CERN Accelerator School
Specialized Course on Magnets
Bruges, Belgium, 16-25 June 2009

# 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)

Introduction in the appliance of finite element codes for practical magnet design, using OPERA 2D of Vector Fields Ltd.

Main goal is to provide a guide book with practical instructions how to start with the design of a standard accelerator magnet focusing on applied and practical design aspects

These lectures are meant for students of magnet design and engineering working in the field of accelerator science – not so much for the experts

Not covered:

- permanent magnet technology (see special lecture by J. Bahrdt)
- super-conducting technology (see special lecture by L. Bottura)

# Disclaimer

Please note:

- Several of the presented equations and formulas are not a precise physical description
- They are meant to be engineering approximations to allow drafting a quick zero-order design and are indicated in the following lectures with (*)
- Usually they are applicable for ´standard ´magnets, which assumes the ration between the magnet length and the aperture to be at least 10

# Content

Lecture 1:

- Basic concepts and magnet types (30')
- What do I need to know before starting ? (30')

Lecture 2:

- Basic analytical design – part 1 (60')

Lecture 3:

- Basic analytical design – part 2 (60')

Lecture 4:

- Numerical design (60')

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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

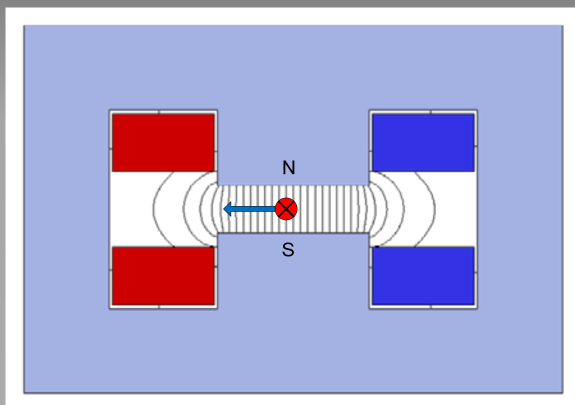
Skew magnets

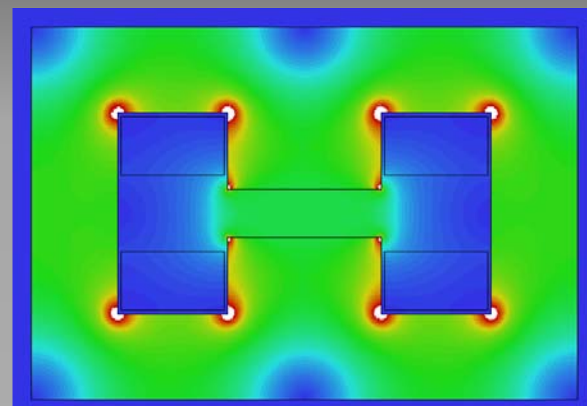
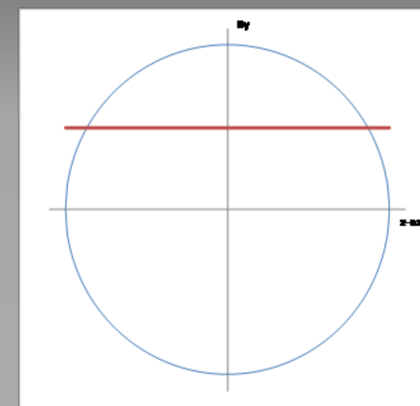
Combined function

Special magnets

# Dipoles

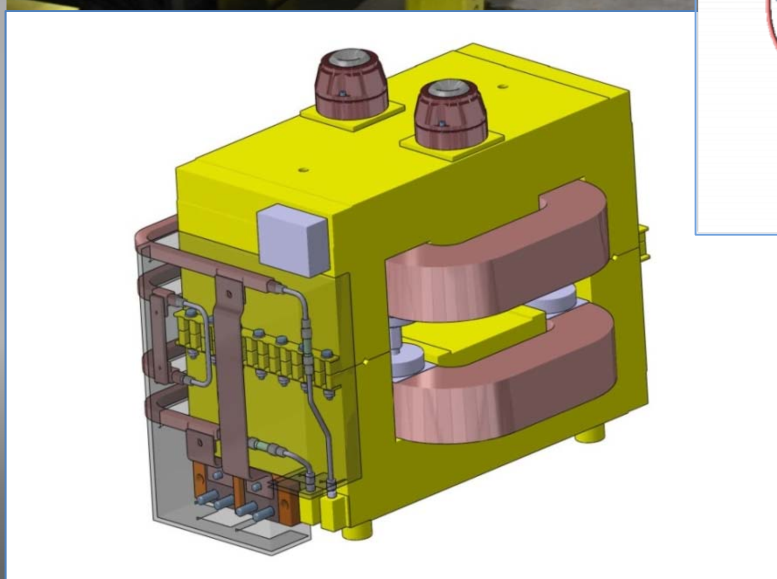
- Purpose: bend or steer the particle beam

