Normal-Conducting Accelerator Magnets

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CERN

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Scope of this lecture

More than 4800 'room temperature' magnets (50 000 tonnes) are installed in the CERN accelerator complex
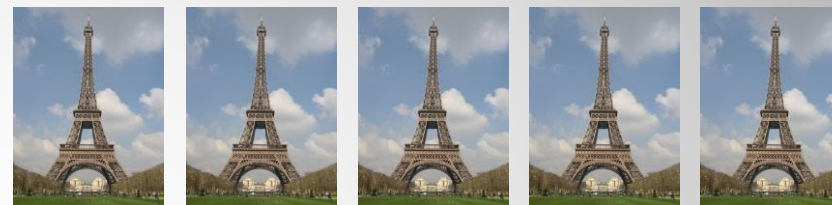
The main goal is to provide an overview on 'room temperature' magnets i.e., normal-conducting, iron-dominated electro-magnets
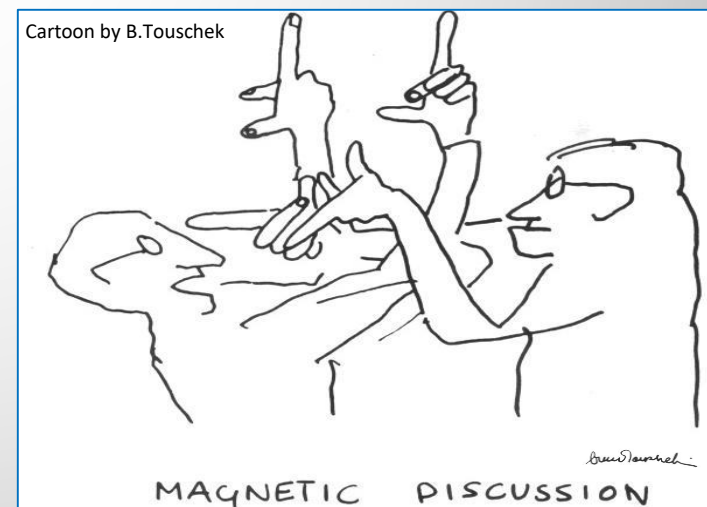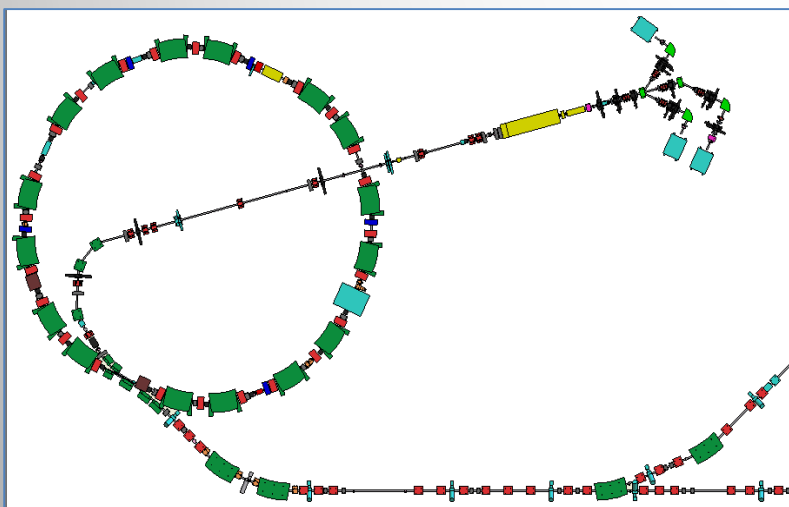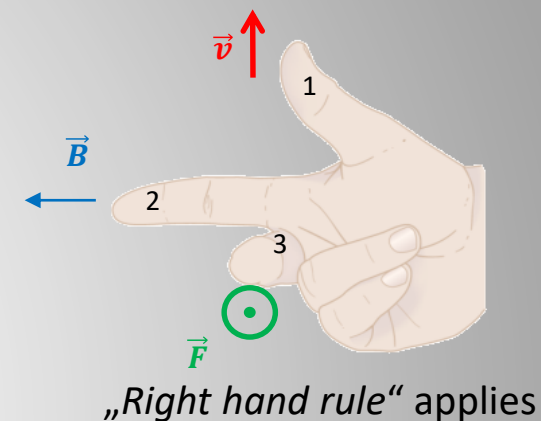
Outline

- Producing magnetic fields
- Magnet technologies
- Magnet types in accelerators
- Design & construction
- Milestones from the past
- New concepts for future accelerators
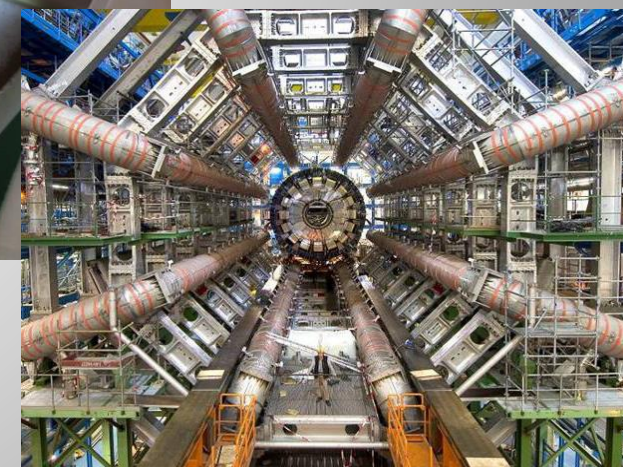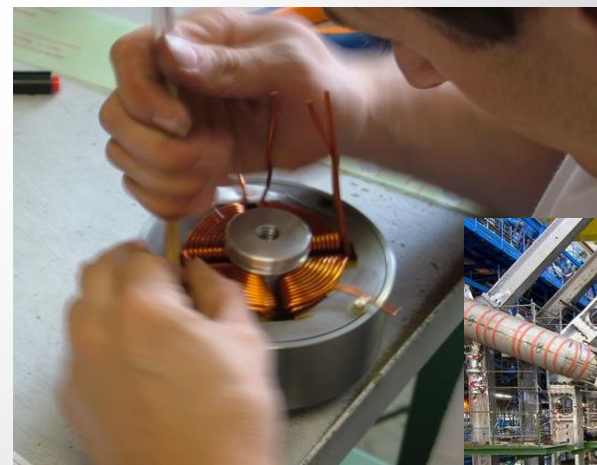
Why do we need magnets?

- Interaction with the beam
  - guide the beam to keep it on the orbit
  - focus and shape the beam
- Lorentz's force: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
  - for relativistic particles this effect is equivalent if $\vec{E} = c\vec{B}$
  - if $B = 1$ T then $E = 3 \cdot 10^8$ V/m(!)

$\vec{v}$

1

$\vec{B}$

2

3

$\vec{F}$

„Right hand rule" applies

Cartoon by B.Touschek

MAGNETIC DISCUSSION
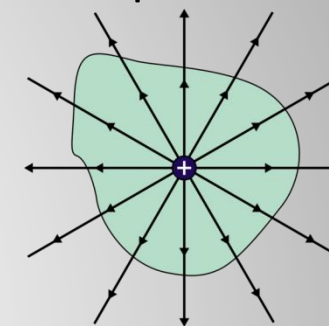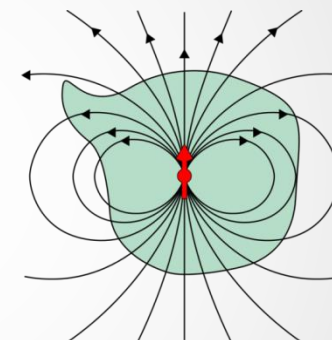
Maxwell's equations

In 1873, Maxwell published "Treatise on Electricity and Magnetism" in which he summarized the discoveries of Coulomb, Øersted, Ampere, Faraday, et. al. in four mathematical equations:

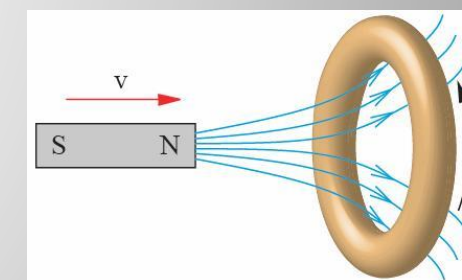Gauss' law for electricity: $\quad \nabla \cdot \vec{D} = \rho \qquad\qquad \vec{D} = \varepsilon \vec{E}$

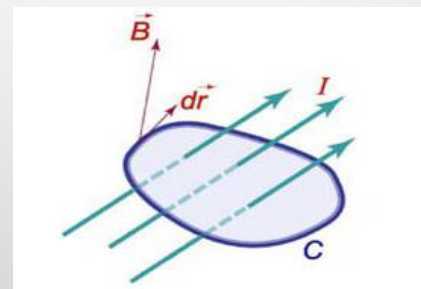Gauss' law of flux conservation: $\quad \boxed{\nabla \cdot \vec{B} = 0}$

Faraday's law of induction: $\quad \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \qquad \boxed{\vec{B} = \mu \vec{H}}$

Ampere's law: $\quad \boxed{\nabla \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t}}$

Magnet vocabulary

IEEE defines the following terms and units:

- Magnetic field:
  - H (vector) [A/m]
  - magnetizing force produced by electric currents
- Magnetic flux density or magnetic induction:
  - B (vector) [T or kg/(A·s^2)]
  - density of magnetic flux driven through a medium by the magnetic field
  - <u>Note</u>: flux or induction is frequently referred to as "Magnetic Field"
  - H, B and μ relates by the constitutive law for materials: $B = \mu H$
- Permeability:
  - $\mu = \mu_0 \mu_r$
  - permeability of free space $\mu_0 = 4·\pi·10^{-7}$ [(V·s)/(A·m) or (kg·m)/(A·s^2)]
  - relative permeability μ_r (dimensionless): $\mu_{air} = 1$; $\mu_{iron} > 1000$ (not saturated)
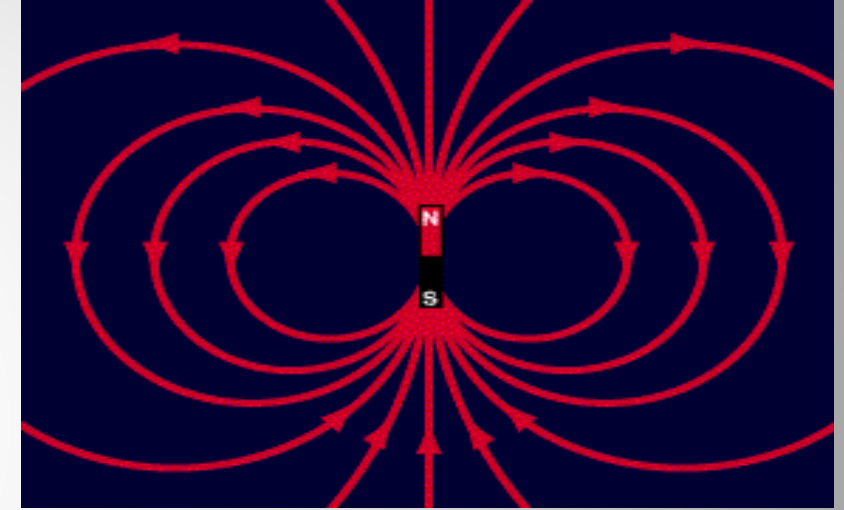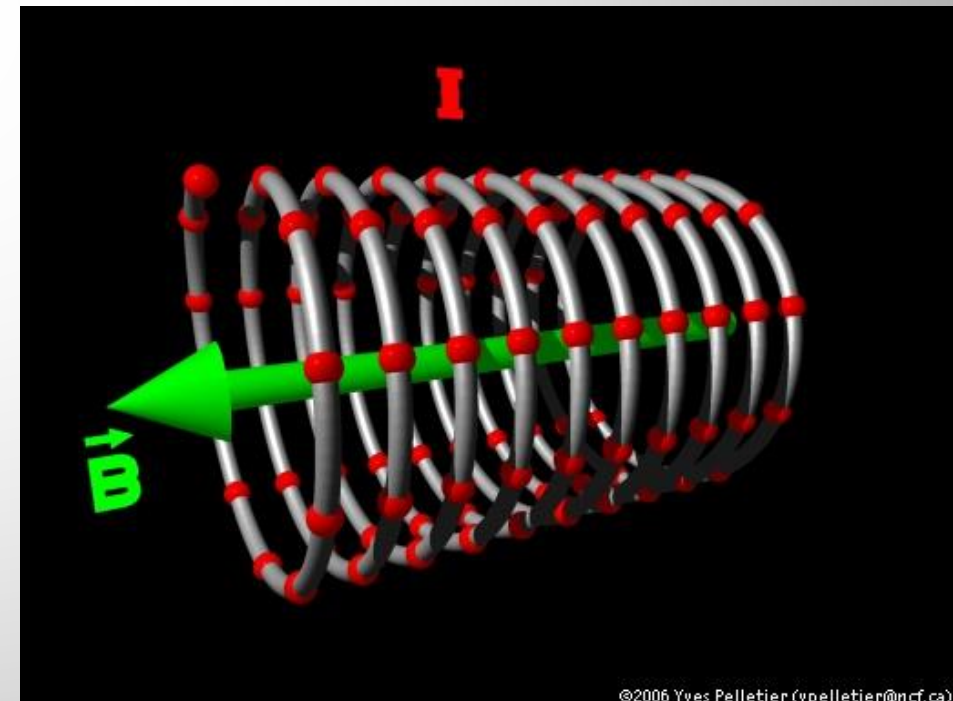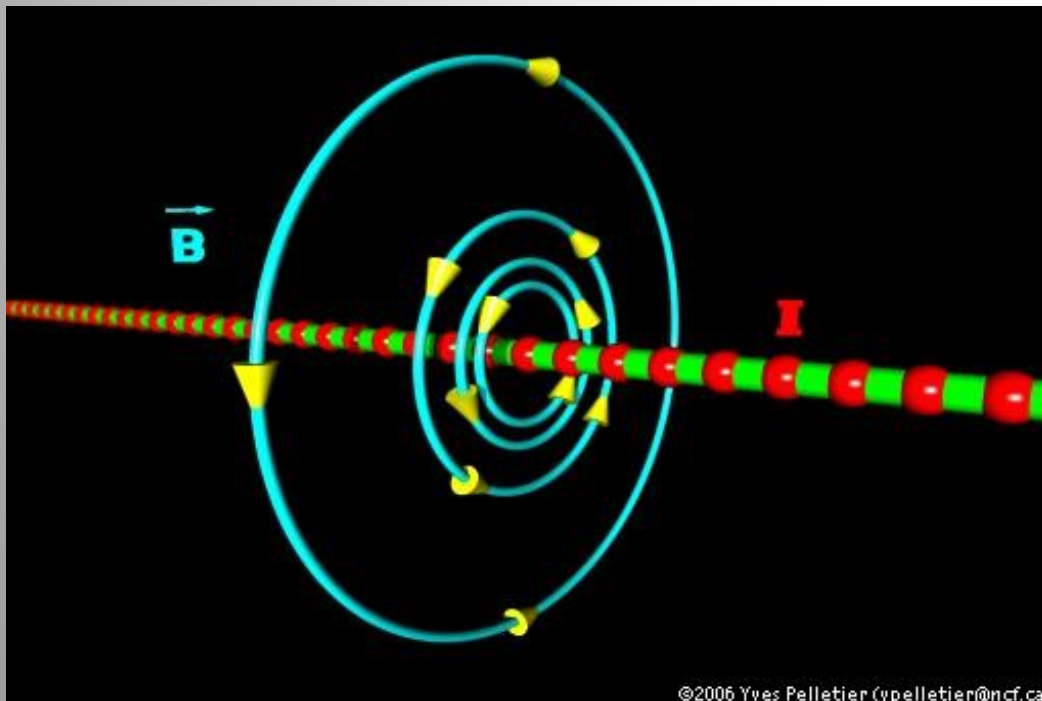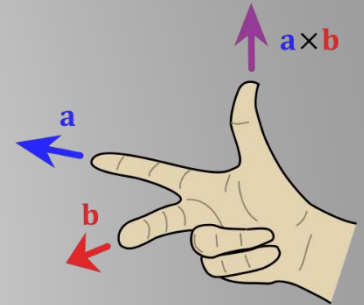
Producing the magnetic field

