CERN Accelerator School
Beam Dynamics and Technologies for Future Colliders
Zürich, Switzerland, 21. Feb. – 6. Mar. 2018

Normal-conducting & Permanent Magnets

Thomas Zickler
CERN

Scope of this lecture

The main goal is to provide an overview on ‘room temperature’ magnets (i.e. normal-conducting, iron-dominated electro-magnets and permanent magnets), to introduce recent innovative concepts and encourage you to take on the challenge developing new ideas for future colliders

Outline

Magnet basics:

- Producing magnetic fields
- Magnet technologies
- Describing magnetic fields
- Magnet types in accelerators

Magnets for future colliders:

- Limitations in conventional magnet designs
- Why RT magnets in future colliders?
- New concepts for future colliders taking the example of FCC-ee & CLIC

Acknowledgements

Many thanks …

… to all my colleagues who contributed to this lecture, in particular:

A.Milanese, M.Bohdanowicz (CERN)
for the slides on FCC-ee Dipole and Quadrupole Magnets

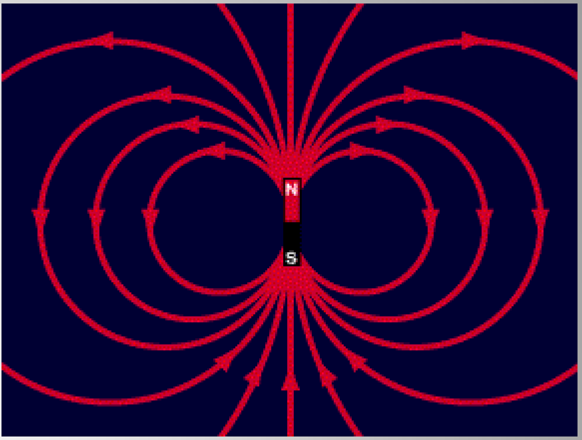
A.Aloev, A.Bartalesi, R.Leuxe, C.Lopez, E.Solodko, M.Struik, P.Thonet, A.Vorozhtsov (CERN)
for the slides on CLIC Main Beam and Final Focusing Magnets

A.Bainbridge, B.Shepherd, N.Collomb, J.Clarke (STFC Daresbury Laboratory, UK)
for the slides on Tuneable Permanent Dipole and Quadrupole Magnets

Magnetic units

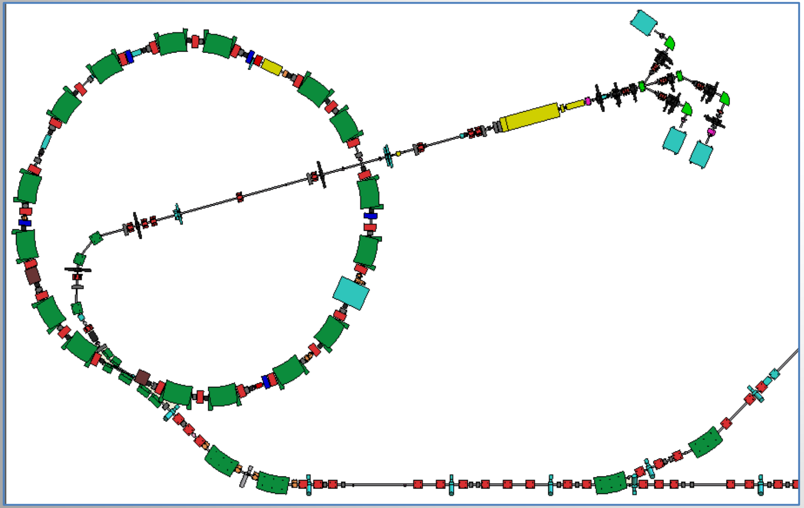
IEEE defines the following units:

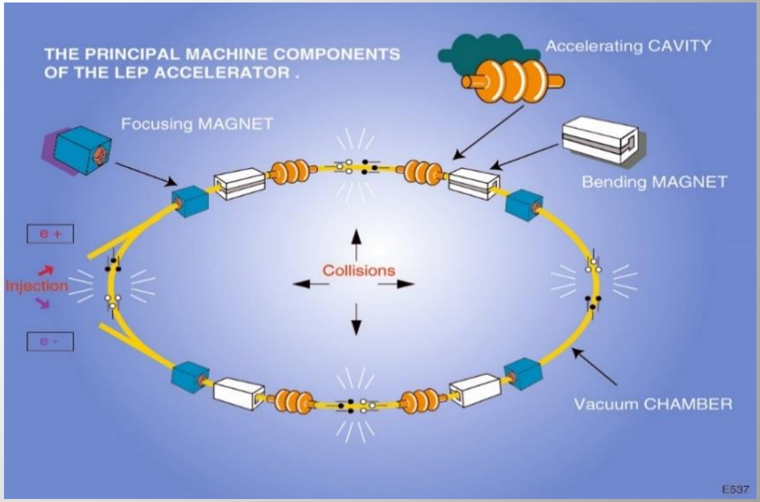
- Magnetic field:
  - H (vector) [A/m]
  - the magnetizing force produced by electric currents
- Electromotive force:
  - e.m.f. or U [V or (kg m^2)/(A s^3)]
  - here: voltage generated by a time varying magnetic field
- Magnetic flux density or magnetic induction:
  - B (vector) [T or kg/(A s^2)]
 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



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(!)

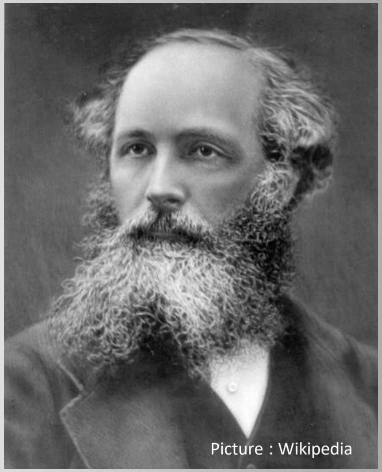




  - Permanent magnets provide only constant magnetic fields
  - Electro-magnets can provide adjustable magnetic fields

Maxwell‘s equations

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


Picture : Wikipedia

Gauss‘ law for electricity:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \qquad \oint_{\partial V} \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$$

Gauss‘ law of flux conservation:

$$\nabla \cdot \vec{B} = 0 \qquad \oint_{\partial V} \vec{B} \cdot d\vec{A} = 0$$

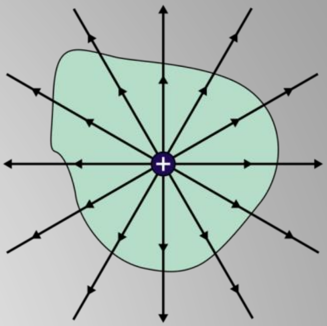
Faraday‘s law of induction:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \oint_{\partial A} \vec{E} \cdot d\vec{s} = -\frac{d\Phi}{dt} = -\frac{d}{dt}\int_A \vec{B} \cdot d\vec{A}$$

Ampere‘s law:

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \qquad \oint_{\partial A} \vec{B} \cdot d\vec{s} = \int_A \mu_0 \vec{J} \cdot d\vec{A} + \frac{d}{dt}\int_A \mu_0 \varepsilon_0 \vec{E} \cdot d\vec{A}$$

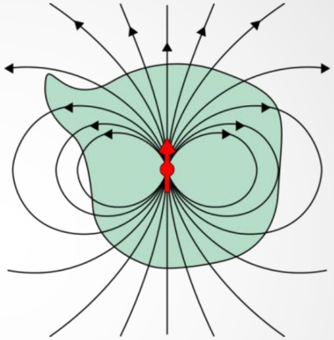
Maxwell‘s equations



Gauss‘ law for electricity:

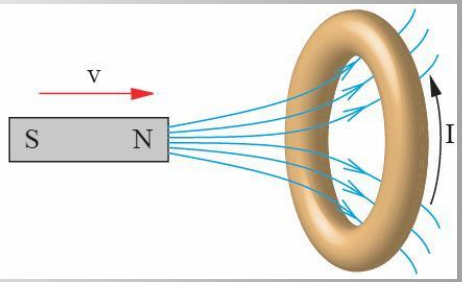
$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

Gauss‘ law of flux conservation:



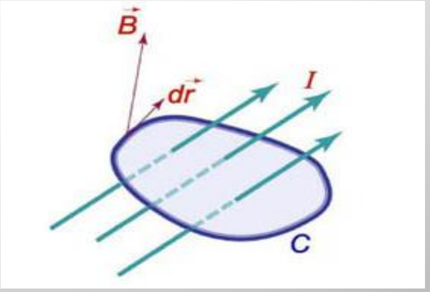
$$\boxed{\nabla \cdot \vec{B} = 0}$$

Faraday‘s law of induction:



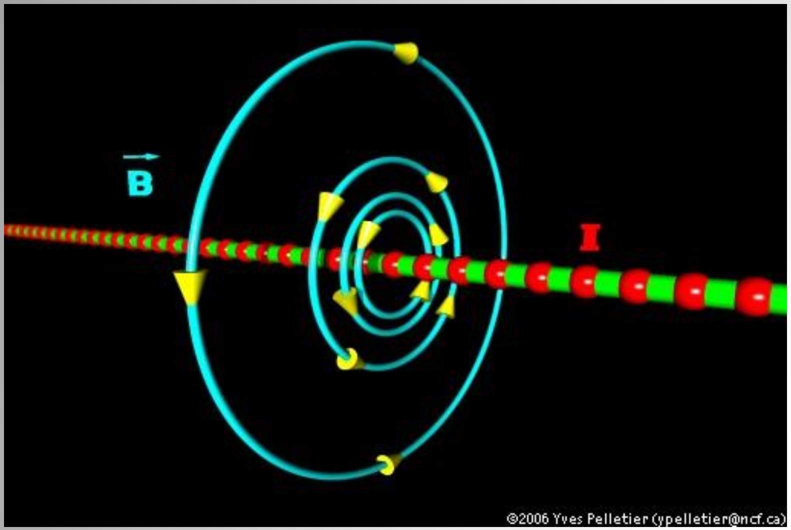
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Ampere‘s law:



$$\boxed{\nabla \times \vec{B} = \mu_0 \vec{J}} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Producing the field



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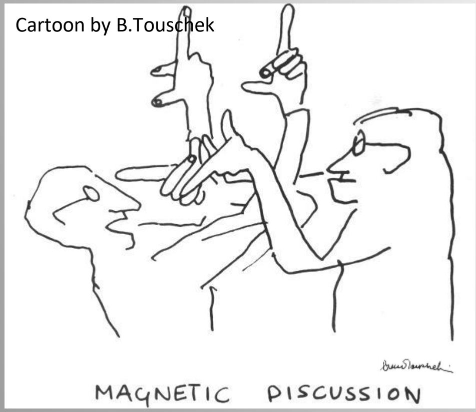
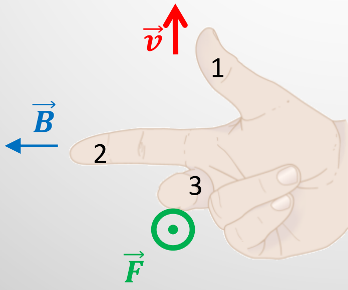
Maxwell & Ampere:

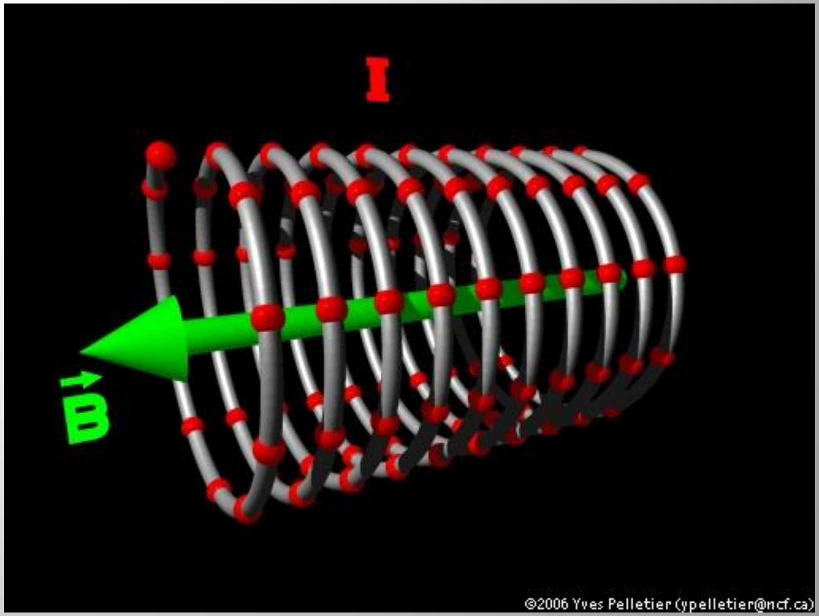
$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

„An electrical current is surrounded by a magnetic field“


Cartoon by B.Touschek



„Right hand rule“ applies



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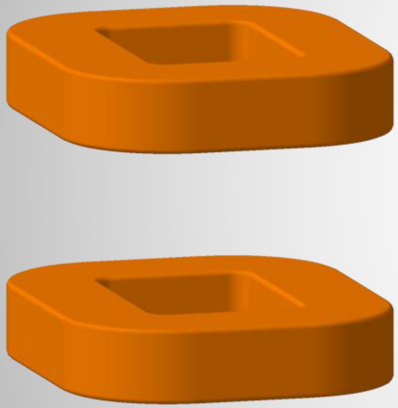
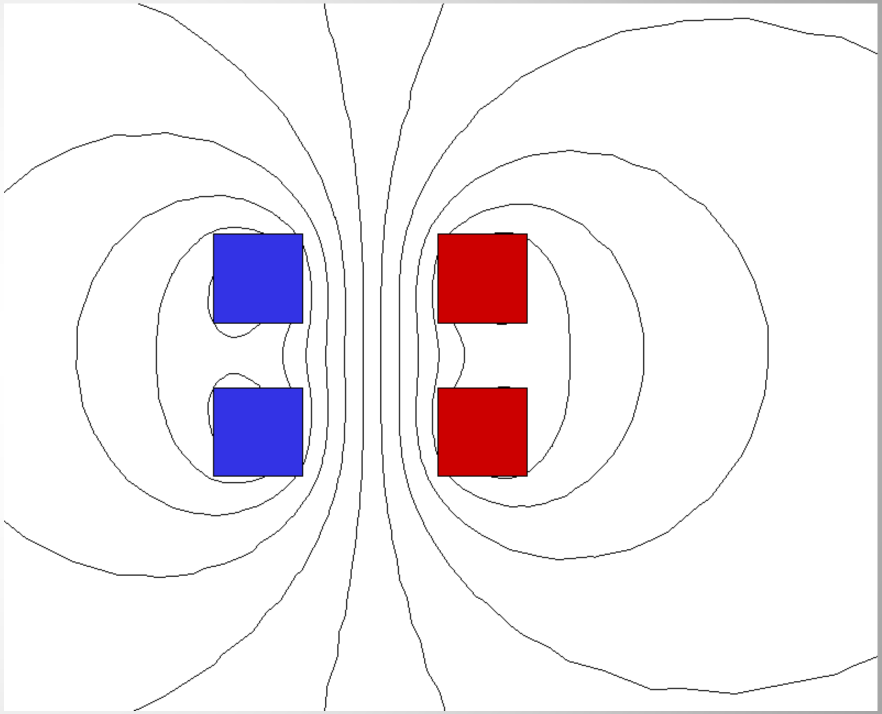
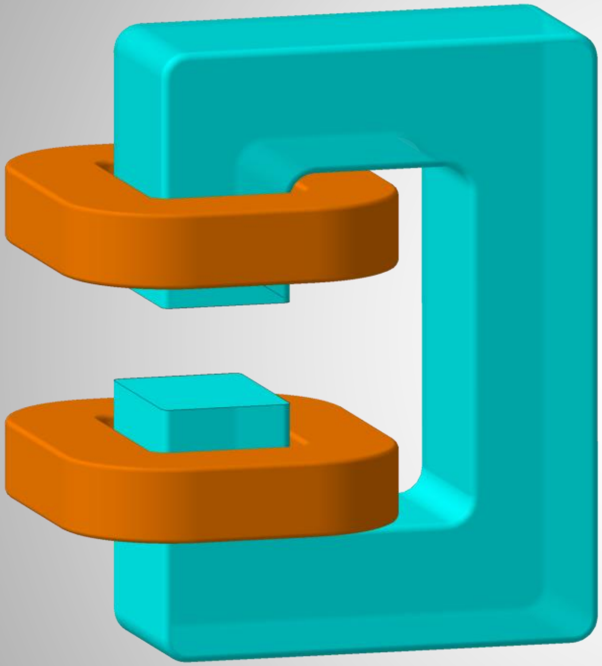
Magnetic circuit

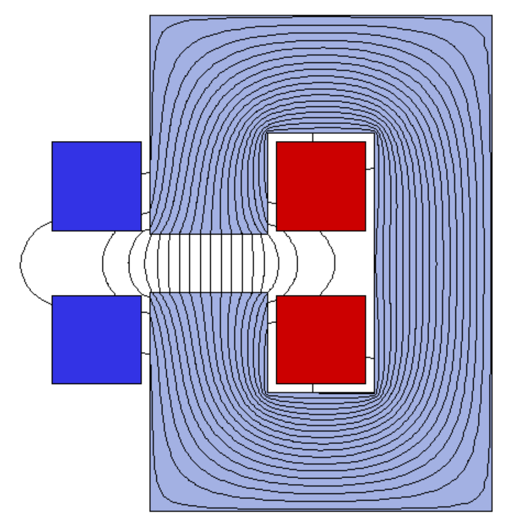




Flux lines represent the magnetic field
Coil colors indicate the current direction

