Joint Universities Accelerator School

JUAS 2012

Archamps, France, 20 February 2012

Basic design and engineering of normal-conducting, iron-dominated electro-magnets

‘Introduction’

Th. Zickler, CERN

Scope of the lectures

Overview of electro-magnetic technology as used in particle accelerators considering *normal-conducting, iron-dominated* electro-magnets (generally restricted to direct current situations)

Main goal is to:

- Create a fundmental understanding in accelerator magnet technology
- Provide a guide book with practical instructions how to start with the design of a standard accelerator magnet
- Focus on applied and practical design aspects using 'real' examples
- Introduce finite element codes for practical magnet design

Not covered:

- permanent magnet technology
- super-conducting technology (see special lecture by M. Wilson)

Content

Lecture 1:

- Basic concepts and magnet types (15’)
- What do I need to know before starting ? (15’)

Lecture 2:

- Basic analytical design (90’)

Lecture 3:

- Numerical design (60’)

Lecture 4 (practical work @ CERN):

- Manufacturing technologies, materials,
- QA tests and measurements (120’)

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Basic design and engineering of normal-conducting, iron-dominated electro-magnets

Lecture 1a

‘Basic concepts and magnet types’

Th. Zickler, CERN

Basic concepts and magnet types

Overview on common magnet types and typical applications:

Dipoles

Quadrupoles

Sextupoles

Octupoles

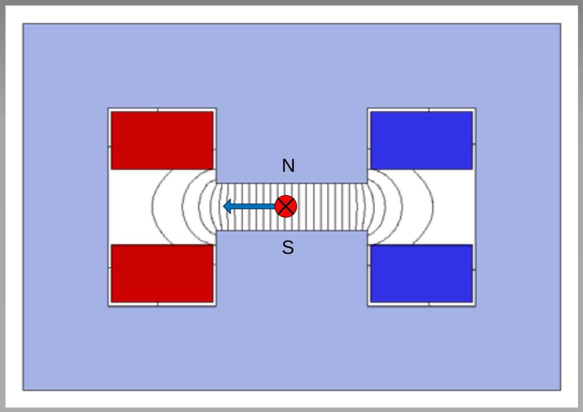
Skew magnets

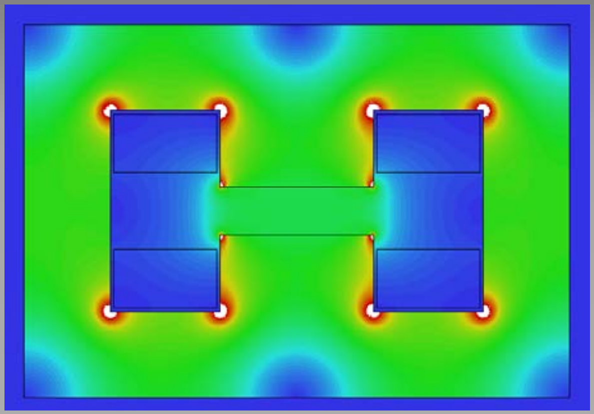
Combined function

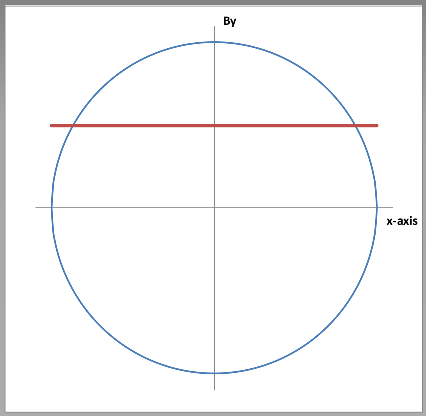
Special magnets

Dipoles

- Purpose: bend or steer the particle beam







- Pole = surface with constant scalar potential
- Equation for normal (non-skew) ideal (infinite) poles: $y = \pm r$ (r = half gap height)
- Magnetic flux density: $B_x = 0$; $B_y = b_1 = \text{const.}$
- System follows right hand convention

CERN

Dipoles

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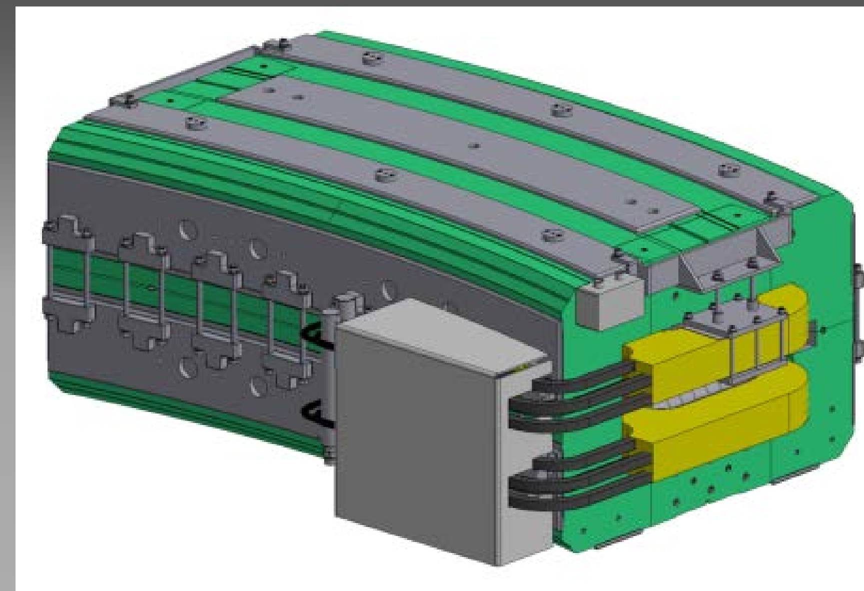
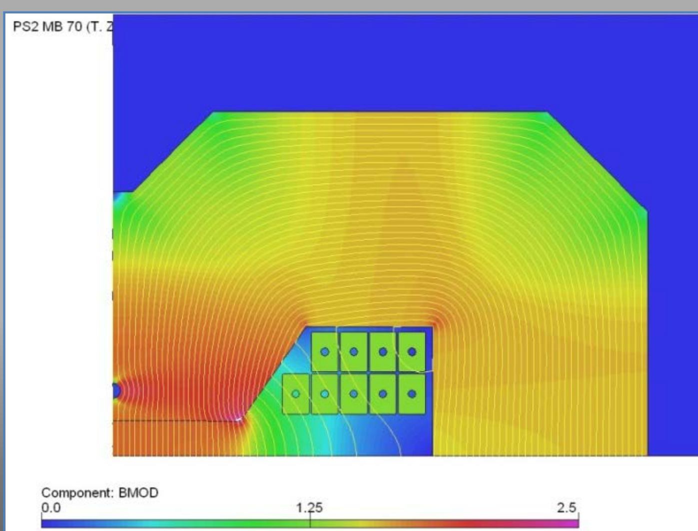
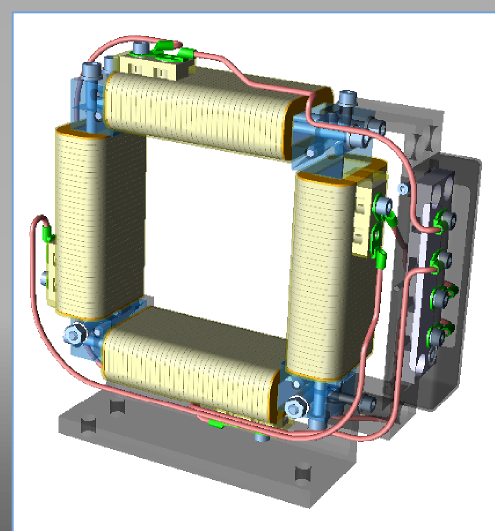
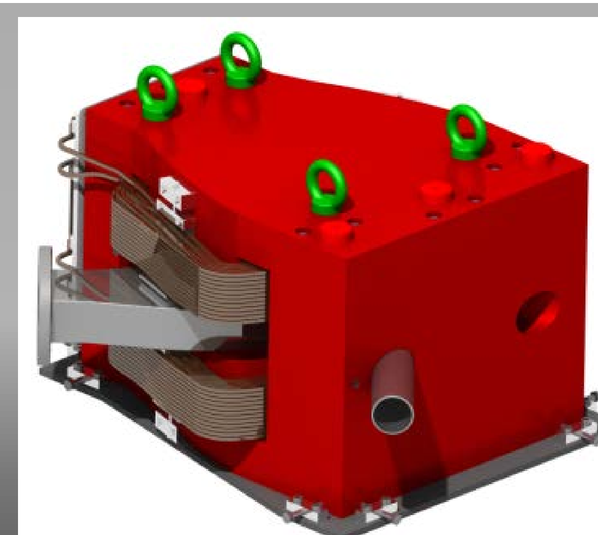