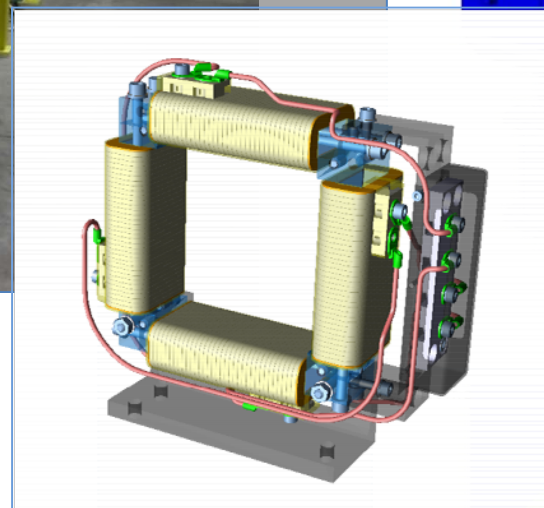


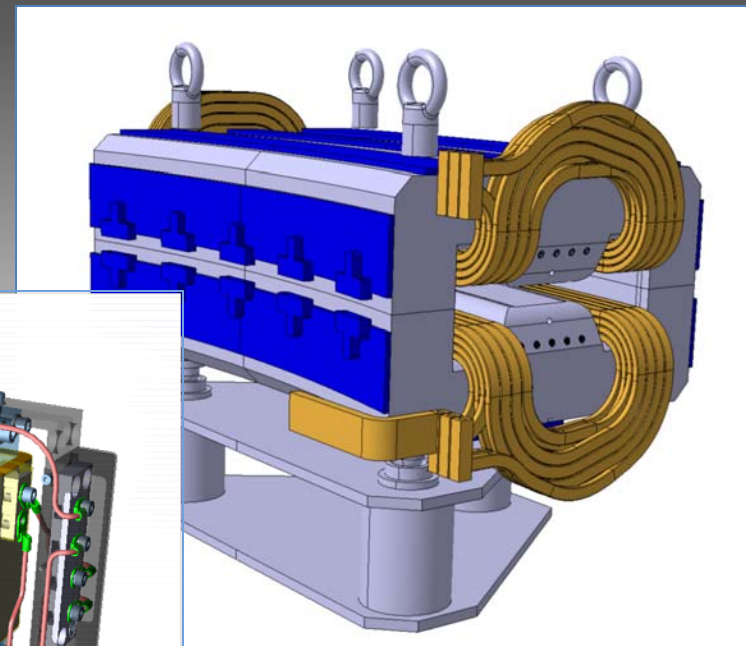



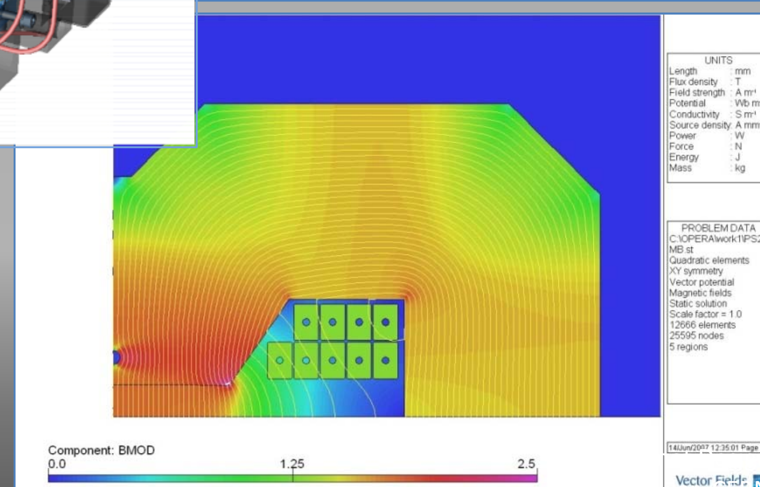
- Equation for normal (non-skew) ideal (infinite) poles: $y = \pm r$ (r = half gap height)
- Magnetic flux density: $B_y = a_1 = B_0 = \text{const.}$
- 'Allowed' harmonics: n = **1**, 3, 5, 7, ... (= 2n pole errors)

# Dipoles



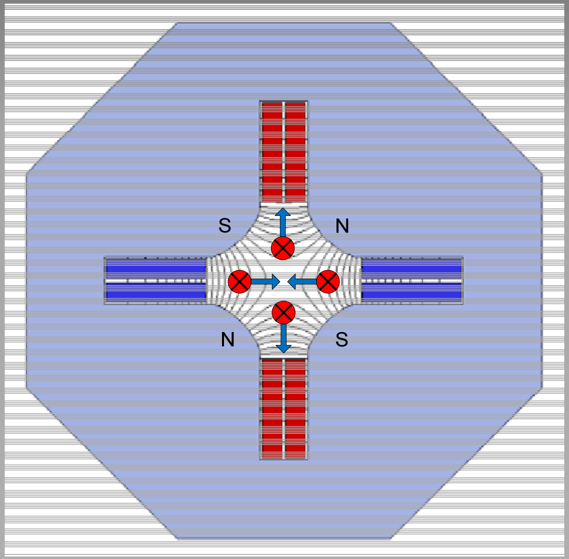


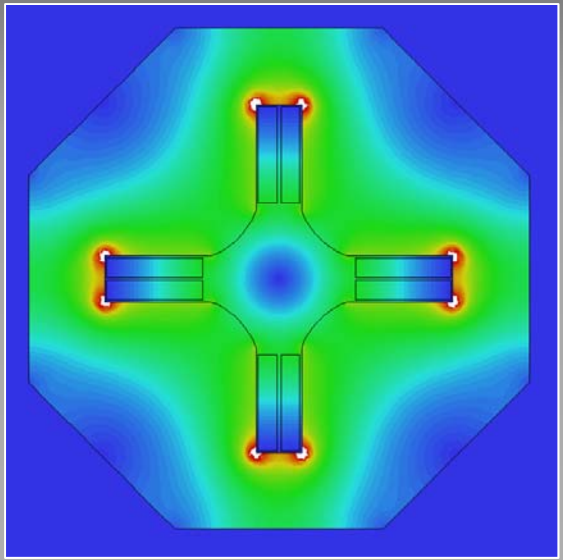


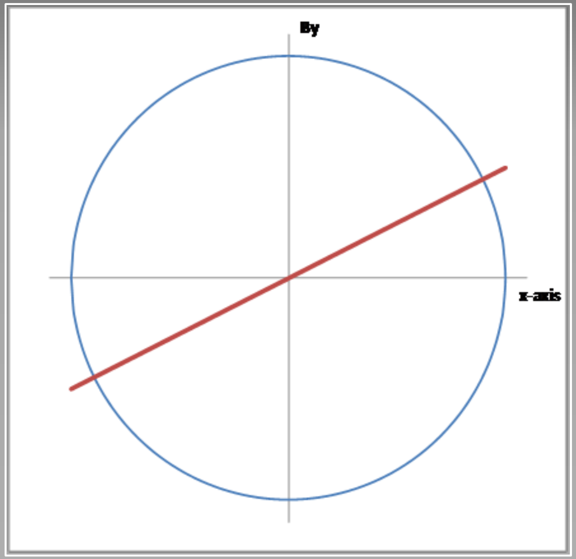

UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density : A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg
PROBLEM DATA
C:\OPERA\work1\PS2
MB.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
12666 elements
25595 nodes
5 regions
14/Jun/2007 12:35:01 Page 38
Component: BMOD
0.0
1.25
2.5
Vector Fields

