Joint Universities Accelerator School

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Normal-conducting accelerator magnets

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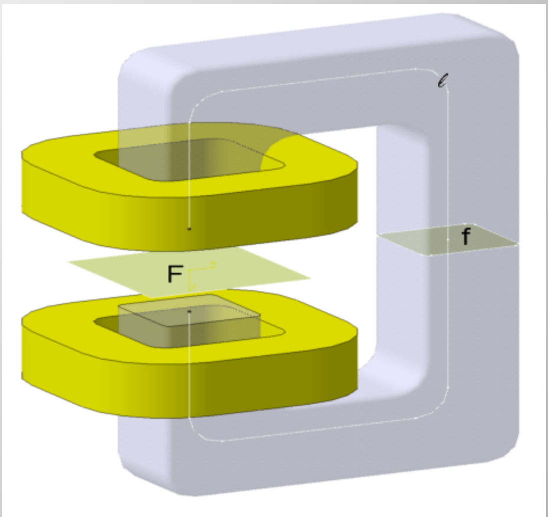
Lecture 2: Analytical design

- Goals in magnet design and coherence
- What do we need to know before starting?
- Defining the requirements & constraints
- Deriving the magnet main parameters
- Coil design and cooling

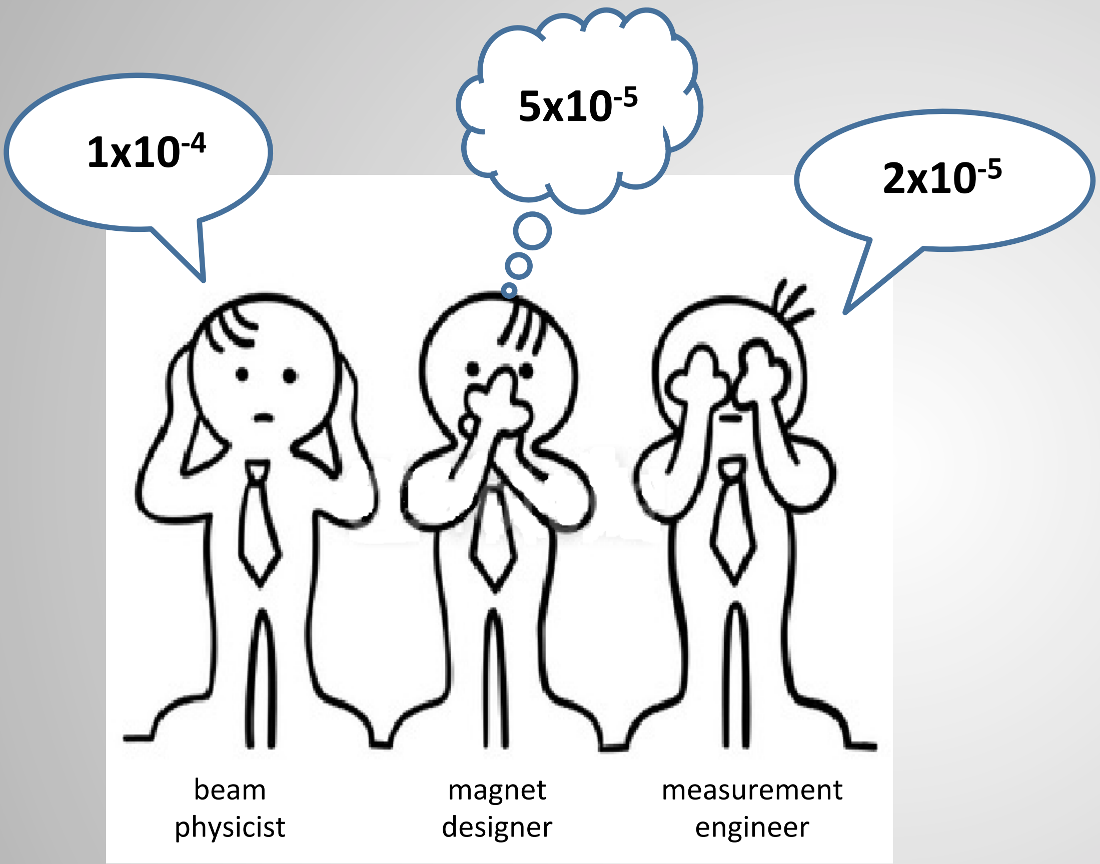


Goals in magnet design

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 are 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!)