Magnetic circuit





Coils hold the electrical current which induces a magnetic effect

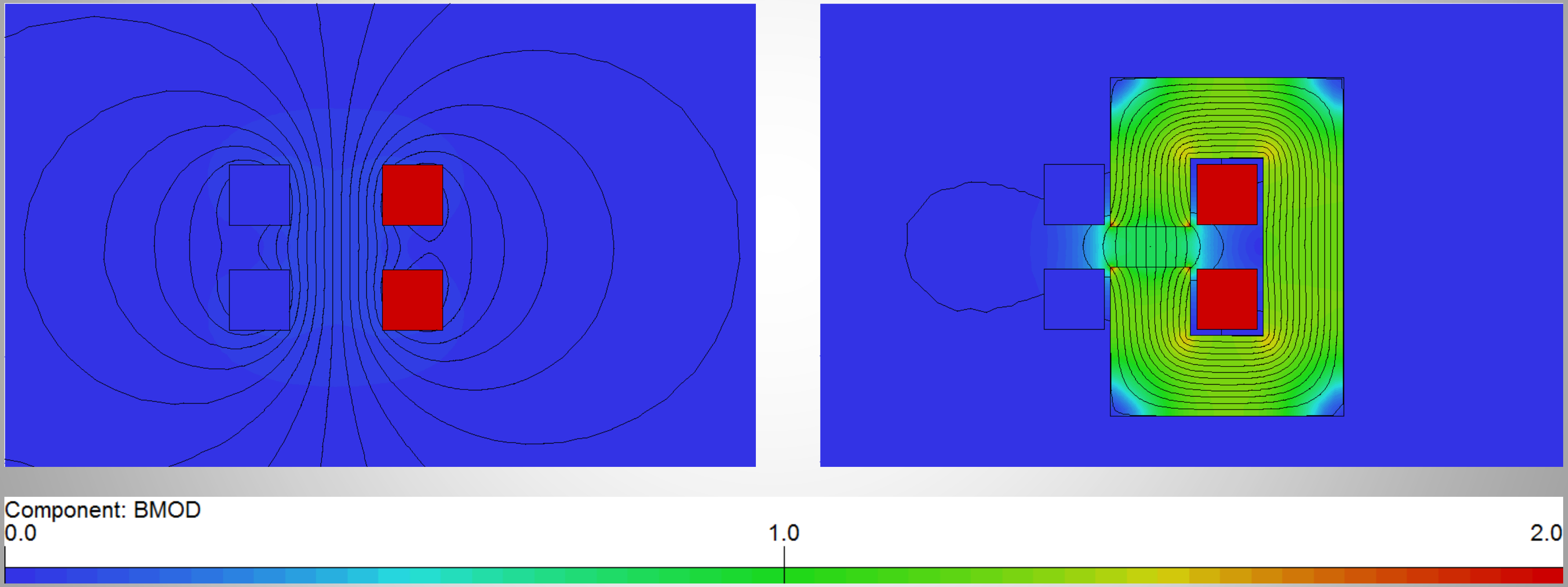
Iron enhance these effects and guides the magnetic flux

→ *"iron-dominated magnet"*

Magnetic circuit

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

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



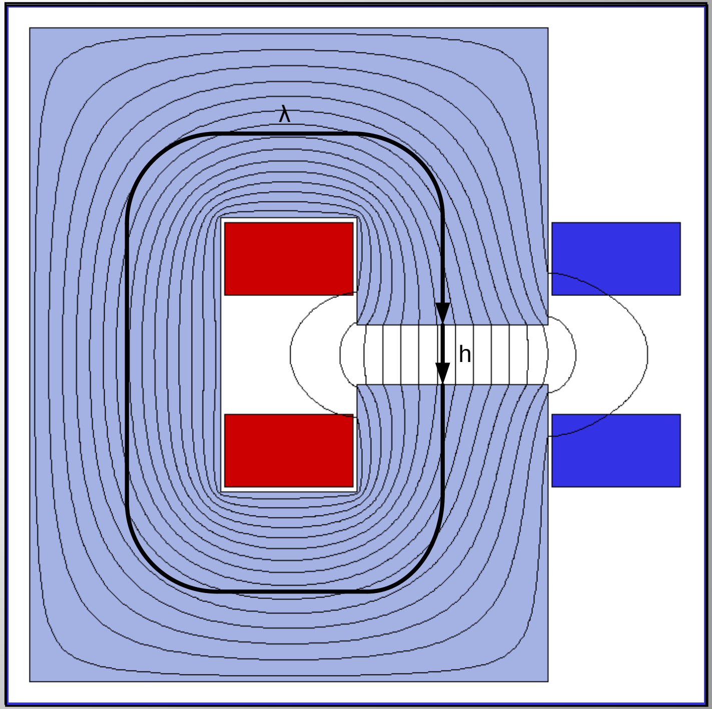
The presence of a magnetic circuit can increase the flux density in the magnet aperture by factors

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

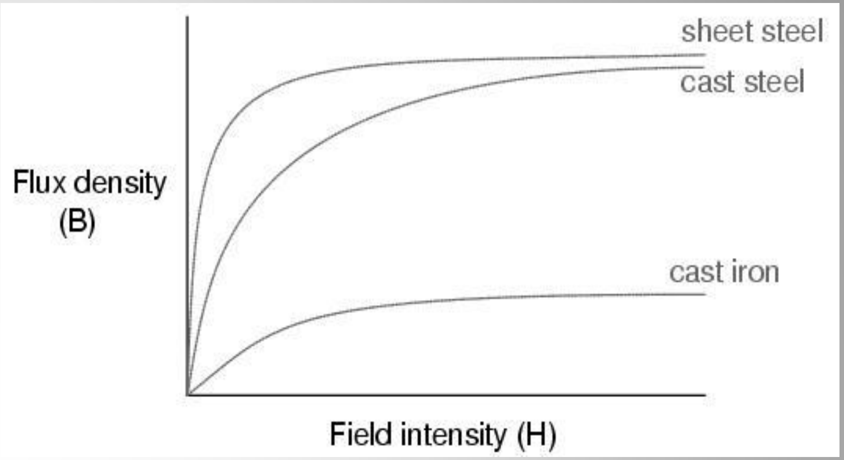
$$\boxed{P_{dip} = \rho\, NI\, j\, l_{avg}}$$

h: gap height [m]
j: current density[A/m^2]
ρ: conductor resistivity [Ωm]
l_{avg}: avg. length of coil [m]

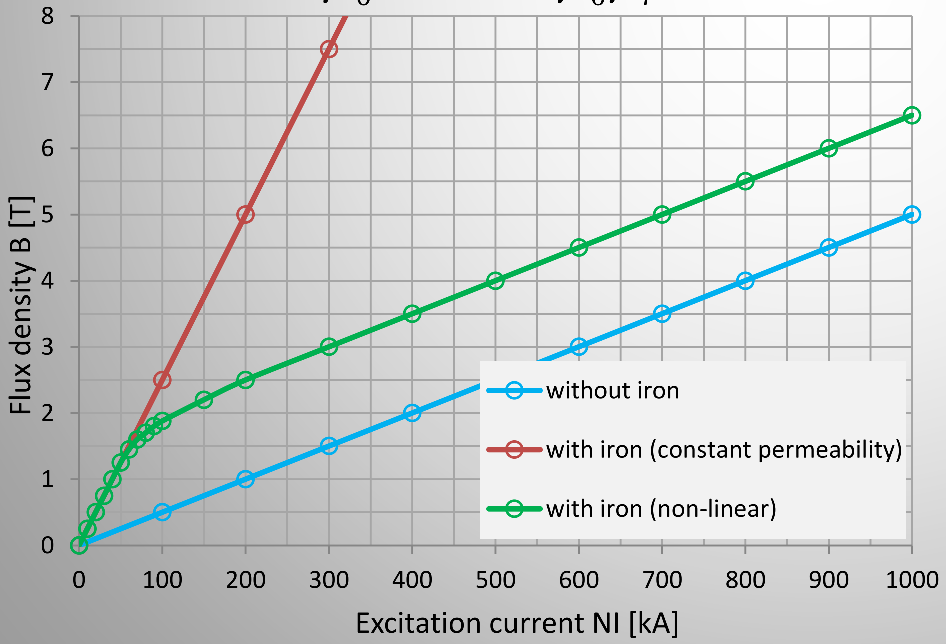
Permeability

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

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

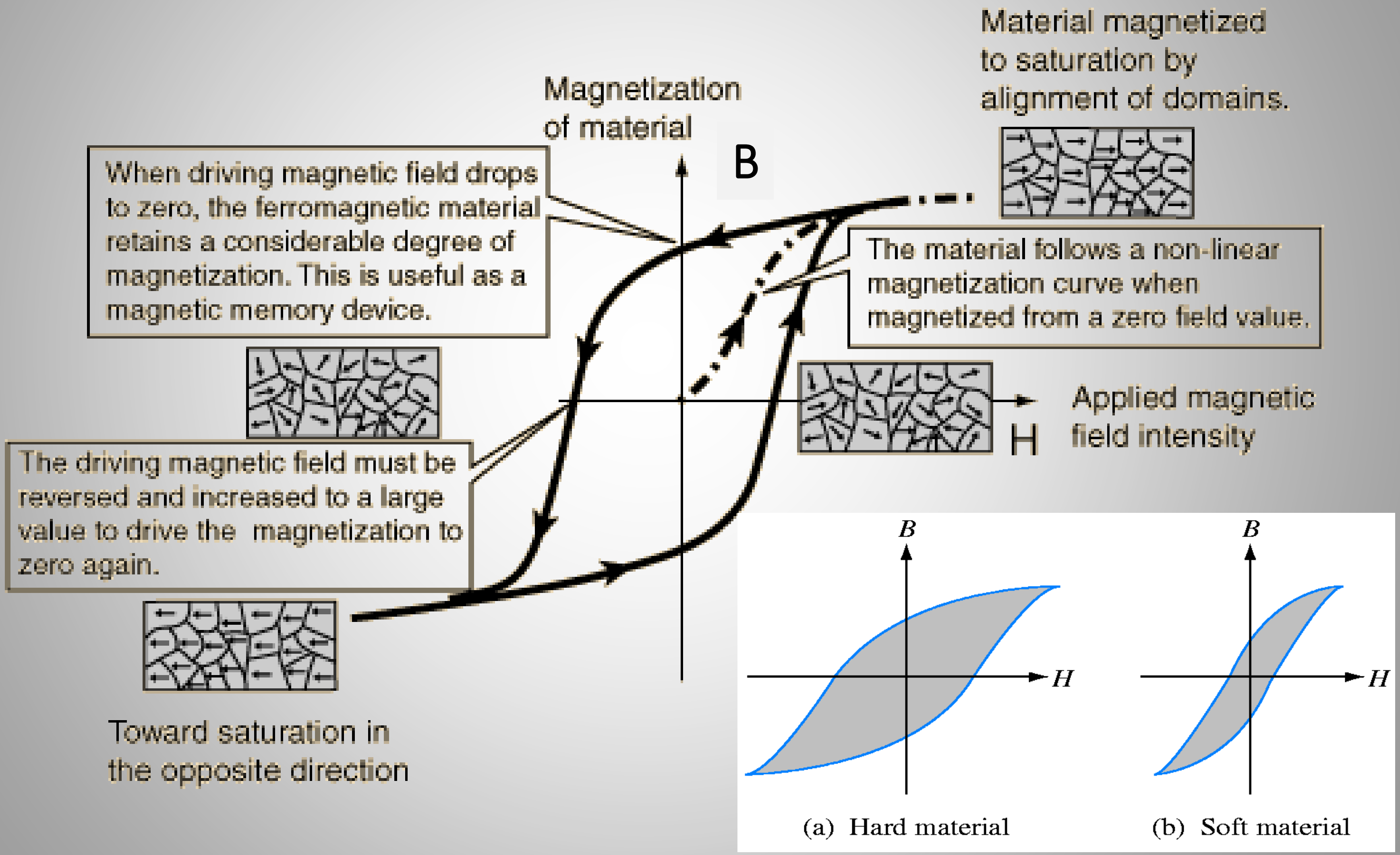


$$\vec{B} = \mu_0\vec{H} + \vec{J} = \mu_0\mu_r\vec{H}$$



Ferro-magnetic materials: high permeability (μ_r>>1), but not constant

Hysteresis & Coercivity



Magnetization of material

Material magnetized to saturation by alignment of domains.

When driving magnetic field drops to zero, the ferromagnetic material retains a considerable degree of magnetization. This is useful as a magnetic memory device.

The material follows a non-linear magnetization curve when magnetized from a zero field value.

Applied magnetic field intensity

The driving magnetic field must be reversed and increased to a large value to drive the magnetization to zero again.

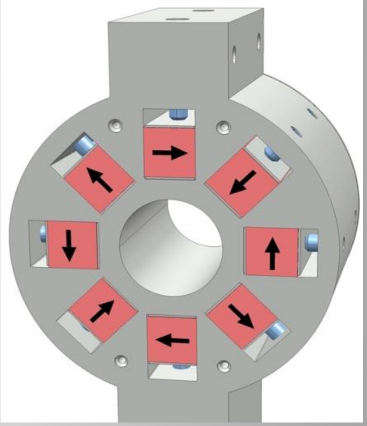
Toward saturation in the opposite direction

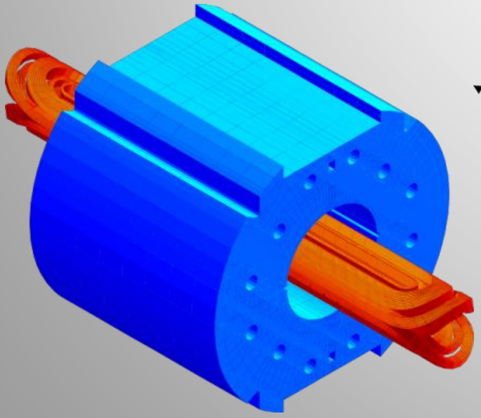
(a) Hard material

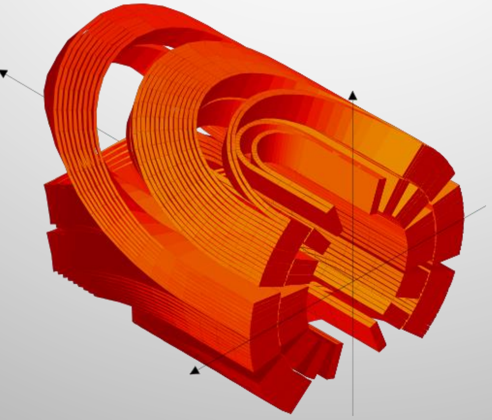
(b) Soft material

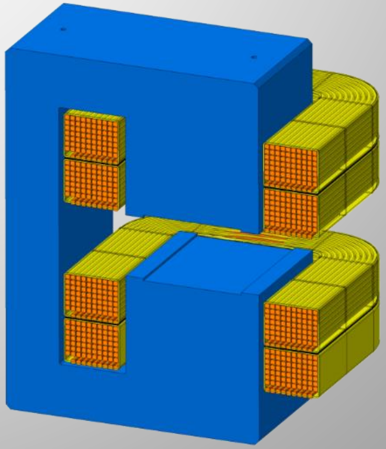
Magnet technologies

- Magnets
  - Electro-magnets
    - Superconducting
      - **Coil dominated** B< 11 T
      - Iron dominated B < 2 T
    - Normal-conducting
      - Coil dominated B < 1 T
      - **Iron dominated** B< 2 T
  - **Permanent magnets**





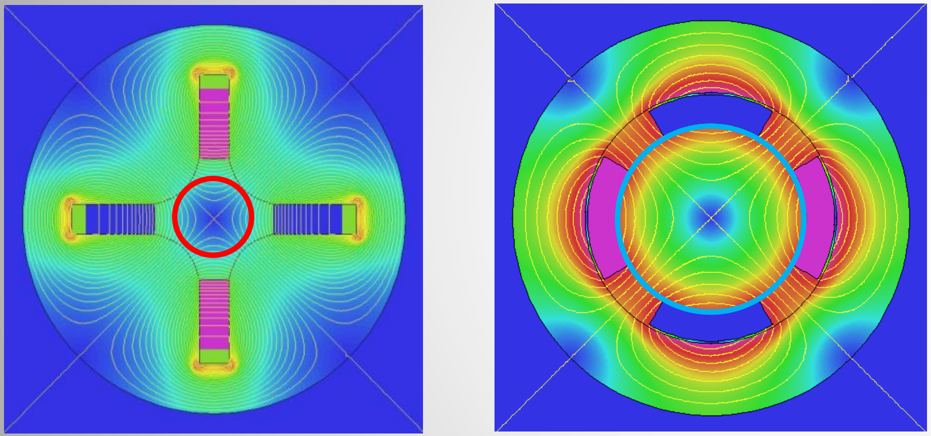


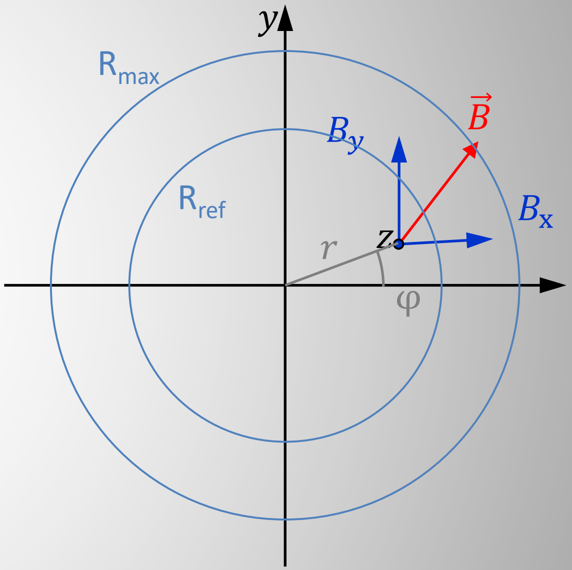


Field description

How can we conveniently describe the field in the aperture?