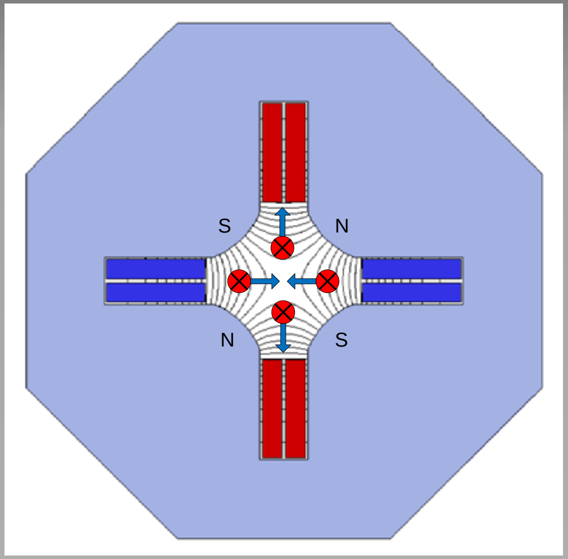


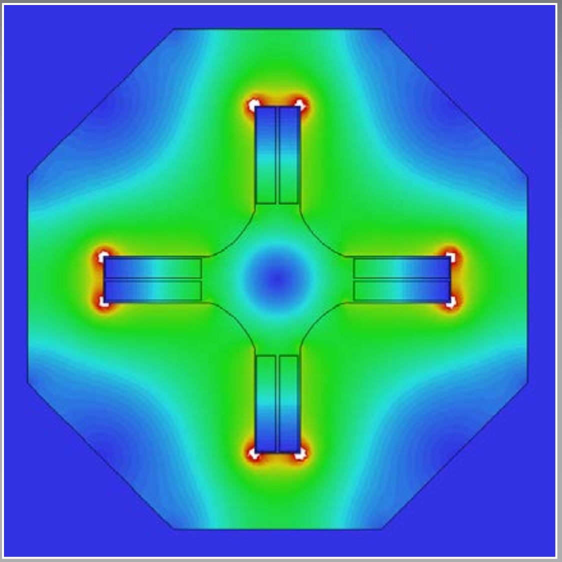


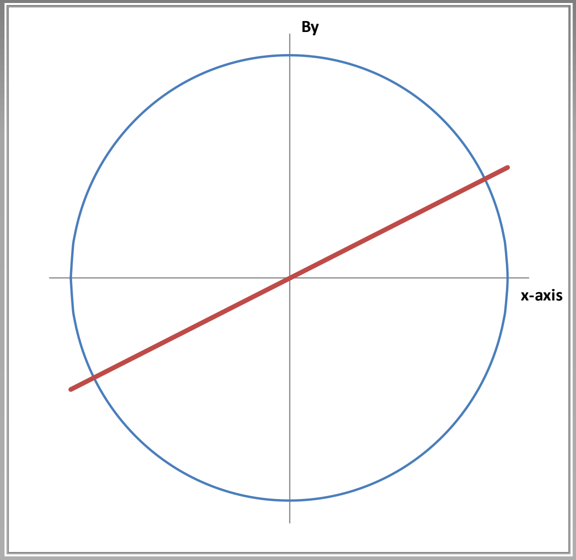


Quadrupoles

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

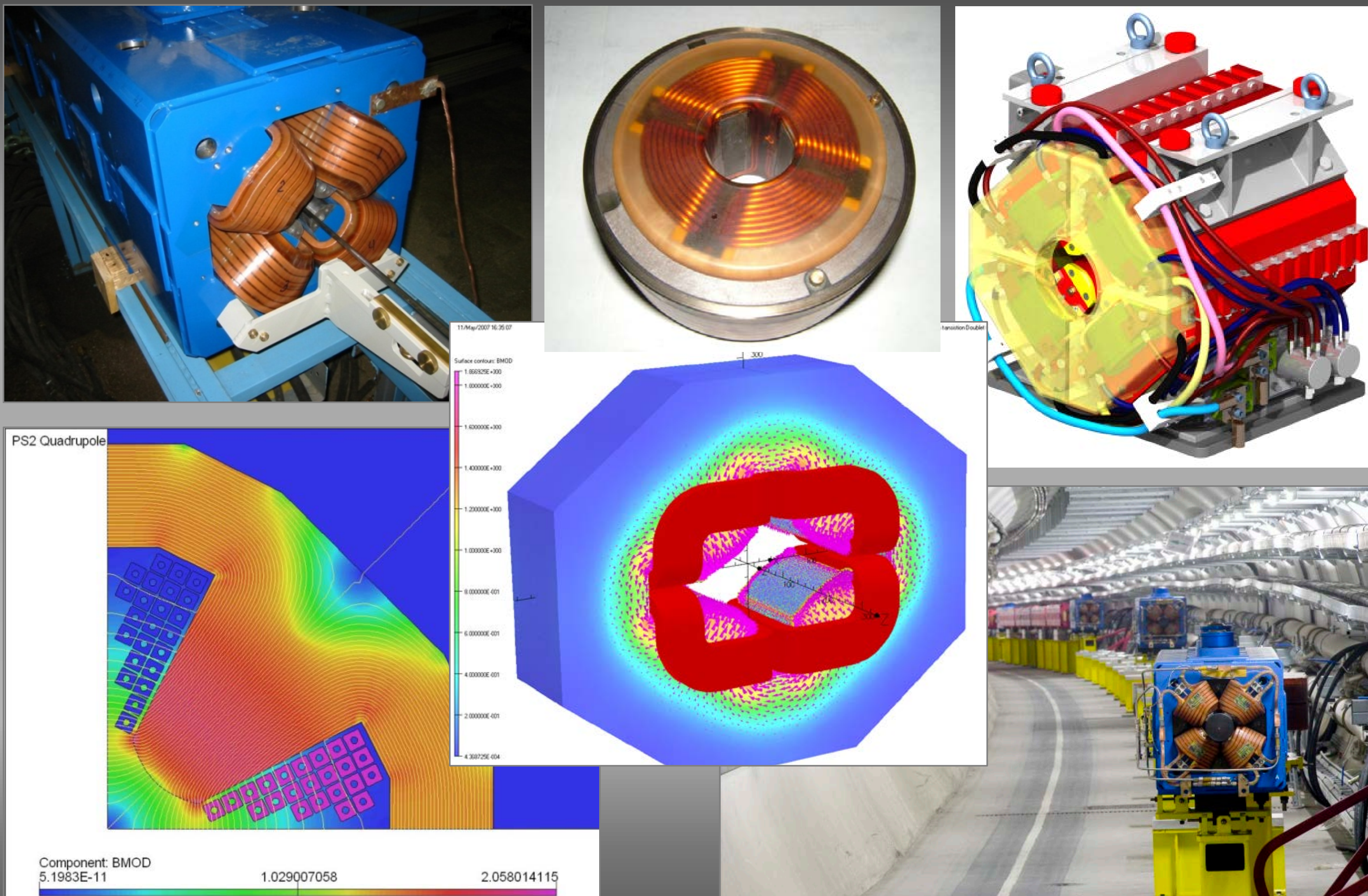






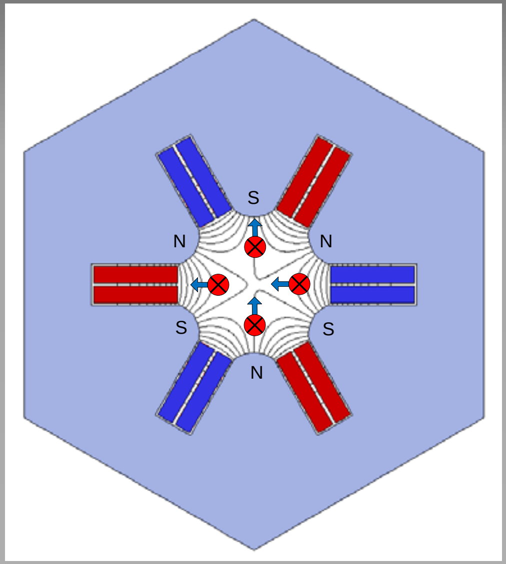
- Equation for normal (non-skew) ideal (infinite) poles: $2xy = \pm r^2$ (r = aperture radius)
- Magnetic flux density: $B_x = b_2 y$; $B_y = b_2 x$

