Joint Universities Accelerator School
JUAS 2025
18. – 24. February 2025

Normal-conducting accelerator magnets
Lecture 3: Magnet types

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CERN

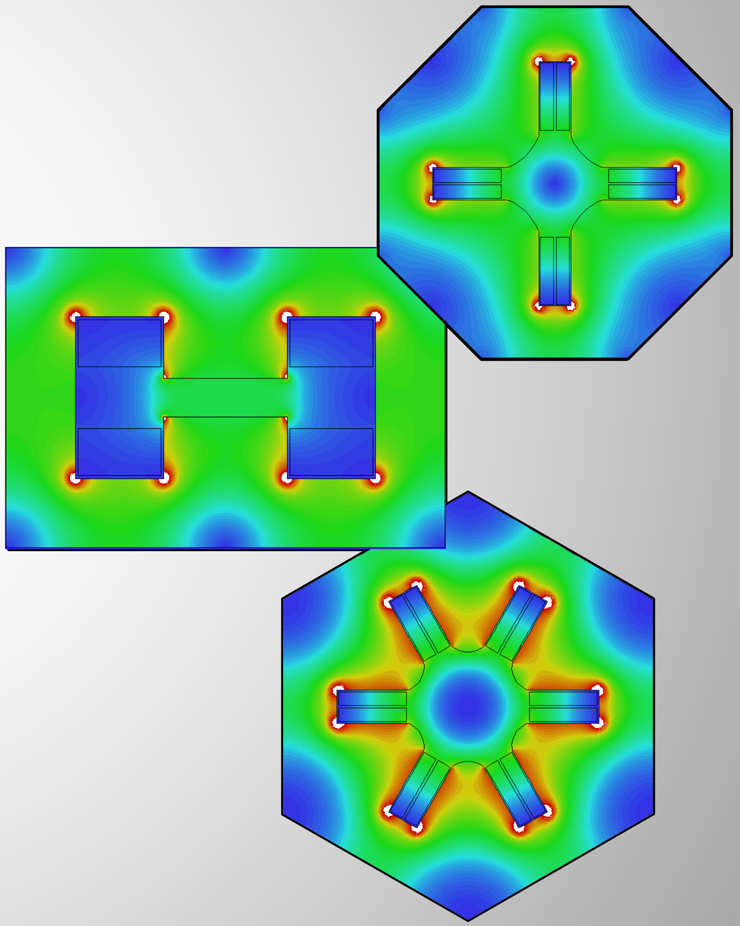
Magnet types

Magnet types and function

Magnets from the past

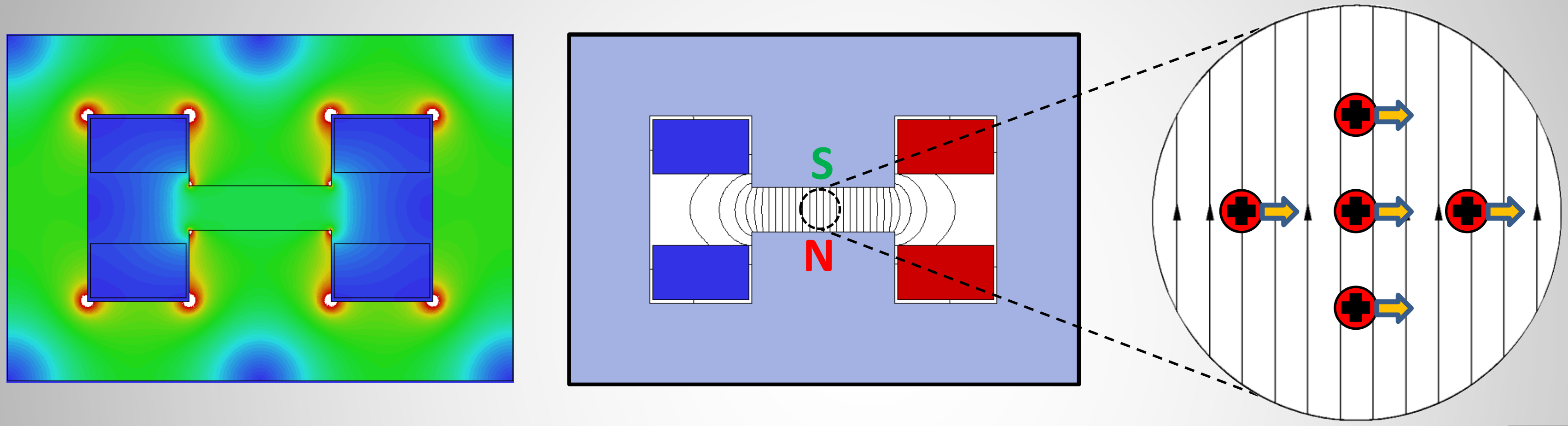
Will we need normal-conducting magnets in the future?

Future challenges in magnet design



Dipole

Purpose: bend or steer the particle beam

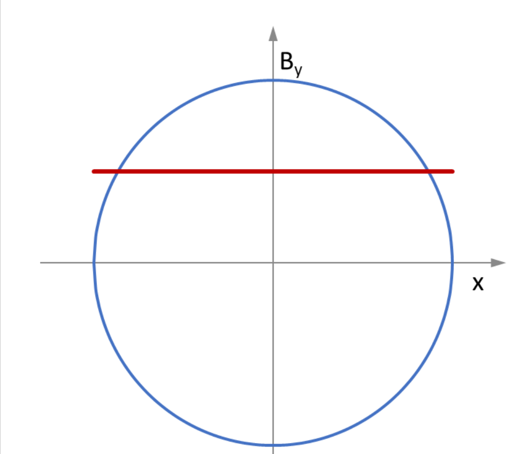


Equation for normal (non-skew) ideal (infinite) poles:

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

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

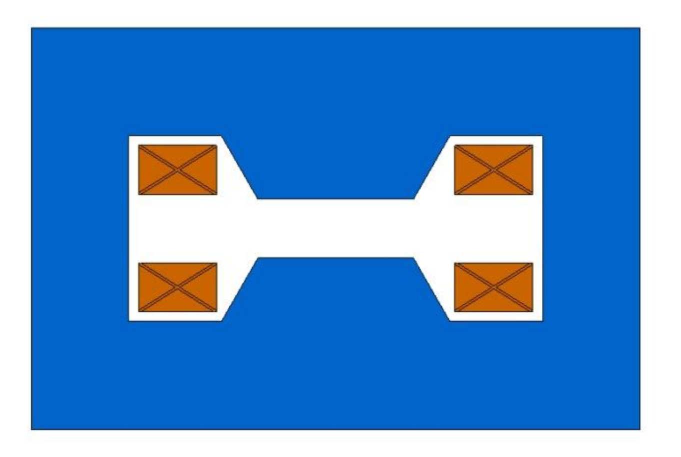
Applications: synchrotrons, transfer lines, spectrometry, beam scanning

