Joint Universities Accelerator School

JUAS 2018

Archamps, France, 26th February – 2nd March 2018

Normal-conducting accelerator magnets
Lecture 3: Magnet construction

Thomas Zickler
CERN

Lecture 3: Magnet construction

Magnetic materials

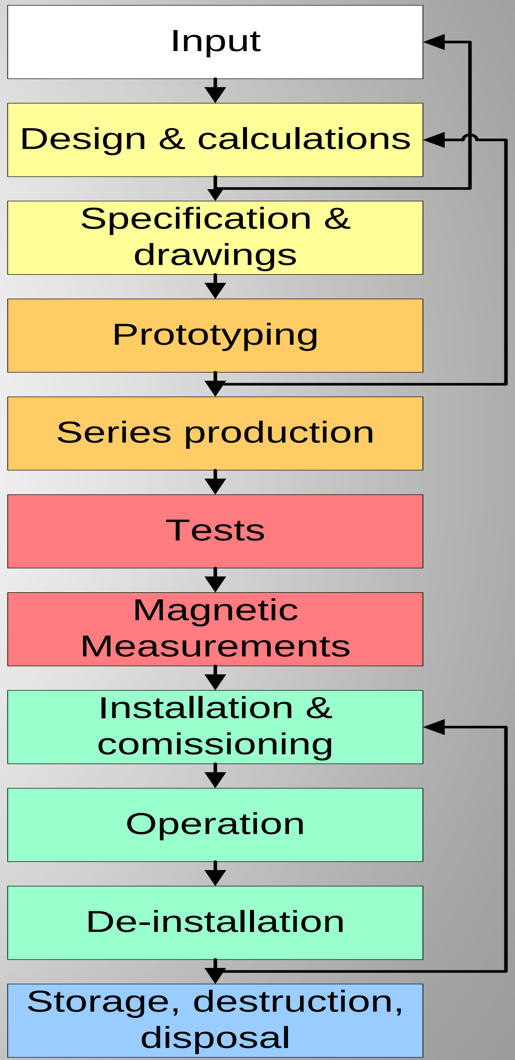
Yoke manufacturing techniques

Coil manufacturing techniques

QA, tests & measurements

(see practical work @ CERN)

Cost estimates and optimization



Magnet manufacturing

Mechanical design

Procurement
- Raw materials
- Tooling

Yoke production

Coil production

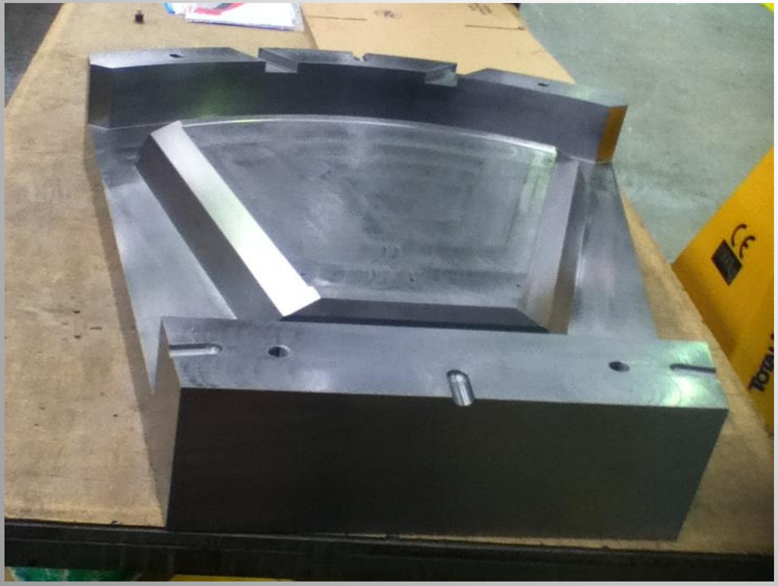
Magnet assembly

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

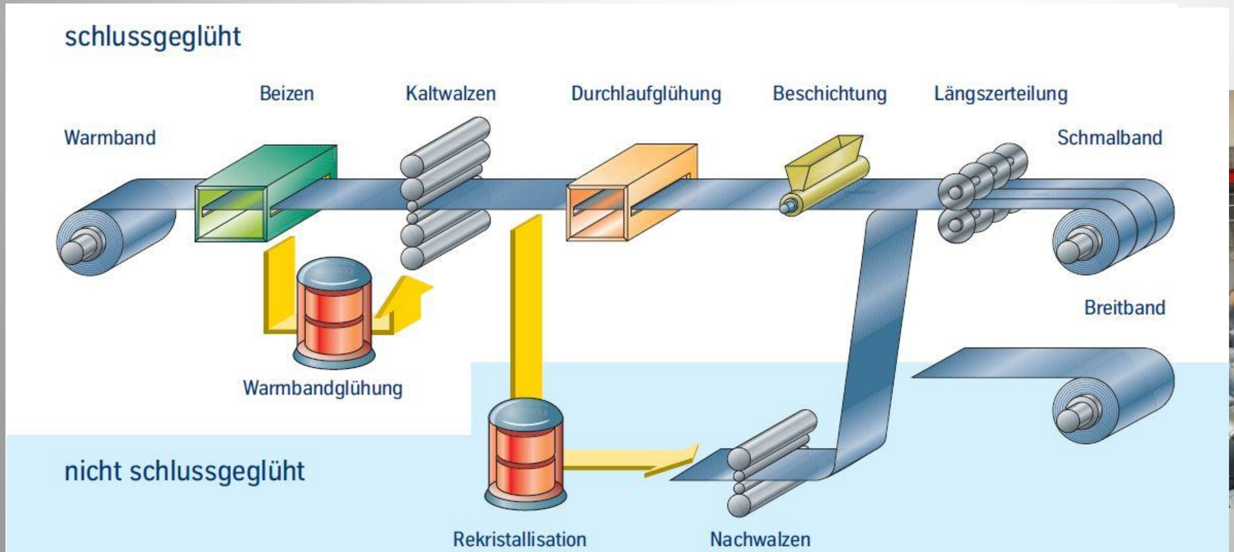


+ steel sheets less expensive than massive blocks (cast ingot)
+ less expensive for larger series
+ steel properties can be easily tailored
+ uniform magnetic properties over large series
- expensive tooling

Magnetic steel

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

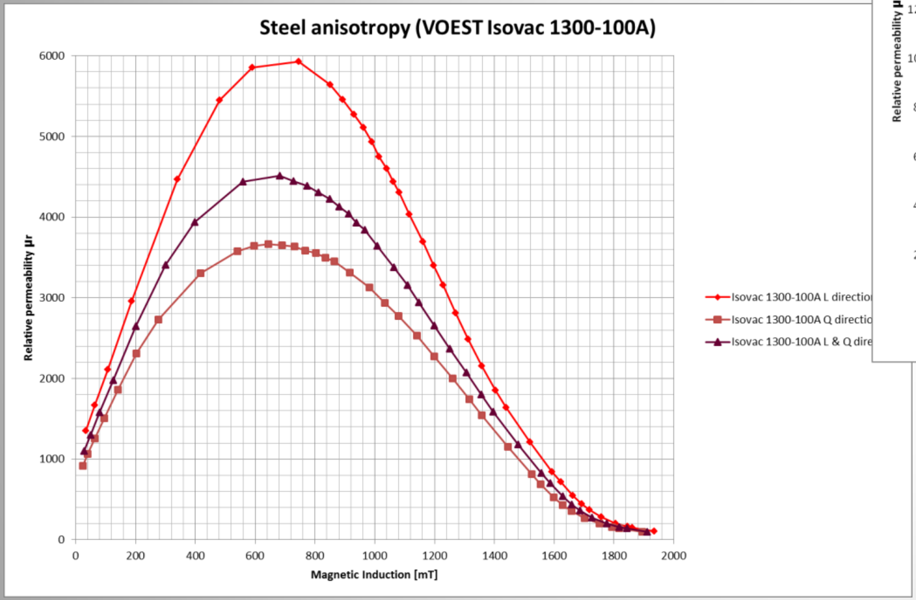
- Magnetic and mechanical properties can be adjusted by final annealing
- Reproducible steel quality even over large productions
- Magnetic properties (permeability, coercivity) within small tolerances
- Homogeneity and reproducibility among the magnets of a series can be enhanced by selecting, sorting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

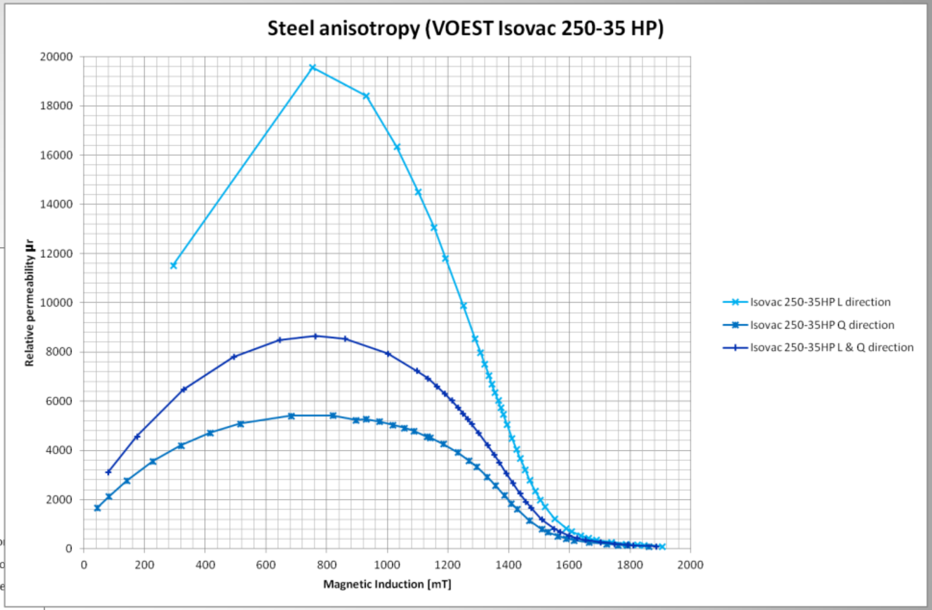


Courtesy of ThyssenKrupp

NGO steel properties

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





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

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

Steel specification

Typical steel characteristics:

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

Sheet insulation

Surface coating:

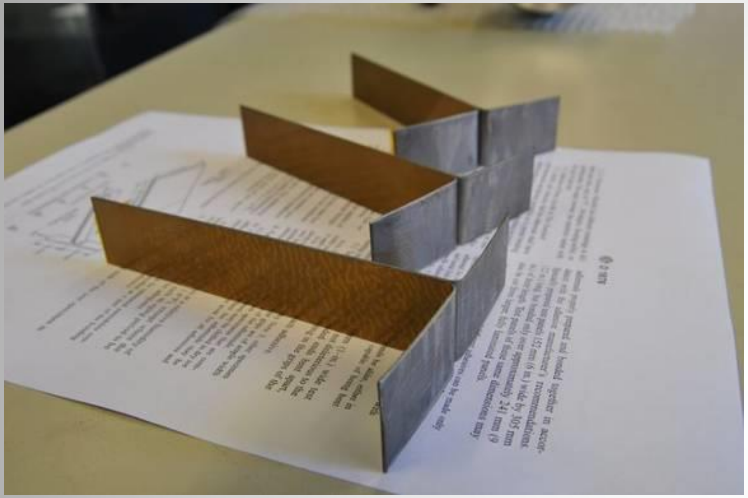
- electrical insulation of several µm thickness
- one or both sides
- oxid layer, phosphate layer, organic or inorganic coating

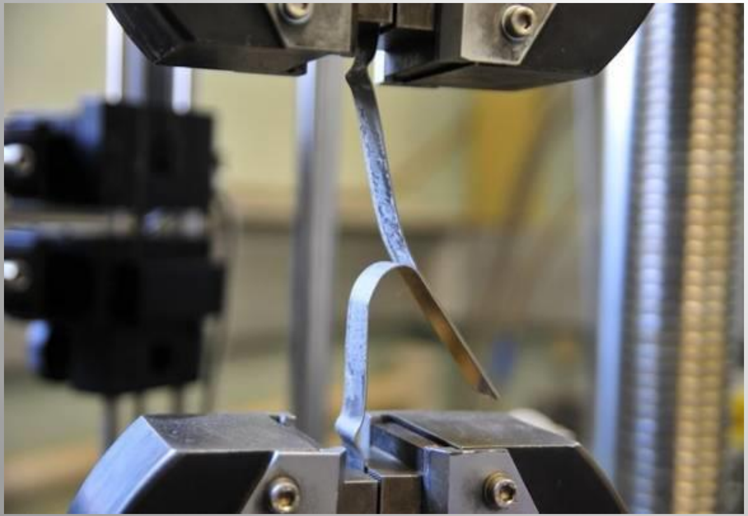
Insulation designation IEC 60404-1-1	**Insulation type**	**Color** [1)]	**Coating**	**Coating thickness each side** in µm	**Insulation resistance at room temperature** to ASTM A717/A717M-95 Ωm²/Lamelle
STABOLIT 10 EC-3 by prior arrangement only	organic	yellow-green	both sides	max. 1.5	> 15
STABOLIT 20 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

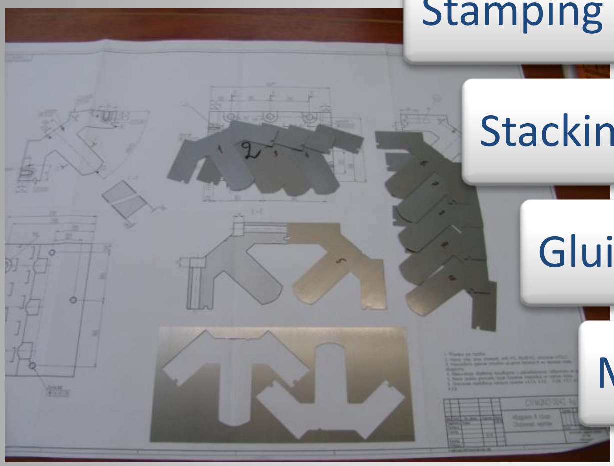
Samples are tested to validate material properties:

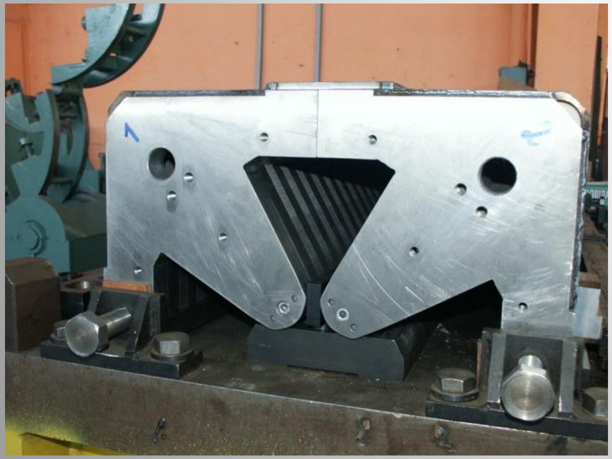


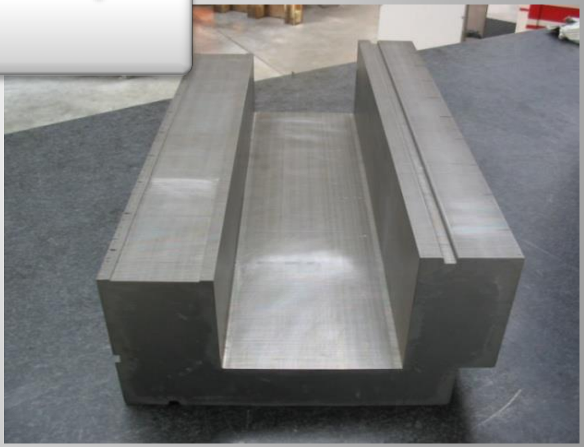


Yoke manufacturing

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

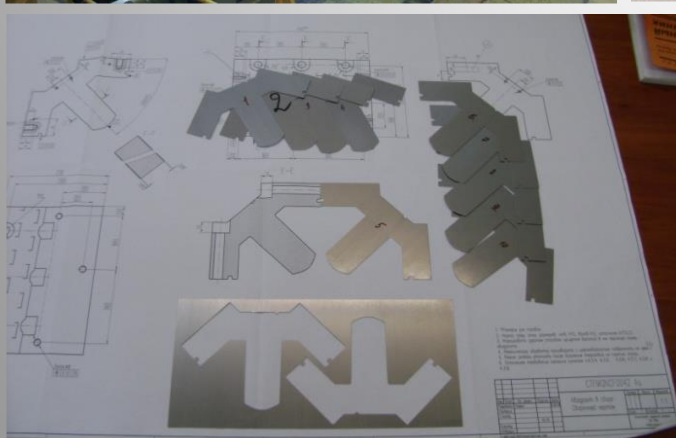


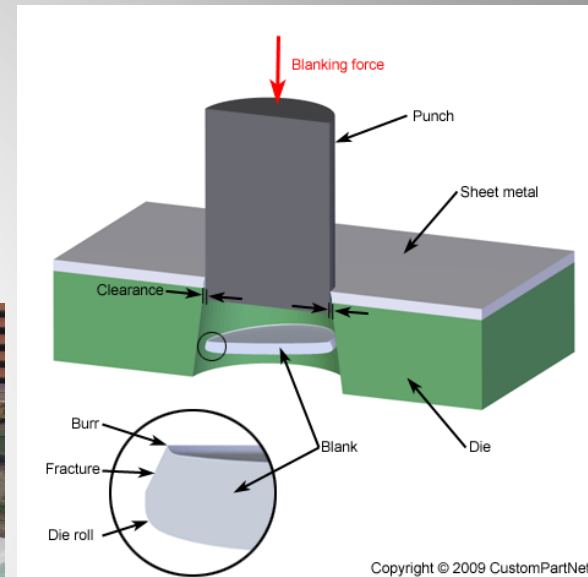


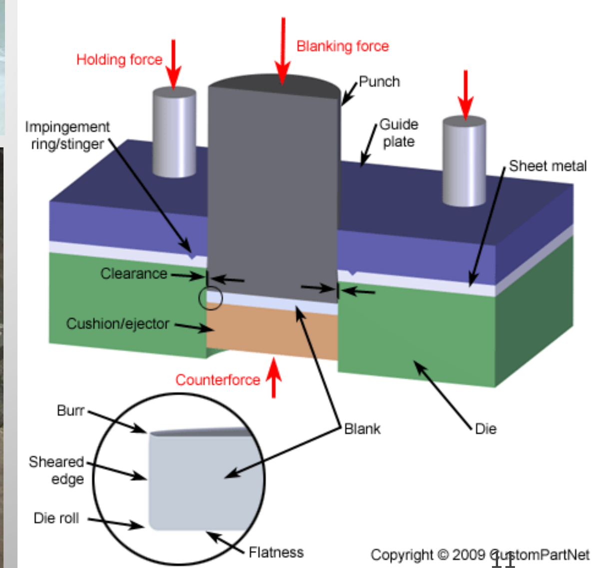


Lamination punching

- 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)

