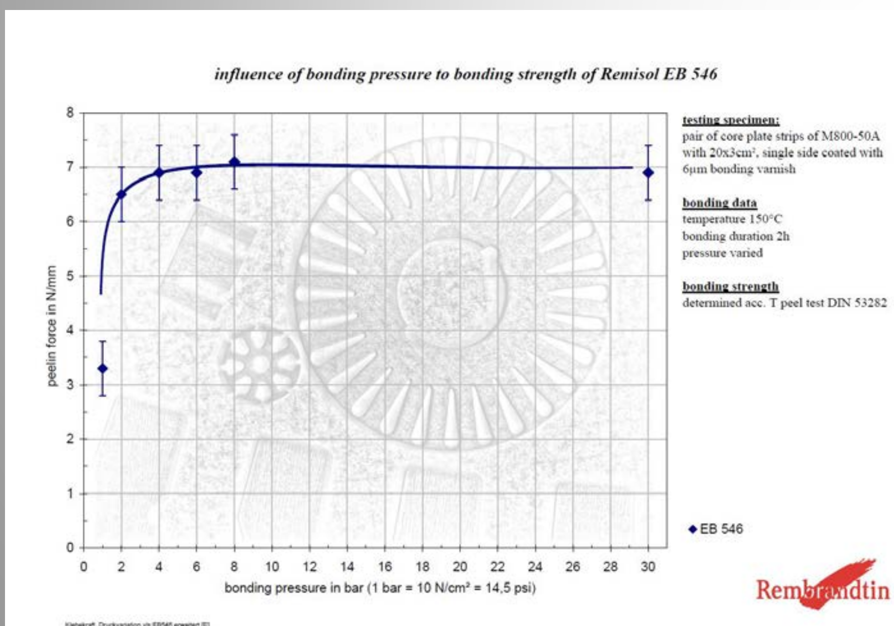


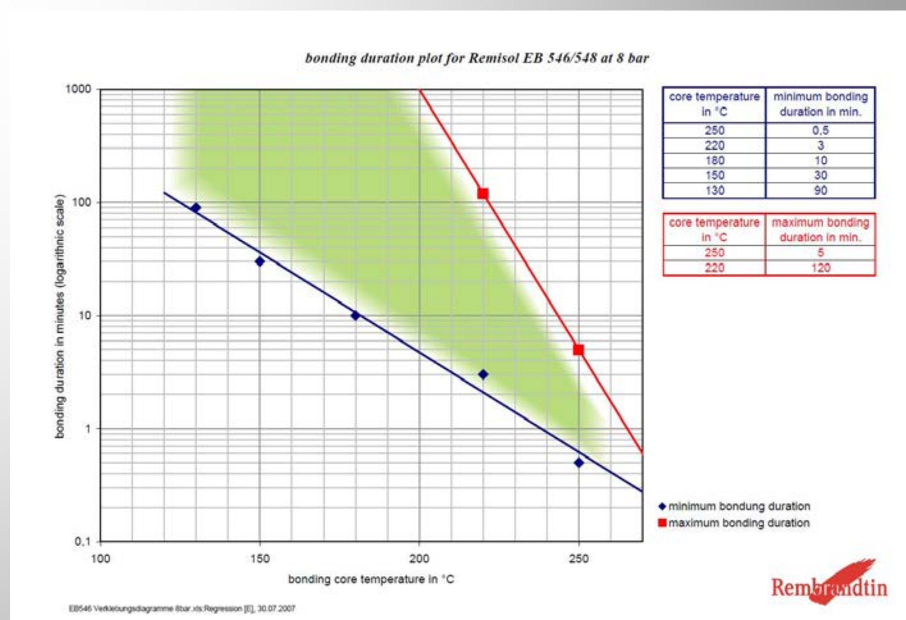


Bonding & insulation

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

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Glueing vs. Welding

Welding

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

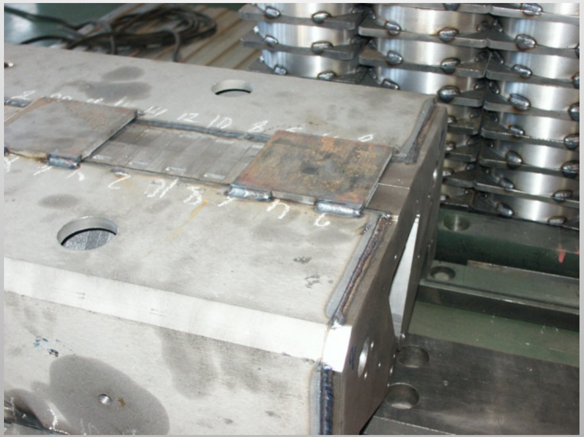
/ requires stacking fixture

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

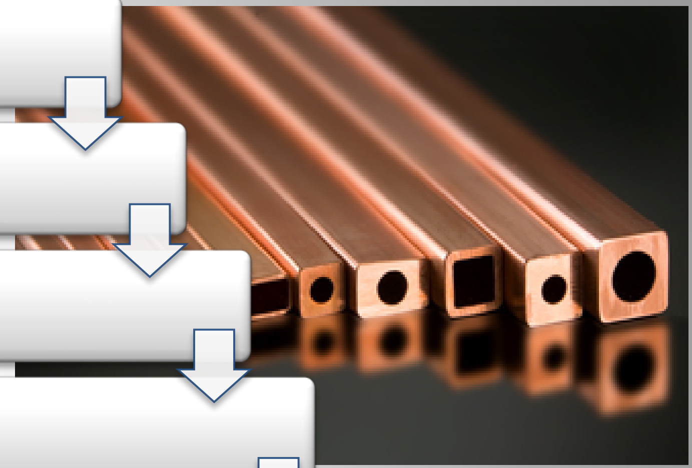
Define conductor type and material

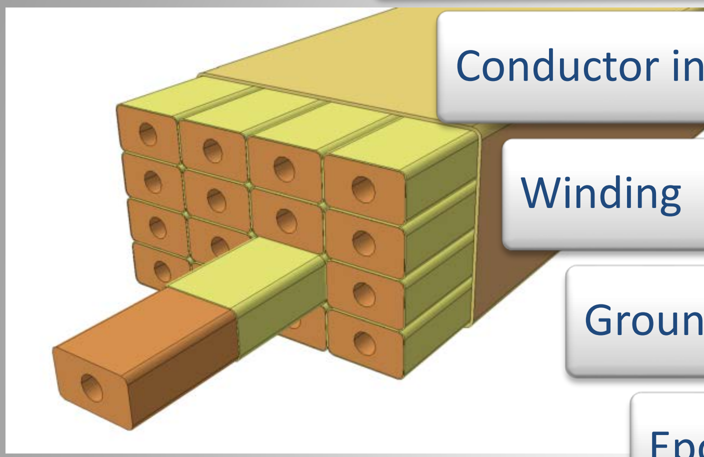
Conductor insulation

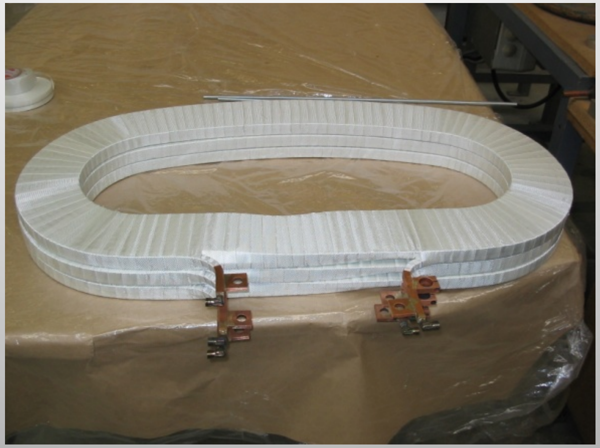
Winding

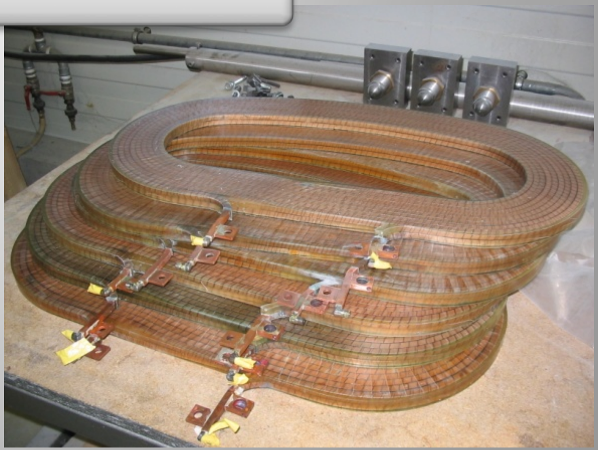
Ground insulation

Epoxy impregnation