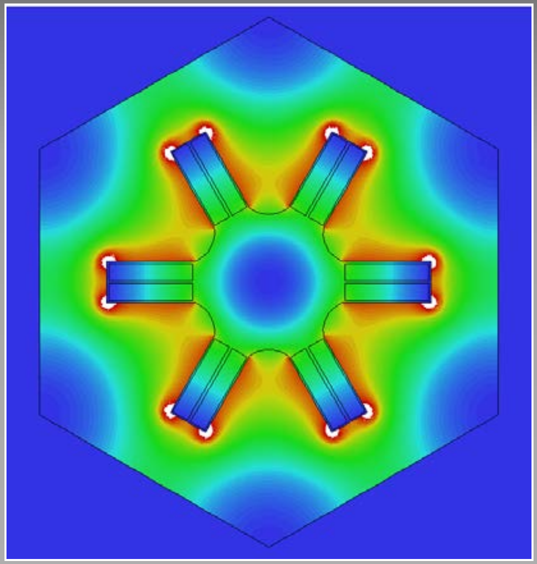
Quadrupoles

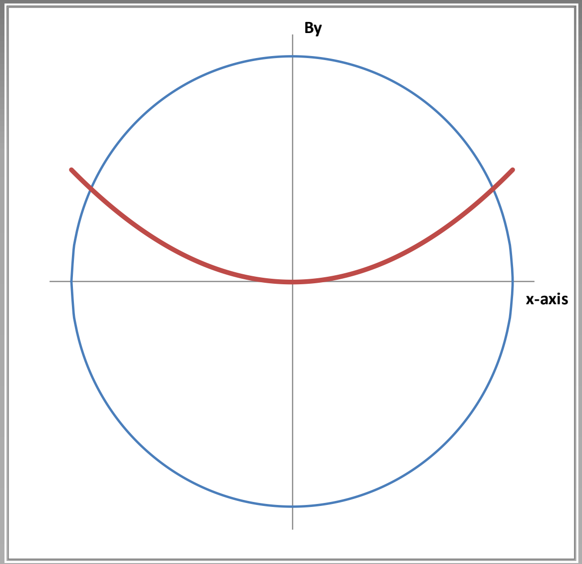


Sextupoles

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

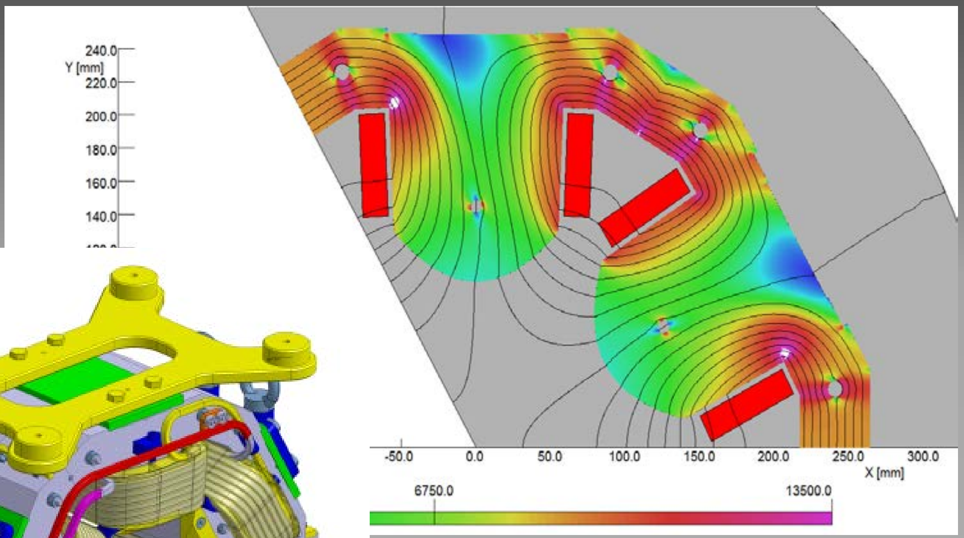






- Equation for normal (non-skew) ideal (infinite) poles: $3x^2y - y^3 = \pm r^3$ (r = aperture radius)
- Magnetic flux density: $B_x = b_3xy$; $B_y = b_3(x^2 - y^2)/3$

Sextupoles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200.0
180.0
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X [mm]
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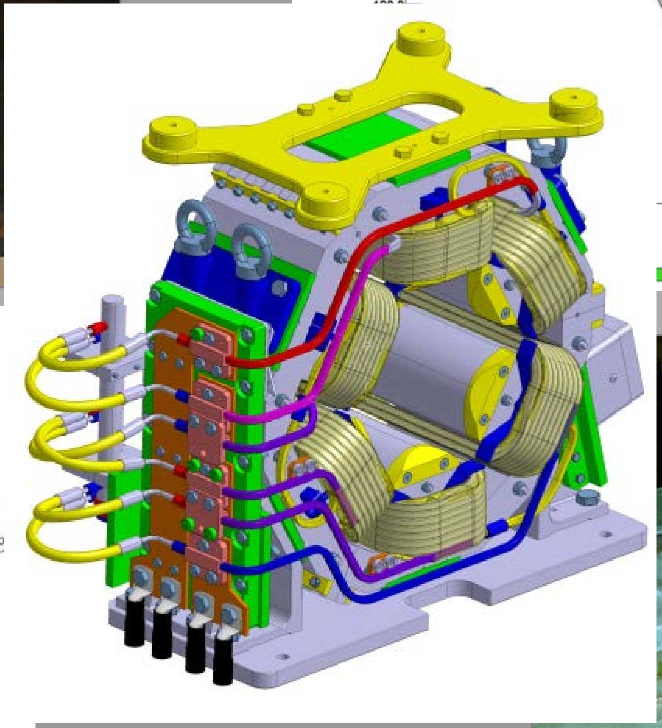
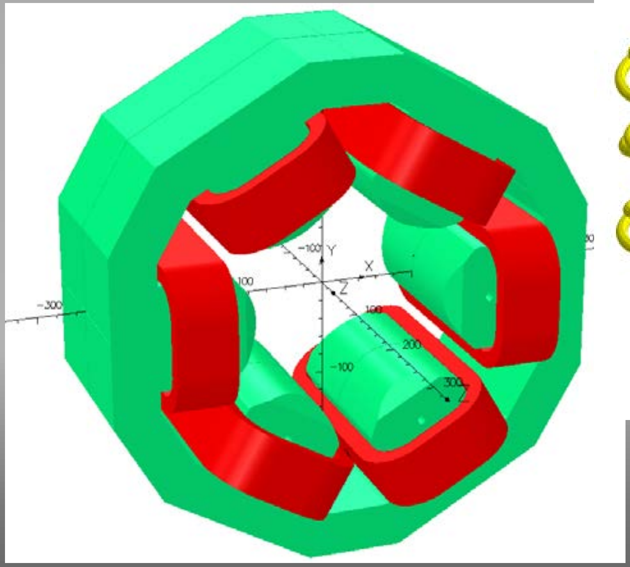
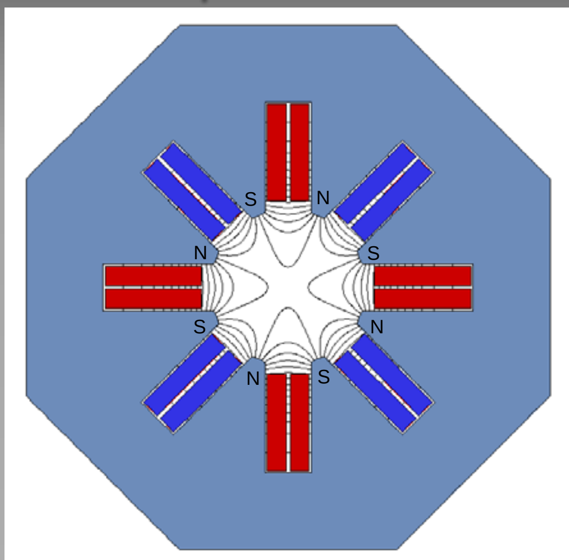
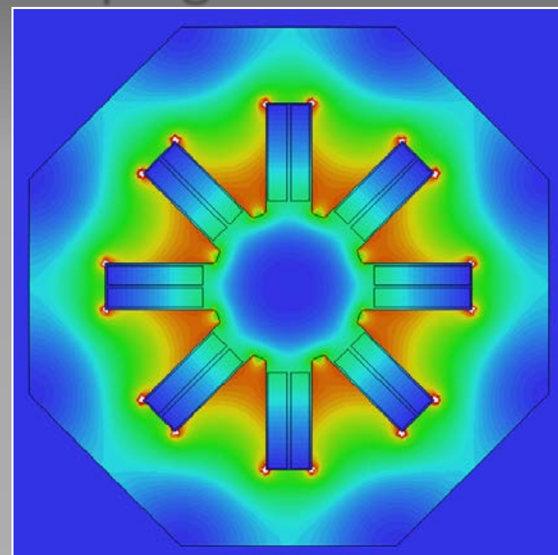