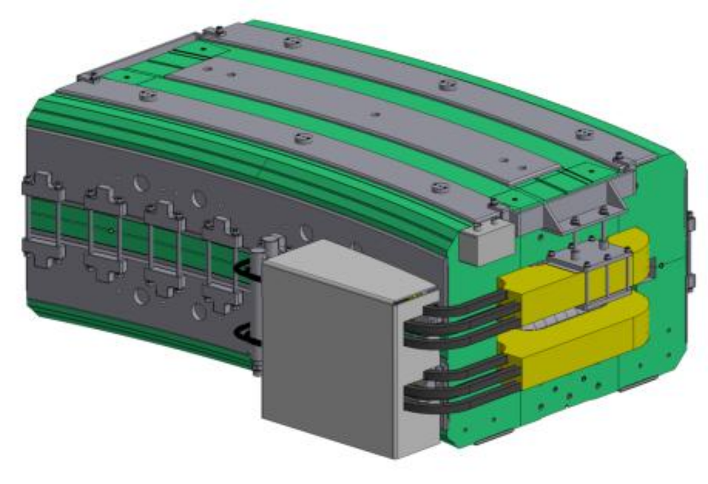


B_y is constant

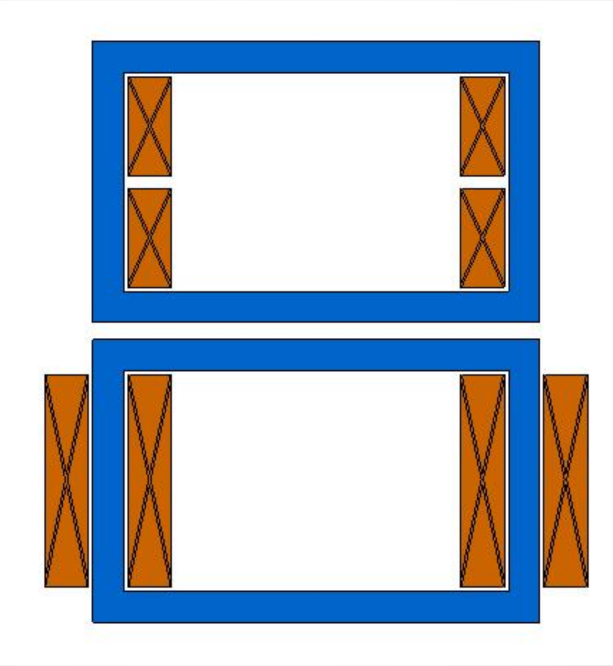
Dipole types

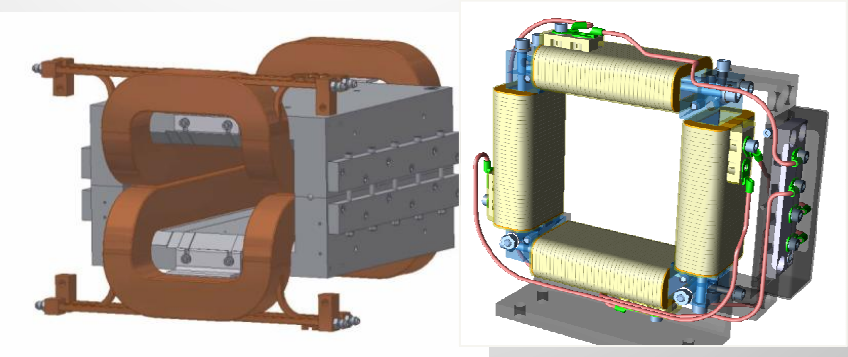
H-Shape



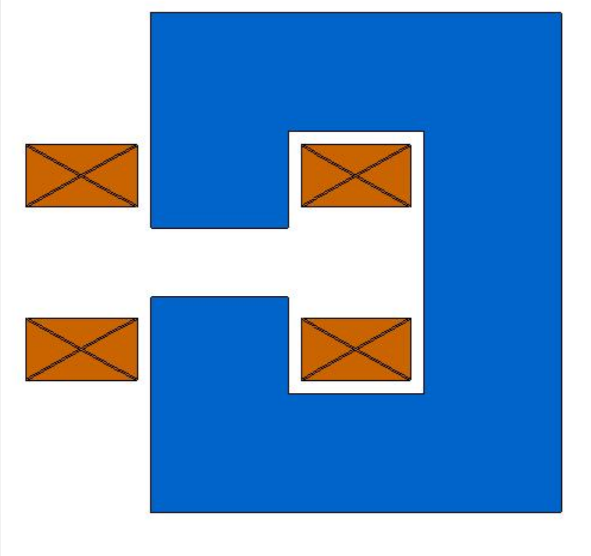


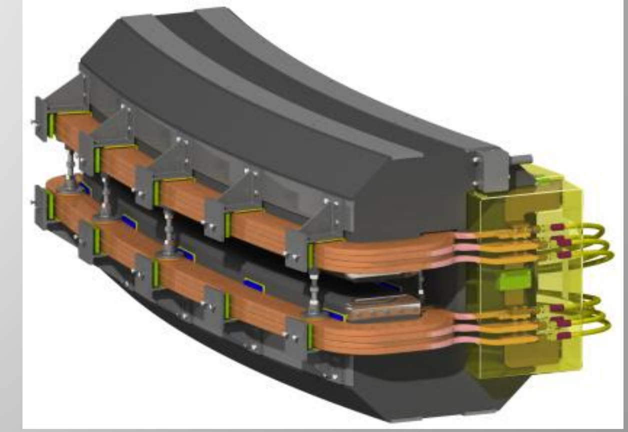
O-Shape





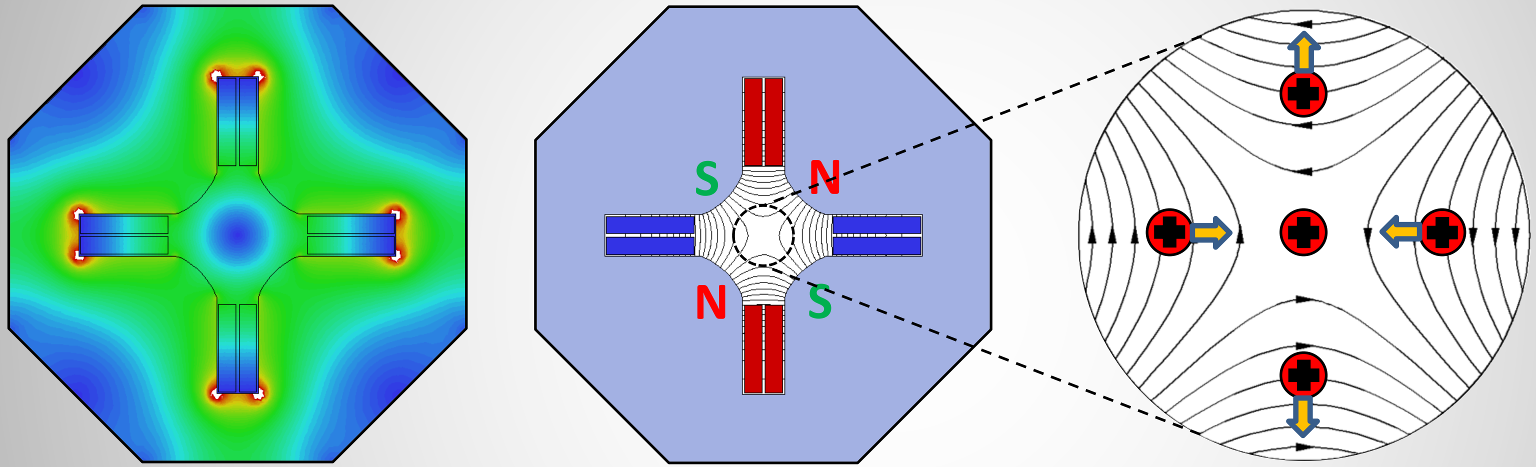
C-Shape



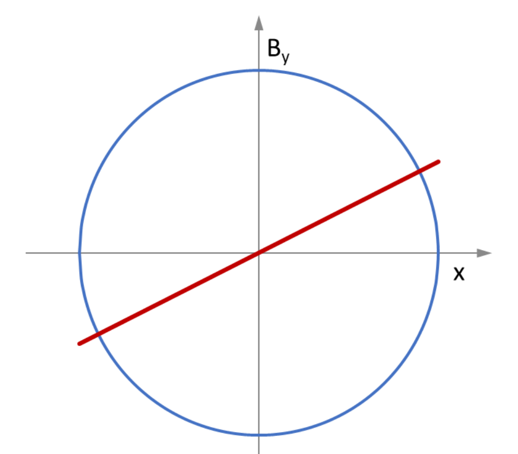


Quadrupole

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



$$G = B' = \frac{B_2}{R_{ref}} = \frac{dB}{dr}$$



B_y varies linearly with x

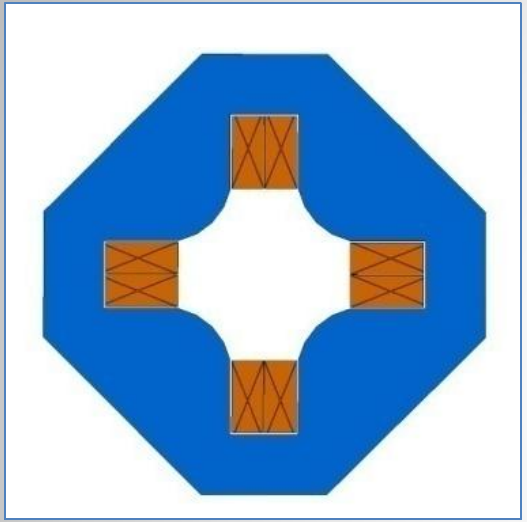
Equation for normal (non-skew) ideal (infinite) poles:

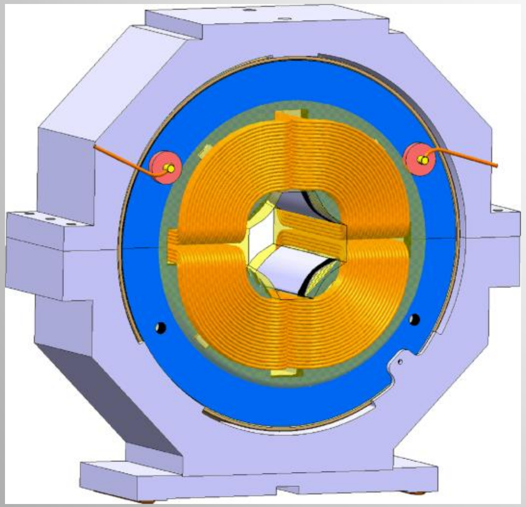
$2xy = \pm r^2$ (→ hyperbola with r = aperture radius)

