Joint Universities Accelerator School

JUAS 2014

Archamps, France, 17th – 21st February 2014

Normal-conducting accelerator magnets

Thomas Zickler,
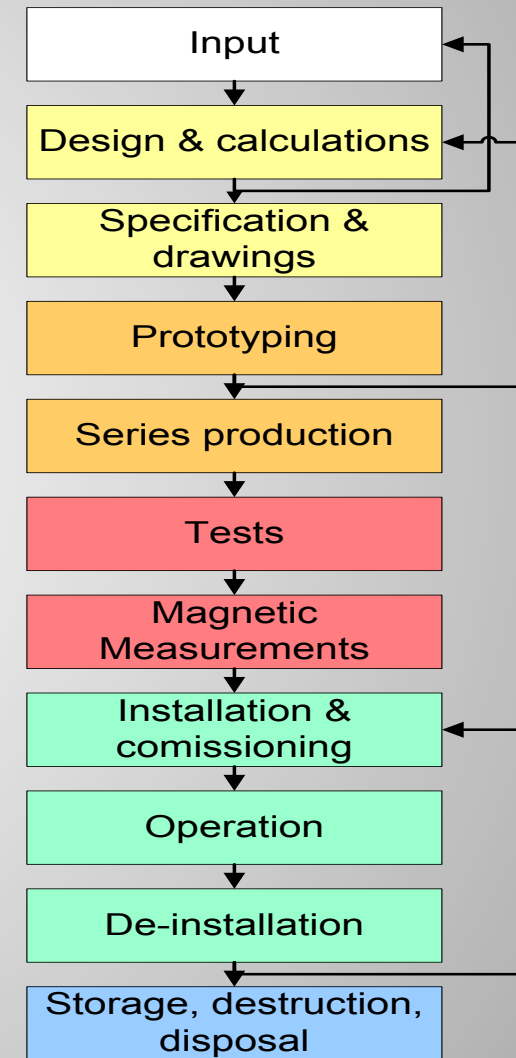
CERN

Lecture 4: Magnet production

Cost estimates and optimization

Magnetic materials

Manufacturing techniques

– Yoke manufacturing

– Coil manufacturing

Assembly and auxiliary equipment

Input

Design & calculations

Specification & drawings

Prototyping

Series production

Tests

Magnetic Measurements

Installation & comissioning

Operation

De-installation

Storage, destruction, disposal

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 type	Dipole
Magnet	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 estimate

Fixed costs		
Punching die [k€]	$\approx 25 \sqrt{\dfrac{Ycs}{Nys}}$	Ycs: yoke cross section SxH [m²] Nys: number of yoke segments
Stacking tool [k€]	$\approx 8 \sqrt{\dfrac{Ymass}{Nys}10^{-3}}$	Ymass: yoke mass [kg] Nys: number of yoke segments
Winding tool [k€]	≈ 12 HTL	HTL – half turn length [m]
Impregnation mold [k€]	≈ 400 CoilV	CoilV – volume of one coil [m³]
Manufacturing costs		
Yoke manufacturing [k€] per magnet	$\approx 16 \cdot Nys \sqrt{\dfrac{Ymass}{Nys}10^{-3}}$	Ymass: yoke mass [kg] Nys: number of yoke segments

Coil manufacturing [k€] per magnet	if CoilMass ≥ 0.5 kg:
	 $\approx 0.8 \cdot Ncoil\left(\sqrt{2 \cdot CoilMass} - 0.945 \sqrt[3]{CoilMass}\right)$
	
	 if CoilMass < 0.5 kg:
	 $\approx 0.4 \cdot Ncoil \cdot CoilMass$
		CoilMass: mass of one coil [kg]
		 Ncoil: number of coils/magnet

Magnet assembly [k€] per magnet	$\approx 0.25 \sqrt{MagMass}$	MagMass: magnet mass [kg]

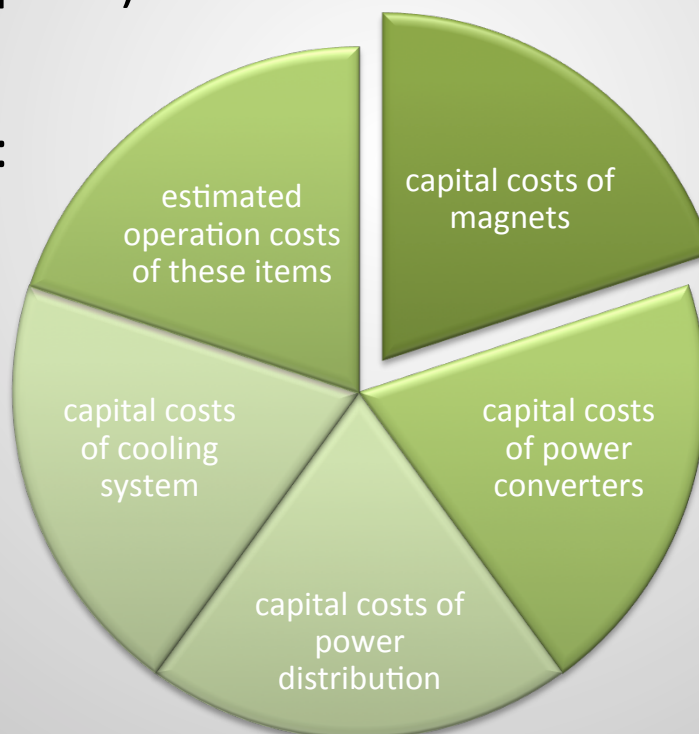Source: D. Tommsini, CERN (empiric formulas based on recently completed magnet projects at CERN)

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:

estimated operation costs of these items

capital costs of magnets

capital costs of cooling system

capital costs of power distribution

capital costs of power converters

Magnet procurement

Some questions to be answered:

- to which detail shall the magnet be defined and specified?

- who will be responsbile for the final magnetic performance: the client or the magnet manufacturer?

- who will do the detailed magnetic, electrical, and mechanical design?

- who will perform the accepance tests?

- who will perform the magnetic measurements and which measurement technology is suitable?

- where does the responsability of the magnet manufacturer start, where does it end?

Depending on the above choices, the scope of the supply needs to be sufficiently defined in a Specification

Low level of specified details	High level of specified details
Functional/performance specification	Technical specification with manufacturing drawings
Main responsability with magnet manufcturer	Main responsability with client

Magnet manufacturing
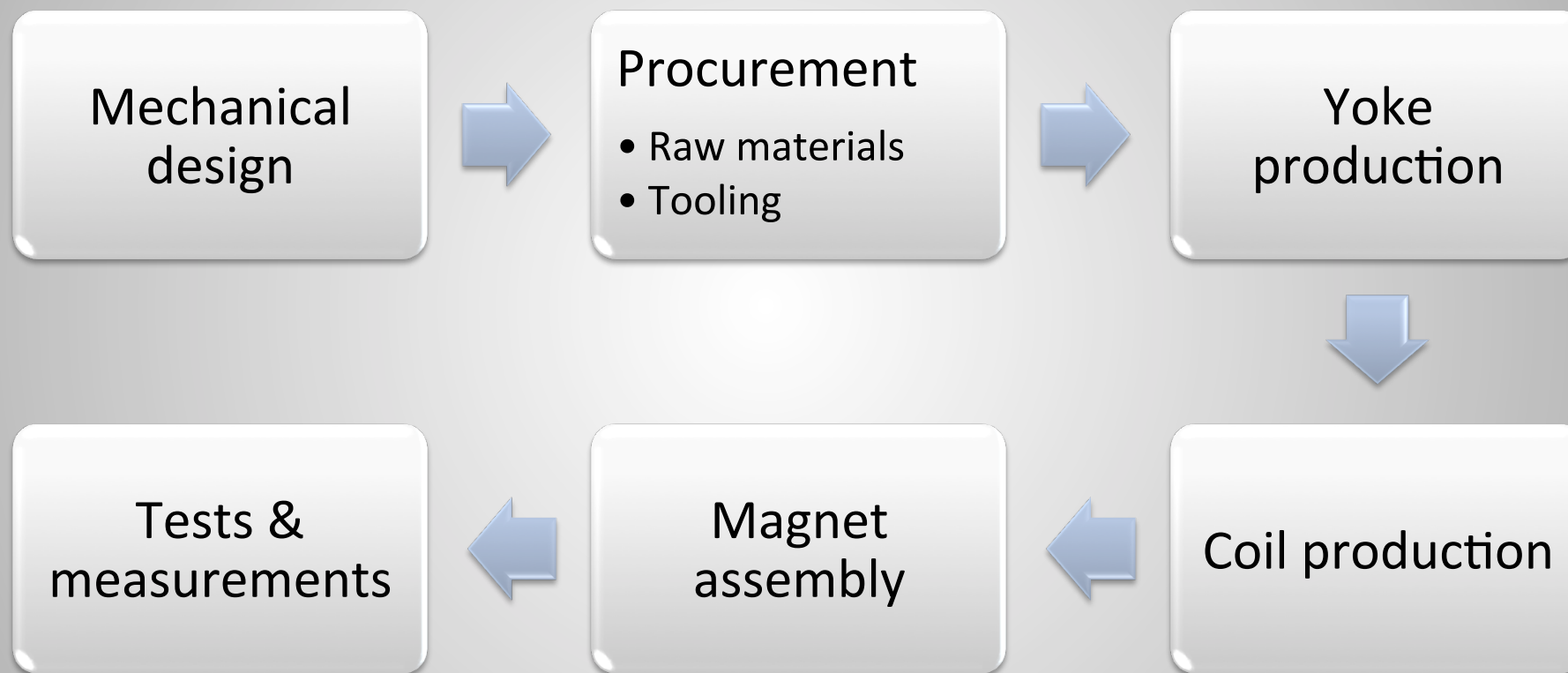
Massive or laminated yokes