- at any point (in 2D) $z = x + iy = re^{i\varphi}$
- for any field configuration
- regardless of the magnet technology





Solution: multipole expansion, describing the field within a circle of validity with scalar coefficients

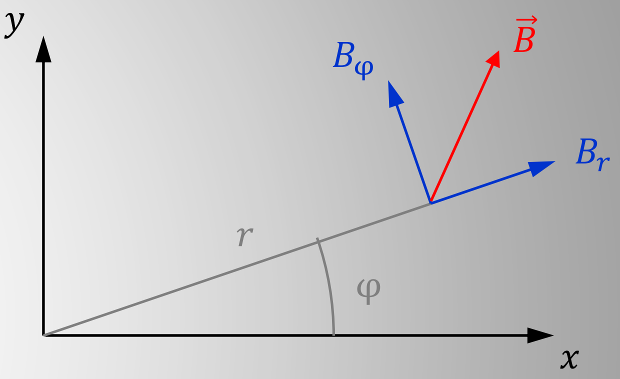
$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R_{ref}} \right)^{n-1}$$

Field description

For radial and tangential components of the field the series contains sin and cos terms (Fourier decomposition):

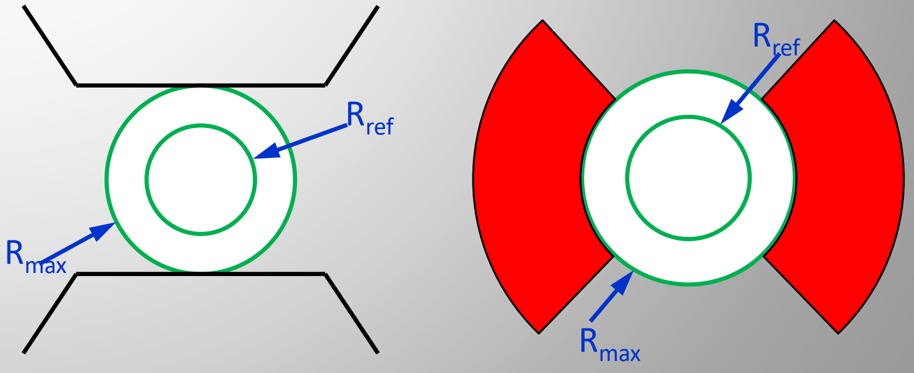
$$B_r(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}}\right)^{n-1} [B_n \sin(n\varphi) + A_n \cos(n\varphi)]$$

$$B_\varphi(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}}\right)^{n-1} [B_n \cos(n\varphi) - A_n \sin(n\varphi)]$$



This 2D decomposition holds only in a region of space:

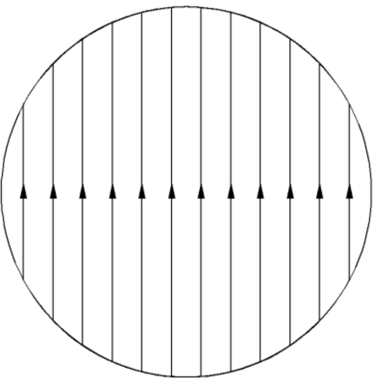
- without magnetic materials ($\mu_r = 1$)
- without currents
- when B_z is constant



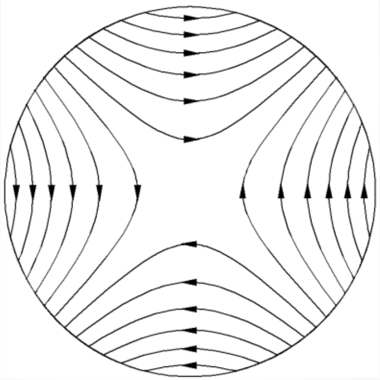
Field description

Each multipole term has a corresponding magnet type:

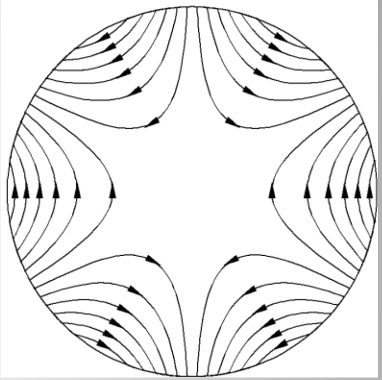
B_1: normal dipole



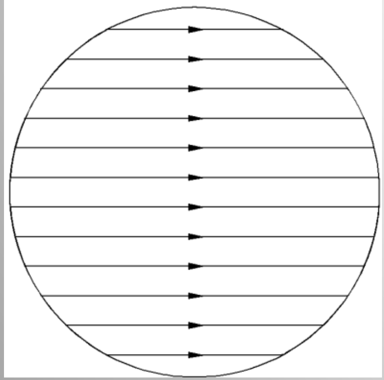
B_2: normal quadrupole



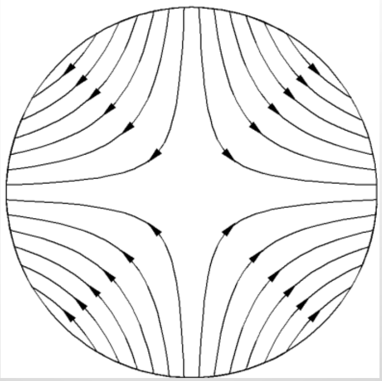
B_3: normal sextupole



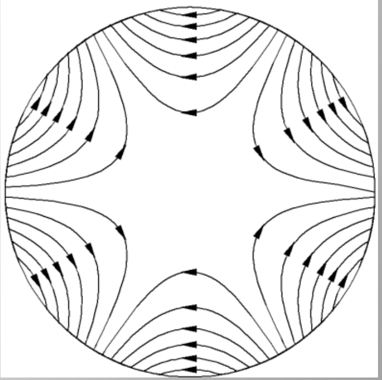
A_1: skew dipole



A_2: skew quadrupole



A_3: skew sextupole



Vector equipotential lines are flux lines. $\vec{B}$ is tangent point by point to the flux lines
Scalar equipotential lines are orthogonal to the vector equipotential lines. They define the boundary conditions for shaping the field (for iron-dominated magnets).

Field quality

Taking

$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R_{ref}}\right)^{n-1}$$

and introducing dimensionless normalized multipole coefficients

$$b_n = \frac{B_\mathrm{n}}{B_\mathrm{N}} 10^4 \quad \text{and} \qquad a_n = \frac{A_n}{B_\mathrm{N}} 10^4$$

with B_N being the fundamental field of a magnet: $B_{\mathrm{N\ (dipole)}}=B_1$; $B_{\mathrm{N\ (quad)}}=B_2$; …

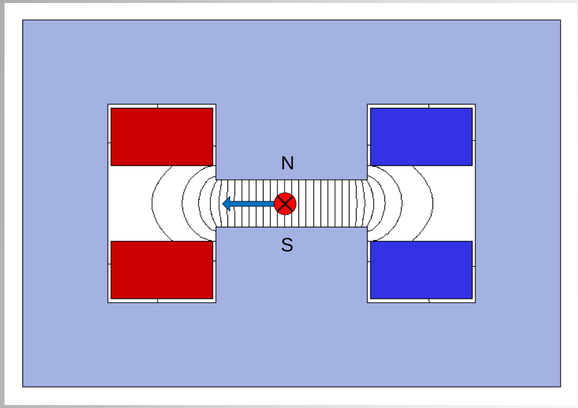
we can describe each magnet by its ideal fundamental field and higher order harmonic distortions:

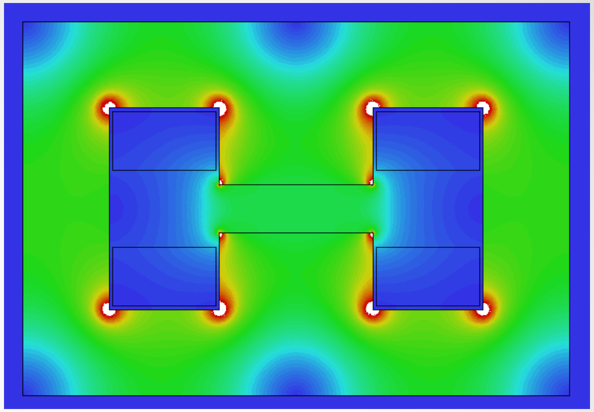
$$B_y(z)+iB_x(z)=\underset{\substack{\uparrow \\ \text{Fundamental field}}}{\frac{B_N}{10^4}}\underbrace{\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{z}{R_{ref}}\right)^{n-1}}_{\text{Harmonic distortions}}$$

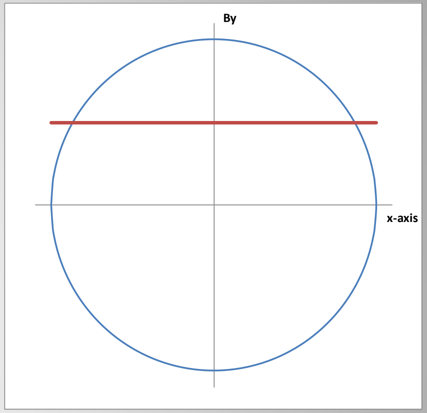
$$\underset{\substack{\uparrow \\ \text{Harmonic distortion factor}}}{F_d} = \sum_{n=1;n\neq N}^{K}\sqrt{b_n^2+a_n^2}$$

Dipole

Purpose: bend or steer the particle beam







Equation for normal (non-skew) ideal (infinite) poles: $y = \pm h/2$

- Straight line ($h =$ gap height)

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

$$B_y(x) = \sum_{n=1}^{\infty} B_n \left(\frac{x}{R_{ref}}\right)^{n-1} = B_1 + B_2 \frac{x}{R_{ref}} + B_3 \left(\frac{x}{R_{ref}}\right)^2 + \cdots$$

Normal-conducting & Permanent Magnets
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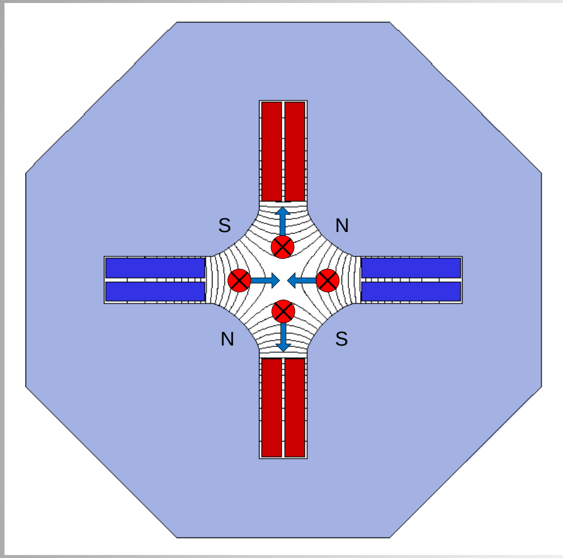
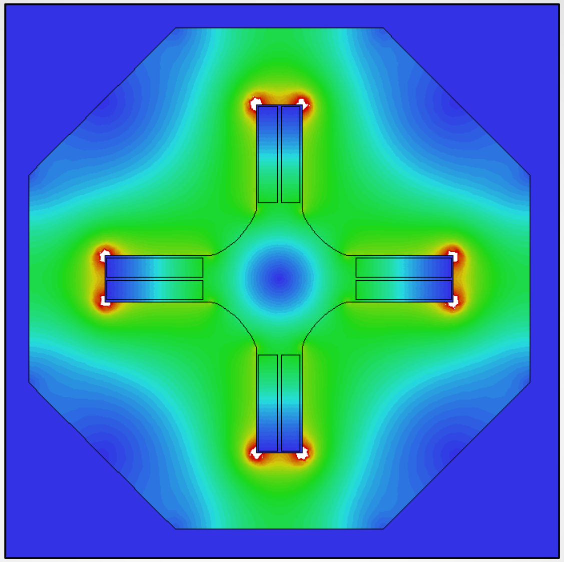
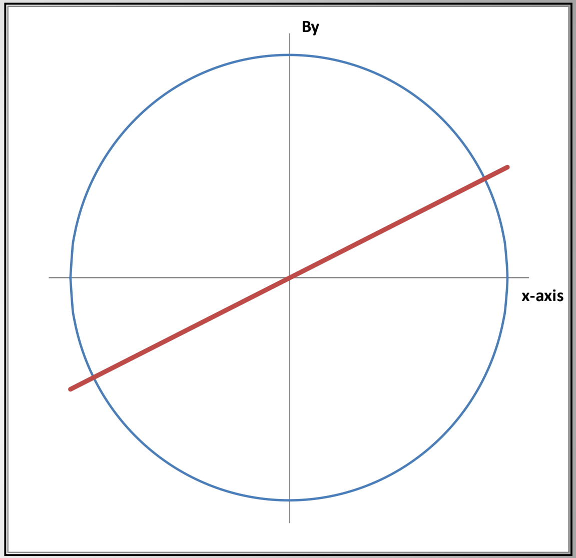
Quadrupole

Purpose: focusing the beam (horizontally focused beam is vertically defocused)







Equation for normal (non-skew) ideal (infinite) poles: $2xy = \pm r^2$

- Hyperbola ($r =$ aperture radius)

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

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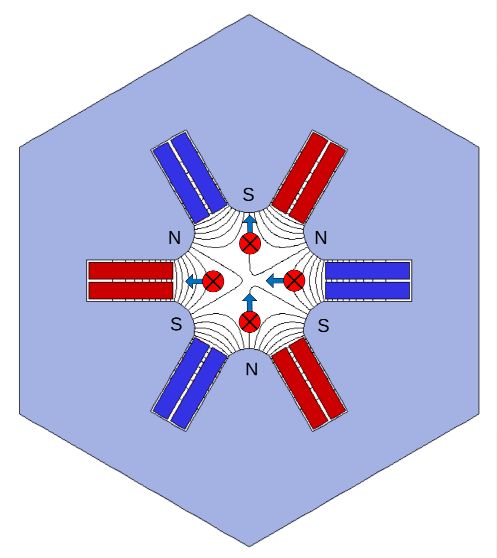
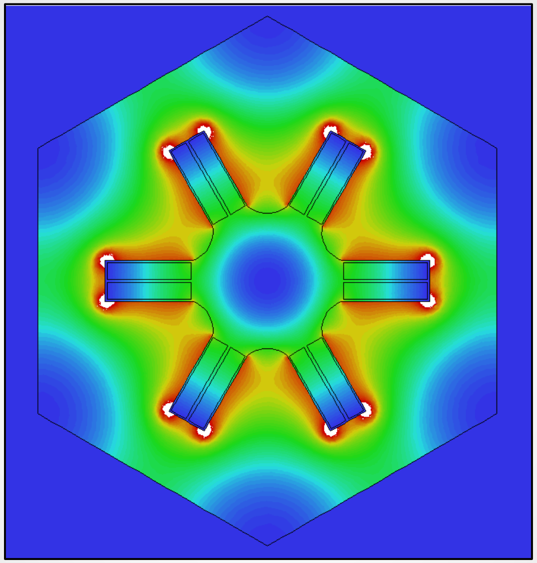
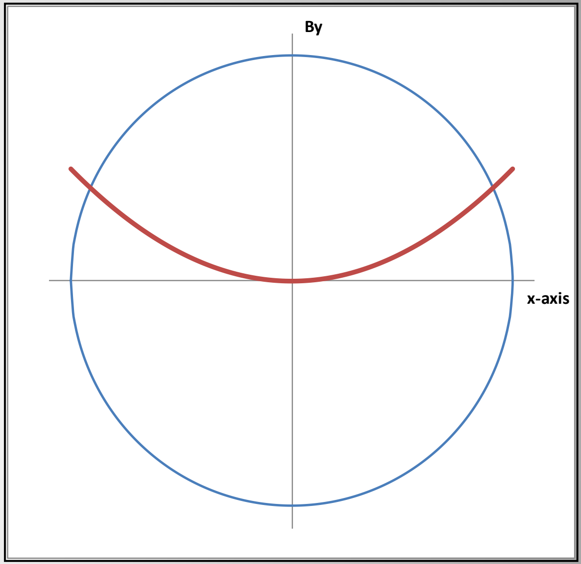
Sextupole

Purpose: correct chromatic aberrations of ‘off-momentum’ particles







Equation for normal (non-skew) ideal (infinite) poles: $3x^2y - y^3 = \pm r^3$

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

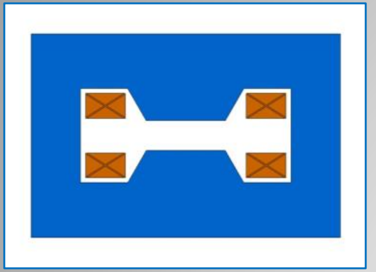
Conventional nc-magnet layout

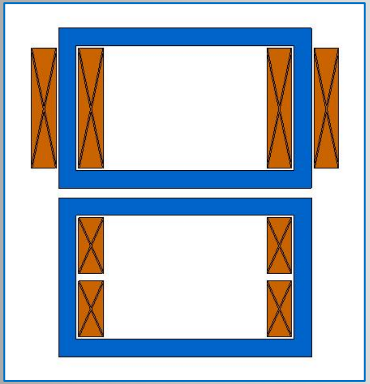
Excitation coils carry the electrical current creating *H*

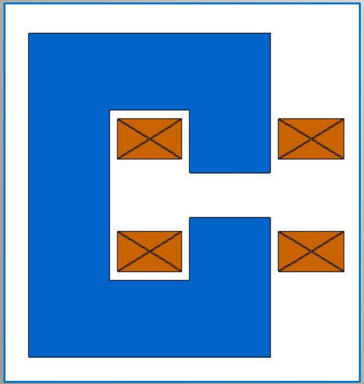
Iron yokes guide and enhance the magnetic flux

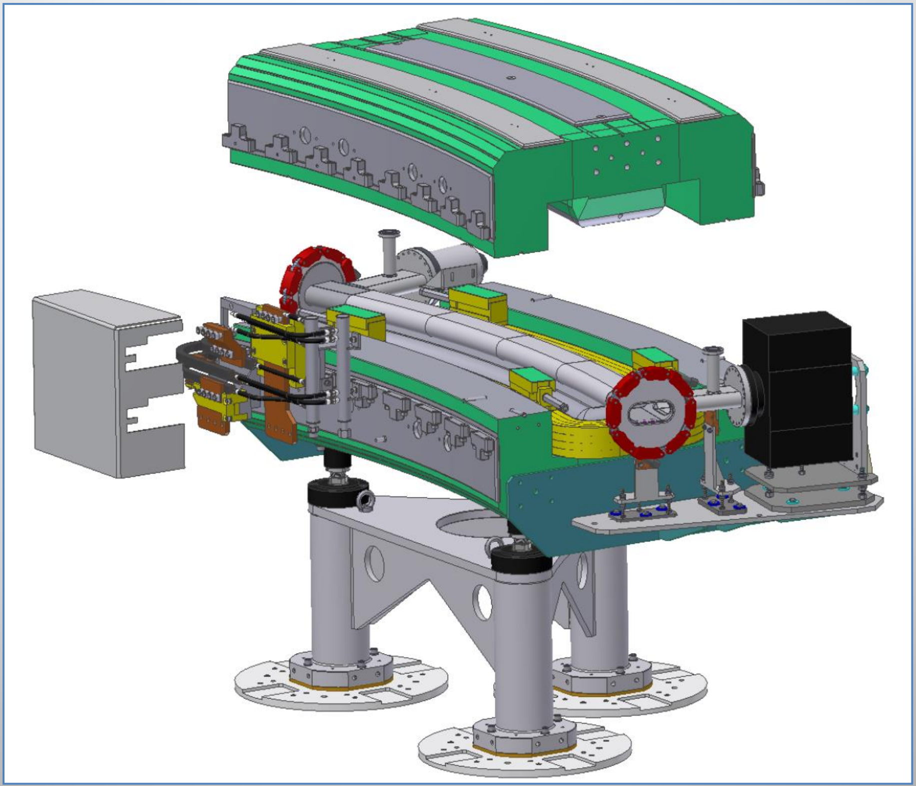
Iron poles shape the magnetic field in the aperture around the particle beam

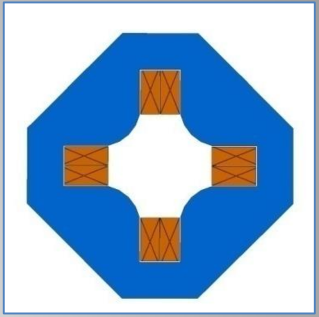
Auxiliaries for cooling, interlock, safety, alignment, ...