Maxwell & Ampere:

$$\nabla \times \vec{H} = \vec{J} + \cancel{\frac{\partial \vec{D}}{\partial t}}$$

$$\vec{B} = \mu \vec{H}$$

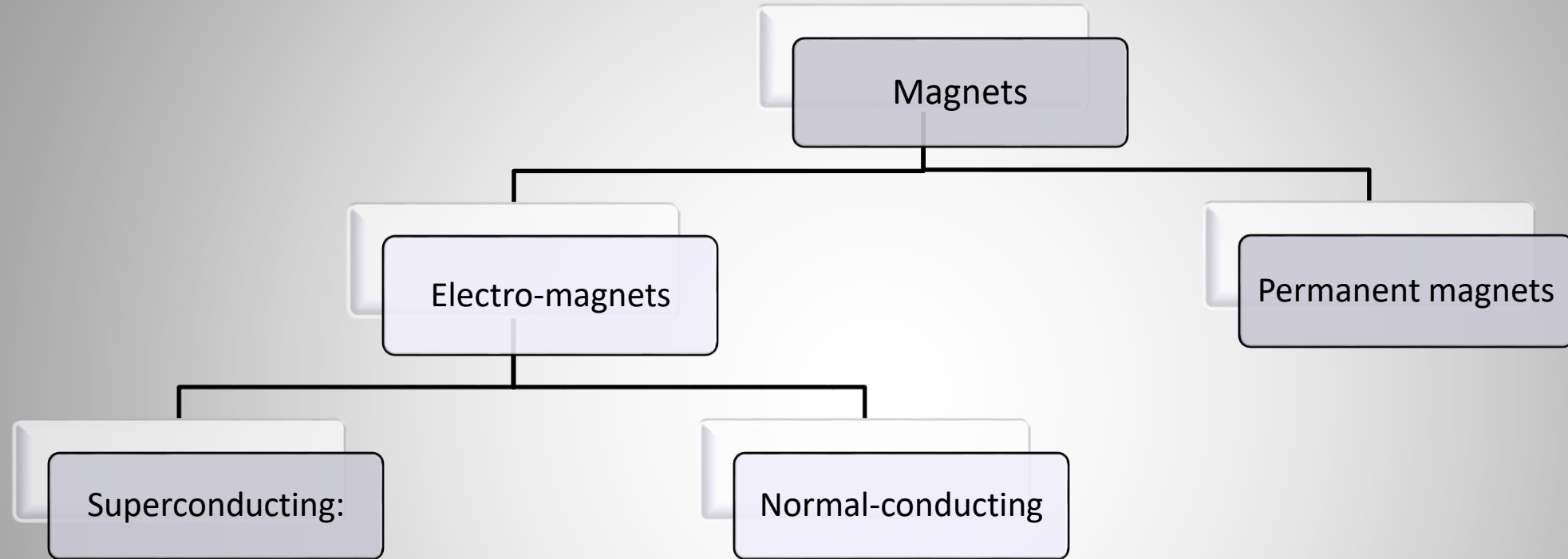$$\nabla \times \vec{B} = \mu_0 \vec{J}$$

„An electrical current is surrounded by a magnetic field"

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Magnet technologies

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                        ┌─────────────────┐
                        │     Magnets     │
                        └────────┬────────┘
                ┌────────────────┴────────────────┐
      ┌──────────────────┐              ┌──────────────────────┐
      │  Electro-magnets │              │   Permanent magnets  │
      └─────────┬────────┘              └──────────────────────┘
        ┌───────┴────────┐
┌─────────────────┐   ┌─────────────────────┐
│ Superconducting:│   │  Normal-conducting  │
└─────────────────┘   └─────────────────────┘
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- zero electrical resistance
- no ohmic losses
- high current densities
- requires cryogenic cooling

- limited by the ohmic losses
- only moderate current densities
- dissipated power to be removed
- requires air or water cooling

Coil dominated – Iron dominated

In coil-dominated magnets, the magnetic field in the aperture is shaped by the position of the conductors respectively the current distribution around the aperture

In iron-dominated magnets, the magnetic field is shaped by the geometry of the poles, which are surfaces of constant scalar potential
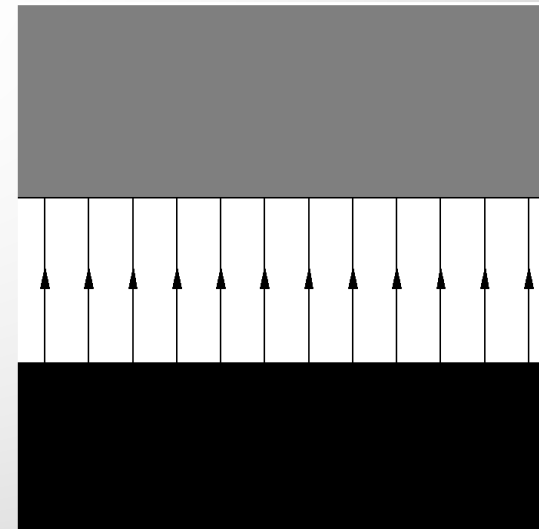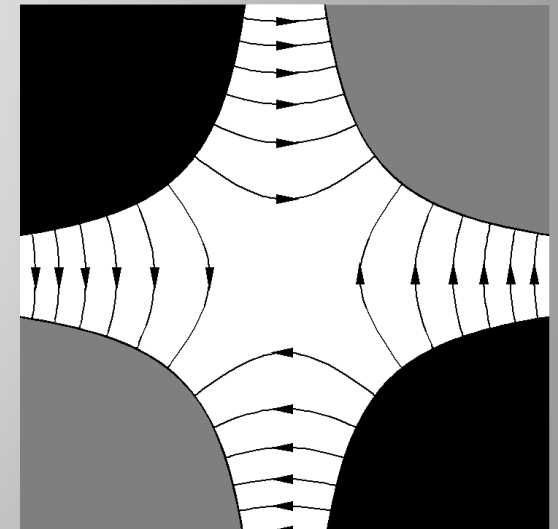
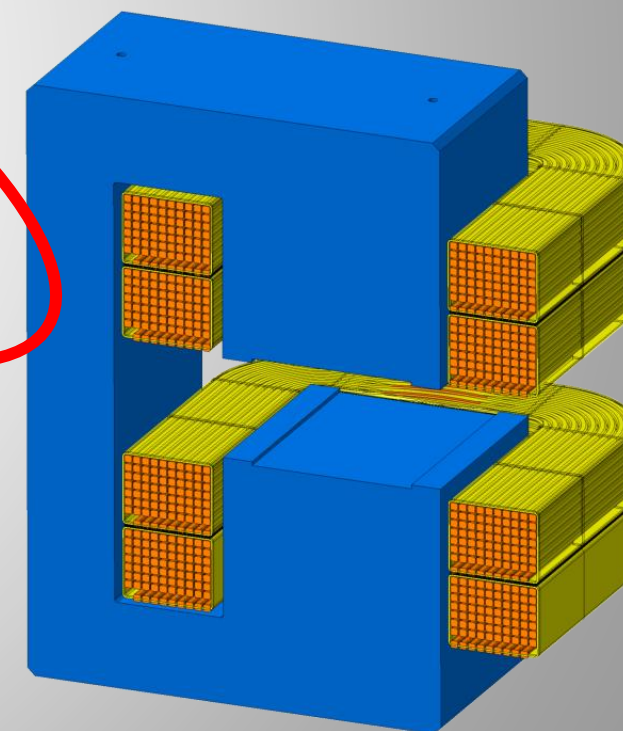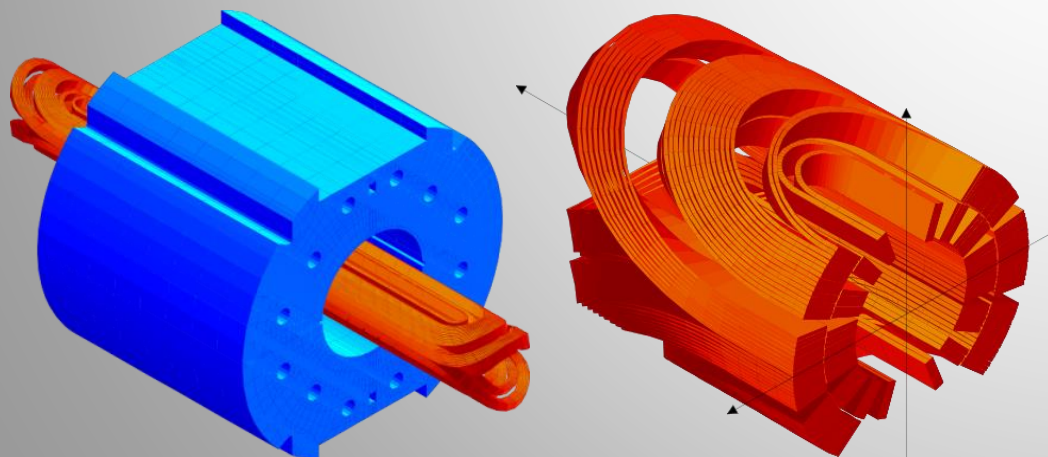B_1: normal dipole
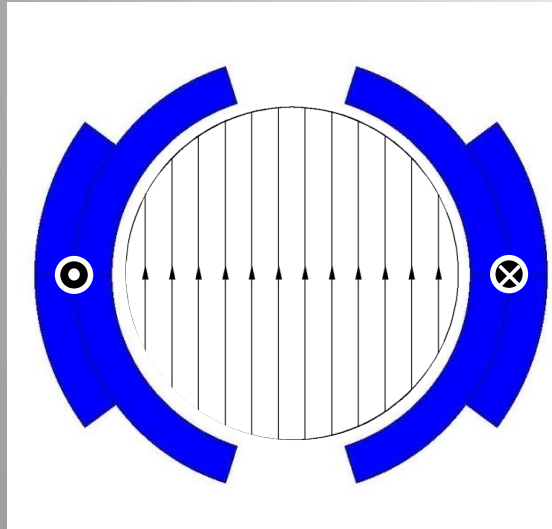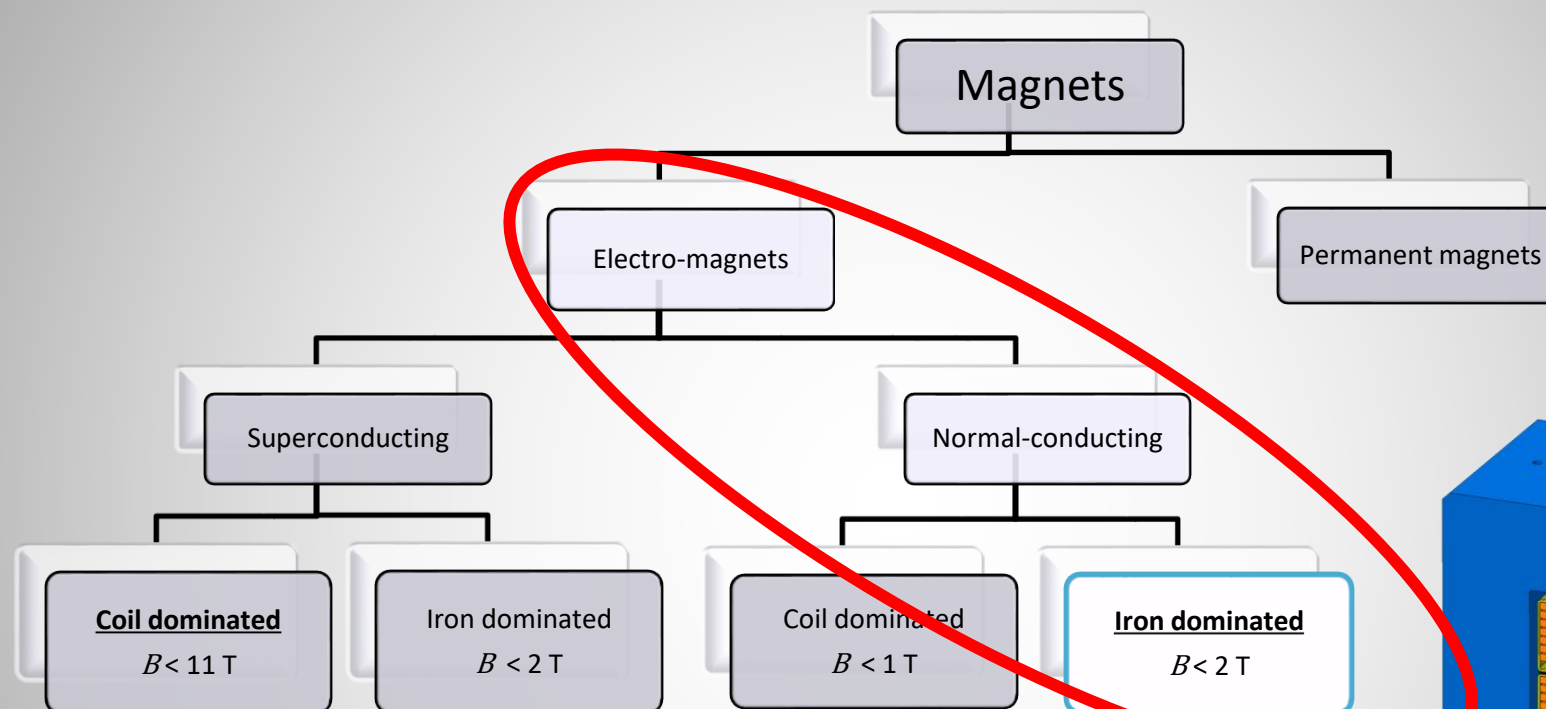
B_2: normal quadrupole
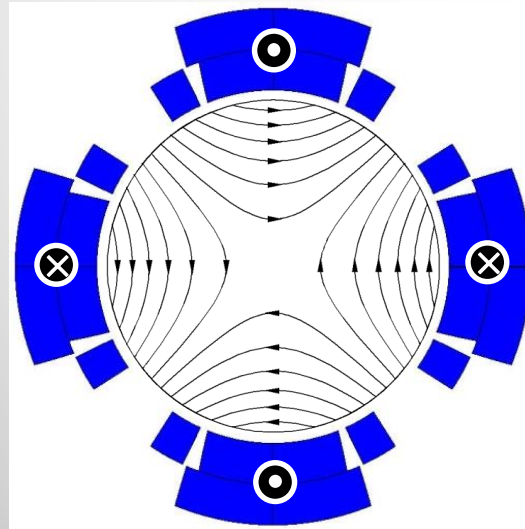
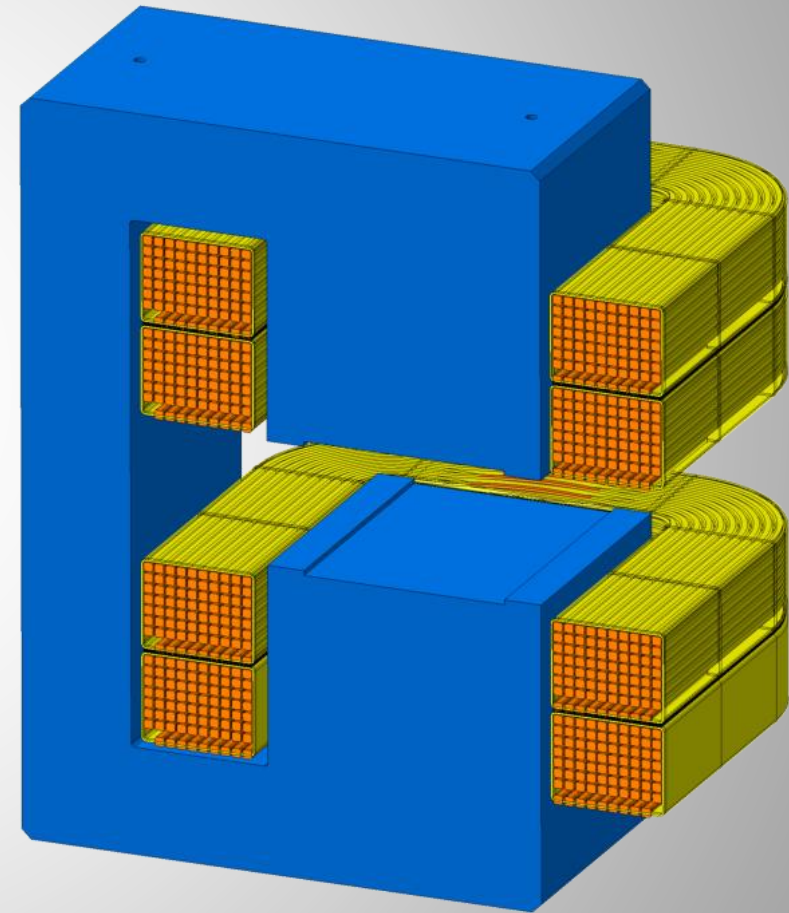B_1: normal dipole