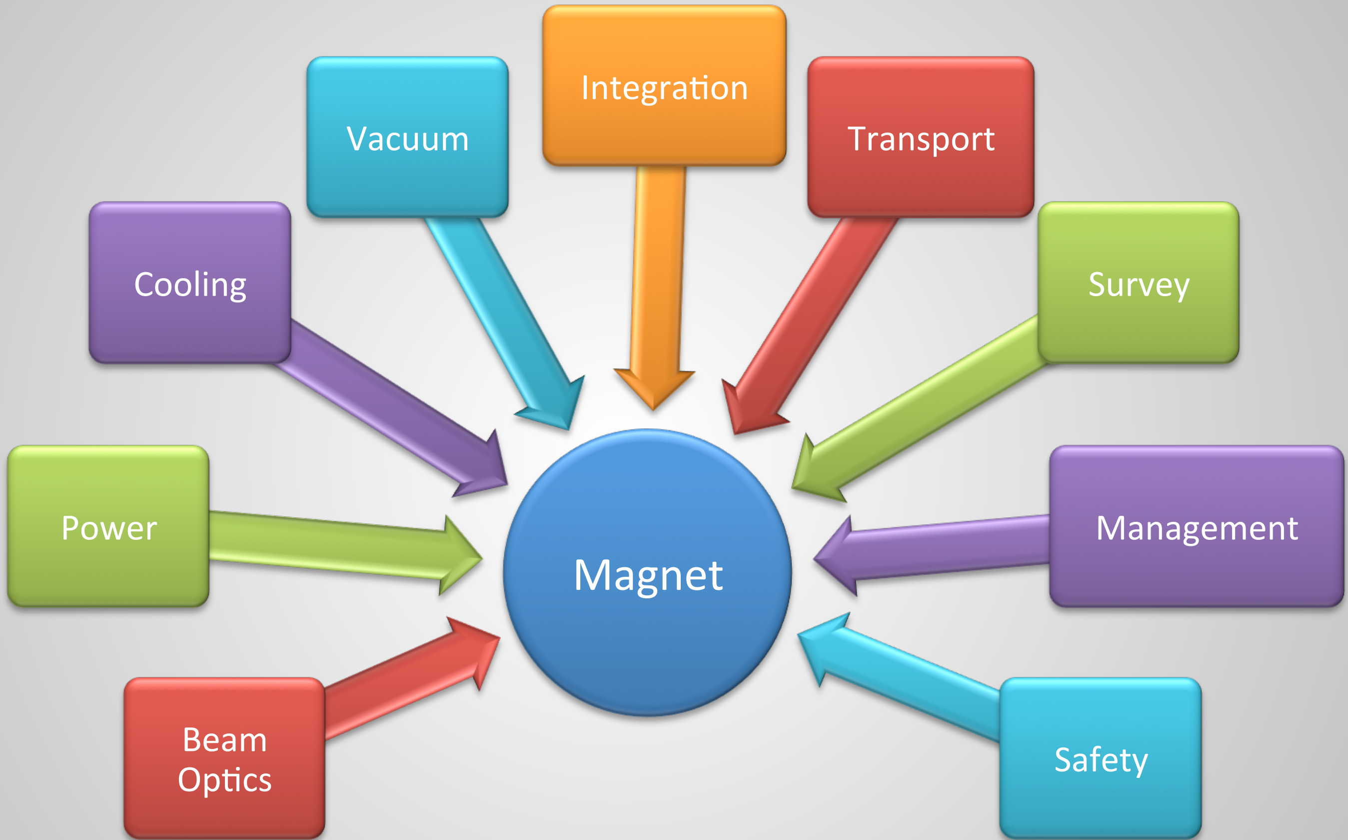
Coherence



- What is really required for design, upgrade and stable operation of an accelerator?
- How can we meet these requirements with economic magnet design?
- To which level do we have confidence in the accuracy of simulations and the precision of measurements?

Establish the coherence between beam physics requirements, magnet design & manufacture, and measurements !

Magnet interfaces



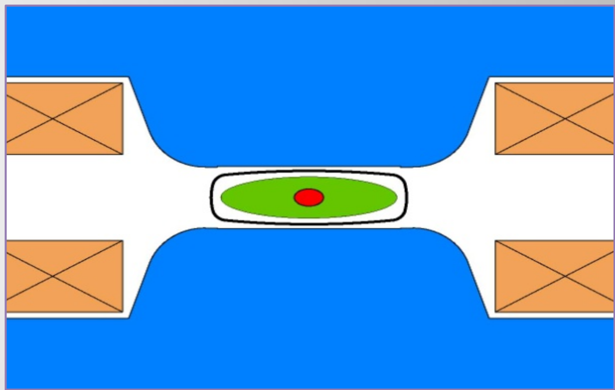
A magnet is not a stand-alone device!

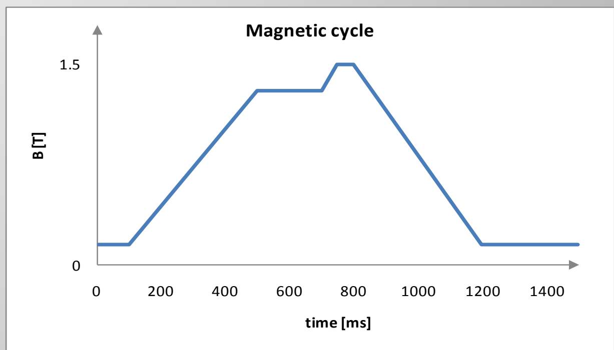
Design process

Electro-magnetic design is an iterative process:

Collect input data → Analytical design → Numerical 2D/3D simulations → Mechanical design → Drawings & specifications

- Field strength (gradient) and magnetic length
- Integrated field strength (gradient)
- Aperture and ‚good field region‘
- Field quality:
  - field homogeneity
  - maximum allowed multipole errors
  - settling time (time constant)
- Operation mode: continous, cycled
- Electrical parameters
- Mechanical dimensions
- Cooling
- Environmental aspects





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

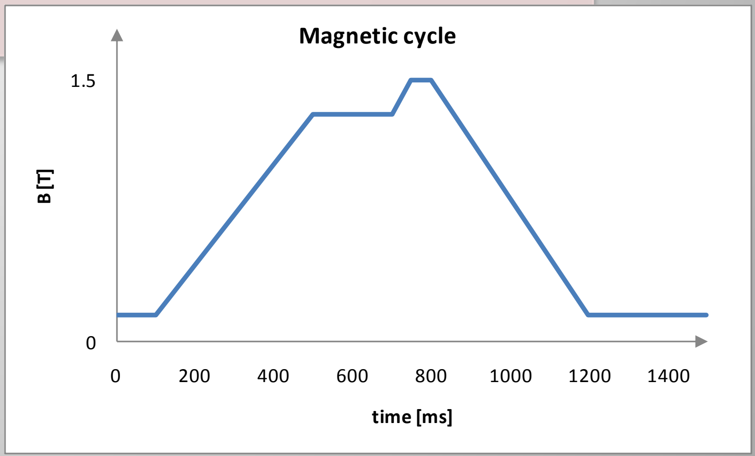
- Type of beam, energy range, deflection angle
- Integrated field (gradient)
- Local field (gradient) and magnetic length

Aperture

- Physical aperture
- 'Good field region'

Operation mode

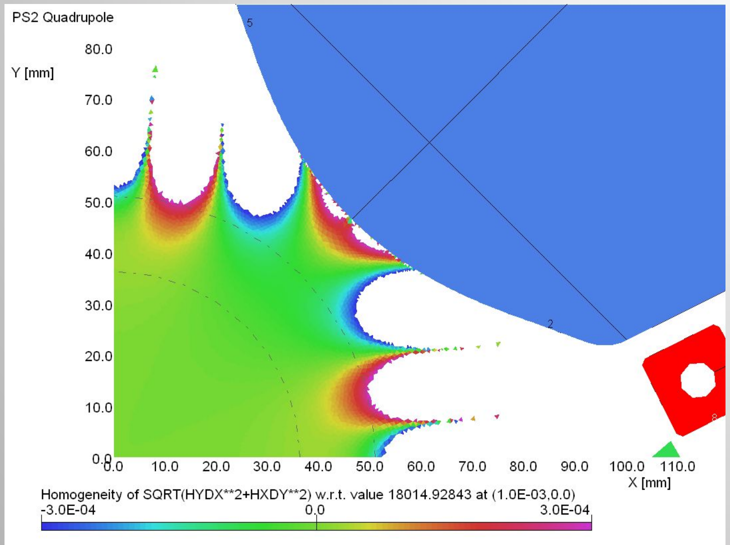
- Continuous
- Pulse-to-pulse modulation (ppm)
- Ramp rate (T/s)

