CERN Accelerator School
BASIC CAS, 6th May 2021

# Normal-Conducting Accelerator Magnets

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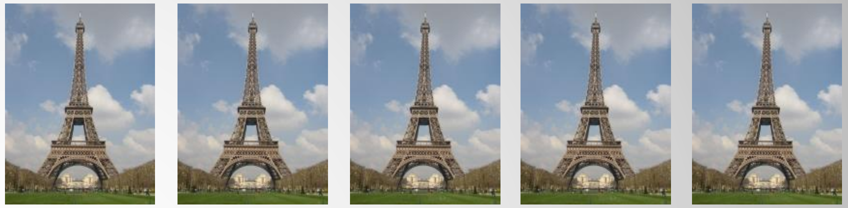
CERN

# Scope of this lecture

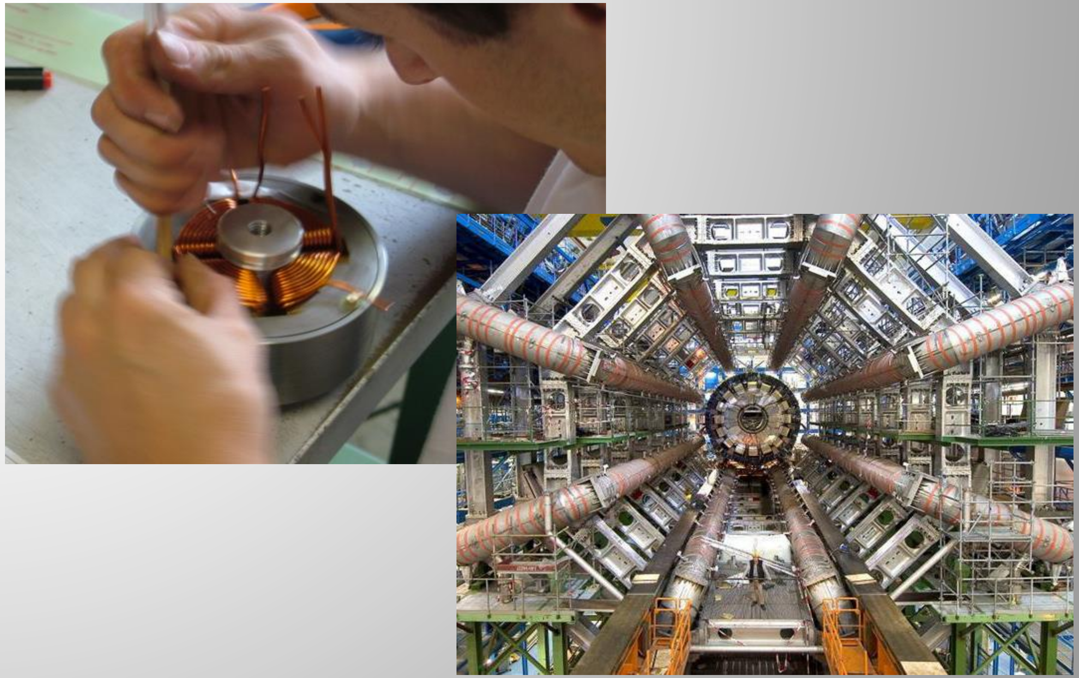
More than 4800 ‘room temperature’ magnets (50 000 tonnes) are installed in the CERN accelerator complex



The main goal is to provide an overview on ‘room temperature’ magnets i.e., normal-conducting, iron-dominated electro-magnets

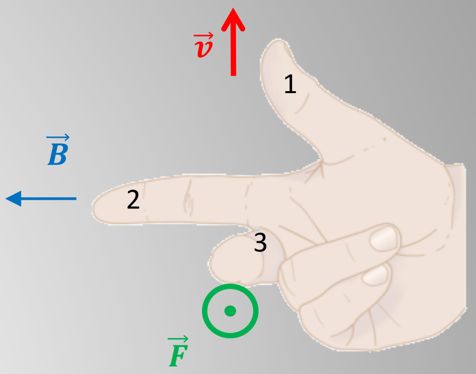
## Outline

- Producing magnetic fields
- Magnet technologies
- Magnet types in accelerators
- Design & construction
- Milestones from the past
- New concepts for future accelerators

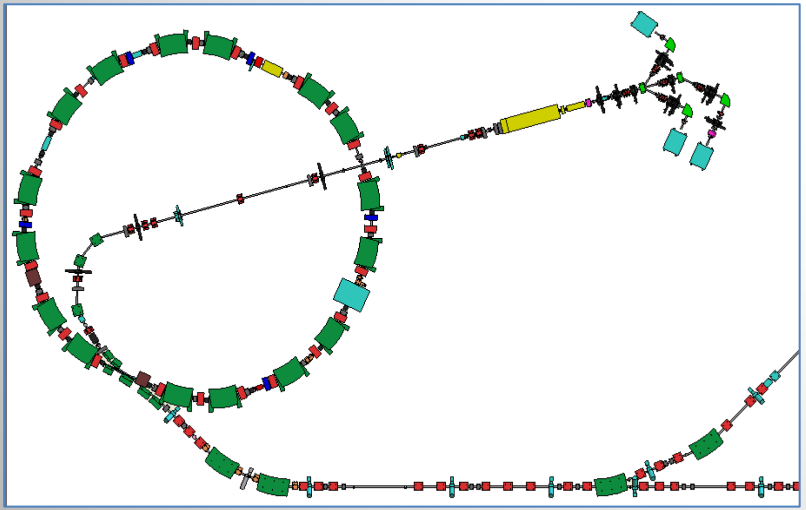


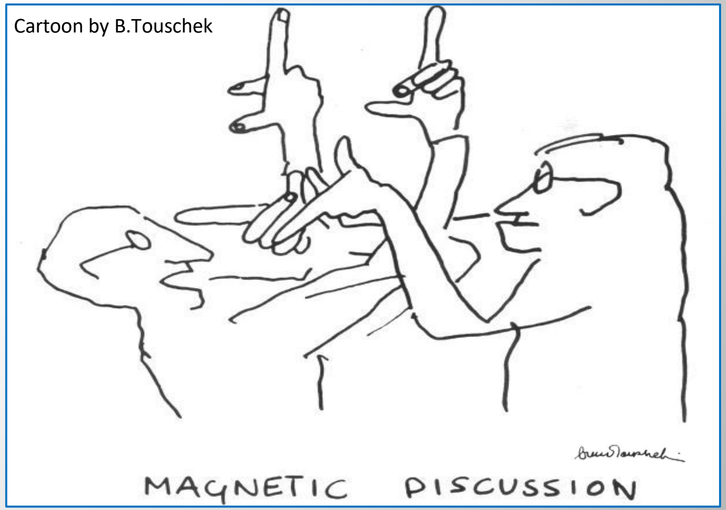
# Why do we need magnets?

- 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 $E = 3\cdot10^8$ V/m(!)



„*Right hand rule*“ applies



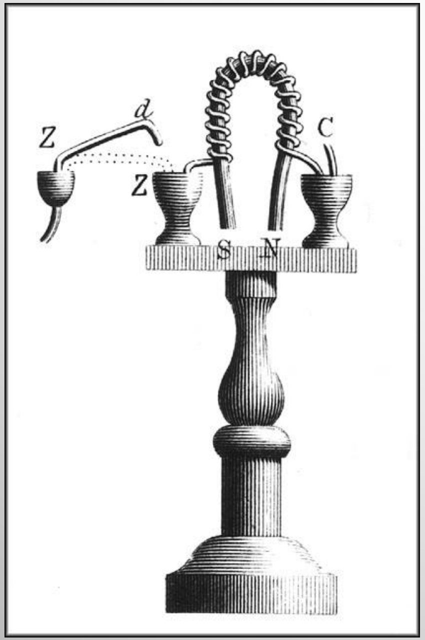

Cartoon by B.Touschek

  - Permanent magnets provide only constant magnetic fields
  - Electro-magnets can provide adjustable magnetic fields

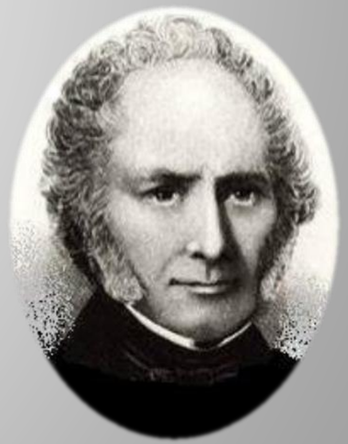
# A bit of history…

1820: Hans Christian Øersted (1777-1851) finds that electric current affects a compass needle

“Electricity and magnetism are somehow related…”



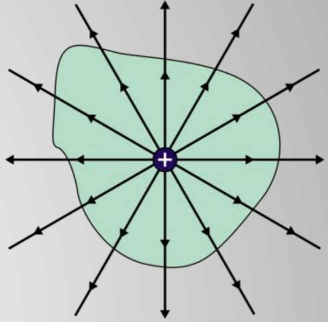
1825: William Sturgeon (1783-1850), a British electrician, invented the first electromagnet

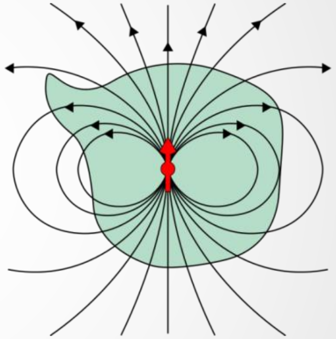


# Maxwell‘s equations

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

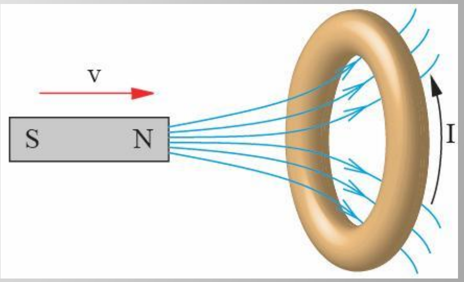
Gauss‘ law for electricity: $\nabla \cdot \vec{D} = \rho$ $\quad$ $\vec{D} = \varepsilon \vec{E}$



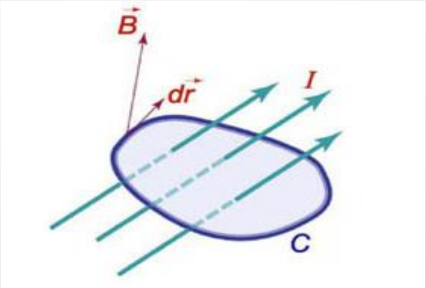


Gauss‘ law of flux conservation: $\boxed{\nabla \cdot \vec{B} = 0}$

Faraday‘s law of induction: $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ $\quad$ $\boxed{\vec{B} = \mu \vec{H}}$

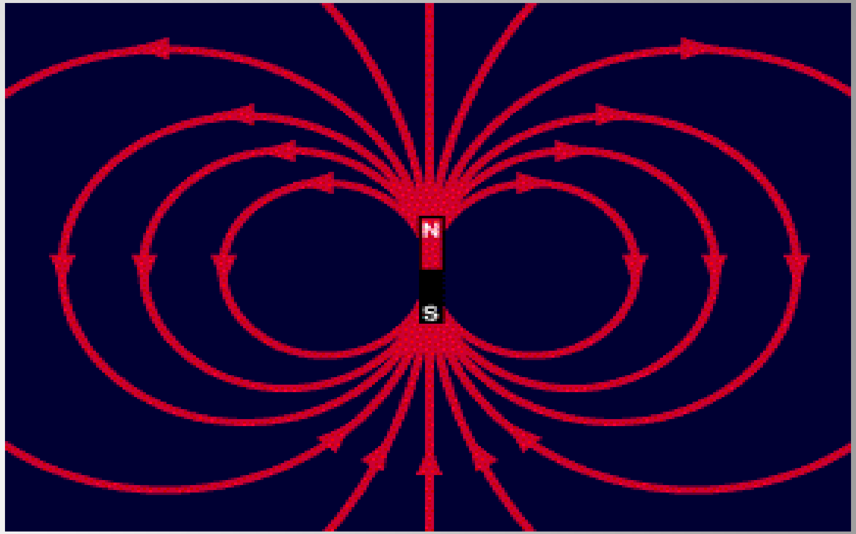


Ampere‘s law: $\boxed{\nabla \times \vec{H} = \vec{J} +}\frac{\partial \vec{D}}{\partial t}$



# Magnet vocabulary

IEEE defines the following terms and units:



- Magnetic field:
  - $\boldsymbol{H}$ (vector) [A/m]
  - magnetizing force produced by electric currents
- Electro-motive force:
  - $U$ [V or (kg·m$^2$)/(A·s$^3$)]
  - voltage generated by a time varying magnetic field
- Magnetic flux density or magnetic induction:
  - $\boldsymbol{B}$ (vector) [T or kg/(A·s$^2$)]
  - density of magnetic flux driven through a medium by the magnetic field
  - Note: flux or induction is frequently referred to as "Magnetic Field“
  - $H, B$ and $\mu$ relates by the constitutive law for materials: $B = \mu H$
- Permeability:
  - $\mu = \mu_0 \mu_r$
  - permeability of free space $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ [(V·s)/(A·m) or (kg·m)/(A·s$^2$)]
  - relative permeability $\mu_r$ (dimensionless): $\mu_{\text{air}} = 1$; $\mu_{\text{iron}} > 1000$ (not saturated)

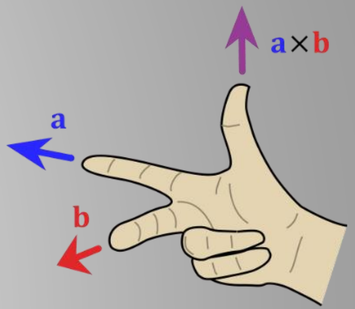
# Producing the magnetic field

Maxwell & Ampere:

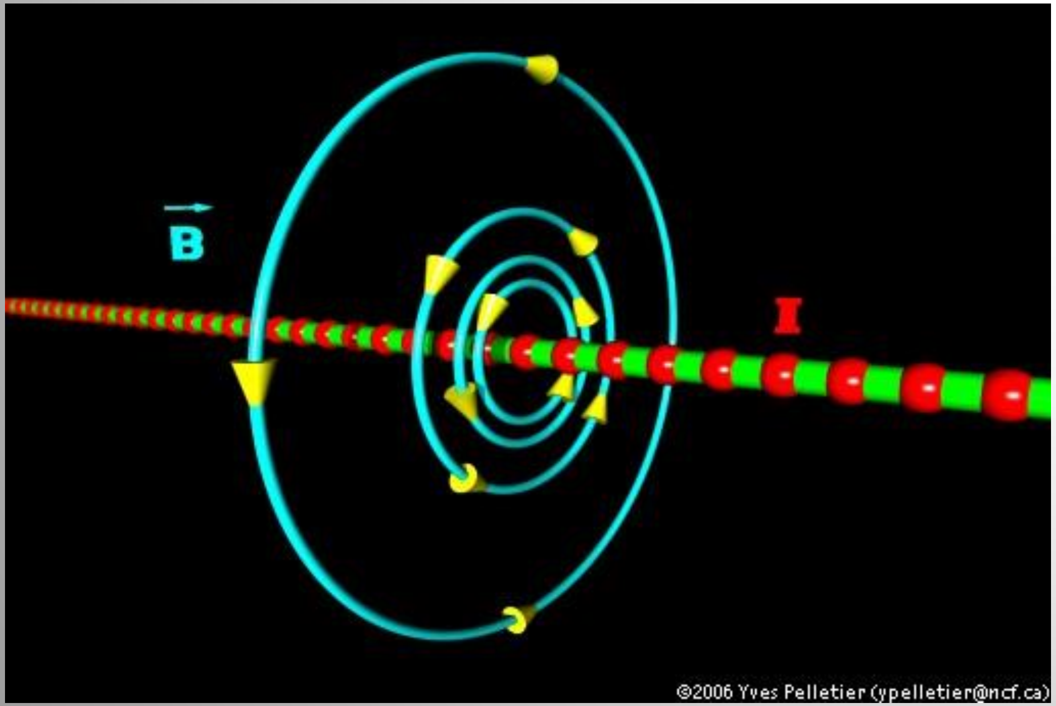
$$\nabla \times \vec{H} = \vec{J} + \cancel{\frac{\partial \vec{D}}{\partial t}}$$

