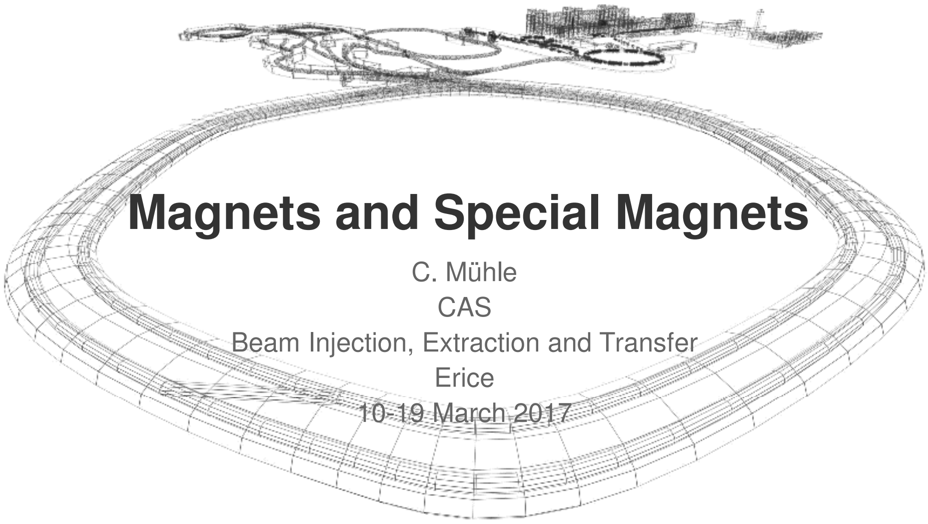
GSI Helmholtzzentrum für Schwerionenforschung GmbH



Magnets and Special Magnets

C. Mühle

CAS

Beam Injection, Extraction and Transfer

Erice

10-19 March 2017

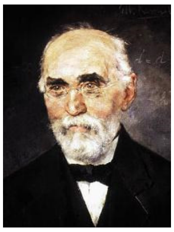
Outline

- Basic physics
- Magnet types
- Coils
- Yokes
- Special magnets
- Magnet examples

Basic physics

Lorentz Equation

Charles Augustin de Coulomb
(1736 – 1806)
Coulomb-Kraft
$\mathbf{F} = q\mathbf{E}$



Hendrik Antoon Lorentz
(1853 – 1928)
Lorentzkraft
$\mathbf{F} = q\mathbf{v}\times\mathbf{B}$

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v}\times\mathbf{B}$$

Maxwell equations

James Clerk Maxwell
(1831 – 1879)

$$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial}{\partial t}\mathbf{D} \qquad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B} \qquad \nabla \cdot \mathbf{D} = \rho$$

$$\mathbf{D} = \varepsilon_0 \underline{\underline{\varepsilon}} \mathbf{E}$$

$$\mathbf{B} = \mu_0 \underline{\underline{\mu}} \mathbf{H}$$

$$\mathbf{j} = \underline{\underline{\sigma}} \mathbf{E}$$

Maxwell equations

Ampere's law:

$$\oint_{\partial A} \mathbf{H} \cdot d\mathbf{s} = \int_A \mathbf{j} \cdot d\mathbf{A} + \frac{d}{dt}\int_A \mathbf{D} \cdot d\mathbf{A} \quad \text{from} \quad \nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial}{\partial t}\mathbf{D}$$

Faraday's law:

$$\oint_{\partial A} \mathbf{E} \cdot d\mathbf{s} = -\frac{d}{dt}\int_A \mathbf{B} \cdot d\mathbf{A} \quad \text{from} \quad \nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B}$$

Gauss's theorem:

$$\oint_{\partial V} \mathbf{D} \cdot d\mathbf{A} = Q \quad \text{from} \quad \nabla \cdot \mathbf{D} = \rho$$

Magnetic field has no charges:

$$\oint_{\partial V} \mathbf{B} \cdot d\mathbf{A} = 0 \quad \text{from} \quad \nabla \cdot \mathbf{B} = 0$$

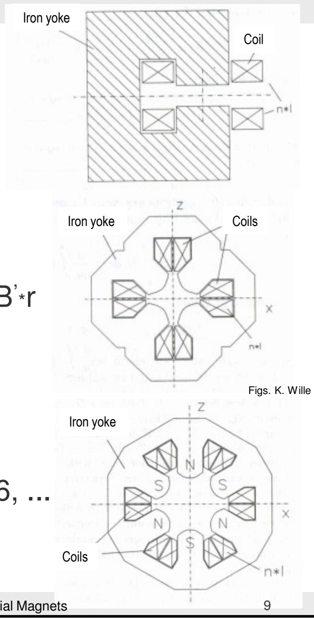
Magnetic material properties

Term	Material
$\underline{\underline{\mu}} = \begin{bmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{bmatrix}$	Permeability tensor
$\mu_{ij} = 0,\ \mu_{ii} = \mu_r \neq 0$	isotropic, homogeneous
$\mu_{ij} = 0,\ \mu_{ii} = \mu_r(x, y, z)$	isotropic, inhomogeneous
$\mu_{ij} = const$	anisotropic, homogeneous
$\mu_{ij} = \mu_{ij}(x, y, z)$	anisotropic, inhomogeneous
$\mu_{ij} = 0,\ \mu_{ii} = \mu_r(H(x, y, z))$	isotropic, homogeneous, nonlinear (massive iron)
$\mu_{ii} = \mu_{ij}(\mathbf{H}(x, y, z))$	anisotropic, homogeneous, nonlinear (laminated iron)

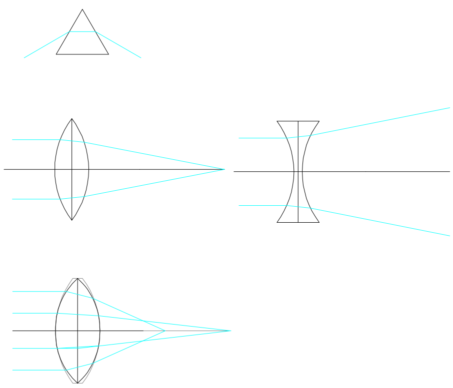
Magnet types

Magnets in the Accelerator

- Bending magnets => Dipole, B = const.
- Focusing magnets => Quadrupole, $B = g \cdot r = B' \cdot r$
- Non linear magnets (corrector magnets)
  => Sextupole, $B = B'' \cdot r^2/2$, Oktupole $B = B''' \cdot r^3/6$, ...



Optical Analogies



- Prism => Dipole
- Spherical lens => Quadrupole
- Aspherical lens => Sextupole, Octupole, ...