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

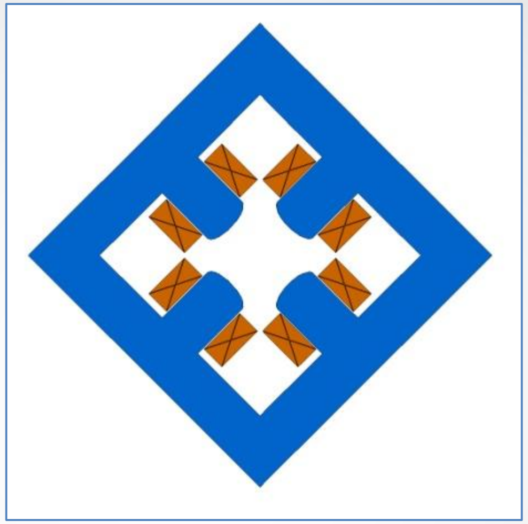
Quadrupole types

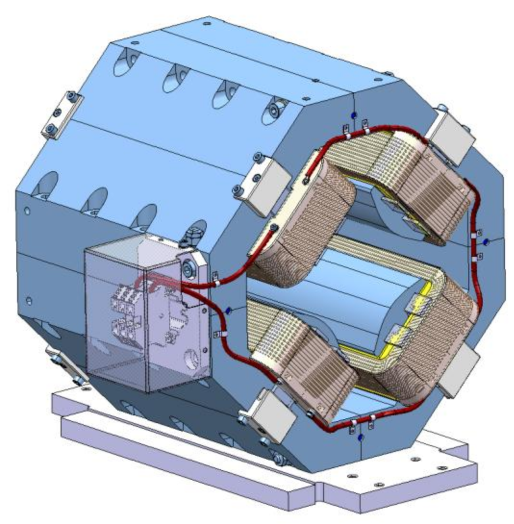
Quadrupole type I



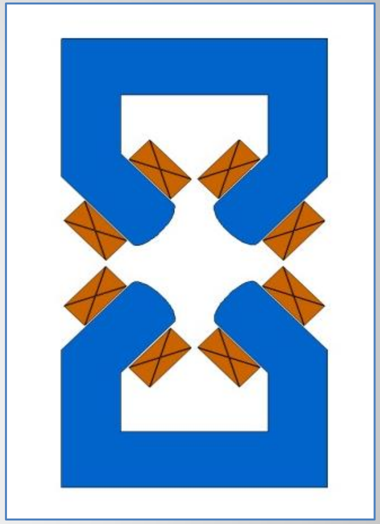


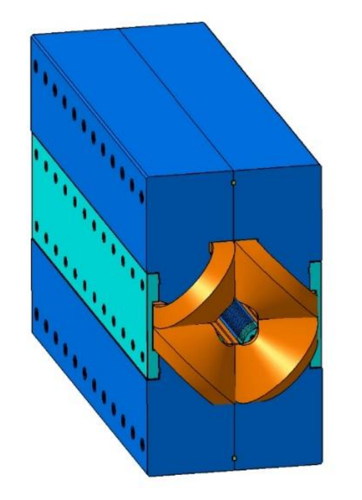
Quadrupole type II





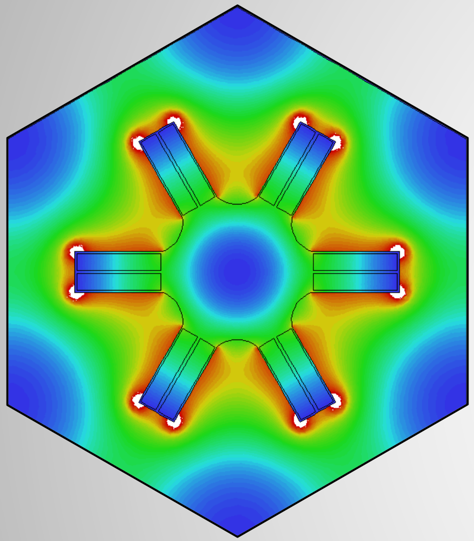
Collins or Figure-of-Eight

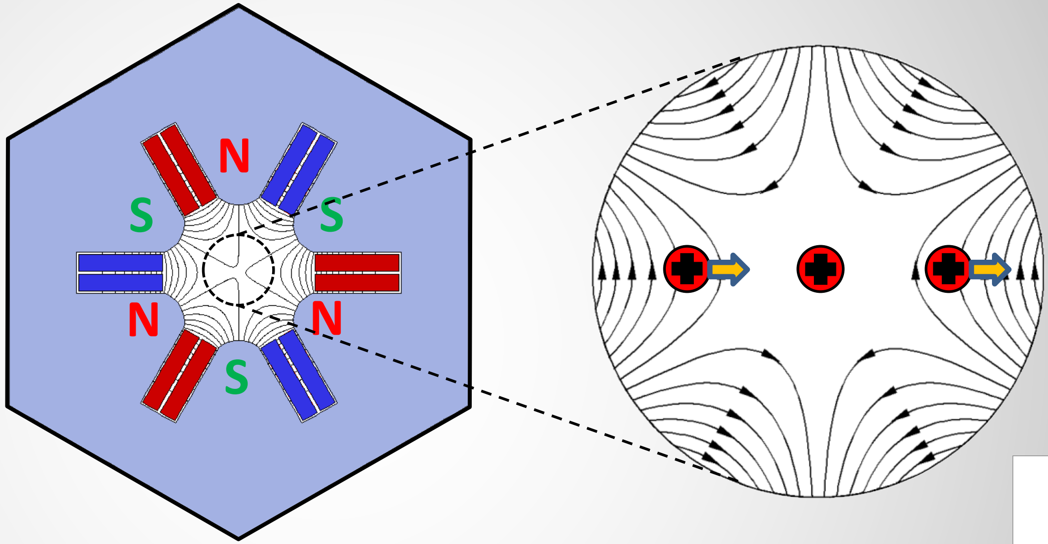




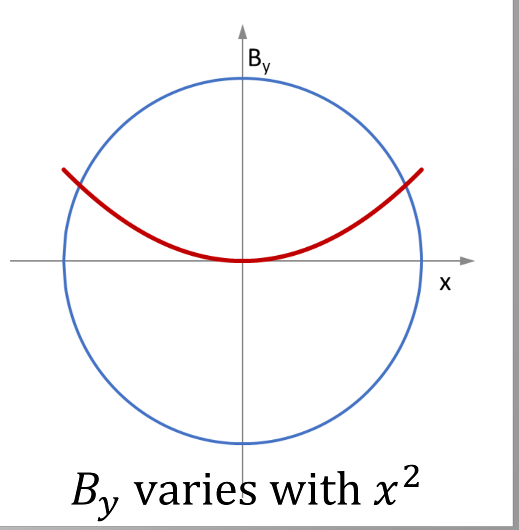
Sextupole

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





$$S = B'' = \frac{2\,B_3}{R_{ref}} = \frac{d^2B}{dr^2}$$



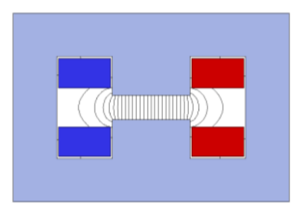
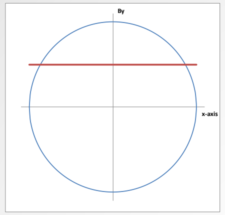
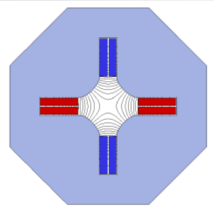
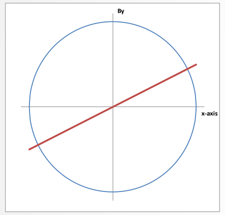
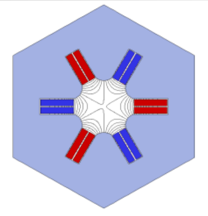
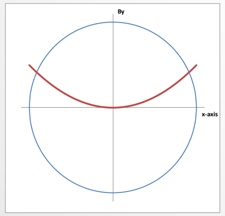
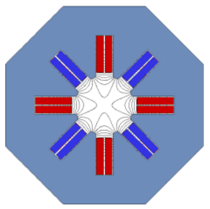
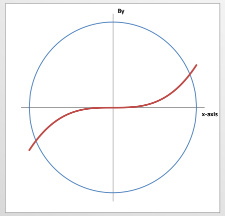
B_y varies with x^2

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

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

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

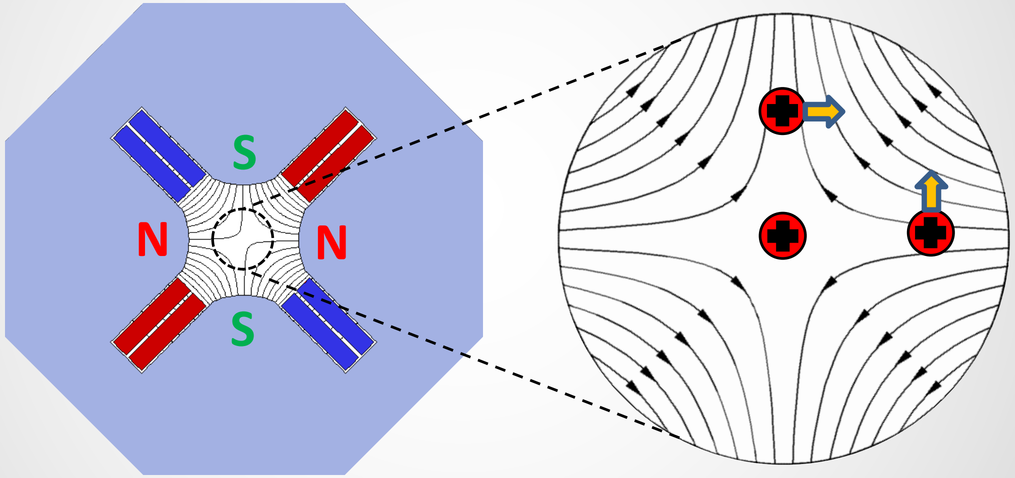
Magnet types

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

Skew quadrupole

Purpose: coupling of horizontal and vertical betatron oscillation

Rotation by $\pi/2n$



Beam with horizontal displacement (but no vertical) is deflected vertically

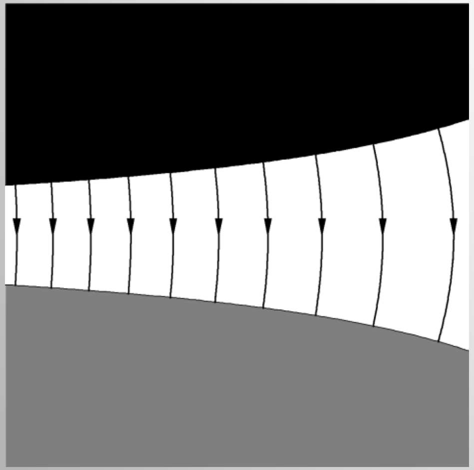
Beam with vertical displacement (but no horizontal) is deflected horizontally

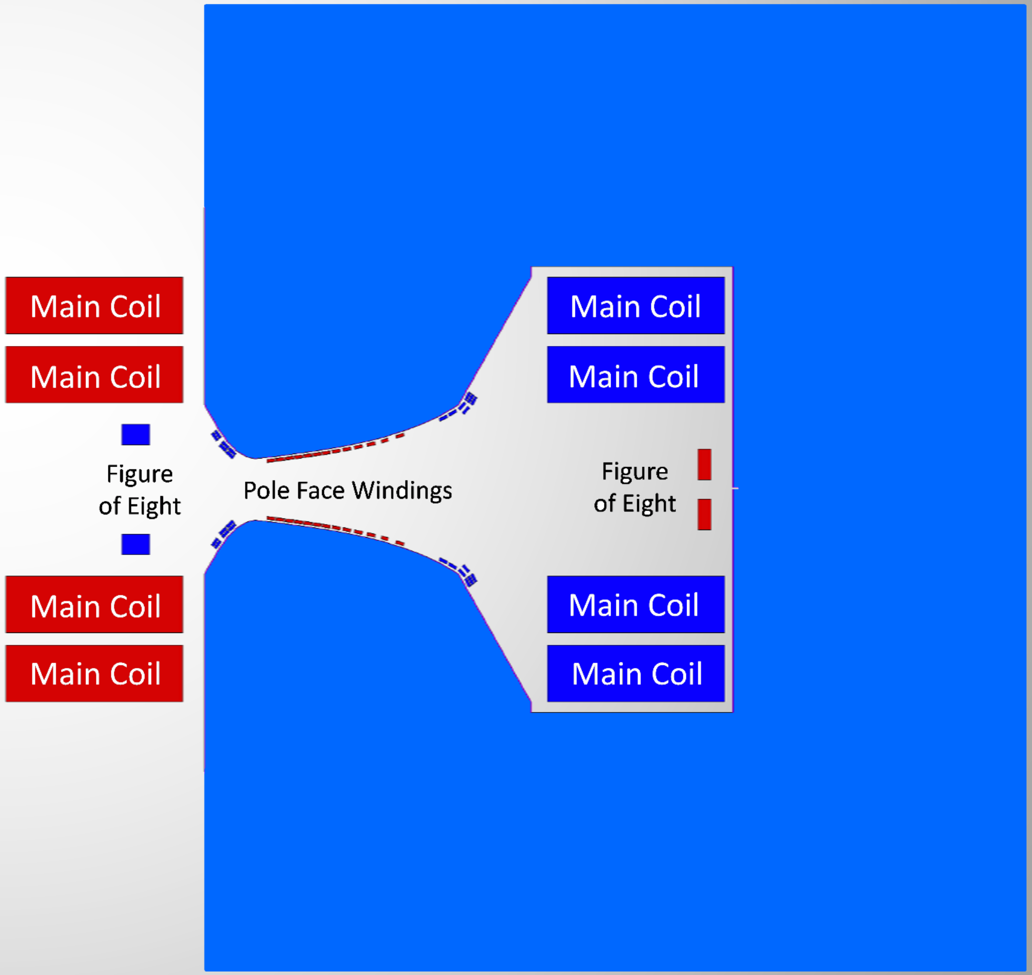
Combined function magnets

Combined function generated by common pole shape (sum a scalar potentials):

Example:

- PS main magnet combines a dipole and a quadrupole in one magnet
- Bending and focusing of the beam at the same time
- Amplitudes of the individual fields cannot be controlled independently