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
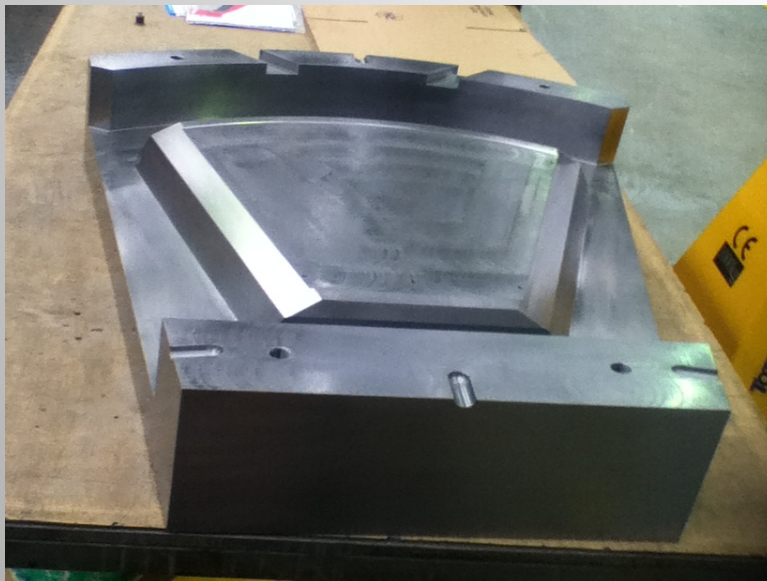
Magnetic steel

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

– Organic or inorganic coating for insulation and bonding

– Material is usually cheaper, but laminated yokes are labour intensive and require more expensive tooling (fine blanking, stacking)

NGO Steel manufacturing

1. Konverter
2. Entgasung
3. Stranggießanlage
4. Warmbandwalzwerk

schlussgeglüht

Beizen   Kaltwalzen   Durchlaufglühung   Beschichtung   Längszerteilung

Warmband   Schmalband

Warmbandglühung

Breitband

nicht schlussgeglüht

Rekristallisation   Nachwalzen

Courtesy of ThyssenKrupp
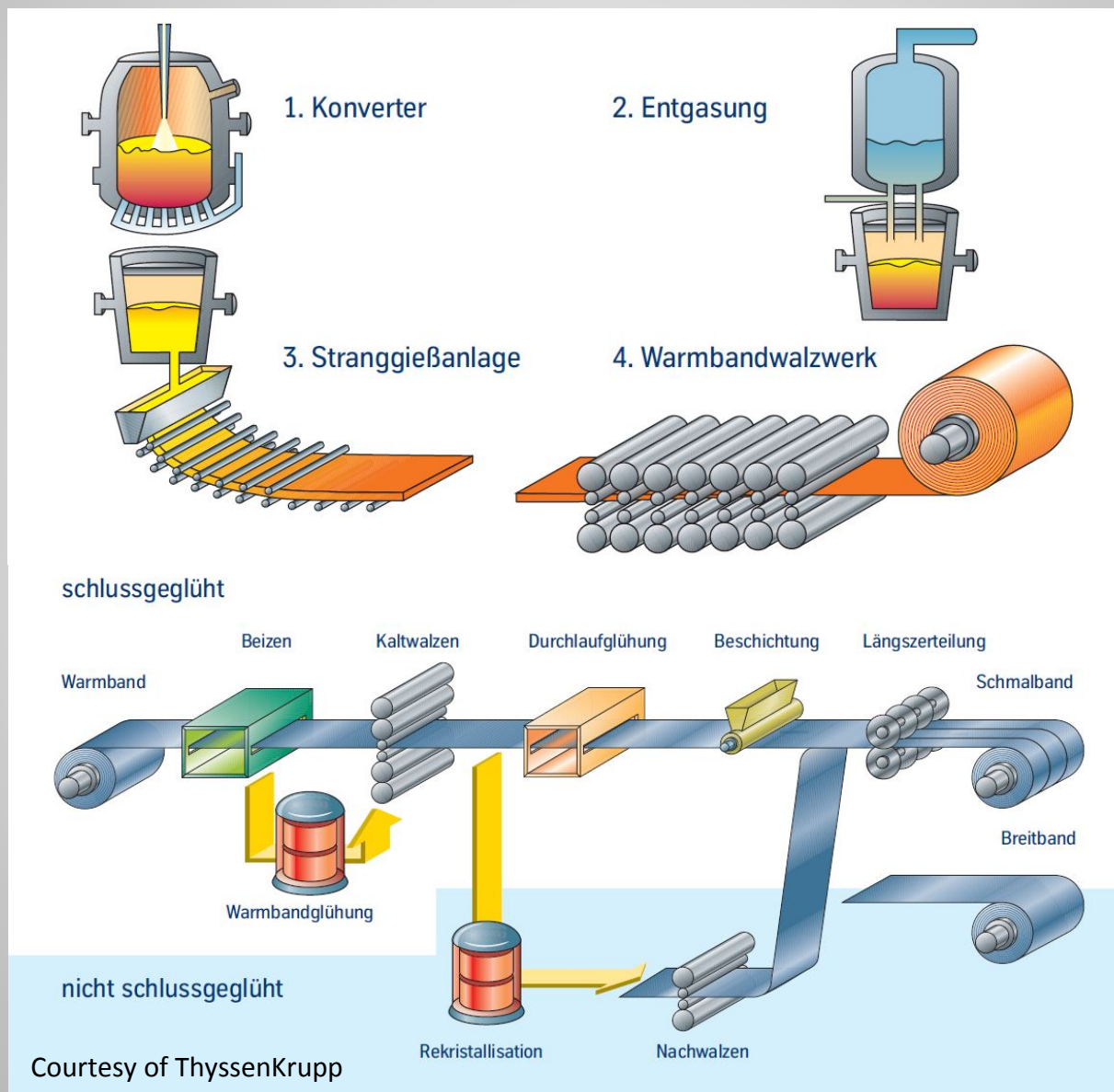
Profile of steel strips

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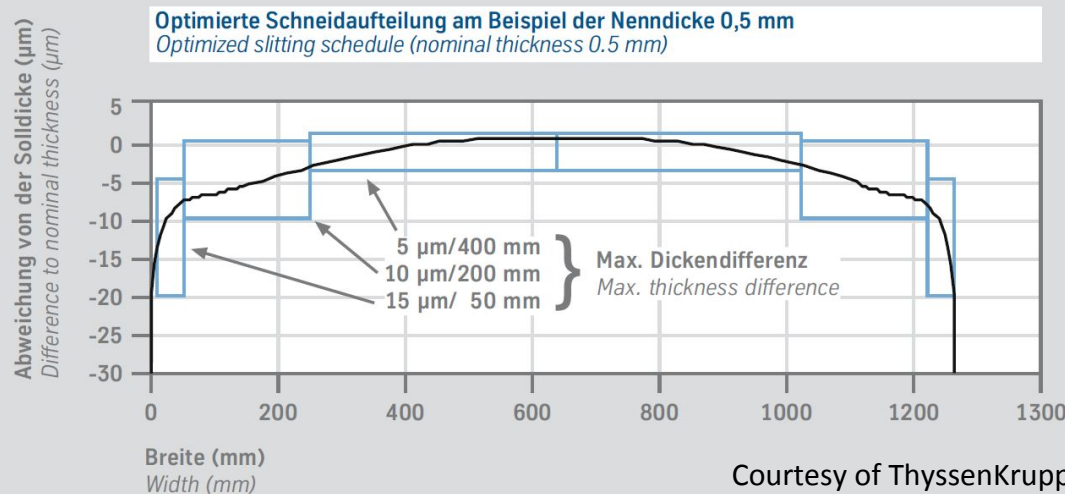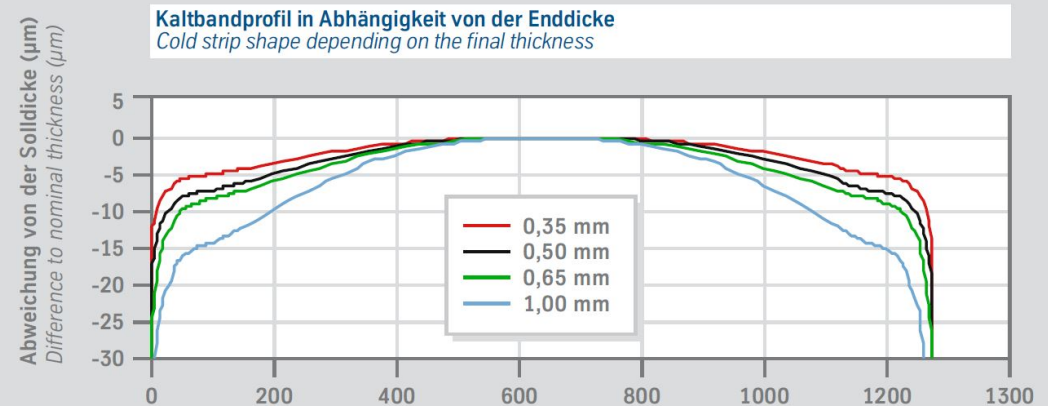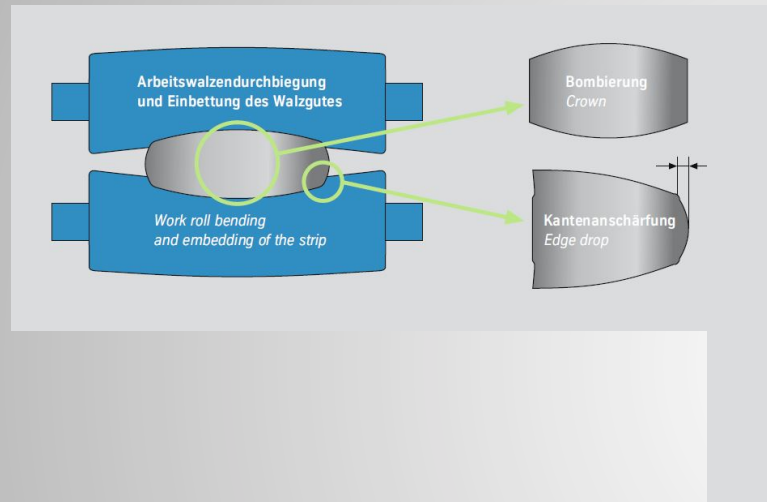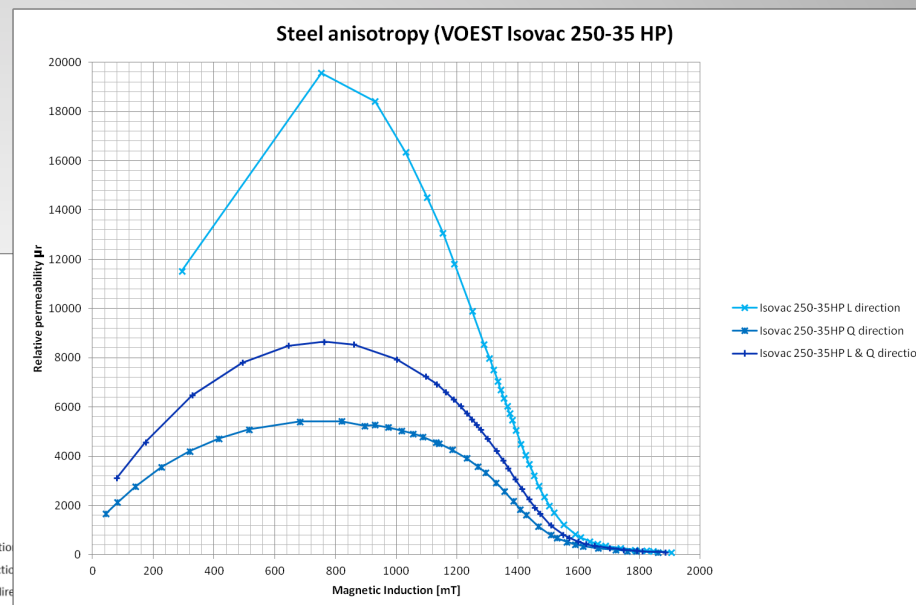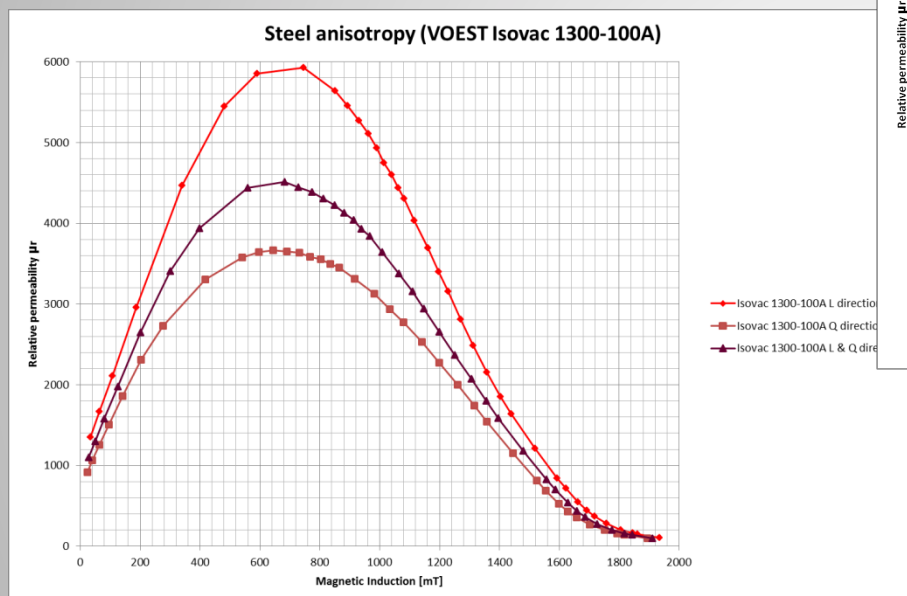