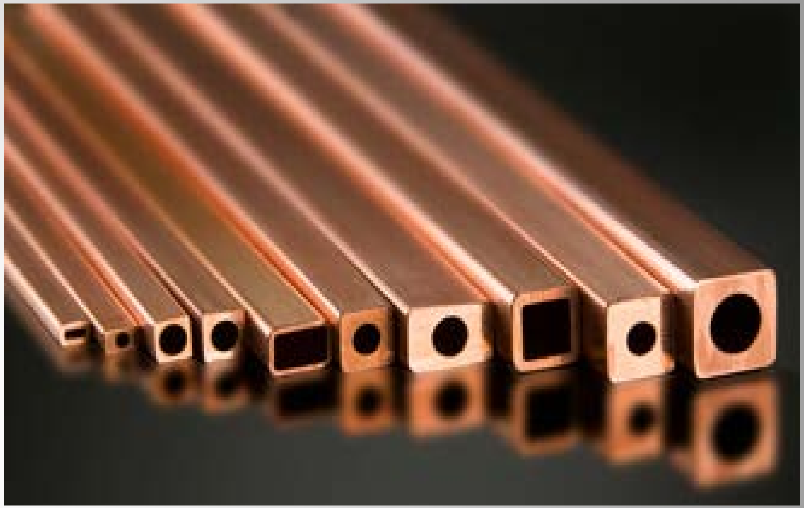




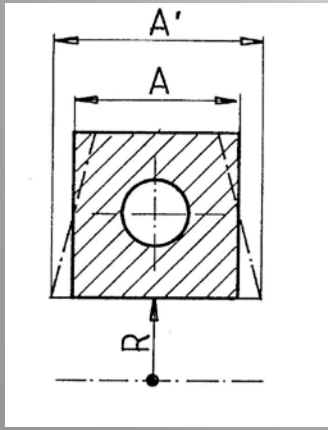


Conductor materials

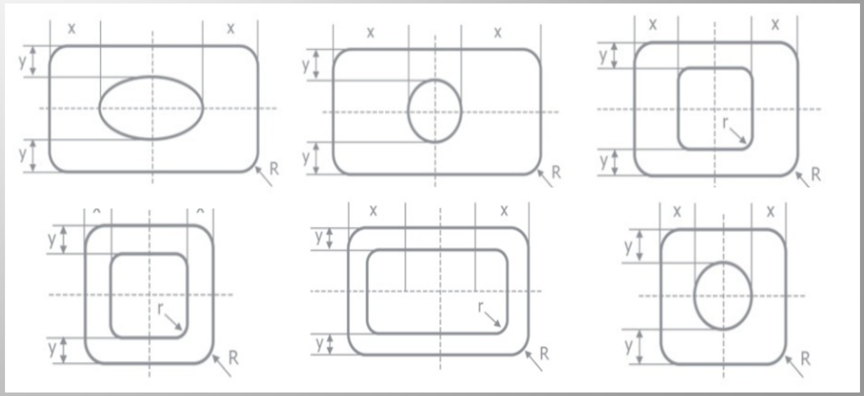
	Al	Cu (OF)
Purity	99.7 %	99.95 %
Resistivity @ 20°C	2.83 μΩ cm	1.72 μΩ cm
Thermal resistivity coeff.	0.004 K^{-1}	0.004 K^{-1}
Specific weight	2.70 g/cm^3	8.94 g/cm^3
Thermal conductivity	2.37 W/cm K	3.91 W/cm K



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)

The electrical insulation is stressed by several factors:

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

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

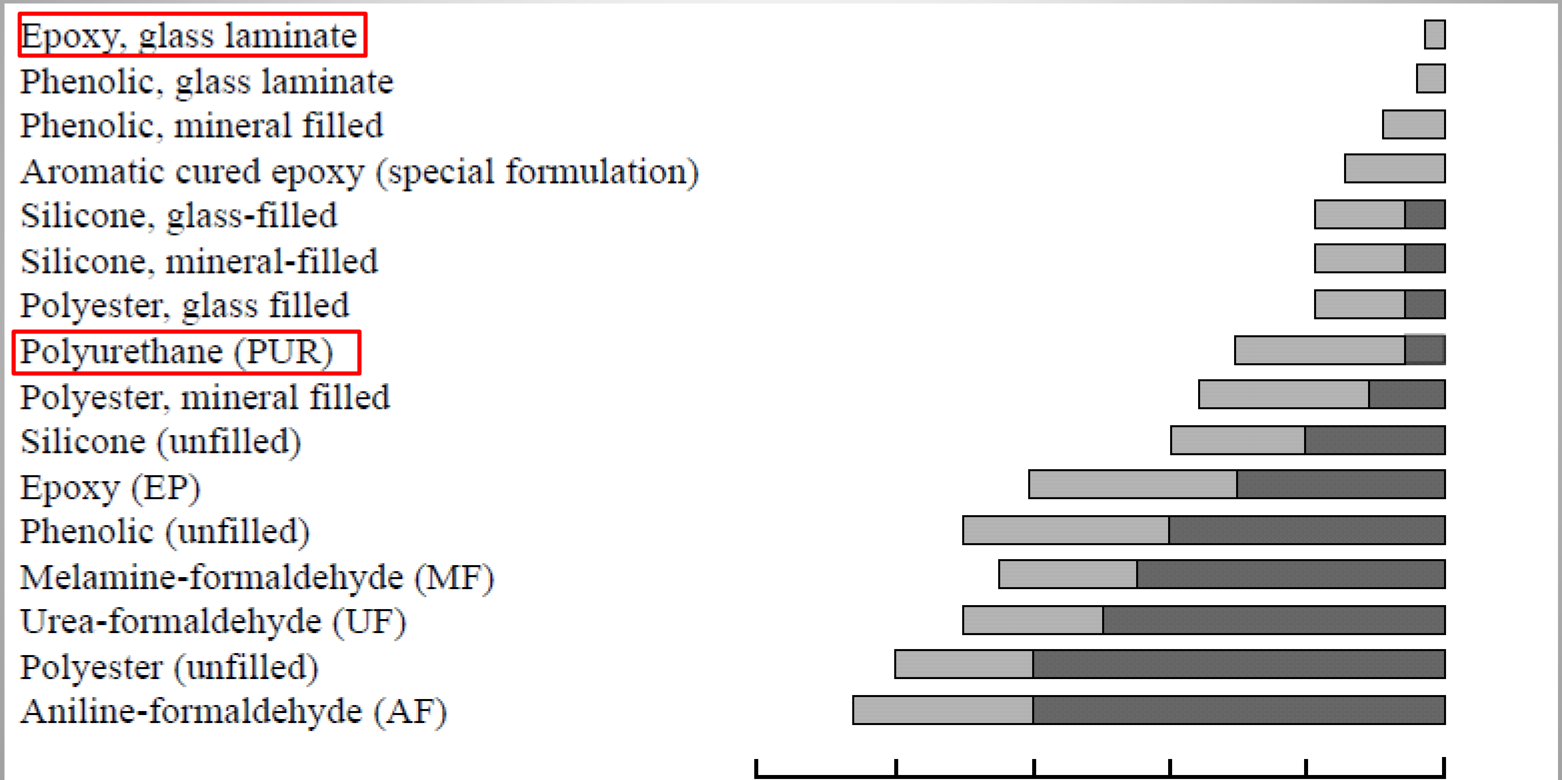
Montsinger's rule / Arrhenius equation: $L(T+10\,K) \approx 0.5\; t(T)$