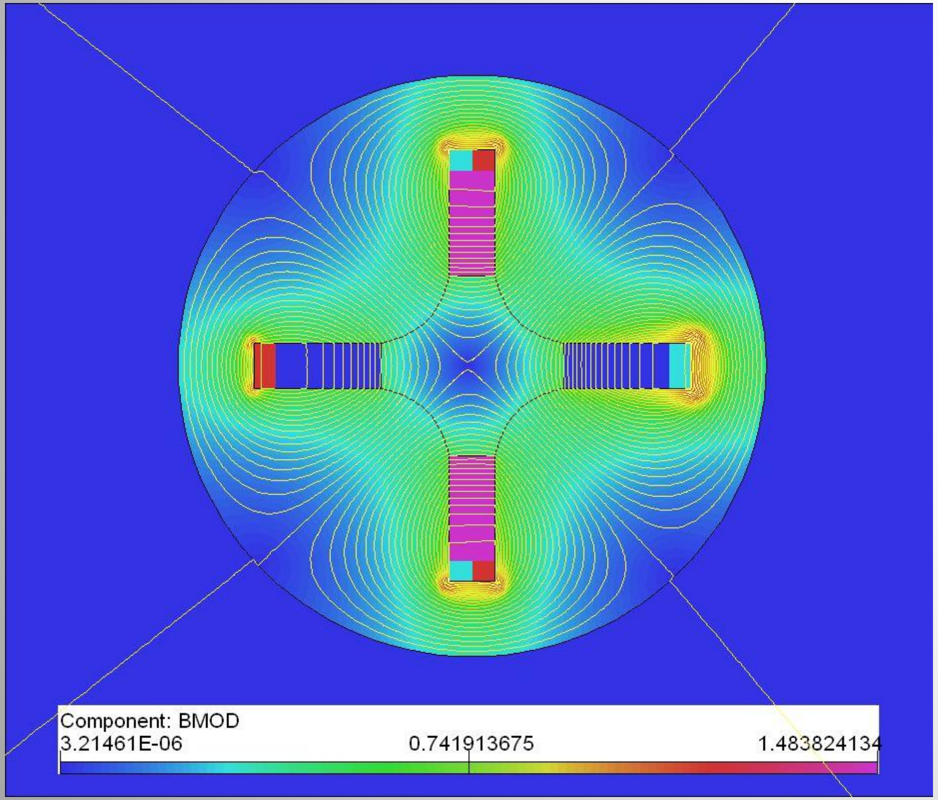


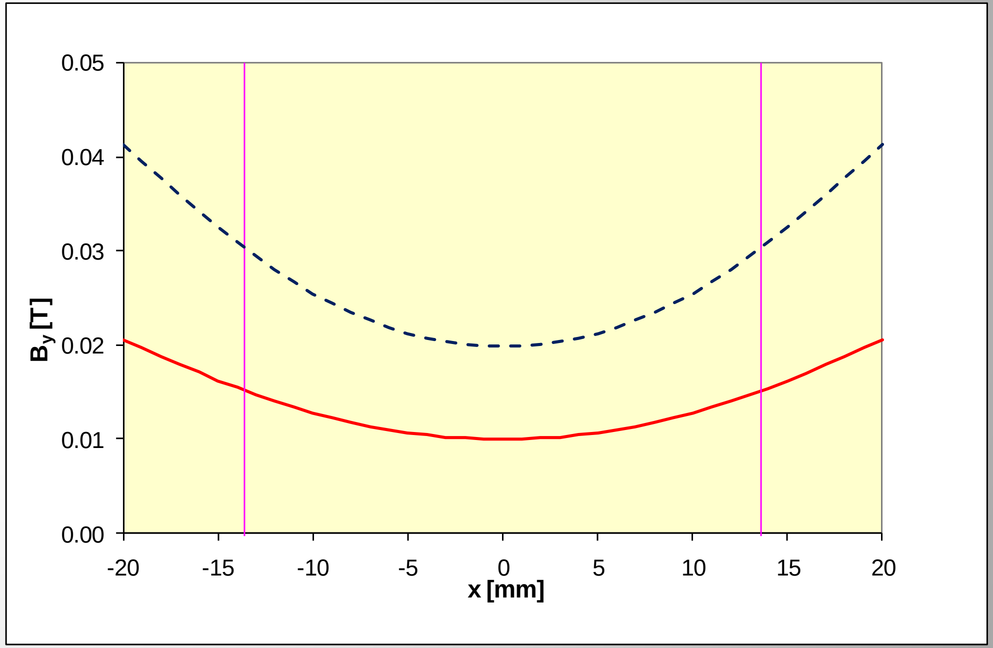
Combined function magnets

Combined function generated by individual coils:

Amplitudes of the individual fields can be controlled independently

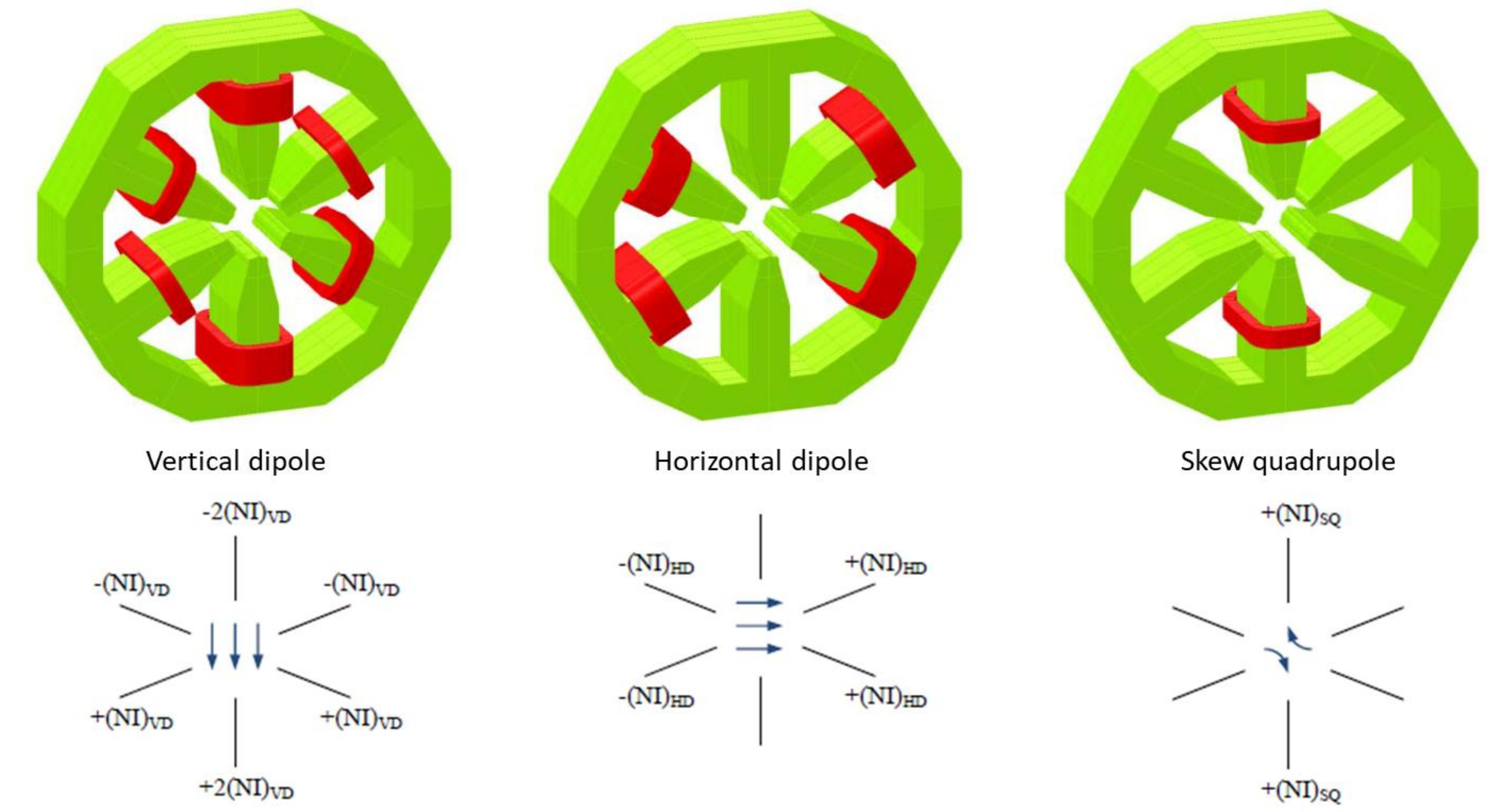
Field quality often poor because the pole is shaped for the primary function





Quadrupole and corrector dipole
(strong sextupole component in dipole field)

Combined function magnets

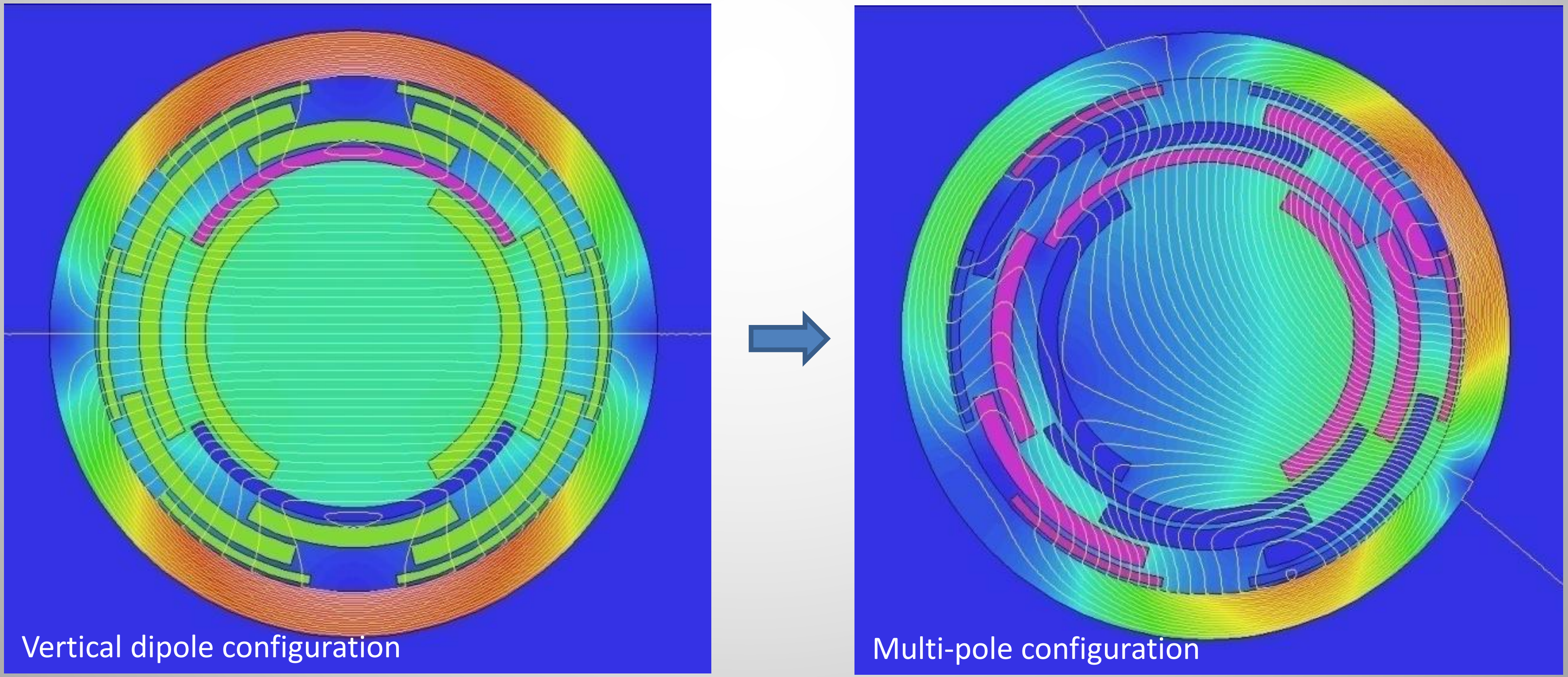


Courtesy of A. Milanese

Note: The coils for exciting the fundamental function (normal sextupole) are not shown