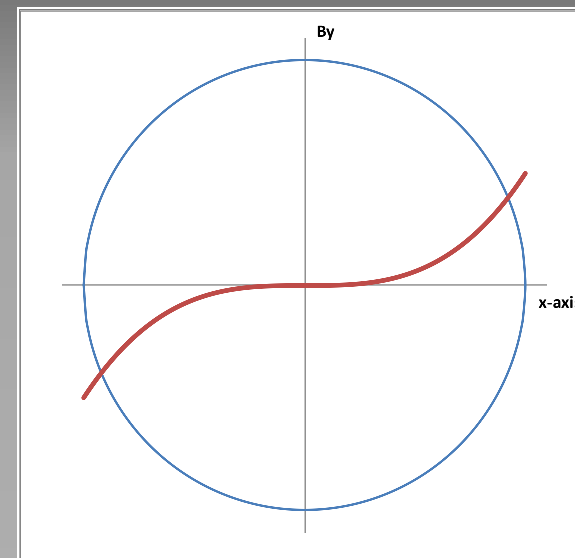


Octupoles

- Purpose: 'Landau' damping

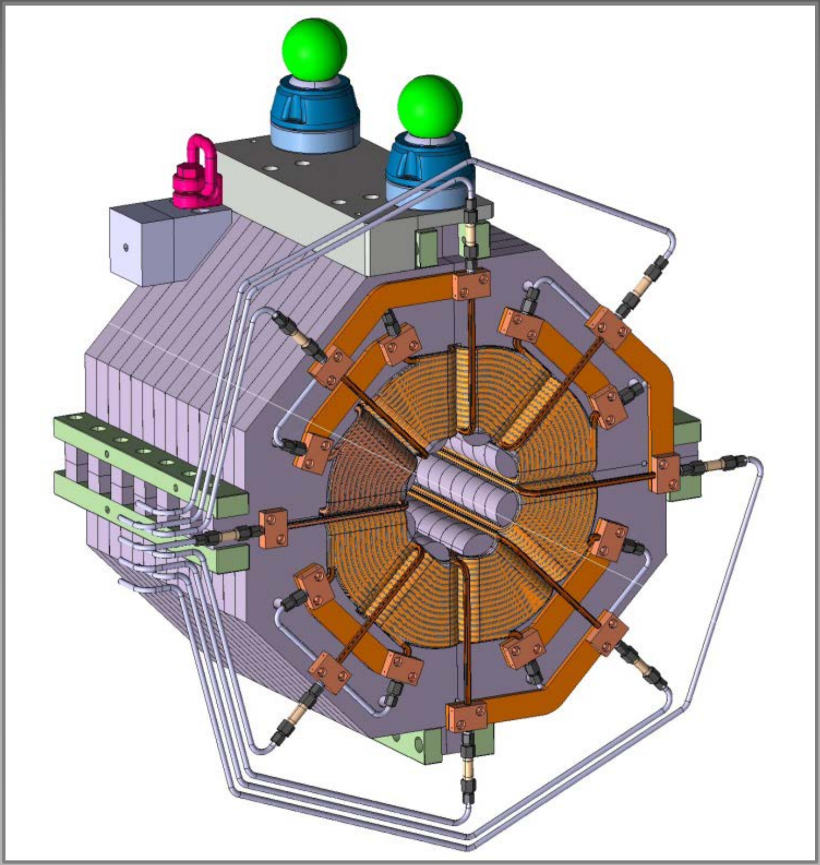
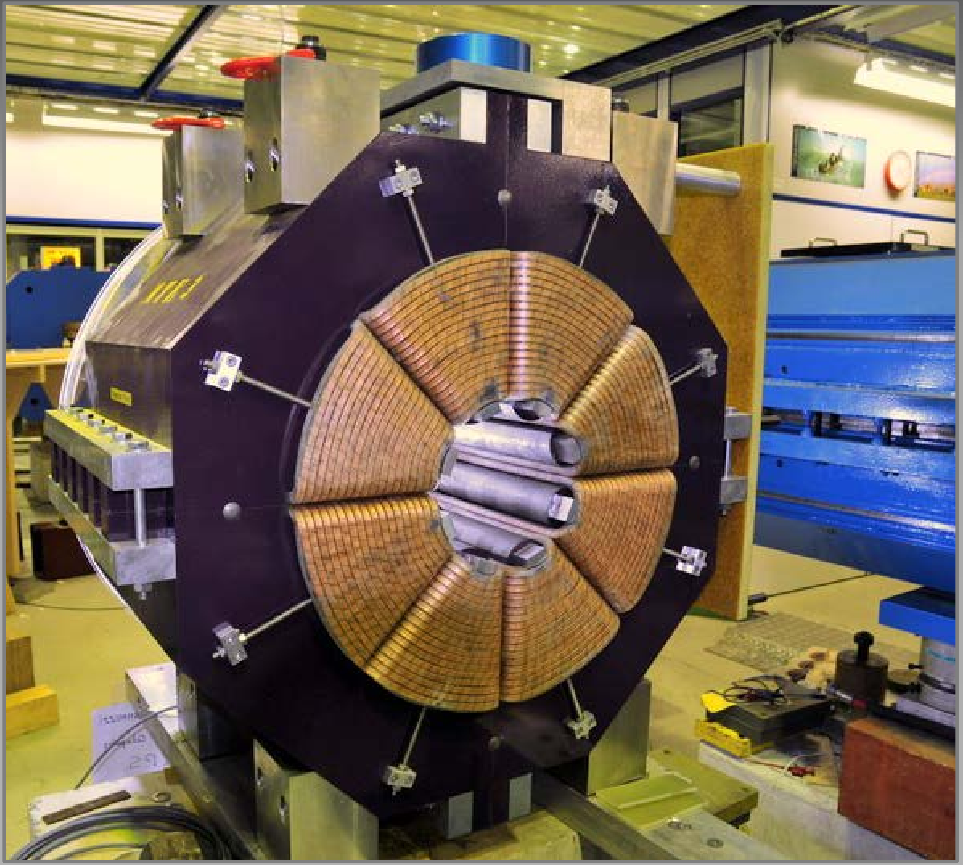