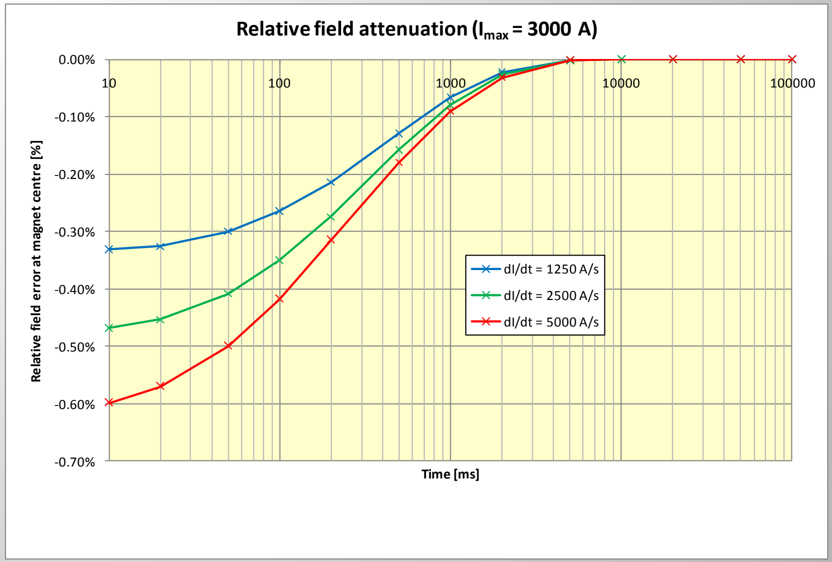


Performance requirements

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 devices 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

Practical example

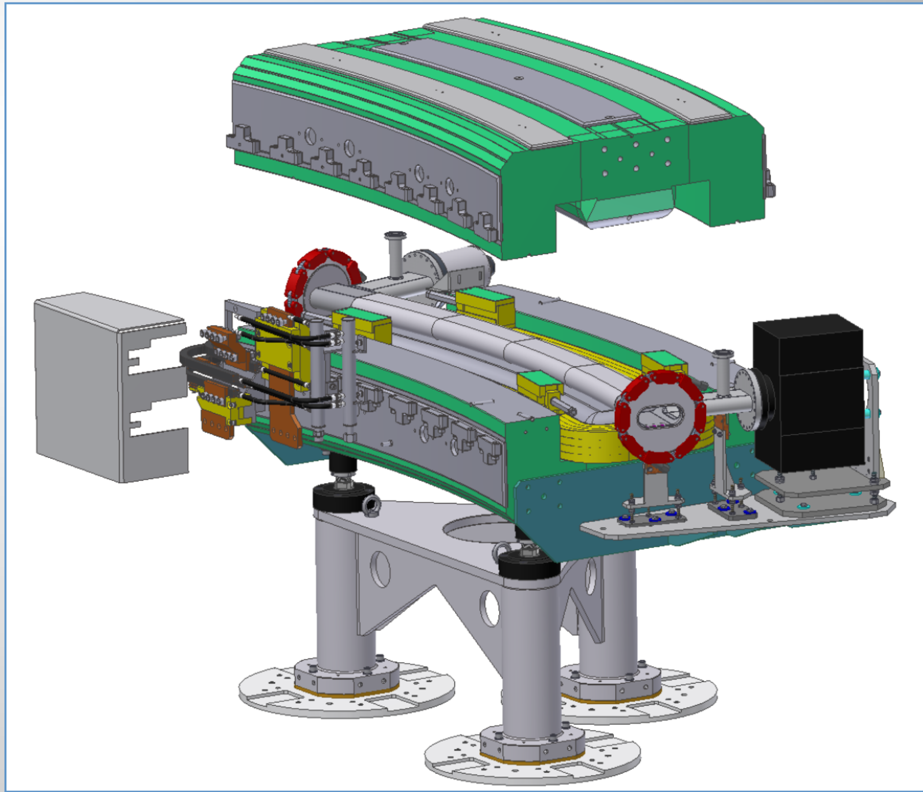
ebg MedAustron

MedAustron: ion therapy facility under construction near Vienna/Austria

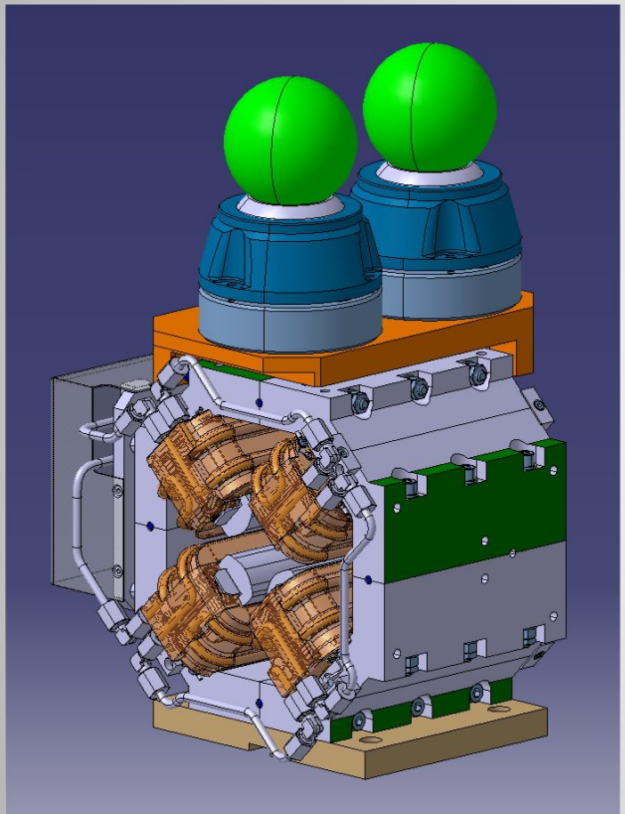
Providing beam energies from 120 to 400 MeV/u for carbon ions and from 60 to 220 MeV for protons