Courtesy of ThyssenKrupp
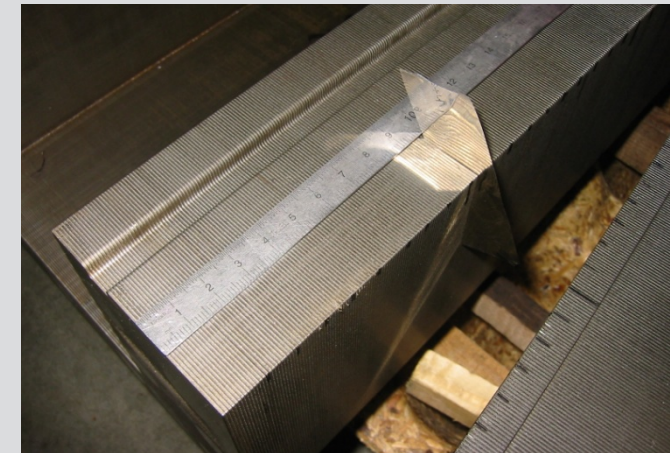
Courtesy of ThyssenKrupp

NGO steel properties

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

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

Steel anisotropy (VOEST Isovac 250-35 HP)

Steel anisotropy (VOEST Isovac 1300-100A)

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) $\leq \rho$
≤ 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

Steel specification

For MedAustron, the following steel parameters have been specified (and achieved)

Material thickness:

Parameter	Value	Unit
Nominal thickness of steel strips	1.00	mm
Max. deviation from nominal thickness	± 0.03	mm
Max. thickness variation in rolling direction	0.004	mm/2 m
Max. thickness variation perpendicular to rolling direction*)	0.007	mm

*) over a width of 1100 mm

Mechanical/electrical properties:

Parameter	Value	Unit
Electrical resistivity	0.13	μΩm
Density	7.800	g/cm^3
Tensile strength R_m	380 ± 10	MPa
Yield strength Re_h	270 ± 20	MPa
Hardness HV5	138 ± 5	
Surface roughness R_a	0.4 – 0.9	μm

Magnetic properties:

Parameter	Value	Unit
Average coercivity	70 ± 2	A/m
Permeability spread at 500 A/m (~1.45 T)	± 1	%

Surface coating:

Parameter	Value	Unit
Coating thickness	4 - 6	μm
Bonding strength of coating (DIN 53262)	> 6	N/mm^2
Surface resistance of coating in B-stage	> 1000	Ω cm

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 F: 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 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

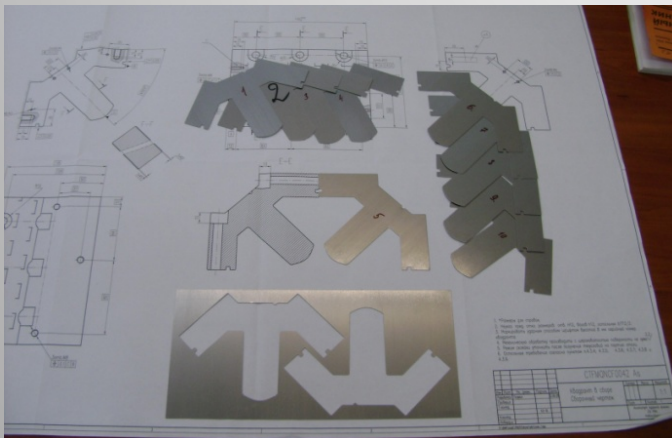Gluing and/or welding

Machining
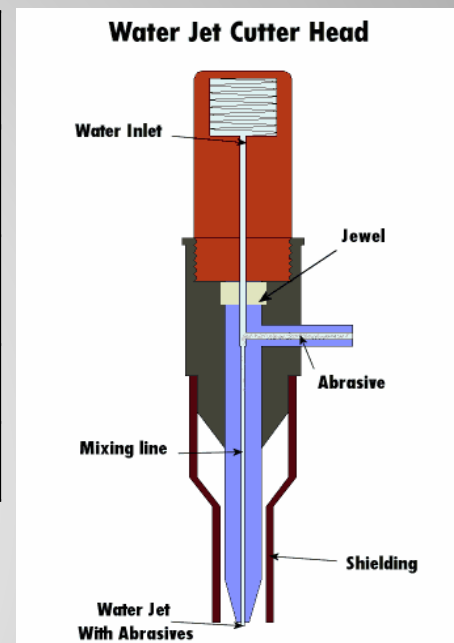
Assembly (preliminary)
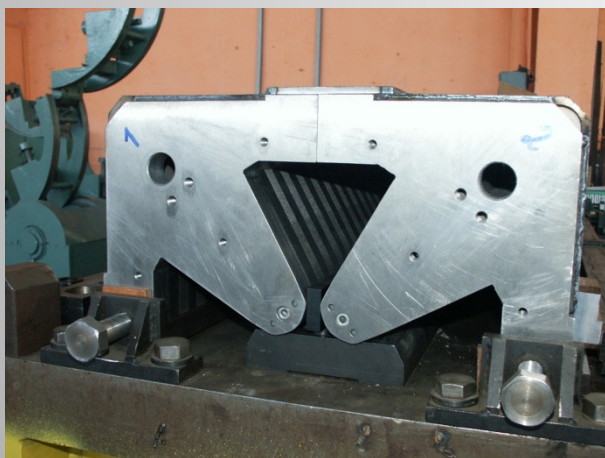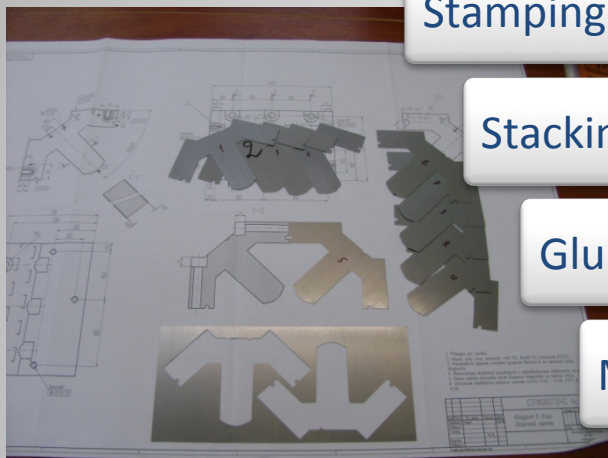
Lamination punching

- 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)
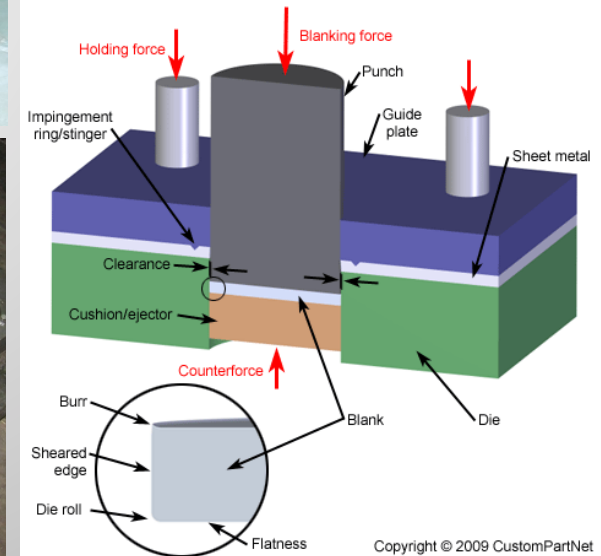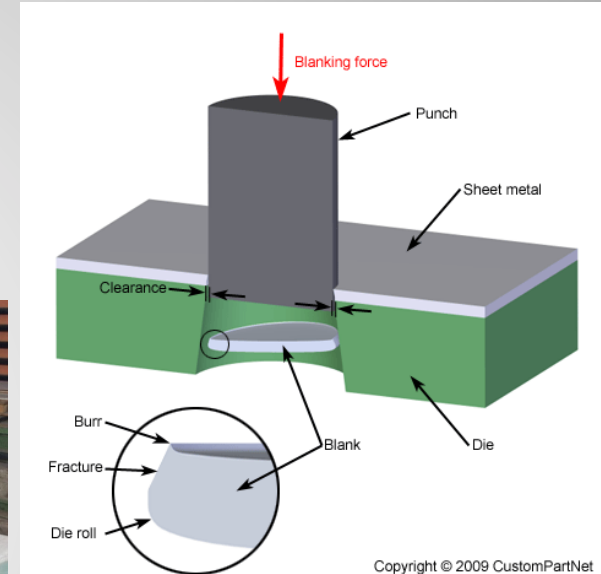
Alternatives to punching