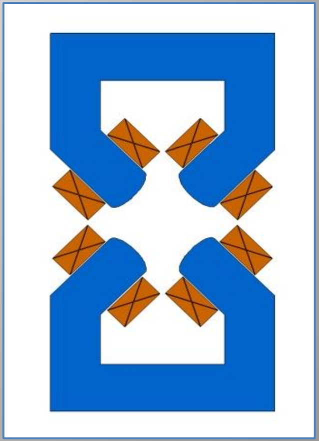




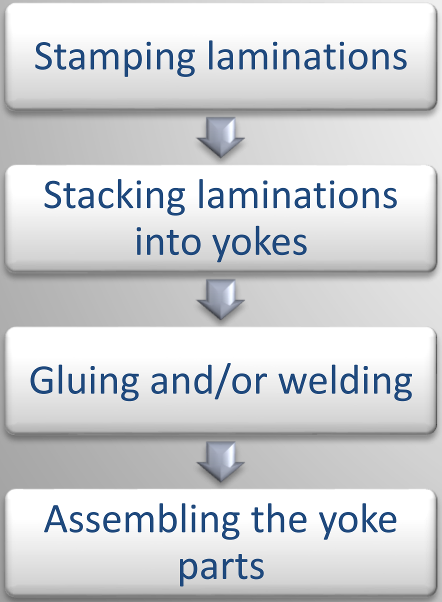








Iron yoke



Stamping laminations

Stacking laminations into yokes

Gluing and/or welding

Assembling the yoke parts

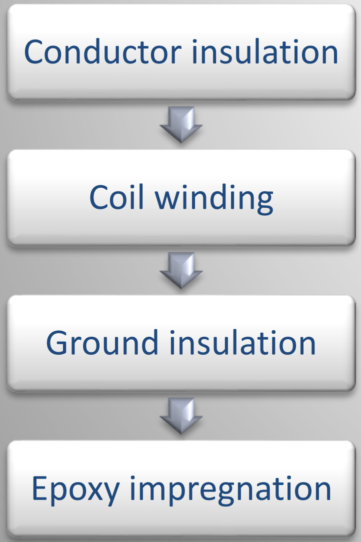
Advantages:

- Well established technology with plenty of experience
- Robust design
- Industrial methods for large series
- Different magnetic materials on the market
- Steel properties are adjustable within a certain range
- Good reproducibility

Limitations:

- Fields limited to 2 T (saturation)
- Field quality dependent on mechanics (machining, assembly)
- Small apertures more sensitive (small tolerances)
- dB/dt limited by eddy current effects
- Steel hysteresis requires magnetic cycling

Excitation coils



Conductor insulation

Coil winding

Ground insulation

Epoxy impregnation

Advantages:

- Adjustable magnetic fields
- Well established technology
- Easy accessible and maintainable
- (Almost) no limit in dB/dt
- Conductor commercially available

Limitations:

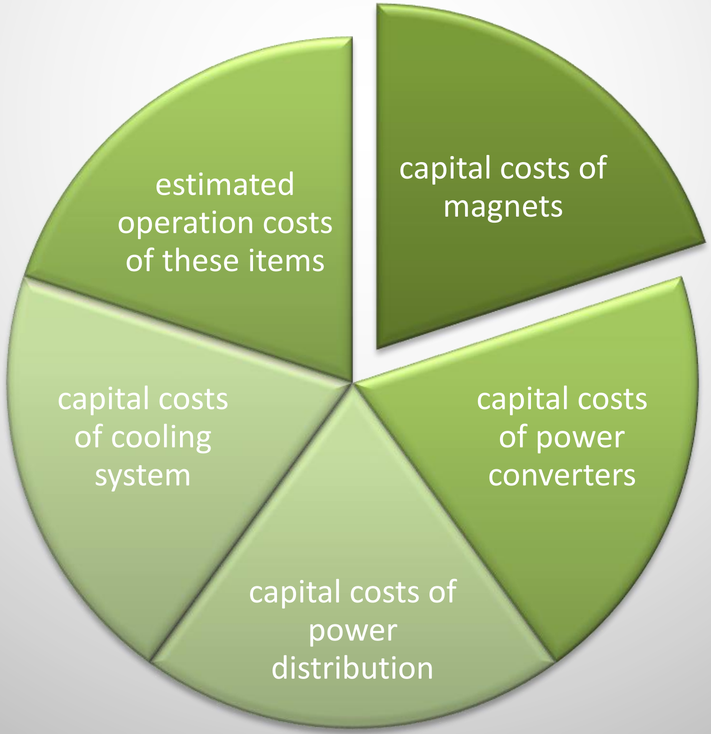
- Power consumption (ohmic losses)
- Moderate current densities ($j < 10$ A/mm^2)
- (Water) cooling required for $j > 2$ A/mm^2
- Insulation lifetime (ionizing radiation)
- Reliability of cooling circuits (water leaks)
- Increase the magnet dimensions

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:



capital costs of magnets

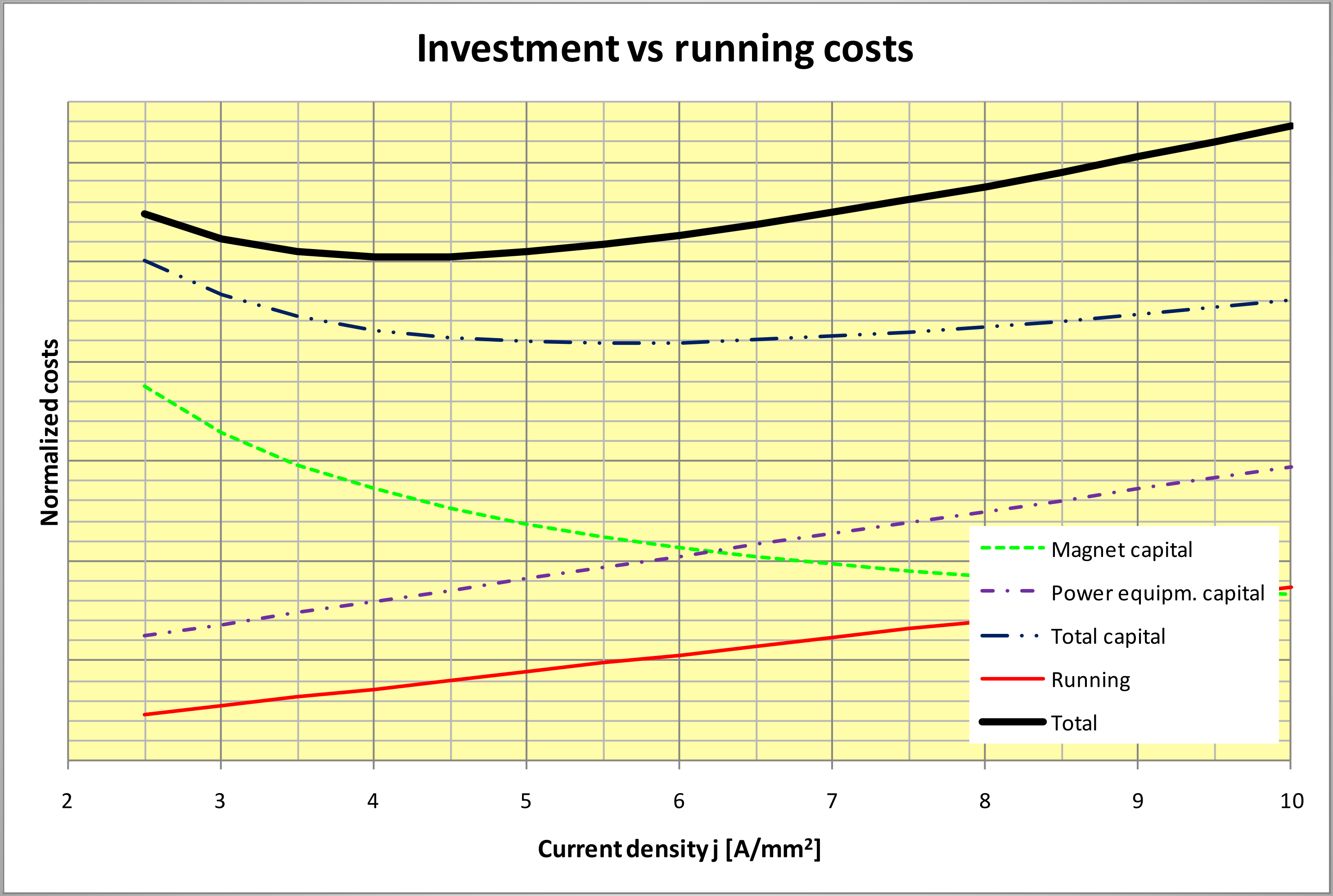
capital costs of power converters

capital costs of power distribution

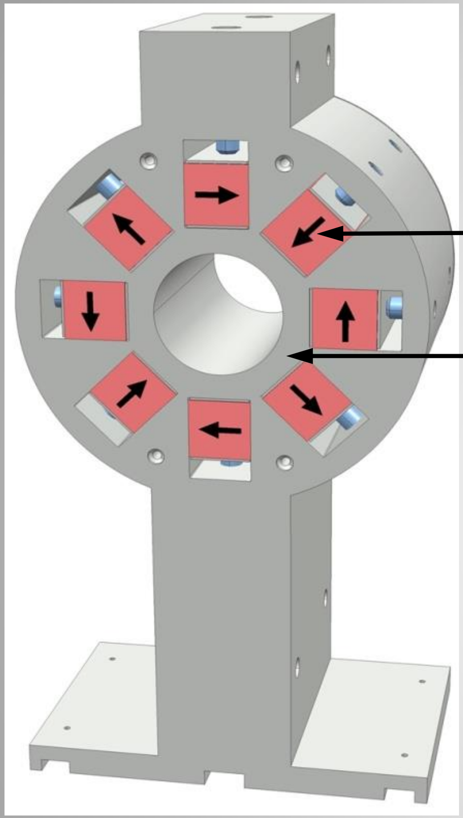
capital costs of cooling system

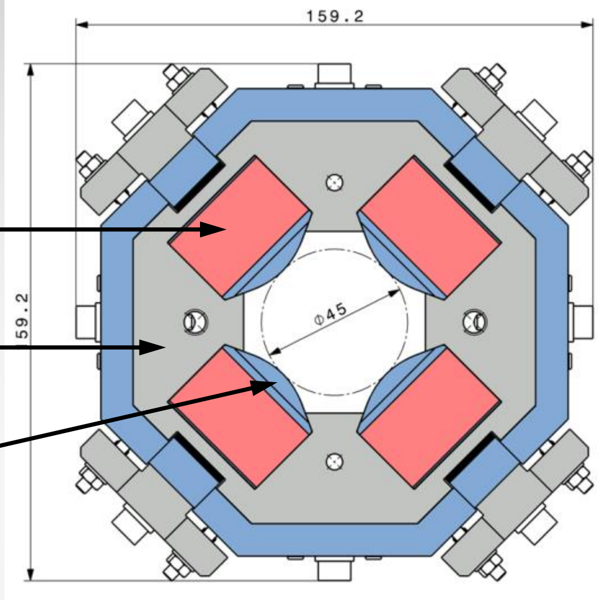
estimated operation costs of these items

Cost optimization



Conventional PM layout





Permanent magnets
(e.g. Sm_2Co_{17})

Non-magnetic yoke
(e.g. austenitic steel 316LN)

Magnetic poles
(e.g. low-carbon steel)

$Nd_2Fe_{14}B$	***$SmCo_5$ or Sm_2Co_{17})***
Typical B_r≈1.4 T	Typical B_r≈1.2 T
Temp. coef. of B_r = -0.11%/°C	Temp. coef. of B_r = -0.03%/°C
Poor corrosion resistance	Good corrosion/radiation resistance

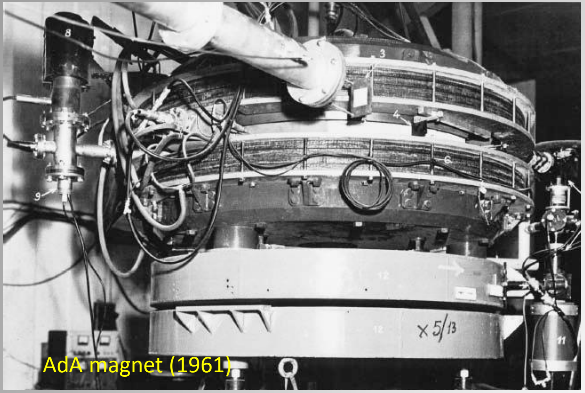
Advantages:

- No electrical power consumption
- No powering/cooling network required
- More compact for small magnets
- No coil heads / small fringe field
- Reliable: no risk of insulation failure or water leaks

Limitations:

- Produce constant fields only
- Complex mechanics when tuneability required
- Risk of radiation damage (→ use of Sm_2Co_{17})
- Sensible to ΔT (→ can be compensated)

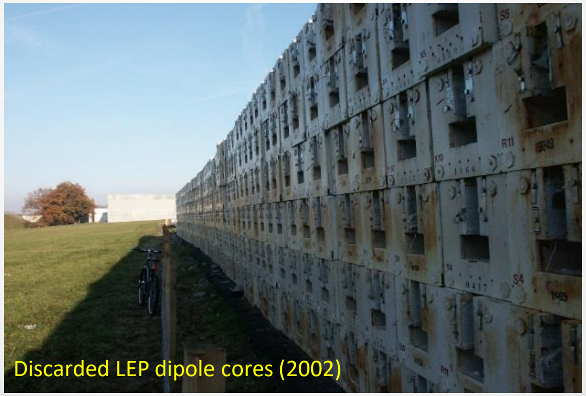
A few examples…

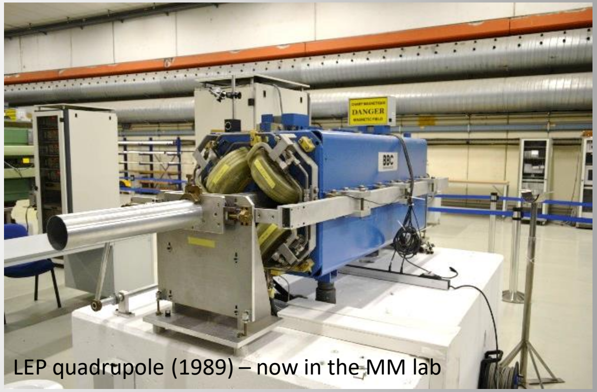

AdA magnet (1961)


ISR dipole (1971) – now in the MM lab

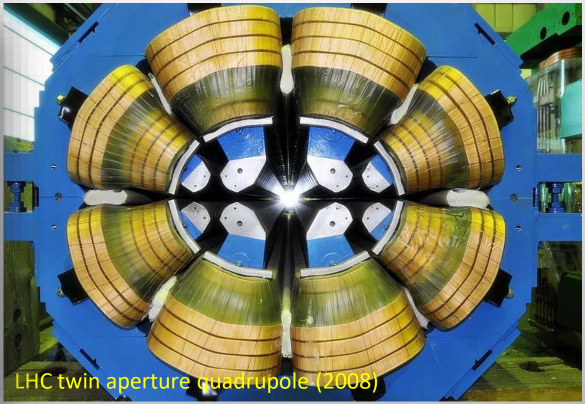

SPS dipoles before installation (1981)


SPS quadrupoles before installation (1981)


Discarded LEP dipole cores (2002)

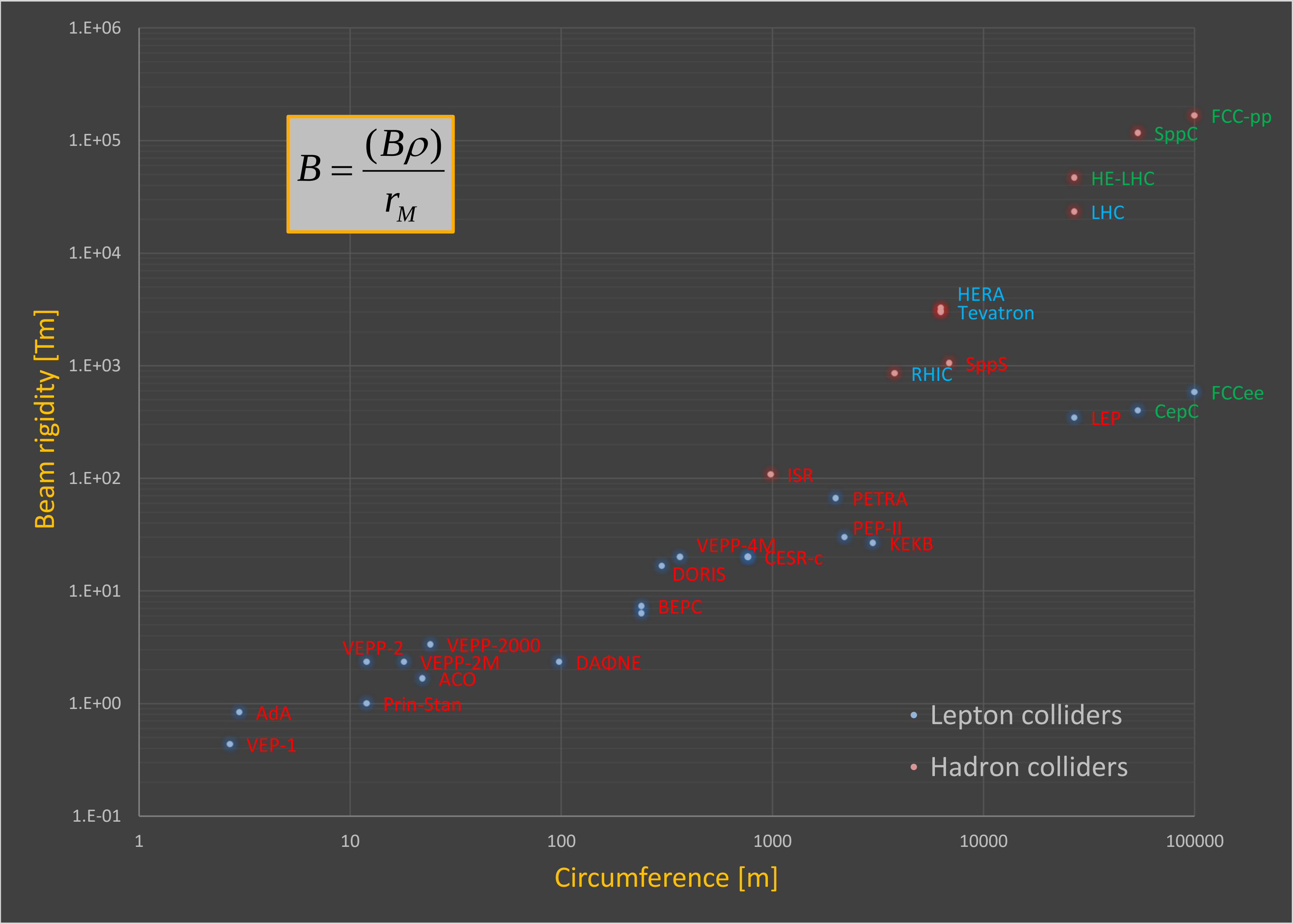

LEP quadrupole (1989) – now in the MM lab


LHC Lambertson Septum (2008)


LHC twin aperture quadrupole (2008)


Future collider magnet (20xx)

Circular Colliders



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

Challenges of future colliders

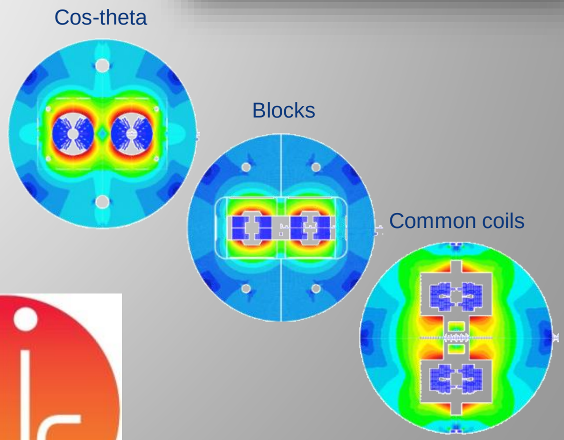
Future collider projects bear a number of financial and technological challenges in general, but also in particular for magnets …

Large scale machines:
- Investment cost: material, production, transport, installation
- Operation costs: low power consumption & cooling
- Reliability & availability: see presentation *M. Zerlauth*
- Logistics: installation, maintenance & service distribution