B_2: normal quadrupole
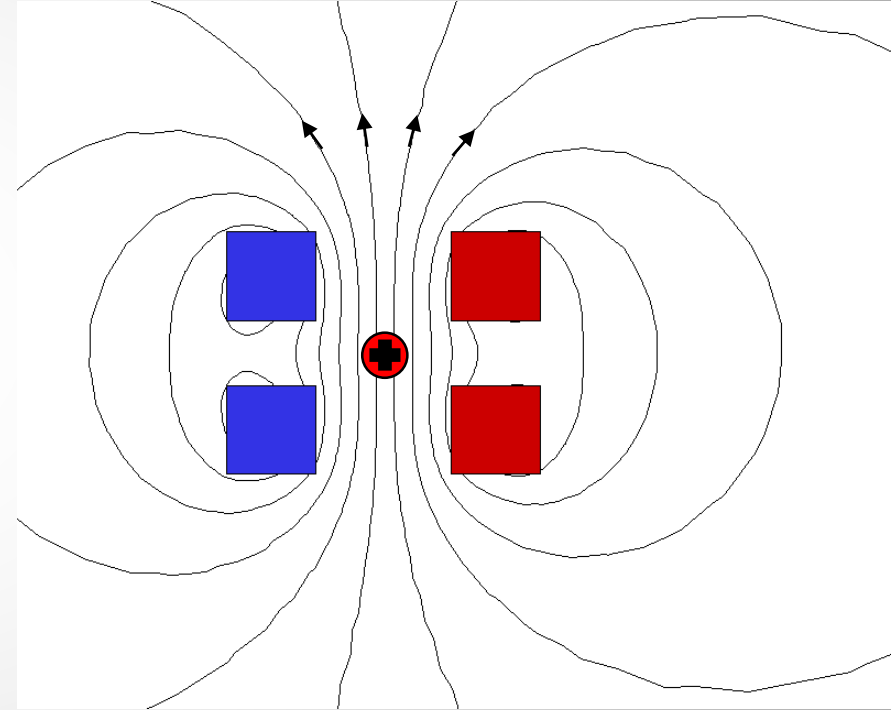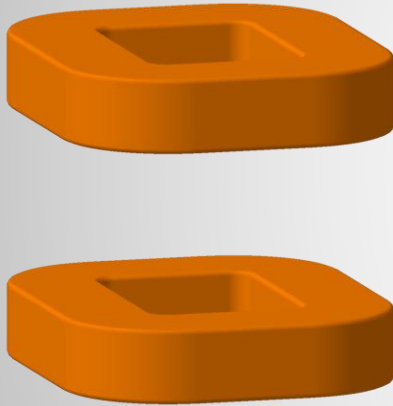
Magnet technologies

The magnetic (iron) circuit

The magnetic (iron) circuit serves several purposes:

- confine the magnetic flux in the circuit to avoid stray flux
- shape the magnetic field distribution in the region of interest
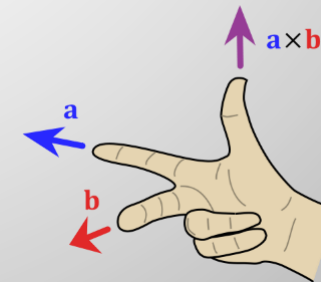- enhance the magnetic effect induced by currents in the coils
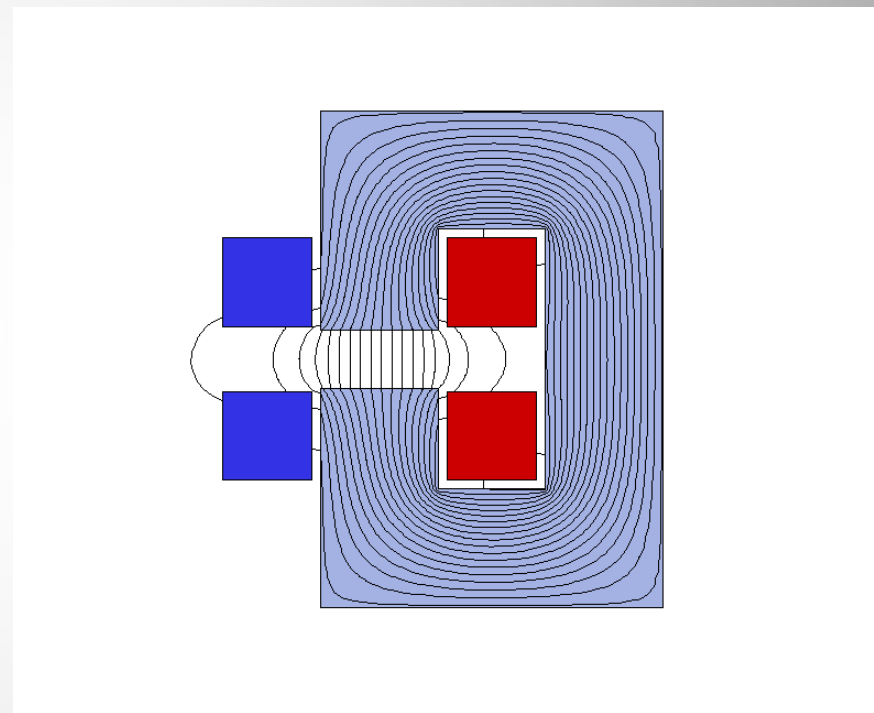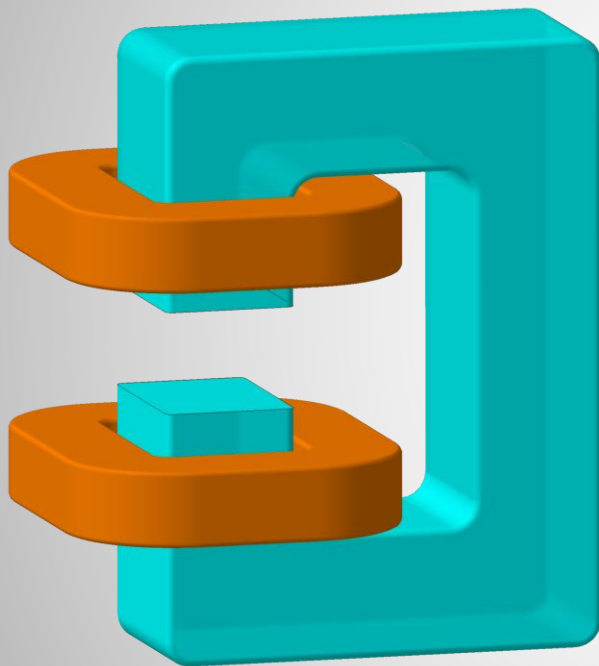
Creating the magnetic field

Flux lines represent the magnetic field
Coil colors indicate the current direction

a×b

a

b
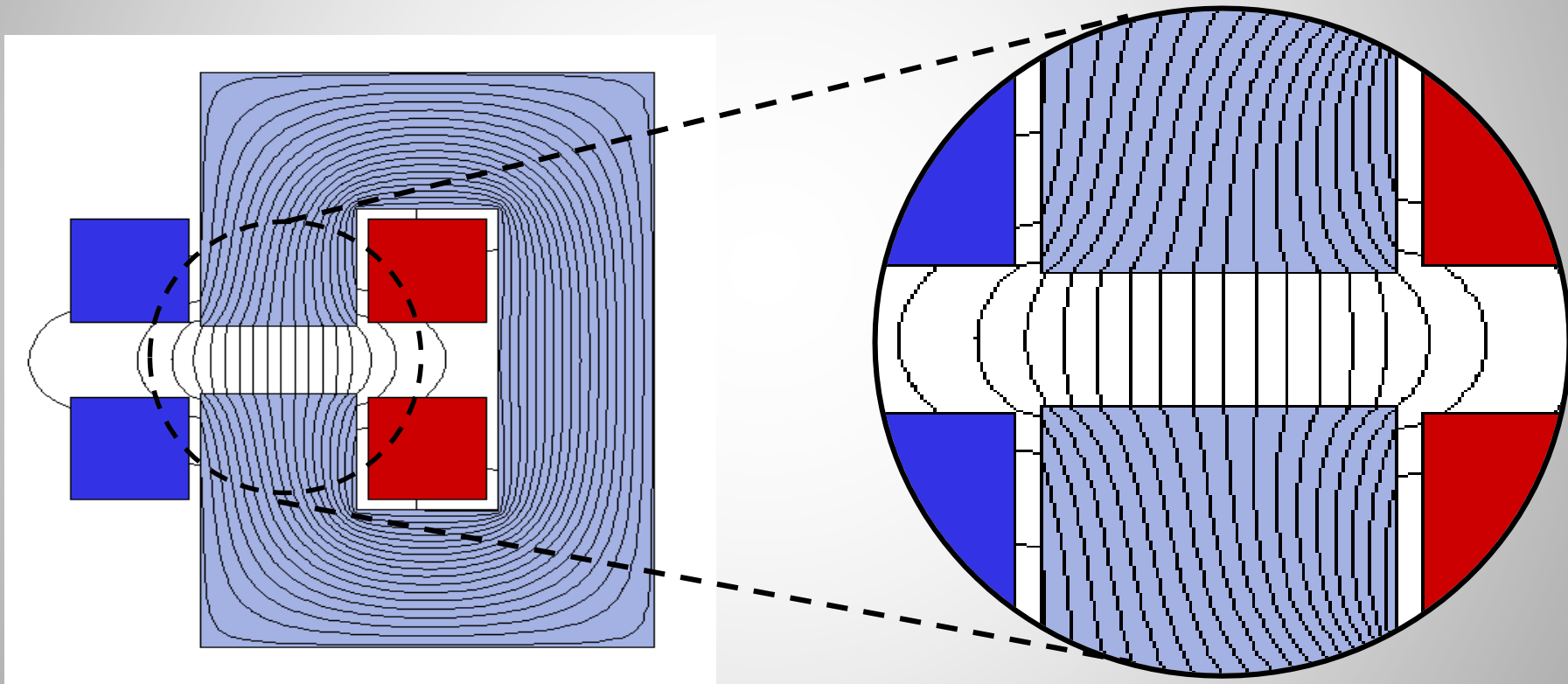
Confining the magnetic field

Coils hold the electrical current
Iron holds the magnetic flux

Shaping the magnetic field

From Gauss' law, Ampere's law and the constitutive relation, we can derive that the flux lines in free space always meet a material with infinite permeability perpendicular to the surface ("surface of constant scalar potential")

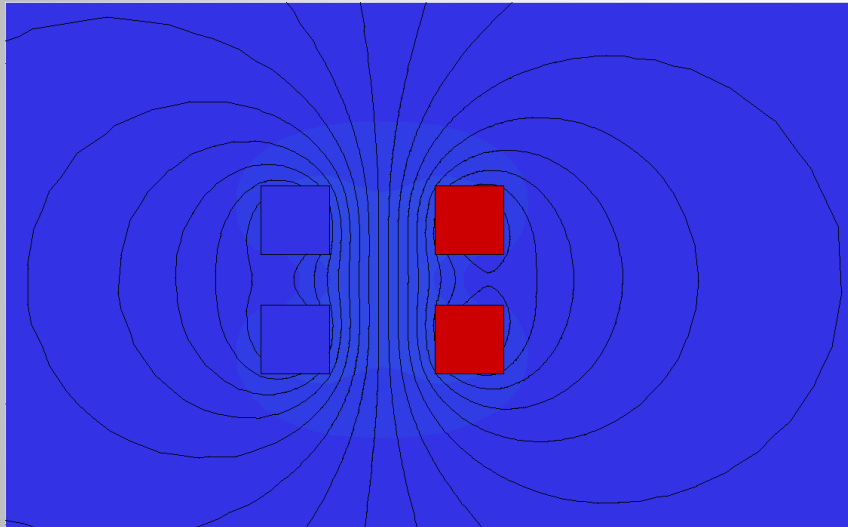If we can shape a material with infinite permeability such that its surface is everywhere perpendicular to our desired field configuration, then the only field that can exist around the material will be this desired field

Enhancing the magnetic field

$I = 32$ kA
$B_{centre} = 0.09$ T

$I = 32$ kA
$B_{centre} = 0.80$ T
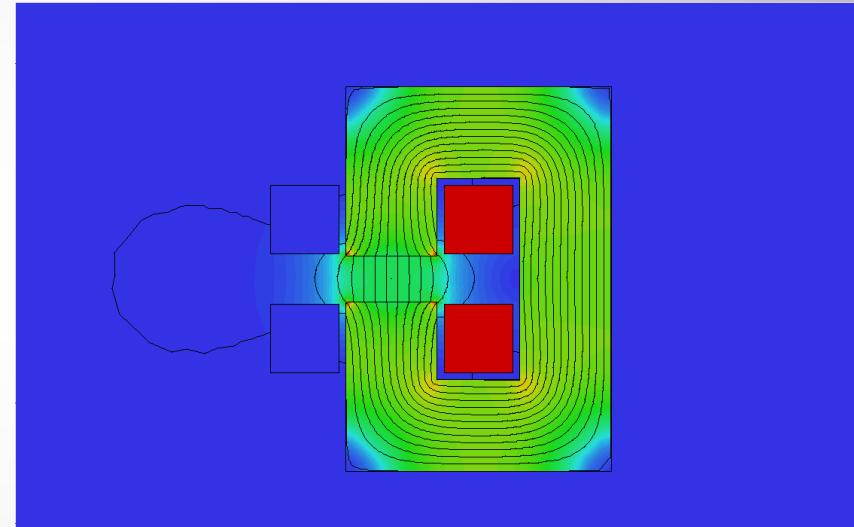
Component: BMOD
0.0   1.0   2.0