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

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



„An electrical current is surrounded by a magnetic field“



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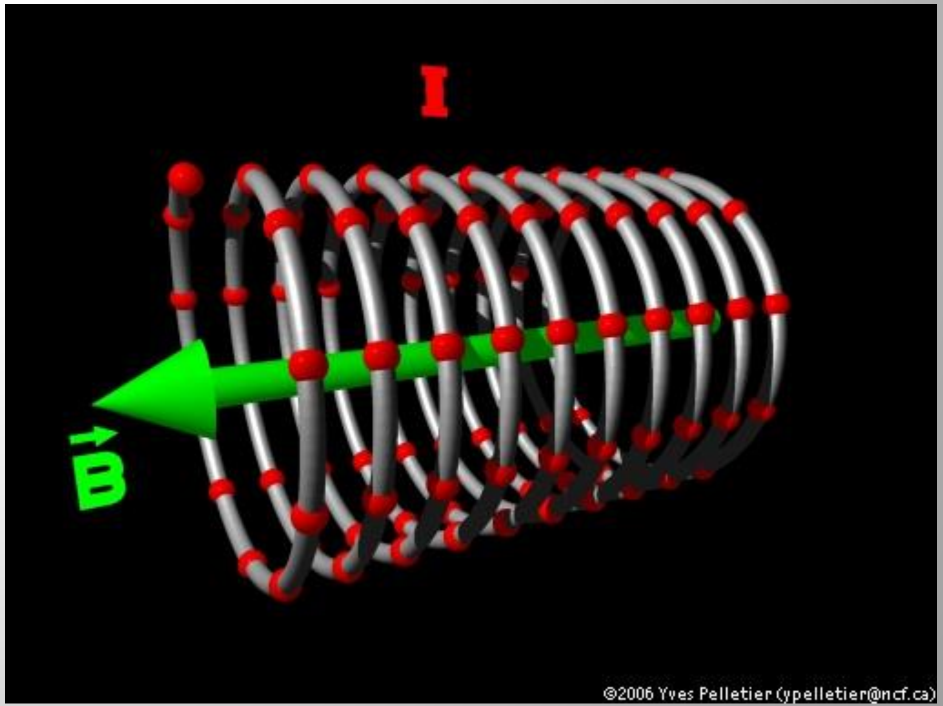

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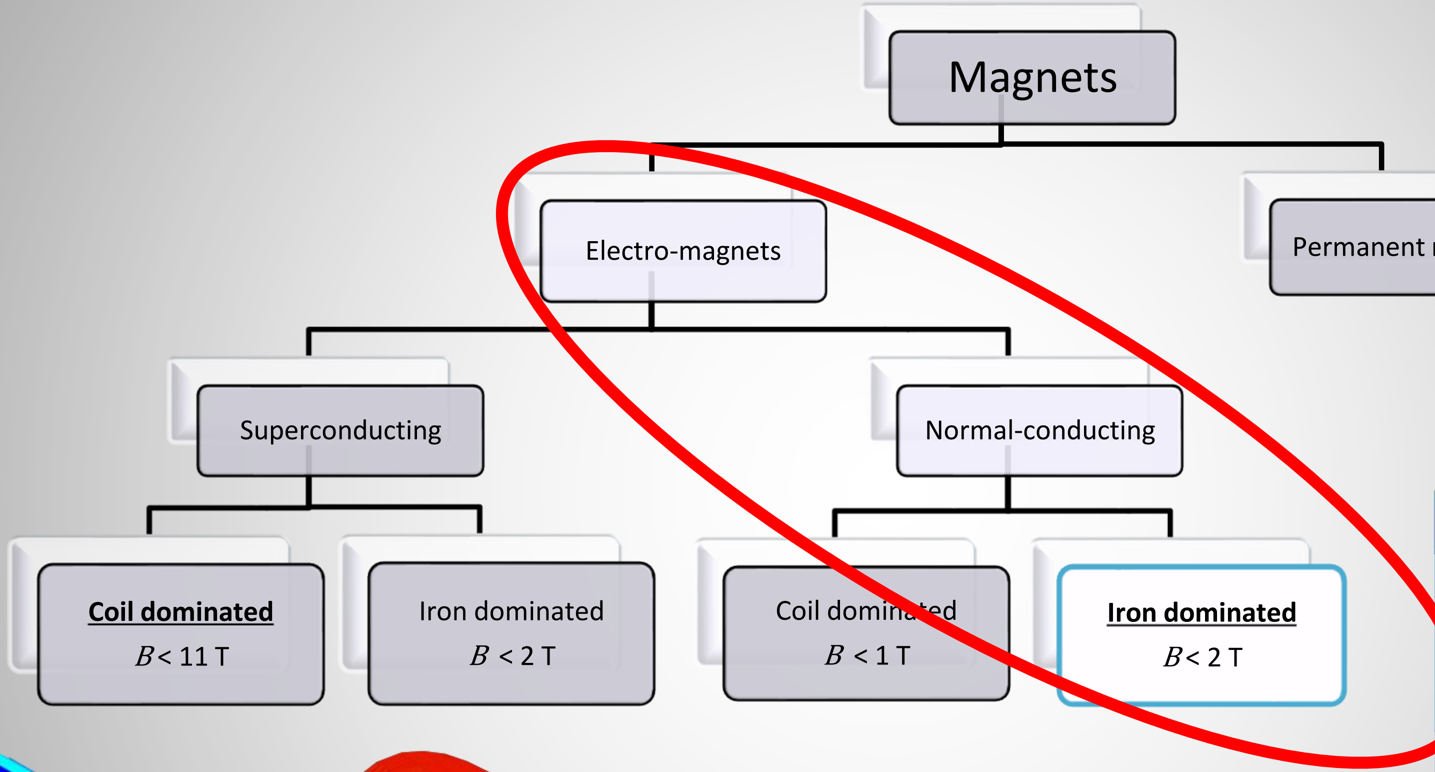
# Magnet technologies



Magnets

Electro-magnets

Permanent magnets

Superconducting

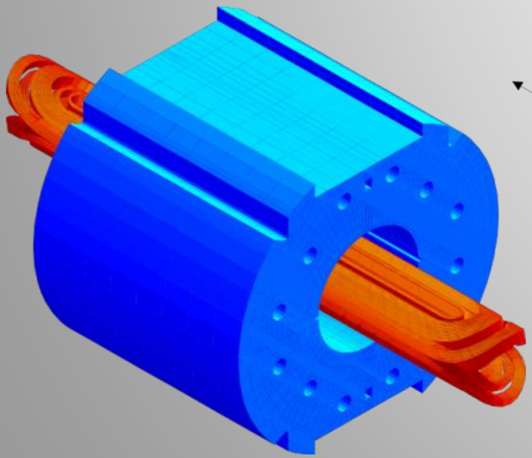
Normal-conducting

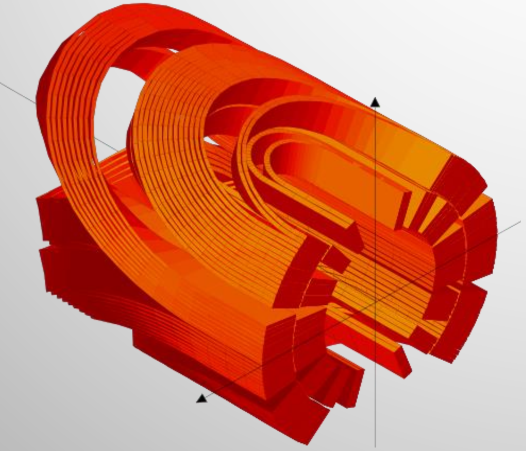
**Coil dominated**
$B < 11$ T

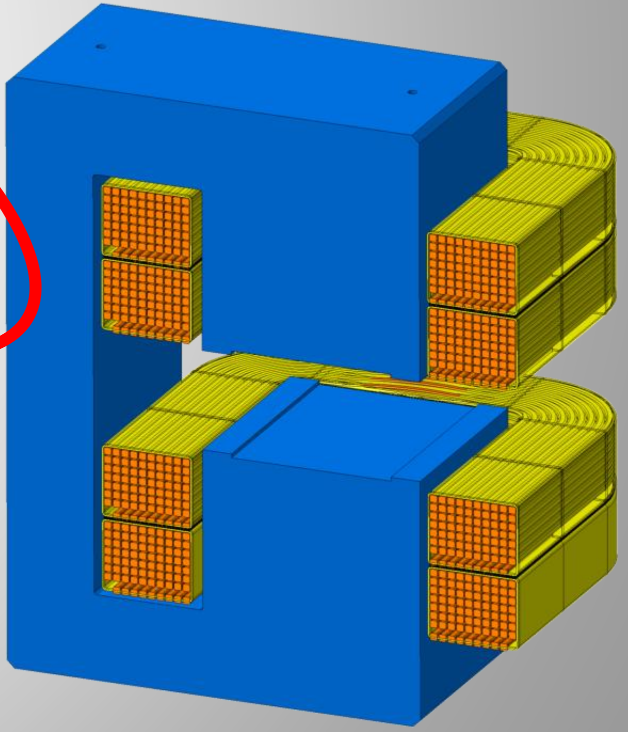
Iron dominated
$B < 2$ T

Coil dominated
$B < 1$ T

**Iron dominated**
$B < 2$ T



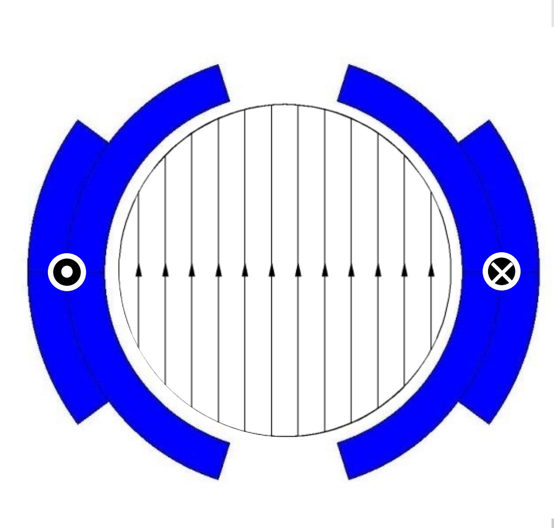


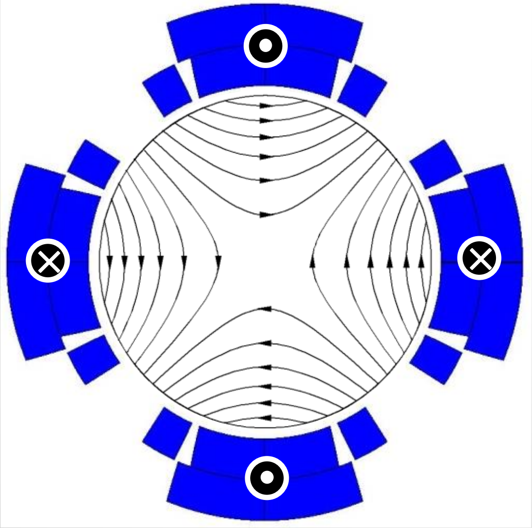


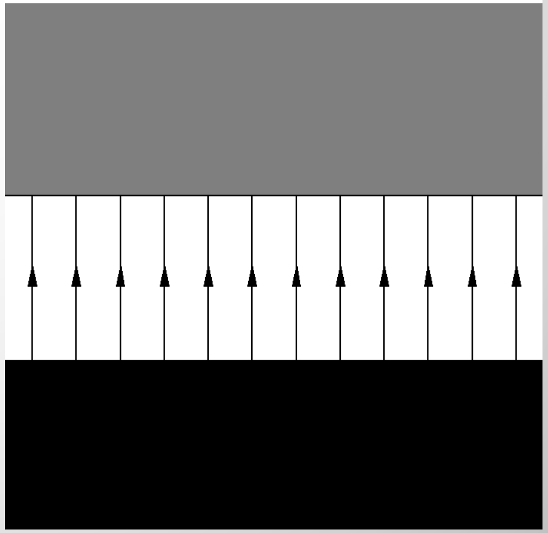
# Coil dominated – Iron dominated

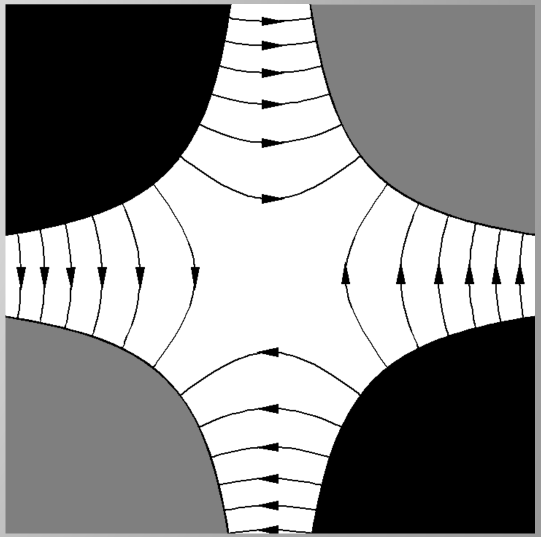
In coil-dominated magnets, the magnetic field in the aperture is shaped by the position of the conductors respectively the current distribution around the aperture