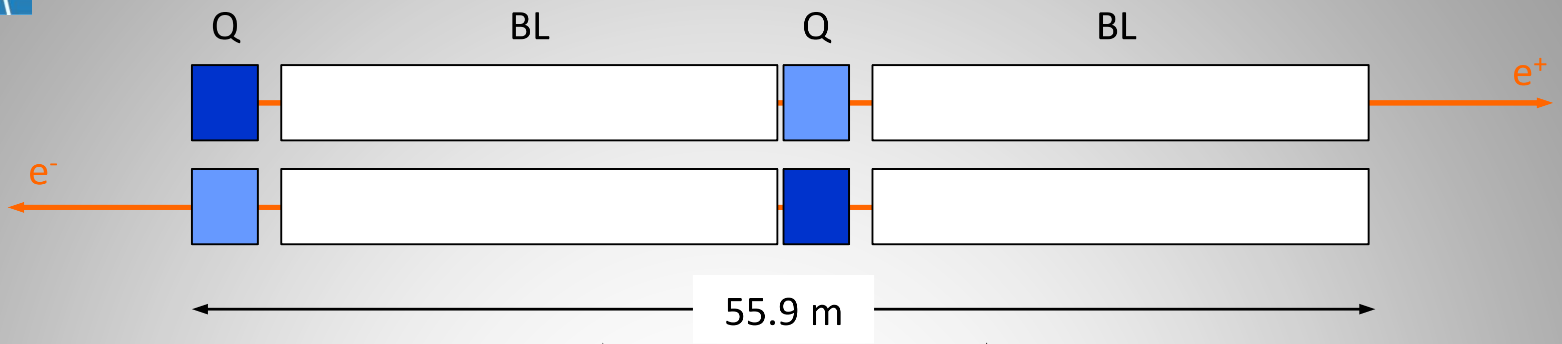
High energy beams and intensities:
- Ionizing radiation impact on materials and electronics

Hadron colliders:
- High magnetic fields: SC magnets, see presentation *L. Bottura*

Lepton colliders: (circular & linear)
- Alignment & stabilization: see presentation *D. Missiaen*
- Compact design & small apertures



Magnet system for FCC-ee



Double collider

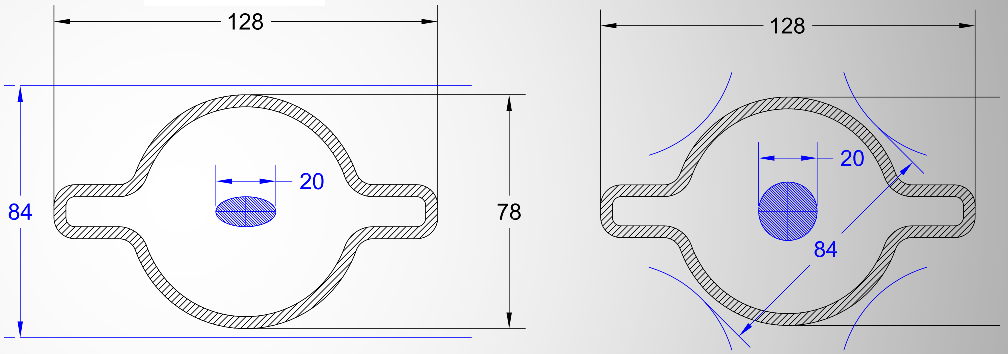
Counter-rotating e+ / e- beams

DC operation with top-up injection

1450 FODO cells (each 55.9 m long)

Tuneability ±1%

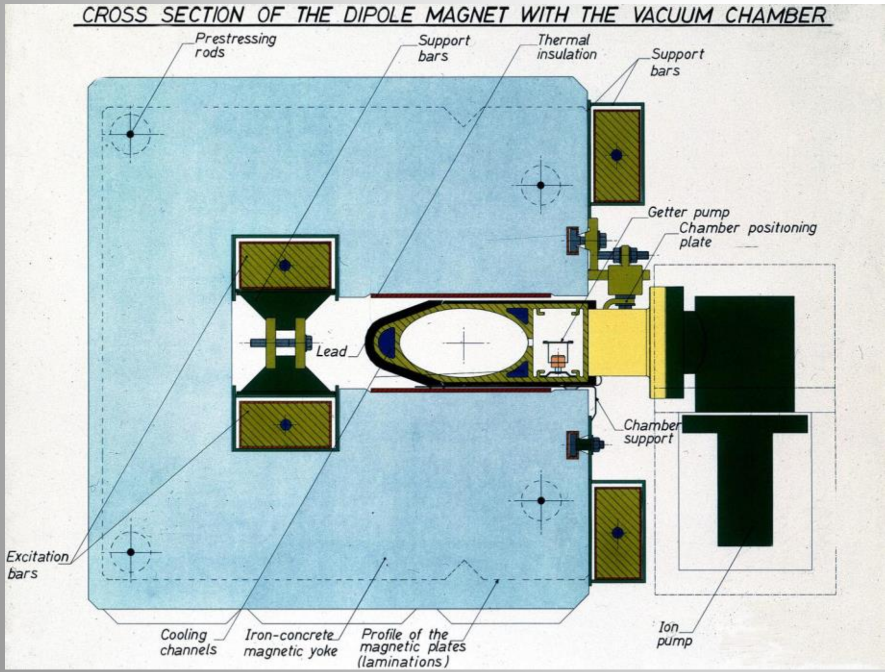
Low-field magnets

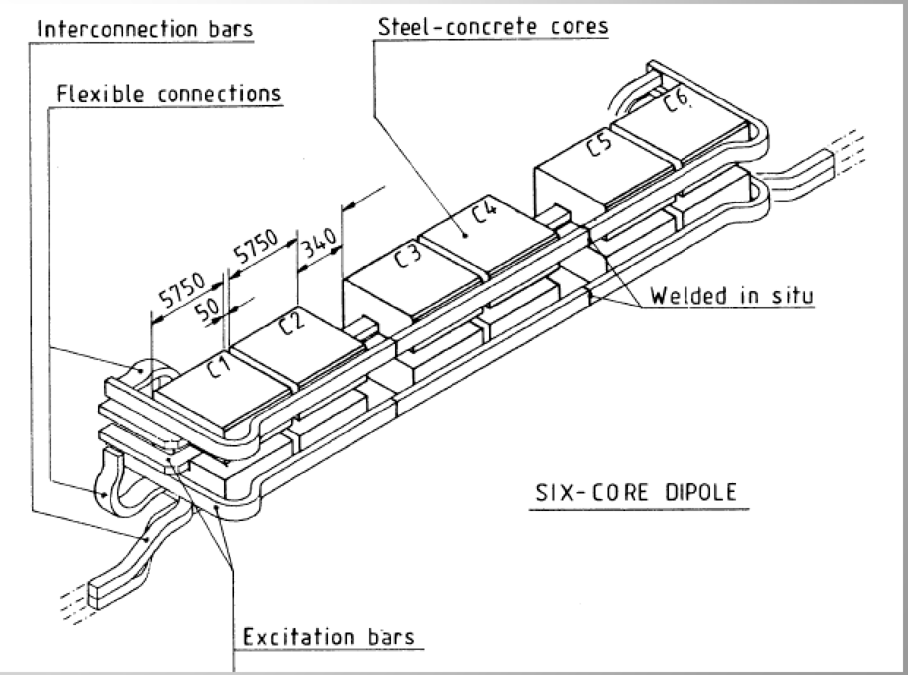


Parameter	**Bending magnets**	**Quadrupole magnets**
Quantity (per ring)	2900	1450 + 1450
Magnetic length	23.94 (21.94) m	3.1 m
Aperture	128 mm x 84 mm	R = 42 mm
Inter-beam distance	300 mm	300 mm
Field / max. gradient at 175 GeV	54.3 mT	9.9 T/m
Goof field region	±10 mm horizontal	R = 10 mm
Field quality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

Recap: LEP dipoles

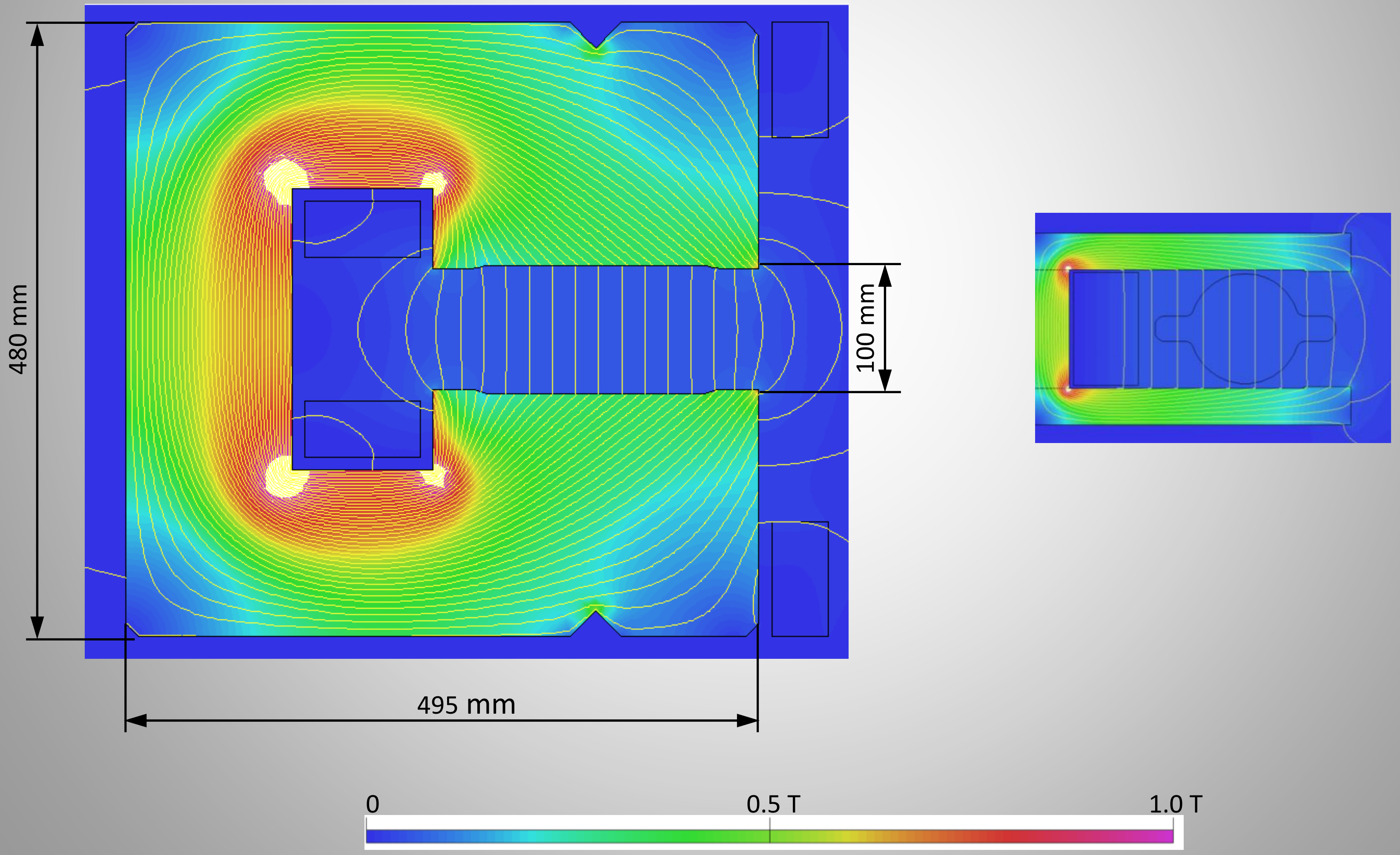
- Cycled field: 22 mT (20 GeV injection) to 108 mT (100 GeV)
- 5.75 m long ‘diluted’ magnet cores: 30% Fe / 70% concrete
- Four water cooled aluminium excitation bars
- Max. current: 4.5 kA



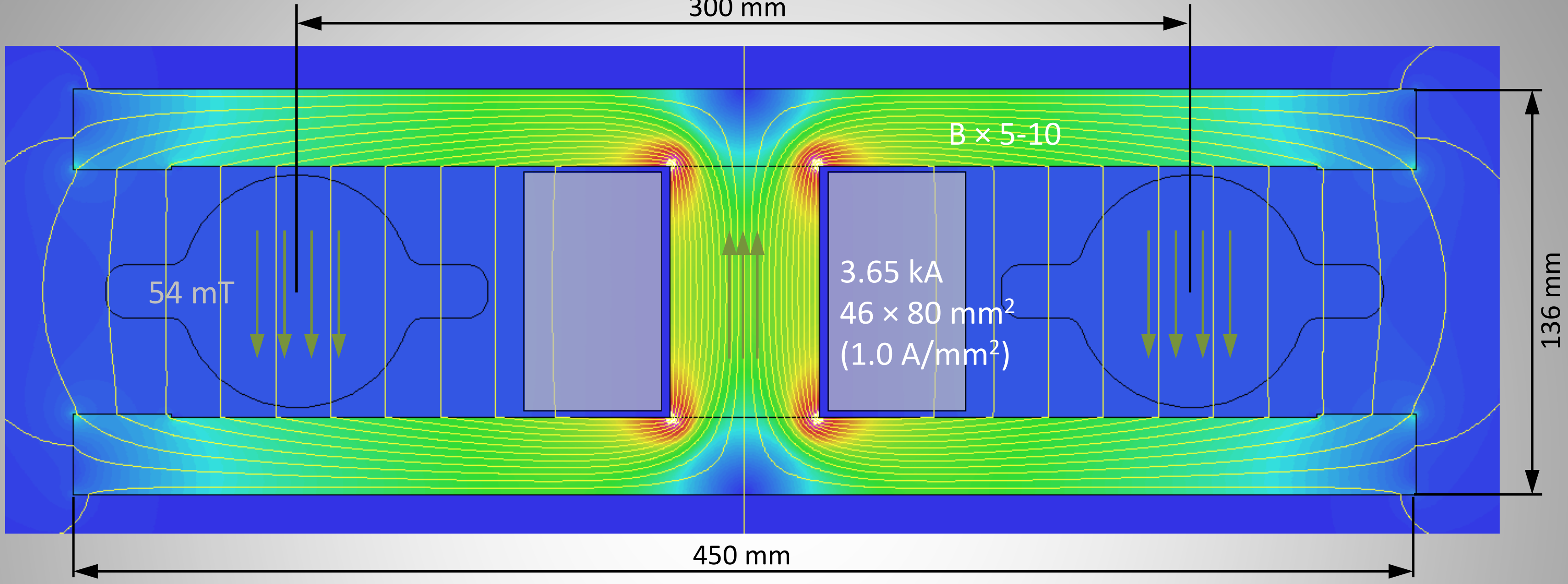


Recap: LEP dipoles

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

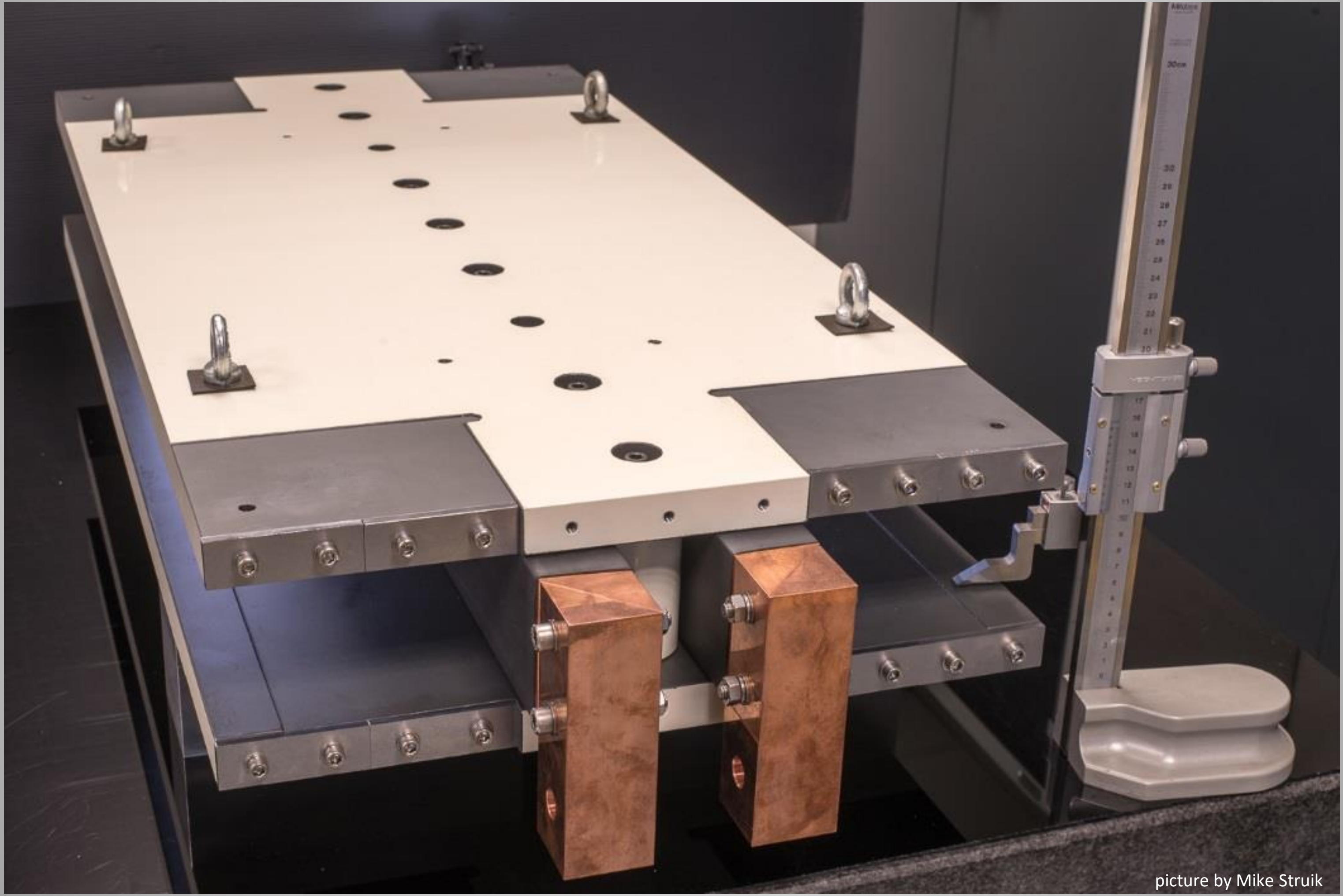


FCC-ee Twin dipole design



- Energy saving: Ampere-turns recycled → 50% power consumption (16 MW)
- Cost saving: 50% less units to manufacture, transport, install, align
- Simple: few components
  - Simple yoke design: thick laminations (5-6 mm) without dilution (easier recycling)
  - Simple coil layout: low coil 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
- Flexible: can be easily adapted for a combined-function design