16 synchrotron bending magnets:

- Bending angle: 22.5°
- Bending radius: 4.231 m
- Field ramp rate: 3.75 T/s
- Max. current: 3000 A
- Overall length: < 2 m
- Good field region: 120 x 56 mm
- Field quality: $\frac{\Delta \int B \cdot dl}{\int B \cdot dl} = 2 \cdot 10^{-4}$



Magnet Components



Alignment targets

Yoke

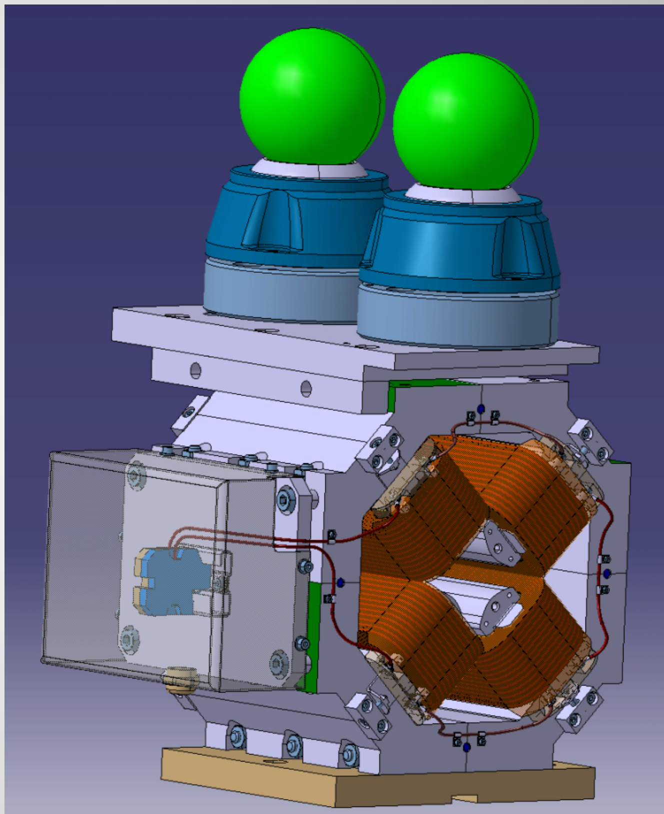
Coils

Sensors

Cooling circuit

Connections

Support



Magnetic design

Translate the beam optic requirements into a magnetic design

1. Required magnetic induction
2. Aperture size
3. Magnet excitations (Amp-turns)
4. Yoke cross-section
5. Yoke material

Beam rigidity

Beam rigidity $B\rho$ [Tm]:

$$B\rho = \frac{1}{qc}\sqrt{T^2 + 2T E_0}$$

- q: particle charge number [Coulombs]
- c: speed of light [m/s]
- T: kinetic beam energy [eV]
- E_0: particle rest mass energy [eV]
  (0.51 MeV for electrons, 938 MeV for protons)

Magnetic induction

Dipole bending field B [T]:

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

- B: Flux density or magnetic induction (vector) [T]
- r_M: magnet bending radius [m]

Quadrupole field gradient B' [T/m]:

$$B' = B\rho k$$

- k: quadrupole strength [m^{-2}]

Sextupole differential gradient B'' [T/m^2]:

$$B'' = B\rho m$$

- m: sextupole strength [m^{-3}]

Example

Beam rigidity *Bρ* [Tm]:

– Max. beam energy:
  400 MeV/u for carbon ions
  220 MeV for protons

$$B\rho = \frac{1}{qc}\sqrt{T^2 + 2T E_0} = 6.35\,Tm$$

Dipole bending field *B* [T]:

– Bending angle: 22.5°
– Bending radius: 4.231 m

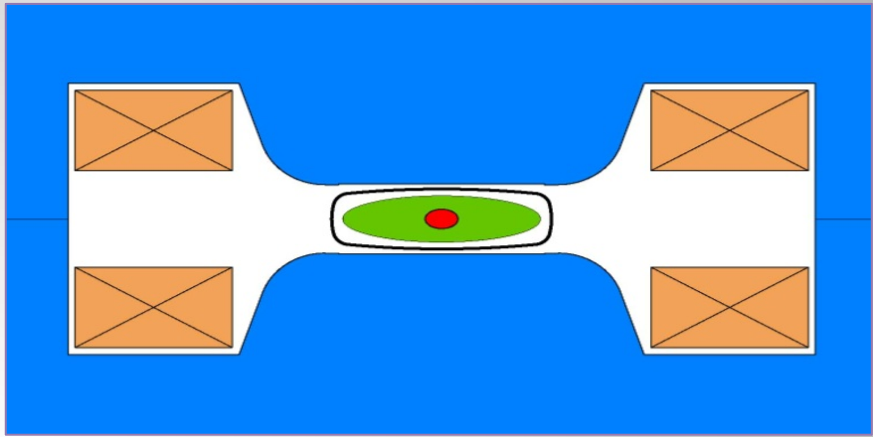
$$B = \frac{B\rho}{r_M} = 1.5\,T$$

Magnetic design

Translate the beam optic requirements into a magnetic design

- Required magnetic induction
- Aperture size
- Magnet excitations (Amp-turns)
- Yoke cross-section
- Yoke material

Aperture size



Aperture =

Good field region

Maximum beam size

- Lattice functions: beta functions and dispersion
- Geometrical transverse emittancies (energy depended)
- Momentum spread
- Envelope (typical 3-sigma)
- Largest beam size usually at injection

$$\sigma = \sqrt{\varepsilon\,\beta + \left(D\frac{\Delta p}{p}\right)^2}$$

\+ Closed orbit distortions (few mm)

\+ Vacuum chamber thickness (0.5 – 5 mm)

\+ Installation and alignment margin (0 – 10 mm)