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

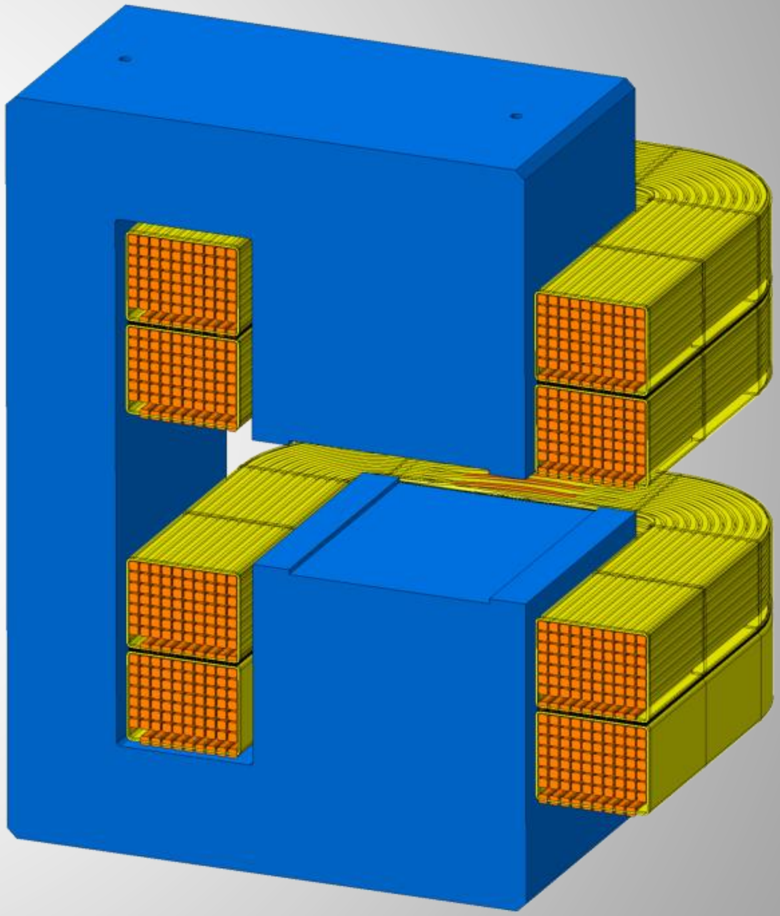

$B_1$: normal dipole


$B_2$: normal quadrupole

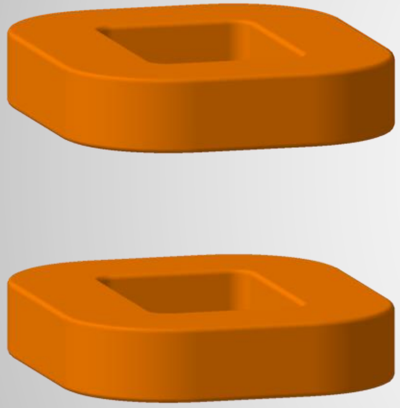
# The magnetic (iron) circuit

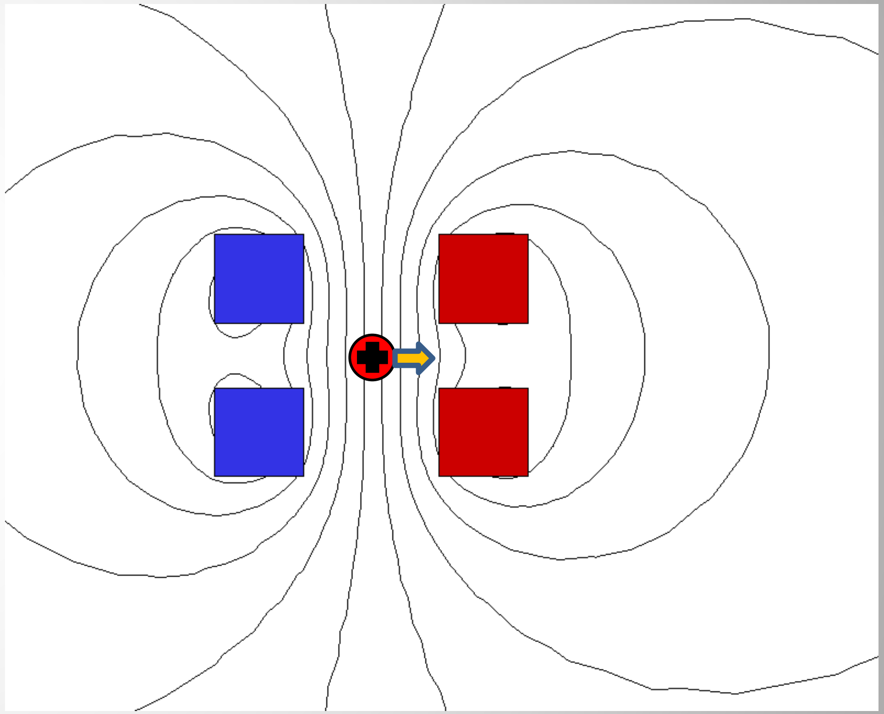
The magnetic (iron) circuit serves several purposes:

- 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



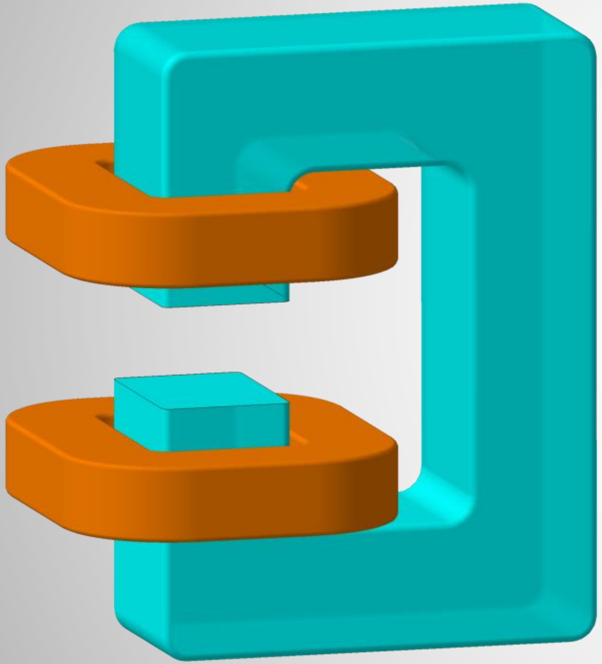
# Producing the magnetic field

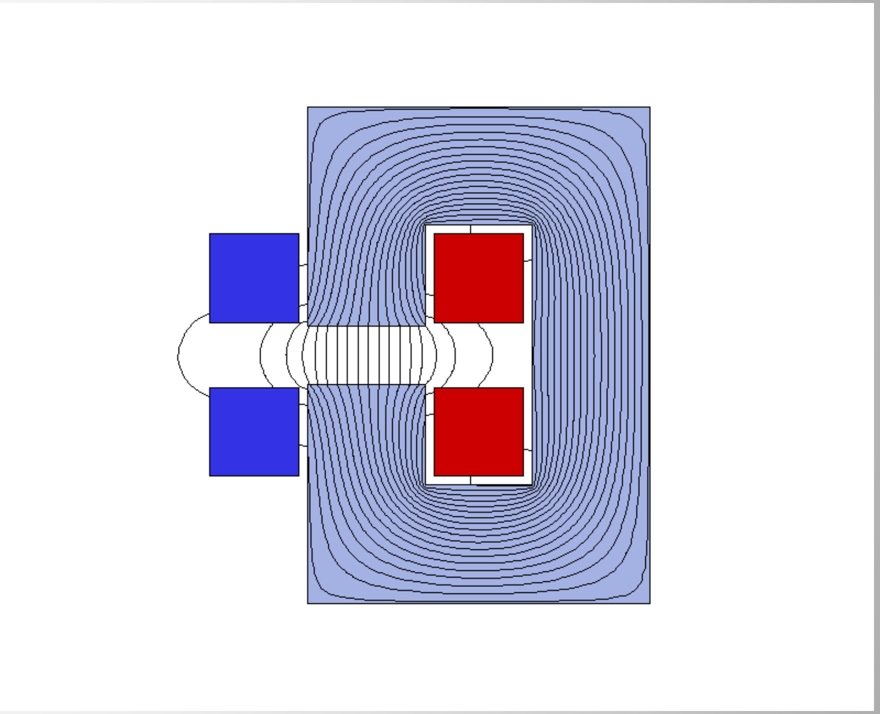




Flux lines represent the magnetic field
Coil colors indicate the current direction

# Confining the magnetic field

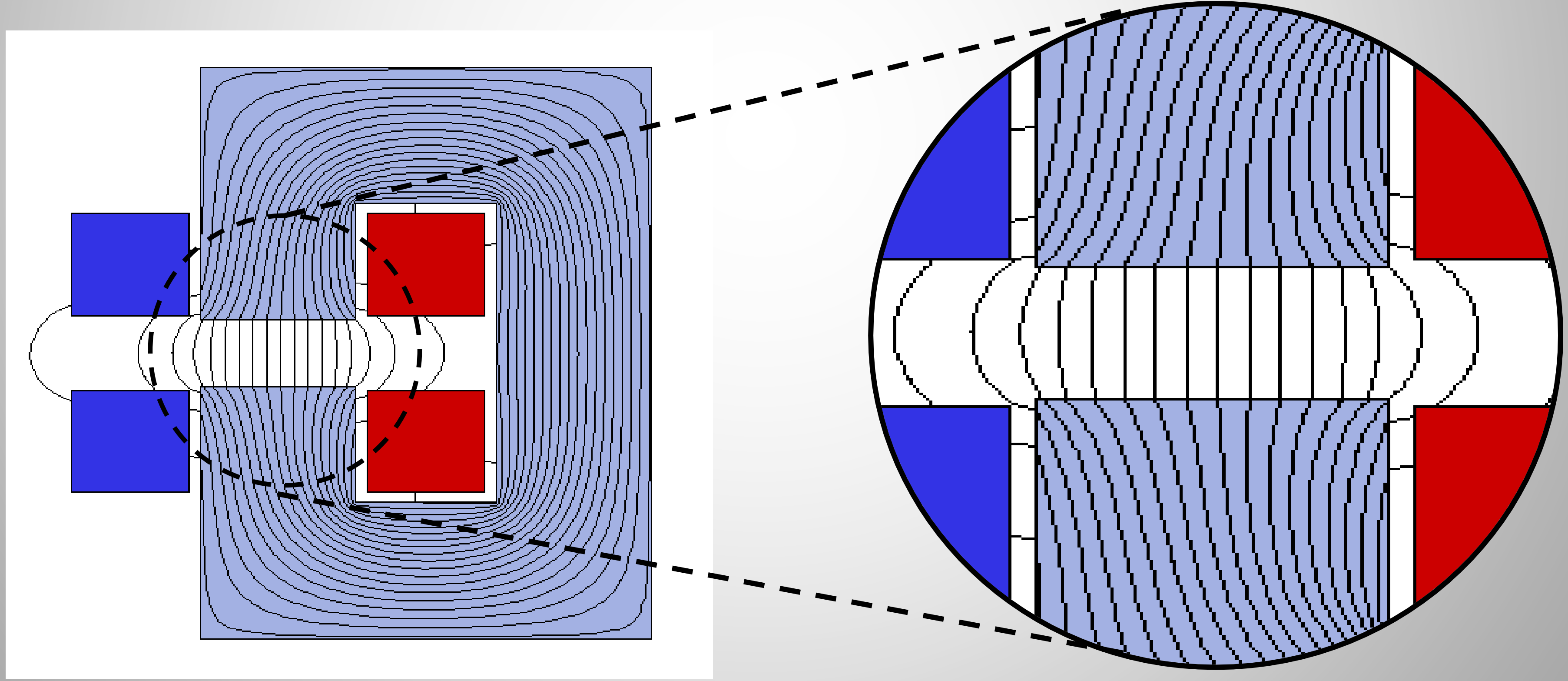




Coils hold the electrical current
Iron holds the magnetic flux

# Shaping the magnetic field

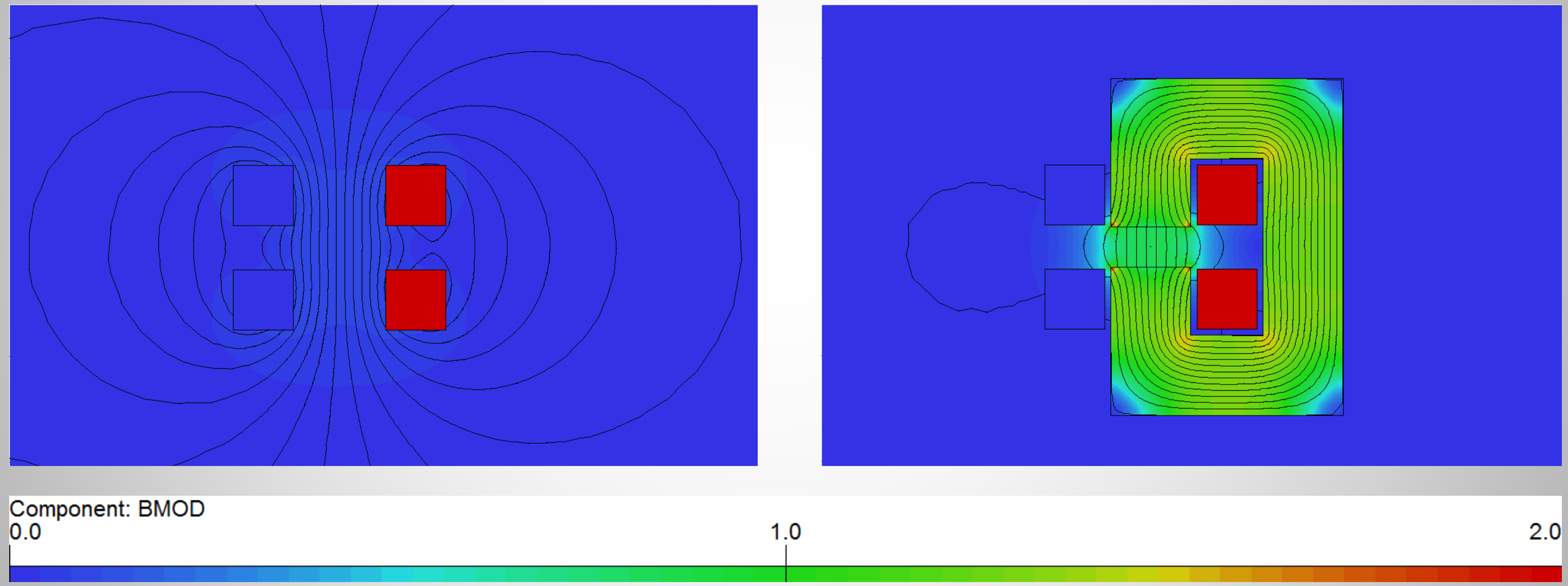
To understand, how the poles can shape the magnetic field, we need to have a closer look at the magnetic flux lines: we note that the flux lines in free space meet a material with infinite permeability perpendicular to the surface



# Enhancing the magnetic field

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

$I = 32$ kA
$B_{centre} = 0.80$ T



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

# Excitation current in a dipole

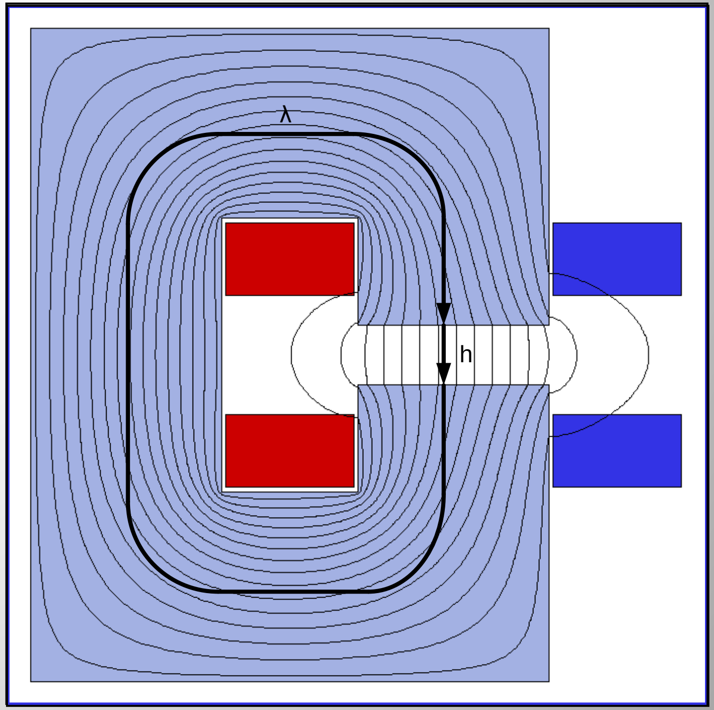
Ampere's law $\oint \vec{H} \cdot d\vec{l} = NI$ and $\vec{B} = \mu\vec{H}$

leads to
$$NI = \oint \frac{\vec{B}}{\mu} \cdot d\vec{l} = \int_{gap} \frac{\vec{B}}{\mu_{air}} \cdot d\vec{l} + \int_{yoke} \frac{\vec{B}}{\mu_{iron}} \cdot d\vec{l} = \frac{Bh}{\mu_{air}} + \frac{B\lambda}{\mu_{iron}}$$

assuming, that $B$ is constant along the path.