The presence of a magnetic circuit can increase the flux density in the magnet aperture by factors!
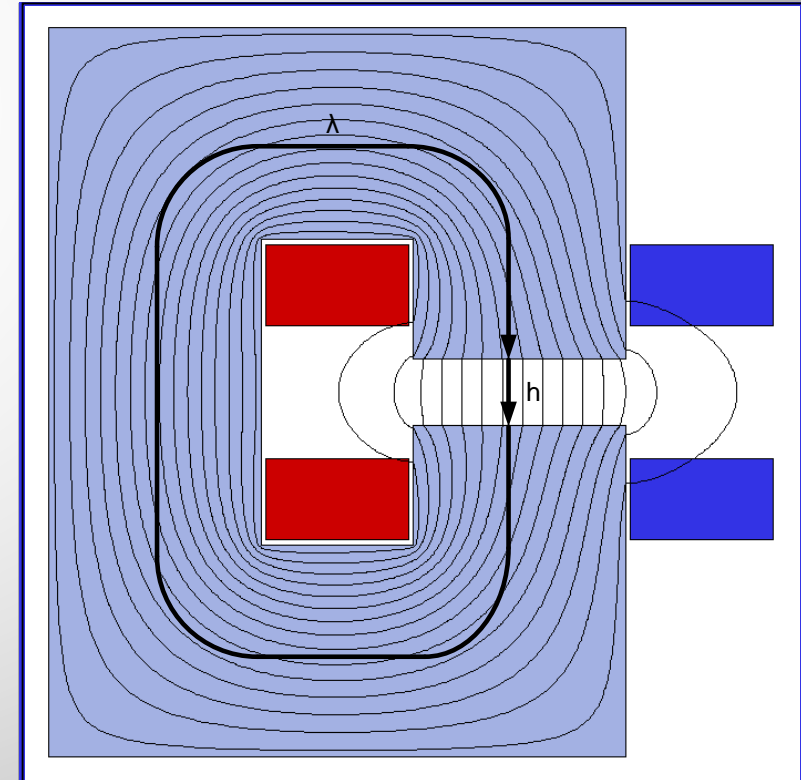
Excitation current in a dipole

Ampere's law $\qquad \oint \vec{H} \cdot d\vec{l} = NI \qquad$ and $\qquad \vec{B} = \mu \vec{H} \qquad$ with $\qquad \mu = \mu_0 \mu_r$

leads to $\qquad NI = \oint \dfrac{\vec{B}}{\mu} \cdot d\vec{l} = \displaystyle\int\limits_{gap} \dfrac{\vec{B}}{\mu_{air}} \cdot d\vec{l} + \int\limits_{yoke} \dfrac{\vec{B}}{\mu_{iron}} \cdot d\vec{l} = \dfrac{Bh}{\mu_{air}} + \dfrac{B\lambda}{\mu_{iron}}$

assuming, that B is constant along the path

If $\mu_{iron} \to \infty$ then $\qquad \dfrac{\lambda}{\mu_{iron}} \to 0$
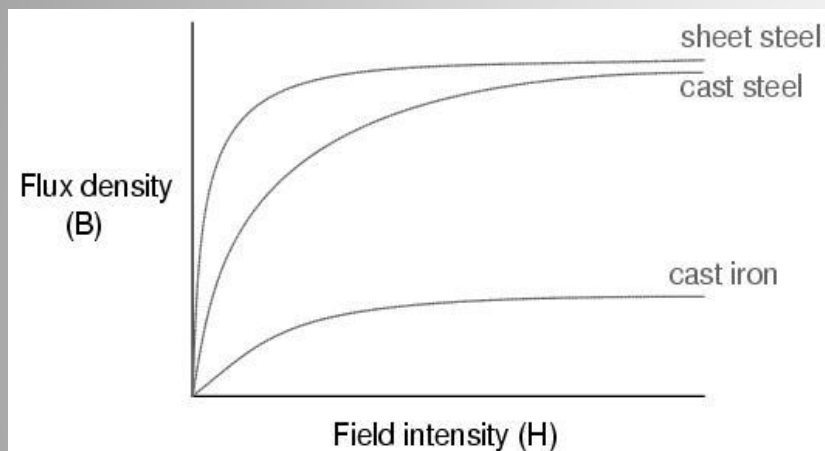
then: $\qquad \boxed{NI = \dfrac{Bh}{\mu_0}}$

Permeability

Permeability: correlation between magnetic field strength H and magnetic flux density B
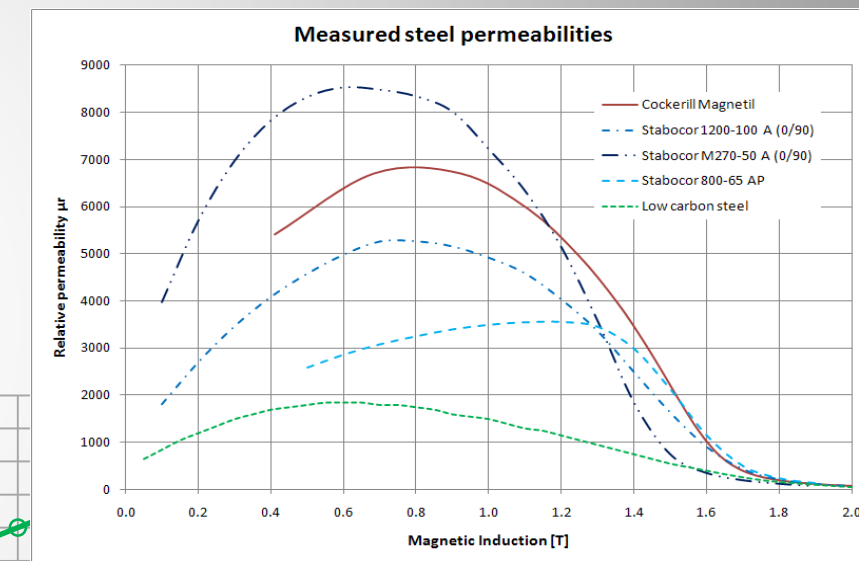
$$\vec{B} = \mu \vec{H}$$

$$\mu = \mu_0 \mu_r$$

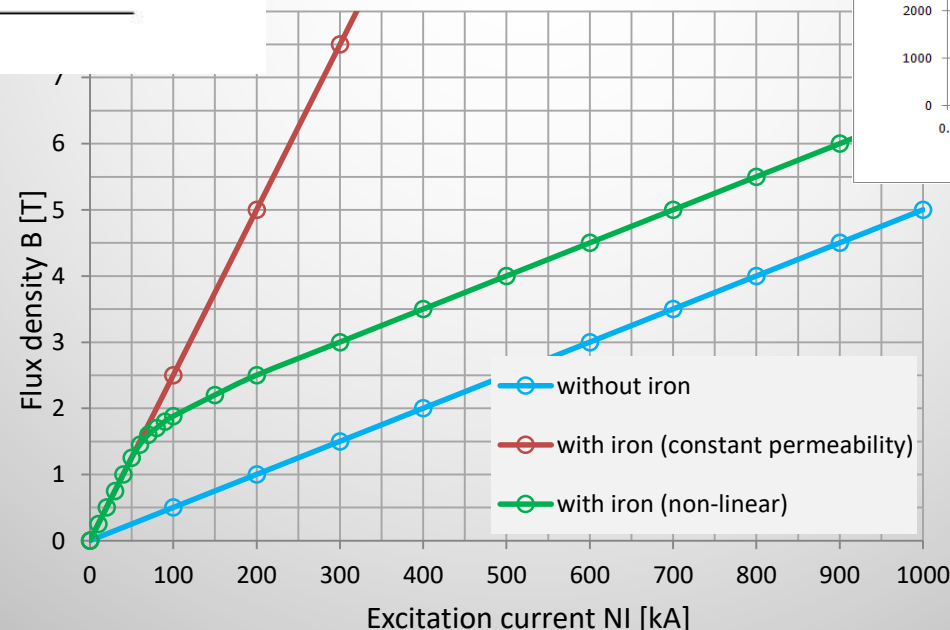Ferro-magnetic materials: high relative permeability ($\mu_r \gg 1$), but not constant

Saturation: Increase of B above 1.5 T in iron requires non-proportional increase of H

Consequence 1:
The path in the iron can no longer be fully neglected
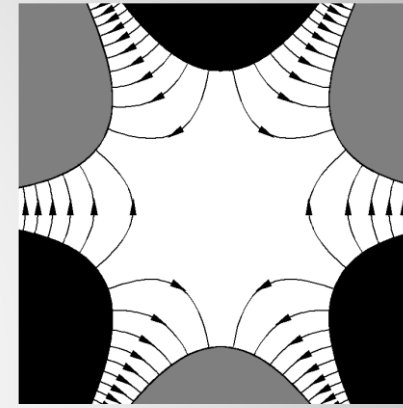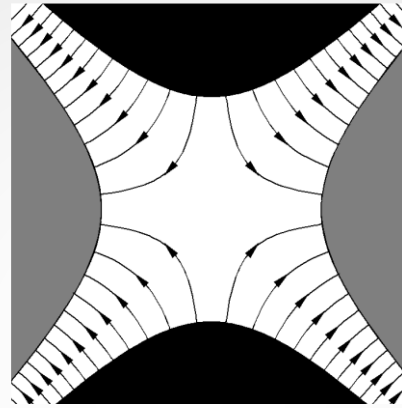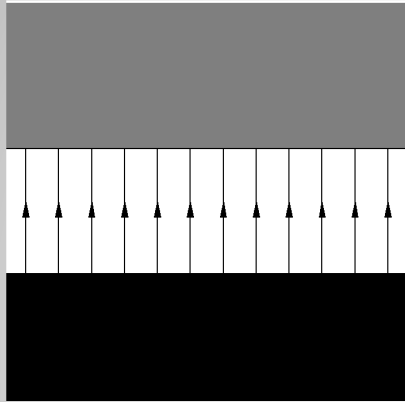
$$NI \approx \frac{Bh}{\mu_0}$$

Consequence 2:
The flux lines will no longer meet the iron perpendicularly creating field imperfections
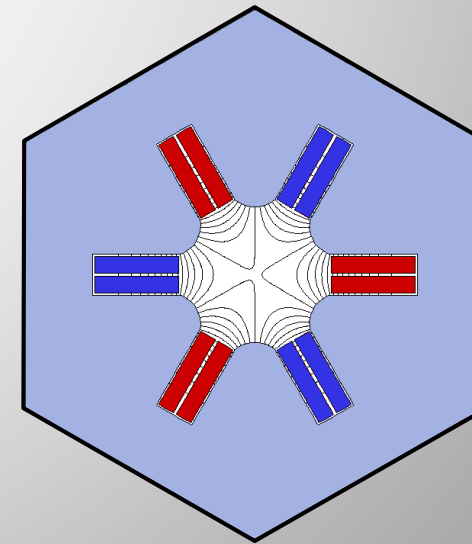
Ideal vs. real magnets

Ideal magnets have infinite permeability, and the poles are extended to infinity in all directions

Real magnets have high, but finite and non-linear permeability, and the poles are truncated to provide space for the coils
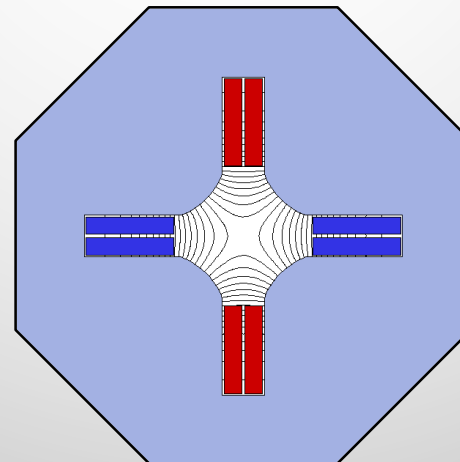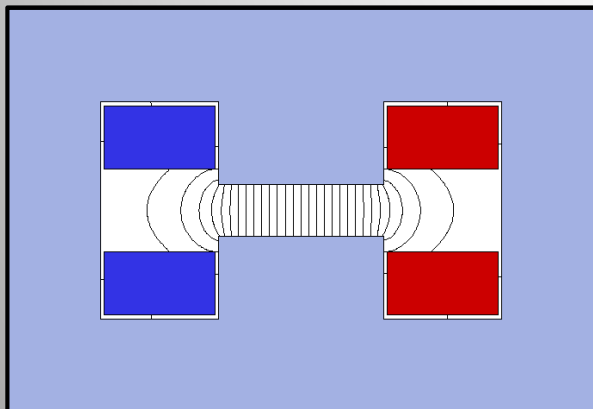
Dipole

Purpose: bend or steer the particle beam
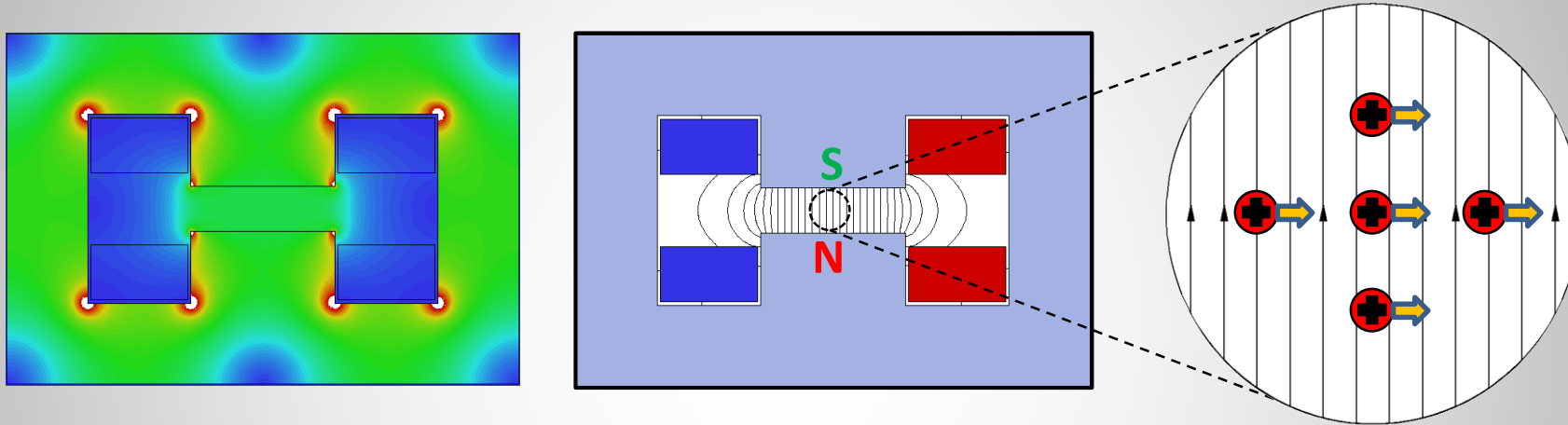
Equation for normal (non-skew) ideal (infinite) poles:

$$y = \pm h/2 \quad (\rightarrow \text{straight line with } h = \text{gap height})$$