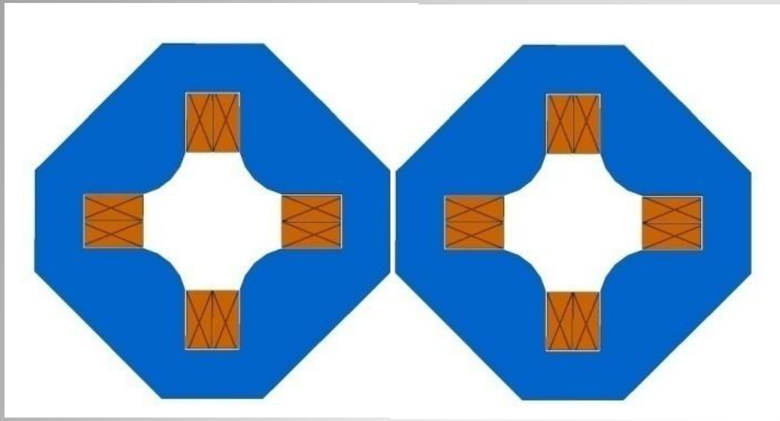
FCC-ee Twin dipole prototype



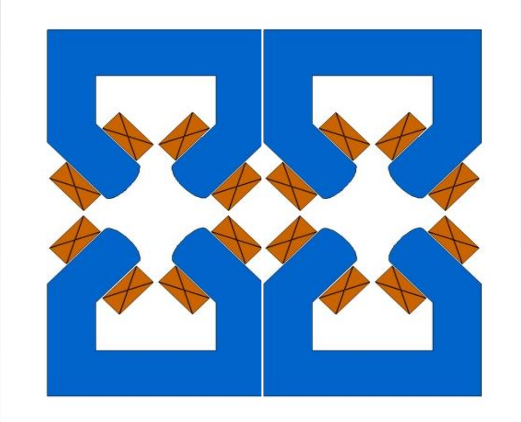
picture by Mike Struik

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)

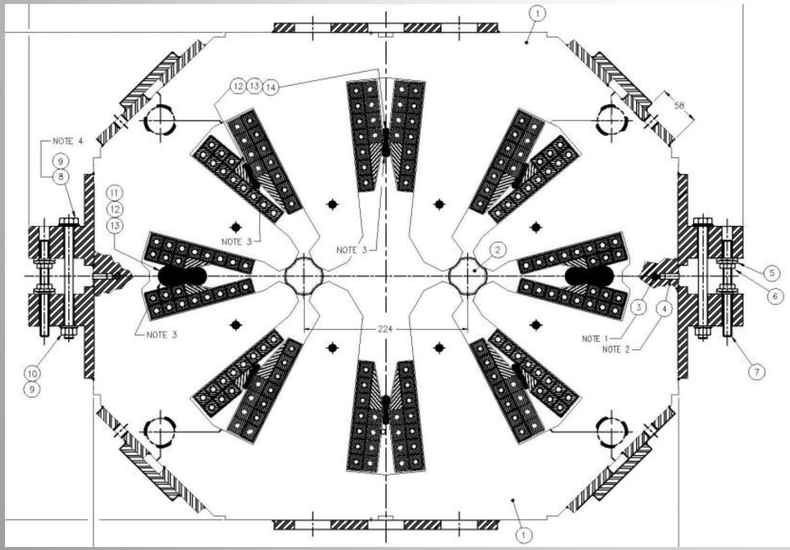
Recap: LHC twin-aperture quad



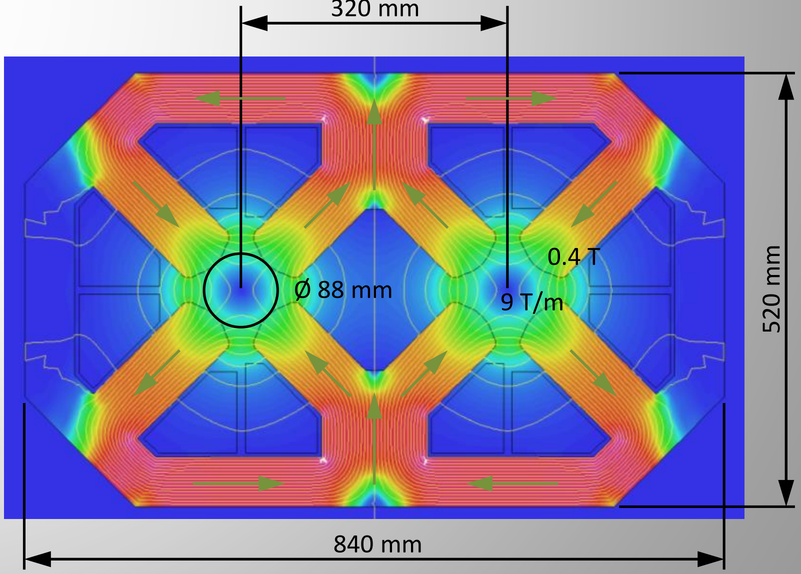
Two-beam layout with separated quadrupoles



Reduced inter-beam distance with Collins quadrupoles



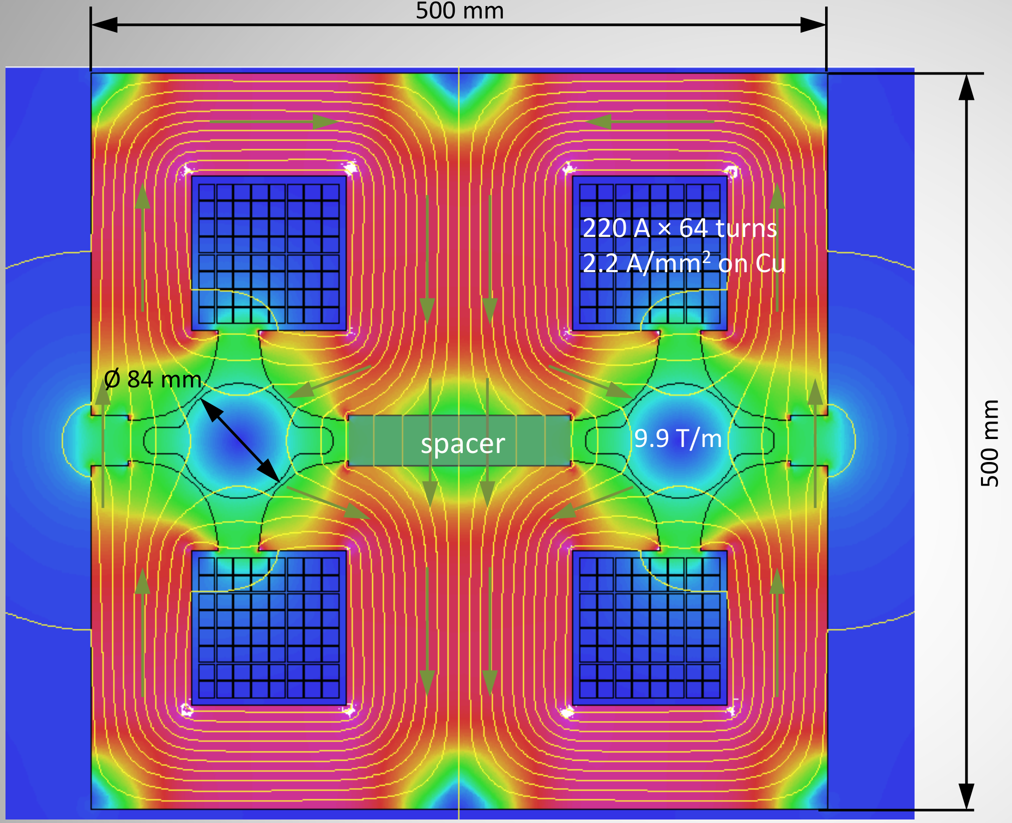
LHC twin-aperture quadrupole MQW with common yoke:

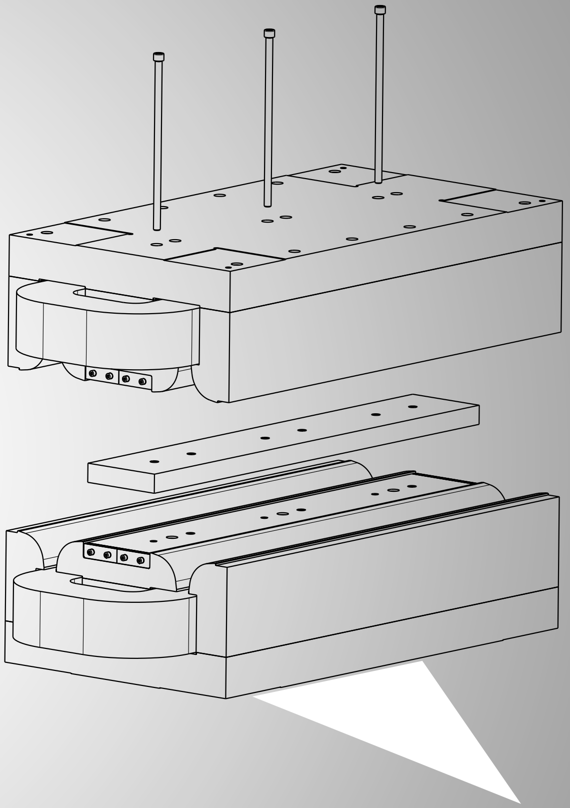


MQW design adopted for FCC-ee

25% power saving (for the same current density) but with constrained F/D polarity

FCC-ee Twin quadrupole design



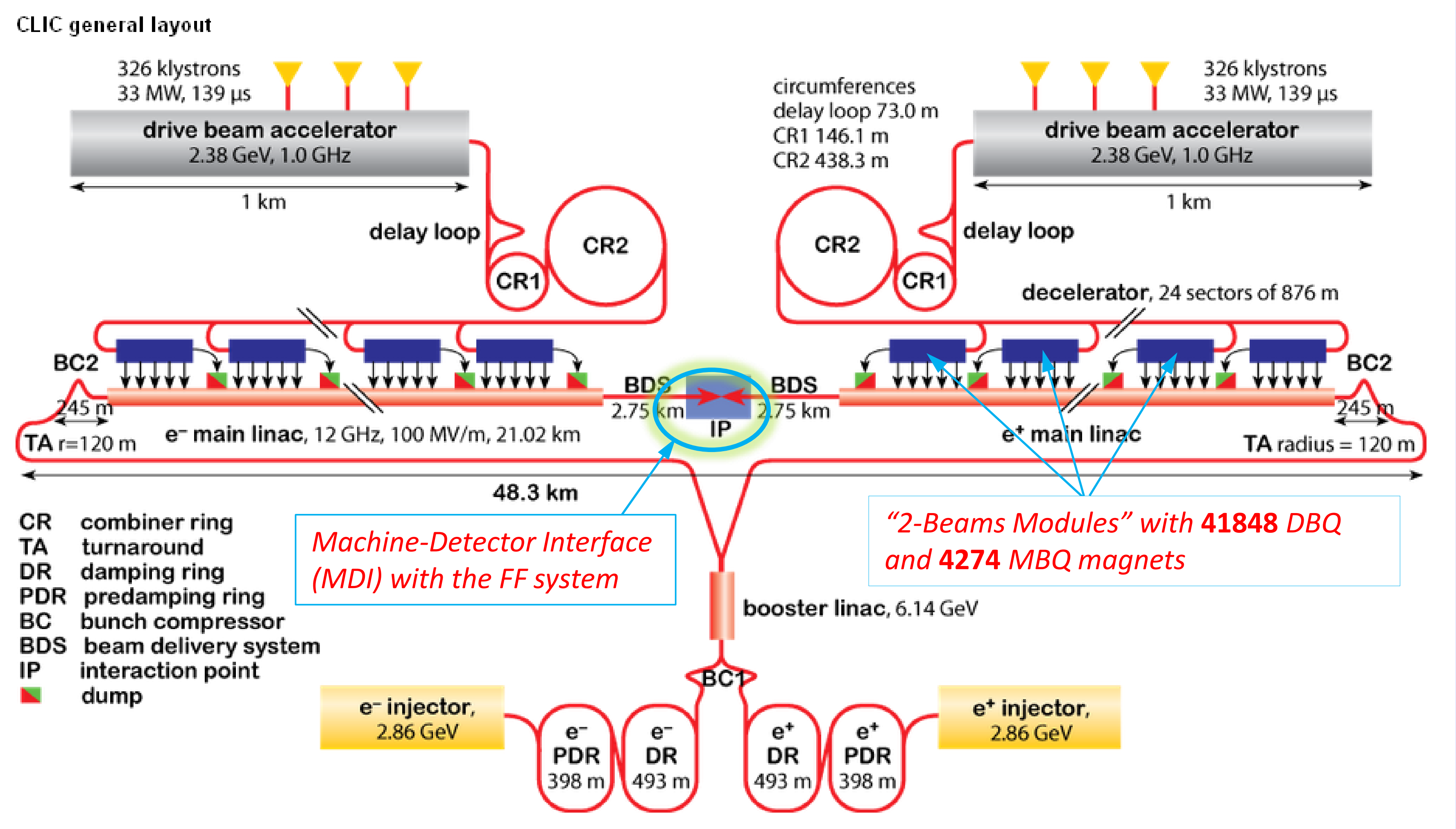


- Energy saving: 50% savings in ampere-turns and power consumption (25 MW)
- Cost saving: 50% less units to manufacture, transport, install, align
- Compact: small dimensions, less material
- Reliable: coils are far from the midplane radiation
- Flexible: compatible with individual trims on the apertures (typically 5%)

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)

CLIC

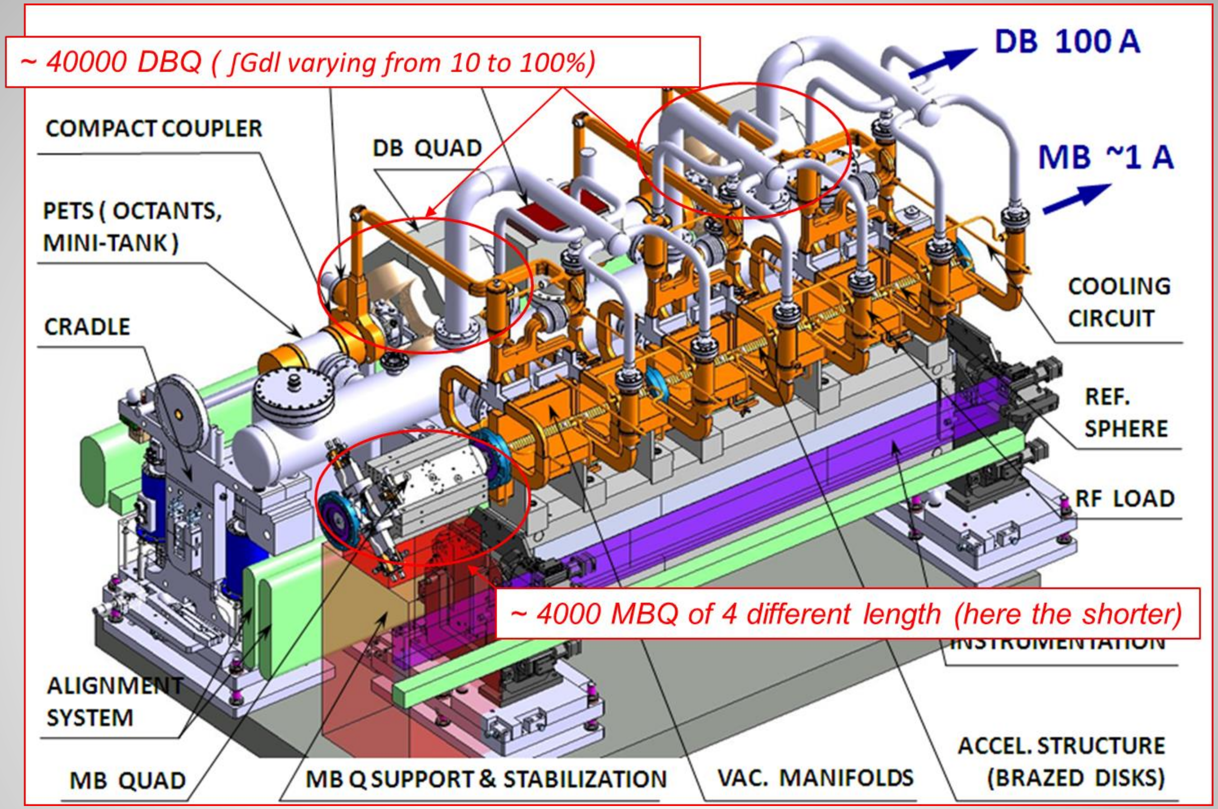
… more than 65000 magnets of more than 100 types!