# Quadrupoles

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

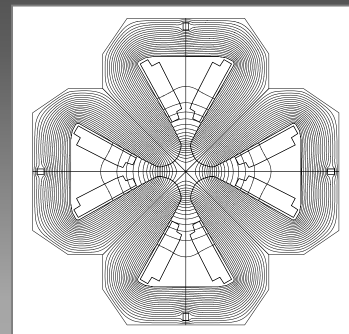


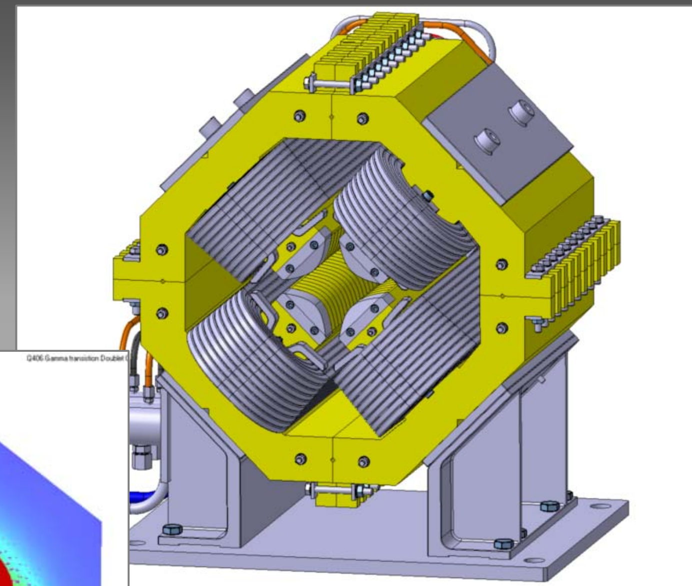



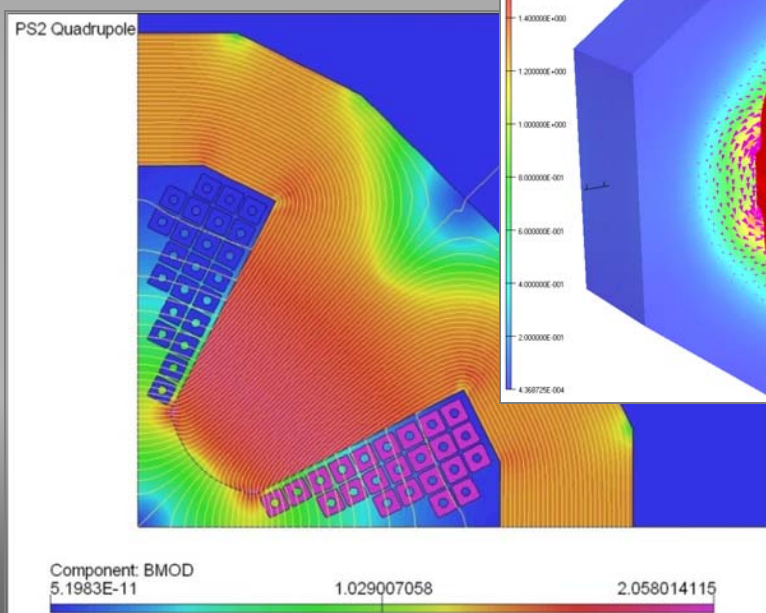


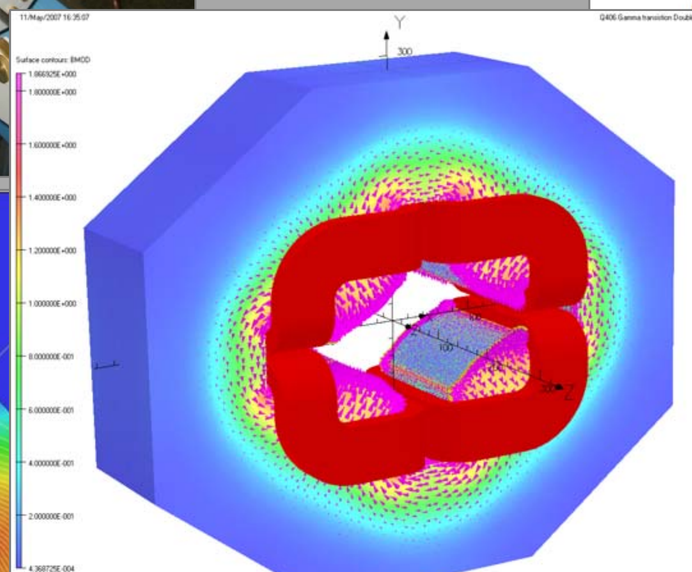

- Equation for normal (non-skew) ideal (infinite) poles: $2xy = \pm r^2$ (r = aperture radius)
- Magnetic flux density: $B_y = a_2 x$
- 'Allowed' harmonics: n = **2**, 6, 10, 14, ... (= 2n pole errors)

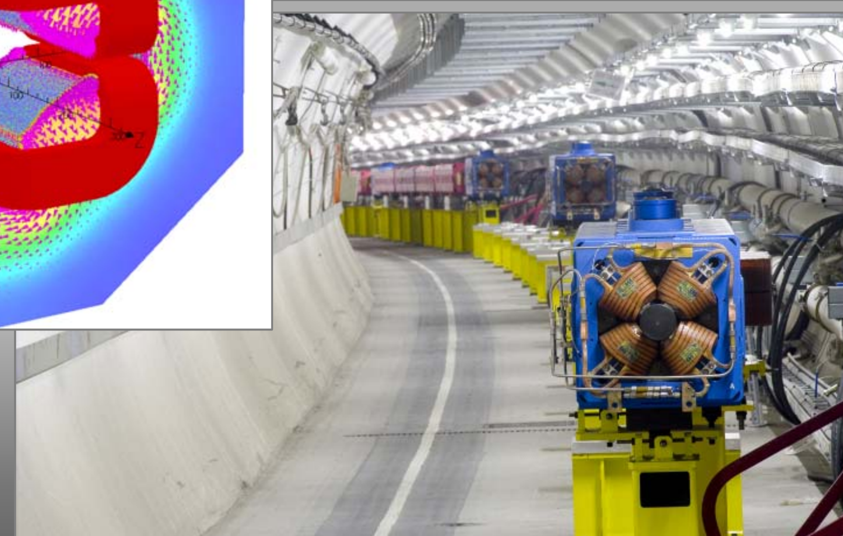
# Quadrupoles





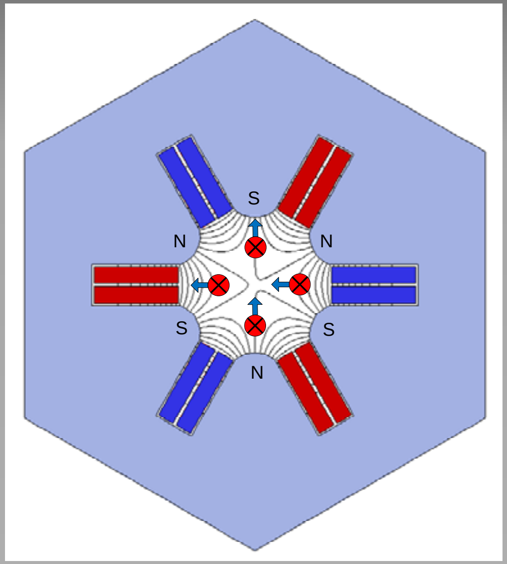


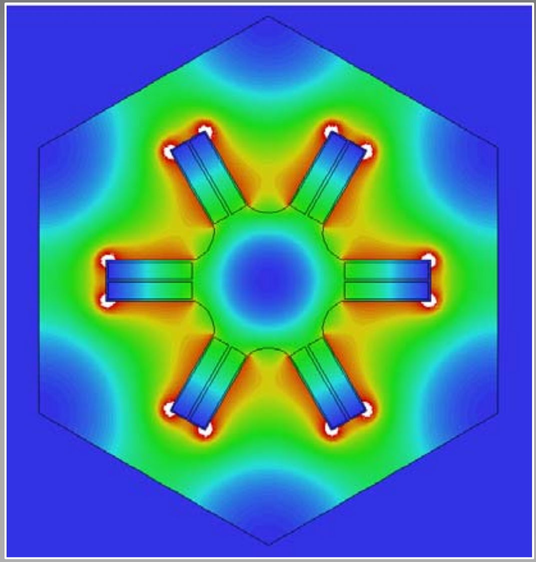
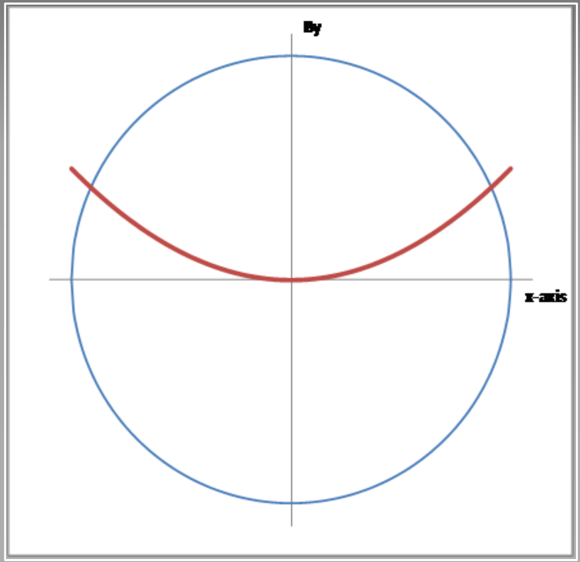





# Sextupoles

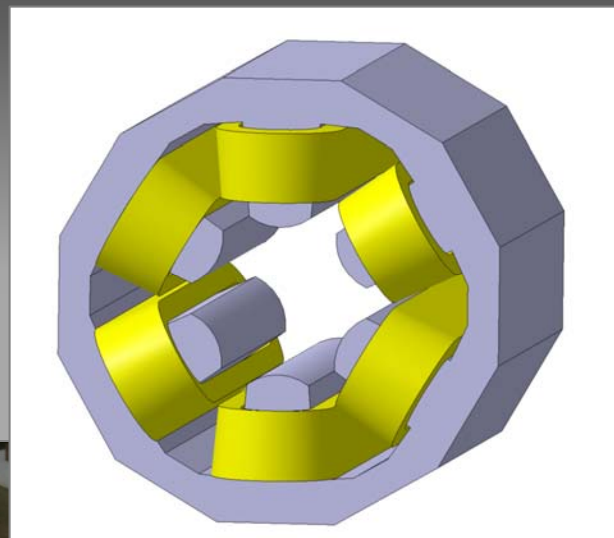
- Purpose: correct chromatic aberrations