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

Water Jet Cutter Head

Water Inlet
Jewel
Abrasive
Mixing line
Shielding
Water Jet With Abrasives
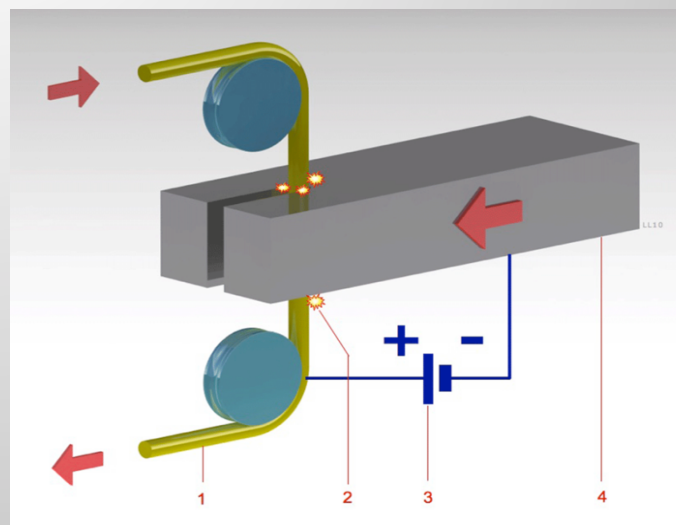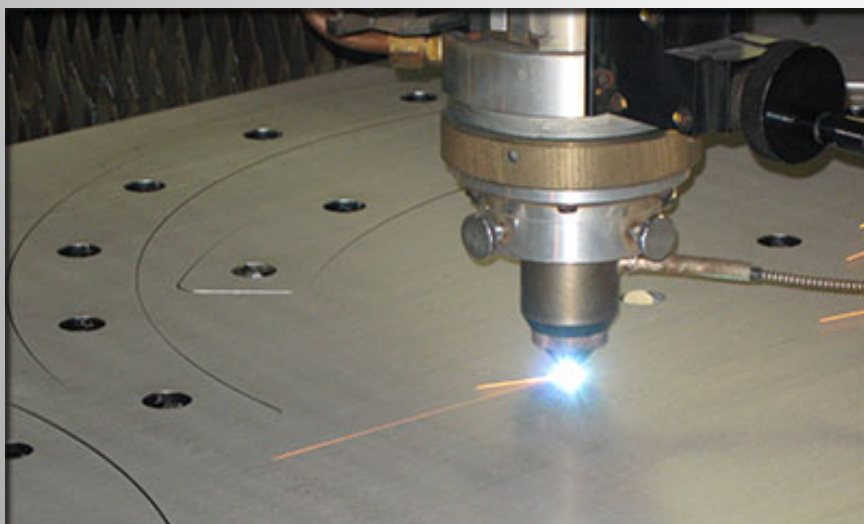
Lamination sorting

Smallest homogenous entity: Melt of several 100 tonnes

(same chemical composition → similar magnetic properties)

↘   Mother coils of ~20 tonnes (width ≈ 1200 mm)

↘   Split coils of several tonnes → lamination stamping

↘   Single sheets   → lamination stamping

Shuffling/mixing/sorting of laminations might be neccessary to obtain
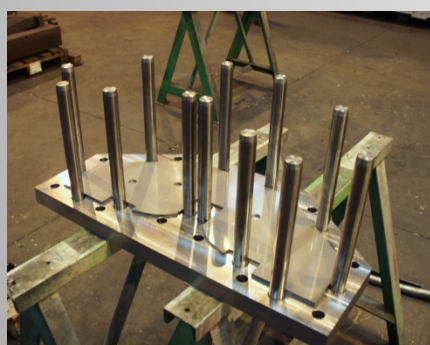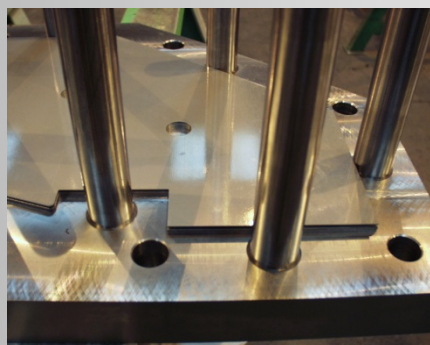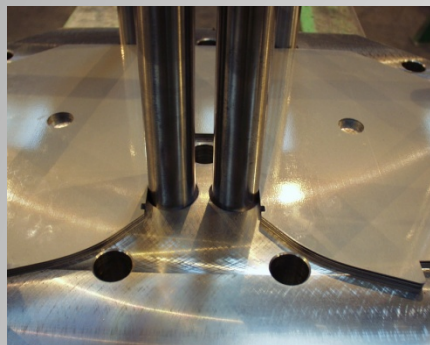max. homogeneity of material properties in a series of magnets

Yoke stacking

Tooling for:

- stacking
- baking
- welding
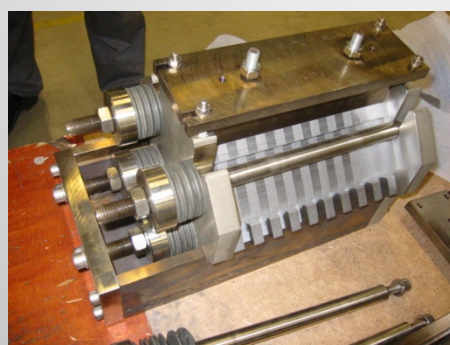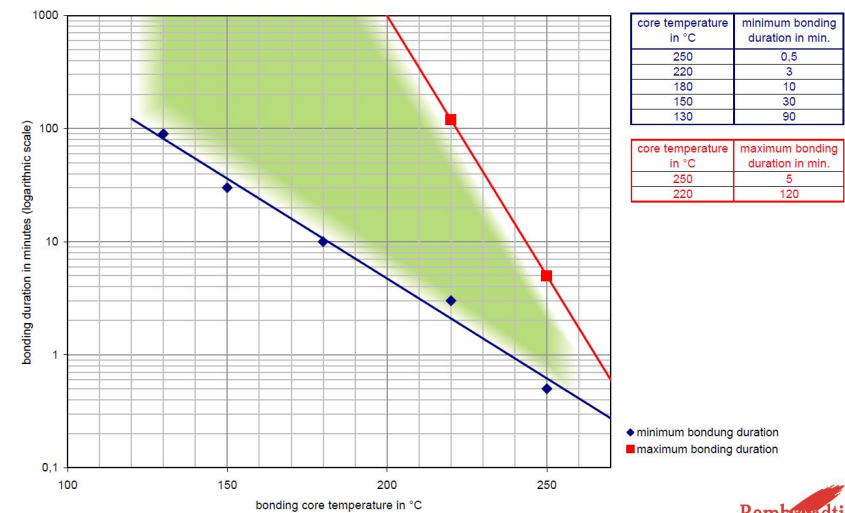
Bonding & insulation

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

influence of bonding pressure to bonding strength of Remisol EB 546

testing specimen:
pair of core plate strips of M800-50A
with 20x3cm², single side coated with
6μm bonding varnish

bonding data
temperature 150°C
bonding duration 2h
pressure varied

bonding strength
determined acc. T peel test DIN 53282

◆ EB 546

Klebekraft, Druckvariation.xls:EB546 erweitert [E]
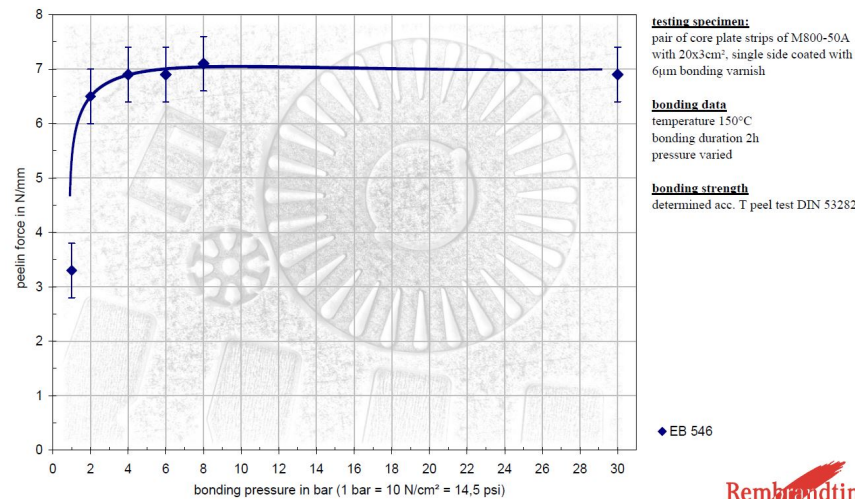
bonding duration plot for Remisol EB 546/548 at 8 bar

core temperature in °C	minimum bonding duration in min.
250	0,5
220	3
180	10
150	30
130	90