Machine-Detector Interface (MDI) with the FF system

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

MBQ for the «2-Beams Module»

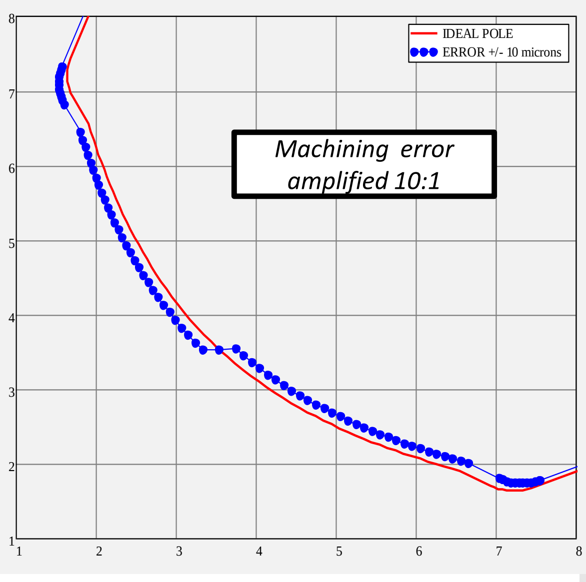


MBQ challenges:

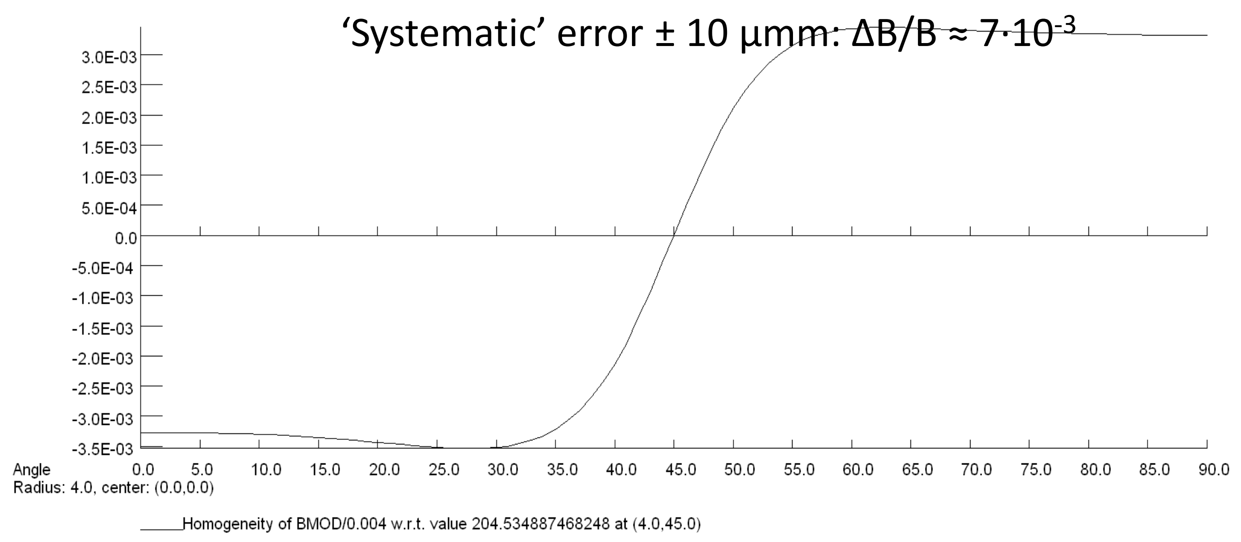
- Limited space: longitudinal and transversal
- Limited mass and maximum rigidity: individual stabilization in the nm range
- Large quantity (< 4000): requires simple design and industrial techniques for production, assembly and testing at reasonable costs
- Performance: good field quality within a small aperture

Sensitivity analysis I

Main challenge: 200 T/m within 10^{-4} and a small aperture (Ø 10 mm)



‘Systematic’ error ± 10 µmm: ΔB/B ≈ $7 \cdot 10^{-3}$

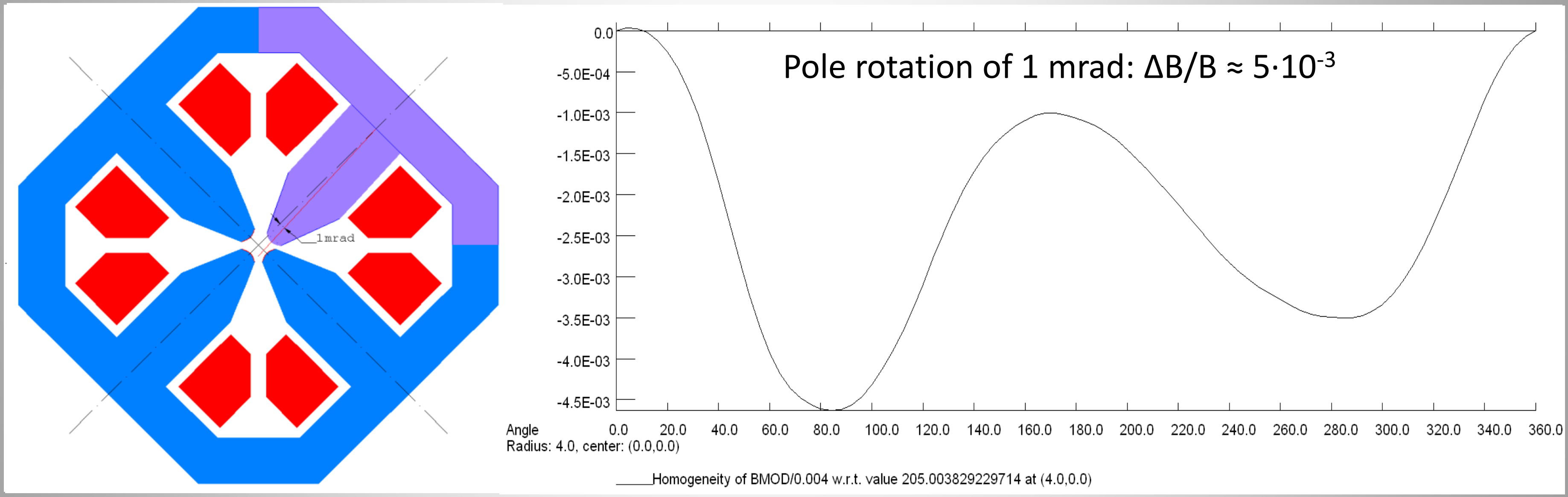


Impact of pole profile errors on the field homogeneity: Perfect magnet ΔB/B ≈ $6 \cdot 10^{-5}$

M. Modena, CERN – “10th International Accelerator School for Linear Colliders” Dec 2016, KEK and Teijin Academy Fuji, Japan

Sensitivity analysis II

Impact of assembly errors on the field homogeneity: Perfect magnet $\Delta B/B \approx 6 \cdot 10^{-5}$

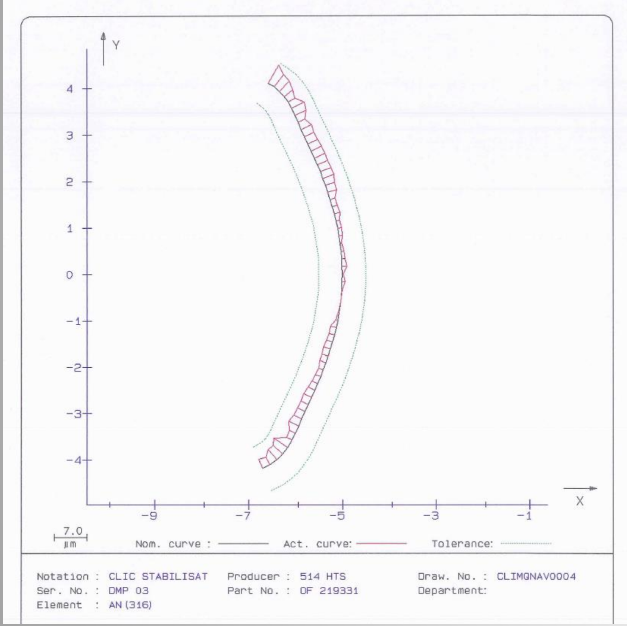


Pole rotation of 1 mrad: $\Delta B/B \approx 5 \cdot 10^{-3}$

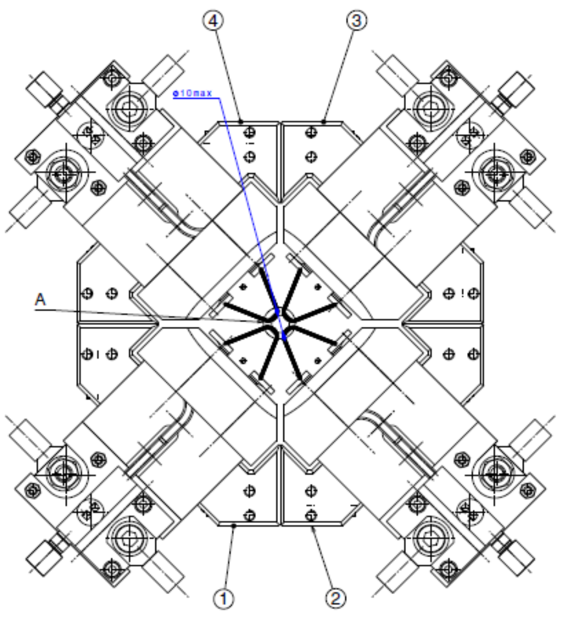
M. Modena, CERN – "10th International Accelerator School for Linear Colliders" Dec 2016, KEK and Teijin Academy Fuji, Japan

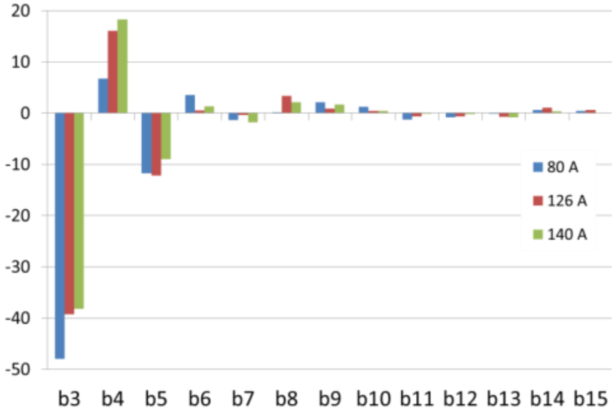
MBQ Prototype

- Main challenge: 200 T/m within 10^{-4} and a small aperture (Ø 10 mm)
- 4 magnet types with different length between 420 mm and 1920 mm
- 3 short and 1 long prototype to study machining precision, assembly tolerances, mechanical stabilization, field quality and magnetic measurement techniques



Notation : CLIC STABILISAT
Ser. No. : DMP 03
Element : AN (316)
Producer : 514 HTS
Part No. : OF 219331
Draw. No. : CLIMGNAV0004
Department:

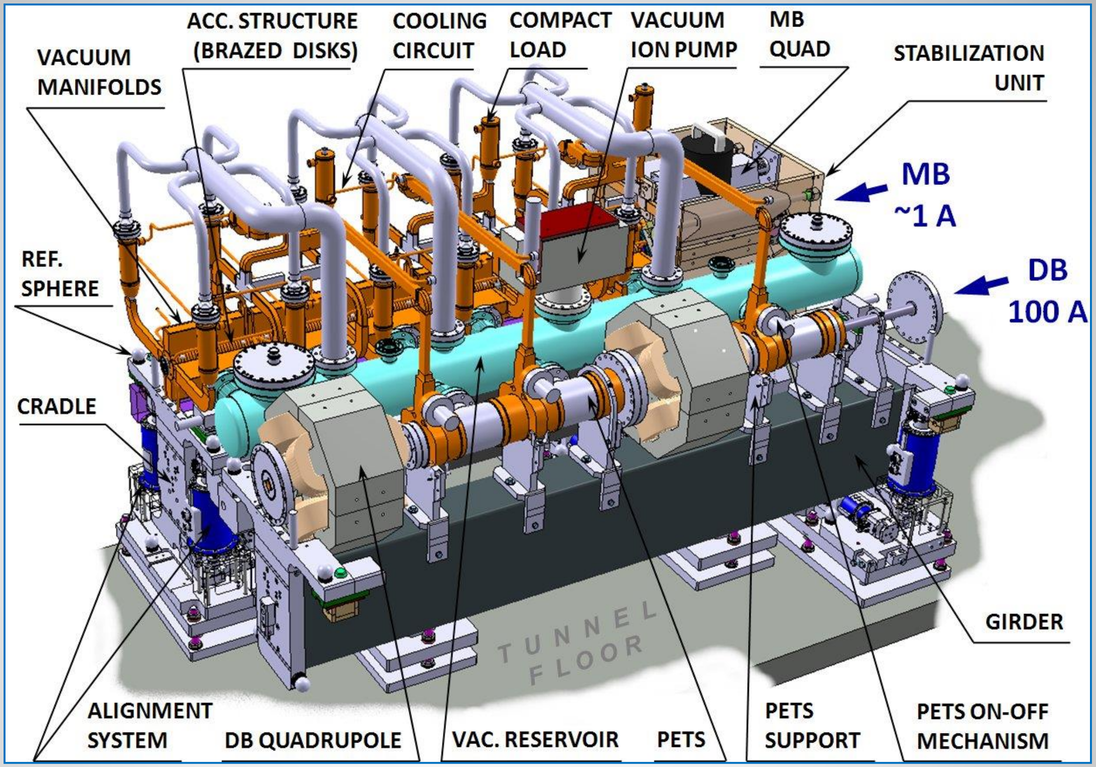




- Short prototype obtained machining precision (±7µm) with "standard" industrial techniques (fine grinding) on all the critical surfaces → can this result also be achieved for the long(er) types?
- Alignment and assembly of the 4 quadrants within a cylindricity of 13 µm has been achieved
- Are there alternatives techniques to improve the precision and achieve the required field quality?
- How can we develop precise, fast, robust machining and assembly methods aiming towards industrial production?

M. Modena *et al.*, "Performances of the Main Beam Quadrupole Type1 Prototypes for CLIC" MT23, Boston, US, July 2013, IEEE Transactions on Applied Superconductivity, Vol. 24, NO. 3, JUNE 2014
M. Modena, R. Leuxe, M. Struik, "Results on Ultra-Precise Magnet Yoke Sectors Assembly Tests", MT23, Boston, July 2013, IEEE Transactions on Applied Superconductivity, Vol. 24, NO. 3, JUNE 2014

DBQ for the «2-Beams Module»



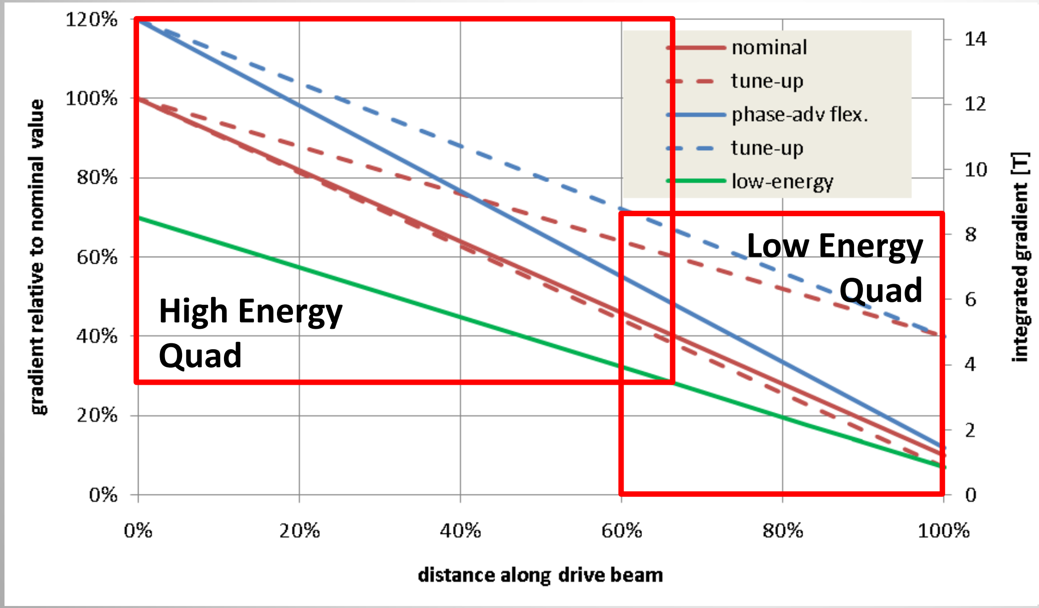
DBQ challenges:

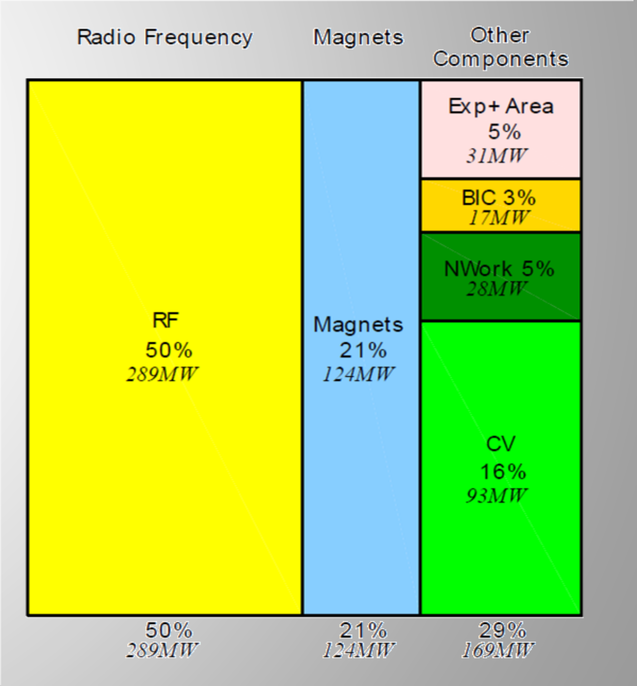
- Tight alignment tolerance: no active stabilization and beam feedback alignment
- Very large series: requires simple design and industrial techniques for production, assembly, testing and installation at reasonable costs
- Performance: wide $\int Gdl$ variation from 7% - 120%
- Reliability: large number of magnets requires short MTTR and long MTBF
- Power consumption: minimize cooling power and heat load to the tunnel

DB Quadrupole

Normal conducting systems on CLIC will result in high electrical power consumption and running costs:

- CLIC estimated to draw >580 MW (compared to 90 MW for LHC)
- 124 MW projected for nc electro-magnets
- 32 MW (> 25%) for DB quadrupoles (20 MW) and DB dipoles (12 MW)



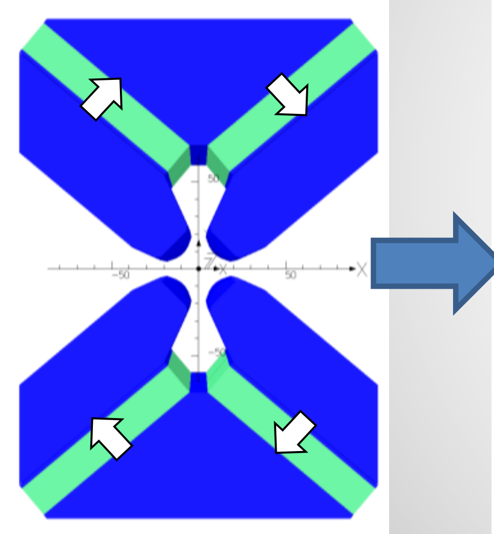


Can we use permanent magnets to save power?

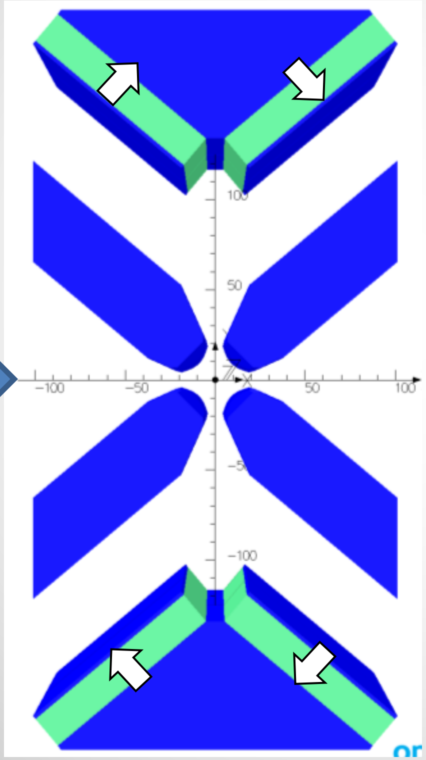
How can we deal with the wide gradient variation from 7% - 120%?