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

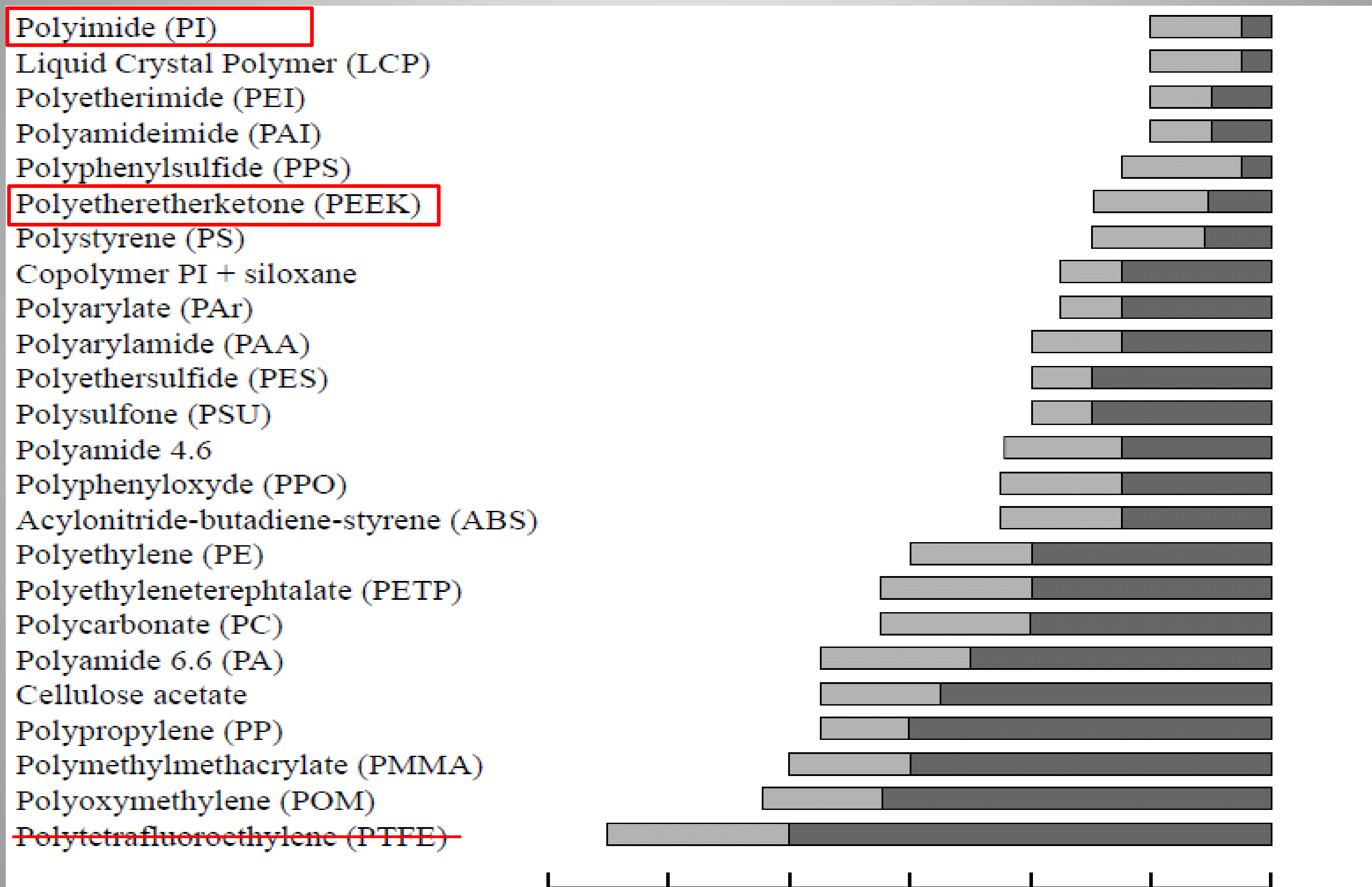
Radiation hardness is an important criterion for insulation materials used for accelerator applications



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

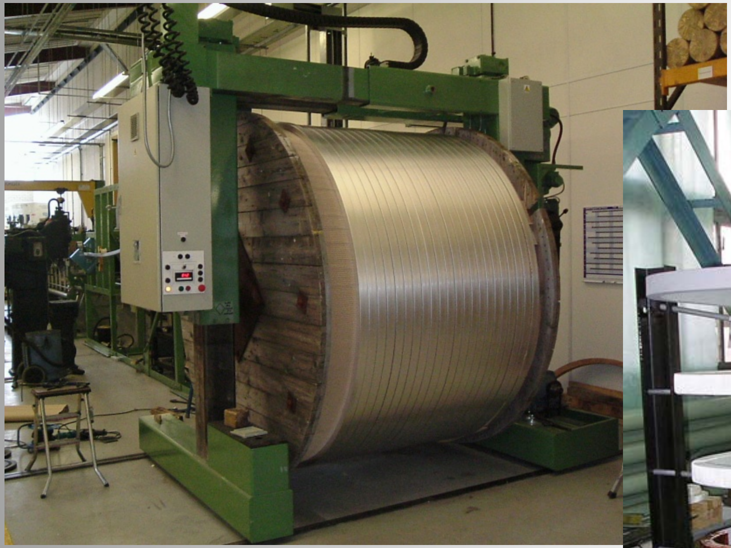
Conductors with small cross-section:

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






Magnet assembly

By hand....