If the iron is not saturated: $\frac{h}{\mu_{air}} >> \frac{\lambda}{\mu_{iron}}$

then: $\boxed{NI \approx \frac{Bh}{\mu_0}}$



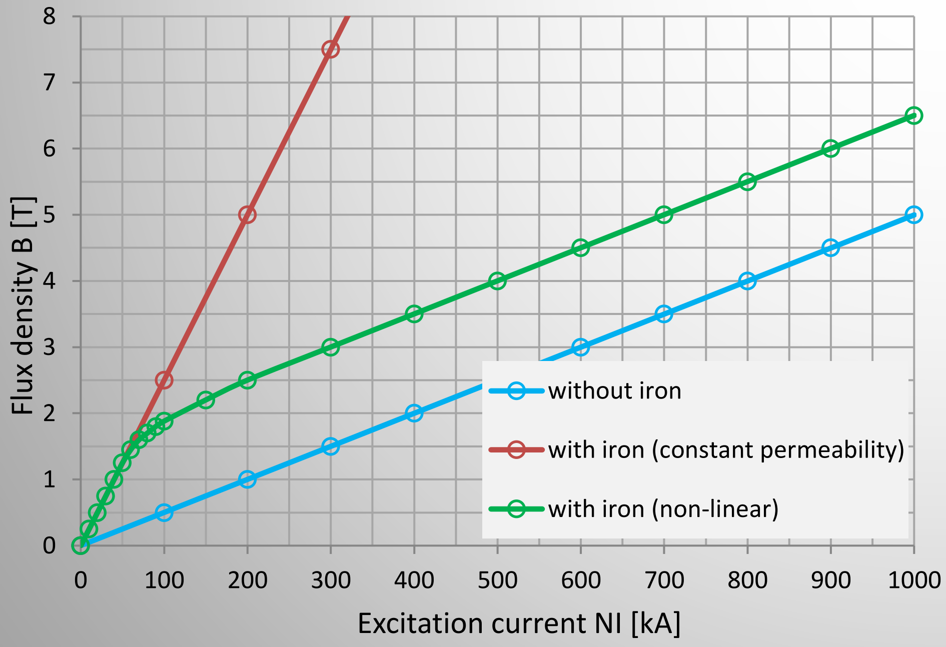
# Permeability

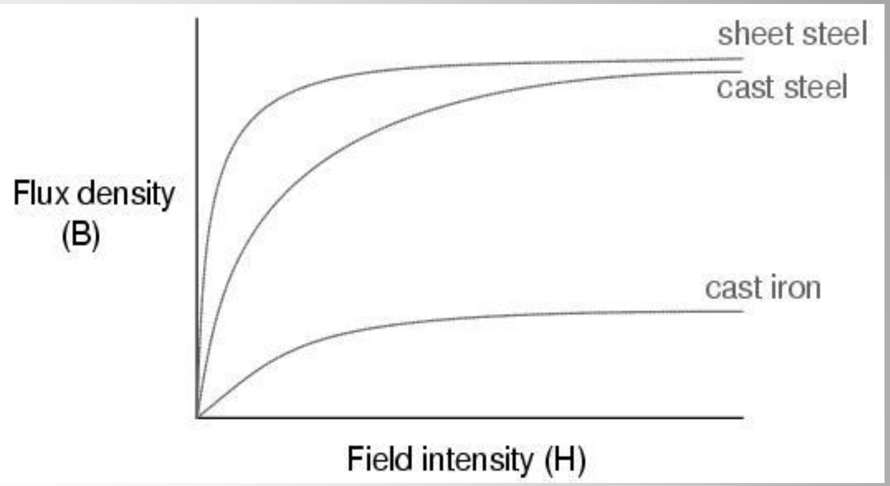
$$\vec{B} = \mu \vec{H} \qquad \mu = \mu_0 \mu_r$$

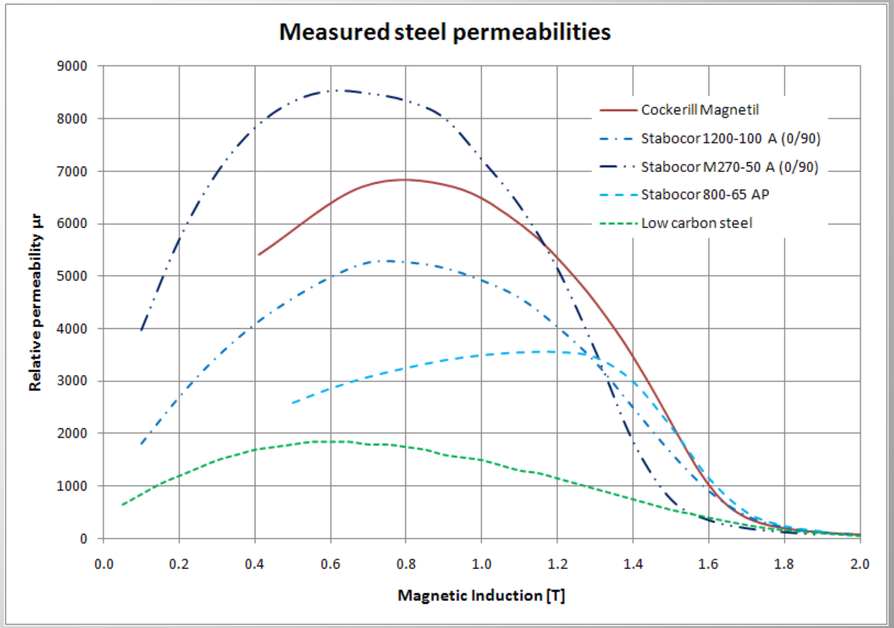
Permeability: correlation between magnetic field strength $H$ and magnetic flux density $B$

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

$$\vec{B} = \mu_0 \vec{H} + \vec{J} = \mu_0 \mu_r \vec{H}$$

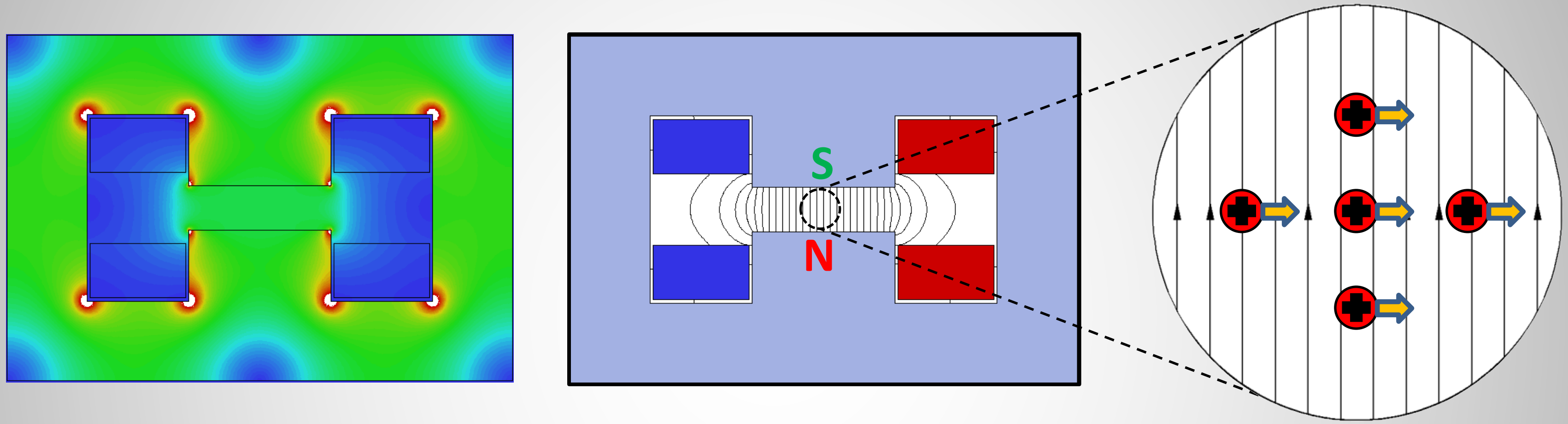






# Dipole

Purpose: bend or steer the particle beam



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

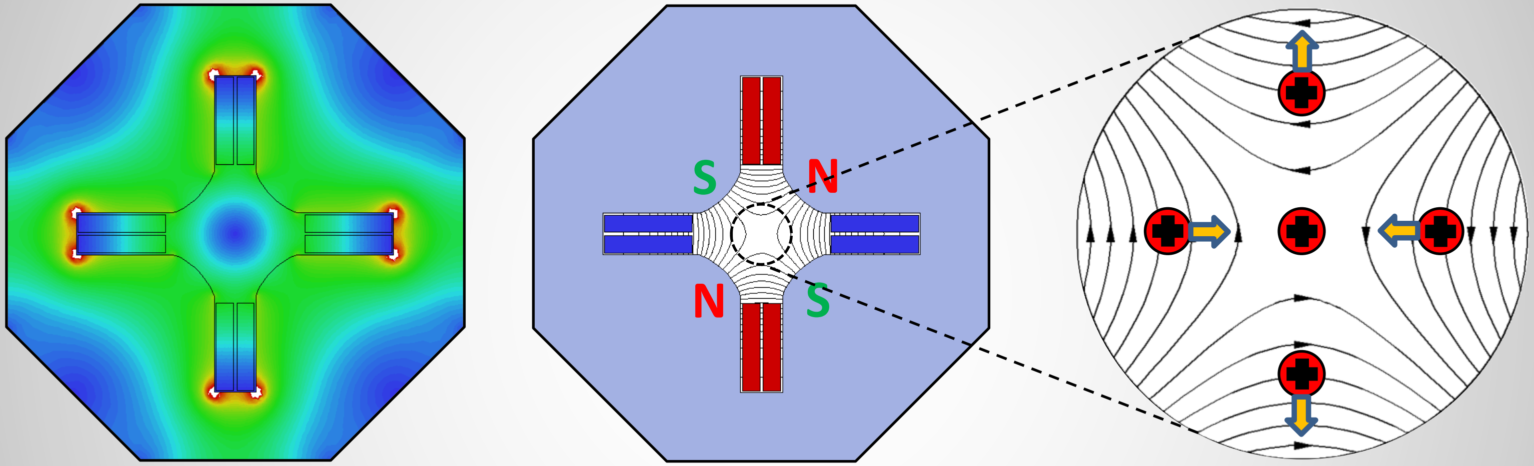
$y = \pm h/2$ (→ straight line with $h$ = gap height)

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)



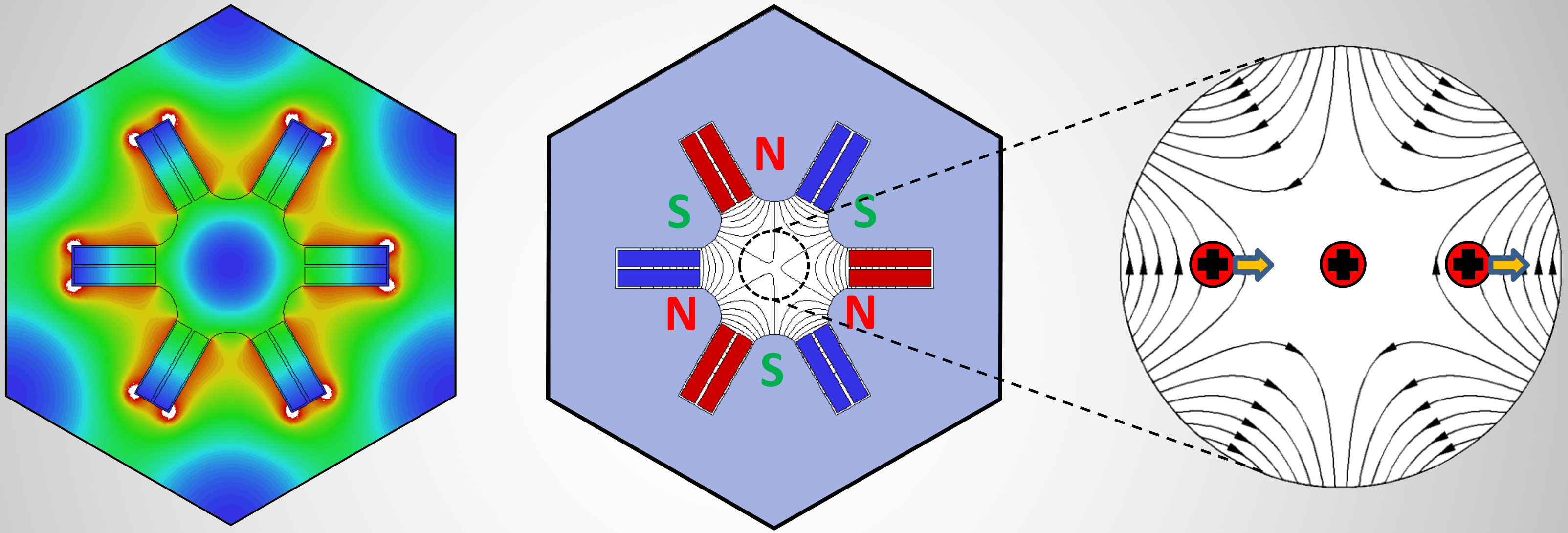
Equation for normal (non-skew) ideal (infinite) poles:

$2xy = \pm r^2$ (→ hyperbola with $r$ = aperture radius)