Coil dominated magnets

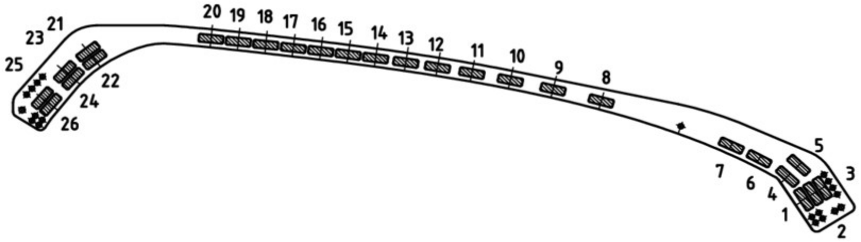
- Nested multi-pole corrector (moderate field levels)
- Iron for shielding only
- Field determined by current distribution



NC-magnets in the 1950s

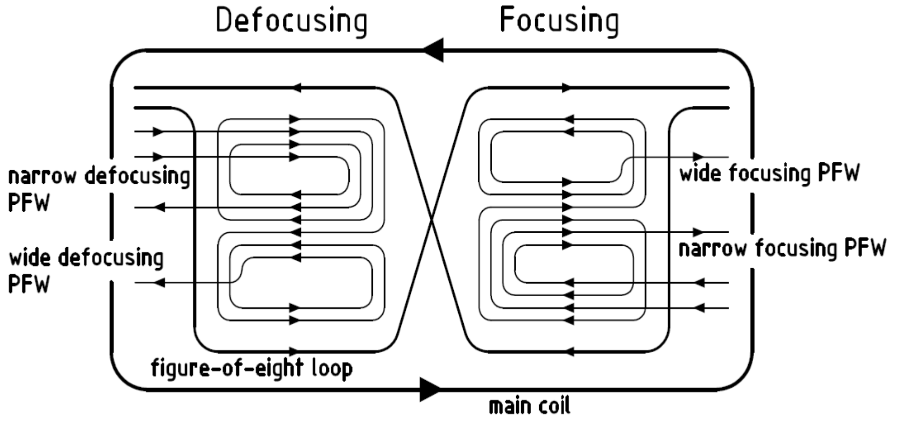
CERN PS (1959), 25 GeV, 628 m

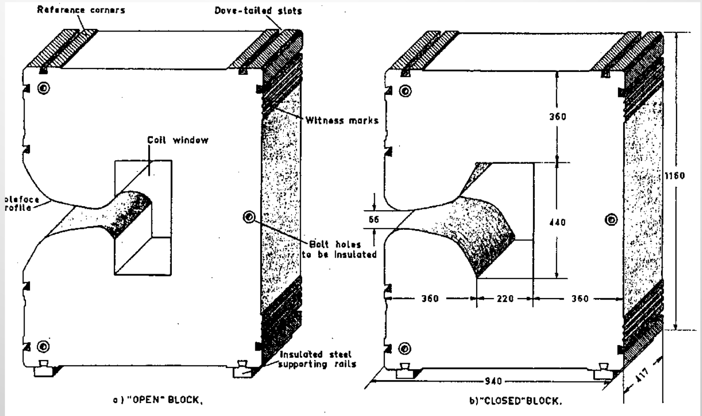
- Combined function magnet: dipole + quadrupole
- Water cooled main coils + Figure-of-Eight windings + Pole-face windings
- Magnetic field B: 0.014 T – 1.4 T
- 100 + 1 magnets in series

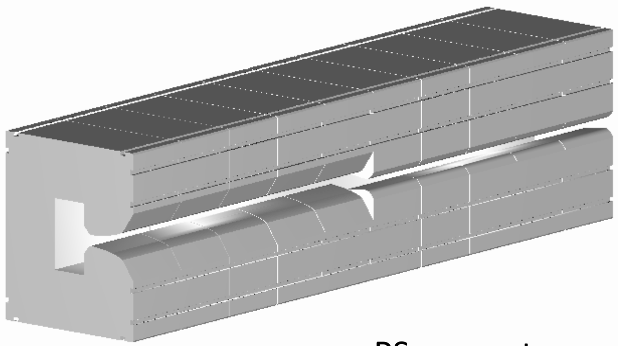


PS Pole-face windings

PS prototype magnet





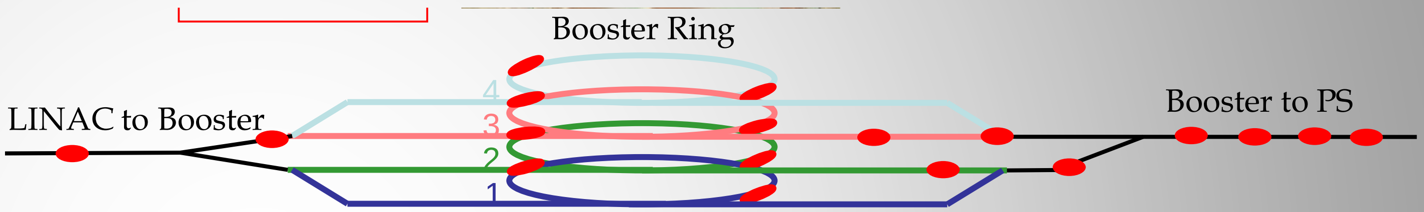


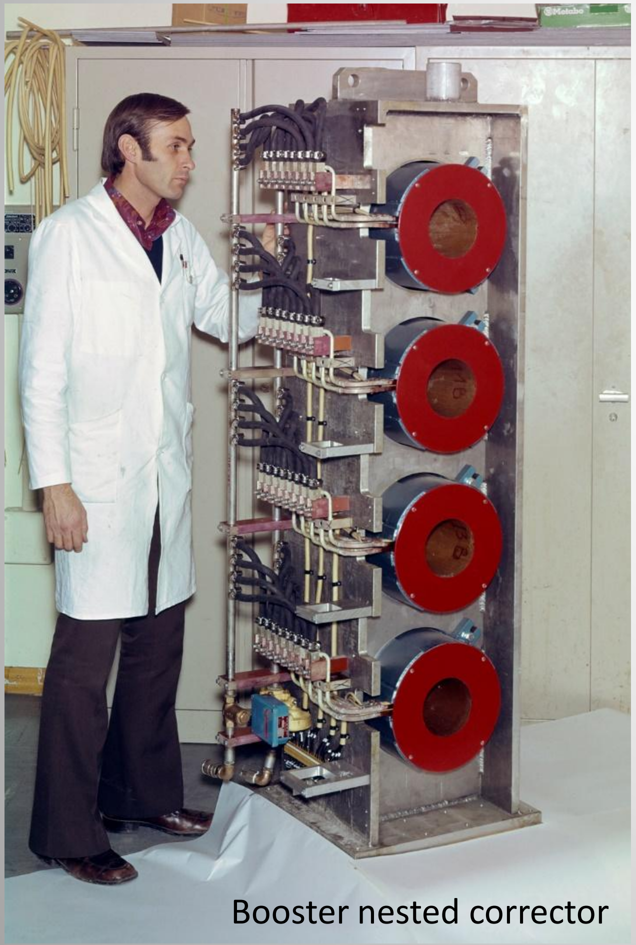
PS magnet core

NC-magnets in the 1960s

CERN PS Booster (1972), 2 GeV (originally designed for 0.8 GeV)

- 4 accelerator rings in a common yoke increase total beam intensity despite space charge effects
- Magnetic field B: 1.48 T