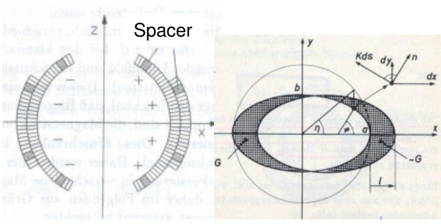
Design Types

Current dominated

- Cos nθ
- Intersecting ellipses

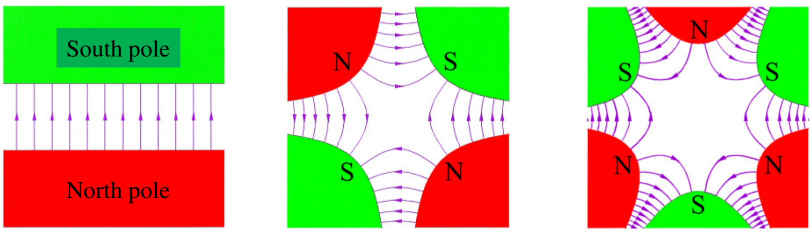
Iron dominated

- H-Magnet
- C-Magnet
- O-Magnet (Window-frame m.)



Figs. K. Wille

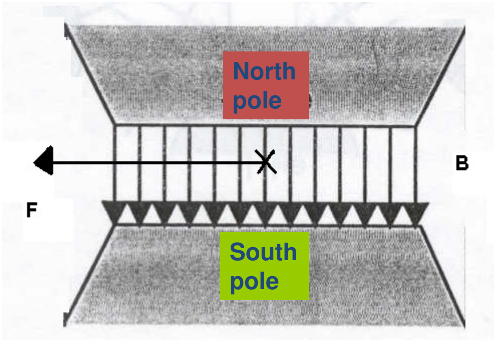
Magnetic Flux Lines



Dipole Quadrupole Sextupole

Quadrupoles and higher orders have a radially symmetric field strength distribution but not the field direction.

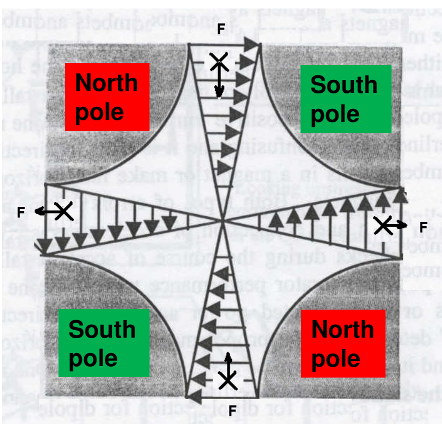
Forces on the Beam - Dipole



- Positive ion into the plane
- Right hand rule
- Direction of a positive ion = technical definition of current
- Constant field => constant force

Fig. J. Tanabe

Forces on the Beam - Quadrupole



- Field increases linearly with the distance from the center => Force increases linearly
- Ion beam
  - Horizontally defocusing
  - Vertically focusing
  - -> More than one QP for focusing in both planes
- Named according to horizontal plane => Defocusing Quadrupole

Fig. J. Tanabe

Forces on the Beam - Sextupole

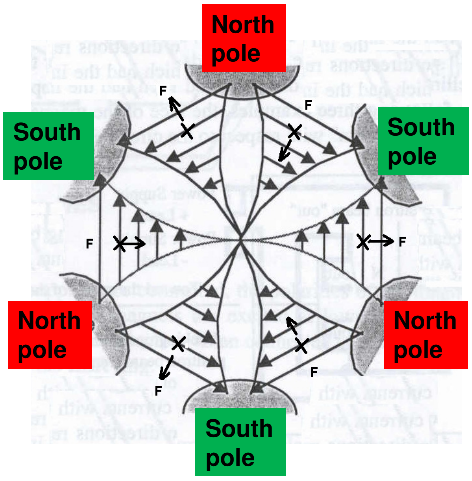


Fig. J. Tanabe

- Field increases quadratically with the distance => force increases quadratically!
- Force has same direction on both sides of the axis
- Named after the horizontal axis w.r.t. the machine center