Magnetic flux density: $B_x = 0$; $B_y = B_1 = \text{const.}$

Applications: synchrotrons, transfer lines, spectrometry, beam scanning

Quadrupole

Purpose: focusing the beam (horizontally focused beam is vertically defocused)
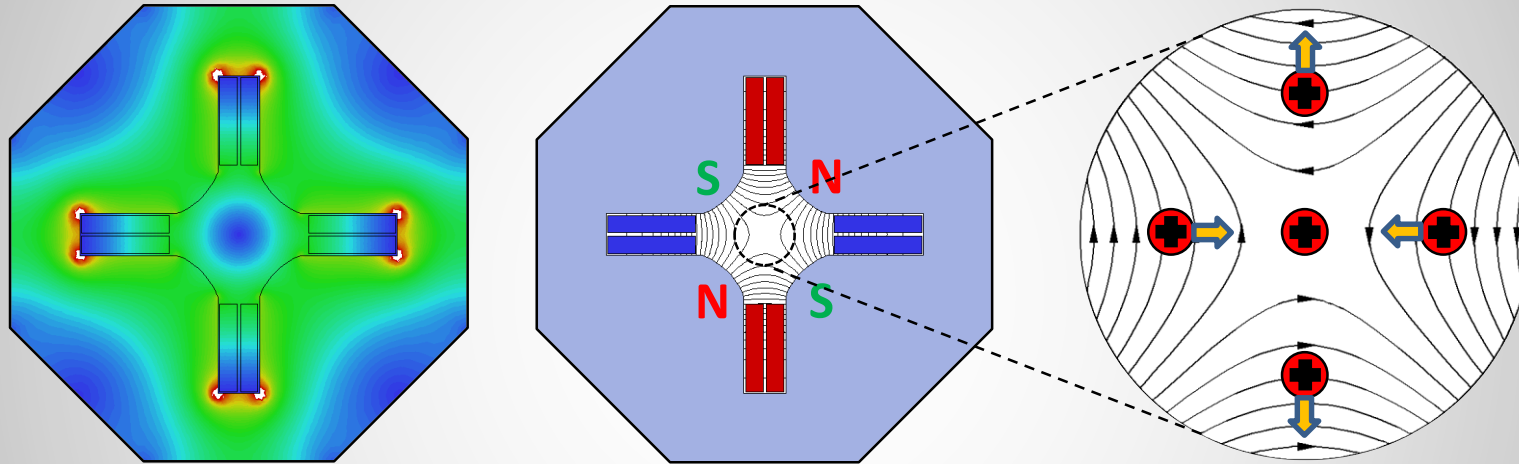
Equation for normal (non-skew) ideal (infinite) poles:

$$2xy = \pm r^2 \ (\rightarrow \text{hyperbola with } r = \text{aperture radius})$$

Magnetic flux density: $B_x = \dfrac{B_2}{R_{ref}} \, y \, ; \quad B_y = \dfrac{B_2}{R_{ref}} \, x$

Sextupole

Purpose: correct chromatic aberrations of 'off-momentum' particles
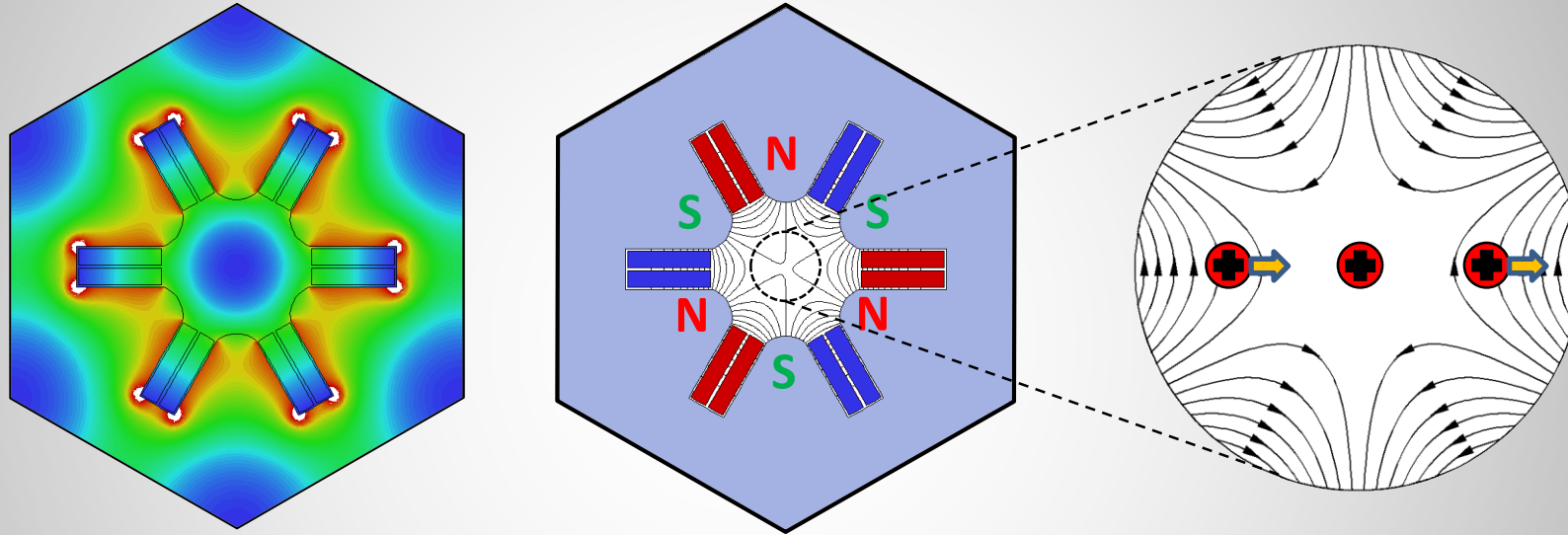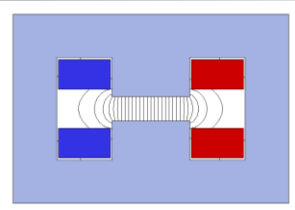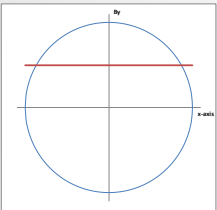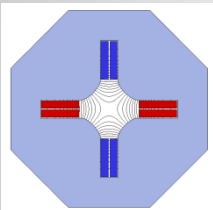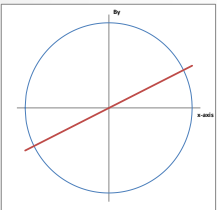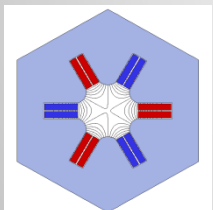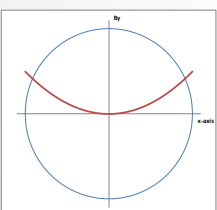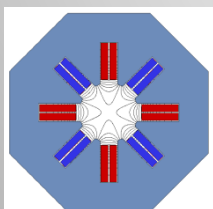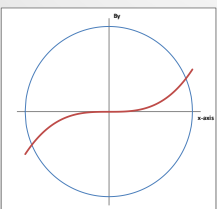

Equation for normal (non-skew) ideal (infinite) poles:

$$3x^2y - y^3 = \pm r^3 \quad \text{(with } r = \text{aperture radius)}$$

Magnetic flux density: $B_x = \dfrac{B_3}{R_{ref}^2}\, xy\,; \quad B_y = \dfrac{B_3}{R_{ref}^2}(x^2 - y^2)$

Magnet types

Pole shape	Field distribution	Pole equation	B_x, B_y
		$y = \pm r$	$B_x = 0$ $B_y = B_1 = \text{const.}$
		$2xy = \pm r^2$	$B_x = \dfrac{B_2}{R_{ref}} y$ $B_y = \dfrac{B_2}{R_{ref}} x$
		$3x^2 y - y^3 = \pm r^3$	$B_x = \dfrac{B_3}{R_{ref}^2} xy$ $B_y = \dfrac{B_3}{R_{ref}^2} (x^2 - y^2)$
		$4(x^3 y - xy^3) = \pm r^4$	$B_x = \dfrac{B_4}{R_{ref}^3} (3x^2 y - y^3)$ $B_y = \dfrac{B_4}{6R_{ref}^3} (x^3 - 3xy^2)$

Design process

Electro-magnetic design is an iterative process:

| Collect input data | Analytical design | Numerical 2D/3D simulations | Mechanical design | Drawings & specifications |
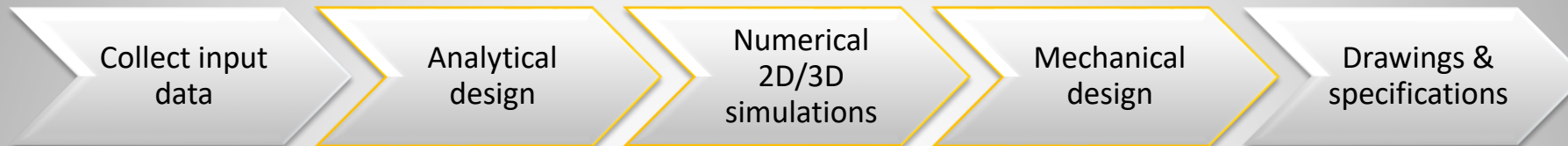
- Field strength (gradient) and magnetic length
- Integrated field strength (gradient)
- Aperture and ‚good field region'
- Field quality:
  - field homogeneity
  - maximum allowed multi-pole errors
  - settling time (time constant)
- Operation mode: continous, cycled
- Electrical parameters
- Mechanical dimensions
- Cooling requirements

Vacuum
Survey
Integration
Cooling
Transport
Power
Certification
Magnet
Beam Optics
Safety
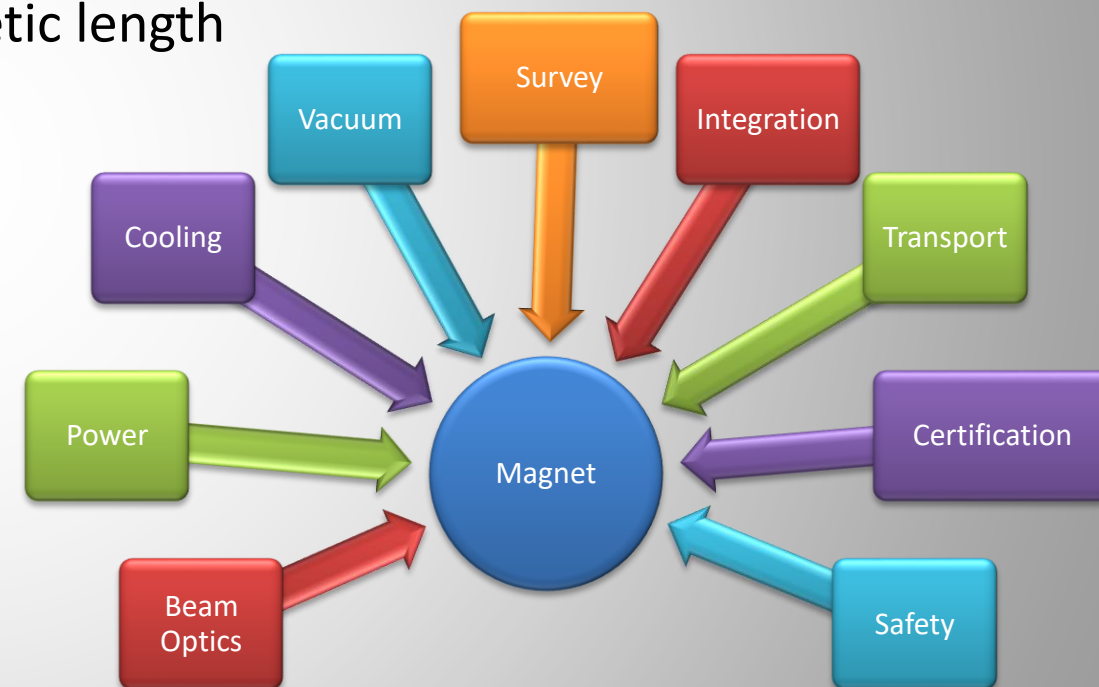
A magnet is not a stand-alone device!

Conventional nc-magnet layout
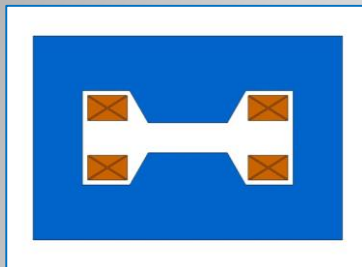
Excitation coils carry the electrical current creating H

Iron yokes guide and enhance the magnetic flux

Iron poles shape the magnetic field in the aperture around the particle beam

Auxiliaries for cooling, interlock, safety, alignment, ...
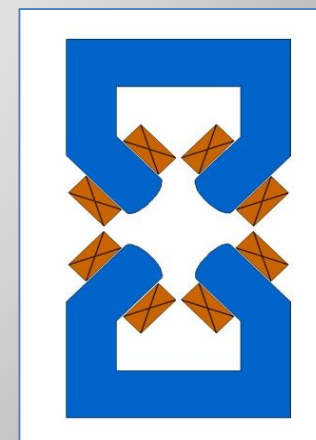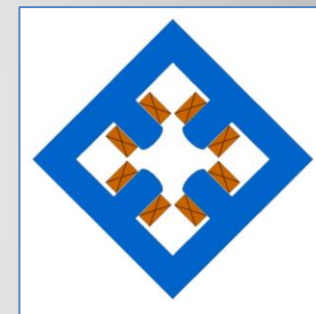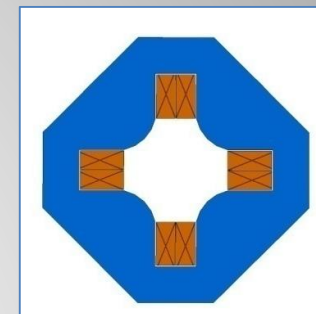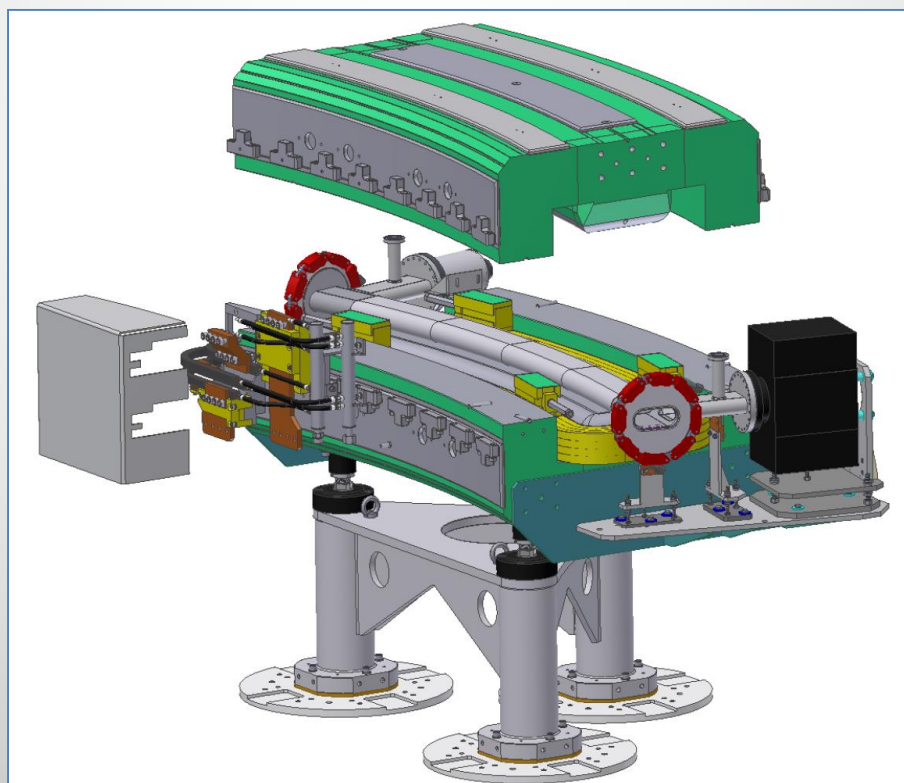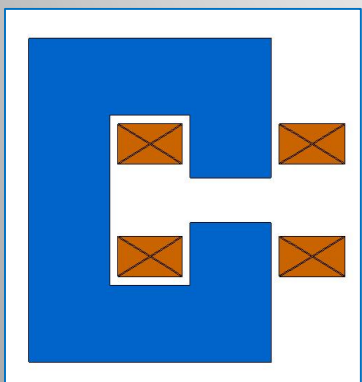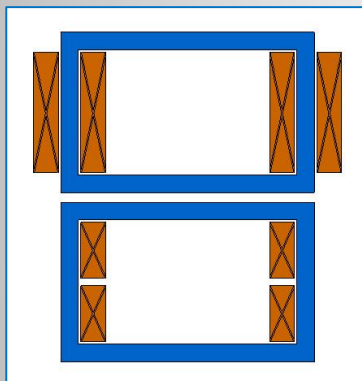
Massive vs. laminated yokes