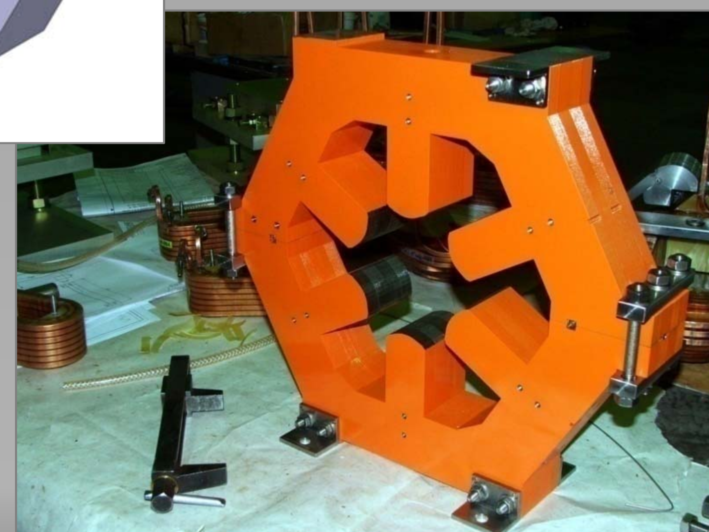



- Equation for normal (non-skew) ideal (infinite) poles: $3x^2y - y^3 = \pm r^3$ (r = aperture radius)
- Magnetic flux density: $B_y = a_3(x^2 - y^2)$
- 'Allowed' harmonics: n = **3**, 9, 15, 21, ... (= 2n pole errors)