Polarity - Dipole

- Field direction according to right hand rule

positive current „into the paper“

positive current „out of the paper“

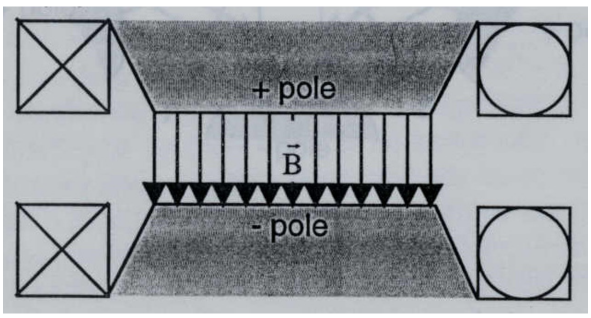


Fig. J. Tanabe

Polarity - Quadrupole

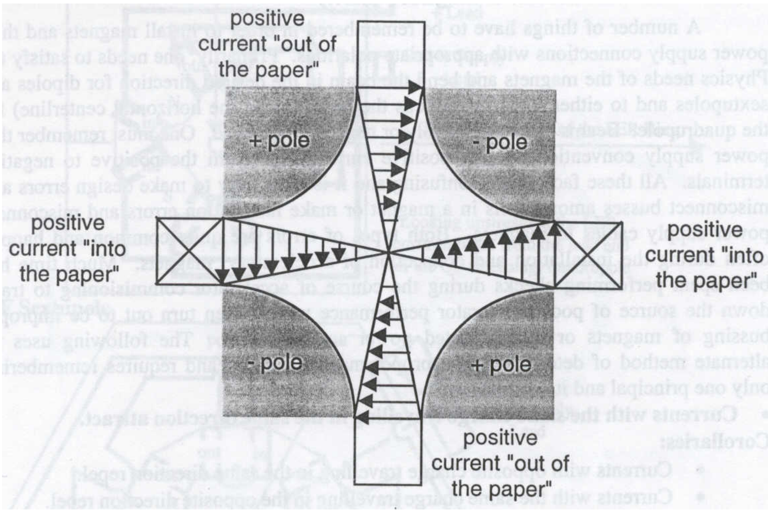


Fig. J. Tanabe

Polarity - Sextupole

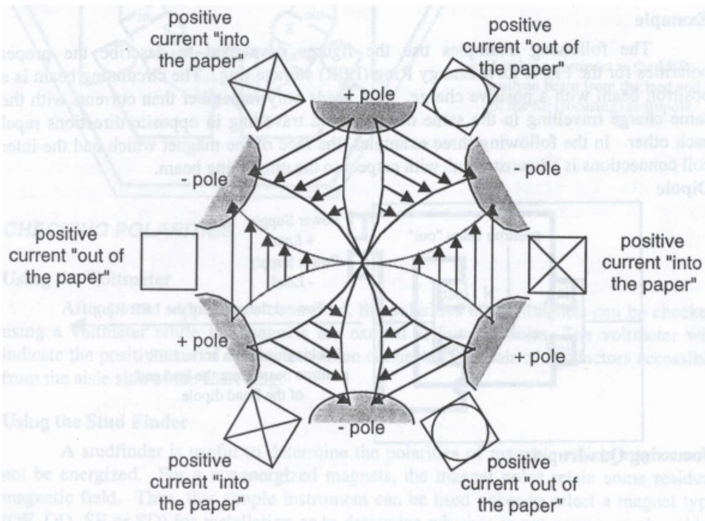


Fig. J. Tanabe

Forces on the Particle Beam – Alternative Formulations

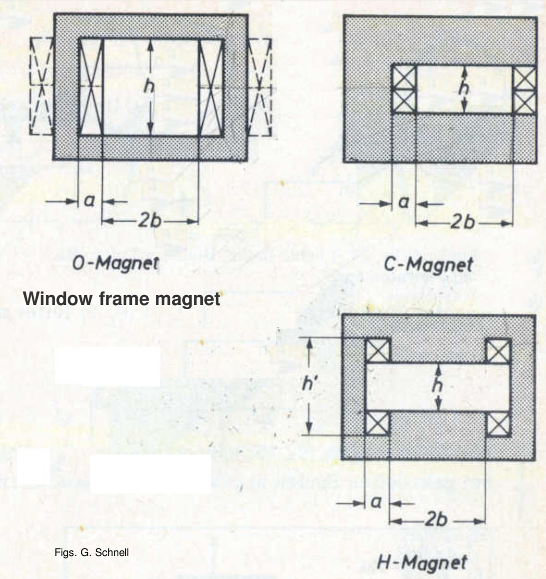
- Currents with equal charge and equal direction of movement attract each other.

Conclusions:

- Currents with opposite charge and equal direction of movement repel each other.
- Currents with equal charge and opposite direction of movement repel each other.
- Currents with opposite charge and opposite direction of movement attract each other.

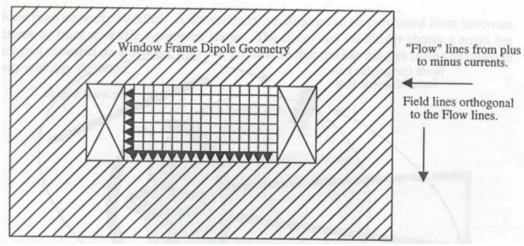
Dipole Types

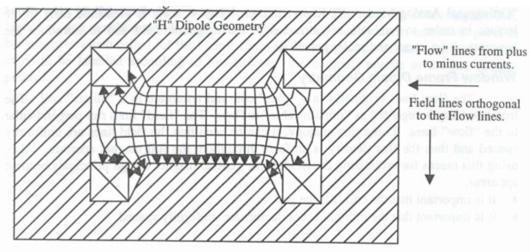
- Named by yoke shape
- Field quality dominated by iron



Figs. G. Schnell

Orthogonal Analog Model





Figs. J. Tanabe

Recipe to judge the field quality (homogeneity)

- Draw lines from plus to minus currents
- Field is perpendical to these

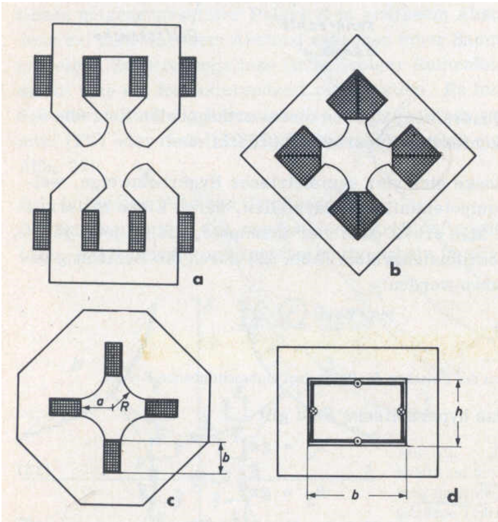
Window frame type dipole has better field quality

- Optimisation by
  - Pole overhang and/or
  - Pole profile

Dipole Types- pros and cons

Magnet	Advantage	Disadvantage
O (Window frame)	Symmetrical	Bedstead coils or cylindrical coils with high flux leakage
C	Saves space at one side, Simple coil assembly	Asymmetrical, bedstead coil, heavy yoke
H	Symmetrical, Simple pancake coils	Bad field quality (compared to WF)

Quadrupole Types



Figs. G. Schnell

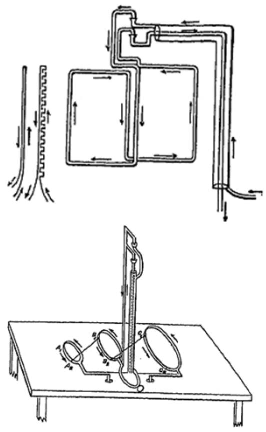
a) Collins-Quadrupole (≈„Figure of 8“-Quadrupole)
b) 1. Standard-Quadrupole (no increase of the pole basis)
c) 2. Standard-Quadrupole (max. increase of the pole basis)
d) Panofsky-Quadrupol

Coils

Ampère‘s Law

André-Marie Ampère
(1775 – 1936)

Experimental set-up by J.C. Maxwell



$$\oint_{\partial A} \mathbf{H} \cdot ds = \int_A \mathbf{j} \cdot d\mathbf{A} + \frac{d}{dt} \int_A \mathbf{D} \cdot d\mathbf{A}$$

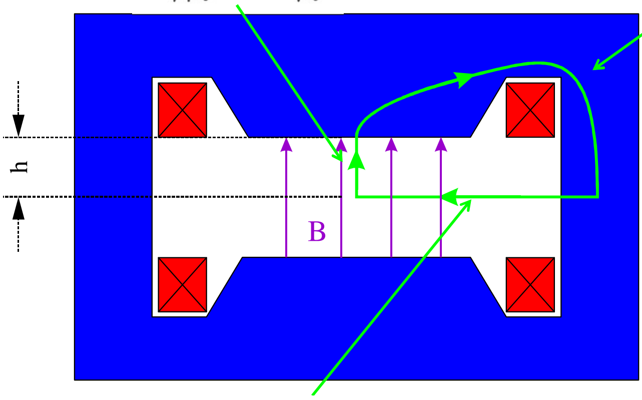
The field intgeral along a closed path equals the enclosed current

Dipole Excitation

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \frac{Bh}{\mu\mu_0}$$

is small, as μ is large

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \frac{Bh}{\mu_0}$$



$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = 0, \quad \text{as } \vec{B} \perp \vec{l}$$

Ampère‘s law:

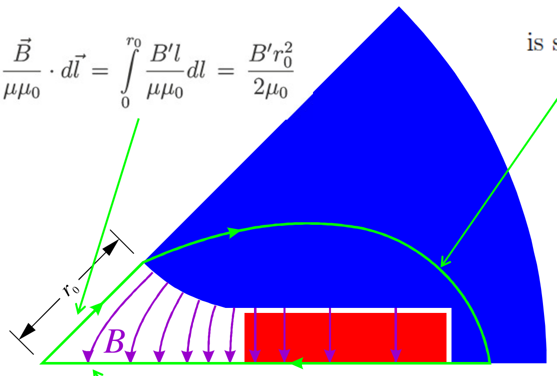
$$NI \approx \frac{Bh}{\mu_0}$$

Quadrupole Excitation

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \frac{Bh}{\mu\mu_0}$$

is small, as μ is large

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \int_0^{r_0} \frac{B'l}{\mu\mu_0} dl = \frac{B' r_0^2}{2\mu_0}$$