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

+ no stamping, no stacking

- time consuming machining, in particular for complicated pole shapes

- difficult to reach similar magnetic performance between magnets

+ less expensive for prototypes and small series
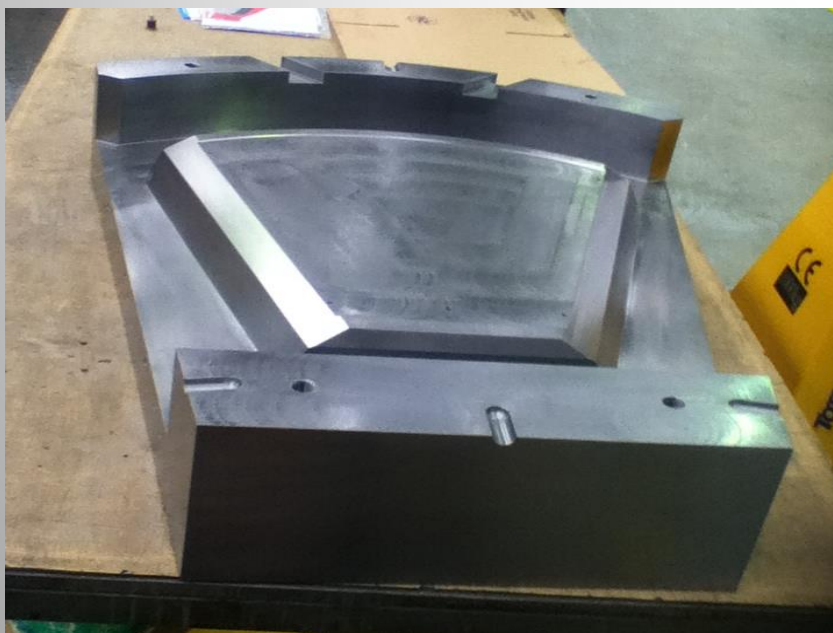
+ steel sheets less expensive than massive blocks

+ steel properties can be easily tailored

+ uniform magnetic properties over large series

- expensive tooling

+ less expensive for larger series

Yoke manufacturing

Stamping laminations

Stacking laminations into yokes

Gluing and/or welding

Assembling the yoke parts

Excitation coils

Conductor insulation

↓

Coil winding

↓

Ground insulation

↓

Epoxy impregnation

↓

Testing
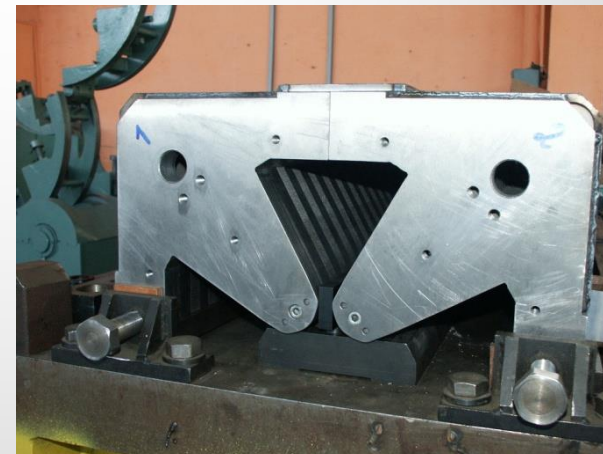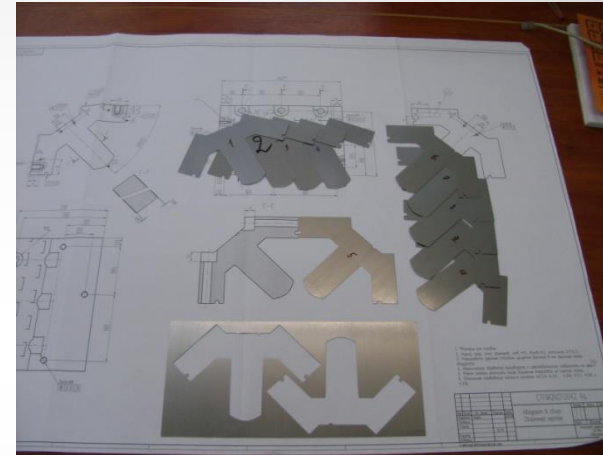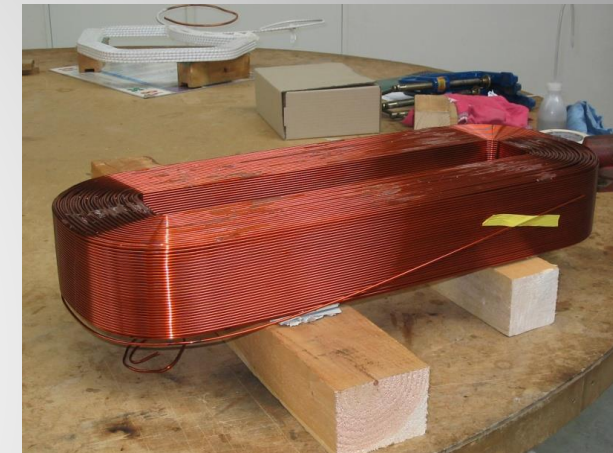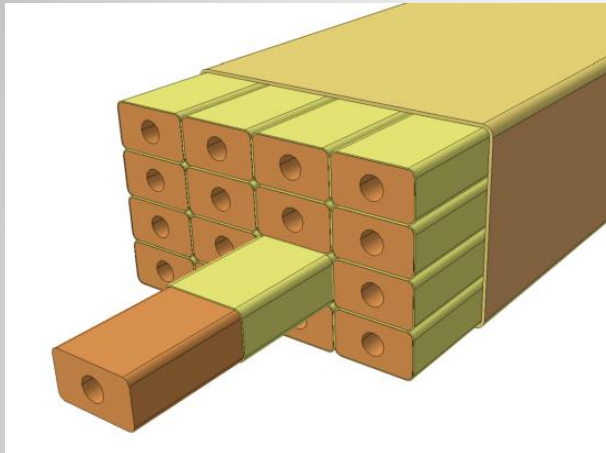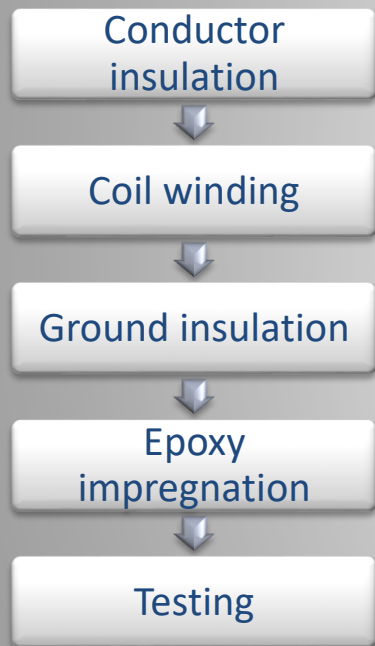
Coil cooling

Cooling is required to remove the dissipated electrical power from the coils

Air cooling by natural convection:

- Only for low densities: $j < 2$ A/mm^2 for small, thin coils

- Cooling enhancement
  - Heat sink with enlarged radiation surface
  - Forced air flow (cooling fan)

- Only for magnets with limited strength (e.g. correctors)

Direct water cooling:

- Typical current density $j \leq 10$ A/mm^2

- Requires demineralized water (low conductivity) and hollow conductor profiles
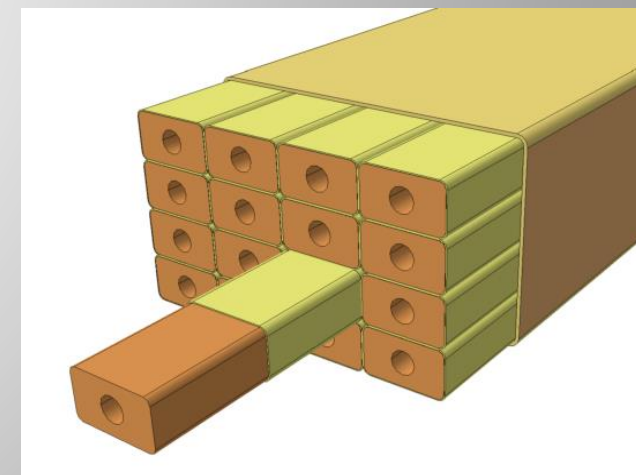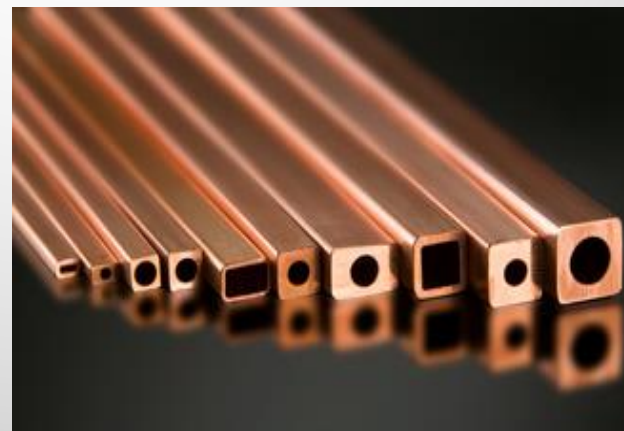
Costs and optimization

Focus on economic design!

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

Total costs include:

operation costs of cooling system

capital costs of magnets

operation costs of power converters

capital costs of power converters

capital costs of cooling system

capital costs of power distribution
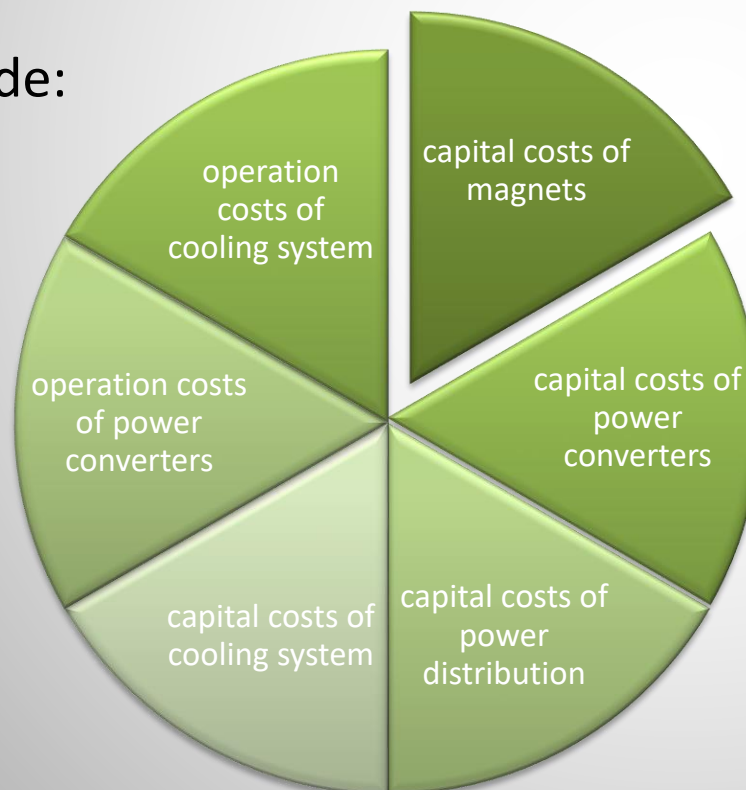
Attention: $Power \propto current\ desity$

Decreasing current density means:
- increasing coil cross section
- increasing material (coil & yoke) cost
- increasing manufacturing cost

But:
- decreasing capital costs for power converter and cooling system
- decreasing operation costs

NC-magnets in the 1950-60s

CERN PS (1959), 25 GeV, 628 m

- Combined function magnet: dipole + quadrupole + higher order multi-poles

- Water cooled main coils + Figure-of-Eight windings + Pole-face windings

- Magnetic field B: 0.014 T – 1.4 T

- 100 + 1 magnets in series
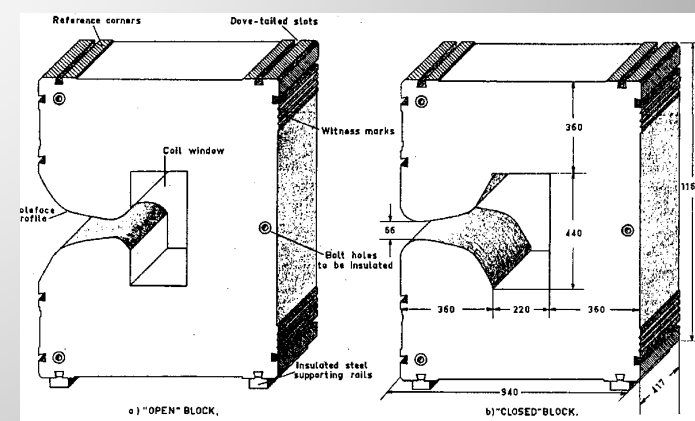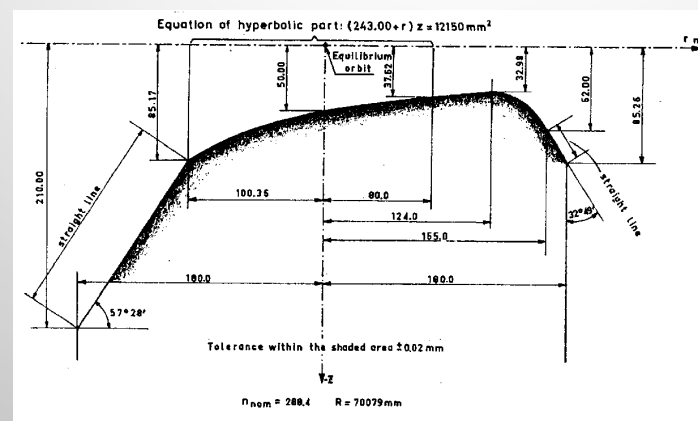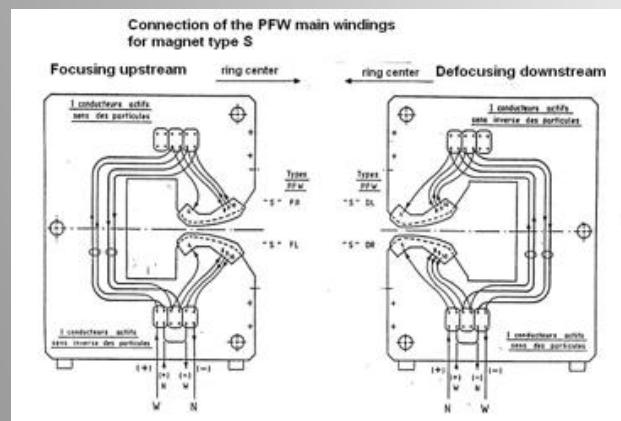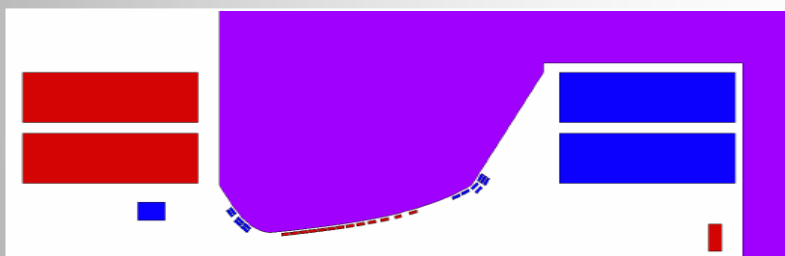
NC-magnets in the 1970s