core temperature in °C	maximum bonding duration in min.
250	5
220	120

◆ minimum bondung duration
■ maximum bonding duration

EB546 Verklebungsdiagramme 8bar.xls:Regression [E], 30.07.2007

Courtesy of Rembrandtin

Gluing 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

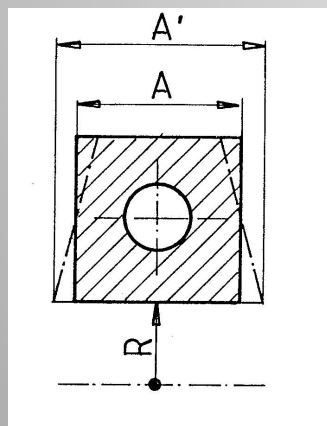Conductor insulation

Winding

Ground insulation

Epoxy impregnation
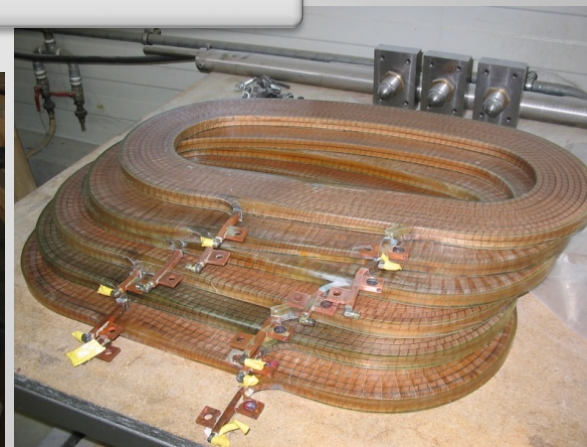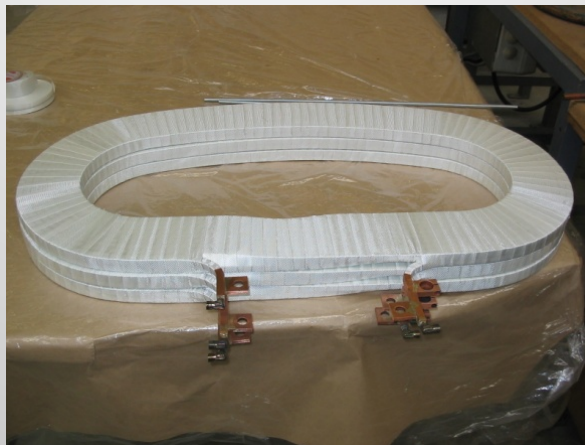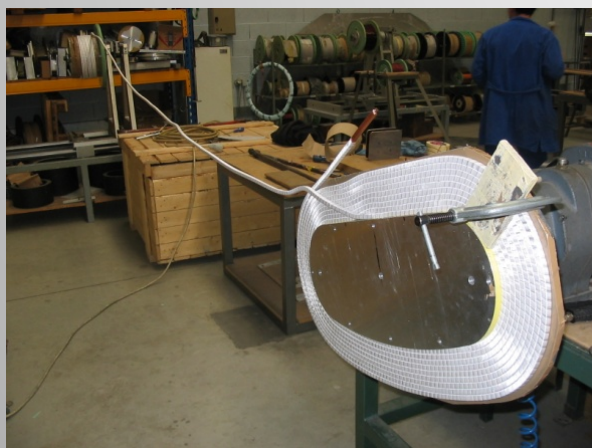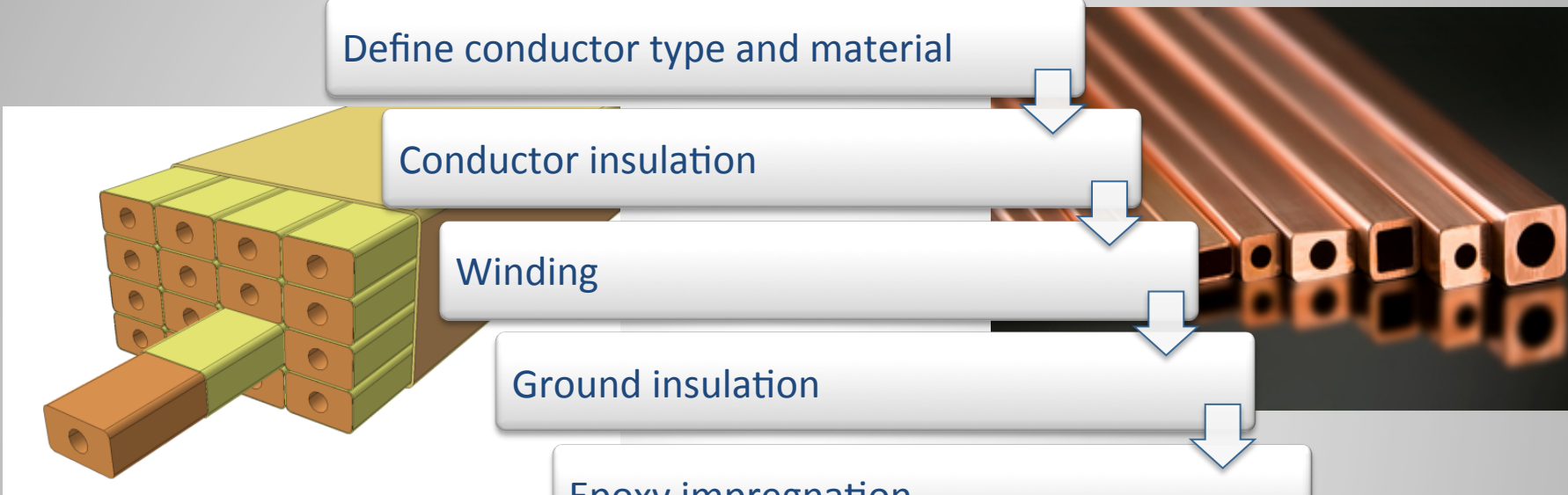
Conductor materials

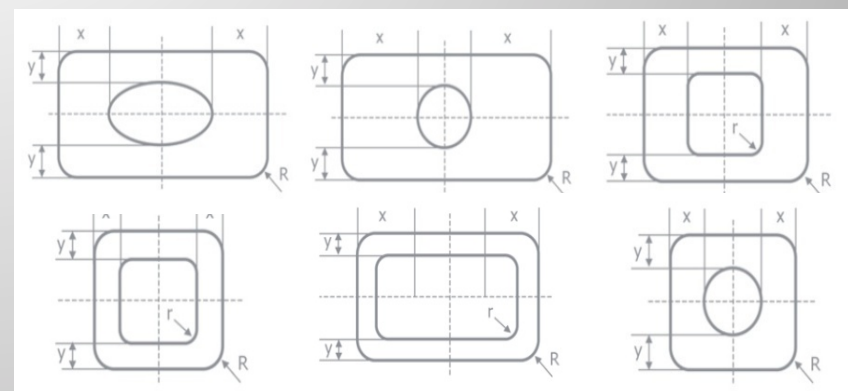|	Al	Cu (OF)
Purity	99.7 %	99.95 %
Resistivity @ 20°C	2.83 μΩ cm	1.72 μΩ cm
Thermal resistivity coeff.	0.004 K^{-1}	0.004 K^{-1}
Specific weight	2.70 g/cm^3	8.94 g/cm^3
Thermal conductivity	2.37 W/cm K	3.91 W/cm K
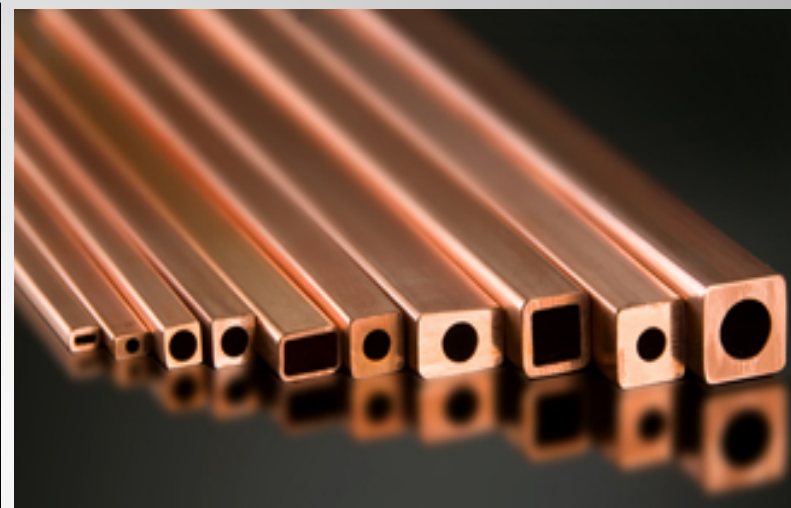
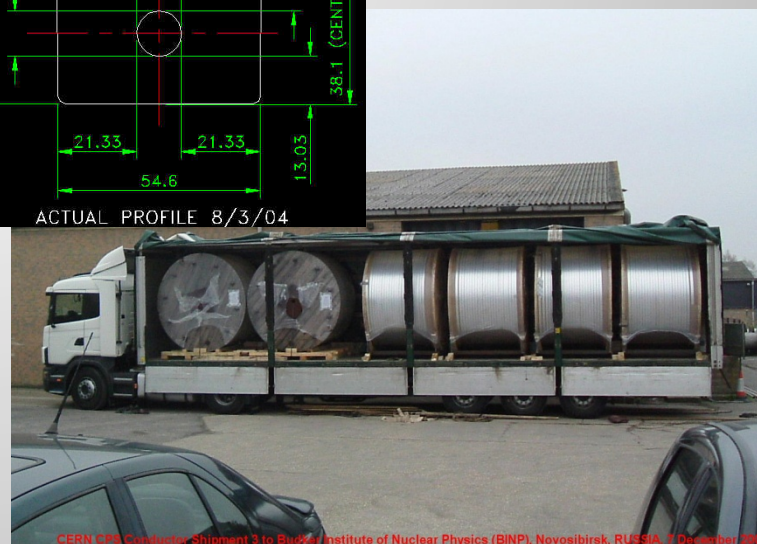**Key-stoning:** risk of insulation damage & decrease of cooling duct cross-section
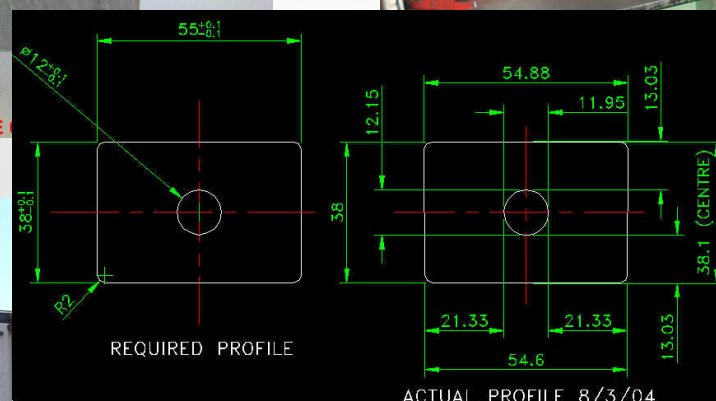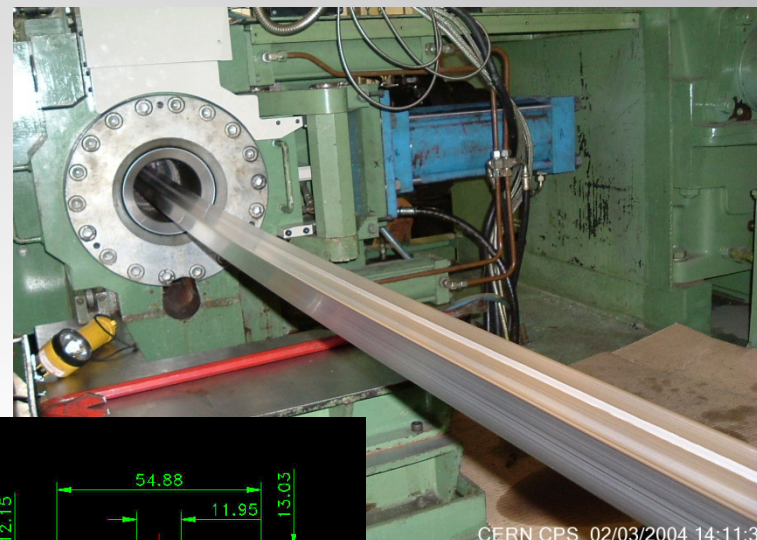