$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = 0, \quad \text{as } \vec{B} \perp \vec{l}$$

Ampère's law:

$$NI \approx \frac{B' r_0^2}{2\mu_0}$$

Similar for sextupole:

$$NI \approx \frac{B'' r_0^3}{6\mu_0}$$

Conductor Materials

	Aluminum (pure, > 99.5%)	Copper (OFHC- Oxygen free high conductivity)
Price (large quantities)	2.7-3.4 EUR/kg	8-16 EUR/kg
Conductivity	36 S m/mm^2	58 S m/mm^2
Specific weight	2,70 g/cm^3	8,96 g/cm^3
Linear expansion coefficient	23*10^{-6} K^{-1}	17*10^{-6} K^{-1}
Elasticity modulus	72.000 N/mm^2	123.000 N/mm^2
Keystoning effect	Smaller	Higher
Oxydation	In air. Dissolves in mixed copper/aluminum cooling circuits	Small
Conclusions (for same N*I)	Larger Lighter Higher transparancy for particles Lower investment costs Higher operating costs => Rather for detector magnets	Smaller Heavier Reduced transparancy for particles Higher investment costs Lower operating costs => Rather for accelerator magnets

=> You need more of the cheaper material!

Coil Cooling

Cooling

- Air
  - Free flow — No measures
  - Forced flow — Fan ventilation
- Water
  - Direct — Internal cooling channnel
  - Indirect

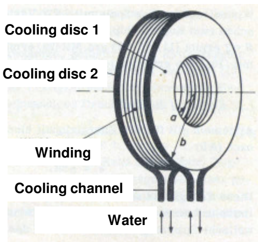


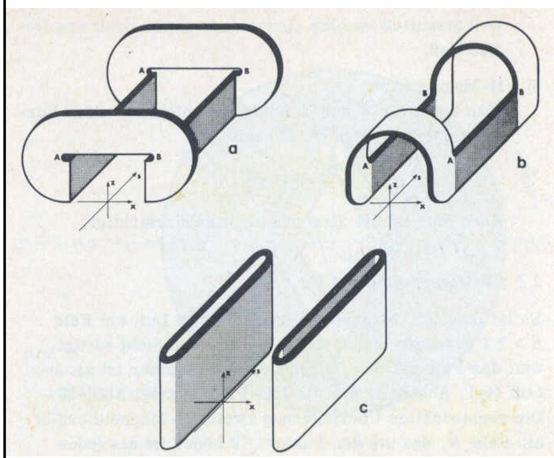
Fig. G. Schnell

Copper Profiles

- Quadratic or rectangular with round bore -> best packing factors
- Round tube -> small coils with tight bends in several directions
- Exotic shapes

e.g. Luvata, buntmetall GmbH

Coil Shapes



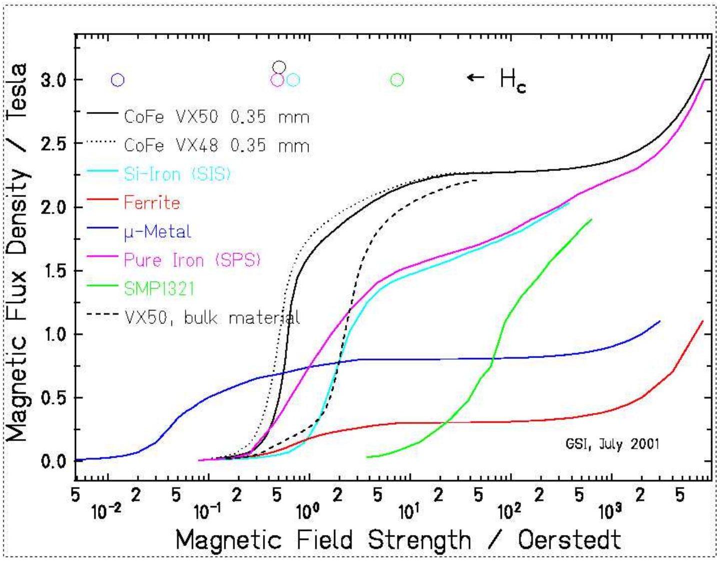
Figs. G. Schnell

Dipoles:
- O-Magnets:
  - a) Saddle shaped (bedstead) coil (type 1, upper part)
  - b) Saddle shaped (bedstead) coil (type 2, upper part)
  - c) Pair of cylindrical coils
- H-Magnets:
  - c) 1 race track coil per pole

Quadrupoles:
- Analog shapes (shape a) bent inside)

Yokes

B(H) Curves



Yoke Material Choice

- Material choice according to required ...
  - ... flux density
  - ... ramp rate
  - ... space requirements
  - ... costs

Flux density

Ferrite	Sintered iron	Soft iron	Cobalt iron

Ramp rate

Ferrite	Sintered iron	Laminated iron	Bulk iron

Saturation Effects

- $\mu_r = \mu_r(B)$, for B > 1.5 T μ_r becomes smaller

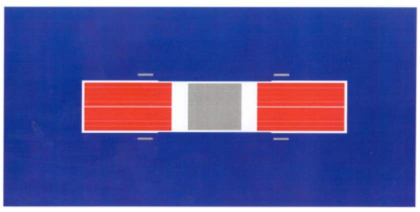
Saturation effects

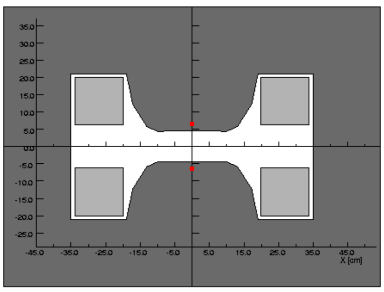
- **Reduced field (loss of Ampere turns)**
  - **Increase N*I**
  - **Adapt yoke design (thicker yoke)**
- **Reduced field quality**
  - **Adapt pole profile (wider pole)**
  - **Correction windings**
  - **Slits in the pole**

Slits in the Pole

2 options

- **Field guidance**
- **Artificial saturation near the center**

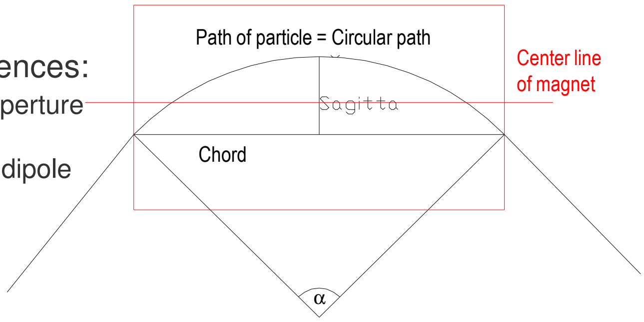




Sagitta

- Asymmetric central trajectory in a straight dipole
- Consequences:
  - Wider aperture or
  - Curved dipole