High-Energy DB quadrupole

Stroke = 0 mm

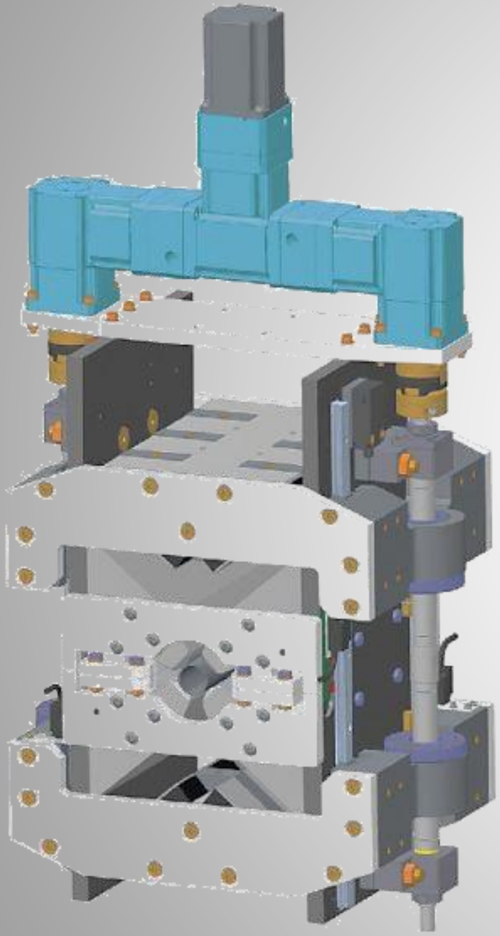


Stroke = 64 mm

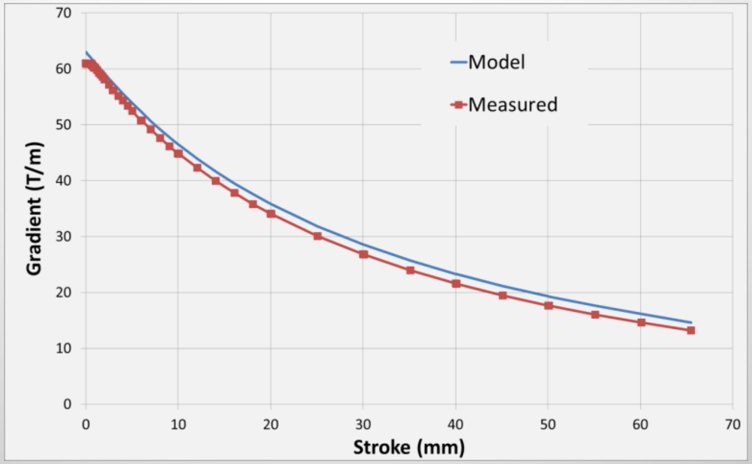


- NdFeB magnets (VACODYM 764 TP)
- B_r = 1.37 T
- Max. gradient = 60.4 T/m (0 mm stroke)
- Min. gradient = 15.0T/m (64 mm stroke)
- 30% - 120% of nom. gradient
- Aperture Ø = 27.2 mm
- GFR Ø = 23 mm
- Field quality = ±0.1%

High-Energy DB quadrupole

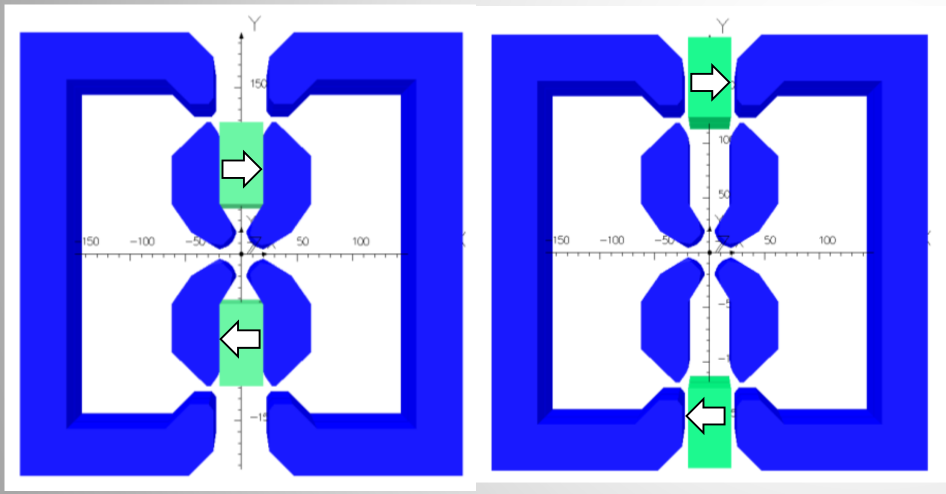


- Single axis motion with one motor and two ballscrews
- Maximum force per side: 16.4 kN (reduced by 10 when stroke = 64 mm)
- PM blocks bonded and strapped to steel bridge piece, protective steel plate also bonded



J.A. Clarke *et al.,* “Novel Tunable Permanent Magnet Quadrupoles For The CLIC Drive Beam”, MT23, Boston July 2013, IEEE Transactions on Applied Superconductivity, Vol. 24, NO. 3, JUNE 2014

Low-Energy DB quadrupole



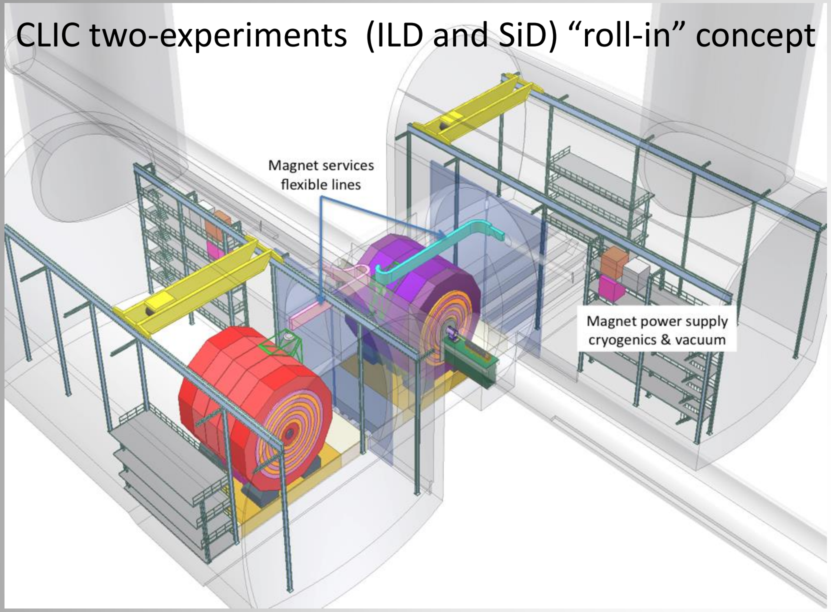
Stroke = 0 mm

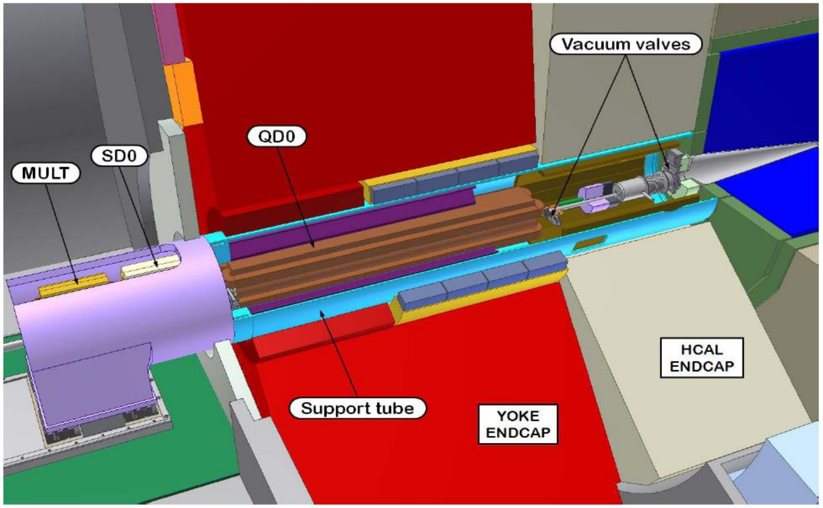
Stroke = 75 mm

- NdFeB magnets (VACODYM 764 TP)
- B_r = 1.37 T
- Max. gradient = 43.4 T/m (0 mm stroke)
- Min. gradient = 3.5T/m (75 mm stroke)
- 7% - 70% of nom. gradient
- Aperture Ø = 27.2 mm
- GFR Ø = 23 mm
- Field quality = ±0.1%
- Maximum force only 0.7 kN per side

CLIC Final Focusing

CLIC two-experiments (ILD and SiD) "roll-in" concept





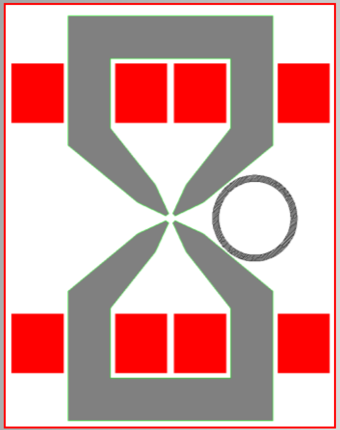
Nominal requirements & boundary conditions for the QD0:

- Gradient: highest possible towards 575 T/m
- Total Length: 2.73 m
- Aperture radius: 4.125 mm
- Field Quality: better than 10^{-3}
- Tunability: -20% minimum

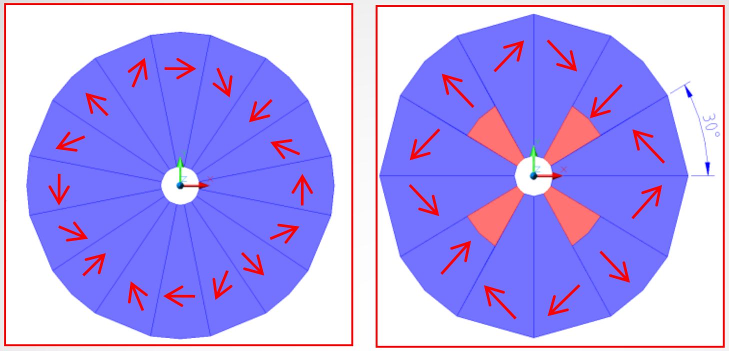
Geometric and other boundary conditions:

- Stabilization: similar to MBQ magnets, the QD0 needs to be actively stabilized in the nm range
- Minimize weight and vibration sources
- Alignment budget: 10 µm
- Compactness: magnet inside Detector Solenoid

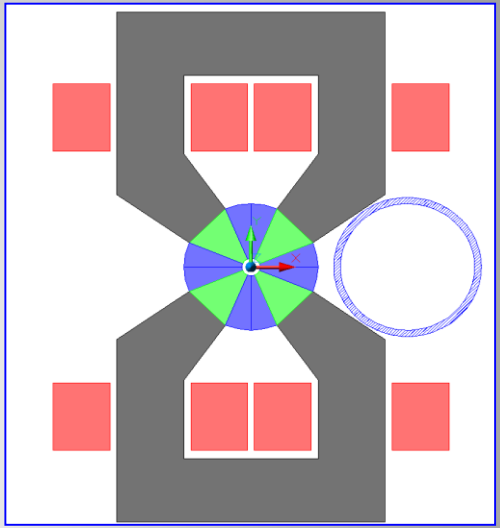
CLIC Final Focusing



Pure EM design

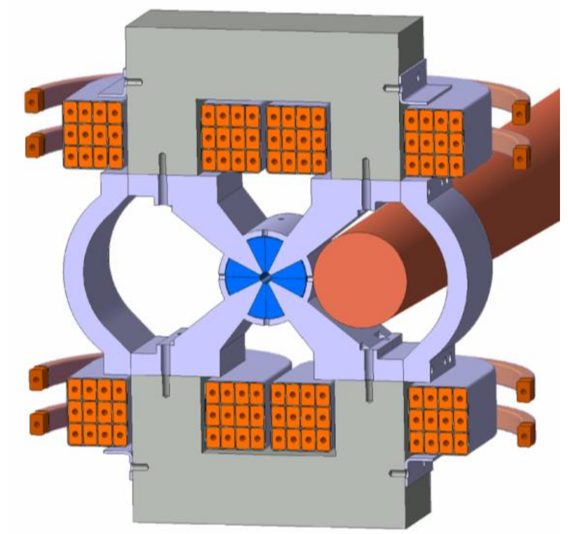


Pure Halbach and "super-strong" design



Hybrid design

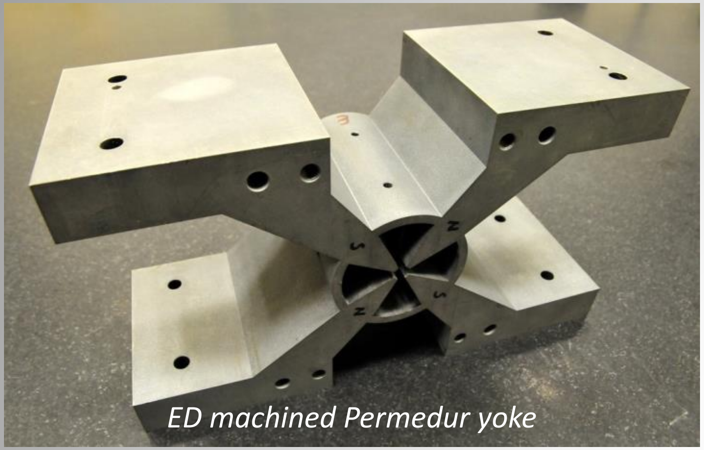
Configuration	**G [T/m] for r = 4.125 mm (2D calculation)**	
Pure EM	0 - 310 (Steel1010); 0 - 365 (Permendur*)	
	Sm_2Co_{17}	$Nd_2Fe_{14}B$
"Pure Halbach"	409	540
"Super Strong"	550	615
"Hybrid"	145 – 550 (531**)	175 – 615 (599**)

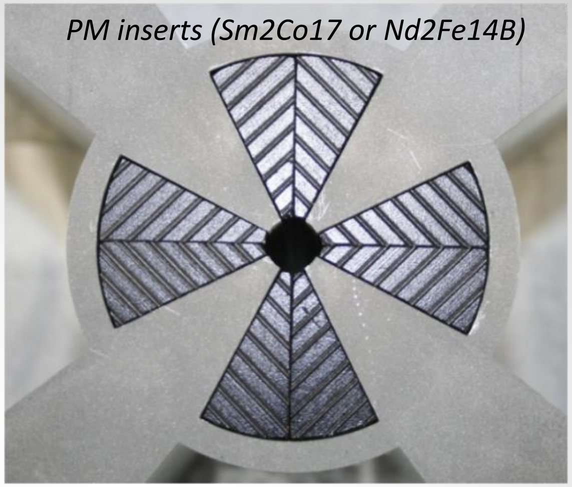


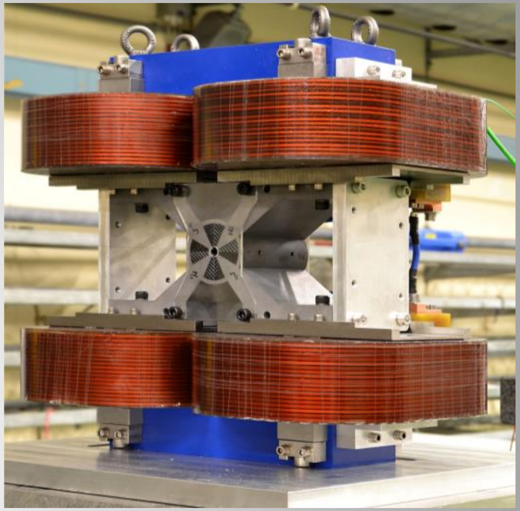
*) Permendur is a Fe-Co alloy (50%-50%) with a high magnetic flux saturation

**) the "ring" decreases slightly the gradient (by 15-20 T/m) but improves assembly precision for the PM

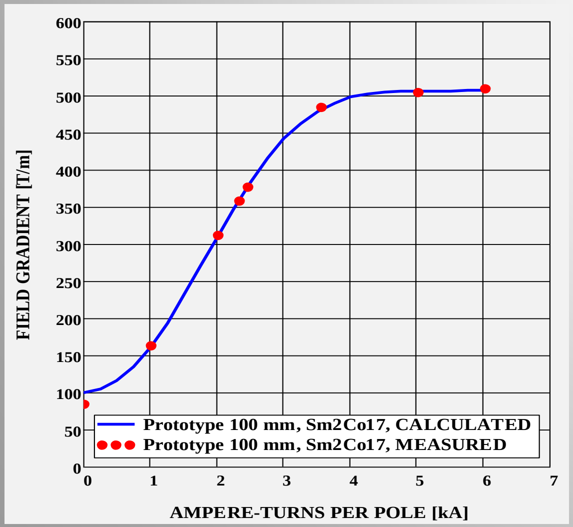
CLIC Final Focusing

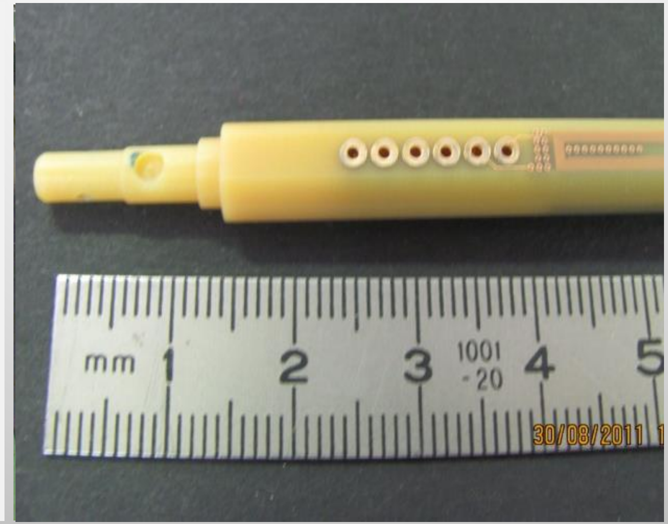

ED machined Permedur yoke

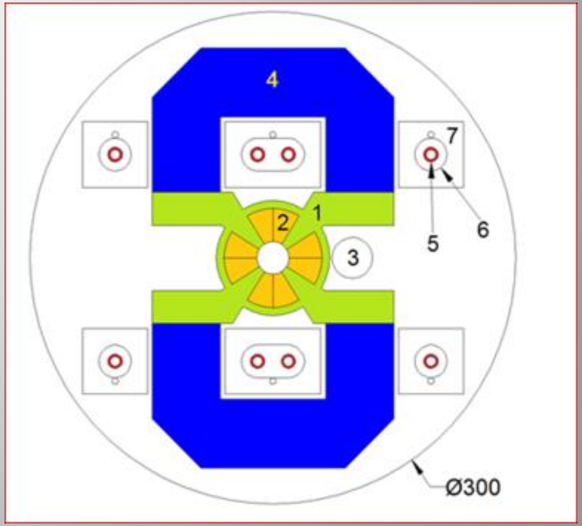

PM inserts (Sm2Co17 or Nd2Fe14B)



What comes next…? A super-ferric solution?







M. Modena *et al.*, “Design, Assembly and First Measurements of a short Model for CLIC Final Focus Hybrid Quadrupole QD0”, IPAC12, New Orleans, May 2012, Conf. Proc. C1205201 (2012)
A. Vorozhtsov, M. Modena, D. Tommasini, “Design and Manufacture of a Hybrid Final Focus Quadrupole Model for CLIC” , presented at MT22

Summary

Main challenges for future collider magnets are:

- Strong fields
- Small apertures
- Power consumption and related operation costs
- Advanced stability
- High reliability

Conventional magnet concepts have clear limitations which we need to overcome with new innovative concepts in:

- Magnet design
- Magnetic materials
- Manufacturing techniques
- Test and measurement methods

Promising alternative concepts:

- Twin-aperture low-field magnets offering a second aperture “for free”
- Tuneable permanent magnets becoming a reality, merging the versatility of electromagnets with savings in operating costs and infrastructure
- Hybrid magnets combining the benefits of two worlds: economics from PM and flexibility of EM

Nevertheless: there is a lot of challenging and interesting work ahead of us to develop these ideas further or to come up with superior concepts …