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

# Sextupole

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

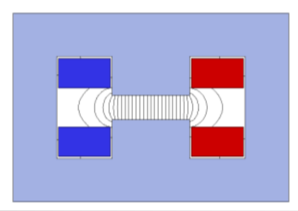
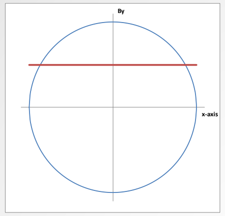
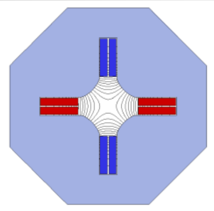
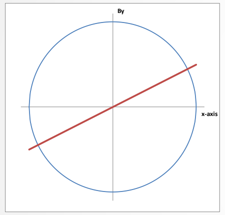
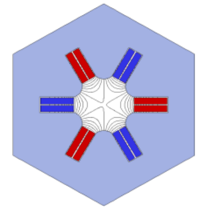
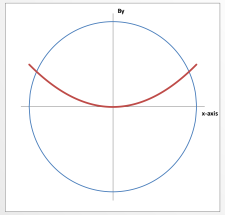
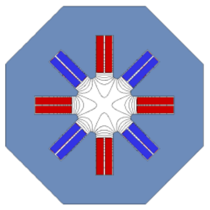
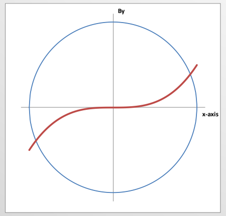


Equation for normal (non-skew) ideal (infinite) poles:

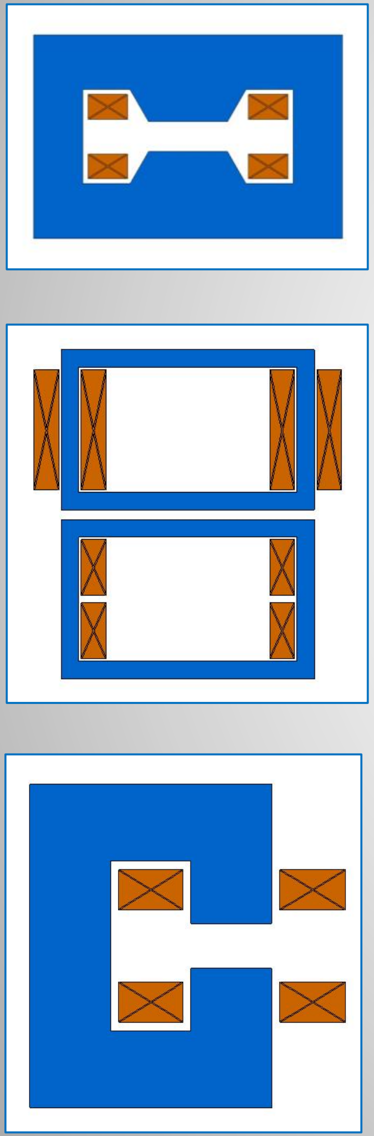
$$3x^2y - y^3 = \pm r^3 \quad \text{(with } r = \text{aperture radius)}$$

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

# Magnet types

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

# Conventional nc-magnet layout

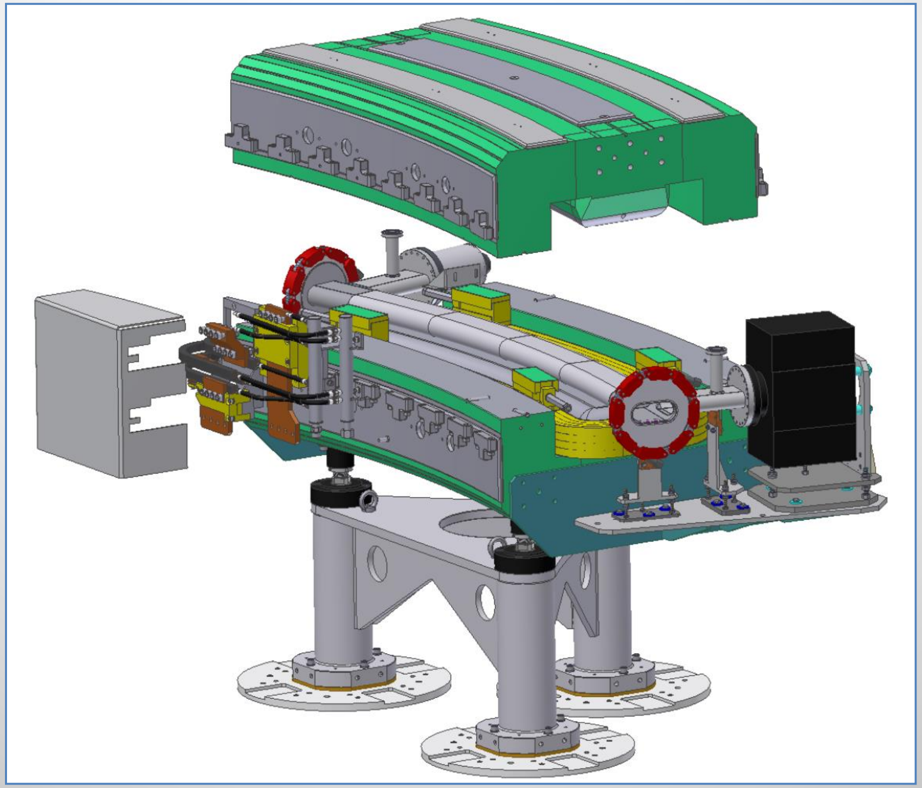


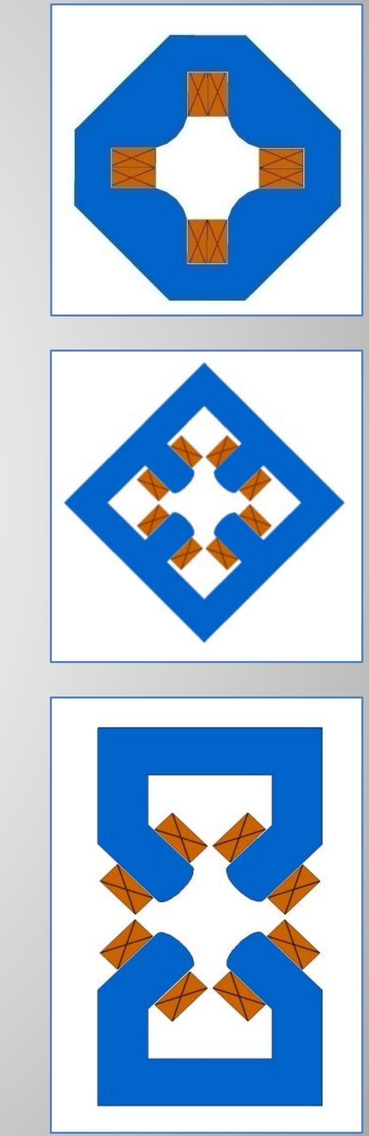
**Excitation coils** carry the electrical current creating $H$

**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, ...



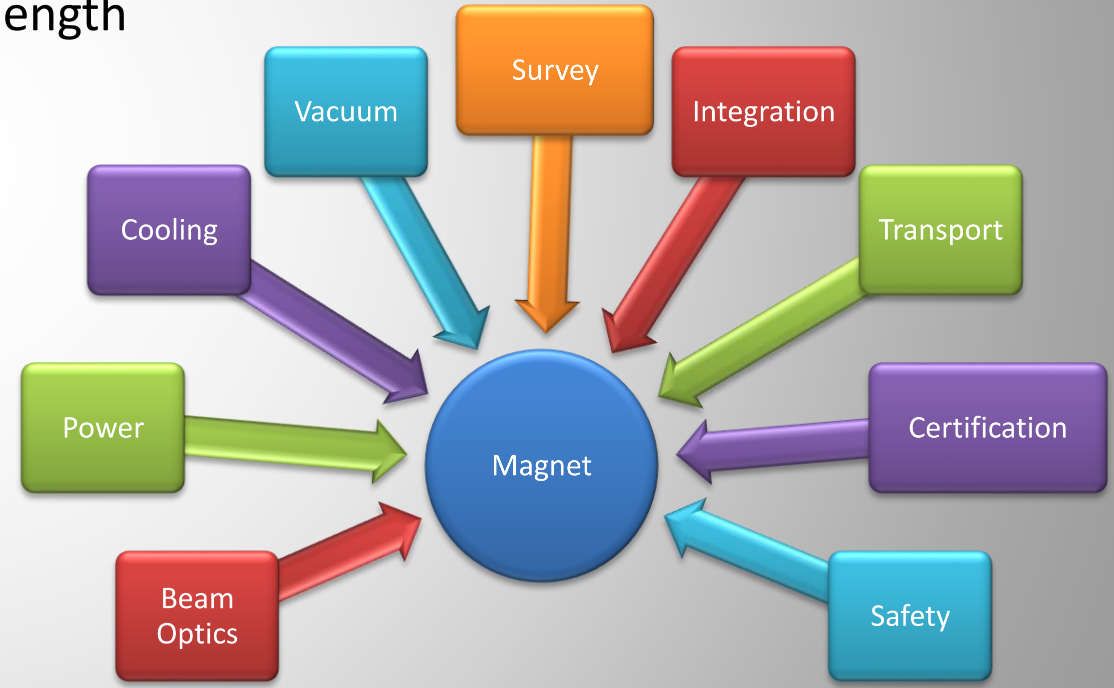


# Design process

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
- Environmental aspects



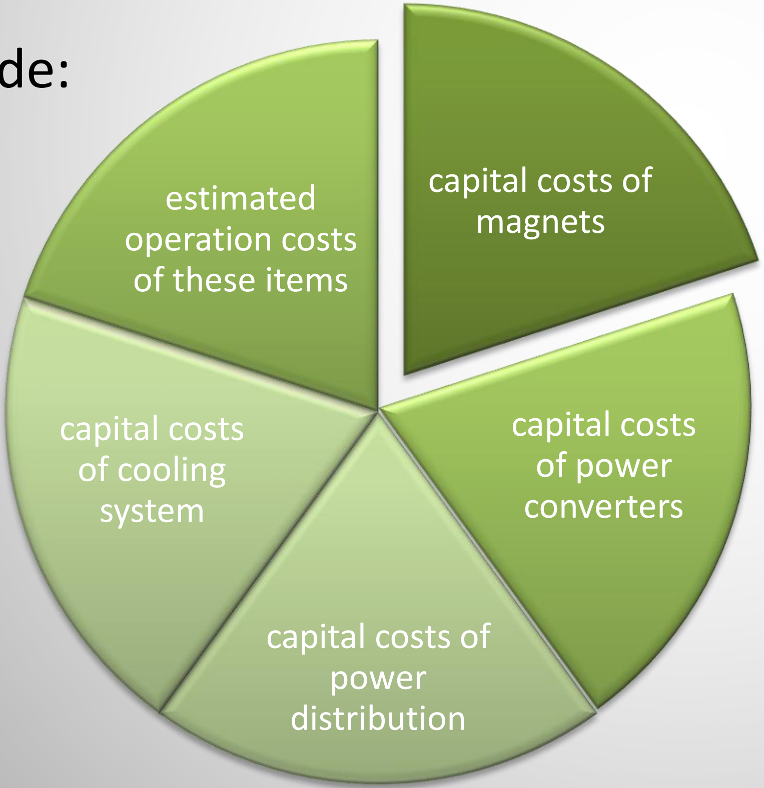
*A magnet is not a stand-alone device!*

# 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:



capital costs of magnets

capital costs of power converters

capital costs of power distribution

capital costs of cooling system

estimated operation costs of these items

Attention: $\boxed{Power \propto current\ desity}$

Decreasing current density means:

- increasing coil cross section
- increasing material (coil & yoke) cost
- increasing manufacturing cost
- but decreasing operation costs

# Numerical design

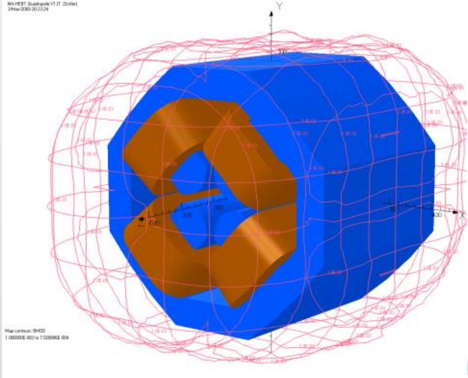
Common computer codes: Opera (2D) or Tosca (3D), Poisson, ANSYS, Roxie, Magnus, Magnet, Mermaid, Radia, FEMM, COMSOL, etc…

Technique is iterative

- calculate field generated by a defined geometry
- adjust geometry until desired distribution is achieved

Computing time <u>increases</u> for high accuracy solutions, non-linear problems and time dependent analysis → compromise between accuracy and computing time

| 2D | 3D |
|---|---|
| • 2D analysis is often sufficient<br>• magnetic solvers allow currents only perpendicular to the plane<br>• fast | • produces large amount of elements<br>• mesh generation and computation takes significantly longer<br>• end effects included<br>• powerful modeller |



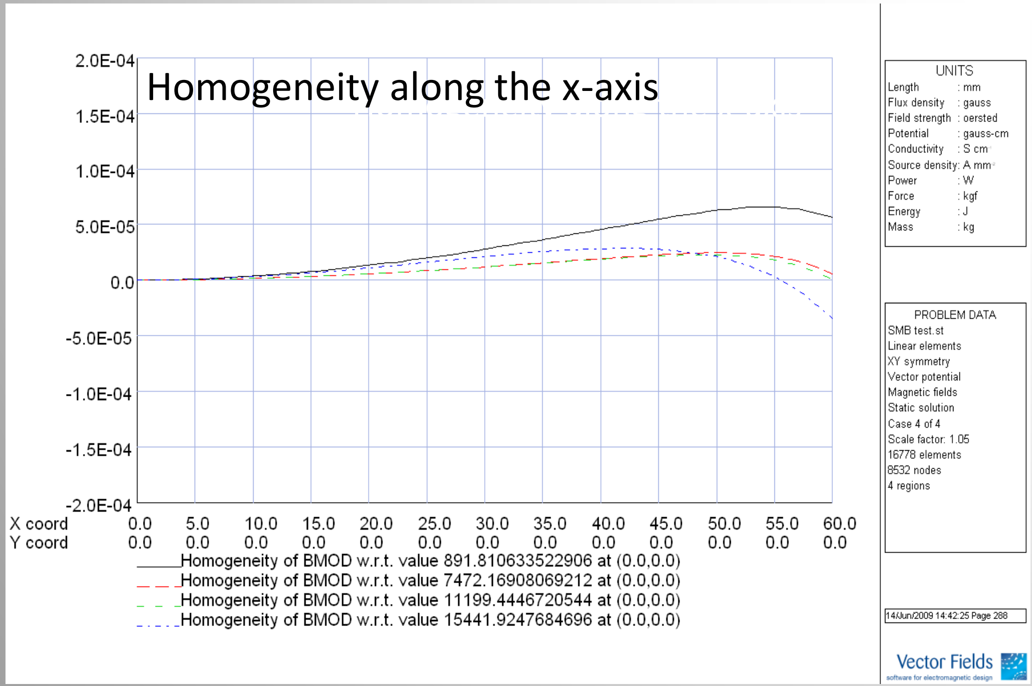
FEM codes are powerful tools, but be cautious:

- Always check results if they are ‘physical reasonable’
- Use FEM for quantifying, not to qualify