Magnetic design

Translate the beam optic requirements into a magnetic design

- Required magnetic induction
- Aperture size
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- Yoke cross-section
- Yoke material

Excitation current in a dipole

Ampere's law $\oint \vec{H} \cdot d\vec{l} = NI$ and $\vec{B} = \mu \vec{H}$ with $\mu = \mu_0 \mu_r$

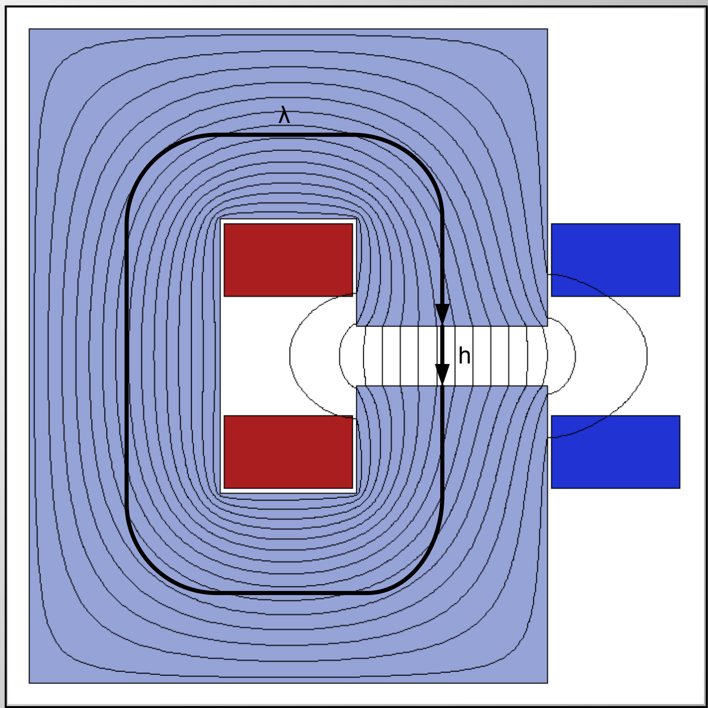
leads to $$NI = \oint \frac{\vec{B}}{\mu} \cdot d\vec{l} = \int_{gap} \frac{\vec{B}}{\mu_{air}} \cdot d\vec{l} + \int_{yoke} \frac{\vec{B}}{\mu_{iron}} \cdot d\vec{l} = \frac{Bh}{\mu_{air}} + \frac{B\lambda}{\mu_{iron}}$$

assuming, that B is constant along the path

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

then: $$NI_{(per\ pole)} \approx \frac{Bh}{2\eta\mu_0}$$

- *h*: gap height [m]
- *η*: efficiency (typically 95% - 99 %)



Example

Magnet aperture:

Horizontal GFR: ±60 mm

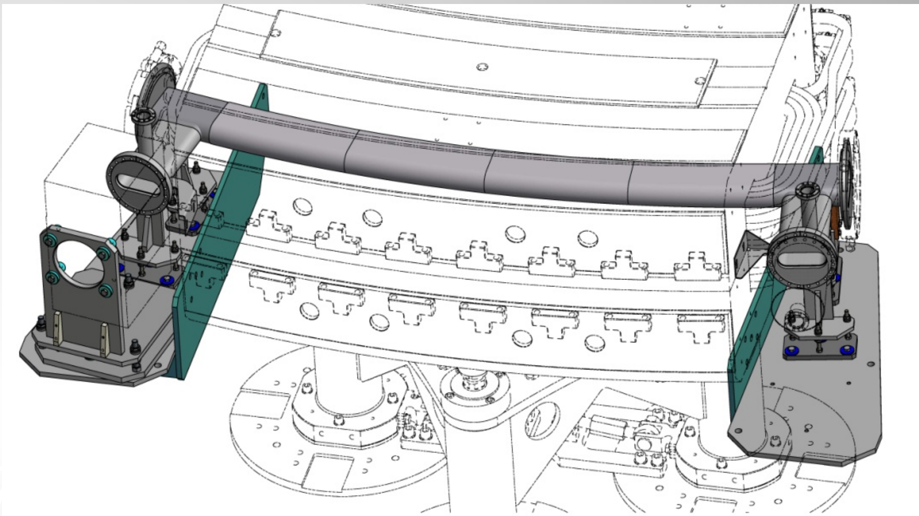
Vertical GFR: ±28 mm

Vacuum chamber thickness: 5 mm

Tolerancies for installation: 2.5 mm

Insulation thickness: 0.5 mm

→ Total aperture height: 72 mm



Excitation current (=magnetomotive force):

Efficiency η = 95%

$$NI_{(per\ pole)} = \frac{Bh}{2\eta\mu_0} = 45120\ A$$

Reluctance and efficiency

Reluctance: $$R_M = \frac{NI}{\Phi} = \frac{l_M}{A_M \mu_r \mu_0}$$

- Φ: magnetic flux [Wb]
- l_M: flux path length in iron [m]
- A_M: iron cross section perpendicular to flux [m^2]

Term ($\frac{\lambda}{\mu_{iron}}$) in previous slide is called 'normalized reluctance' of the yoke

Keep iron yoke reluctance less than a few % of air reluctance ($\frac{h}{\mu_0}$) by providing sufficient iron cross section (B_{iron} < 1.5 T)

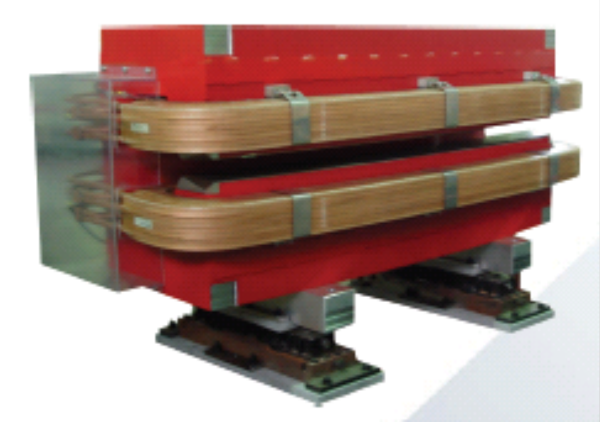
Efficiency: $$\eta = \frac{R_{M,gap}}{R_{M,gap} + R_{M,yoke}} \approx 99\%$$