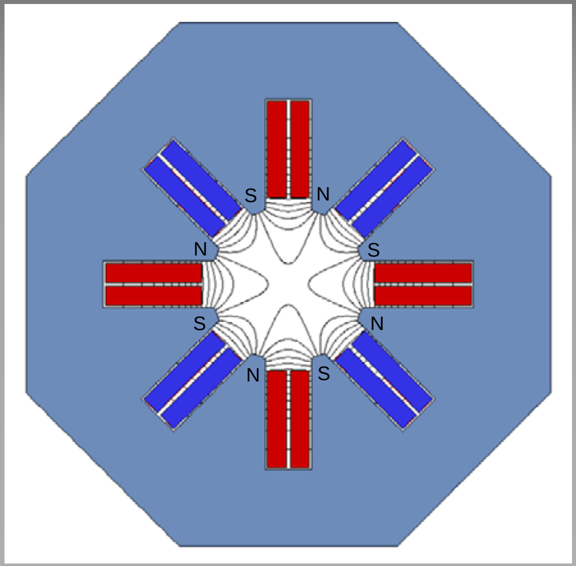
# Sextupoles

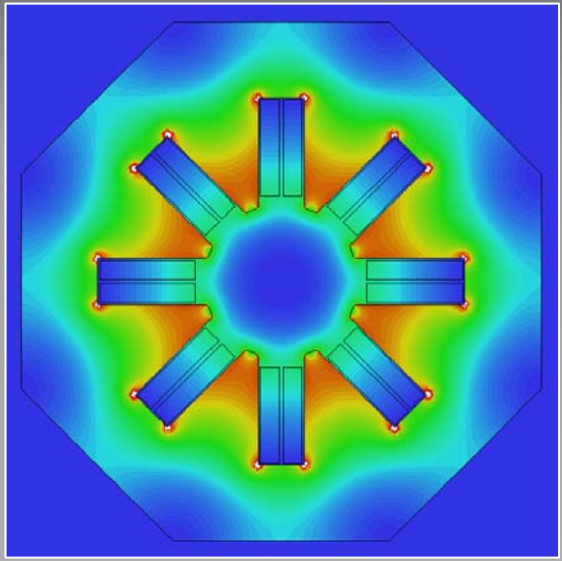


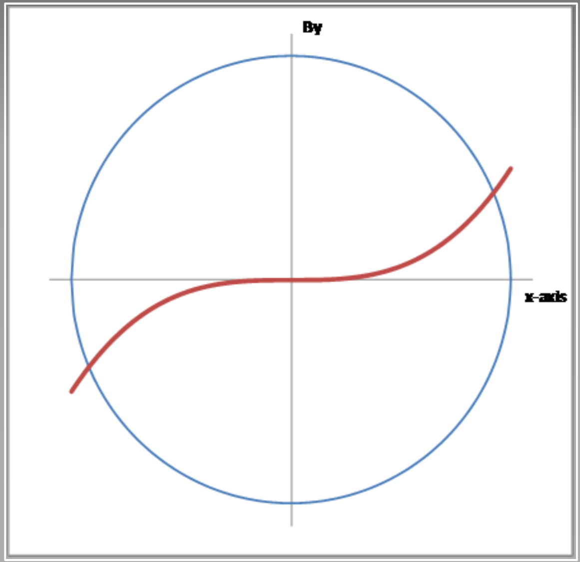


# Octupoles

- Purpose: 'Landau' damping

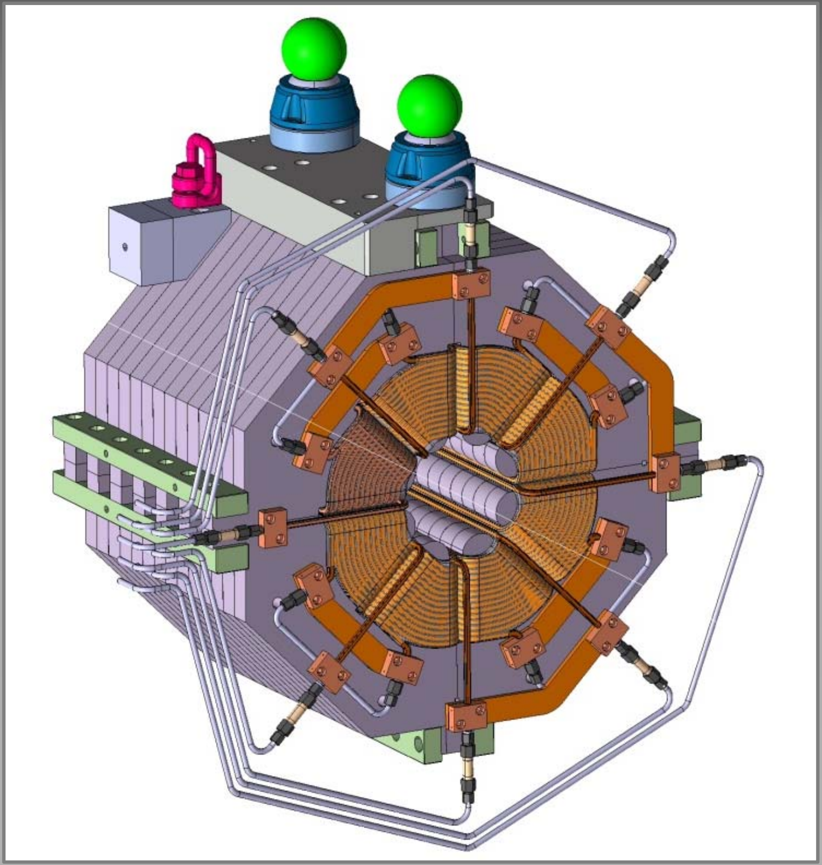


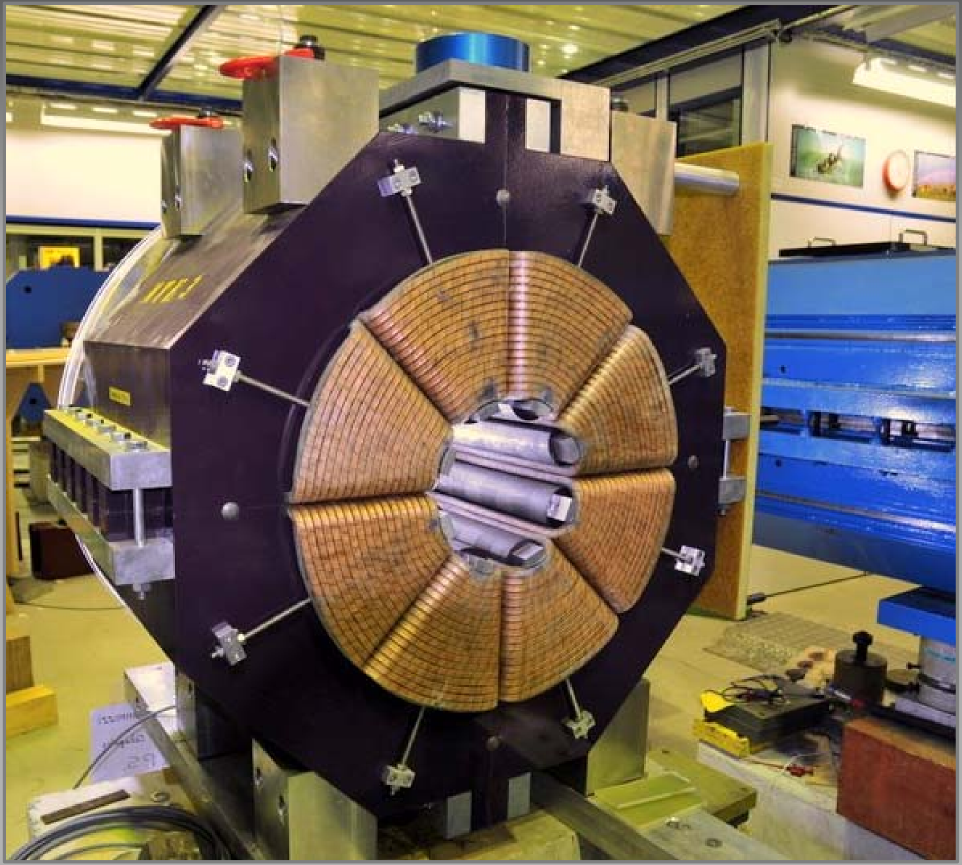






- Equation for normal (non-skew) ideal poles: $4(x^3y - xy^3) = \pm r^4$ (r = aperture radius)
- Magnetic flux density: $B_y = a_4(x^3 - 3xy^2)$
- 'Allowed' harmonics: n = **4**, 12, 20, 28, ... (= 2n pole errors)

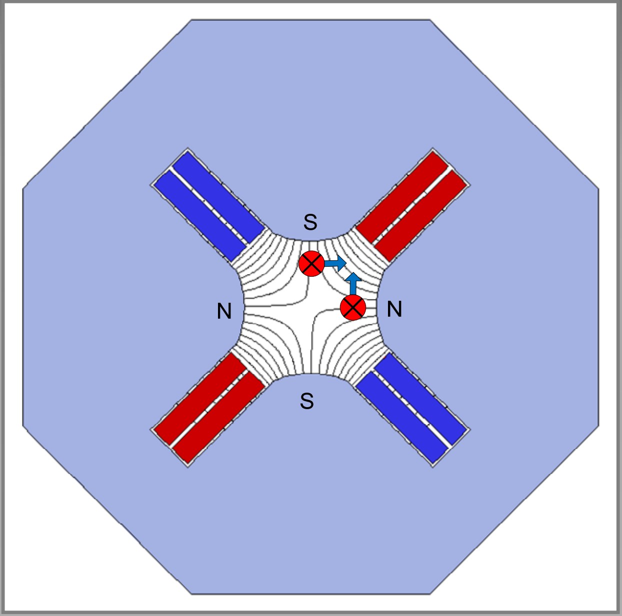
# Octupoles





# Skew quadrupole

- Purpose: coupling horizontal and vertical betatron oscillations

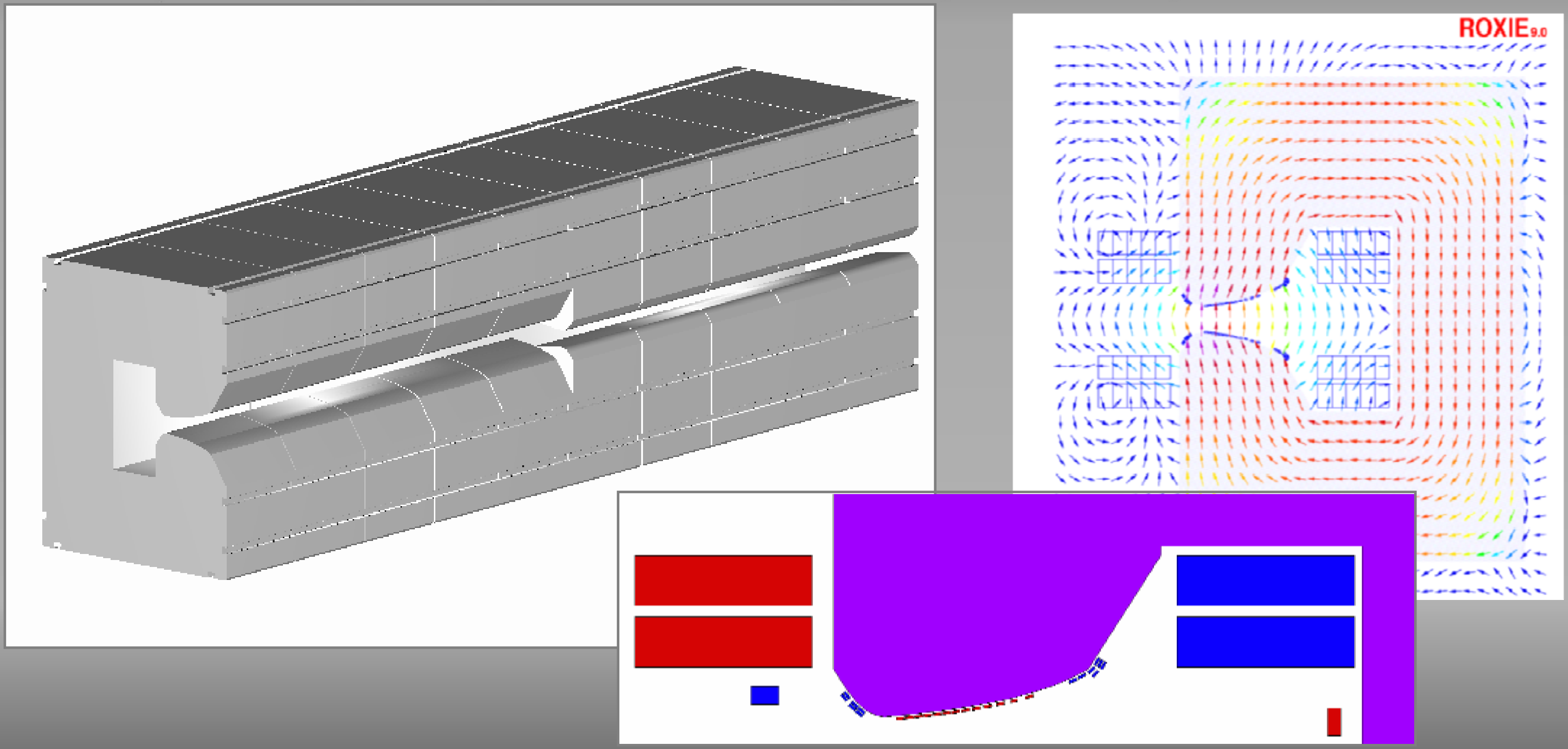



- Beam that has horizontal displacement (but no vertical) is deflected vertically
- Beam that has vertical displacement (but no horizontal) is deflected horizontally