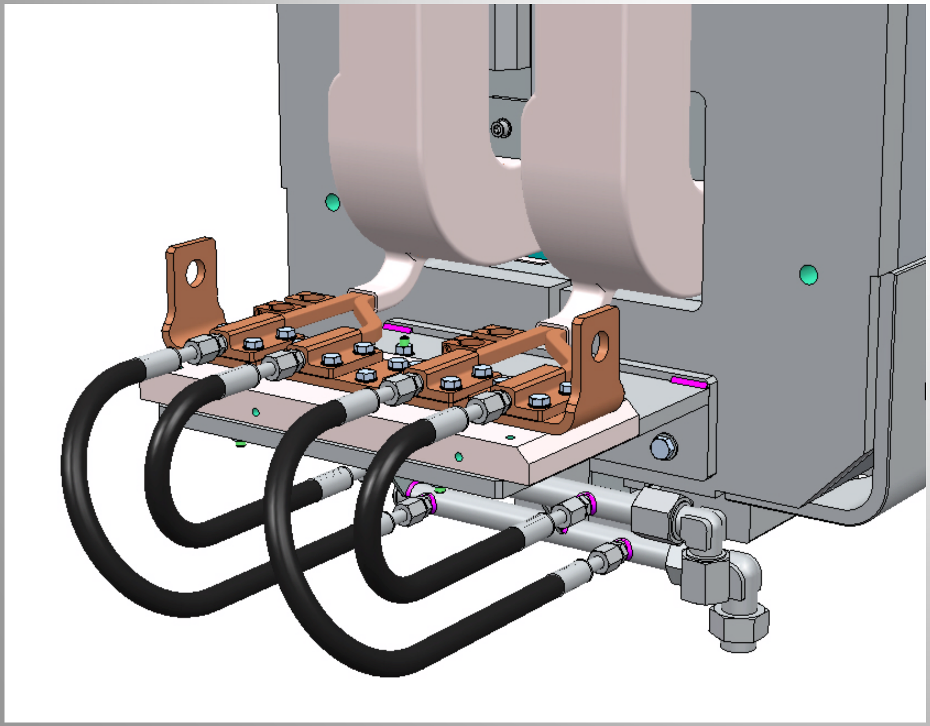


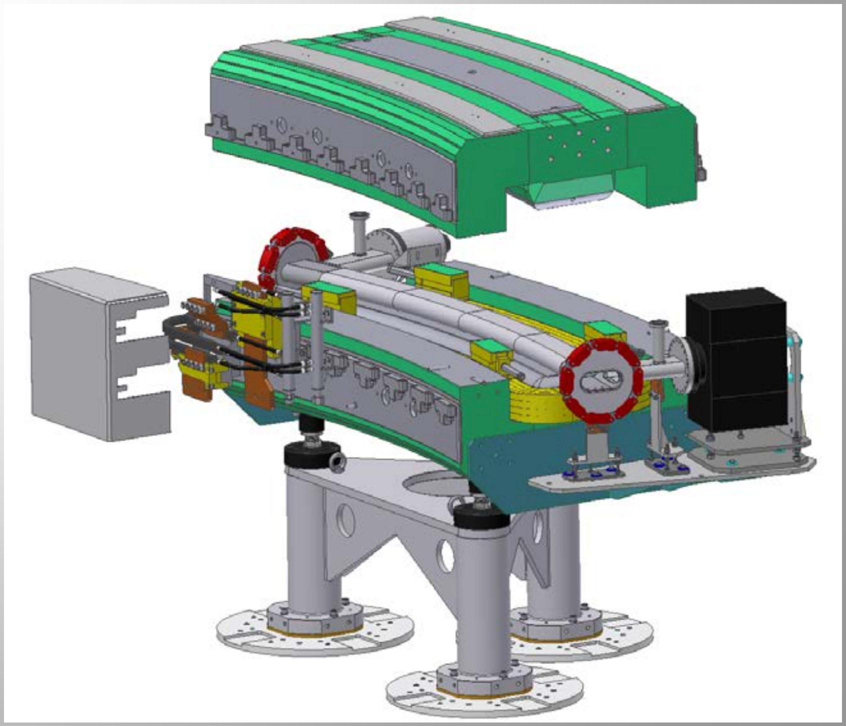

... or with the help of tooling




Auxiliary components

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





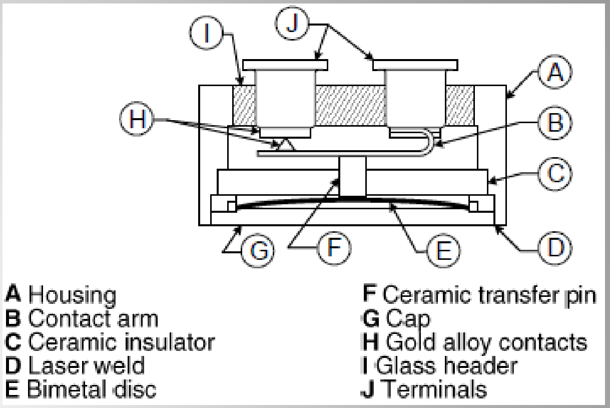
Hydraulic circuits

- 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

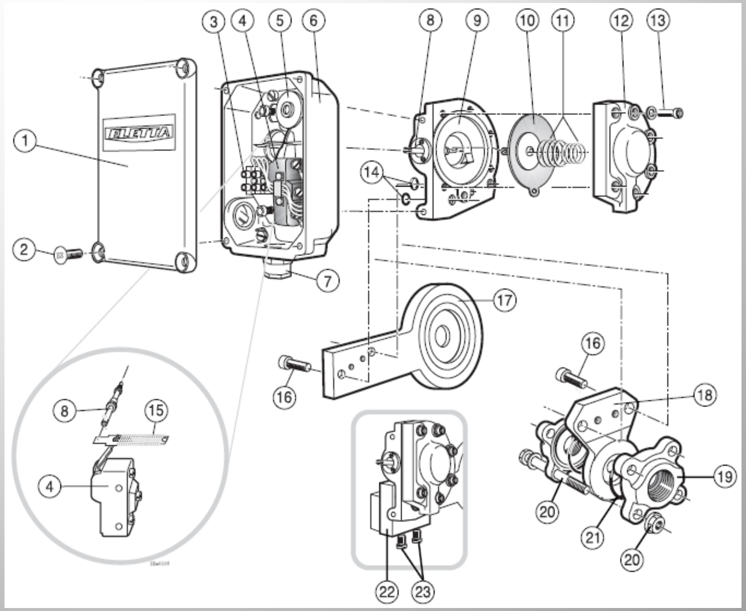
- Leaks can be detected and repaired during magnet acceptance tests and commissioning...
- ... but, many leaks occur only after years in operation
- Often not monitored $\rightarrow$ magnet damage (short cicuits, corrosion of iron yoke) <u>and</u> collateral damages on other equipment possible

Interlock Sensors

Thermo-switch:



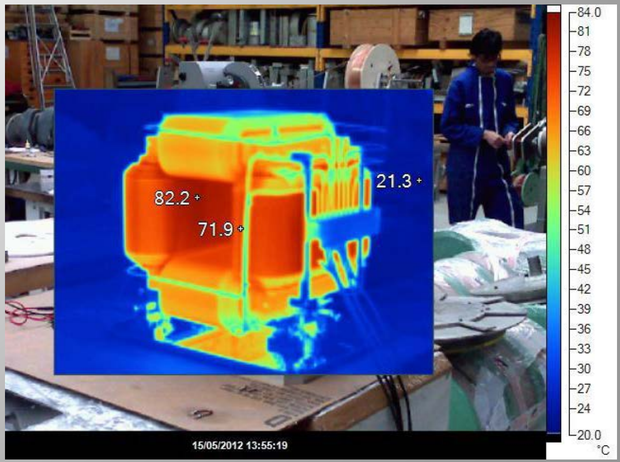
Flow-switch:



QA & Acceptance tests

QA is important at each production stage

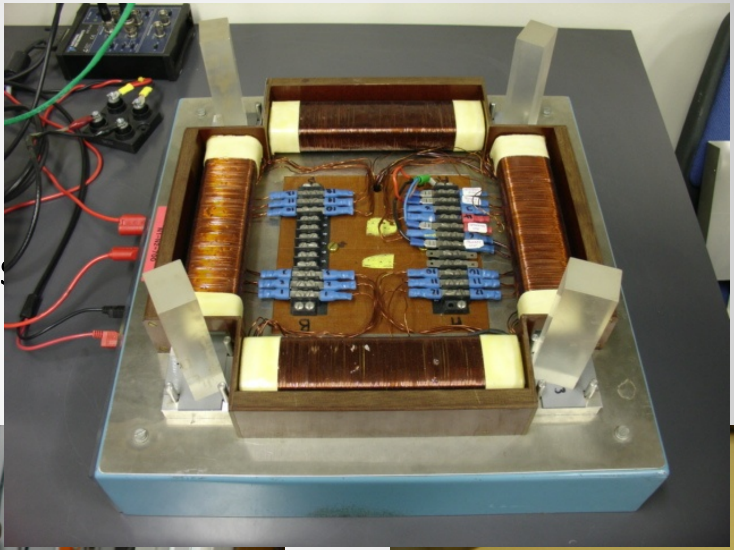
- Constant monitoring of critical items from the raw material, to semi-finished parts, to sub-components to the final product
- Sample testing (destructive or non-destructive) to qualify materials, manufacturing techniques and processes
- Acceptance test can include electrical, hydraulic, mechanical, 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)

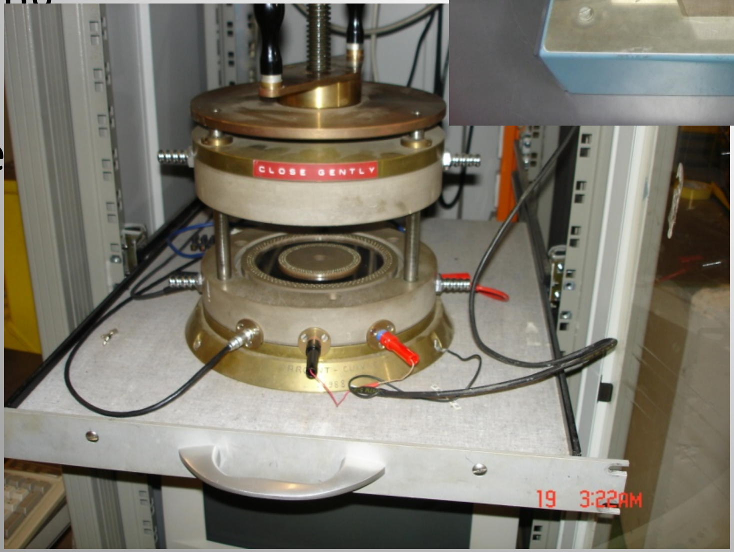


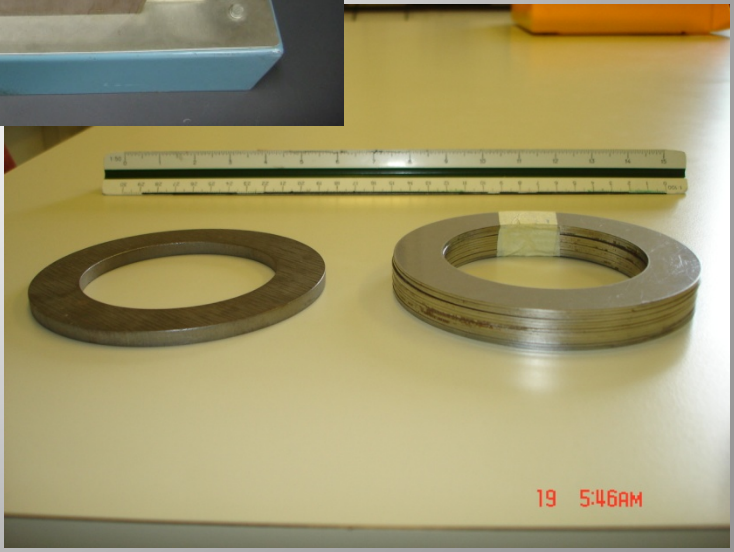
Sample testing

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

- Magnetic steel
- Laminations
- Bond strenght (lamination
- Brazing
- Welding
- Bond
- Impre







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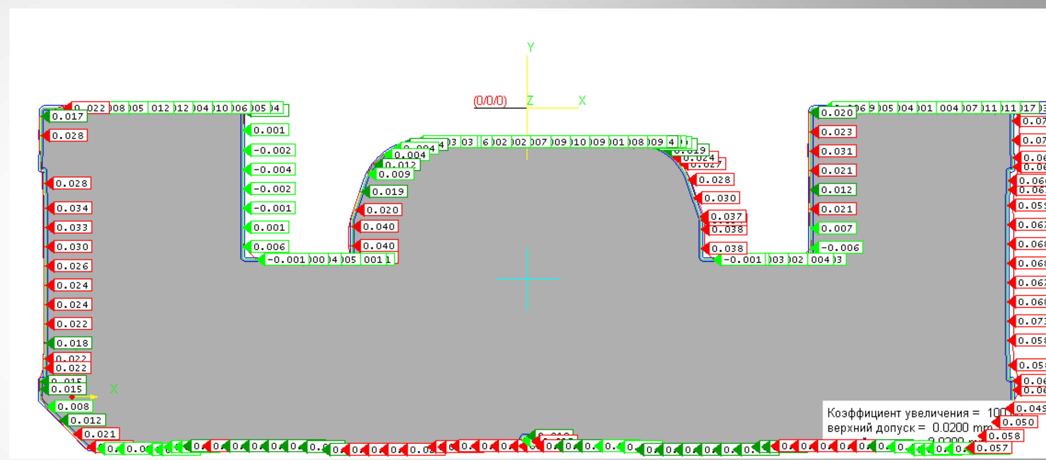
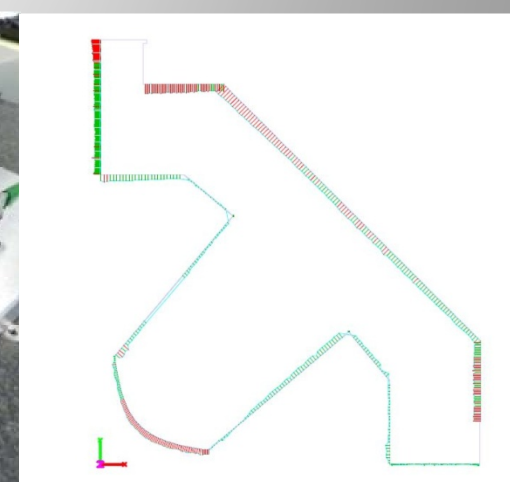
- Bond strength (coil)