# Field quality

A simple judgment of the field quality can be done by plotting the field homogeneity

$$\frac{\Delta B}{B_0} = \frac{B_y(x,y)}{B_y(0,0)} - 1 \qquad \frac{\Delta B}{B_0} \le 0.01\%$$



Homogeneity of BMOD w.r.t. value 891.810633522906 at (0.0,0.0)
Homogeneity of BMOD w.r.t. value 7472.16908069212 at (0.0,0.0)
Homogeneity of BMOD w.r.t. value 11199.4446720544 at (0.0,0.0)
Homogeneity of BMOD w.r.t. value 15441.9247684696 at (0.0,0.0)

UNITS

| | |
|---|---|
| Length | : mm |
| Flux density | : gauss |
| Field strength | : oersted |
| Potential | : gauss-cm |
| Conductivity | : S cm⁻¹ |
| Source density | : A mm⁻² |
| Power | : W |
| Force | : kgf |
| Energy | : J |
| Mass | : kg |

PROBLEM DATA
SMB test.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 4 of 4
Scale factor: 1.05
16778 elements
8532 nodes
4 regions

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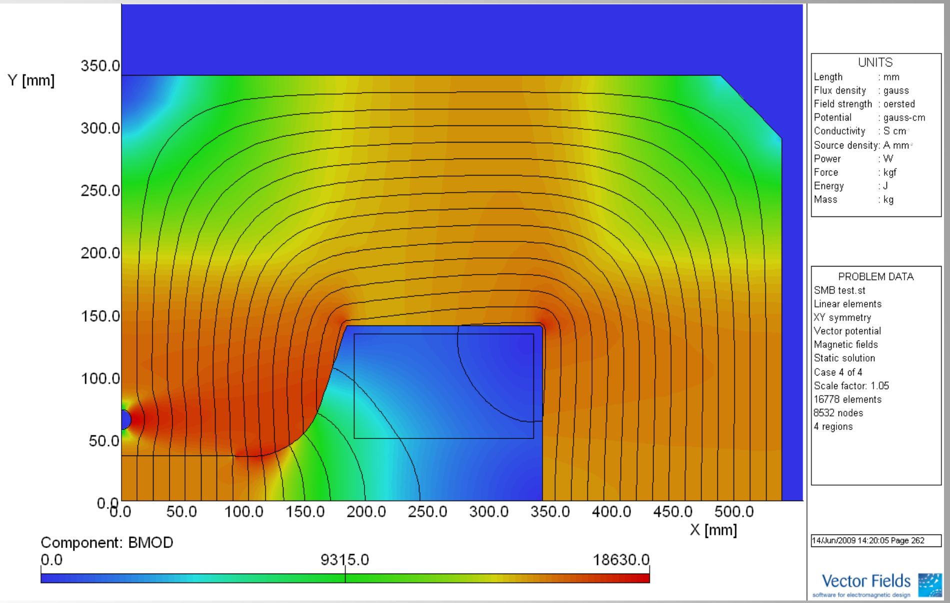

UNITS

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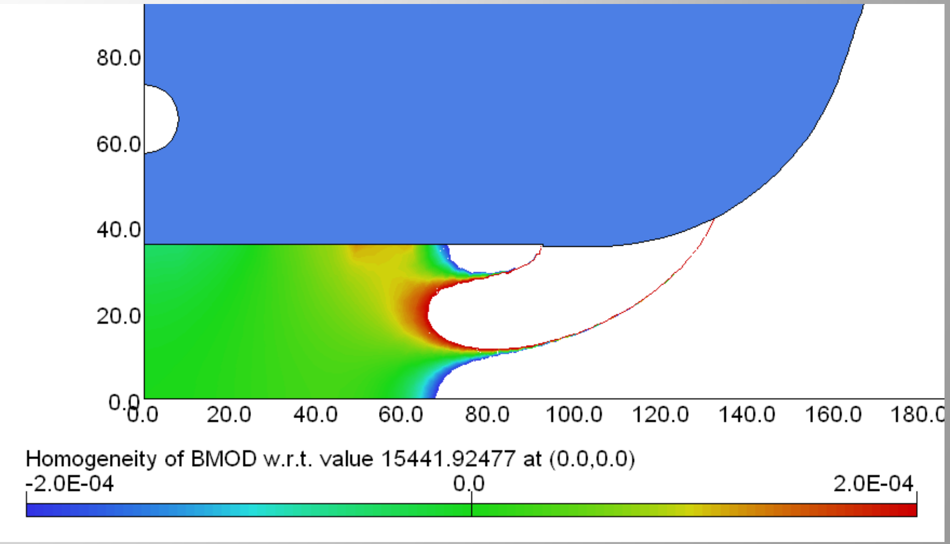
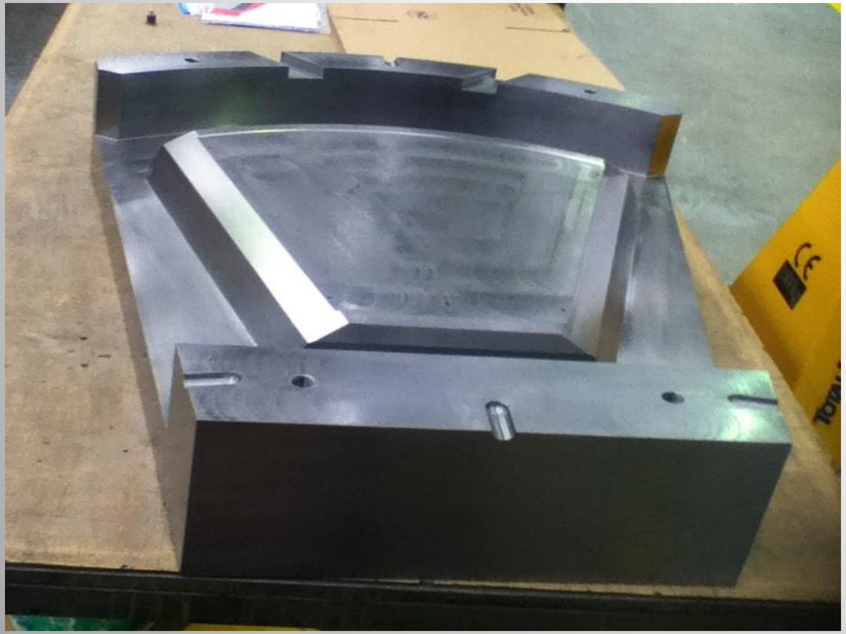


Homogeneity of BMOD w.r.t. value 15441.92477 at (0.0,0.0)

# 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



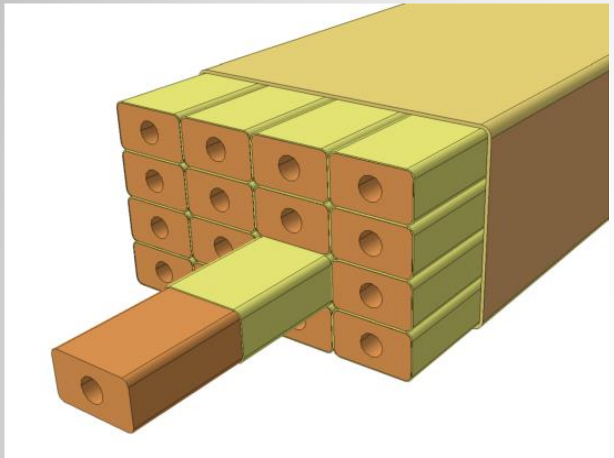
+ steel sheets less expensive than massive blocks (cast ingot)
+ less expensive for larger series
+ steel properties can be easily tailored
+ uniform magnetic properties over large series
- expensive tooling

# 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

Air cooling by natural convection:

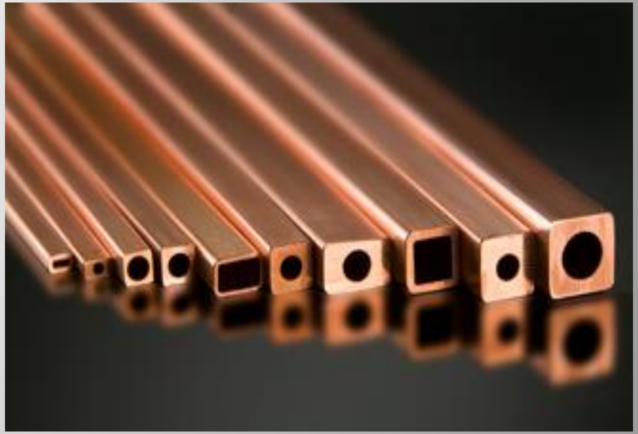
- Current density
  - $j < 2$ A/mm$^2$ for small, thin coils
- Cooling enhancement
  - Heat sink with enlarged radiation surface
  - Forced air flow (cooling fan)
- Only for magnets with limited strength (e.g. correctors)

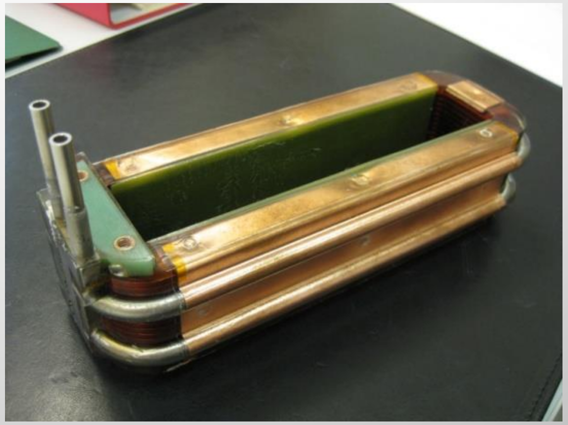
Direct water cooling:

- Typical current density $j \leq 10$ A/mm$^2$
- Requires demineralized water (low conductivity) and hollow conductor profiles

Indirect water cooling:

- Current density $j \leq 3$ A/mm$^2$
- Tap water can be used

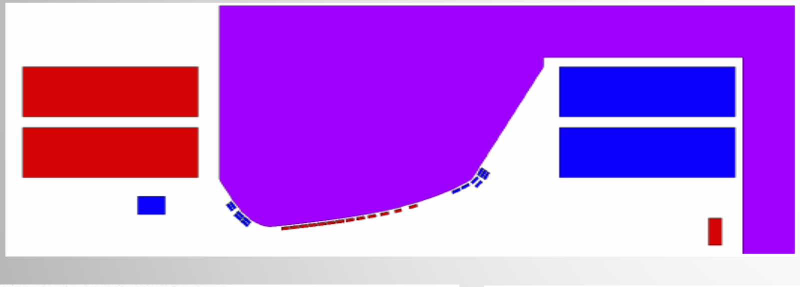


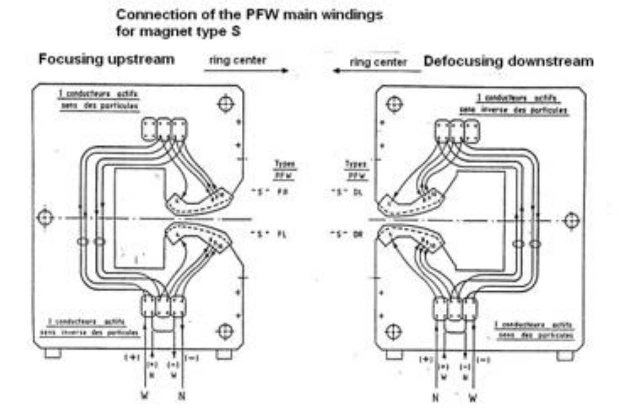


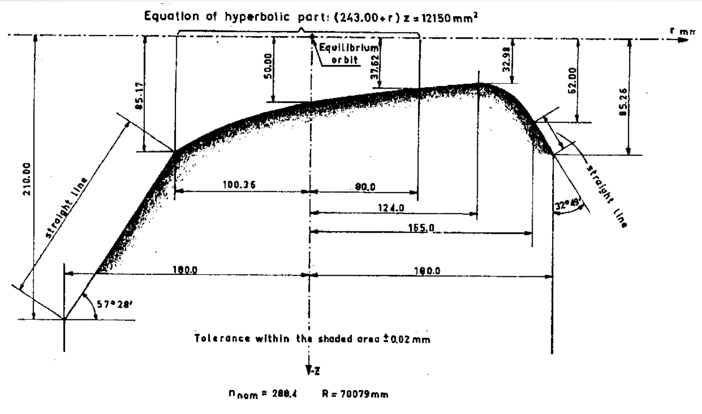
# NC-magnets in the 1950-60s

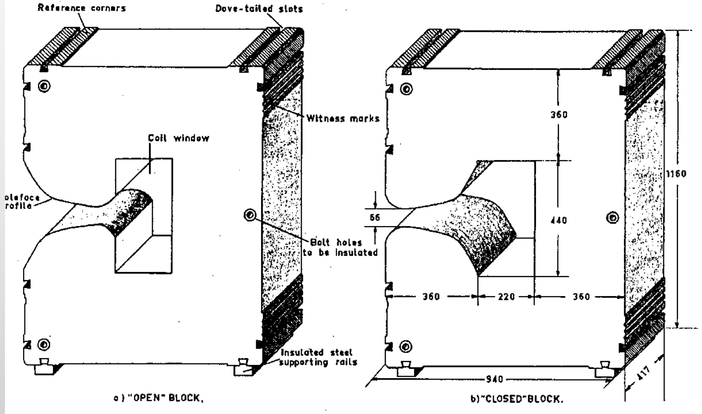
CERN PS (1959), 25 GeV, 628 m

- 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





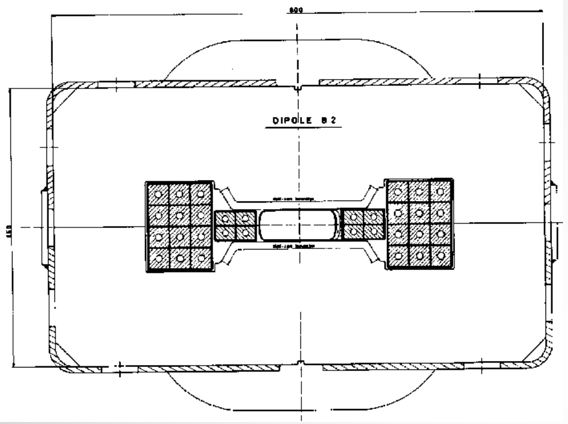


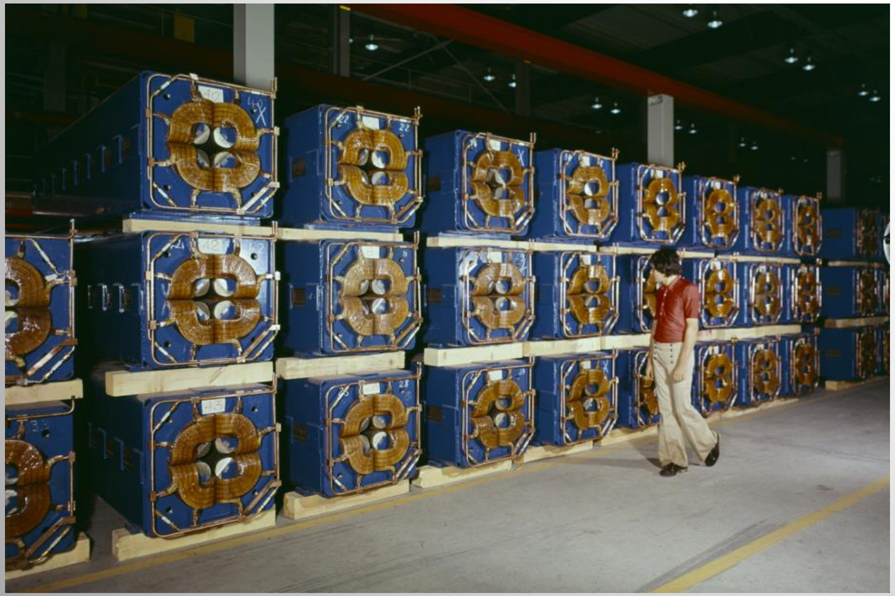


# NC-magnets in the 1970s

CERN SPS (1976), 7 km, 450 GeV

- 744 H-type bending magnets with $B$ = 2.05 T

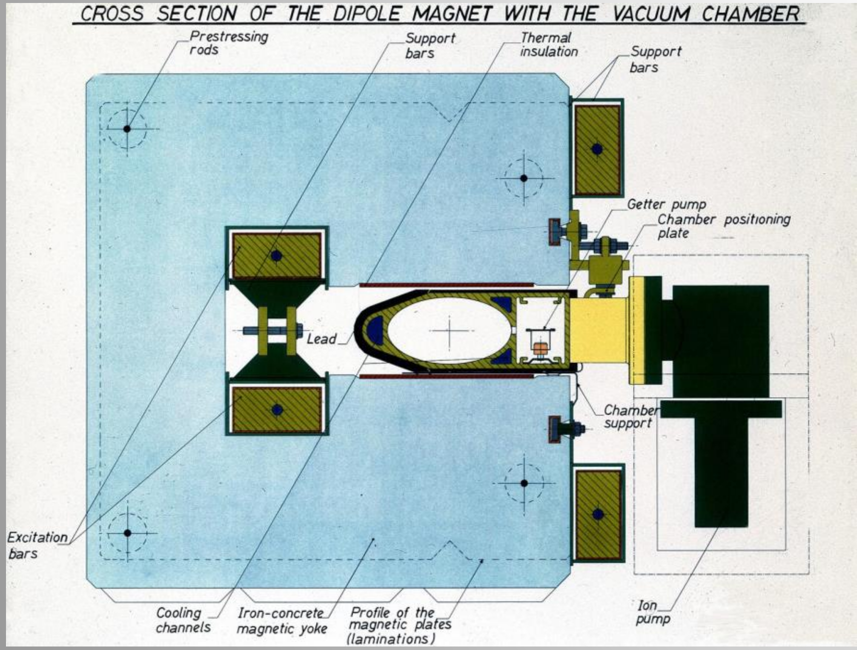


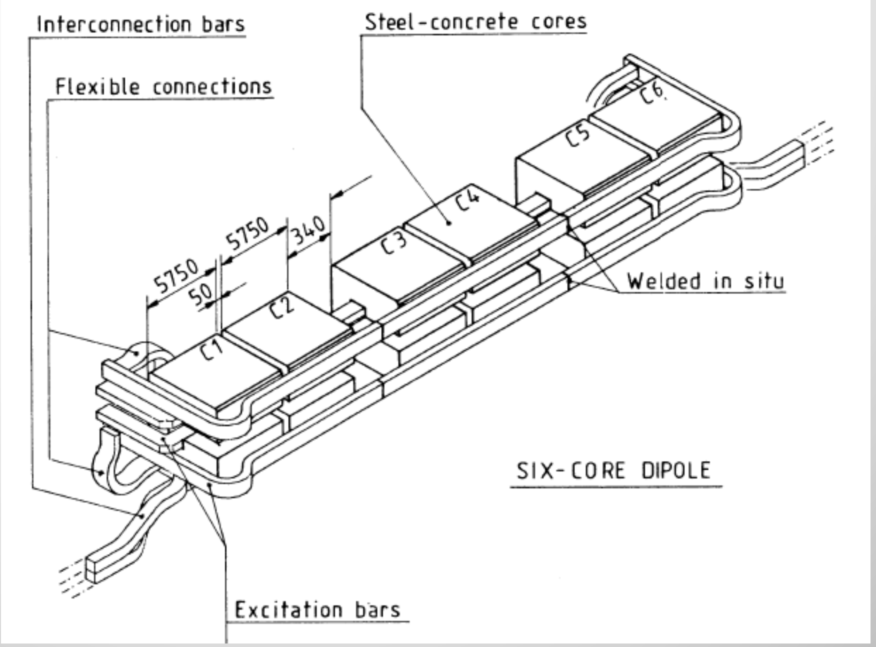


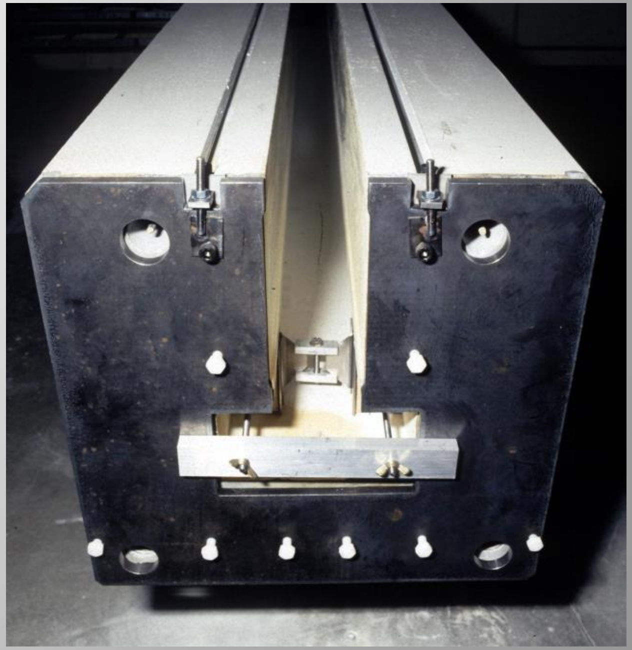
# NC-magnets in the 1980s

LEP (1989), 27 km

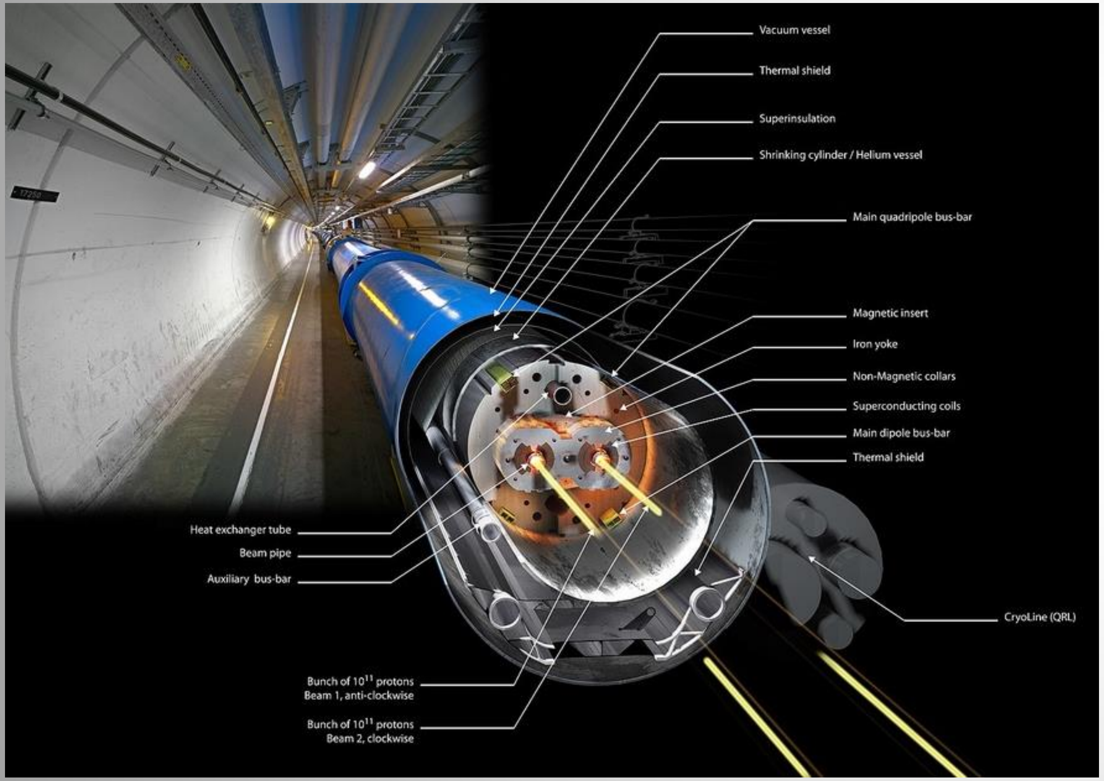
- Cycled field: 22 mT (20 GeV injection) to 108 mT (100 GeV)
- 5.75 m long ‘diluted’ magnet cores: 30% Fe / 70% concrete
- Four water cooled aluminium excitation bars
- Max. current: 4.5 kA



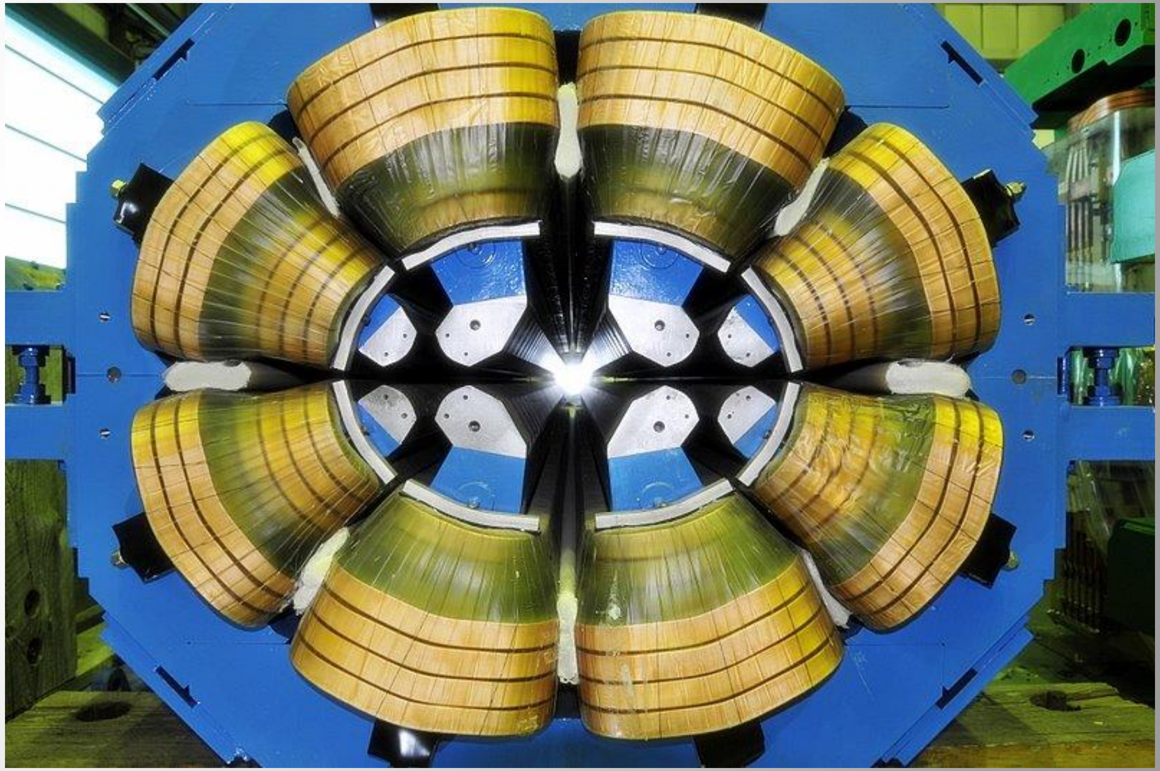




# NC-magnets even in the LHC …

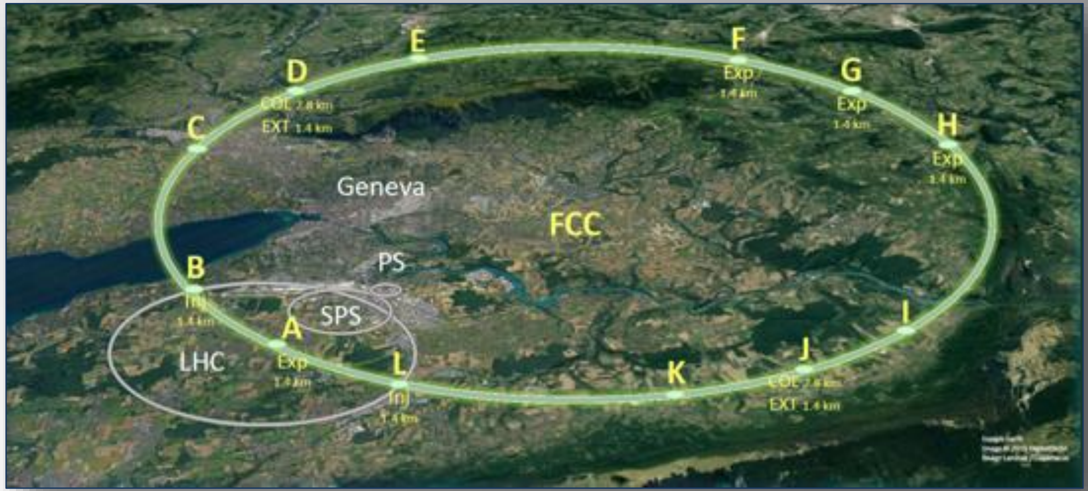


LHC Main Dipole



Double-aperture LHC quadrupole

# Future challenges



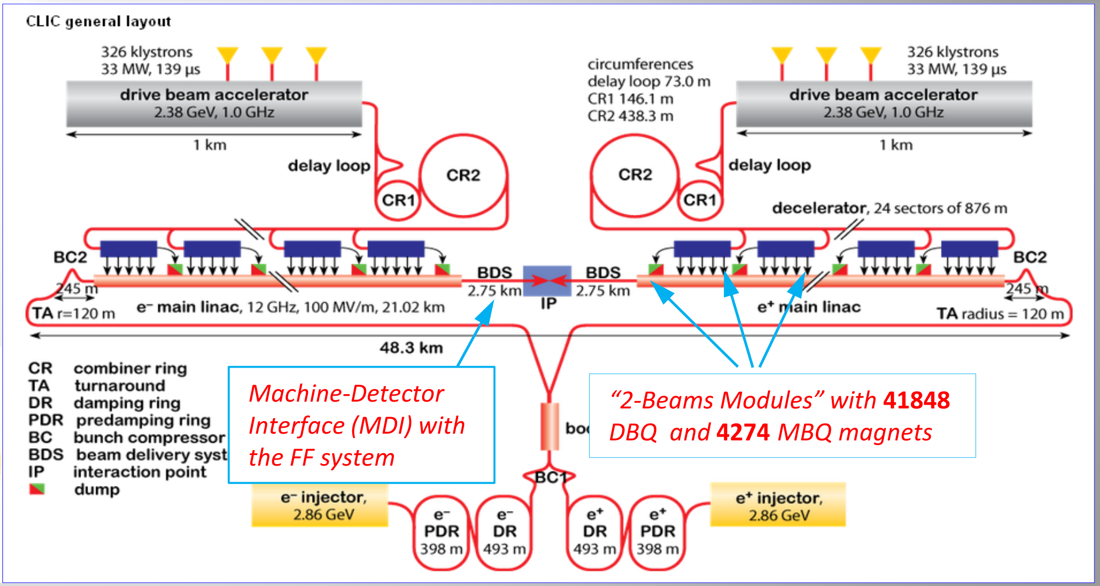
Future accelerator projects bear a number of financial and technological challenges in general, but also in particular for magnets …