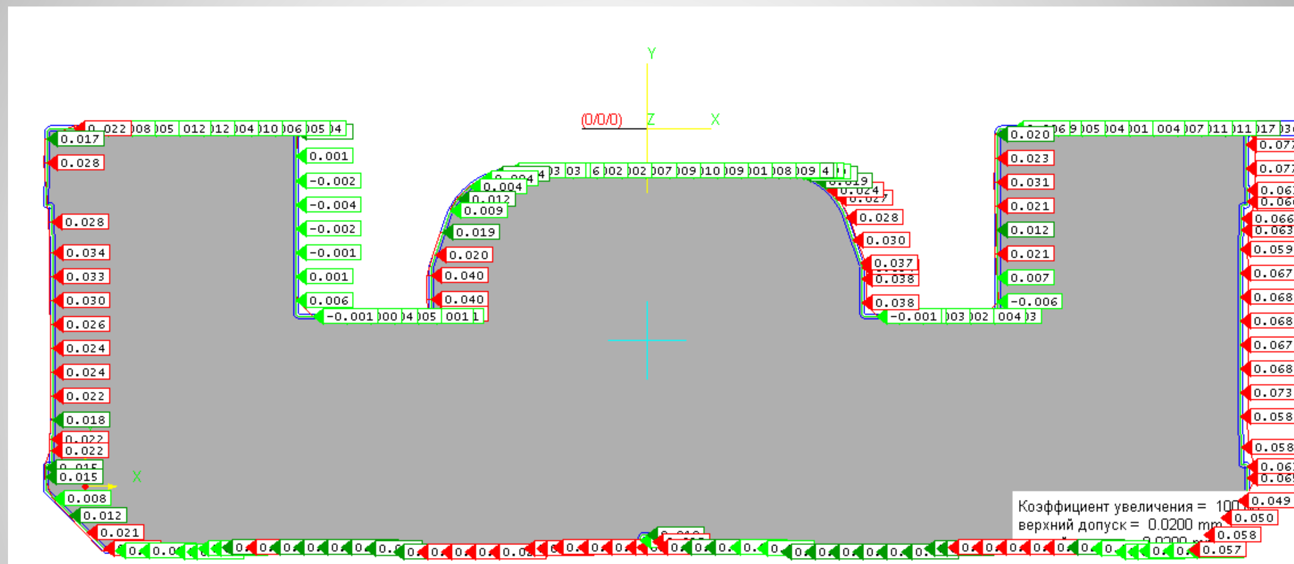


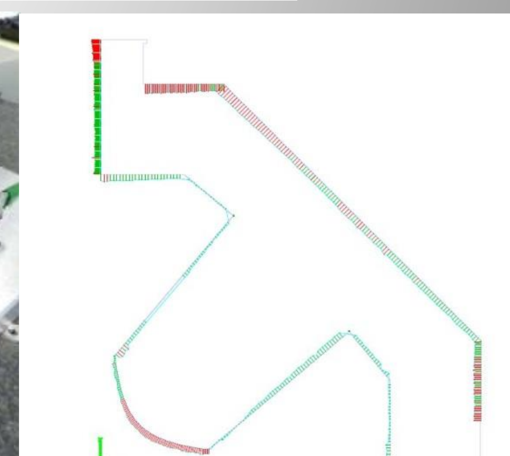




Sample testing

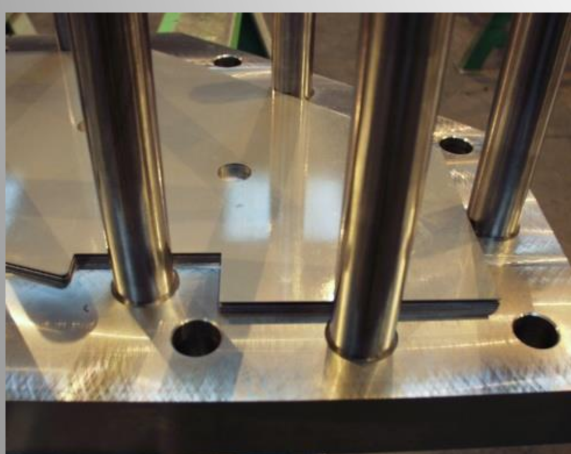
Samples are tested to validate the lamination contour:

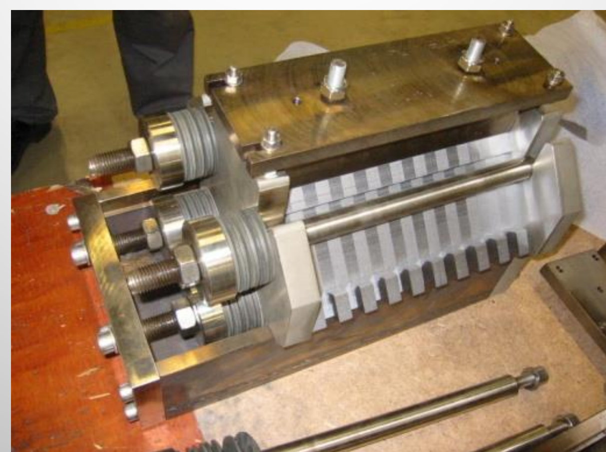




Yoke stacking

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

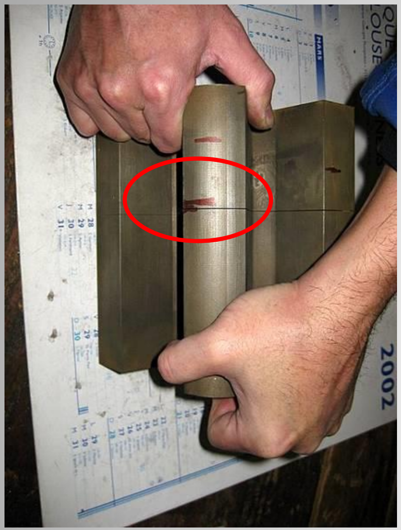
\- requires baking oven

/ requires stacking fixture

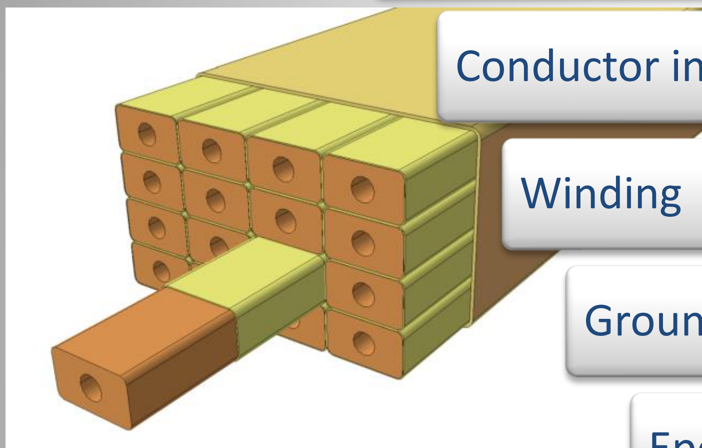
Recommendation: combine gluing, welding & bolting