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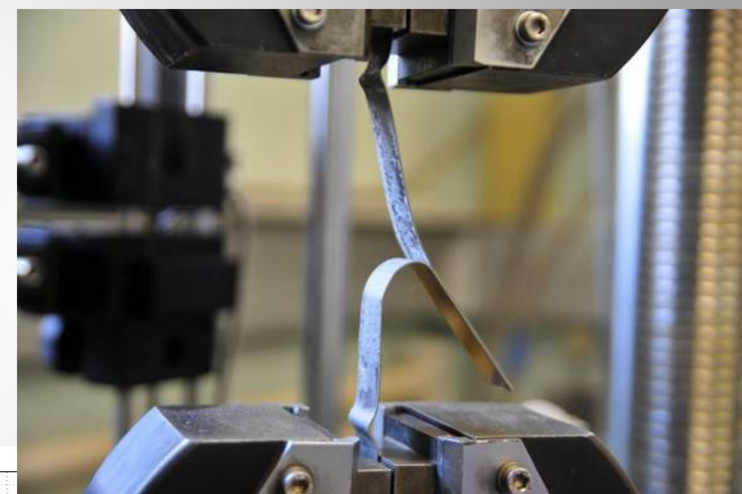

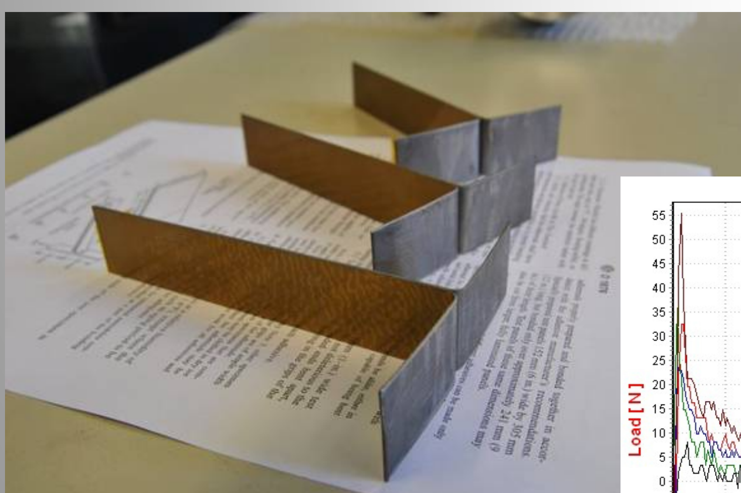

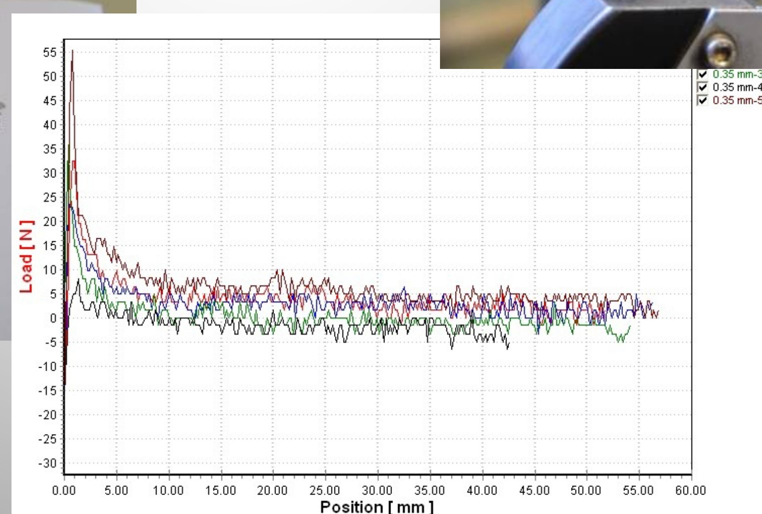

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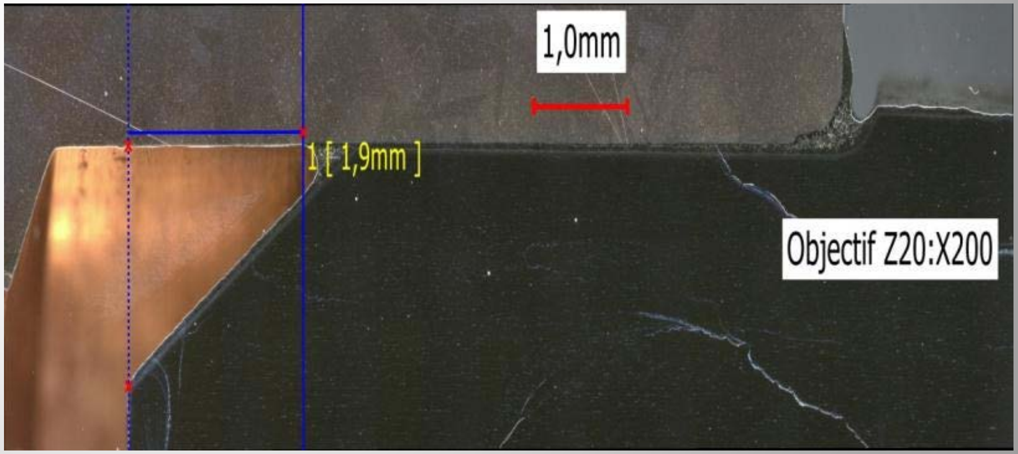
- Impregnation



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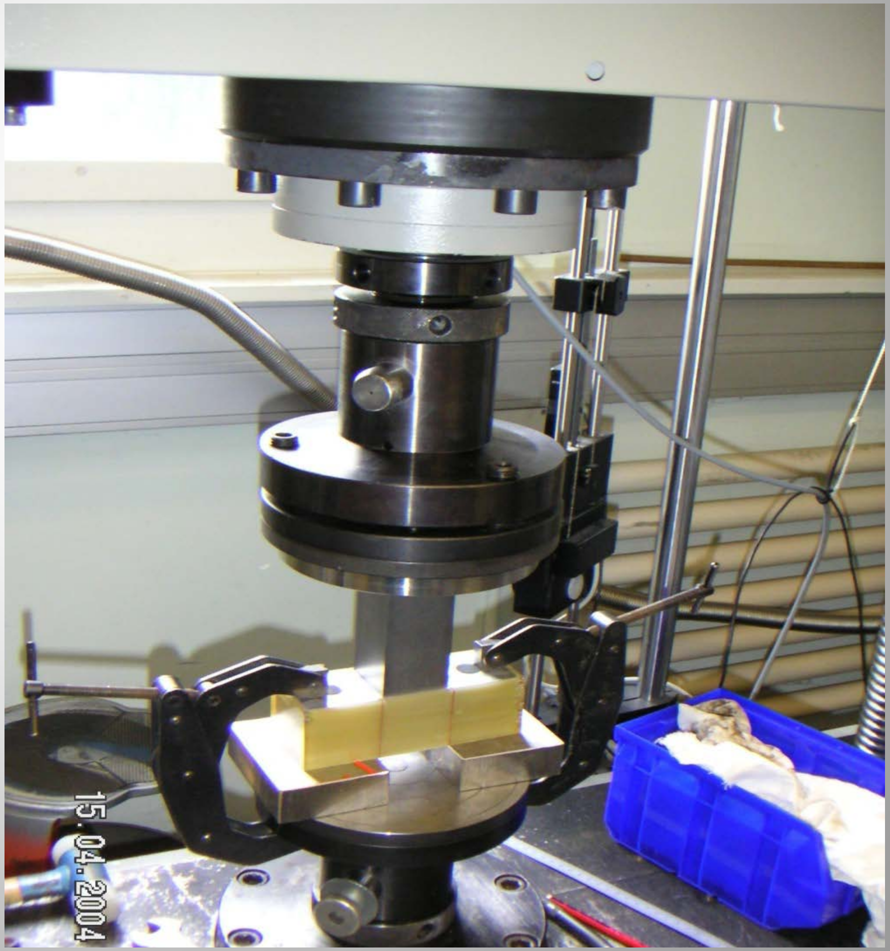