CERN SPS (1976), 7 km, 450 GeV

- 744 H-type bending magnets with B = 2.05 T
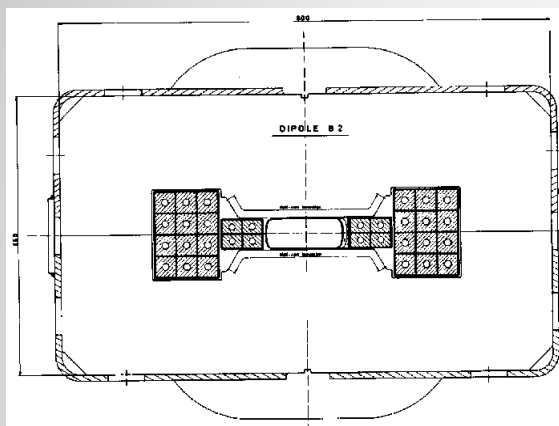
NC-magnets in the 1980s

LEP (1989), 27 km

- Cycled field: 22 mT (20 GeV injection) to 108 mT (100 GeV)
- 5.75 m long 'diluted' magnet cores: 30% Fe / 70% concrete
- Four water cooled aluminium excitation bars
- Max. current: 4.5 kA

CROSS SECTION OF THE DIPOLE MAGNET WITH THE VACUUM CHAMBER

SIX-CORE DIPOLE
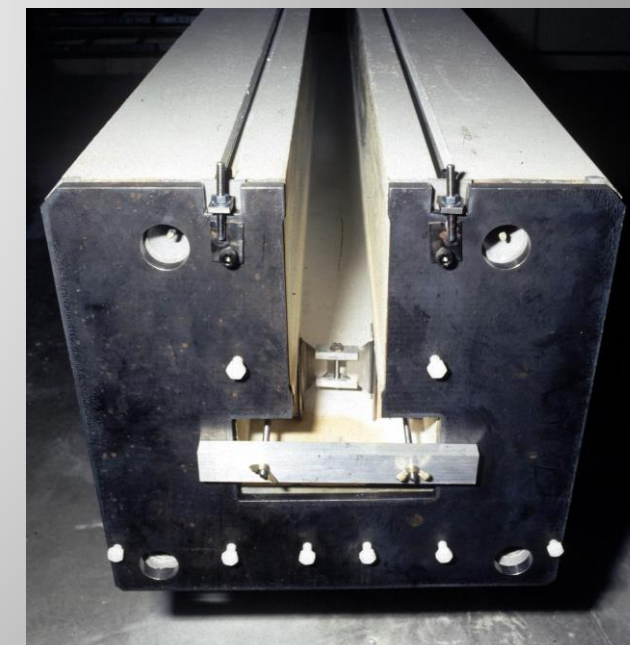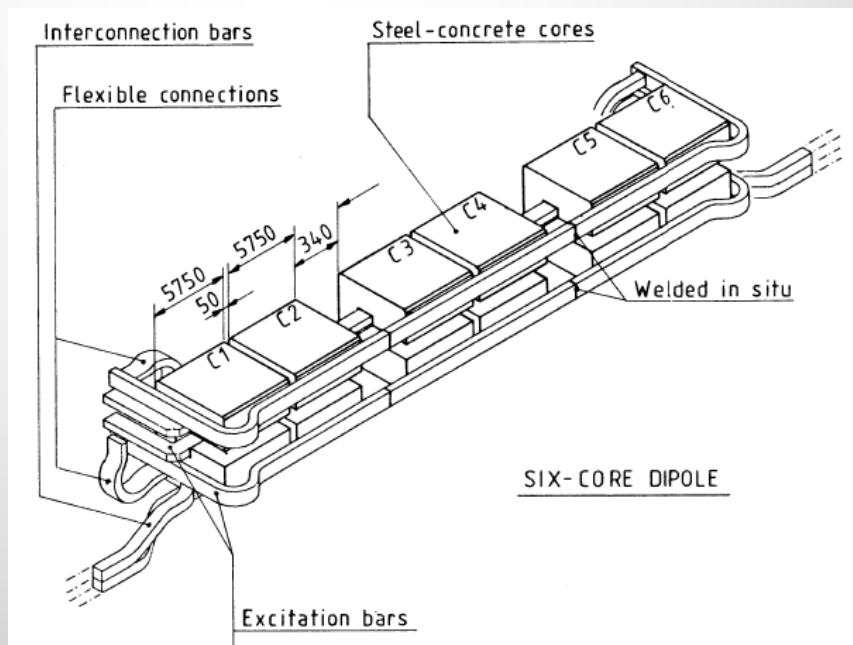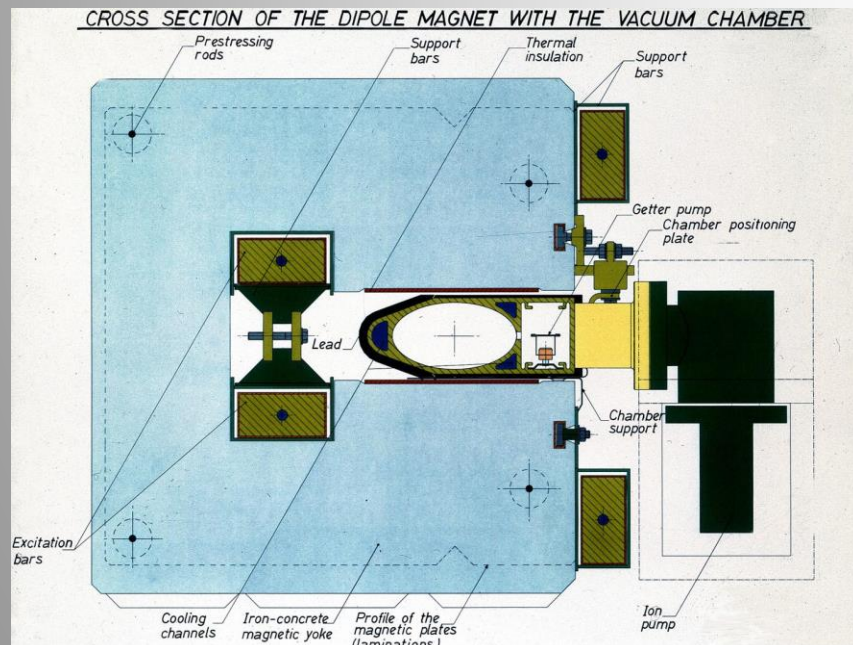
NC-magnets even in the LHC …
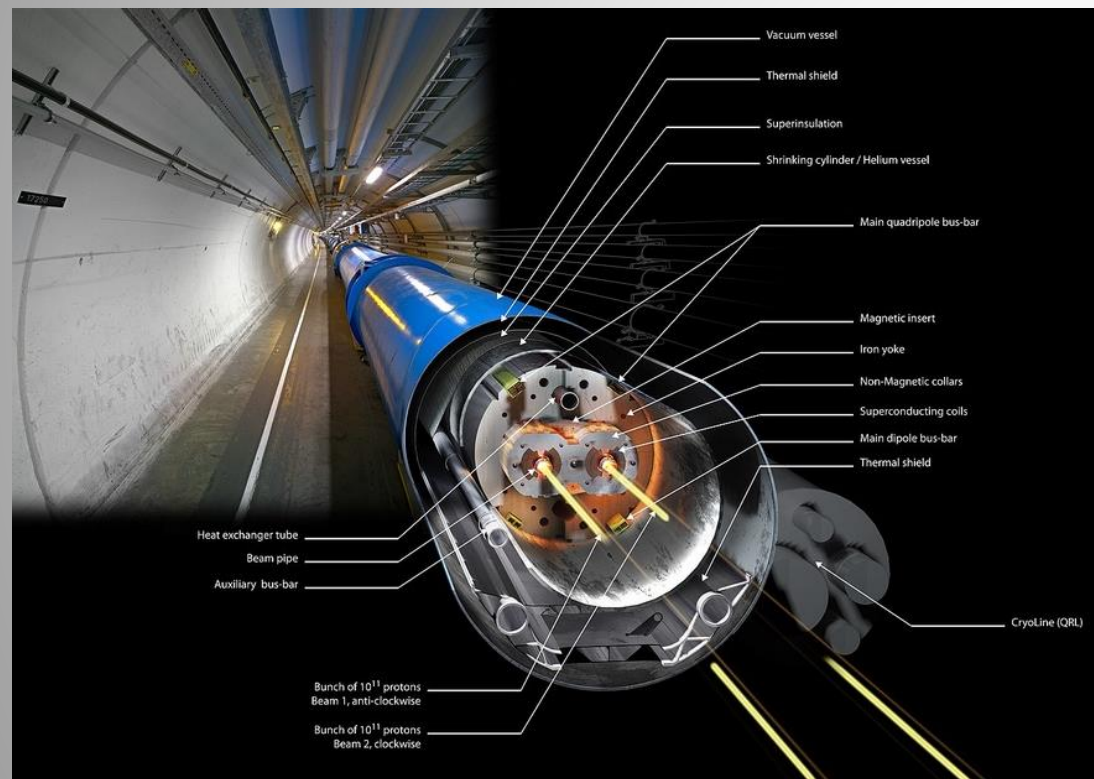
LHC Main Dipole

Double-aperture LHC quadrupole

Circular Colliders

$$B = \frac{(B\rho)}{r_M}$$

Beam rigidity [Tm]

1.E+06	
1.E+05	FCC-pp, SppC
1.E+04	HE-LHC, LHC
1.E+03	HERA, Tevatron
1.E+02	RHIC, SppS, LEP, CepC, FCCee
1.E+01	ISR, PETRA, PEP-II, KEKB, VEPP-4M, CESR-c, DORIS, BEPC
1.E+00	VEPP-2, VEPP-2000, VEPP-2M, ACO, DAΦNE, Prin-Stan, AdA, VEP-1
1.E-01	

Circumference [m]

1   10   100   1000   10000   100000

• Lepton colliders
• Hadron colliders
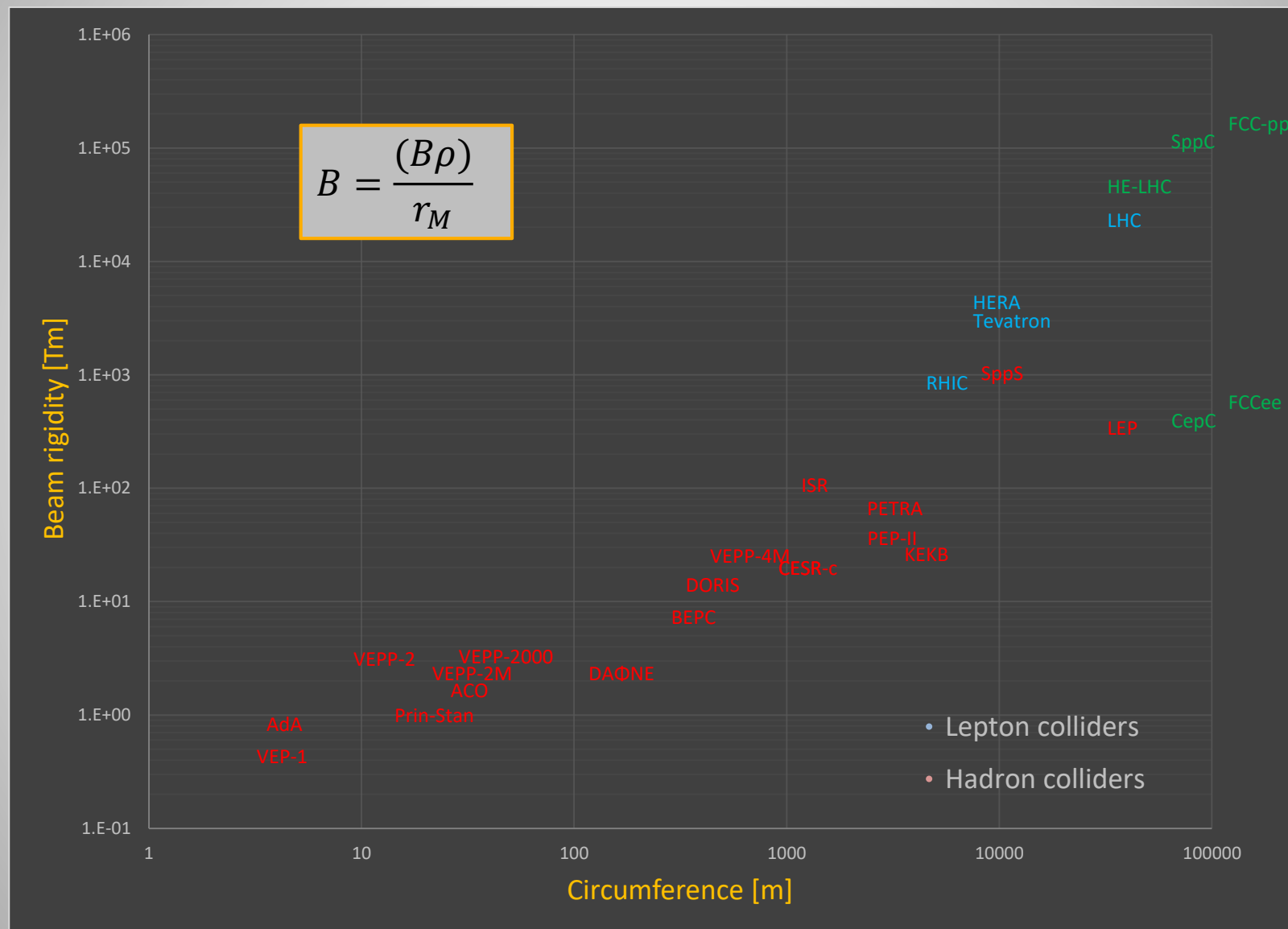
Future challenges

Future accelerator projects bear a number of financial and technological challenges in general, but also in particular for magnets …

Large scale machines:
- Investment cost: material, production, transport, installation
- Operation costs: low power consumption & cooling
- Reliability & availability

High energy beams and intensities:
- Ionizing radiation impact on materials and electronics