$$R = 3 \cdot A \Rightarrow \frac{\Delta A}{A} = 3.6\%$$

Hollow Aluminium Conductor

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. We distinguish electrical insulation between:

– the individual turns in a coil
– different active parts
– active parts and ground

The electrical insulation is stressed by several factors:

– electric
– thermal
– mechanical
– chemical (including oxidation),
– radiation
– contamination

→ These factors can produce short and/or long term degradation

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 (→ magnetic field distortion)
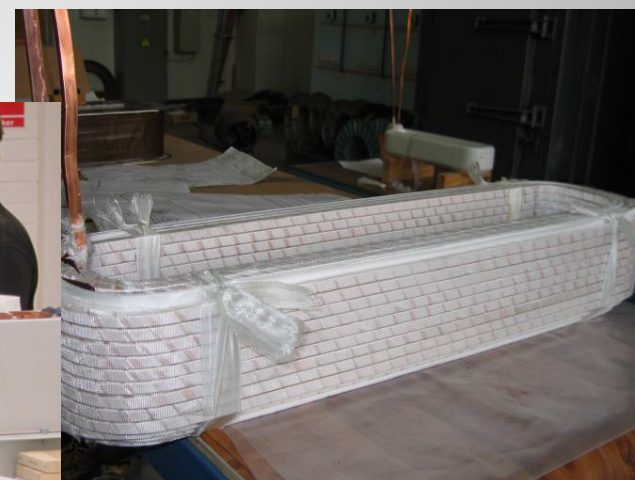– incorrect functioning of protections

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

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

Insulation materials

Dielectric materials can be gaseous, liquid, or solid

For coil insulation, mainly solid dielectric materials are relevant

Solid dielectric materials can be distinguished in three main classes:

- inorganic materials:
  - Ceramics: porcelain, alumina
  - Glass, quartz
  - Cements and minerals (e.g. mica)
- organic materials:
  - thermoplastic: Rubber (natural, butyl, silicone), Polyamide (Nylon), Polyesther (Mylar), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), Polymethylmetachrylate (PMMA), Polycarbonate (PC), Polytetrafluoroethylene (PTFE)
  - thermosetting: Polyethylene (PE,LDPE,MDPE,HDPE,XLPE), Ethylene-Propylene (EPR), Polyimide (PI), Polyetheretherketone (PEEK), Epoxy, phenolic, silicon, polyester resins
- composites:
  - fully organic (aramidic fibres-epoxy tapes) or mixed (epoxy-mica tapes)

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

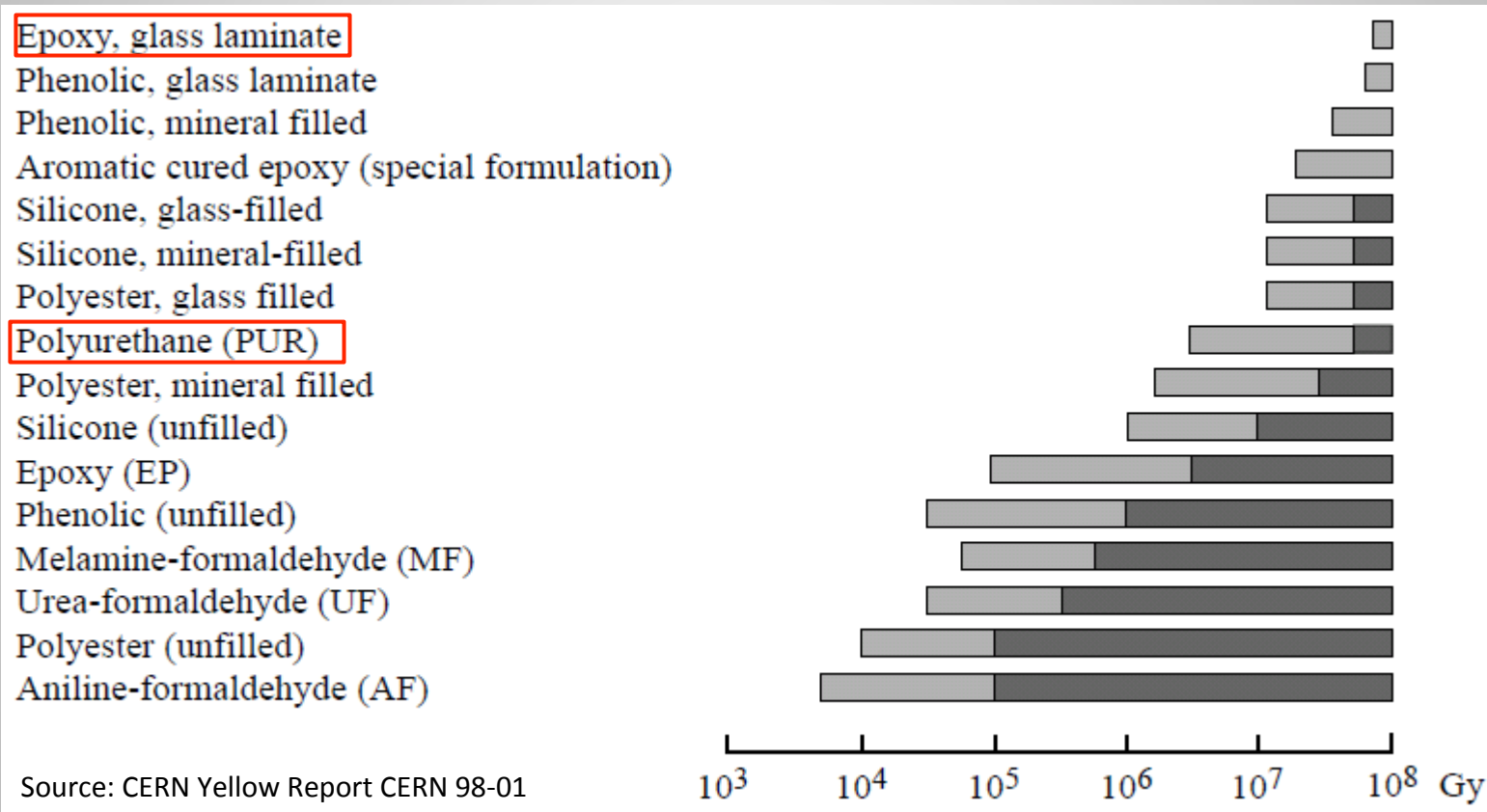A temperature rise of 10 K halves the expected live time of an insulation system

Radiation hardness

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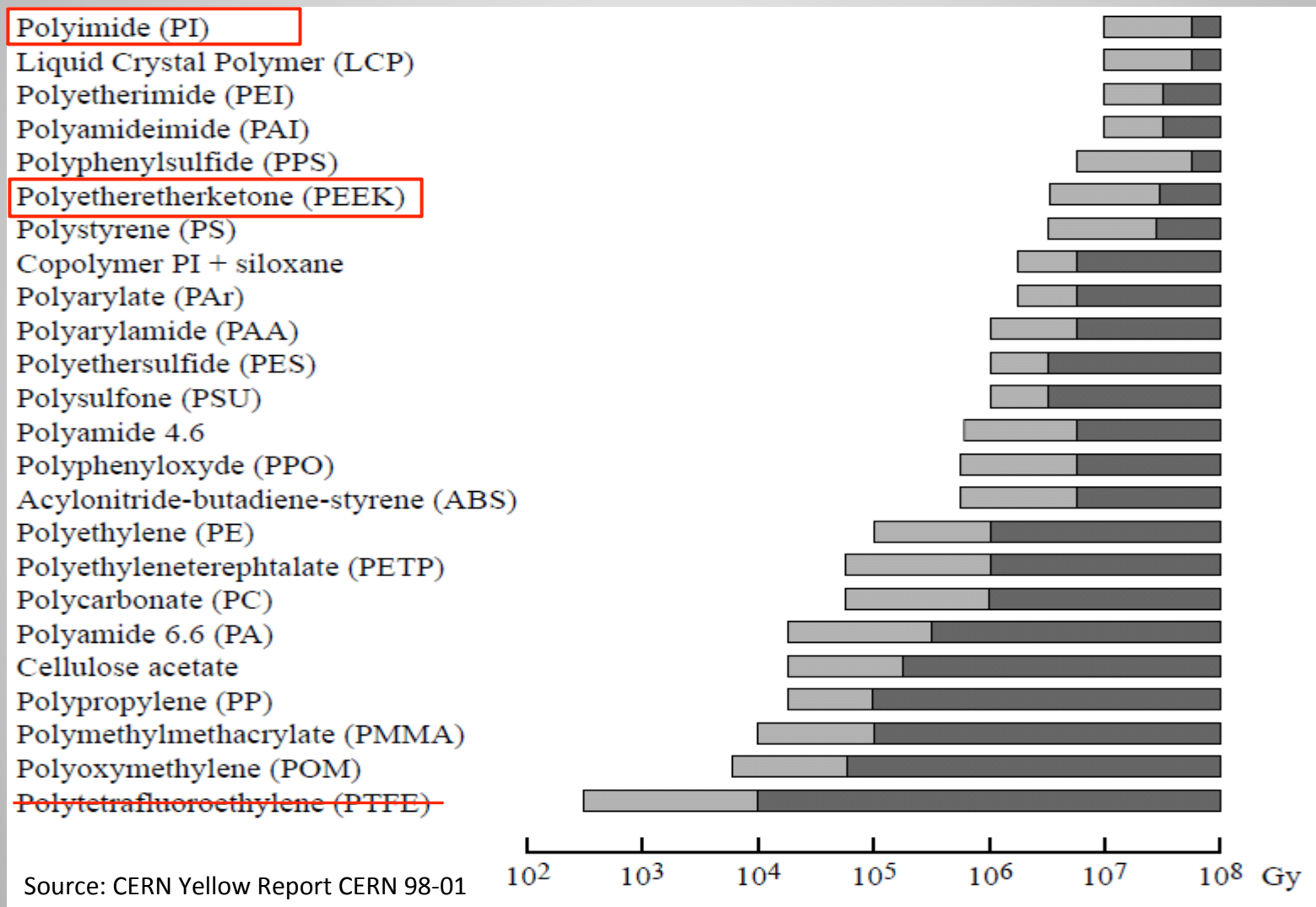

Source: CERN Yellow Report CERN 98-01

Above 10^8 Gy special insulation techniques are required!