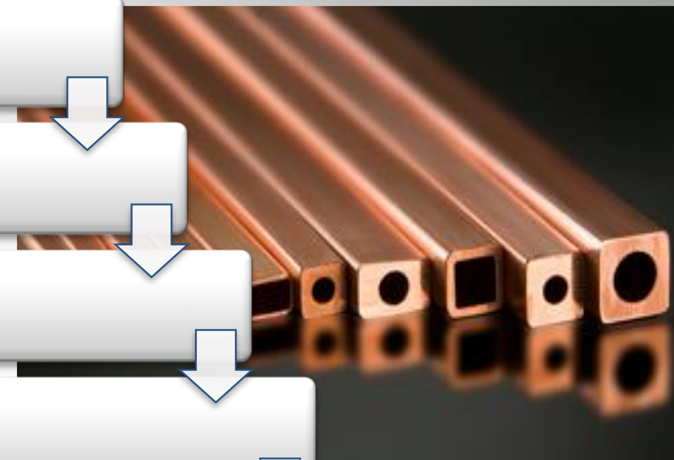
Recurrent quality issues

Poor lamination bonding stength



Coil manufacturing





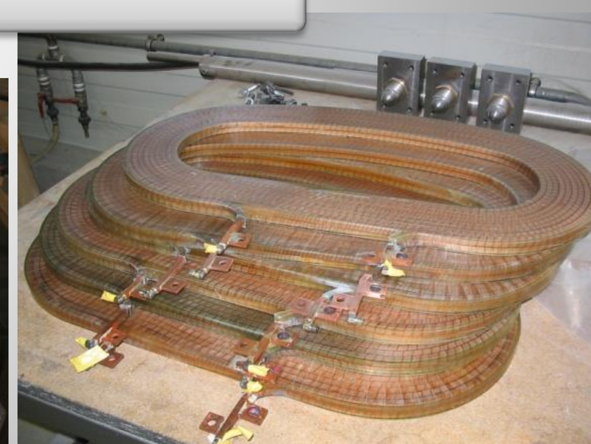
Define conductor type and material

Conductor insulation

Winding

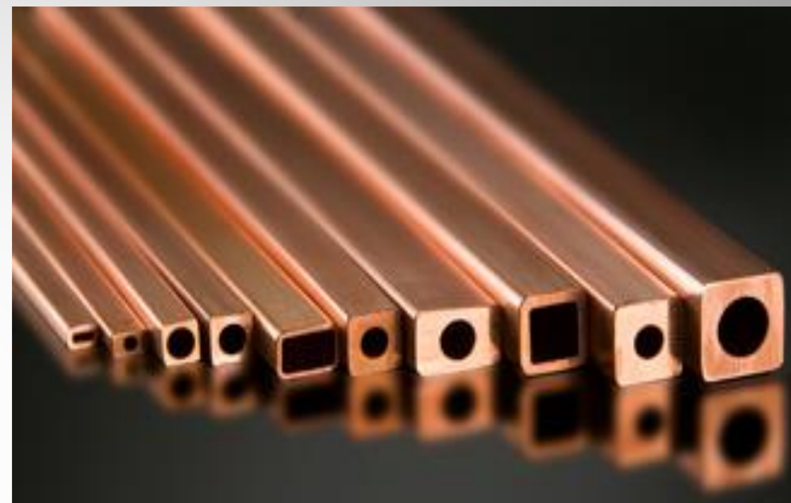
Ground insulation

Epoxy impregnation

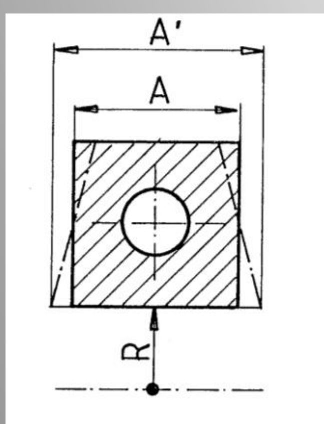


Conductor materials

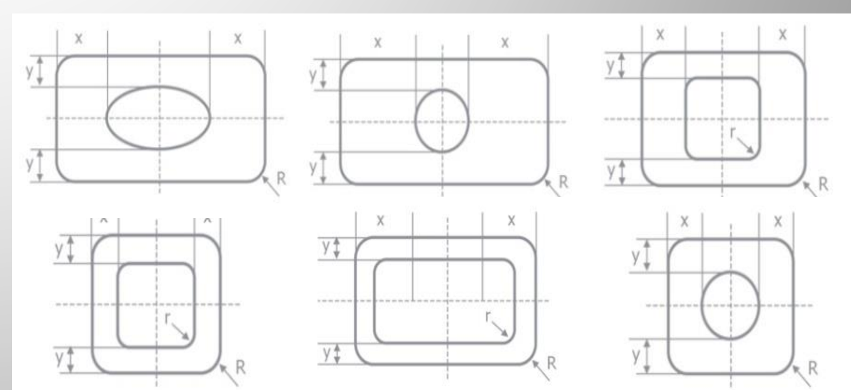
	Al	Cu (OF)
Purity	99.7 %	99.95 %
Resistivity @ 20°C	2.83 μΩ cm	1.72 μΩ cm
Thermal resistivity coeff.	0.004 K^{-1}	0.004 K^{-1}
Specific weight	2.70 g/cm^3	8.94 g/cm^3
Thermal conductivity	2.37 W/cm K	3.91 W/cm K



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

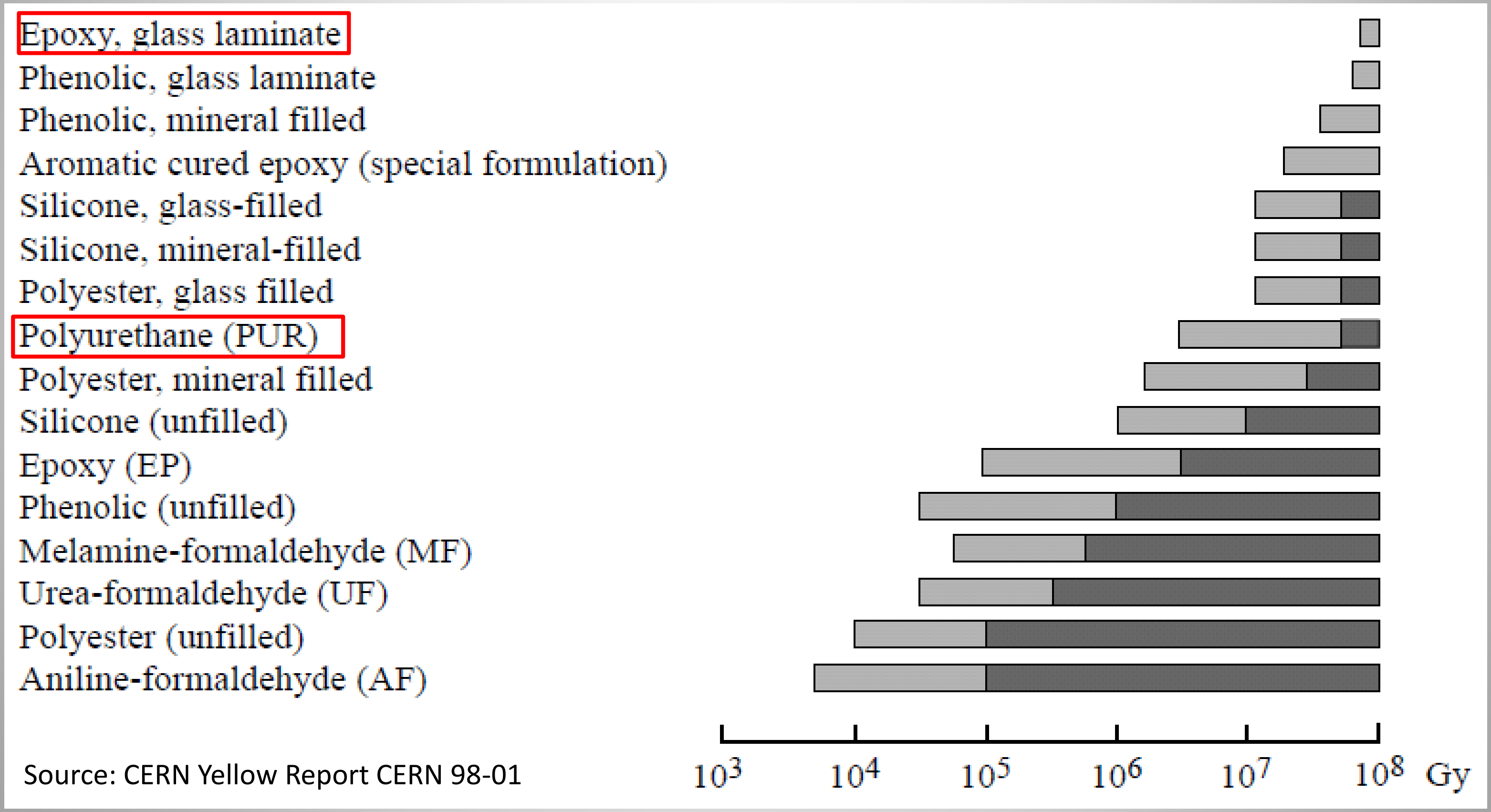
Montsinger's rule / Arrhenius equation: $L(T + 10\,K) \approx 0.5\; t(T)$

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

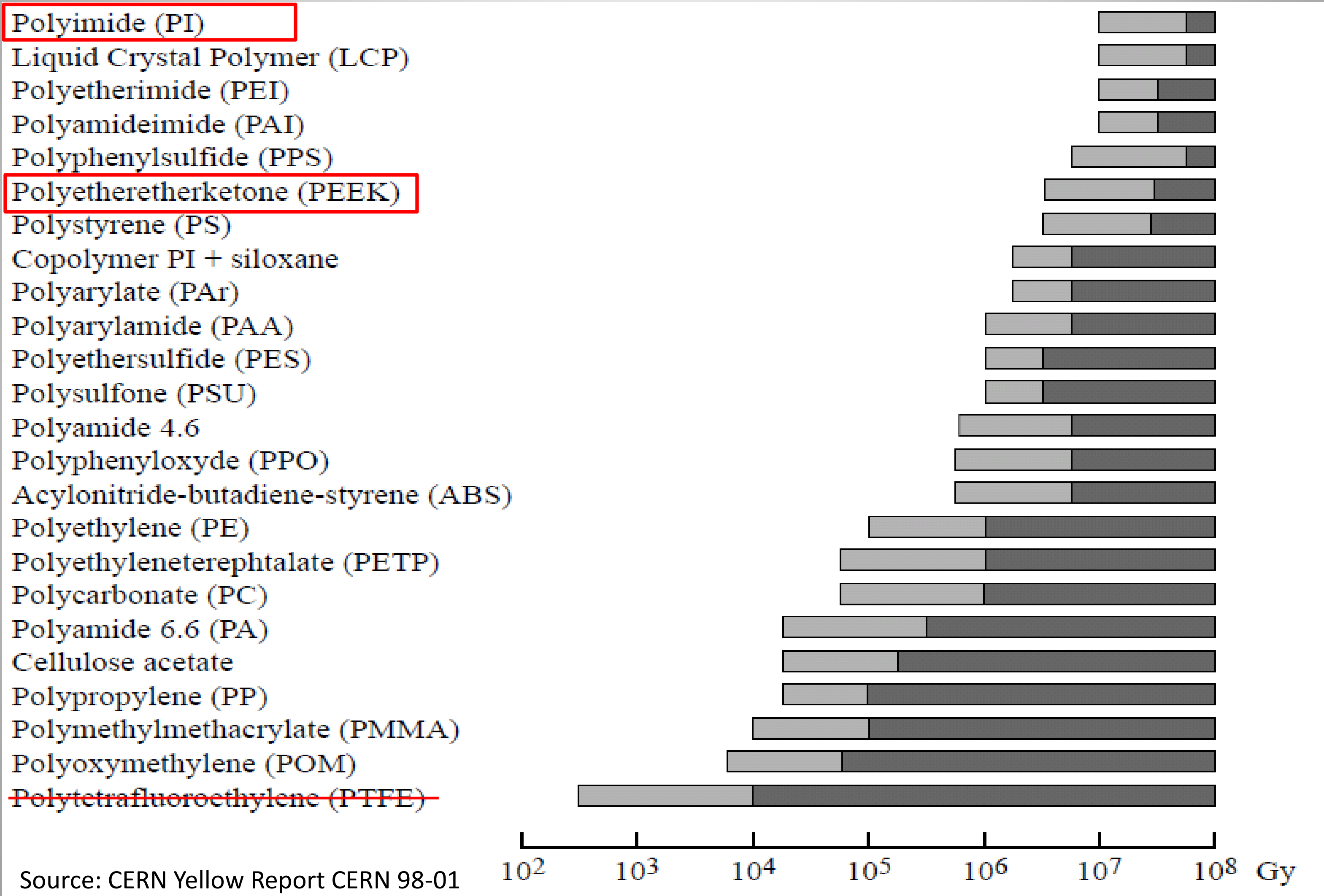
Radiation hardness is an important criterion for insulation materials used for accelerator applications



Source: CERN Yellow Report CERN 98-01

Above 10^8 Gy special insulation techniques are required!