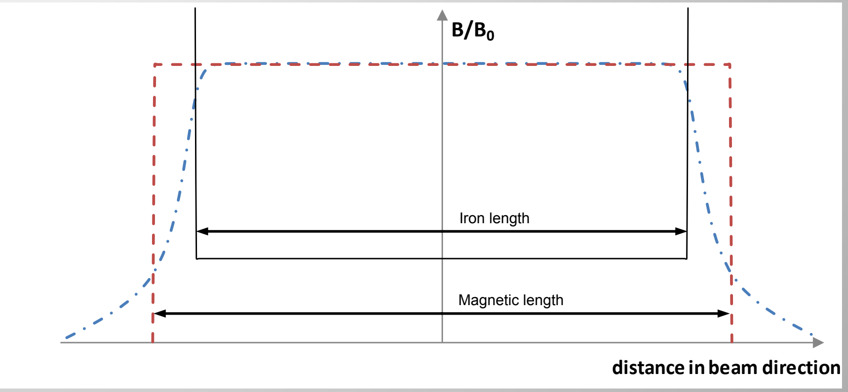
Magnet(ic) length

Magnetic length: $$l_{mag} = \frac{\int_{-\infty}^{\infty} B(z) \cdot dz}{B_0}$$

'Magnetic' length > iron length

Approximation for a dipole: $l_{mag} = l_{iron} + 2hk$





Excitation current in a Quadrupole

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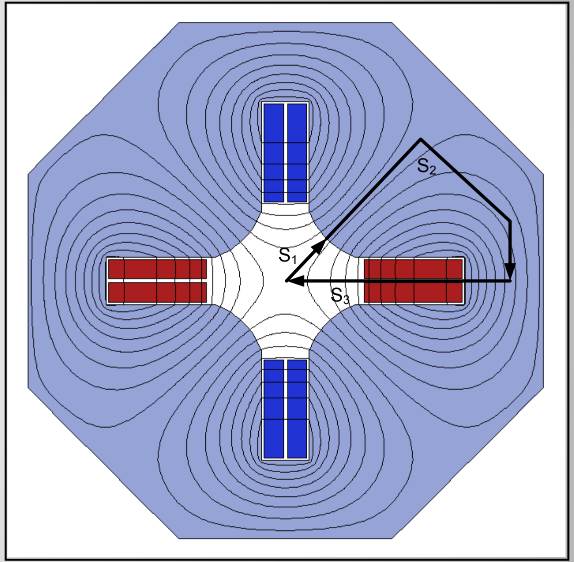
Choosing the shown integration path gives:

$$NI = \oint \vec{H} \cdot \vec{dl} = \int_{s1} \vec{H}_1 \cdot \vec{dl} + \int_{s2} \vec{H}_2 \cdot \vec{dl} + \int_{s3} \vec{H}_3 \cdot \vec{dl}$$

For a quadrupole, the gradient $B' = \frac{dB}{dr}$ is constant

and $B_y = B'x \qquad B_x = B'y$

Field modulus along s_1: $H(r) = \frac{B'}{\mu_0}\sqrt{x^2 + y^2} = \frac{B'}{\mu_0} r$



Neglecting H in s_2 because: $R_{M,s2} = \frac{s_2}{\mu_{iron}} << \frac{s_1}{\mu_{air}}$

and along s_3: $\int_{s3} \vec{H}_3 \cdot \vec{dl} = 0$

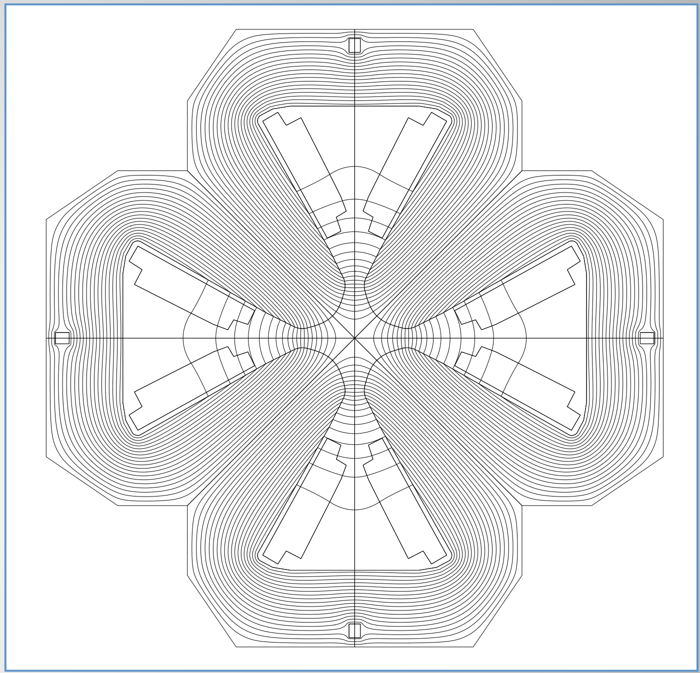
Leads to: $NI \approx \int_0^R H(r)\,dr = \frac{B'}{\mu_0}\int_0^R r\,dr$

$$NI_{(per\ pole)} = \frac{B' r^2}{2\eta\mu_0}$$

Magnetic length

Magnetic length for a quadrupole:

$$l_{mag} = l_{iron} + 2r\,k$$



NI increases with the square of the quadrupole aperture:

$$NI \propto r^2 \qquad P \propto r^4$$

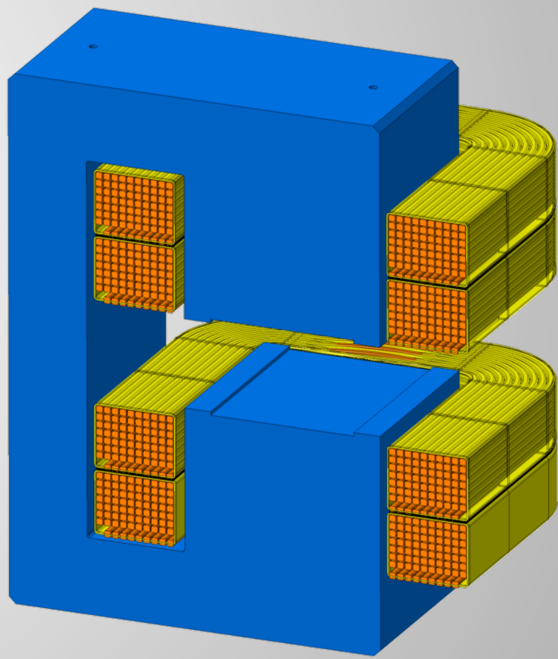
More difficult to accommodate the necessary Ampere-turns (= coil cross section)