Booster nested corrector

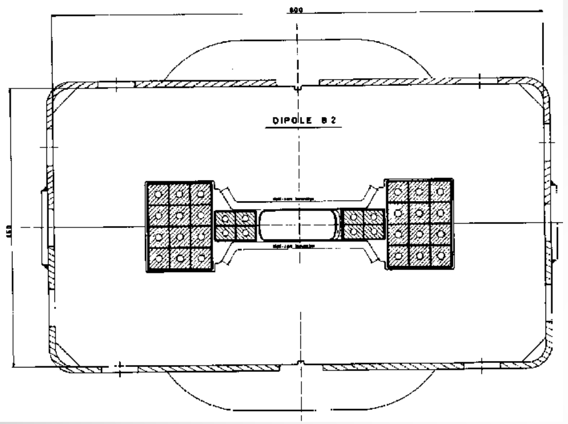

Booster quadrupole


Booster dipole

NC-magnets in the 1970s

CERN SPS (1976), 7 km, 450 GeV

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




SPS main dipoles

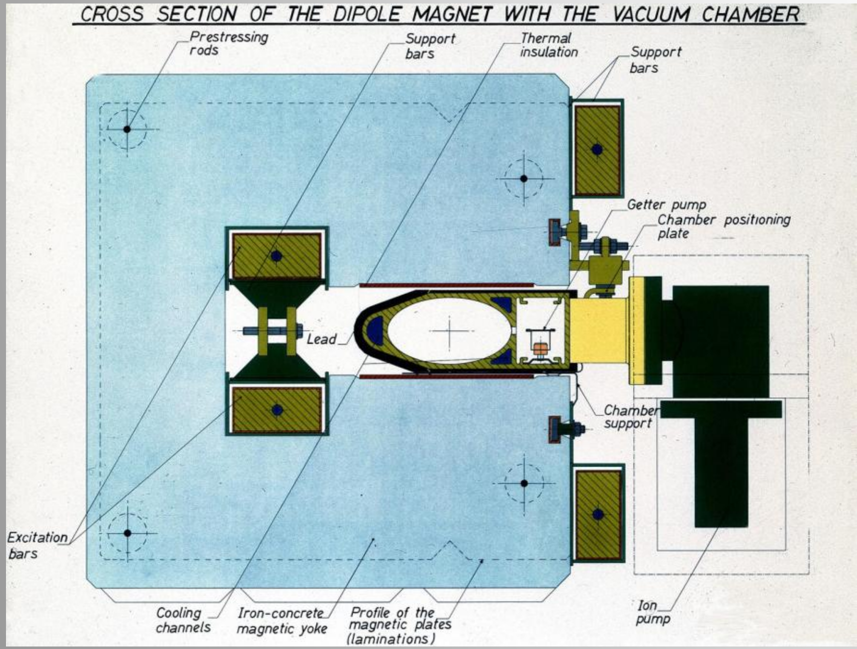

SPS quadrupoles

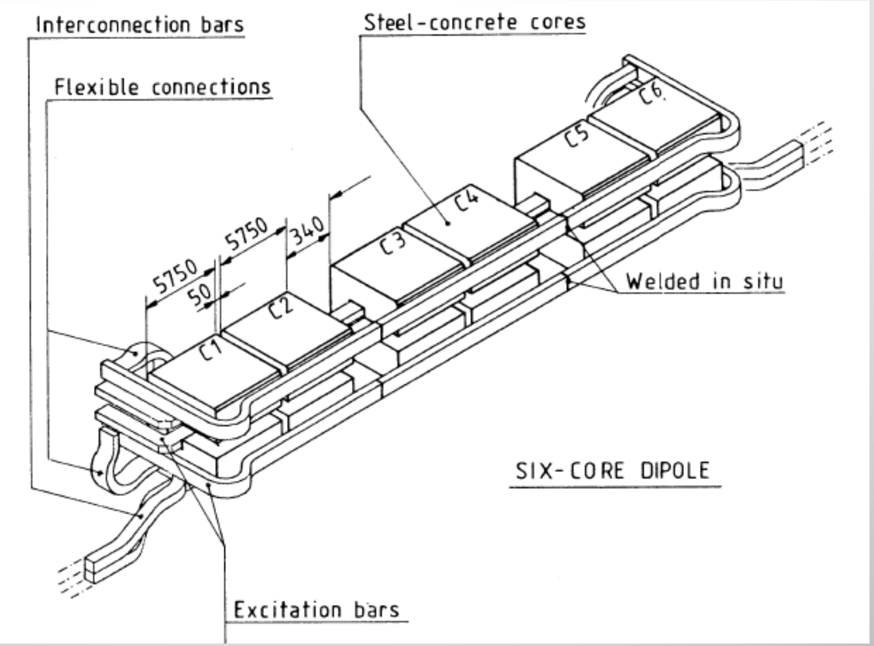

SPS main dipoles

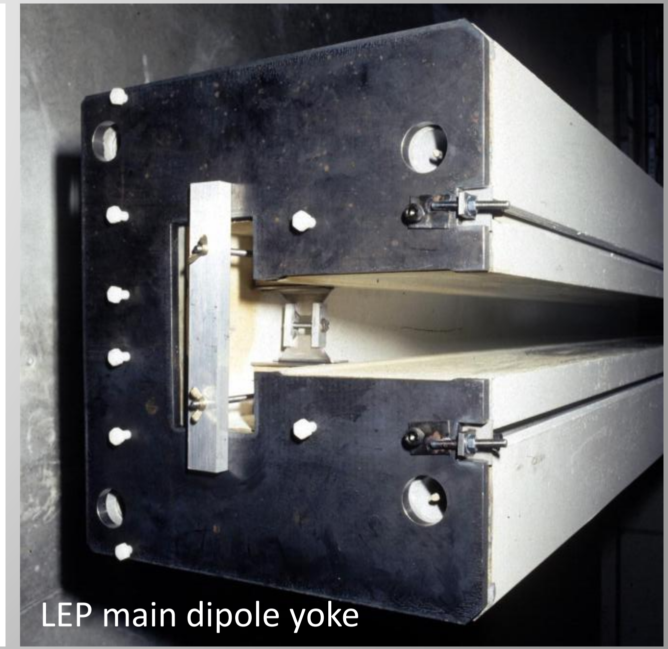
NC-magnets in the 1980s

LEP (1989), 27 km

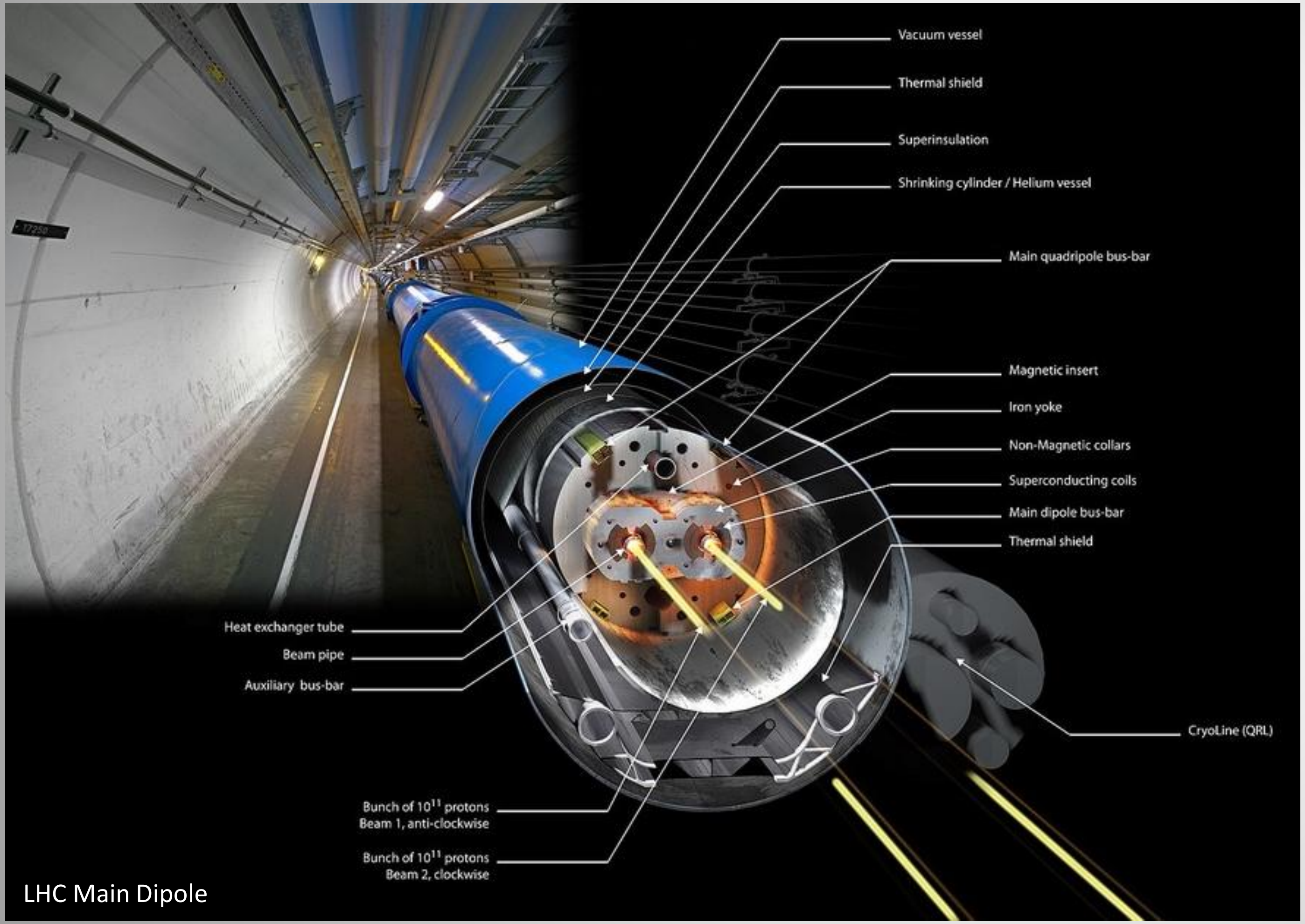
- Cycled field: 22 mT (20 GeV injection) to 108 mT (100 GeV)
- 5.75 m long ‘diluted’ magnet cores: 30% Fe / 70% concrete
- Four water cooled aluminium excitation bars
- Max. current: 4.5 kA