Radiation hardness

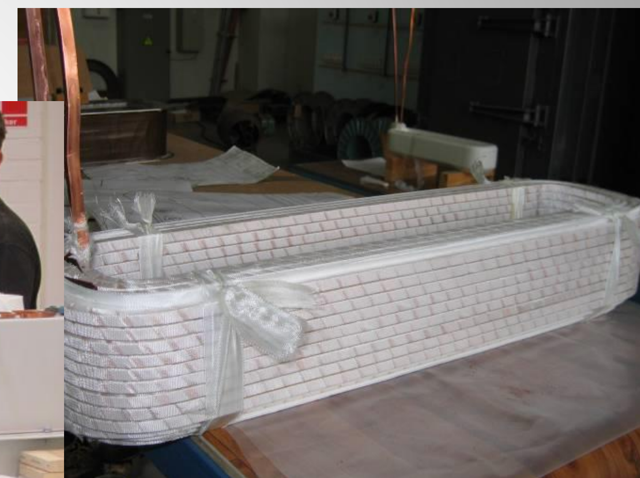


Source: CERN Yellow Report CERN 98-01

Coil insulation

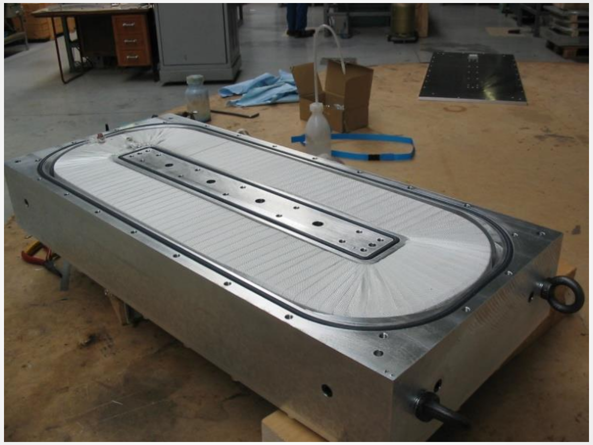
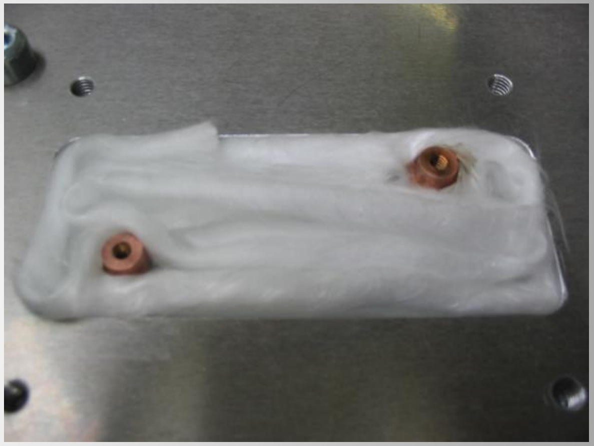
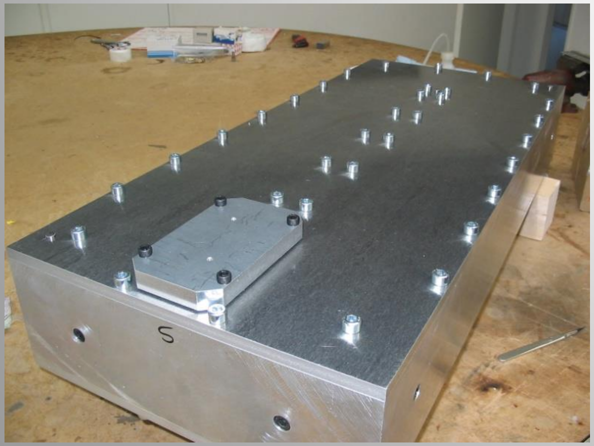
Conductors with small cross-section:

straigthening → cleaning → conductor insulation → winding → ground insulation



Coil impregnation

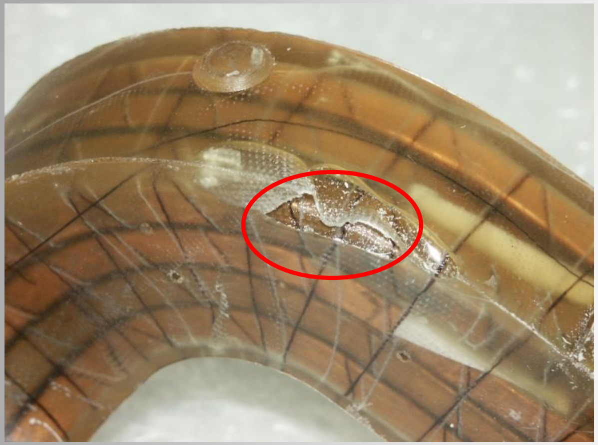
heating and evacuating mold and coil (auto-clave or vacuum mold) → mixing resing → heating and degassing resin → injecting resin → curing cycle → cooling

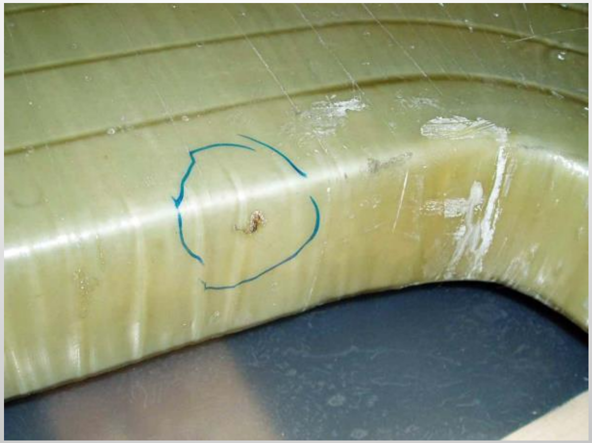





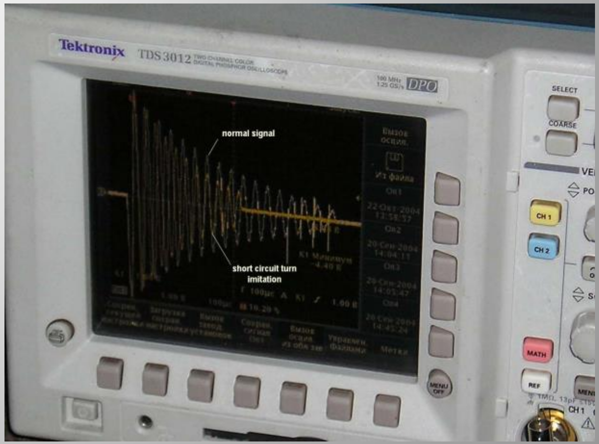
Recurrent quality issues

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

Electrical HV and discharge insulation test shall reveal 'hidden' defects

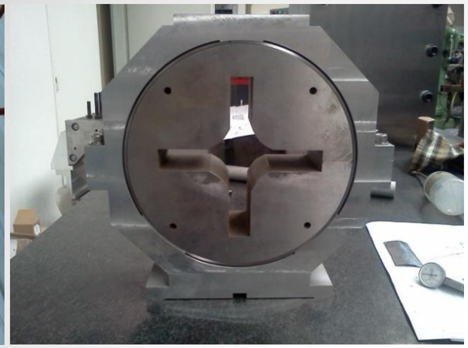






Magnet assembly

By hand....