→ truncating the hyperbola leads to a decrease in field quality

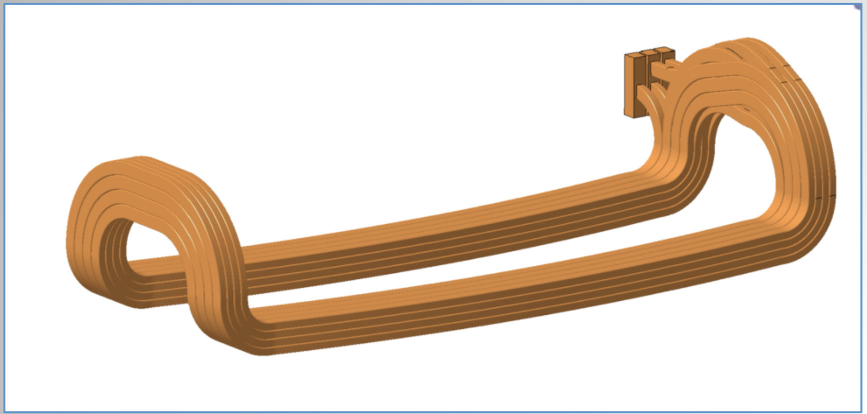
Coil design

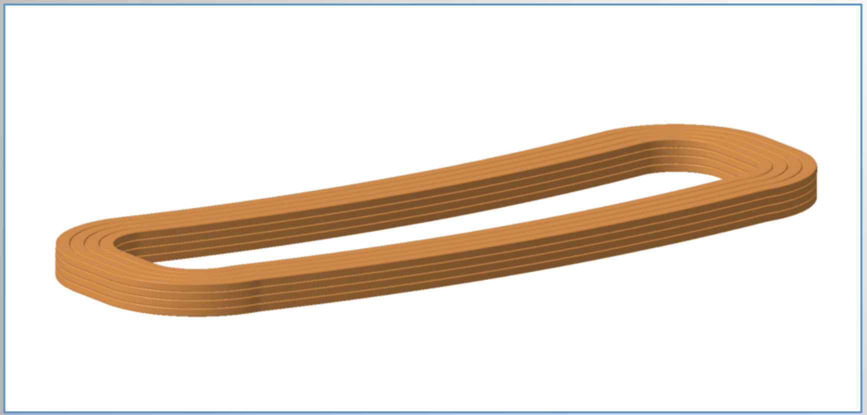
Ampere-turns NI are determined, but the current density j, the number of turns N and the coil cross section need to be defined

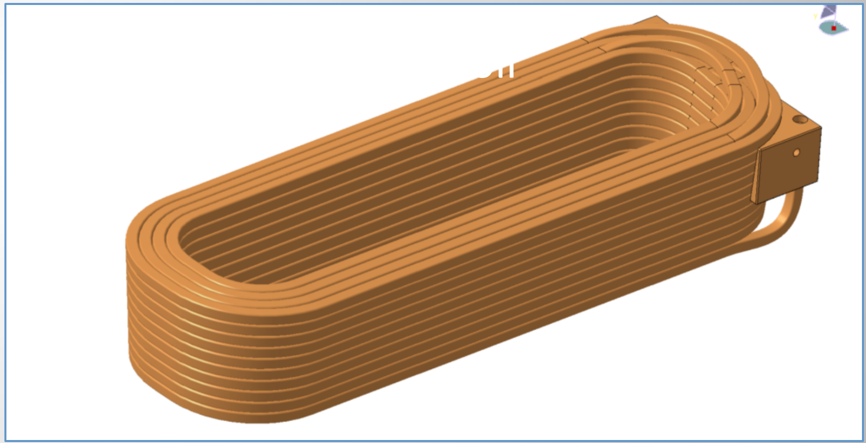
- Coil type selection
- Power requirements
- Cooling circuit computation
- Conductor selection
- Optimization



Standard coil types







Power requirements

Assuming the magnet cross-section and the yoke length are known, one can estimate the total dissipated power per magnet:

$$P_{dipole} = \rho \frac{Bh}{\eta \mu_0} j l_{avg}$$

$$P_{qudrupole} = 2\rho \frac{B' r^2}{\eta \mu_0} j l_{avg}$$

- *j*: current density [A/m²]: $j = \frac{NI}{f_c A} = \frac{I}{a_{cond}}$
- *ρ*: resistivity [Ωm] of coil conductor
- l_{avg}: average turn length [m]; approximation: 2.5 $l_{iron} < l_{avg} < 3\ l_{iron}$ for racetrack coils
- a_{cond}: conductor cross section [m²]
- *A*: coil cross section [m²]
- f_c: filling factor = $\frac{\text{net conductor area}}{\text{coil cross section}}$ (includes geometric filling factor, insulation, cooling duct, edge rounding)

Note: for a constant geometry, the power loss *P* is proportional to the current density *j*

Number of turns

The determined power can be divided into voltage and current: $P = UI$

Basic relations: $P_{magnet} \propto j$ $V_{magnet} \propto Nj$ $R_{magnet} \propto N^2 j$

The number of turns N are chosen to match the impedances of the power converter and connections:

Large N = low current = high voltage

- Small terminals
- Small conductor cross-section
- Thick insulation for coils and cables
- Less good filling factor in the coils
- Large coil volume
- Low power transmission loss

Small N = high current = low voltage

- Large terminals
- Large conductor cross-section
- Thin insulation in coils and cables
- Good filling factor in the coils
- Small coil volume
- High power transmission loss