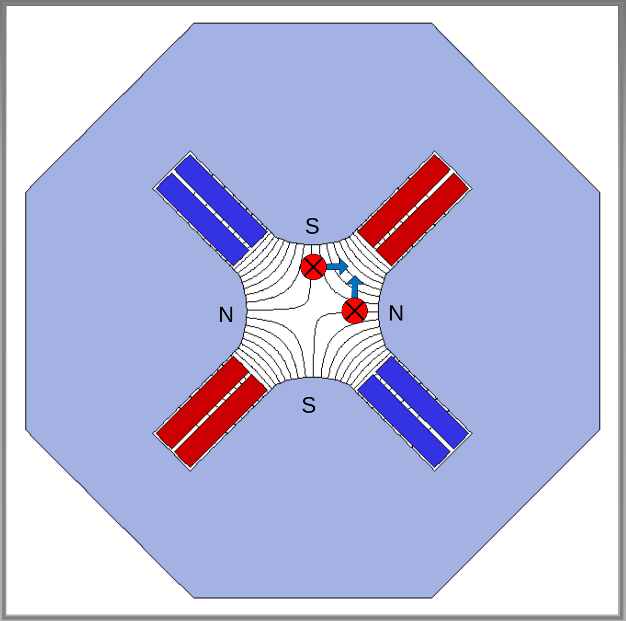
- Equation for normal (non-skew) ideal poles: $4(x^3y - xy^3) = \pm r^4$ (r = aperture radius)
- Magnetic flux density: $B_x = b_4(3x^2y - y^3)/6$; $B_y = b_4(x^3 - 3xy^2)/6$

Octupoles

Skew quadrupole

- Purpose: coupling horizontal and vertical betatron oscillations



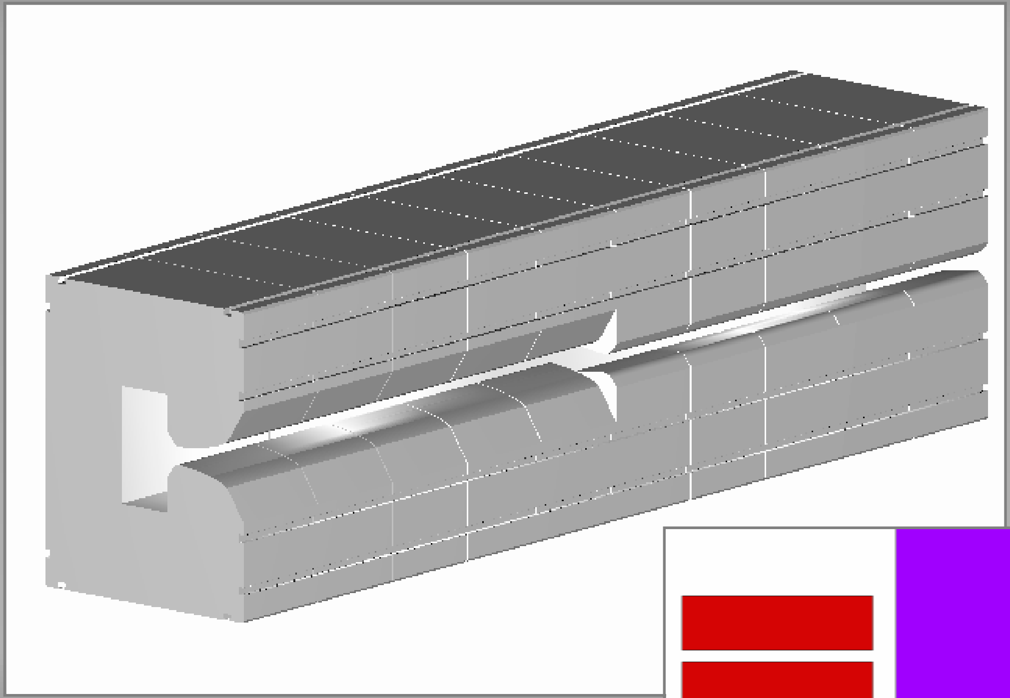
Rotation by π/2n

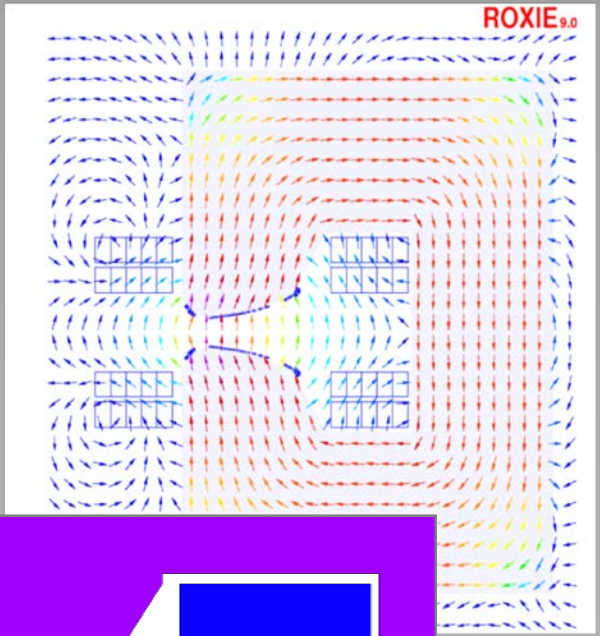
- Beam that has horizontal displacement (but no vertical) is deflected vertically
- Beam that has vertical displacement (but no horizontal) is deflected horizontally

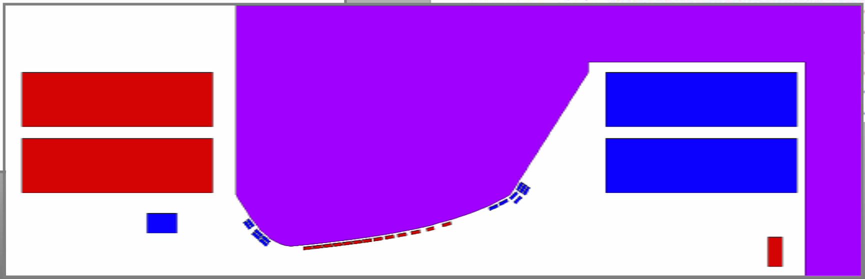
Combined function

Functions generated by pole shape (sum a scalar potentials):

- Amplitudes cannot be varied independently
- Dipole and quadrupole: PS main magnet (PFW, Fo8…)



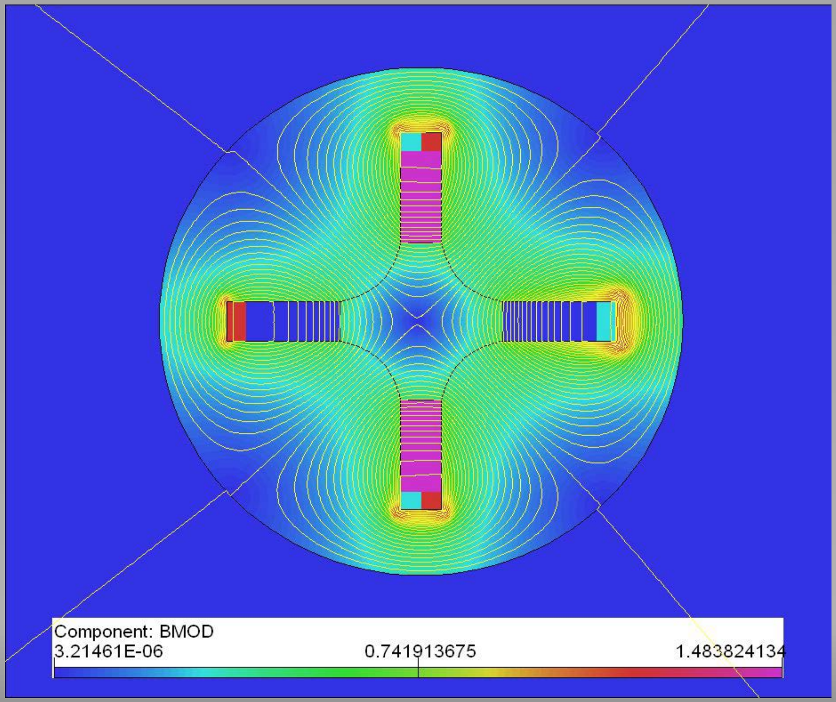


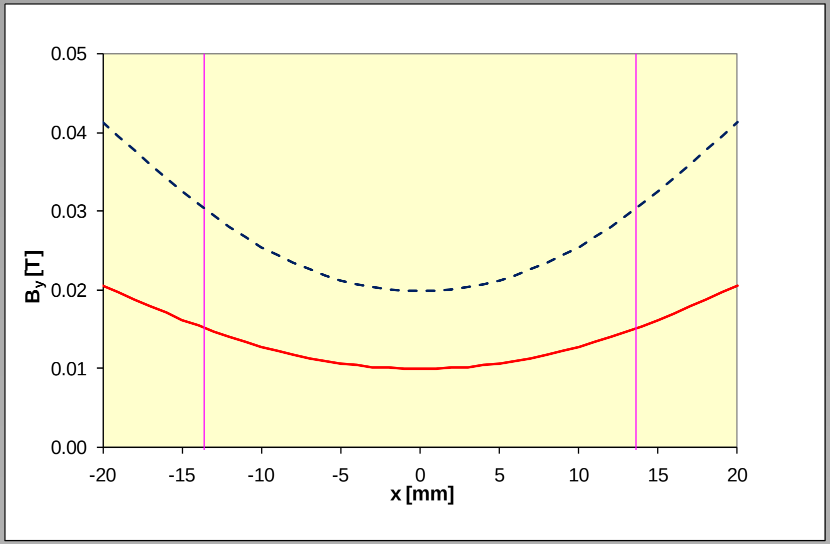


Combined function

Functions generated by individual coils:

Amplitudes can be varied independently

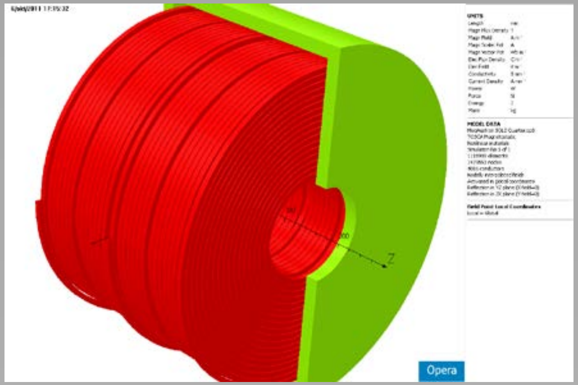


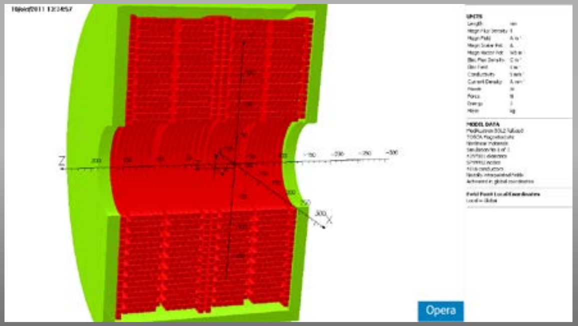


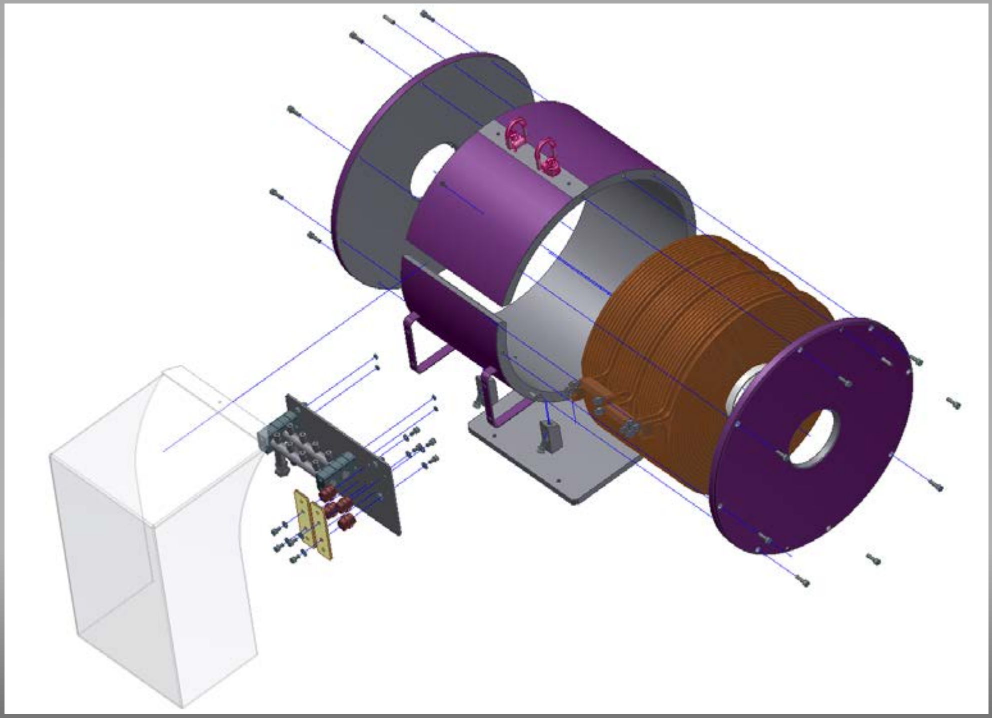
Quadrupole and corrector dipole (strong sextupole component in dipole field)

Solenoids

- Weak focusing, non-linear elements
- Main field component in z-direction, focusing by end fields
- Often used in experiments or low-energy lines







Special magnets

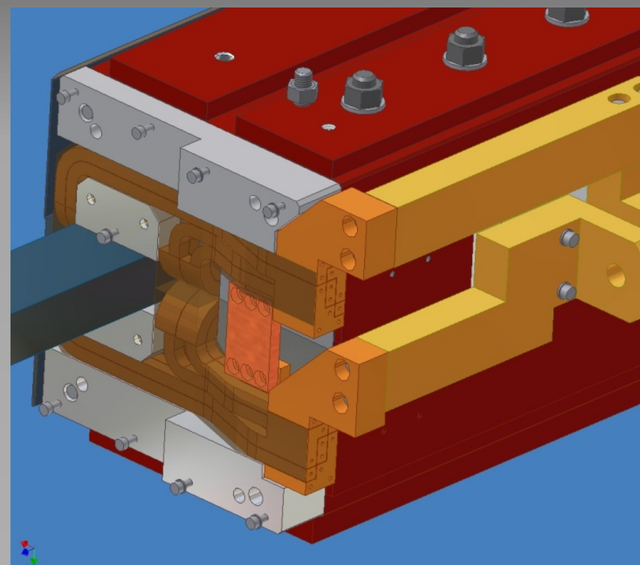
Septa

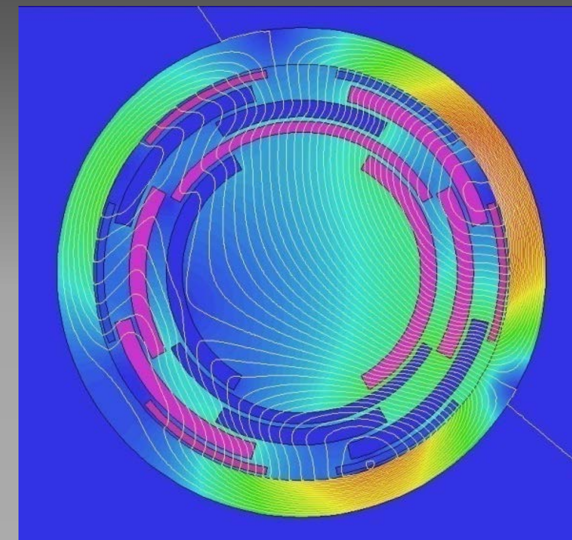
Kicker magnets

Bumper magnets

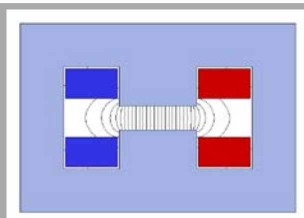
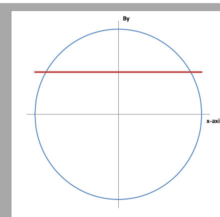
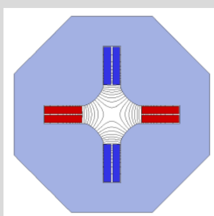
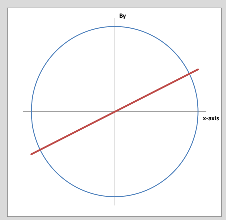
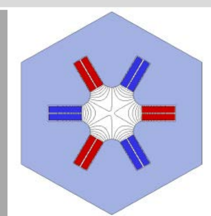
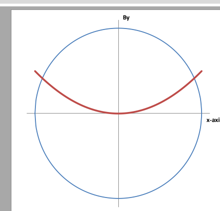
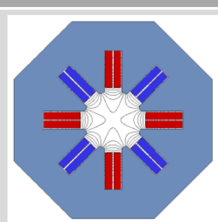
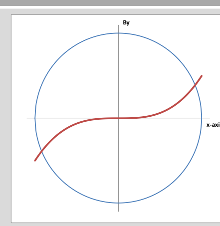
Scanner magnets

Multipole correctors





Summary

Pole shape	Field distribution	Pole equation	B_x, B_y
		$y = \pm r$	$B_x = 0$ $B_y = b_1 = B_0 = \text{const.}$
		$2xy = \pm r^2$	$B_x = b_2 y$ $B_y = b_2 x$
		$3x^2y - y^3 = \pm r^3$	$B_x = b_3 xy$ $B_y = b_3(x^2 - y^2)/2$
		$4(x^3y - xy^3) = \pm r^4$	$B_x = b_4(3x^2y - y^3)/6$ $B_y = b_4(x^3 - 3xy^2)/6$

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Lecture 1b

‘What do I need to know before starting?’