Sagitta h
Radius r
Deflection angle α



$$h = r*(1-\cos(\alpha/2)) \propto l^2$$

Aperture Reduction for Laminated Dipoles

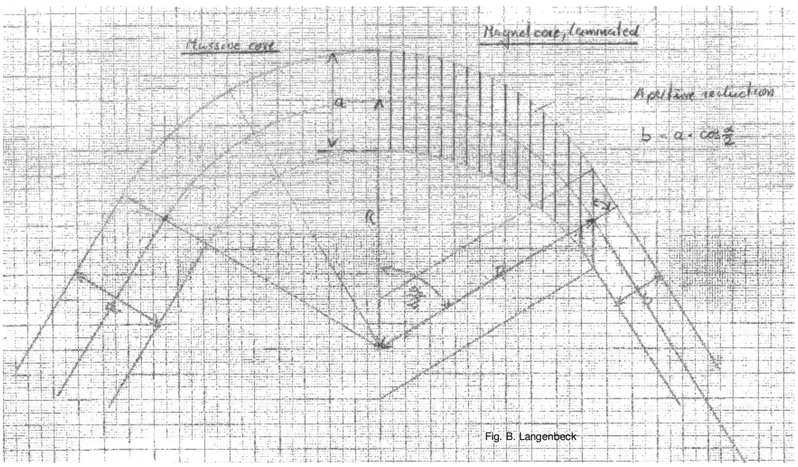


Fig. B. Langenbeck

- Laminations are stacked parallel on radius R => Aperture reduction
  -> Use several blocks with adapted stacking direction along the magnet

Special magnets (incl. examples)

Special Magnets

- Magnets with special technical features or materials in their design
  - Magnetic Septa -> separate talk
  - Kicker Magnets -> separate talk
  - Radiation Resistant Magnets
  - Special Yoke Shapes
  - Integrated Magnets
  - Magnets with Cobalt iron yokes
  - ...
- Magnets which cannot be described by multipoles as shown in the beginning
  - Solenoids
  - Magnetic Horns
  - Toroids
  - ...

Radiation

Beam loss

Intended

Targets
Charge state separation
Mass separation

Unavoidable

Any beam loss process:
Charge exchange reaction
(at residual gas particles, at el. septum wires)
Resonances
....

The materials for the magnet must be choosen according to the expected radiation level. Coil insulation is the most sensitive one.

Standard epoxy resin	Improved plastics (e.g. Isocyanates, Polyimide)	Fully anorganic
10^7Gy	10^8Gy	>10^9 Gy

Radiation Resistant Magnets

- Coil potting with polyimide or isocyanates
  - Conductor and coil design unchanged
  - Potting mould to be adopted for different material (e.g. cooling)
  - Coils for external beam line at KEK


Fig. K.H. Tanaka

- Fully anorganic
  - MIC (metall oxide insulated) conductor

  - Coil solder potted
  - Dipole for SuperFRS pre-separator

Special Yoke Shapes

- Imposed by external requirements
  - Other beamlines at injection/extraction or branching points
  - ...
  - Examples
    - Branching dipole (HEBT Heidelberger Ionentherapie) – opening for straight beam path including yoke reinforcement
    - Sextupole for Australian Light Source – opening for light beam line

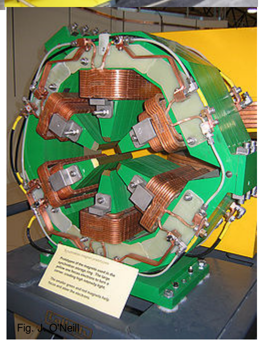


Fig. J. O'Neill

Integrated Magnets

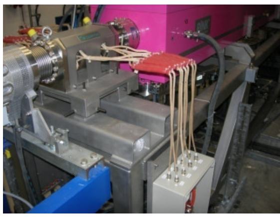
- Radial or longitudinal integration of several multipoles
  - Reduced space requirements
  - Reduced installation and alignment effort
  - Enlarged vibration stability
  - Examples
    - Corrector magnet in SIS18 (current dominated; normal and skew quadrupoles, skew sextupole)
    - Main magnet for MAX IV (common massive yoke, dipole, quadrupoles, sextupole, steering magnets)

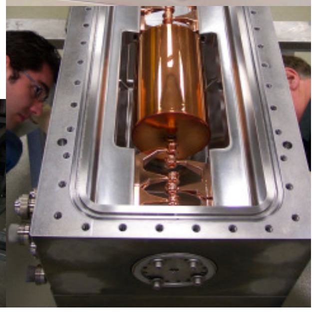
Fig. M. Johansson

Special Yoke Materials: CoFe

- Enlarged saturation flux density (2.2-2.3T)
- Compact design with high field/gradient
- But
  - High material price
  - Brittle material
  - Risk of activation
- Example
  - Internal quadrupoles for IH-type LINAC
  - Maximum Pole basis
  - CoFe yoke laminations (0.35mm)
  - One layer coil
  - Up to 124T/m

  - In addition an example of an integrated magnet – triplet in copper plated housing





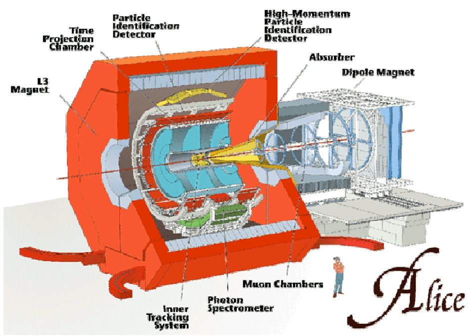
Solenoids

- In general a long coil
- Focusing magnet (in both planes)
- Field along the beam path
- Principle of focusing
  - Stray field creates radial motion of particles
  - Radial motion is perpendicular to main field and causes therefore focusing
- Application
  - Focusing in LEBT (typically NC)
  - Focusing in LINAC (typically SC)
  - Magnet for particle tracking in experiments (NC or SC)

Solenoids

- LEBT-Solenoid
- 0.54T
- ~0.5t
- Diam. ~0.6m, length ~0.3m

- Alice central magnet
- 0.55T
- ~10,000t
- Diam. ~12m, length ~12m



Magnetic Horn

- Focusing magnet close to targets
- Central path field free
- Focusing of off-axis particles