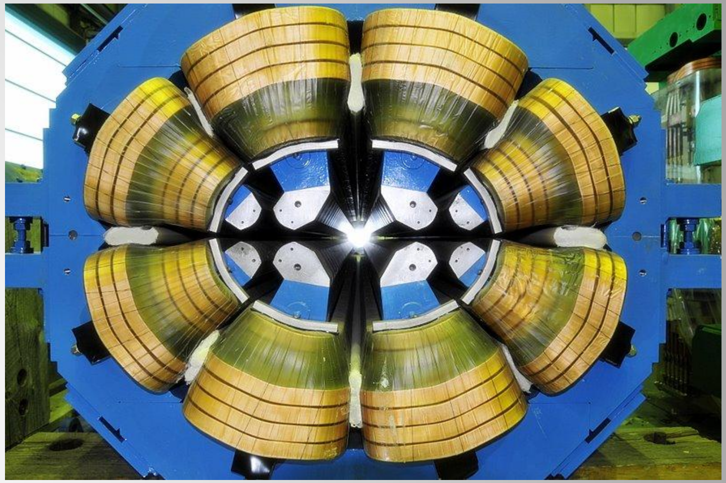



LEP main dipole yoke

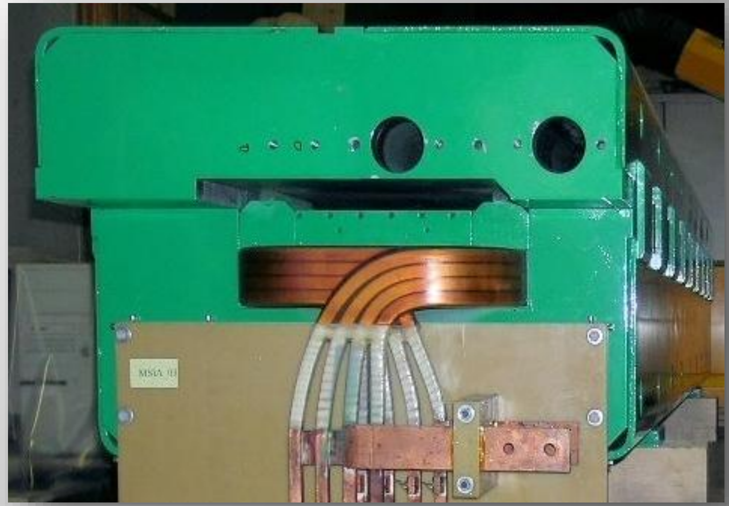
NC-magnets even in the LHC …



LHC Main Dipole

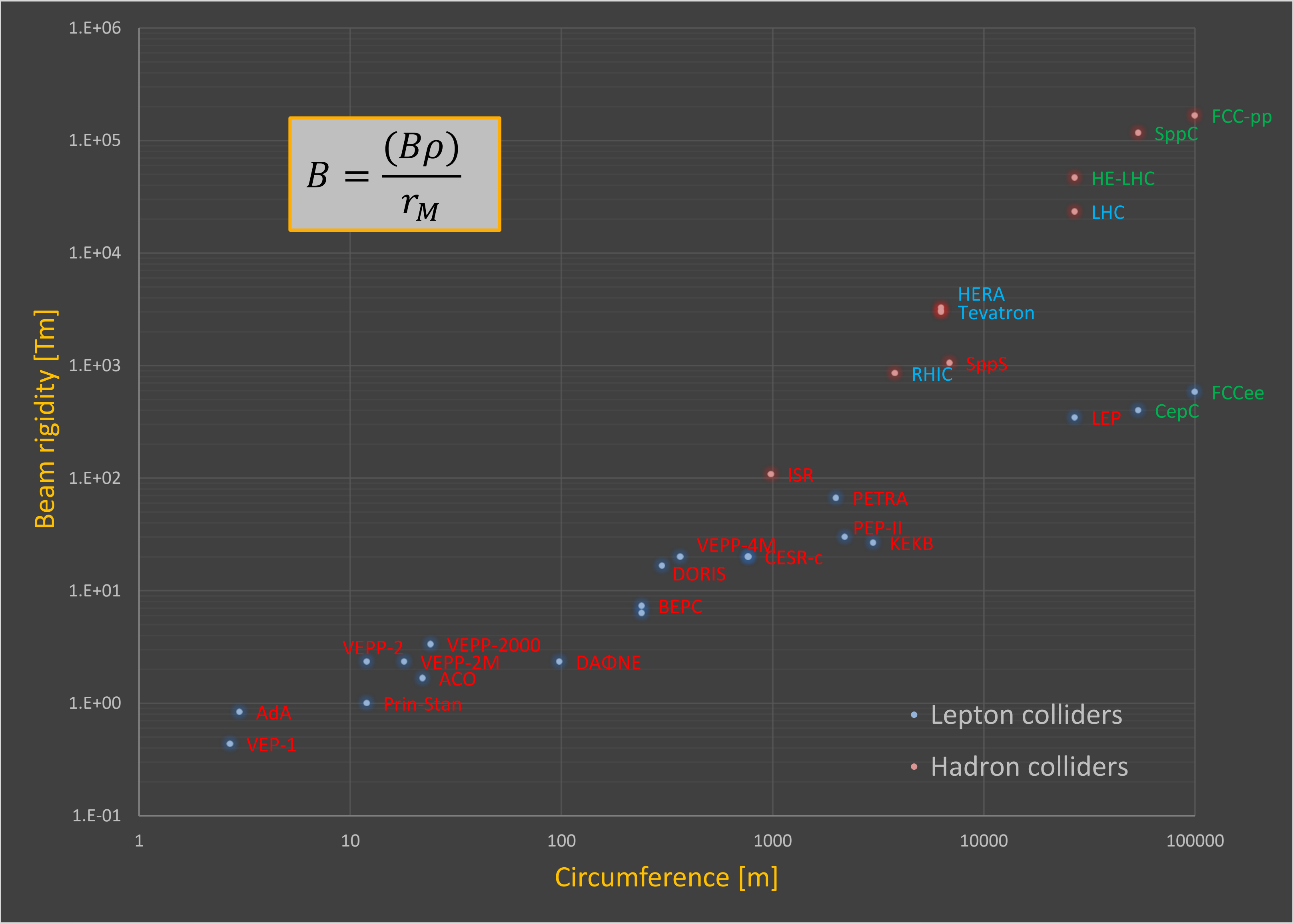


Double-aperture LHC quadrupole



LHC Lambertson Septum

Circular Colliders



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

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 and high-intensity beams:

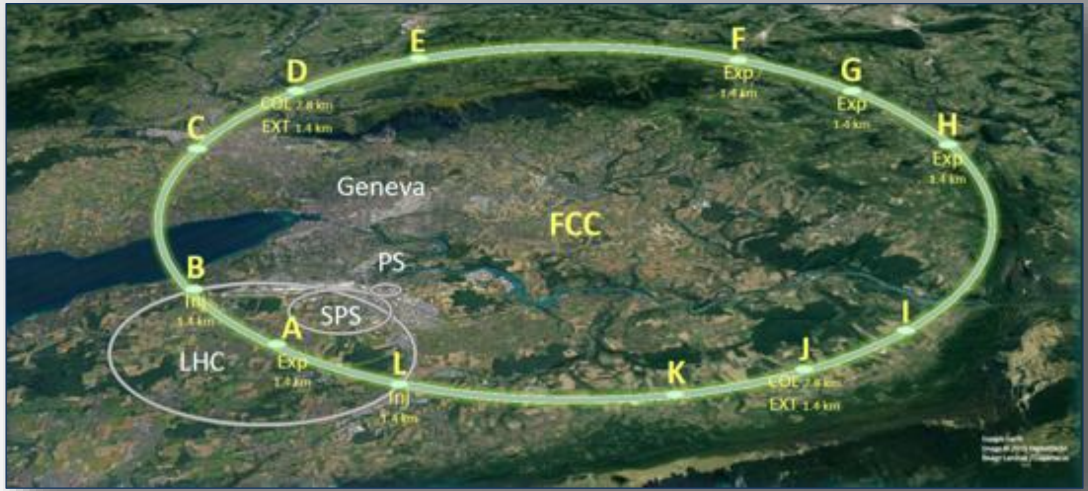
- Ionizing radiation impact on materials and electronics

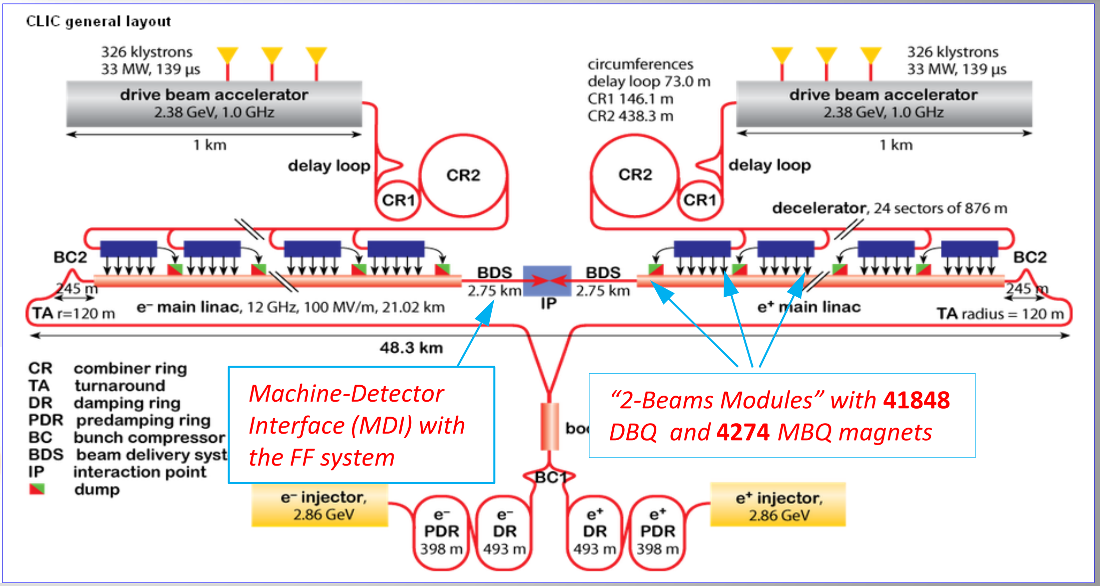
Hadron colliders:

- High magnetic fields

Lepton colliders (circular & linear):