Th. Zickler, CERN

What do I need to know before starting the design?

Goals in magnet design

Magnet life cycle

Input parameters

General requirements

Performance requirements

Physical requirements

Interfaces

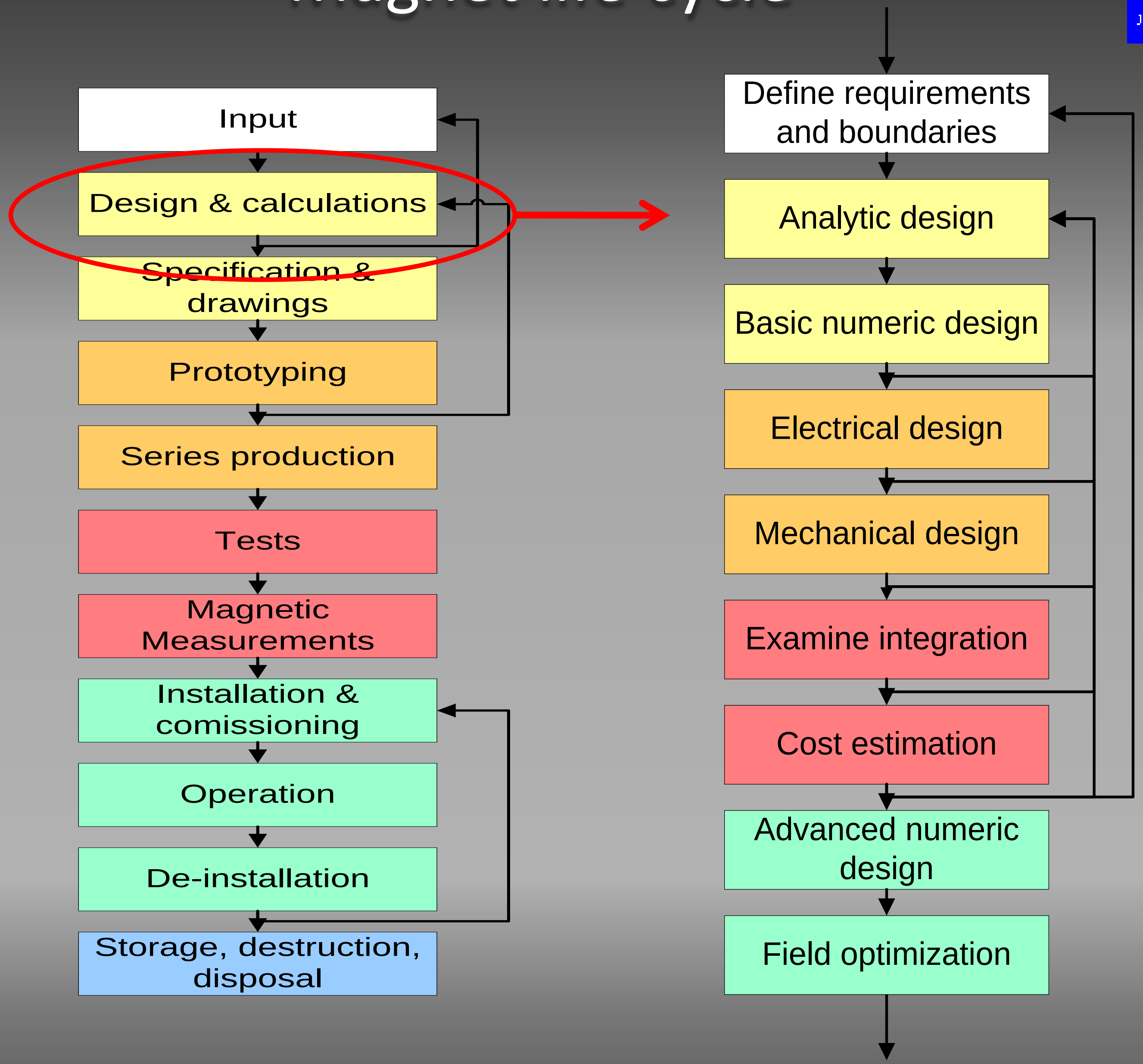
Environmental aspects

Goals in magnet design

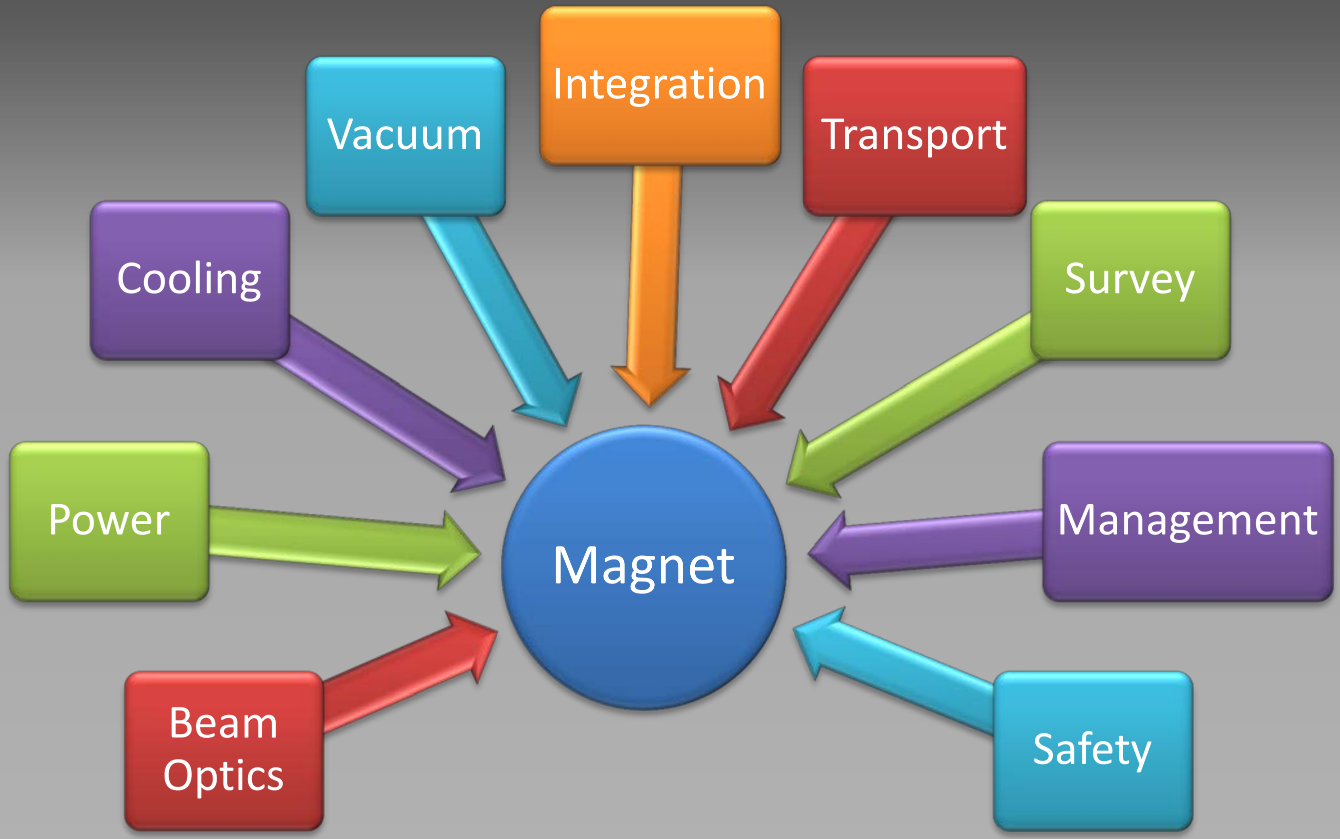
The goal is to produce a product just good enough to perform reliably with a sufficient safety factor at the lowest cost and on time.