# Combined function

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

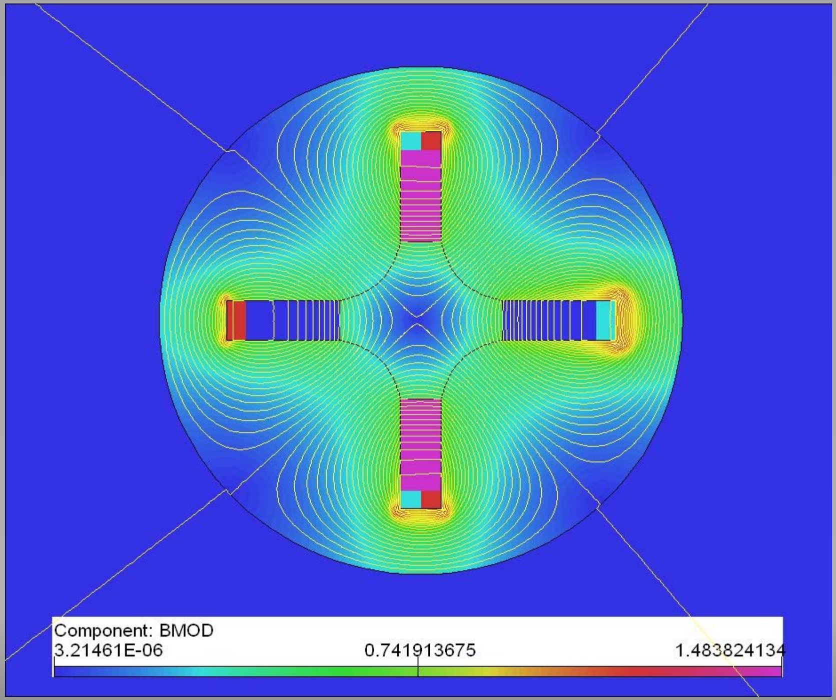
- Amplitudes cannot be varied independently
- Dipole and quadrupole: PS main magnet (PFW, Fo8…)

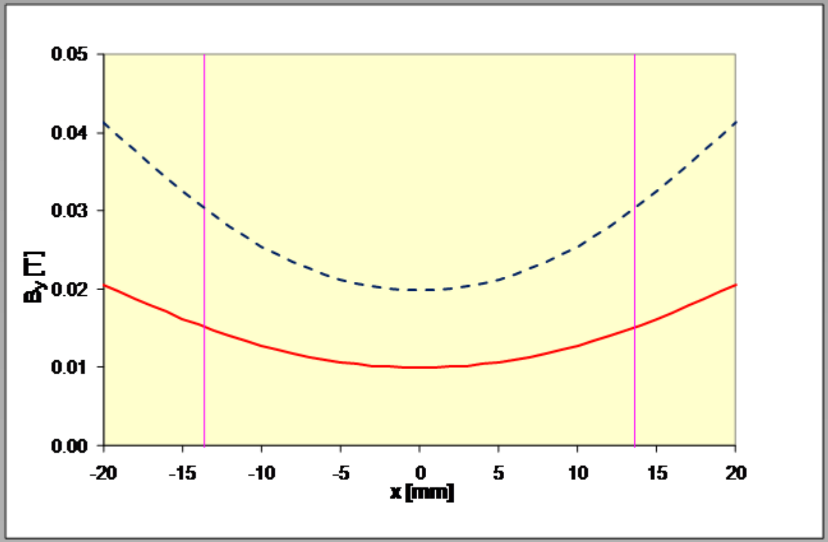


# Combined function

Functions generated by individual coils:

Amplitudes can be varied independently

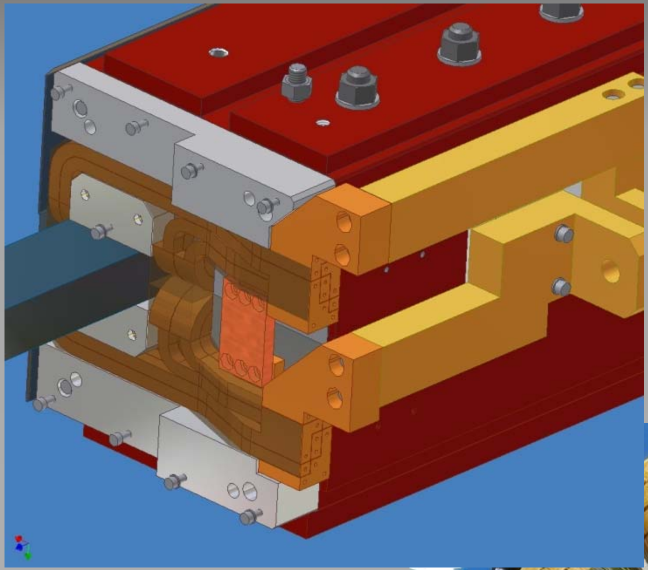


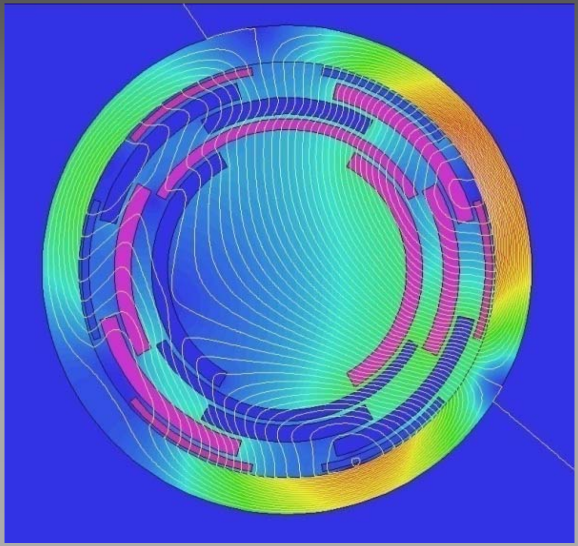




Quadrupole and corrector dipole
(strong sextupole in dipole field)