- Alignment & stabilization
- Compact design & small apertures

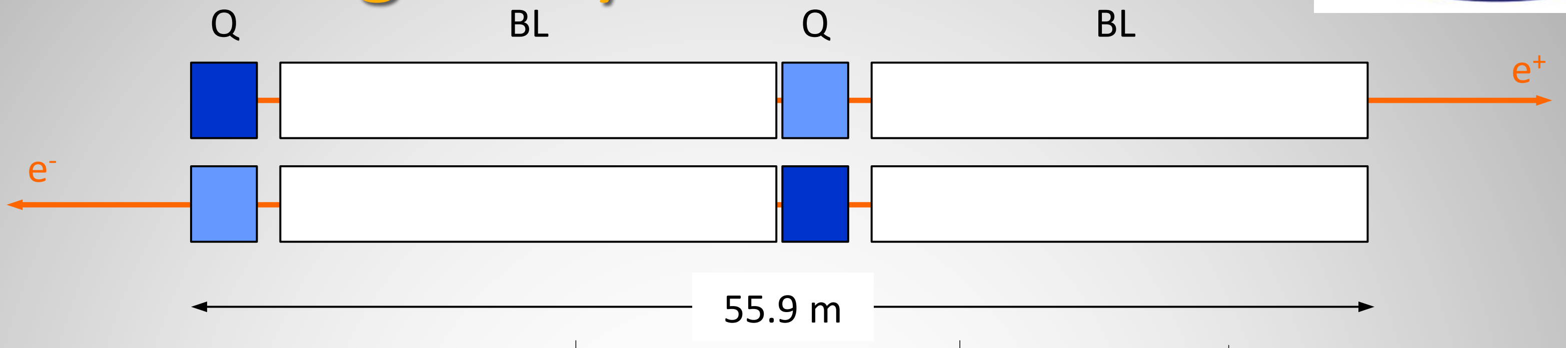




Machine-Detector Interface (MDI) with the FF system

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

Magnet system for FCC-ee



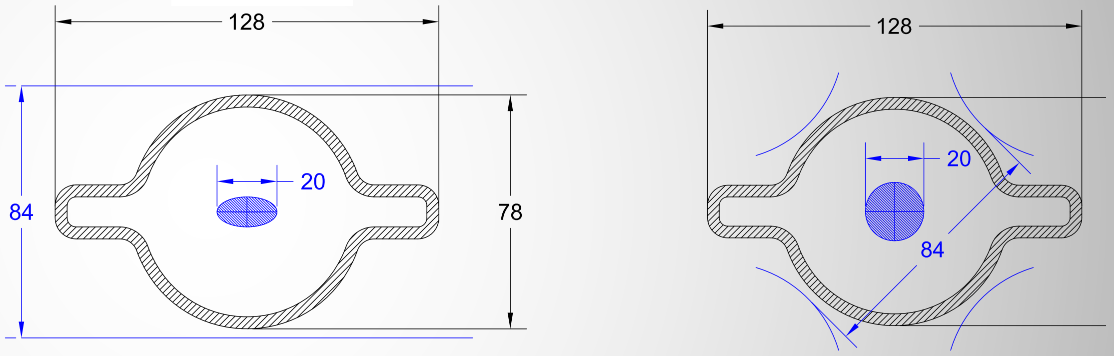
Double collider ~100 km circumference

Counter-rotating e+ / e- beams

DC operation with top-up injection

1450 FODO cells (each 55.9 m long)

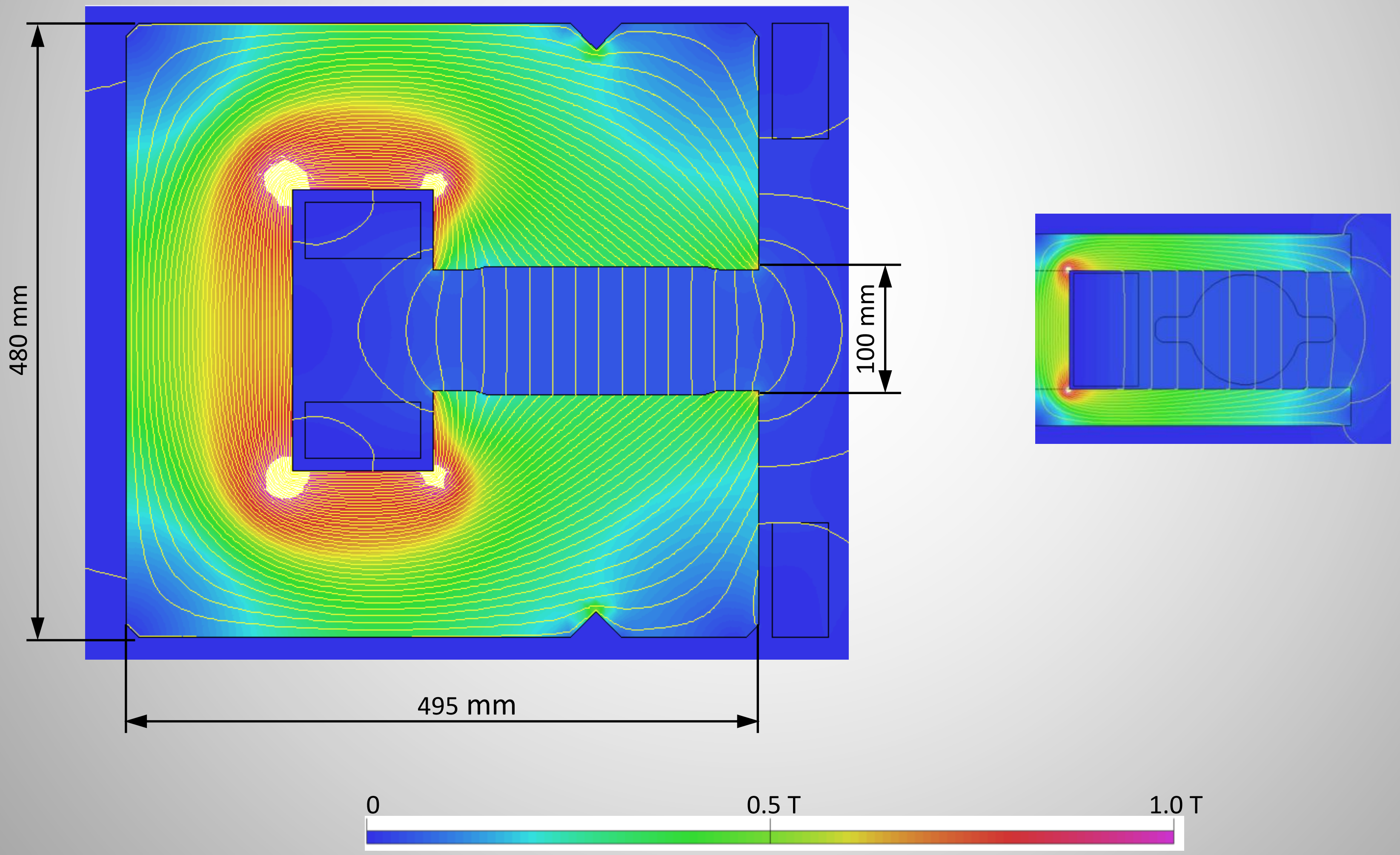
Tuneability ±1%



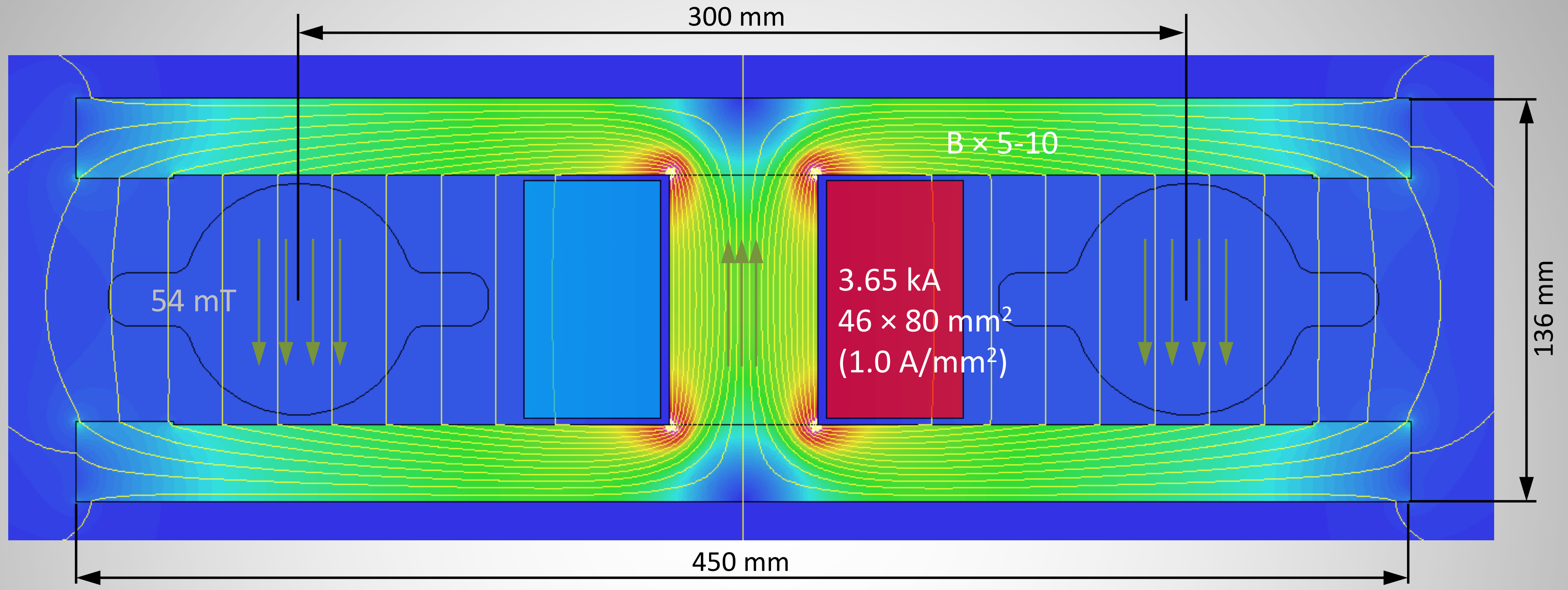
Parameter	Bending magnets	Quadrupole magnets
Quantity (per ring)	2900	1450 + 1450
Magnetic length	23.94 m	3.1 m
Aperture	128 mm x 84 mm	R = 42 mm
Inter-beam distance	300 mm	300 mm
Field / max. gradient at 175 GeV	54.3 mT	9.9 T/m
Goof field region	±10 mm horizontal	R = 10 mm
Field quality	< 10^{-4}	<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

Recap: LEP dipoles

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

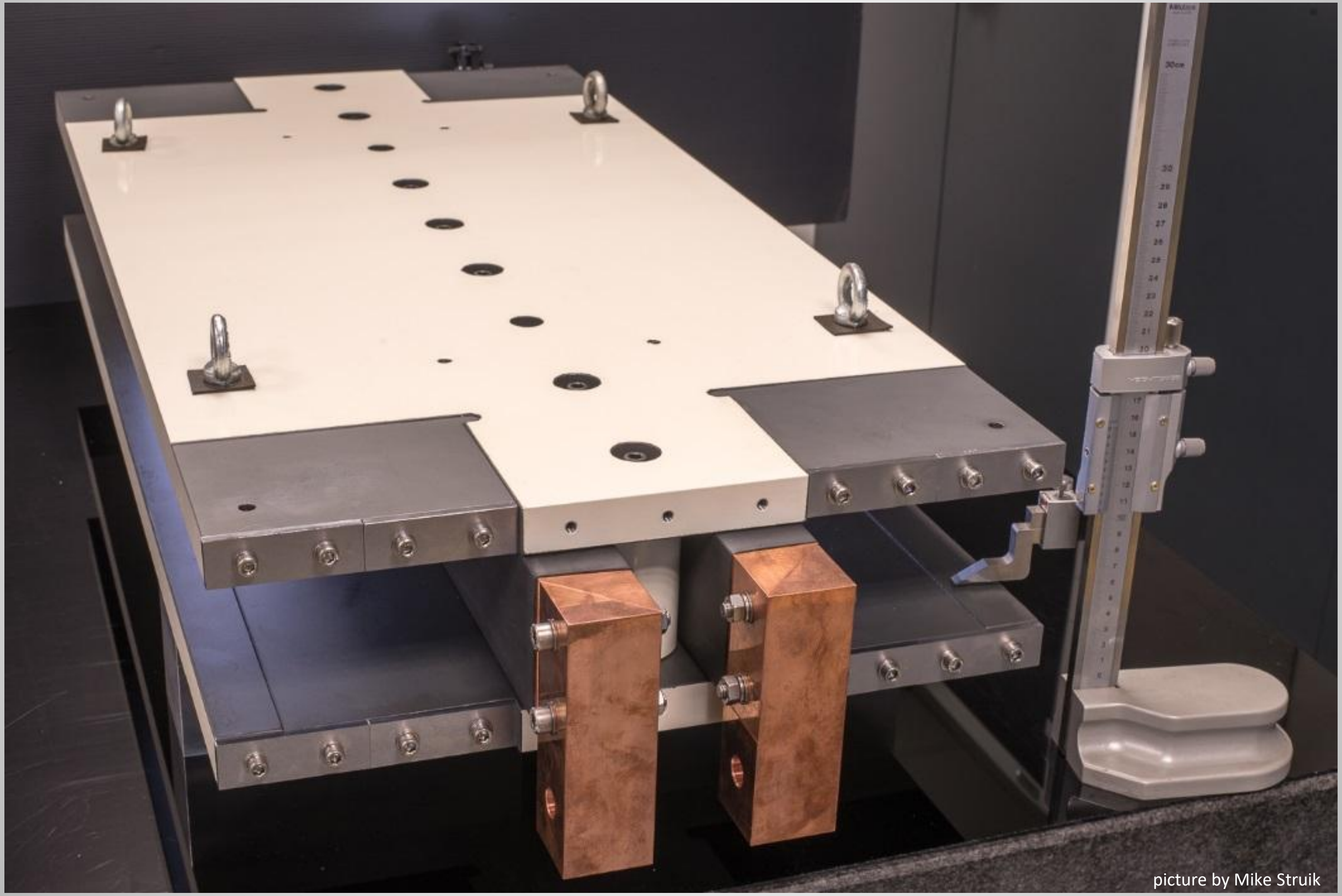


FCC-ee Twin dipole design



- 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 & 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)

Thanks for your attention…