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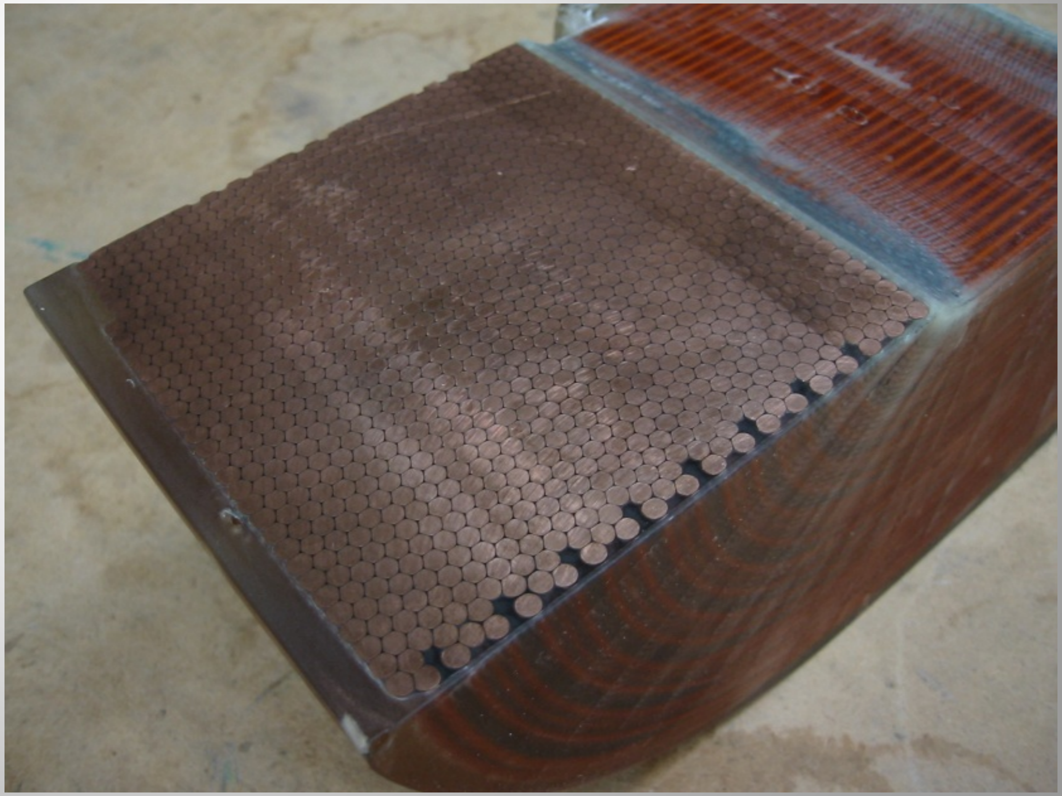
- Brazing
- Welding
- Bond strength (coil)
- Impregnation



Recurrent quality issues

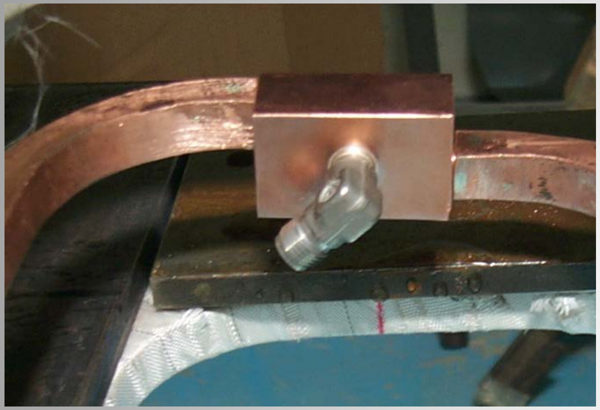
Despite a severe quality control by the manufacturer, we often find quality deficiencies during the acceptance tests and certification at CERN

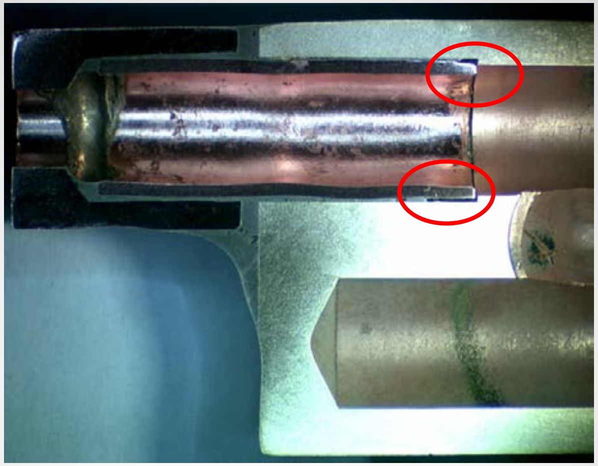
Amongst several other recurrent issues, the following are the most frequent and most serious:

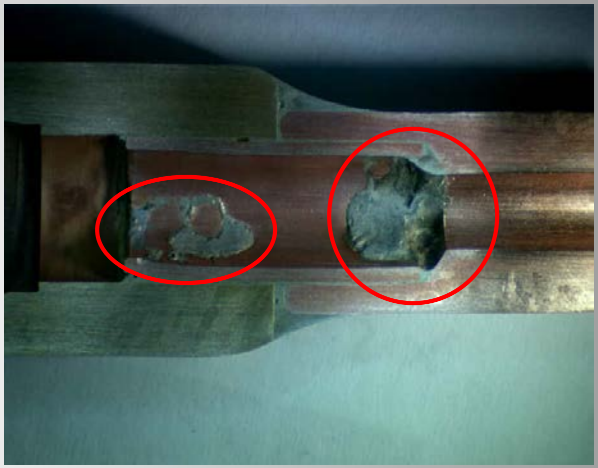
- Poor brazing quality
- Poor bonding stength
- Poor coil insulation/impregantion
- Insufficient rust protection
- Loose or moving parts
- Covers not respecting IP2X
- Insufficient cable cross-section
- Obstructed cooling circuits
- Transport damages due to inadequate packaging