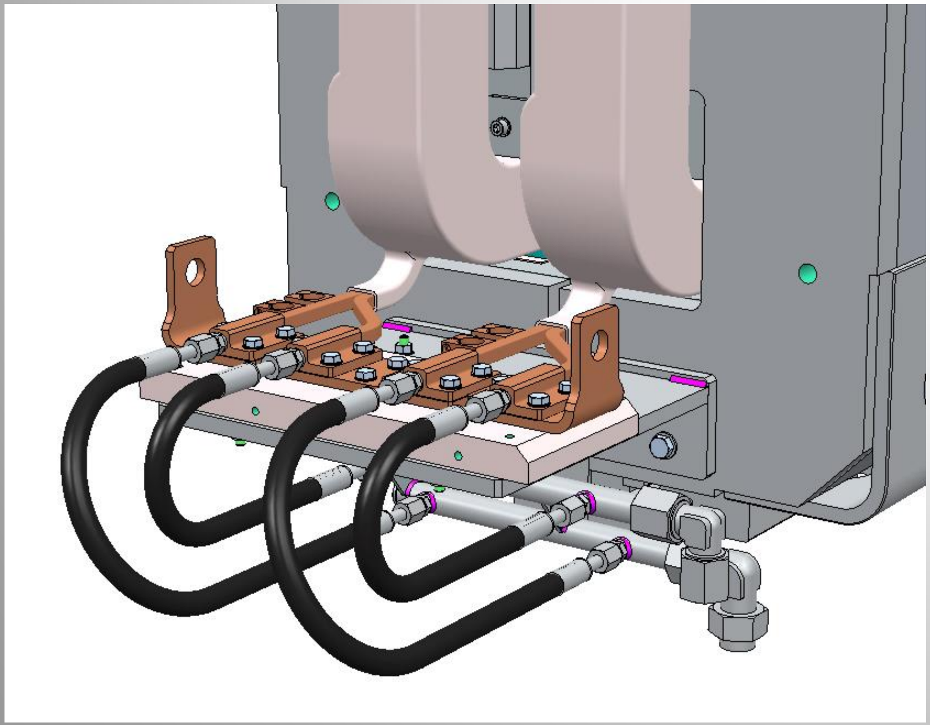



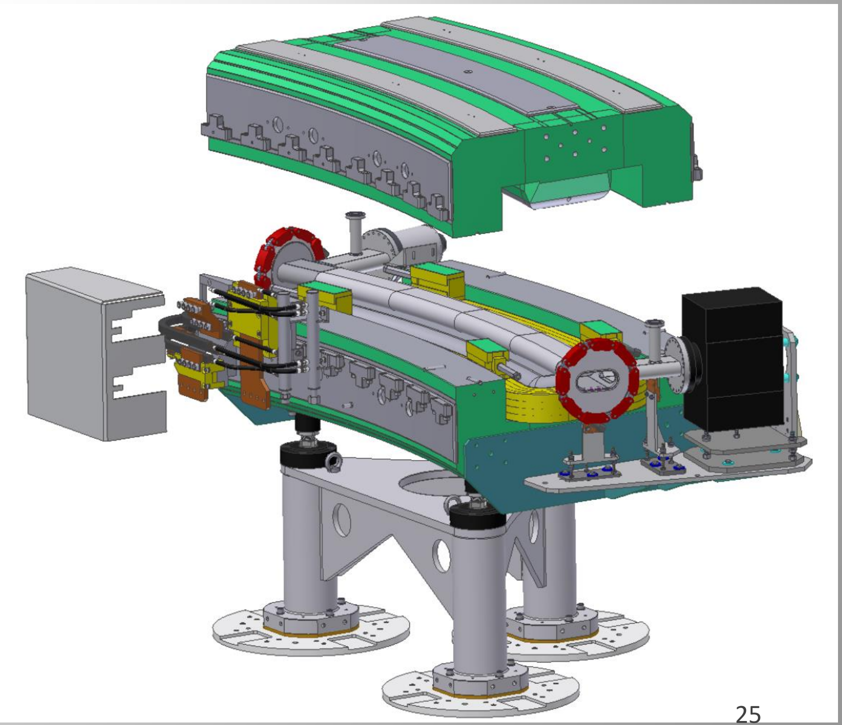
... or with the help of tooling




Auxiliary components

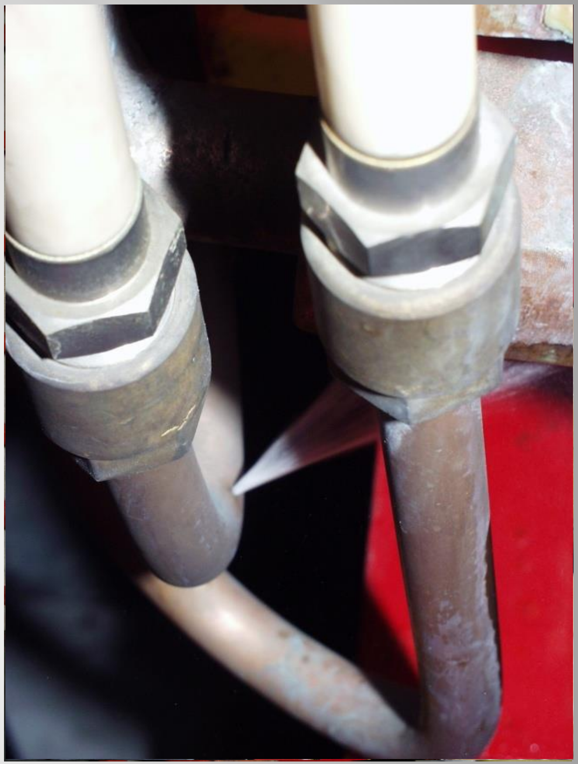
- Electrical connections
- Hydraulic connections
- Interlock sytem (temperature, pressure, water flow)
- Alignment tragets, adjustment tables and support jacks
- Magnetic measurement devices (pick-up coils, hall probes)





Hydraulic circuits

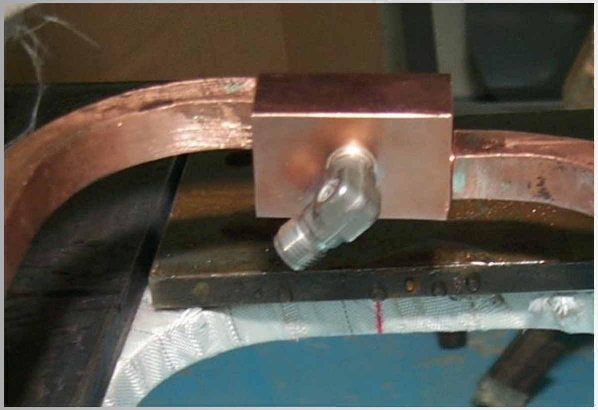
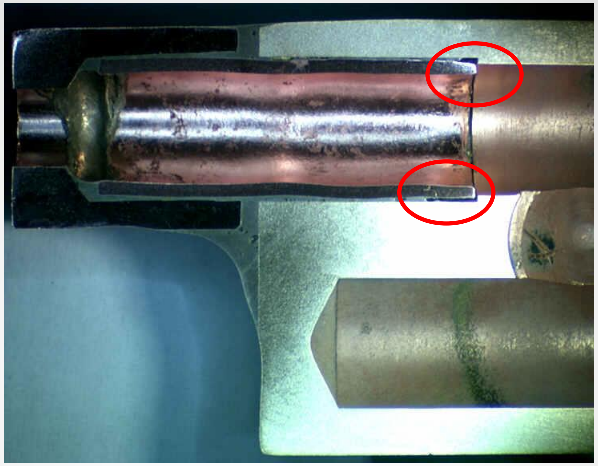
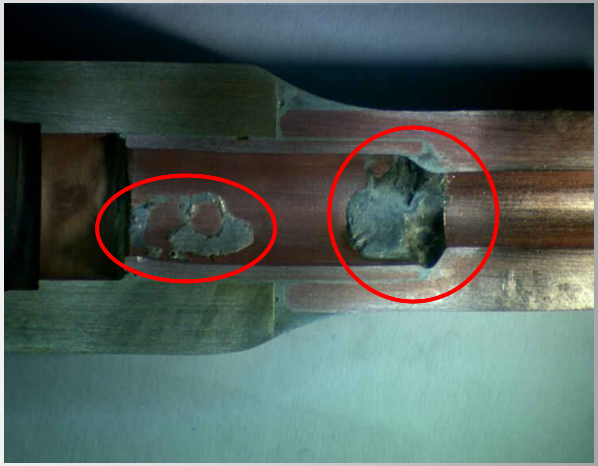
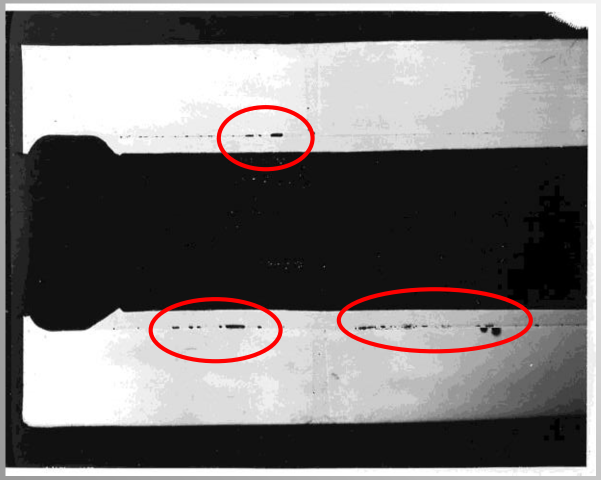
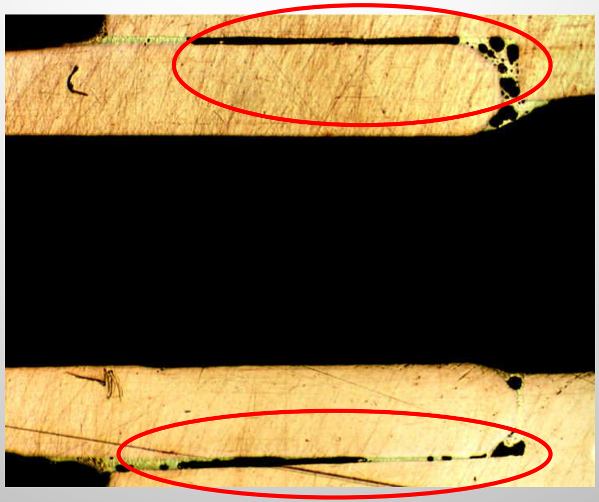
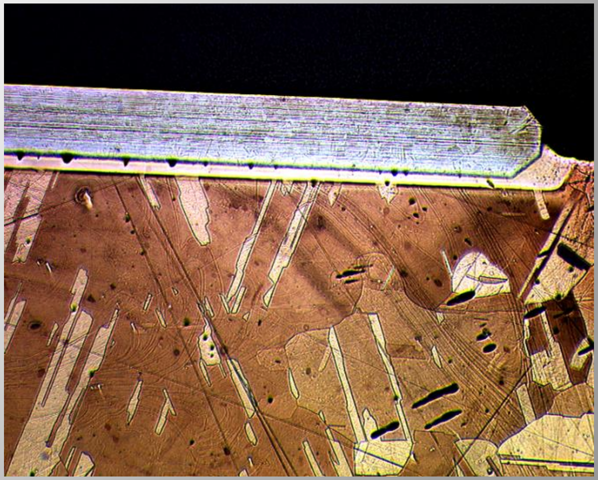
- Water cicuits are most critical items
- 95% of all magnet failures due to water leaks:
  - Corrosion
  - Errosion
  - Poor brazing quality
  - Poor welding quality
  - Failure or aging of joints
  - Inadequate materials
  - Incorrect assembly
  - Radiation damage
  - Inadequate design