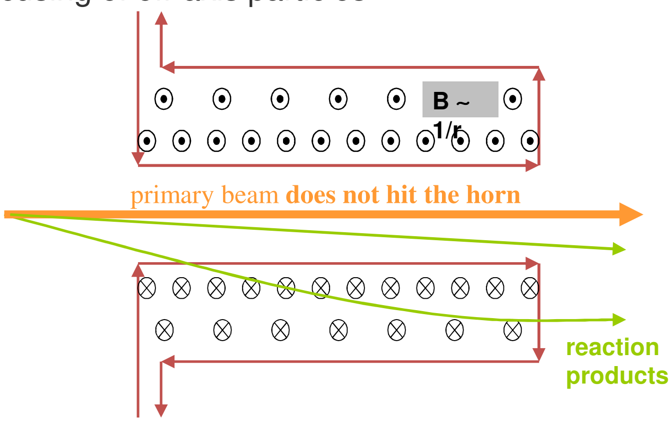
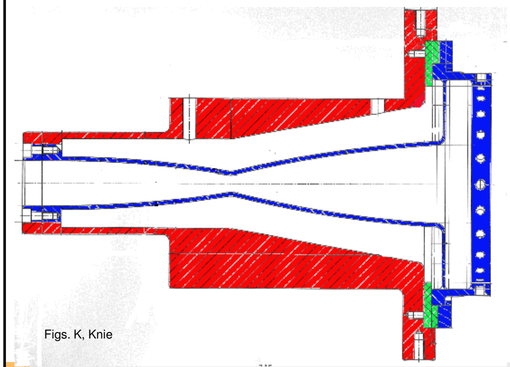


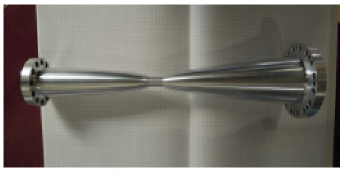
Fig. K. Knie

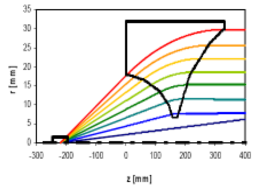
Magnetic Horn

- Focusing after pbar production target planned at FAIR
- 400kA/15kV
- Inner conductor shaped to generate a parallel beam independend from original angle of the particles



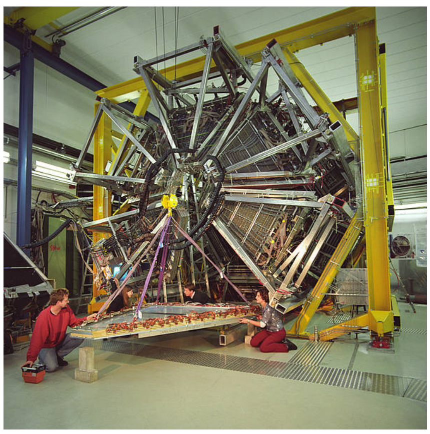
Figs. K, Knie





Toroid

- For charged particle tracking in detectors
- Example
  - HADES (High Acceptance Dielectron Spectrometer) at GSI
  - Toroidal field generated by 6 super-conducting air coils



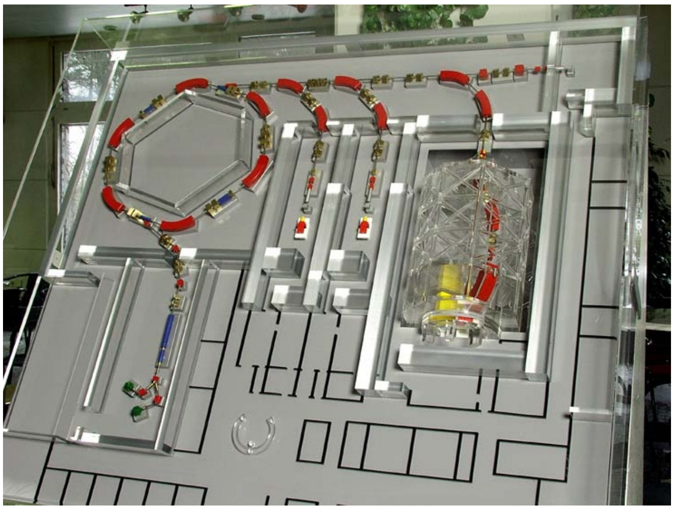
Examples

Magnets for HIT (Heidelberger Ionentherapie)

- Dedicated facility for cancer therapie with ions in Heidelberg
- Developed by GSI
- 2 commercial facilities were built (Siemens, Danfysik)
- More similiar facilties are operational or in commissioning

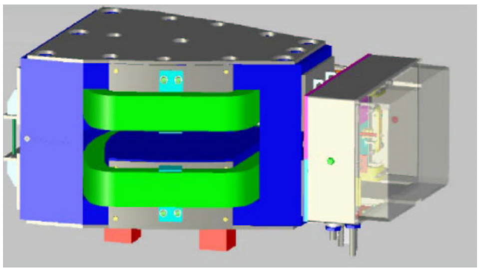
- Compact accelerator
- 120 magnets
- Footprint ~70m x 70m

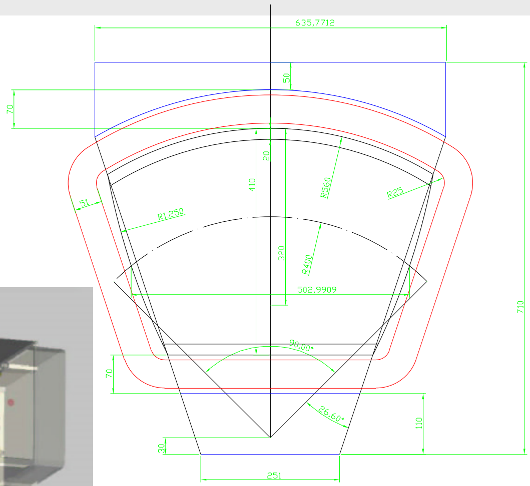
- Most magnets described before can be found here.



Analysis Dipole (1.1)

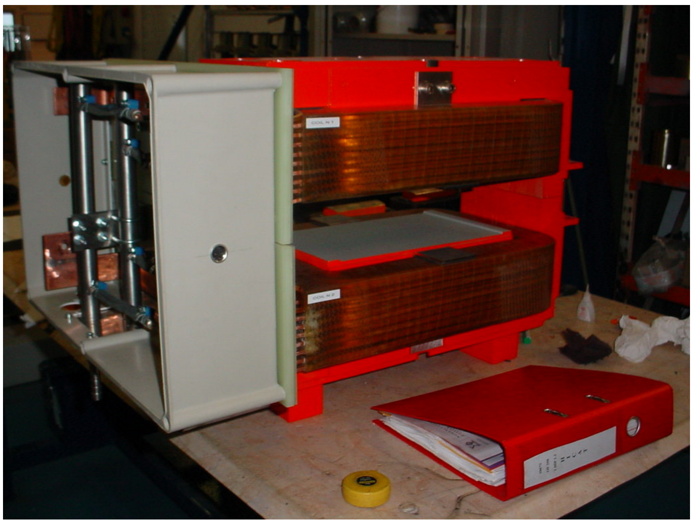
- H type magnet
- D shaped coil
- 0.2T
- Small bending radius
- 90°