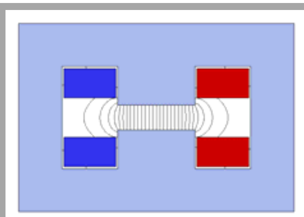
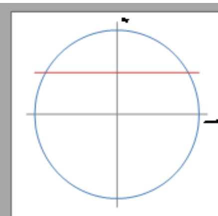
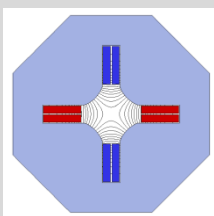
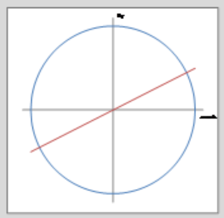
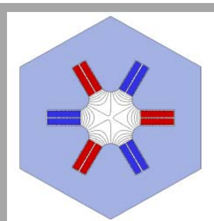
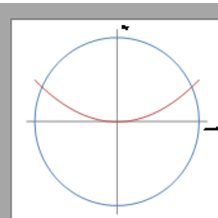
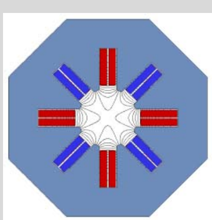
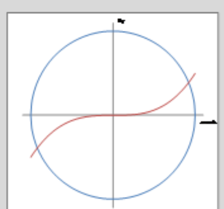
# Special magnets

- Solenoids
- Septa
- Betatron cores
- Kicker magnets
- Bumper magnets
- Scanner magnets
- Multipole correctors





# Summary

| Pole shape | Field distribution | Pole equation | $B_y$ on x-axis |
|---|---|---|---|
|  |  | $y = \pm r$ | $B_y = a_1 = B_0 = \text{const.}$ |
|  |  | $2xy = \pm r^2$ | $B_y = a_2 x$ |
|  |  | $3x^2y - y^3 = \pm r^3$ | $B_y = a_3(x^2 - y^2)$ |
|  |  | $4(x^3y - xy^3) = \pm r^4$ | $B_y = a_4(x^3 - 3xy^2)$ |

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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?