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: SC magnets

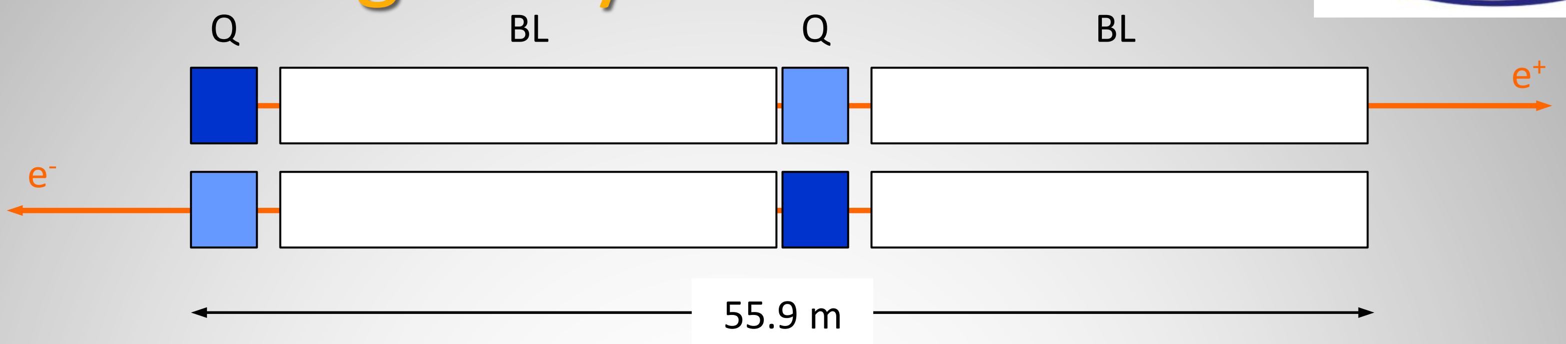
Lepton colliders (circular & linear):
- Alignment & stabilization
- Compact design & small apertures



*Machine-Detector Interface (MDI) with the FF system*

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

# Magnet system for FCC-ee



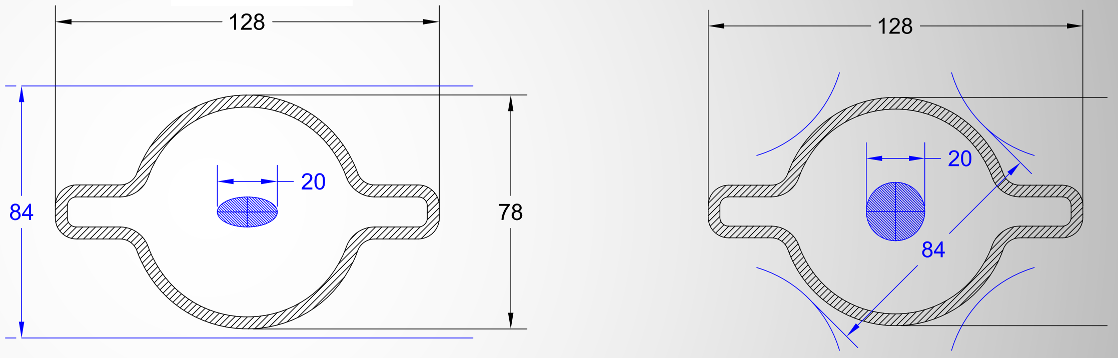
Double collider

Counter-rotating e+ / e- beams

DC operation with top-up injection

1450 FODO cells, each 55.9 m long

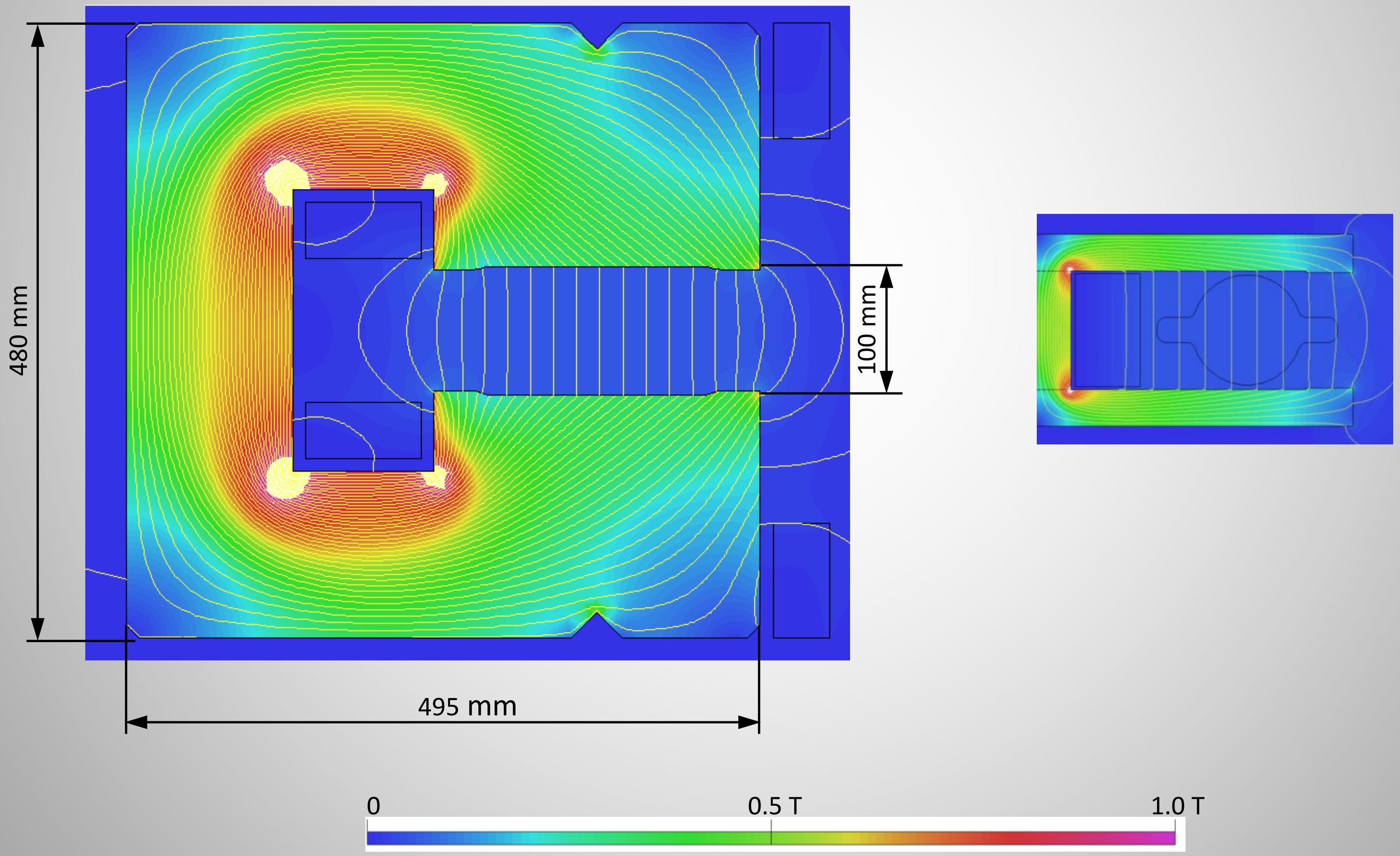
Tuneability ±1%



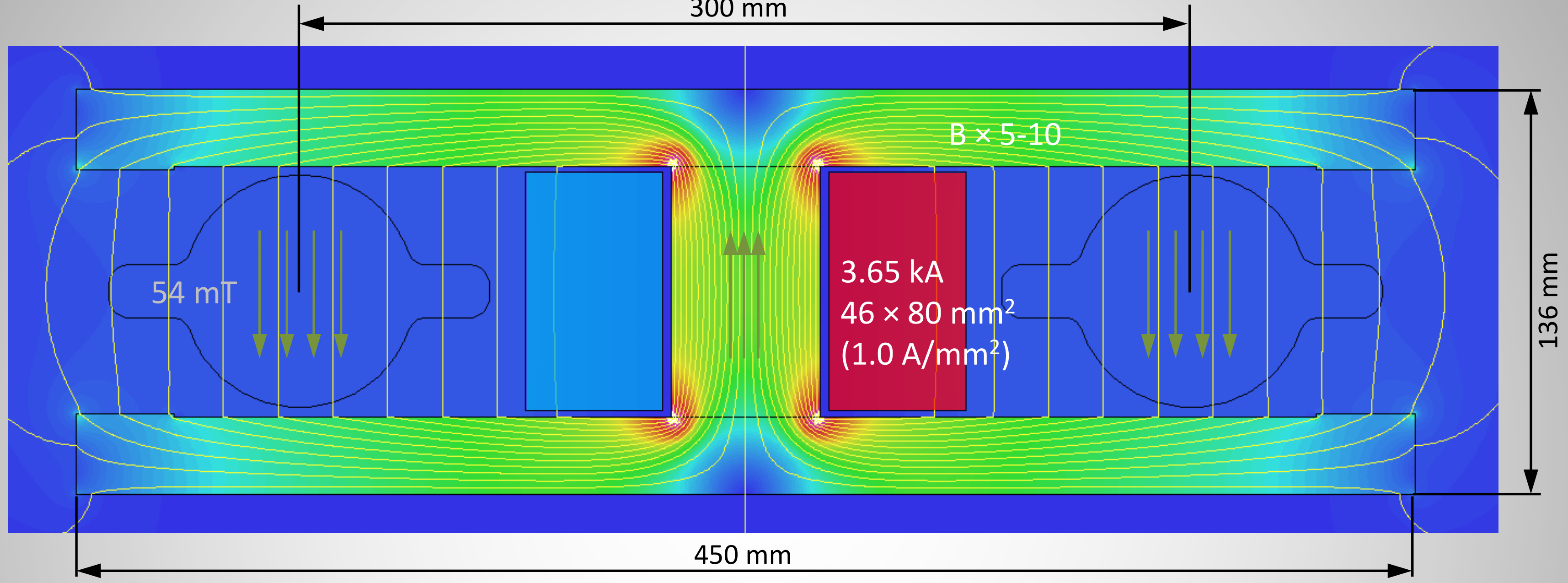
| **Parameter** | **Bending magnets** | **Quadrupole magnets** |
|---|---|---|
| Quantity (per ring) | 2900 | 1450 + 1450 |
| Magnetic length | 23.94 (21.94) m | 3.1 m |
| Aperture | 128 mm x 84 mm | R = 42 mm |
| Inter-beam distance | 300 mm | 300 mm |
| Field / max. gradient at 175 GeV | 54.3 mT |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

# Recap: LEP dipoles

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

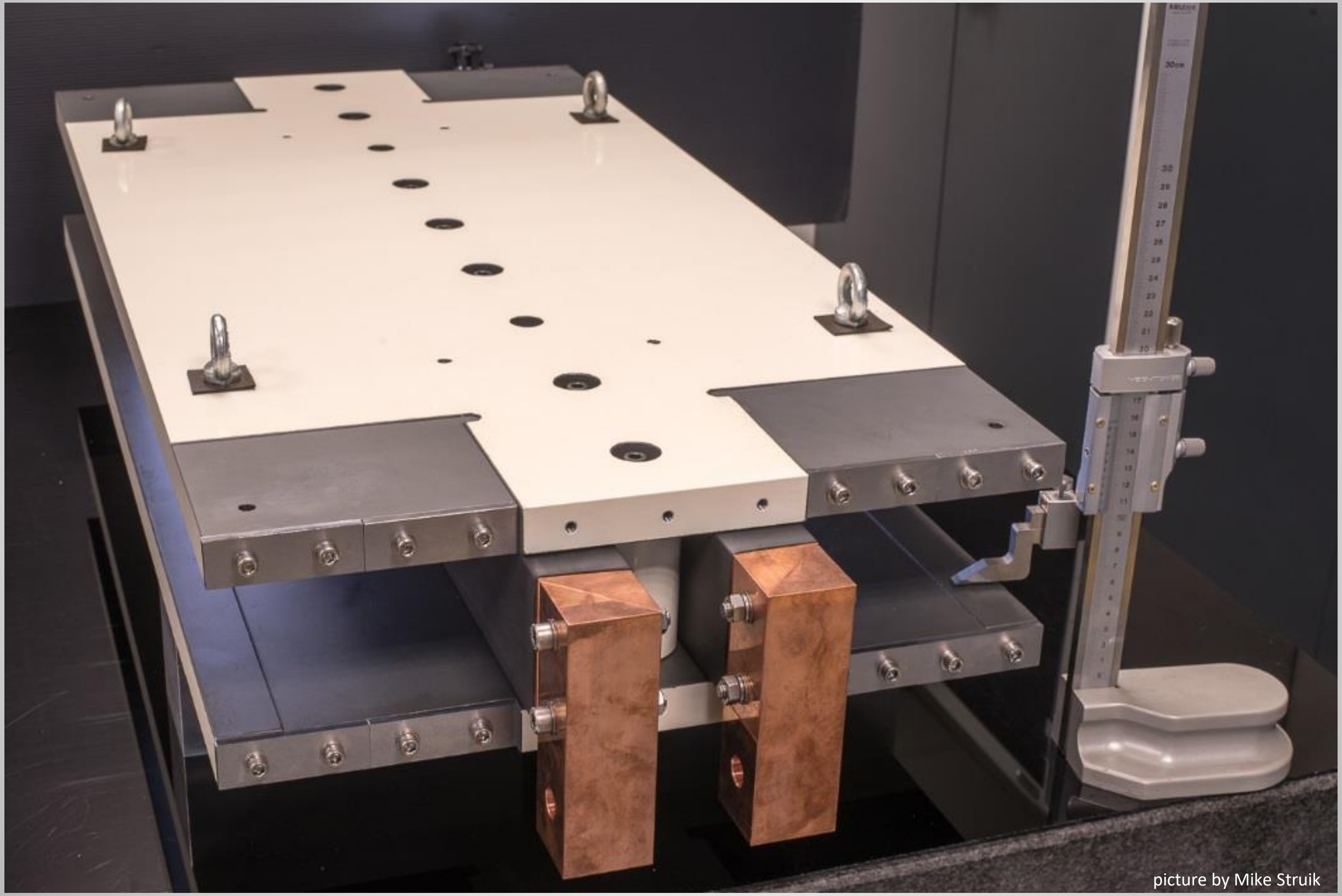


# FCC-ee Twin dipole design



- 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 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 23 years!

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