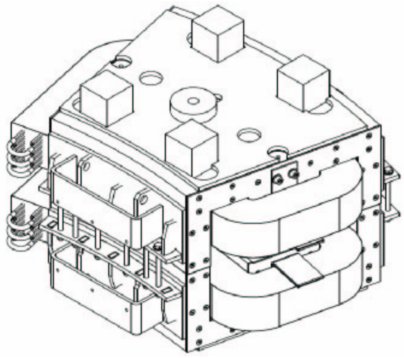
Switch Yard Dipole (1.2)

- H type magnet
- Straight
- 0.1T
- Funneling of beams from 2 ion sources



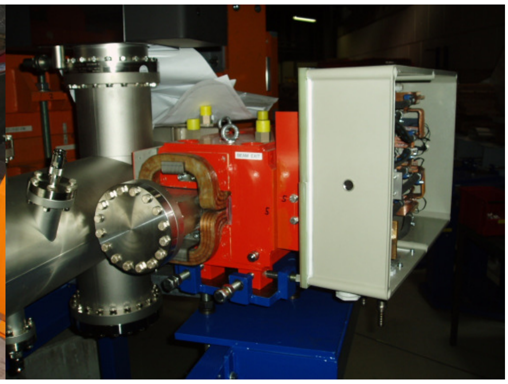
MEBT Dipole (1.3)

- H type magnet
- Curved
- 25°
- 0.57T



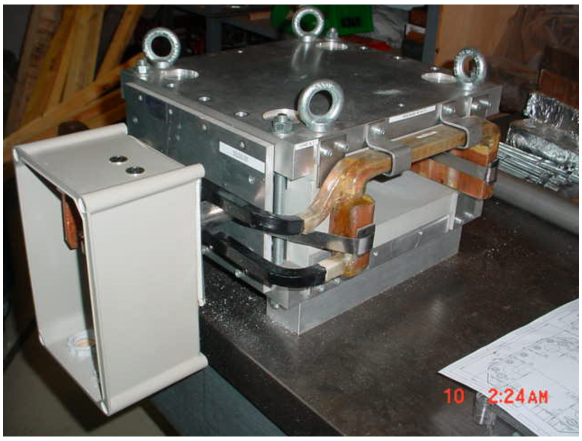
Inflector Dipole(1.4)

- Window frame type magnet
- Yoke c-shaped
- Curved
- 15°
- 0.42T



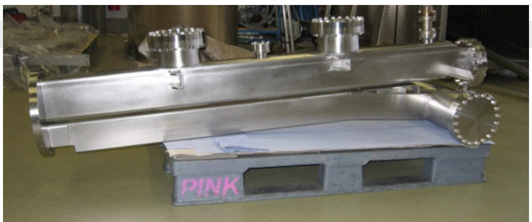
Bumper (1.5)

- Window frame type magnet
- Very fast (560T/s):
  - Powder composite material
  - 2 turns
- 0.0195T



Septum I (1.6)

- Window frame type magnet
- Yoke c-shaped
- Straight (2x)
- Septum coil (soldered out of different parts)
- 6.5°
- 0.75T



Septum II (1.7)

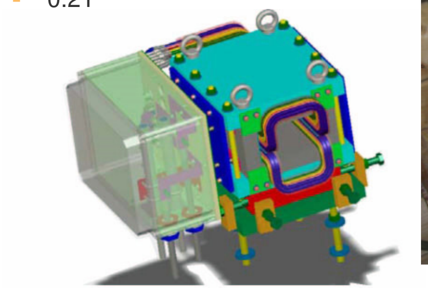
- Window frame type magnet
- Yoke c-shaped
- Curved
- Septum (soldered)
- Operated in series with synchrotron dipoles
- 13.5°
- 0.9T

Synchrotron Dipole (1.8)

- H type magnet
- Curved – stacked in 3 blocks along the magnet to avoid aperture reduction
- Removable endplates for length adjustment
- Integrated correction windings for horizontal steering
- 1.53T, 1.53T/s
- 60°

Spill Abortion Bumper(1.9)

- Window frame type magnet
- Safety function
- Fast Magnet (1000T/s ramp down)
  - Yoke: Powder composite material
  - Few turns
- 0.69°
- 0.2T



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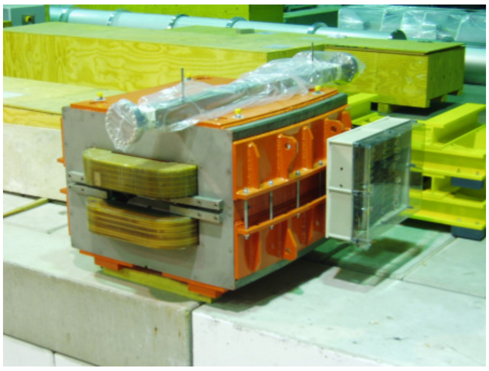
15° HEBT Dipole (1.10)

- H type magnet
- Curved
- Same cross section as 1.11
- ‚Zero-field' correction coil integrated for straight beamline
- 1.51T



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45° HEBT Dipole (1.11)

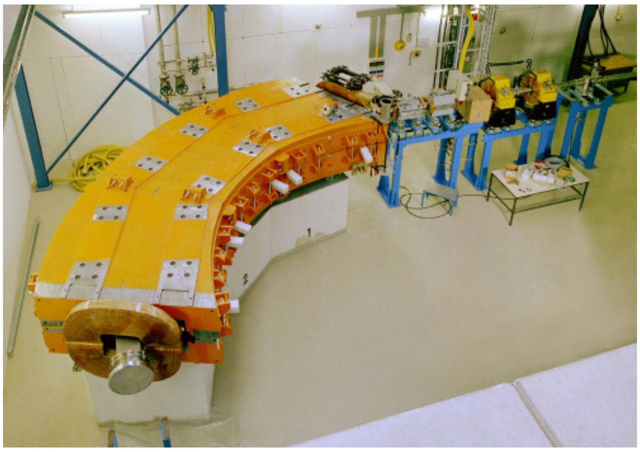
- H type magnet
- Curved – 3 blocks along the magnet
- ‚Zero-field'-coil integrated
- Return yoke width enlarged cross section for compensation of straight beam line channel
- 1.51T

45° Gantry Dipole (1.12)

- Hybrid type magnet
  - Inner coil – window frame type
  - Outer coil – H type (around poles), but bedstead shape
- Curved – 2 blocks along the magnet
- 1.81T