Coil examples

MedAustron Synchrotron

Dipole

- # of turns $N_{(per\ pole)}$: 16
- Current: 3000 A
- Voltage: 100 V

Quadrupole

- # of turns $N_{(per\ pole)}$: 20
- Current: 650 A
- Voltage: 12 V

Sextupole

- # of turns $N_{(per\ pole)}$: 14
- Current: 650 A
- Voltage: 16 V

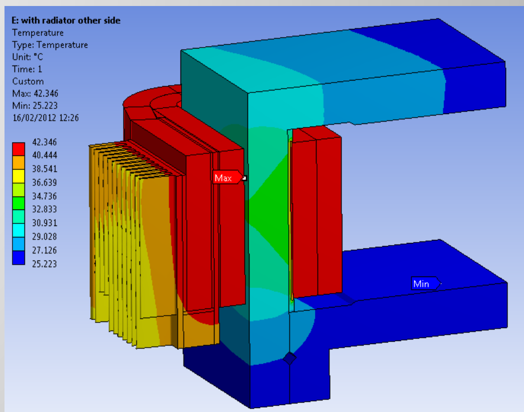
Corrector

- # of turns $N_{(per\ pole)}$:240/96
- Current: 15/30 A
- Voltage: 7/3 V

Coil cooling

Air cooling by natural convection:

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

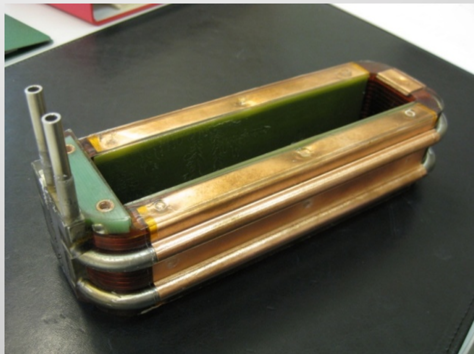


Direct water cooling:

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

Indirect water cooling:

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



Direct water cooling

Practical recommendations and canonical values:

- Water cooling: 2 A/mm^2 ≤ j ≤ 10 A/mm^2
- Pressure drop: 0.1 ≤ Δp ≤ 1.0 MPa (possible up to 2.0 MPa)
- Low pressure drop might lead to more complex and expensive coil design
- Flow velocity should be high enough so flow is turbulent
- Flow velocity u_{avg} ≤ 5 m/s to avoid erosion and vibrations
- Acceptable temperature rise: ΔT ≤ 30°C
- For advanced stability: ΔT ≤ 15°C

Assuming:

- Long, straight and smooth pipes without perturbations
- Turbulent flow = high Reynolds number (*Re* > 4000)
- Good heat transfer from conductor to cooling medium
- Temperature of inner conductor surface equal to coolant temperature
- Isothermal conductor cross section

Direct water cooling

Useful simplified formulas using water as cooling fluid:

Reynolds number *Re* []: $\mathrm{Re} = \frac{u_{avg} d}{\nu}$

dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations

Average coolant velocity u_{avg} [m/s]: $u_{avg} \approx 0.3926 \cdot d^{0.714} \left(\frac{\Delta p}{l} \right)^{0.571}$

Water flow *Q* [litre/s] necessary to remove heat *P*: $Q_{water} = 0.2388 \frac{P}{\Delta T} 10^{-3}$

Water flow *Q* [litre/s] inside a round tube : $Q = u_{avg} \frac{\pi d^2}{4} 10^3$

Temperature increase *ΔT* [°C] : $\Delta T = 304 \frac{P}{u_{avg} d^2} 10^{-9}$

- *P:* power [W]
- *l,d*: cooling circuit length [m] and diameter [m]
- *ν:* kinematic viscosity of coolant is temperature depending, for simplification it is assumed to be constant ($9.85 \cdot 10^{-7}$ m^2/s @ 21°C for water)

Direct water cooling

Number of cooling circuits per coil: $\Delta p \propto \frac{1}{K_W^3}$

→ Doubling the number of cooling circuits reduces the pressure drop by a factor of eight for a constant flow

Diameter of cooling channel: $\Delta p \propto \frac{1}{d^5}$

→ Increasing the cooling channel by a small factor can reduce the required pressure drop significantly

Cooling circuit design

Already determined: current density *j*, power *P*, current *I*, # of turns *N*

1. Select # of layers *m* and # of turns per layer *n*
2. Round up *N* if necessary to get reasonable (integer) numbers for n and m
3. Define coil height *c* and coil width *b*: $A = bc = \frac{NI}{j f_c}$ (Aspect ratio *c* : *b* between 1 : 1 and 1 : 2 and $0.6 \le f_c \le 0.8$)
4. Calculate l_{avg}= pole perimeter + 4 x coil width *b*
5. The total length of cooling circuit: $l = \frac{K_c N l_{avg}}{K_w}$ (start with single cooling circuit per coil)
6. Select *ΔT*, *Δp* and calculate cooling hole diameter *d*: $d = 5.59 \cdot 10^{-3} \left(\frac{P}{\Delta T\, K_w} \right)^{0.368} \left(\frac{l}{\Delta p} \right)^{0.21}$
7. Change *Δp* or number of cooling circuits, if necessary
8. Determine conductor area *a*: $a = \frac{I}{j} + \frac{d^2 \pi}{4} + r_{edge}(4 - \pi)$
9. Select conductor dimensions and insulation thickness
10. Verify if resulting coil dimensions, *N, I, V, ΔT* are still compatible with the initial requirements (if not, start new iteration)
11. Compute coolant velocity and coolant flow
12. Verify if Reynolds number is inside turbulent range (Re > 4000)

- K_c: Number of coils
- K_w: Number of cooling circuits per coil

Cooling water properties

- For the cooling of hollow conductor coils demineralised water is used (exception: indirect cooled coils)
- Water quality essential for the performance and the reliability of the coil (corrosion, erosion, short circuits)
- Resistivity > 0.1 x 10^6 Ωm
- pH between 6 and 6.5 (= neutral)
- Dissolved oxygen below 0.1 ppm
- Filters to remove particles and loose deposits to avoid cooling duct obstruction

Summary

- Magnetic desing means translating beam optic requirements
- Before starting the design, all input parameters, requirements, contraints and interfaces have to be known and well understood
- Establishing the coherence between beam physics requirements, magnet design & manufacture, and measurements is indispensible for the success of a project
- Analytical design is neccessary to derive the main parameters of the future magnet before entering into a detailed design using numerical methods
- Magnet design is an iterative process often requiring a high level of experience