- 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

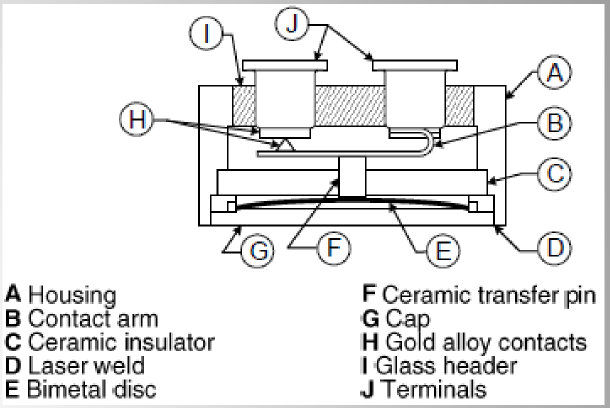
Recurrent quality issues

Lack/excess of brazing filler

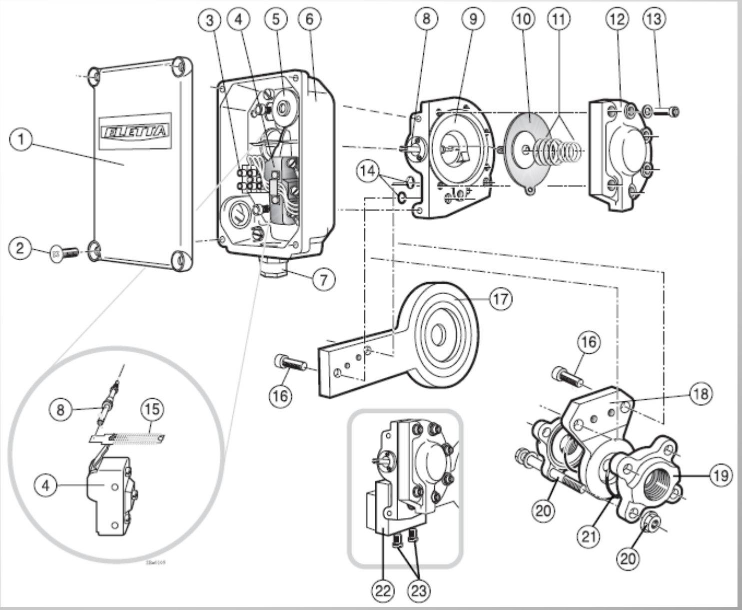







Interlock Sensors

Thermo-switch:



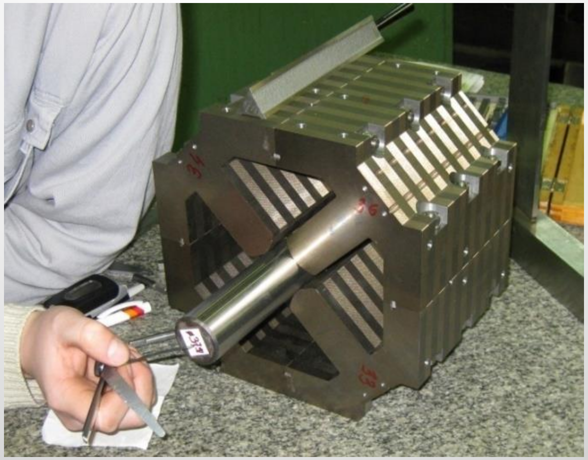
Flow-switch:

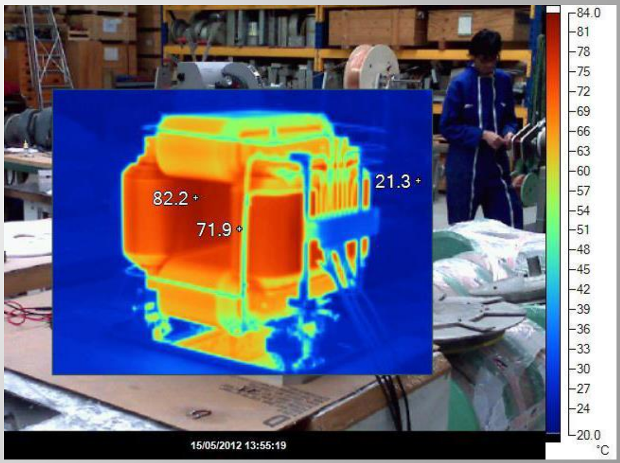


QA & Acceptance tests

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



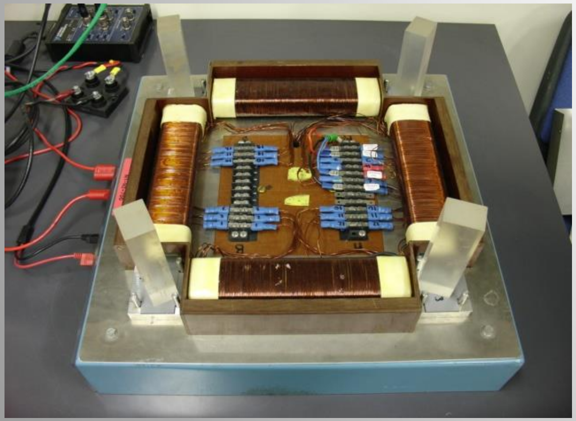


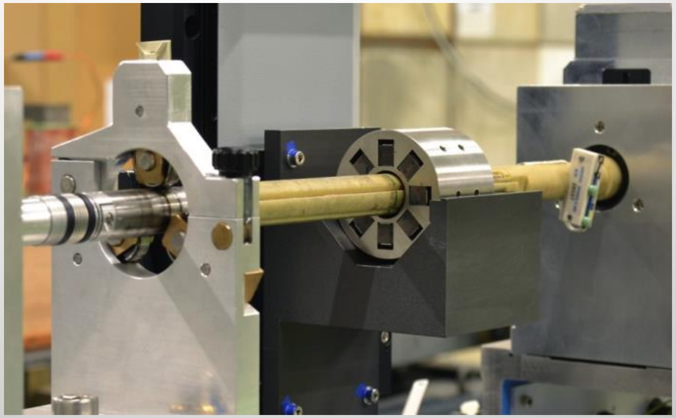
More details: see practical work @ CERN

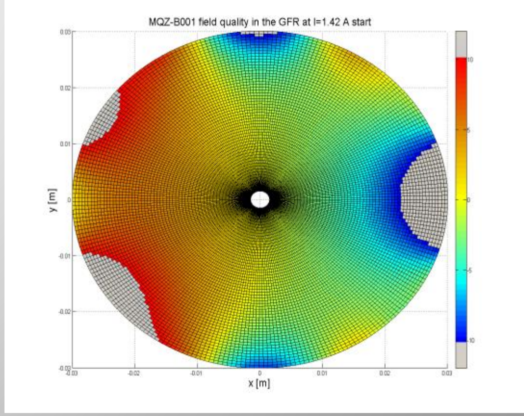
Magnetic measurements

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







More details: see practical work @ CERN

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**

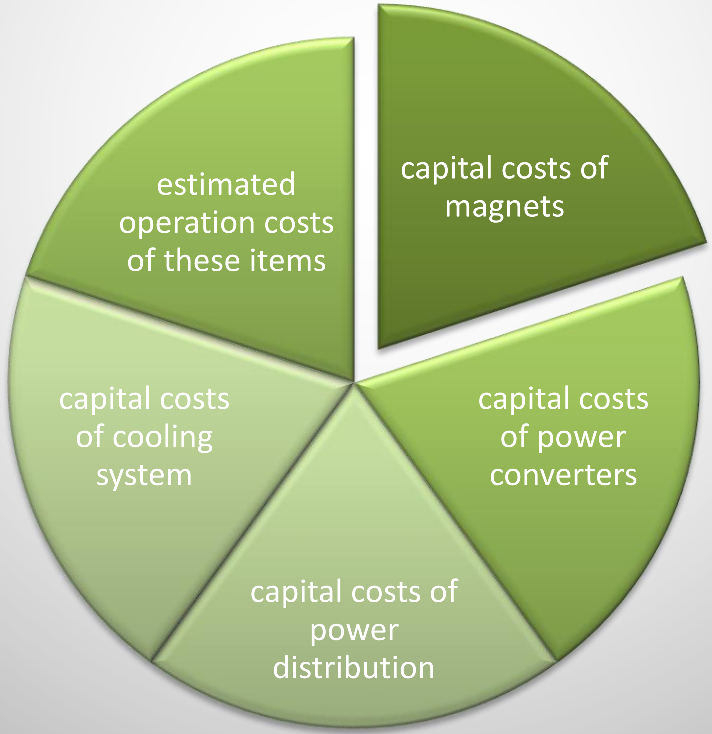
NOT included: magnetic design, supports, cables, water connections, alignment equipment, magnetic measurements, transport, installation
Prices for 2011