Hadron colliders:
- High magnetic fields

Lepton colliders (circular & linear):
- Alignment & stabilization
- Compact design & small apertures

CLIC general layout

326 klystrons
33 MW, 139 µs

drive beam accelerator
2.38 GeV, 1.0 GHz

circumferences
delay loop 73.0 m
CR1 146.1 m
CR2 438.3 m

326 klystrons
33 MW, 139 µs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

delay loop

CR2

CR1

CR2

CR1

delay loop

1 km

decelerator, 24 sectors of 876 m

BC2

BDS
2.75 km

BDS
2.75 km

BC2

245 m

TA r=120 m   e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km   IP   e⁺ main linac   TA radius = 120 m

245 m

48.3 km

CR   combiner ring
TA   turnaround
DR   damping ring
PDR   predamping ring
BC   bunch compressor
BDS   beam delivery syst
IP   interaction point
      dump

Machine-Detector Interface (MDI) with the FF system

*"2-Beams Modules" with **41848** DBQ and **4274** MBQ magnets*

e⁻ injector,
2.86 GeV

e⁺ injector,
2.86 GeV

e⁻
PDR
398 m

e⁻
DR
493 m

e⁺
DR
493 m

e⁺
PDR
398 m

Magnet system for FCC-ee

Q   BL   Q   BL

e⁺

e⁻

55.9 m

Double collider ~100 km circumference

Counter-rotating e+ / e- beams

DC operation with top-up injection

1450 FODO cells, each 55.9 m long

Tuneability ±1%
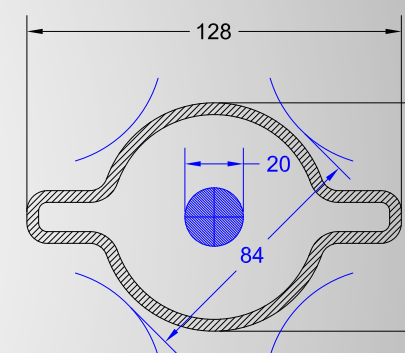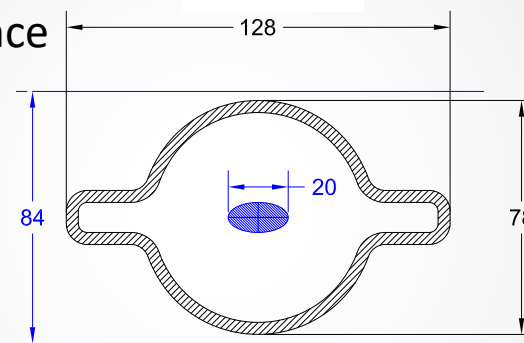
Parameter	Bending magnets	Quadrupole magnets
Quantity (per ring)	2900	1450 + 1450
Magnetic length	23.94 (21.94) m	3.1 m
Aperture	128 mm x 84 mm	R = 42 mm
Inter-beam distance	300 mm	300 mm
Field / max. gradient at 175 GeV	54.3 mT	9.9 T/m
Goof field region	±10 mm horizontal	R = 10 mm
Field quality	< 10^{-4}	< 10^{-4}

Recap: LEP dipoles

Using the 'diluted' LEP
dipoles for FCC-ee at 54 mT…

… and a 'non-diluted'
alternative design

480 mm

100 mm

495 mm

0   0.5 T   1.0 T
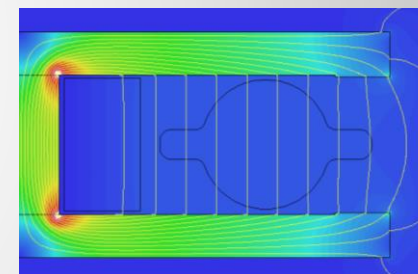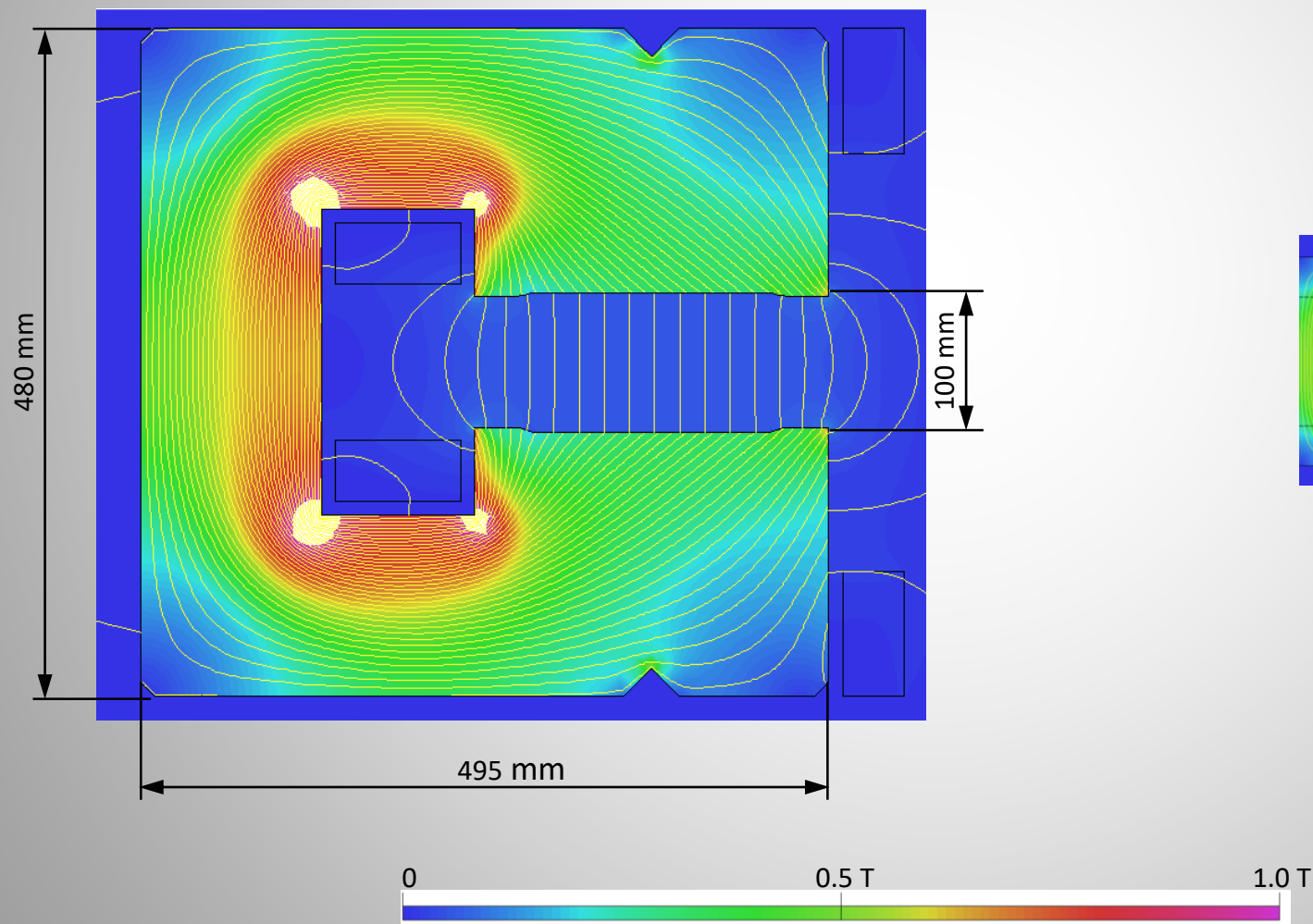
FCC-ee Twin dipole design

300 mm

B × 5-10

136 mm

54 mT

3.65 kA
46 × 80 mm^2
(1.0 A/mm^2)

450 mm
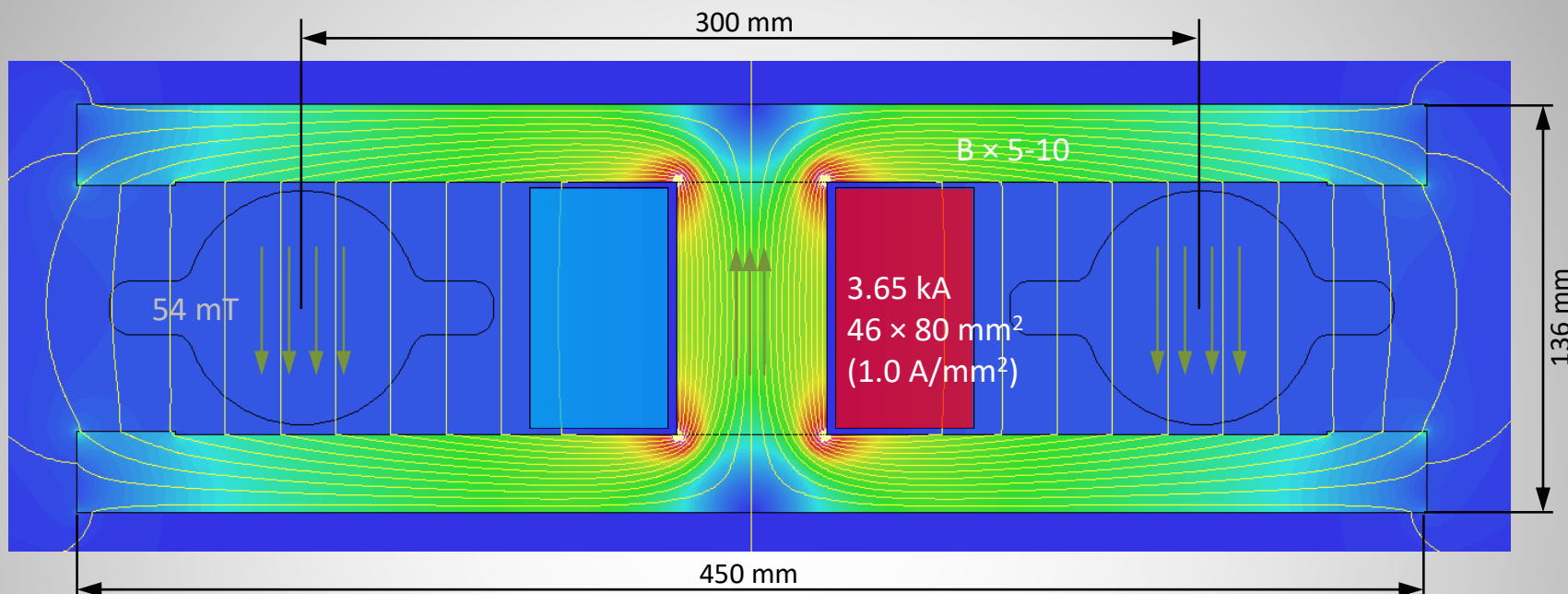
- **Energy saving:** Ampere-turns recycled → 50% less power consumption (16 MW)
- **Cost saving:** 50% less units to manufacture, transport, install, align
- **Simple:** few components
  - Simple yoke design and coil layout → low manufacturing costs
- **Compact:** small dimensions, less material
  - Yoke: 200 kg/m → total 13500 t (low carbon) steel
  - Coil: 1-turn conductor busbar, 20 kg/m → total 1650 t hollow Al conductor
- **Reliable:** no coil inter-turn insulation & no water cooling needed

FCC-ee Twin dipole prototype

picture by Mike Struik

A. Milanese, M. Bohdanowicz, Twin Aperture Bending Magnets and Quadrupoles for FCC-ee, IEEE Transactions on Applied Superconductivity, Vol. 28, NO. 3, APRIL 2018
A. Milanese, Efficient twin aperture magnets for the future circular e⁻e⁺ collider, PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 112401 (2016)
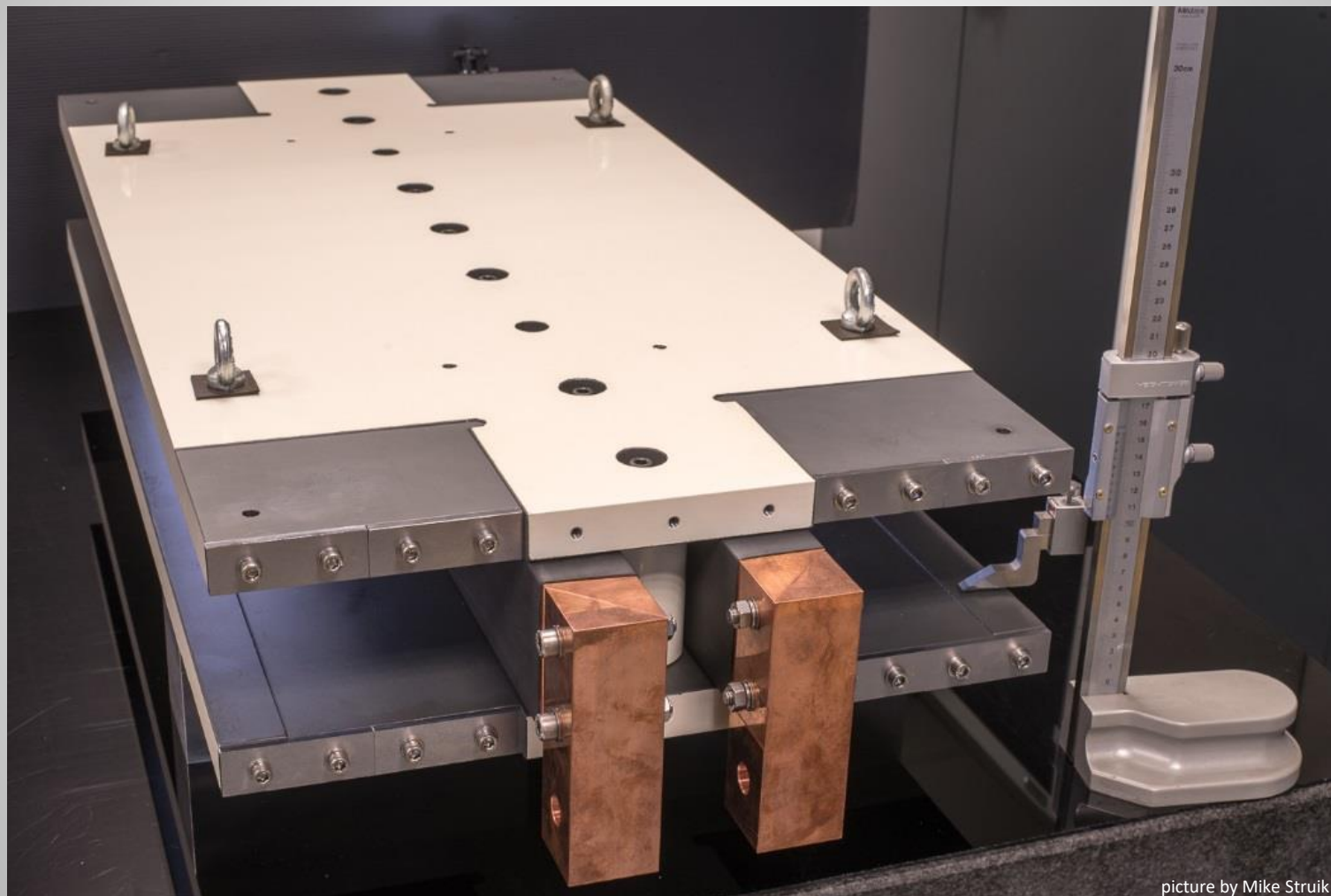
Many thanks …

… for your attention …

… and to all my colleagues who contributed to this lecture and who supported me in questions related to magnet design and measurements in the past 24 years!

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