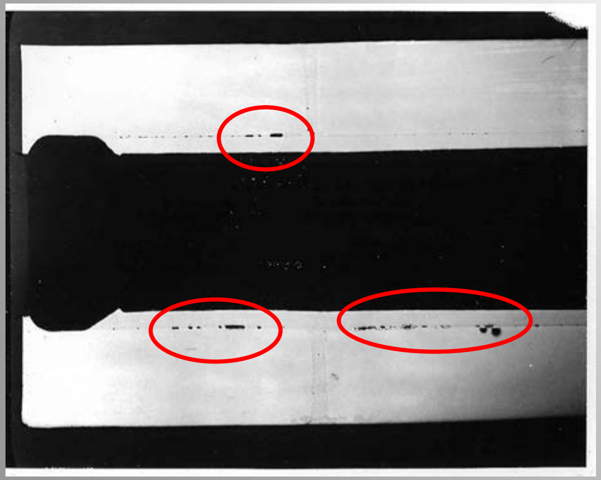
Recurrent quality issues

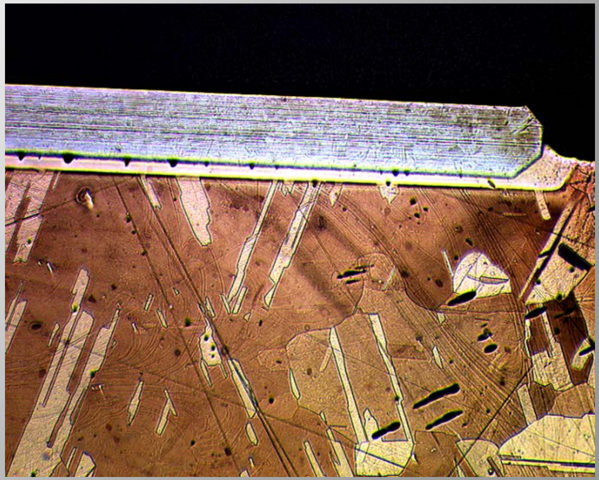
Lack/excess of brazing filler







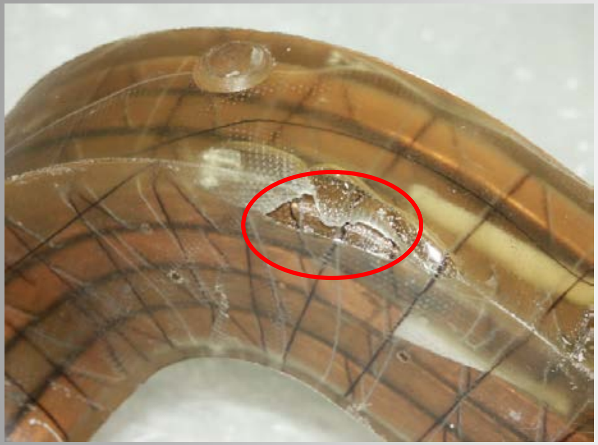




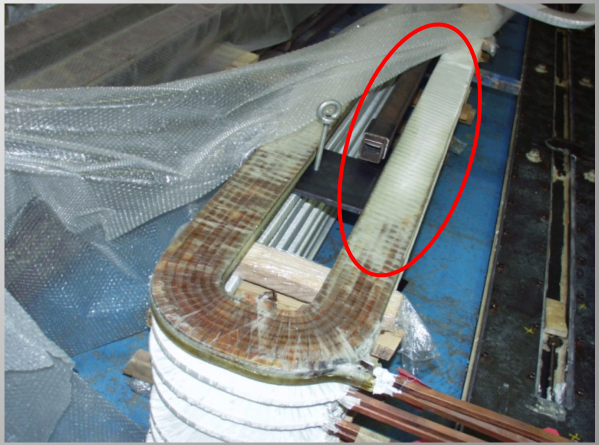
Recurrent quality issues

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

Excess of resin: volumes of pure resin





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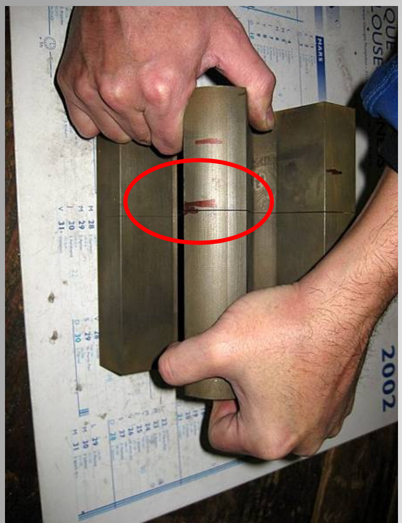
Recurrent quality issues

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**

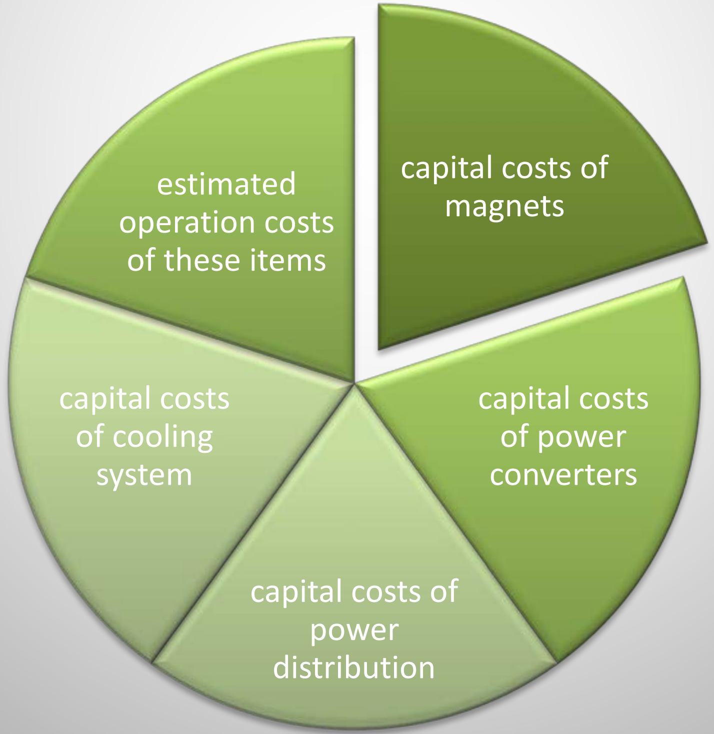
NOT included: magnetic design, supports, cables, water connections, alignment equipment, magnetic measurements, transport, installation
Prices for 2011

Cost optimization

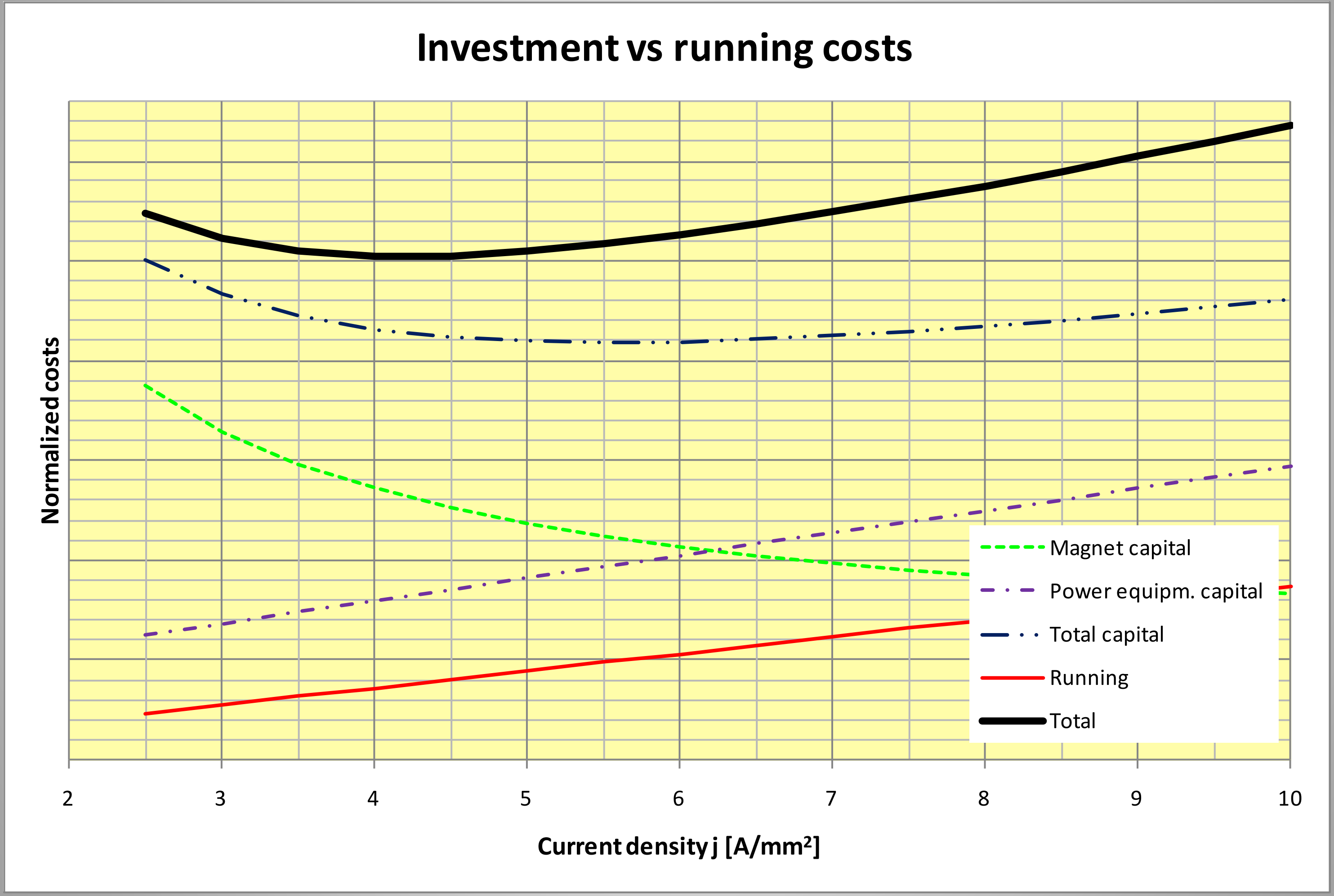
Focus on economic design!