Radiation hardness

Source: CERN Yellow Report CERN 98-01

Epoxy resins

- Invented in 1938 (patent by P. Castan)

- They contain the epoxyde group:

$$CH_2 - CH - R$$

with O bridging the CH_2 and CH
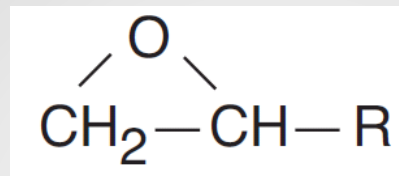
- Composed by:
  - base resin (aromatic, cycloaliphatic, or phenolic)
  - hardener (amine, anhydride)
  - accelerator
  - flexibilizer
  - fillers (Al_2O_3, MgO, quartz, Dolomite…)
  - other additives (to modify the viscosity for example)

Fig.4.1: **Loss factor (tan δ) and dielectric constant (εr) as a function of temperature**
(measurement frequency: 50 Hz
IEC 60250/ DIN 53483)
Curing Cycle: 6h at 100°C + 12h at 135°C

Fig.5.1: **Ultimate flexural strength and deflection at break as a function of the radiation**   Source: HUNTSMAN
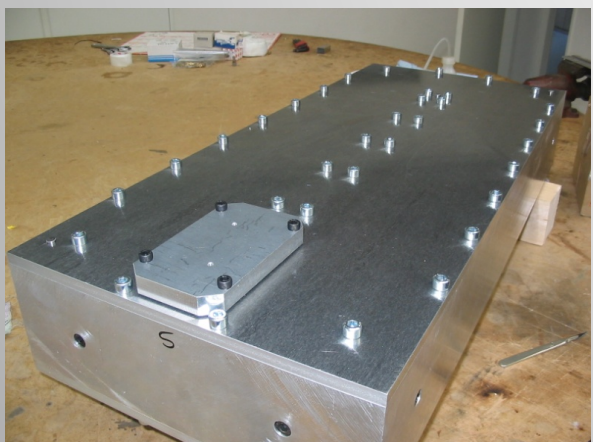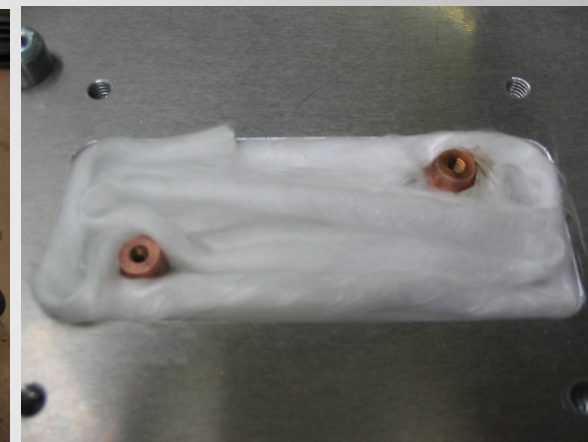
- Good results in accelerator magnets are being obtained with bisphenol-A + anhydride hardener + amine accelerator
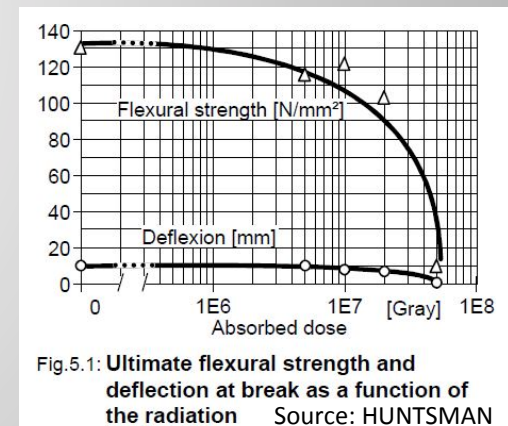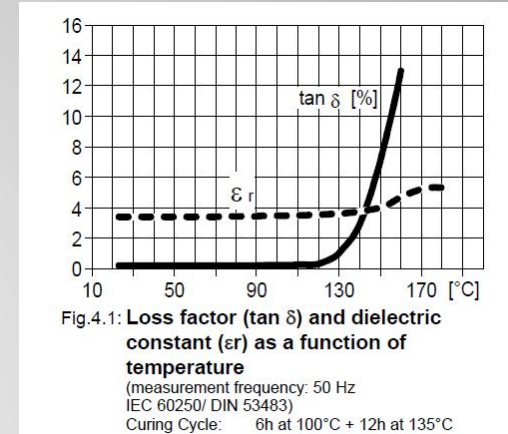
Coil impregnation

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)

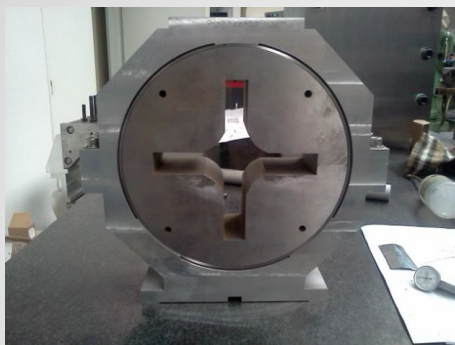- ejection more difficult

Release tape

+ no excess of resin on the finished coil

+ inexpensive mold

+ easy de-molding

- poor surface finish

- higher resin consumption
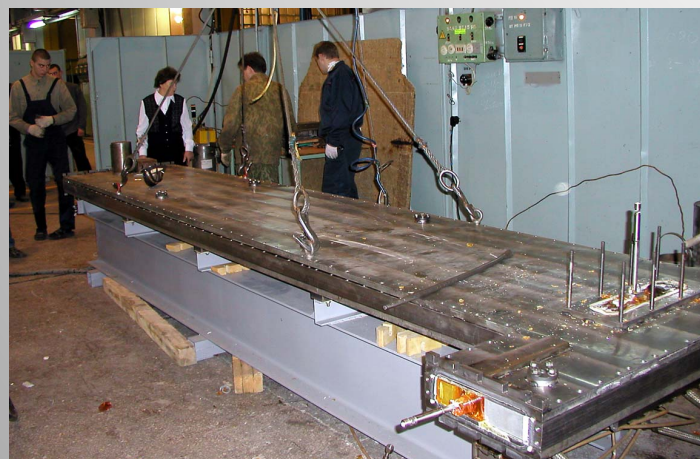
Magnet assembly
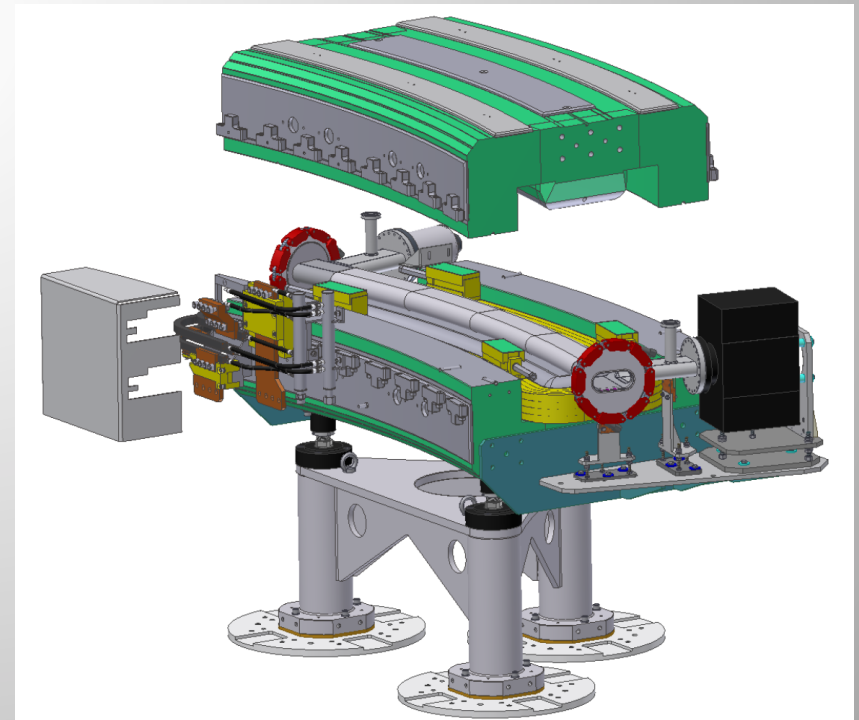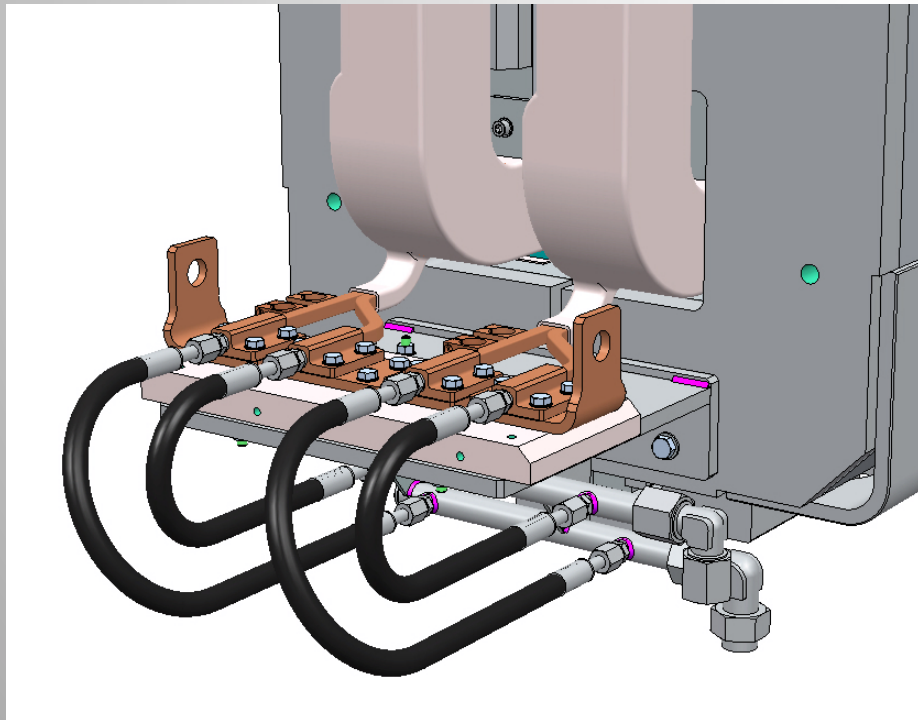
By hand....