Cost optimization

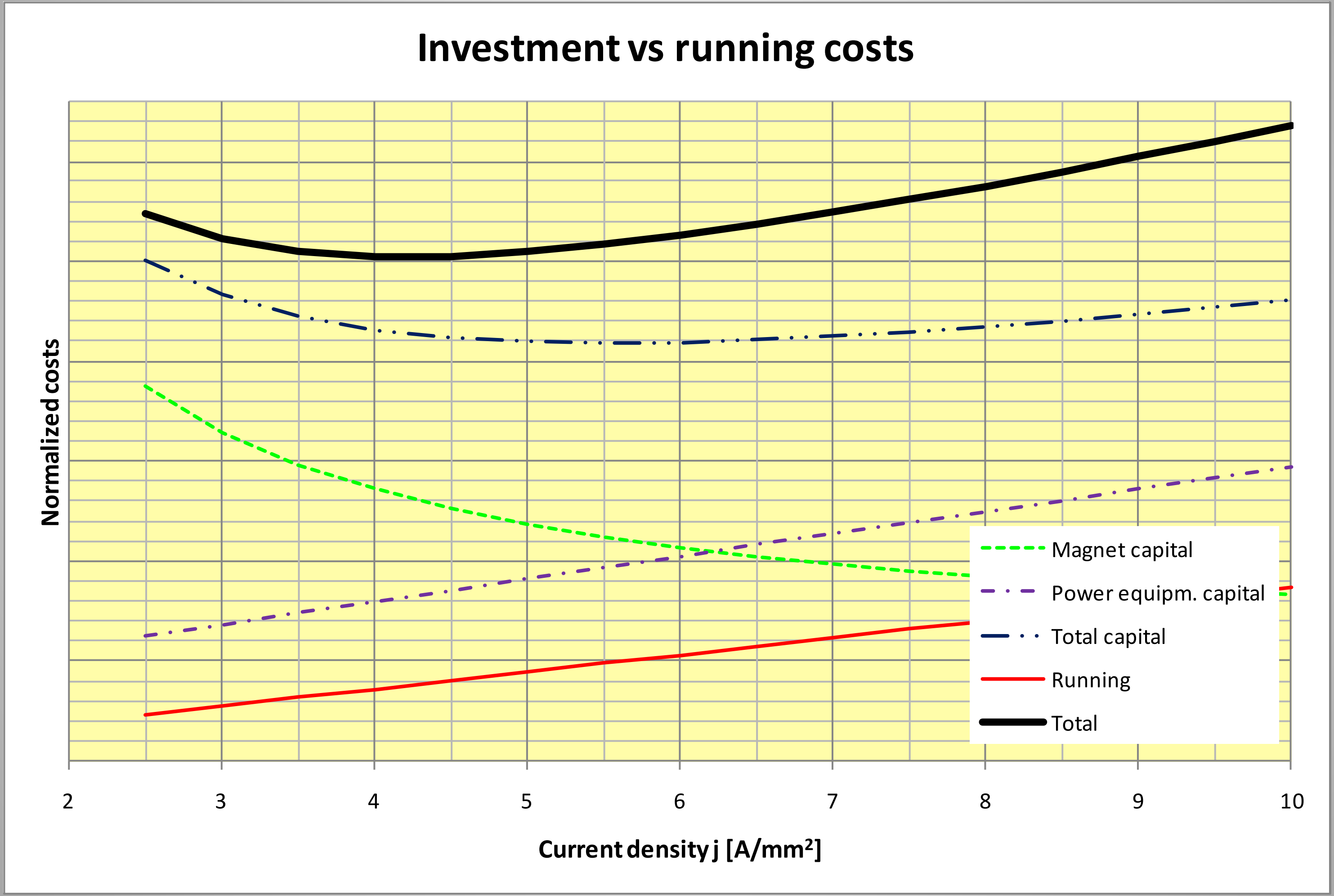
Focus on economic design!

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

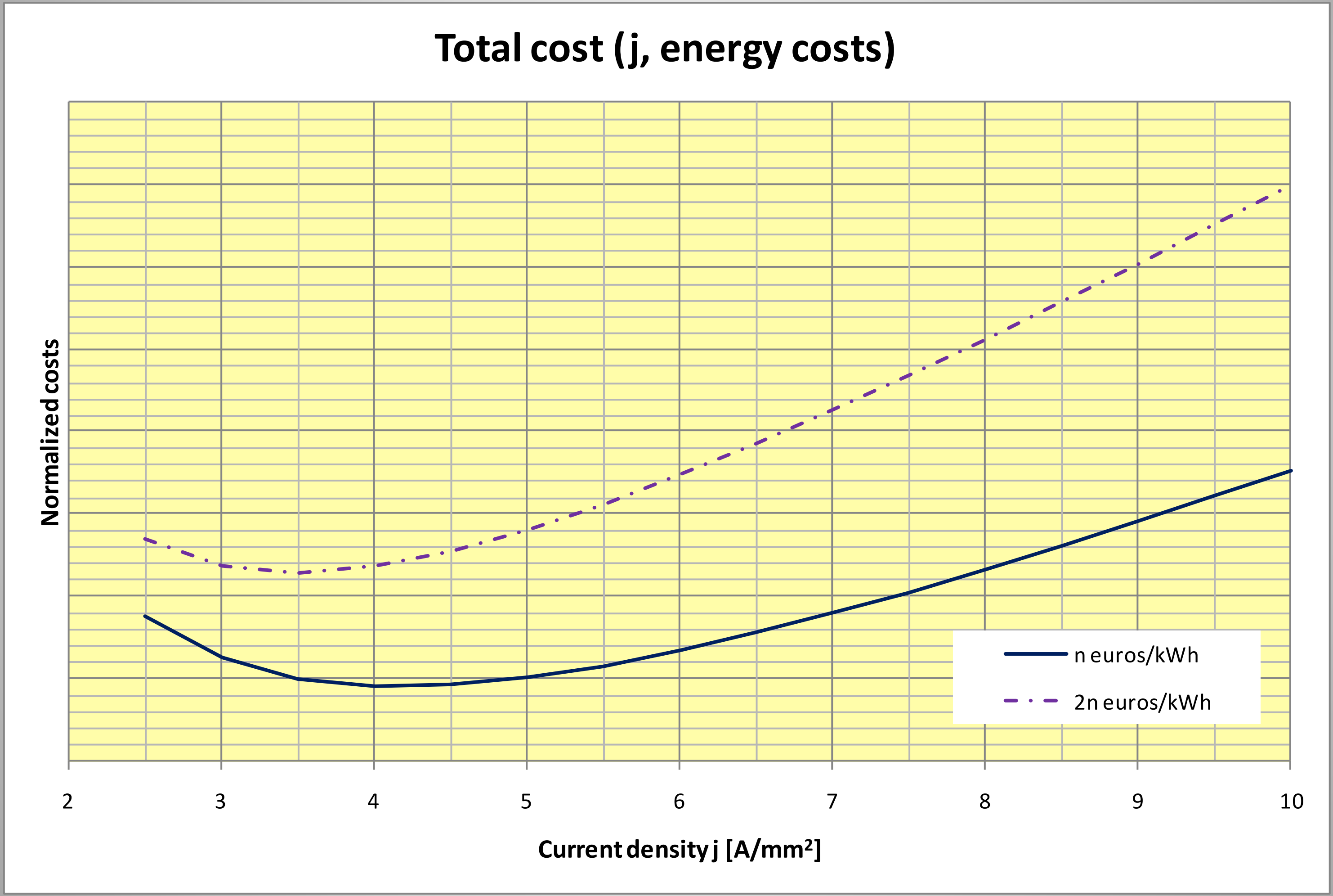
Total costs include:



Cost optimization



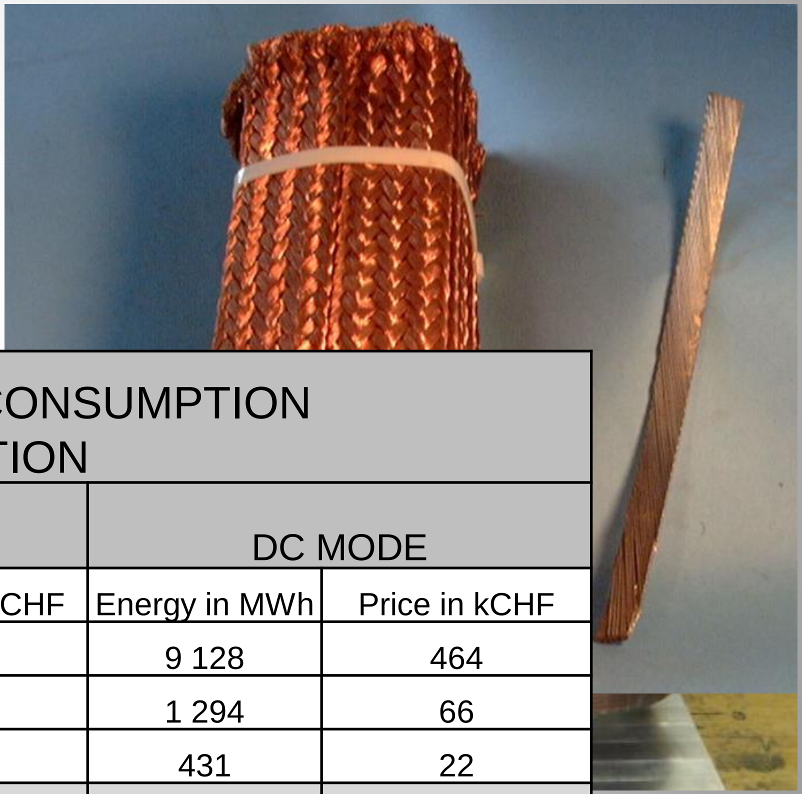
Cost optimization



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 (Sm_2Co_{17})
- 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 manufacturing (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