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

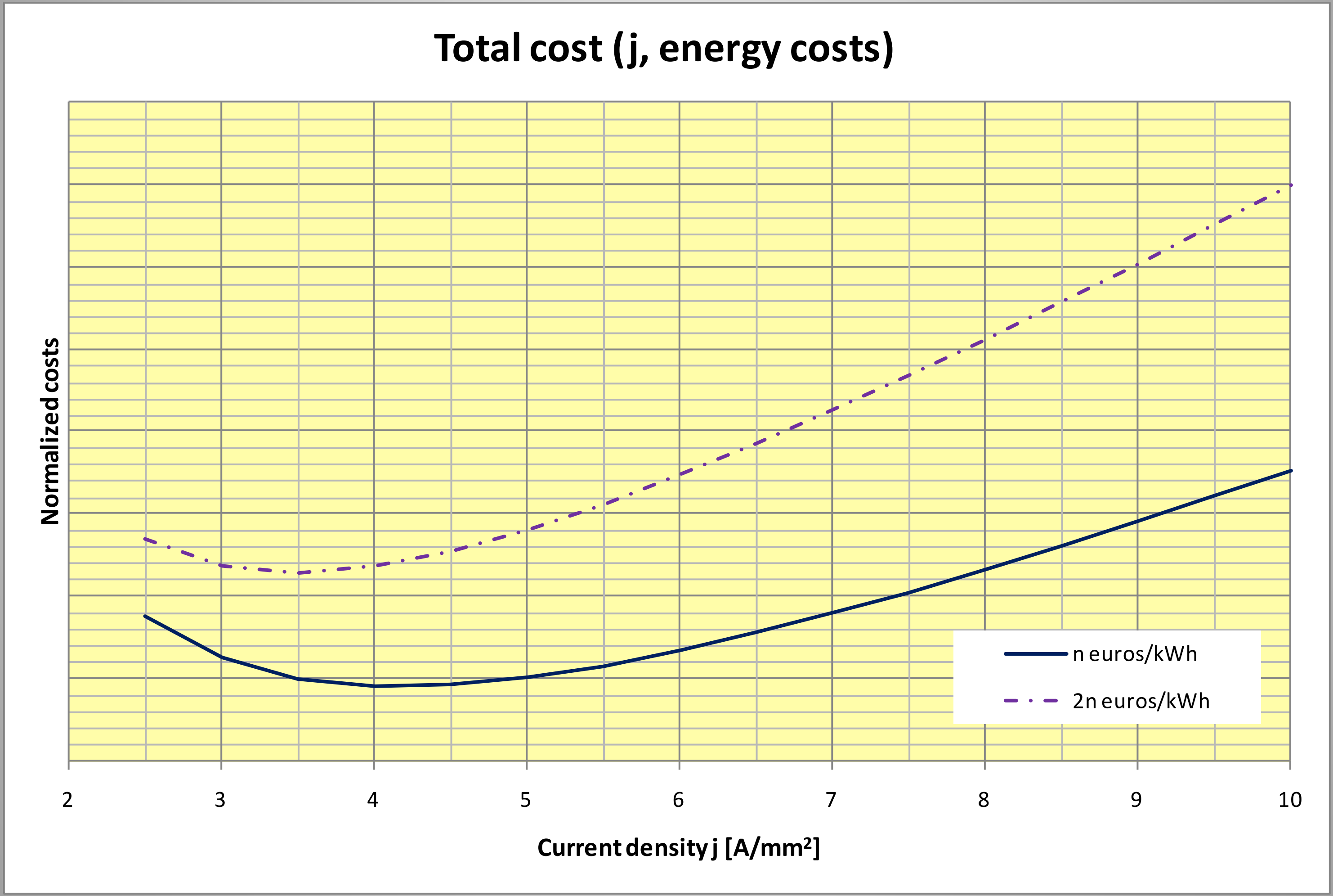
Total costs include:



Cost optimization



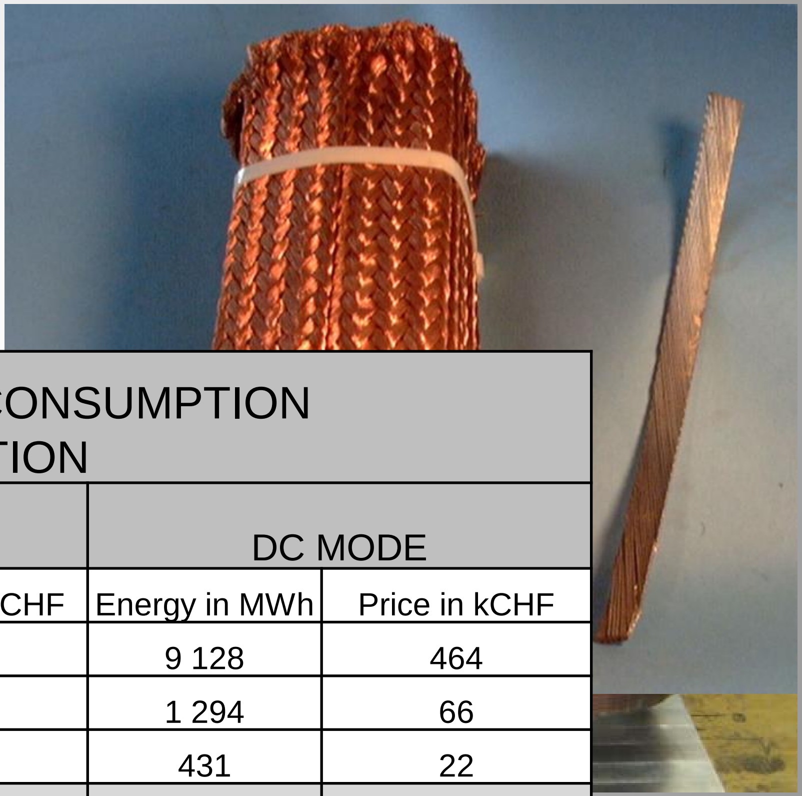
Cost optimization



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!

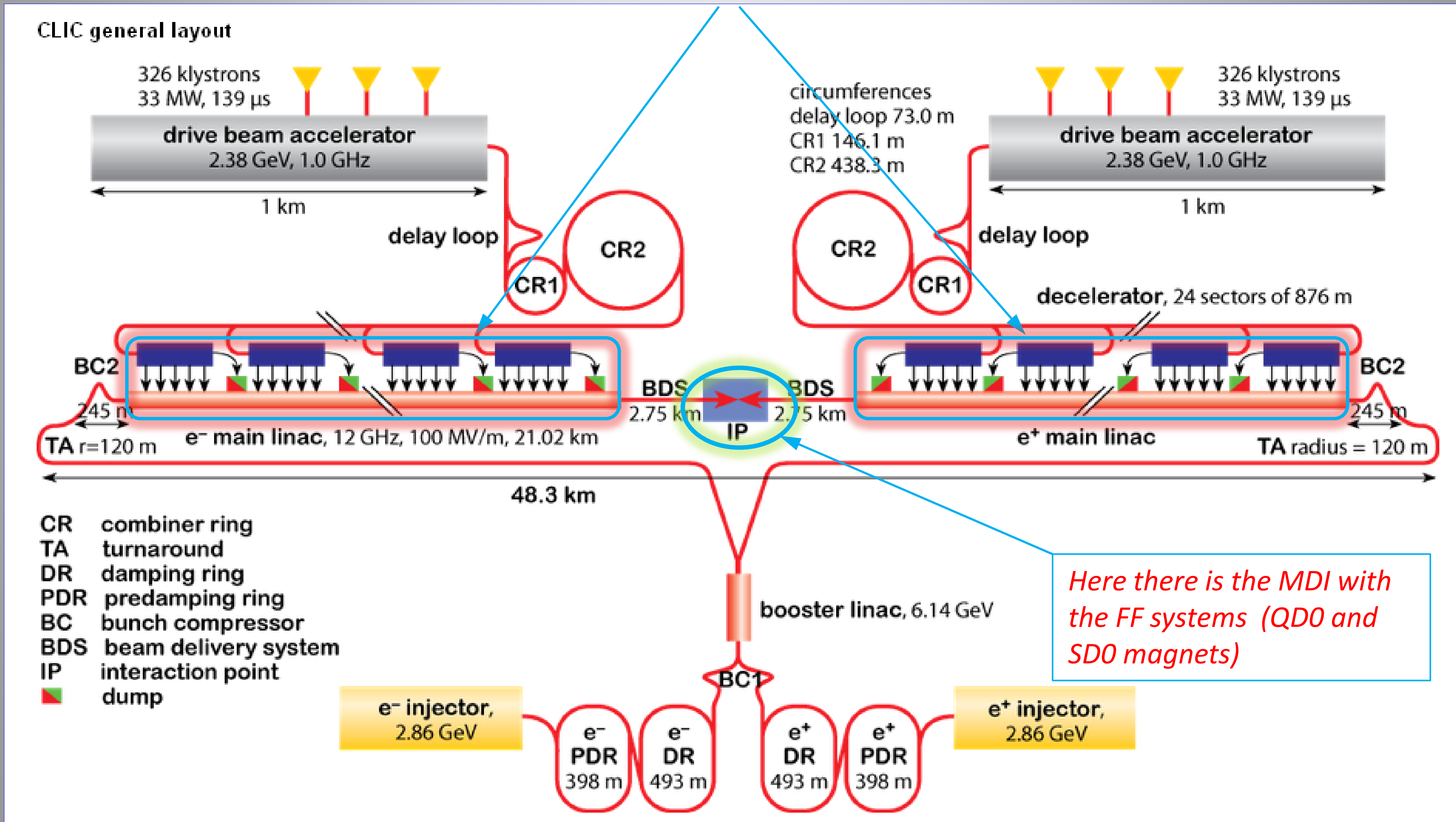
- Permanent magnets (Sm2Co17)
- Hybrid magnets
- Use of high-saturation materials
- Superconducting / super-ferric magnets
- Pulsed operation



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**

Future challenges: CLIC

Here there are the ~ 20000 “2-Beams Modules” with ~40000 DBQ and ~4000 MBQ magnets



Courtesy: M. Modena, WS on “Compact and Low Consumption Magnet Design for Future Linear and Circular Colliders”.