... or with the help of tooling

Auxiliary components

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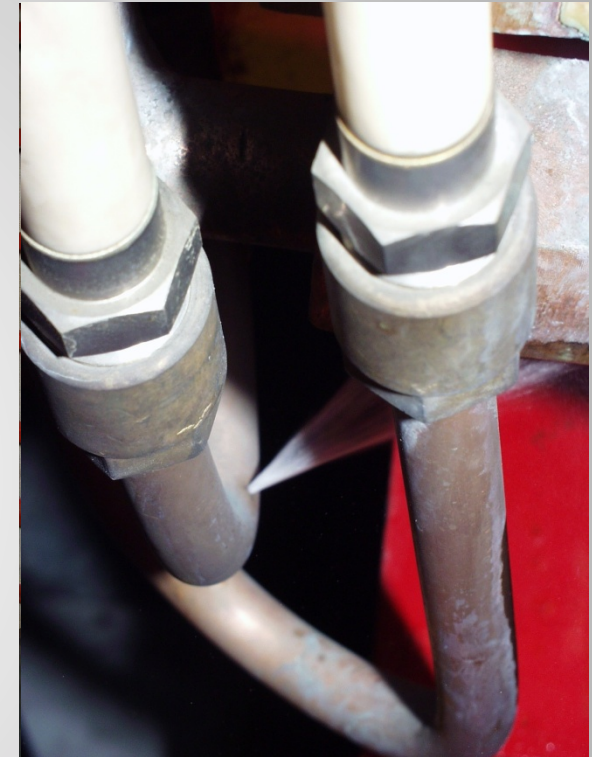- Alignment tragets, adjustment tables and support jacks
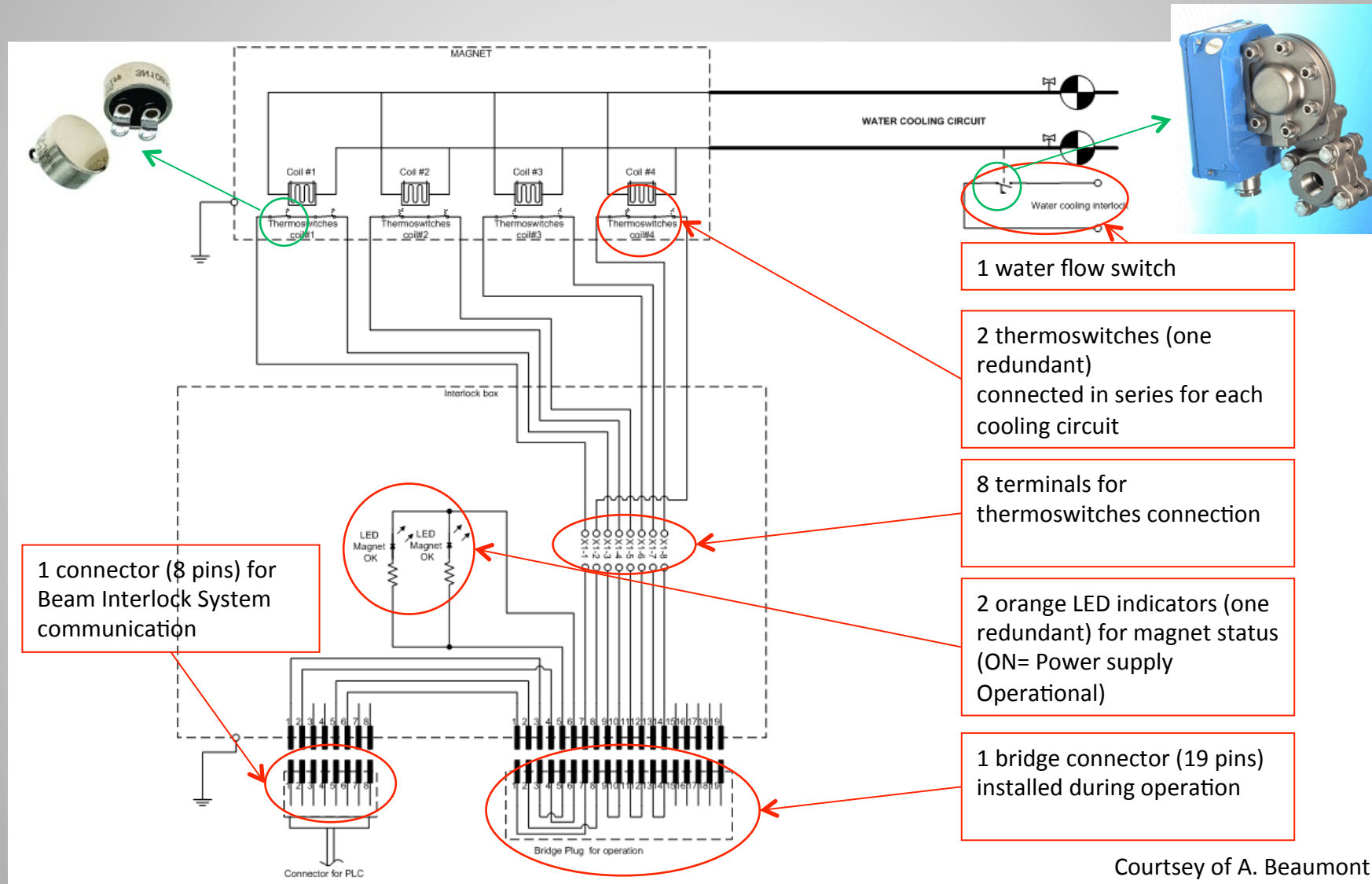
Hydraulic circuits

- 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 → magnet damage (short cicuits, corrosion of iron yoke) and collateral damages on other equipment possible

Magnet Interlock System

1 water flow switch

2 thermoswitches (one redundant) connected in series for each cooling circuit

8 terminals for thermoswitches connection

2 orange LED indicators (one redundant) for magnet status (ON= Power supply Operational)

1 connector (8 pins) for Beam Interlock System communication

1 bridge connector (19 pins) installed during operation

Courtsey of A. Beaumont

Interlock Sensors

Thermo-switch:

A Housing
B Contact arm
C Ceramic insulator
D Laser weld
E Bimetal disc
F Ceramic transfer pin
G Cap
H Gold alloy contacts
I Glass header
J Terminals
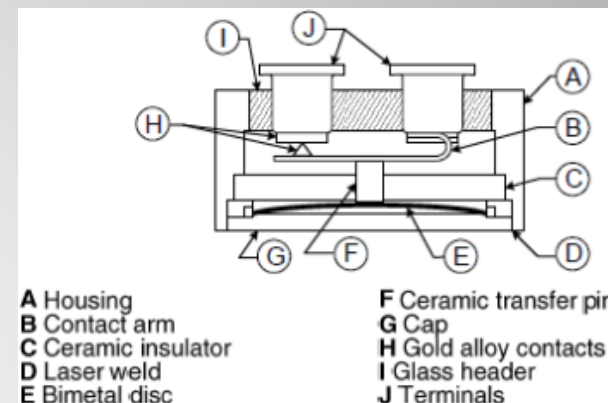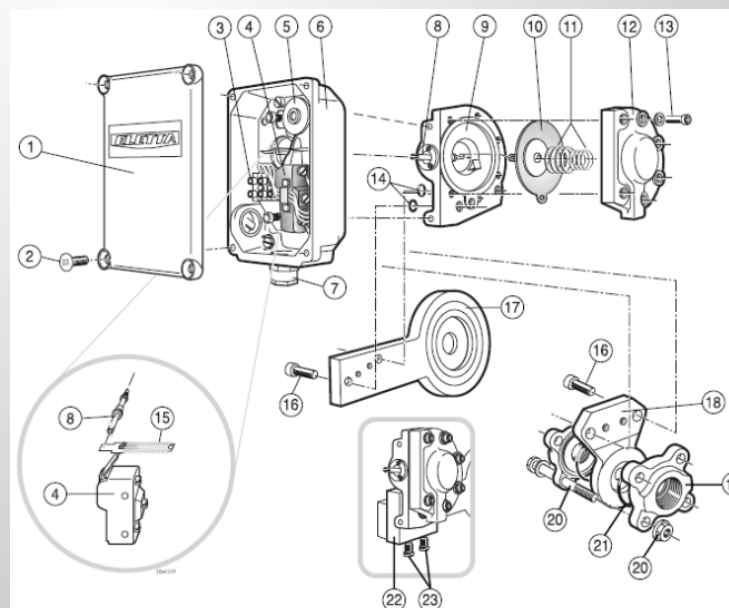
Flow-switch:

Summary

- Cost optimization is an important design aspect, in particular in view of future energy costs

- Engineers have a vast choice of materials and manufactring techniques available influencing the performance of the magnet

- Selecting appropriate materials is not always trivial and requires specific know-how about the material properties

- The manufacturing techniques shall be adapted to meet the specified requirements of the finial product in all respects

- The engineer has to make his choice about the foreseen manufacturing techniques in an early stage of the project since it has a signifcant impact on the magnet costs