- Good enough:
  - Obvious parameters clearly specified, but tolerance difficult to define
  - Tight tolerances lead to increased costs
- Reliability:
  - Get MTBF and MTTR reasonably low
  - Reliability is usually unknown for new design
  - Requires experience to search for a compromise between extreme caution and extreme risk (expert review)
- Safety factor:
  - Allows operating a device under more demanding condition as initially foreseen
  - To be negotiated between the project engineer and the management
  - Avoid inserting safety factors a multiple levels (costs!)

Magnet life cycle



Input parameters



A magnet is not a stand-alone device!

General requirements

Magnet type and purpose	• Dipole: bending, steering, extraction • Quadrupole, sextupole, octupole • Combined function, solenoid, special magnet
Installation	• Storage ring, synchrotron light source, collider • Accelerator • Beam transport lines
Quantity	• Installed units • Spare units (~10 %)

Performance requirements

Beam parameters

- Type of beam, energy range and deflection angle (k-value)
- Integrated field (gradient)
- Local field (gradient) and magnetic length

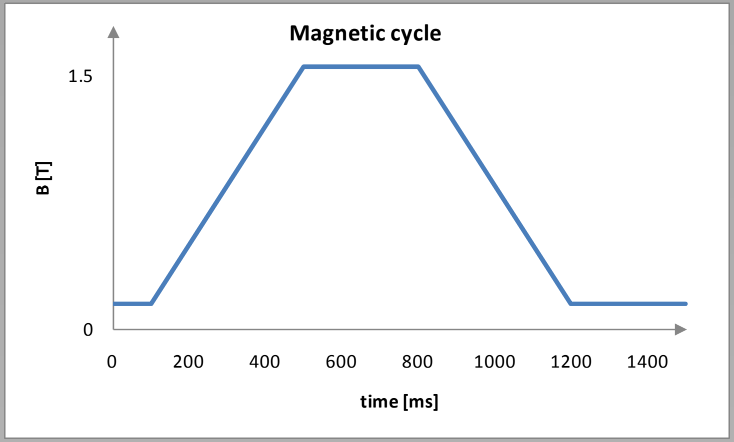
Aperture

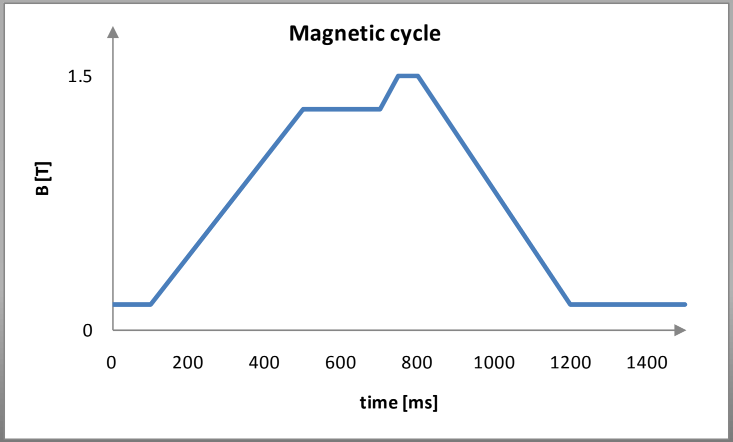
- Physical aperture
- ‘Good field region’

Performance requirements

Operation mode

- Continuous
- Pulse-to-pulse modulation (ppm)
- Fast pulsed
- Ramp rate (T/s)

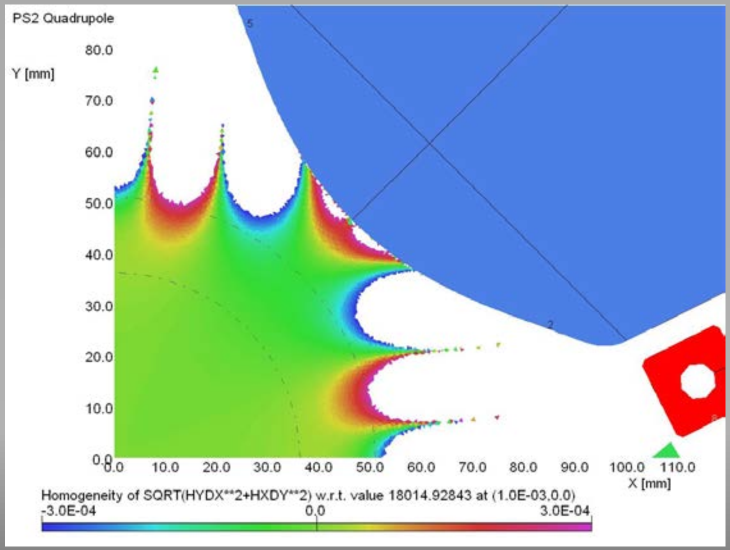


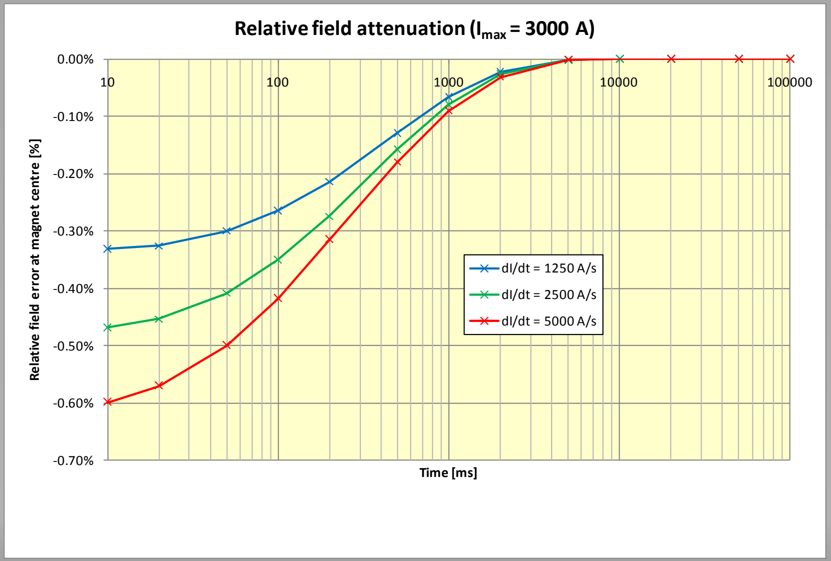


Performance requirements

Field quality

- Homogeneity (uniformity)
- Maximum allowed multipole errors
- Stability & reproducibility
- Settling time (time constant)
- Allowed residual field





Physical requirements

Geometric boundaries

- Available space
- Transport limitations
- Weight limitations

Accessibility

- Crane
- Connections (electrical, hydraulic)
- Alignment targets

Interfaces

Equipment linked to the magnet is defining the boundaries and constraints

Power converter	• Max. current (peak, RMS) • Max. voltage • Pulsed/dc
Cooling	• Max. flow rate and pressure drop • Water quality (aluminium/copper circuit) • Inlet temperature • Available cooling power
Vacuum	• Size and material of vacuum chamber • Space for pumping ports, bake out • Captive vacuum chamber

Environmental aspects

Other aspects, which can have an influence on the magnet design

Environment temperature	• Risk of condensation • Heat dissipation into the tunnel
Ionizing radiation	• High radiation levels require radiation hard materials • Special design to allow fast repair/ replacement
Electro-magnetic compatibility	• Magnetic fringe fields disturbing other equipment (beam diagnostics) • Surrounding equipment perturbing field quality
Safety	• Electrical safety • Interlocks

Summary

1. Collect all necessary information

2. Understand the requirements, constraints and interfaces

3. Summarize them in a functional specification