Magnet life cycle

Input parameters

General requirements

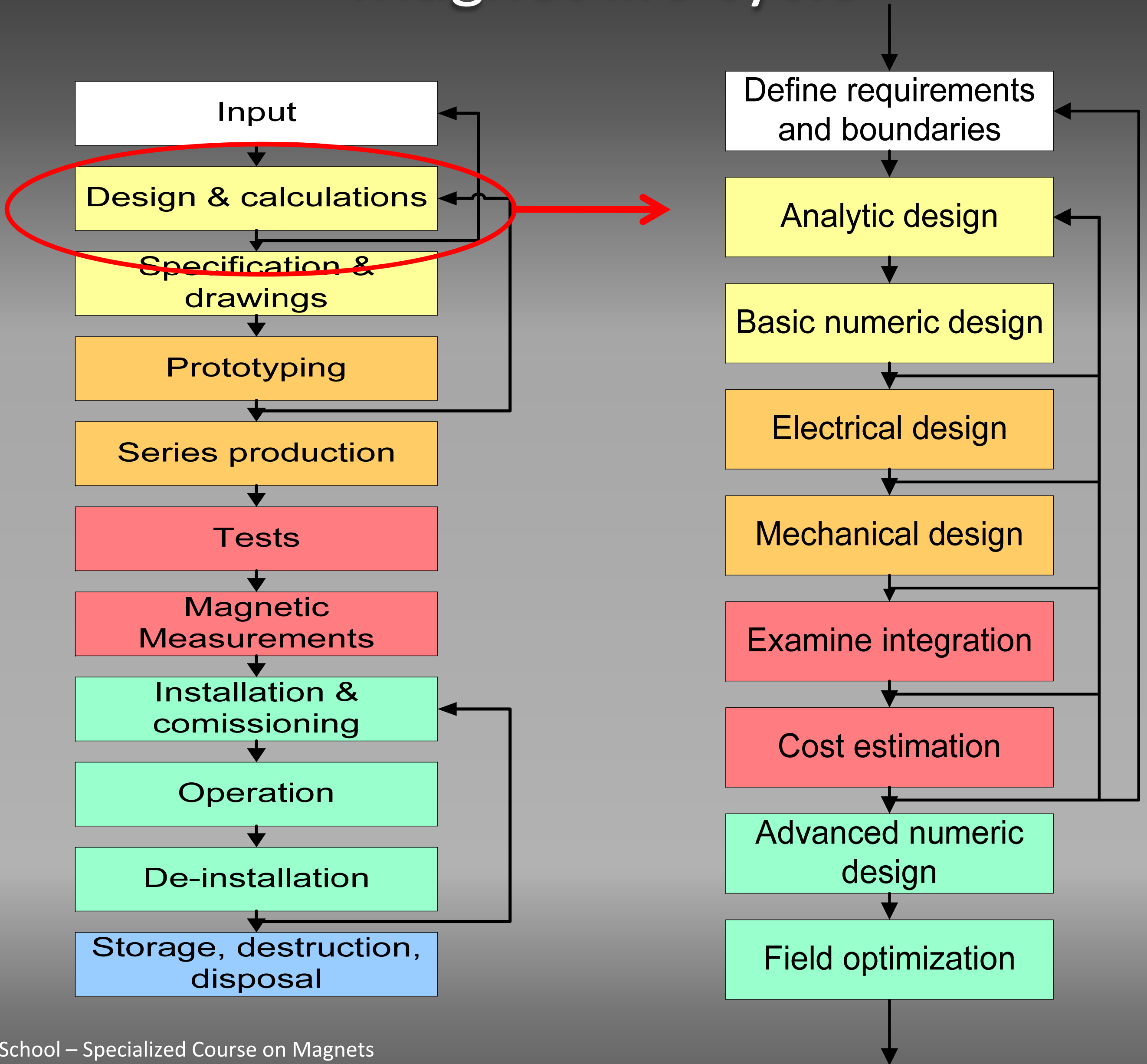
Performance requirements

Physical requirements

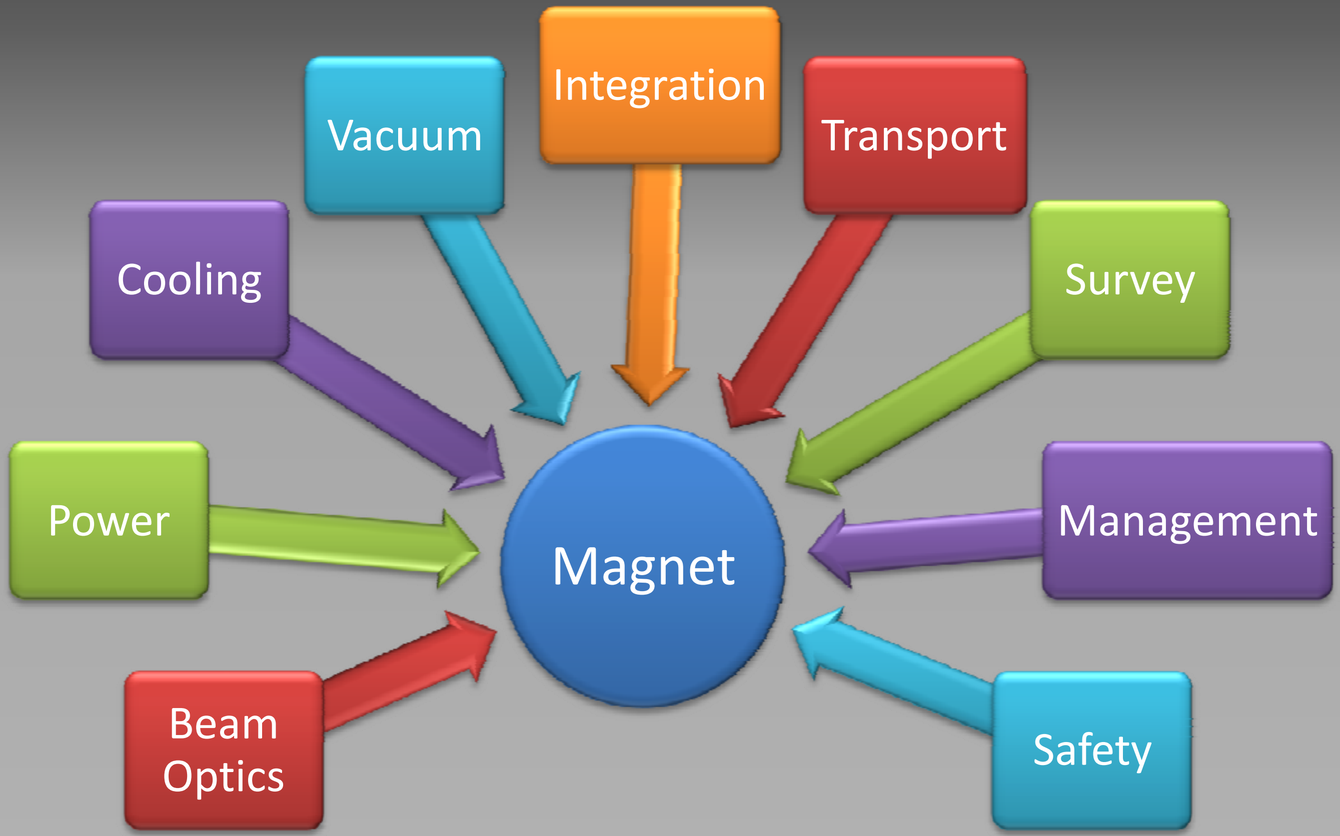
Interfaces

Environmental aspects

# Magnet life cycle



# Input parameters




A magnet is not a stand-alone device!

# General requirements

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

# Performance requirements

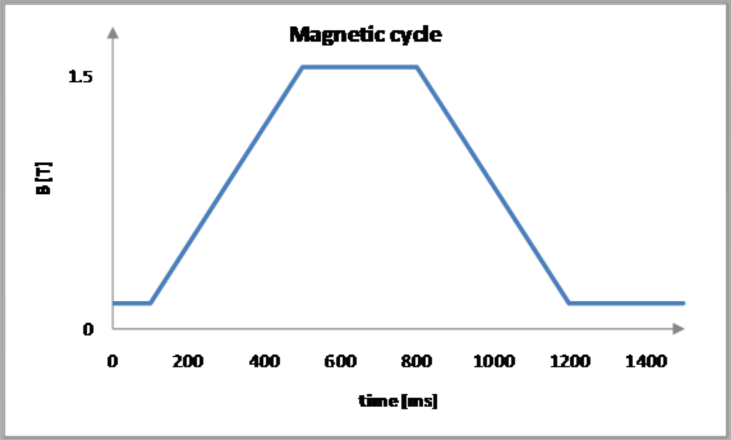
**Beam parameters**

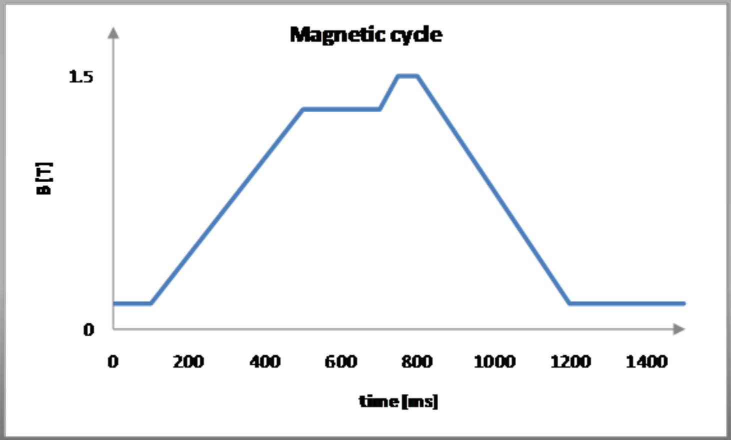
- Type of beam, energy range and deflection angle (k-value)
- Integrated field (gradient)
- Local field (gradient) and magnetic length

# Performance requirements

**Operation mode**

- Continuous
- Pulsed-to pulse modulation (ppm)
- Ramped – ramp rate (T/s)
- Fast pulsed

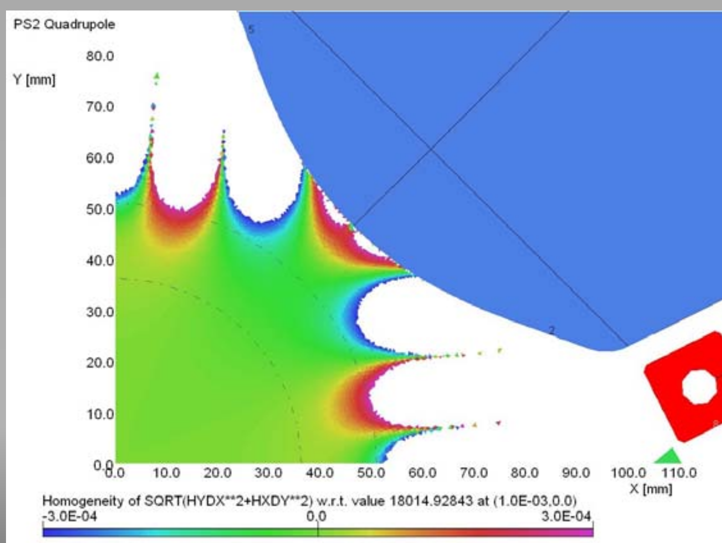


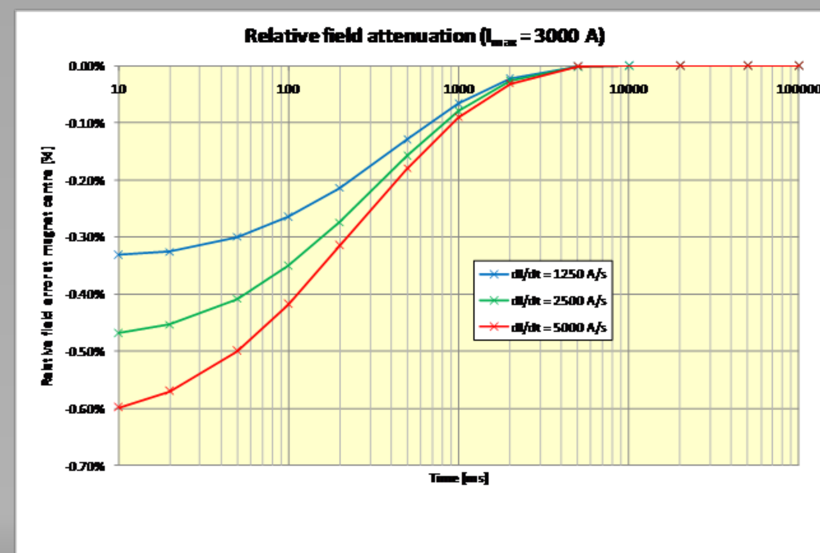



# Performance requirements

## Field quality

- Homogeneity (uniformity)
- Allowed harmonic content
- Stability & reproducibility
- Settling time (time constant)



# Physical requirements

| | |
|---|---|
| Geometric boundaries | • Available space<br>• Transport limitations<br>• Weight limitations |
| Accessibility | • Crane<br>• Connections (electrical, hydraulic)<br>• Alignment targets |
| Aperture | • Physical aperture<br>• 'Good field region' |

# Interfaces

Equipment linked to the magnet is defining the boundaries and constraints

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

# Environmental aspects

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

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

# Summary

1. Collect all necessary information

2. Understand the requirements, constraints and interfaces

3. Summarize them in a functional specification