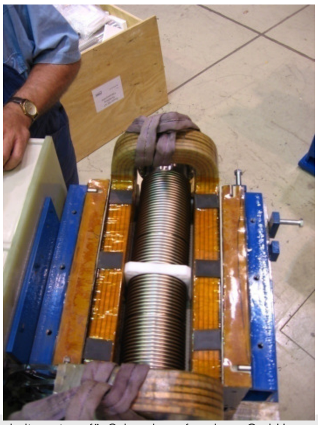
90° Gantry Dipole

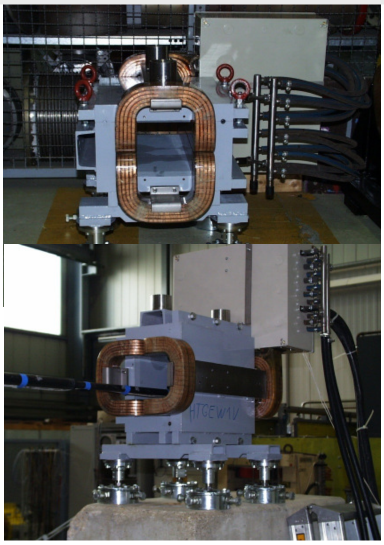
- Window frame type magnet
- Extremly large Aperture – must accomodate scanned beam
- Curved – 3 blocks along the magnet
- 1.81T



Scanning dipole (1.13)

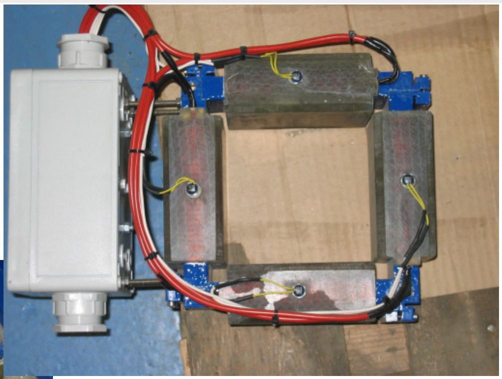
- Window frame type magnet
- Lamination thickness 0.35 mm
- Thin–walled vacuum chamber
- 0.31T, 62T/s





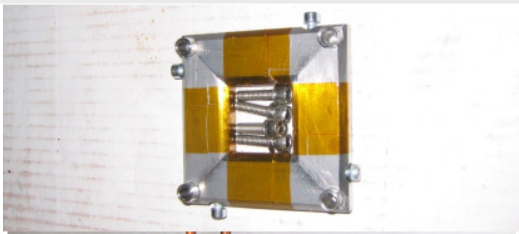
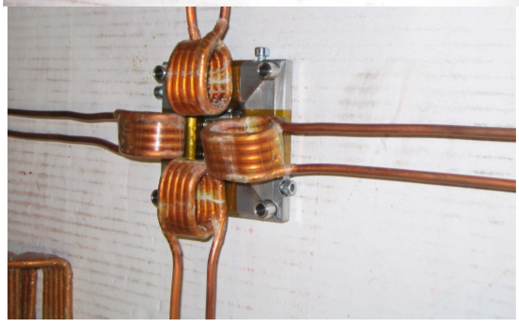
LEBT Steerer (2.1)

- Double steering magnet (horiz./vert.)
- Window-Frame-Magnet (x,y)
- Cylindrical coils
- No active cooling
- 0.0252T



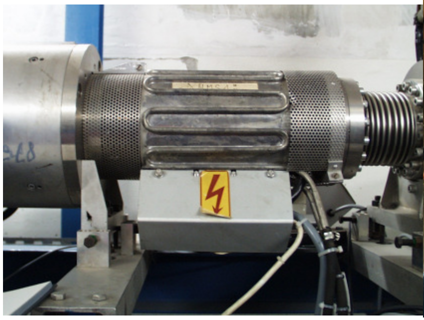

Matching Steerer (2.2)

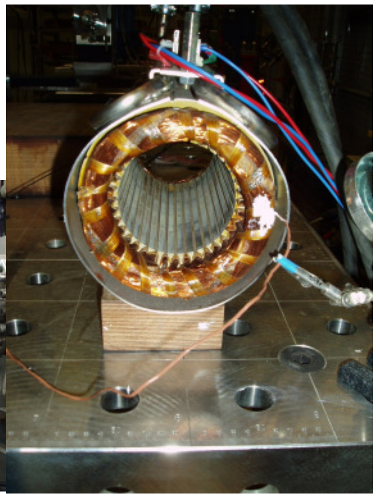
- Double steering magnet (x,y)
- Window-Frame-Magnet (x,y)
- 0.085T

Rohrsteerer (2.3)

- (Beam) Pipe Steering Magnet
- Coil-dominated => cosθ-Design
- Double steering (x,y)
- Low-Cost-Steering magnet
  - Yoke: stator of standard electrical motor
- Indirect cooling
- 0.05T





Synchrotron (Vertical) Steerer (2.4)

- Simple vertical steering magnet
- Window frame type magnet
- Cylindrical coils
- 0.134T

HEBT Steerer (2.5)

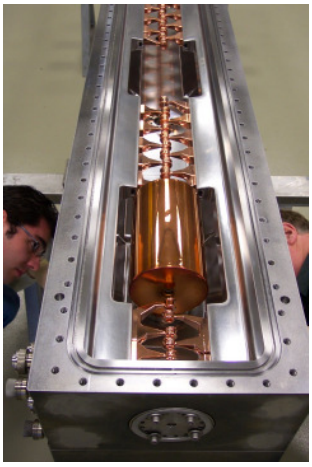
- Simple steering magnet (x or y)
- Window frame type magnet
- Cylindrical coils
- 0.1T

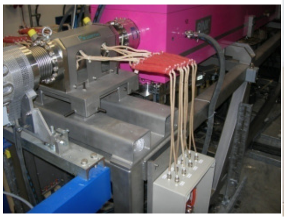
LEBT Quadrupole (3.1 and 3.2)

- Quadrupole without increased pole basis
- Singulett and triplett
- 3.2T/m

IH Quadrupole (3.3, 3.4)

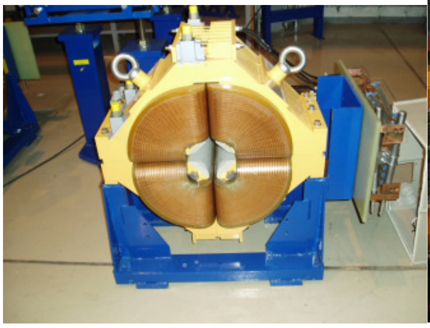
- Compact design with highest gradient
  - Maximum Pole basis
  - CoFe yoke laminations (0.35mm)
  - One layer coil
- Up to 124T/m

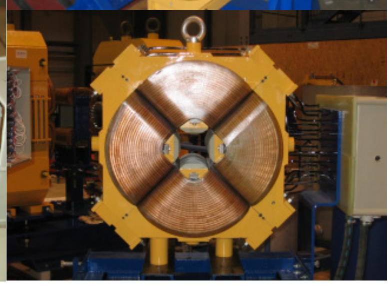




MEBT Quadrupole (3.5) / Gantry Quadrupole (3.6)

- Maximum pole basis
- 18.8T/m
- 1 skew quadrupole





HEBT Quadrupole (3.7)

- Cross section as 3.5 und 3.6, but longer yoke
- 19.3T/m

Synchrotron Quadrupole (3.8)

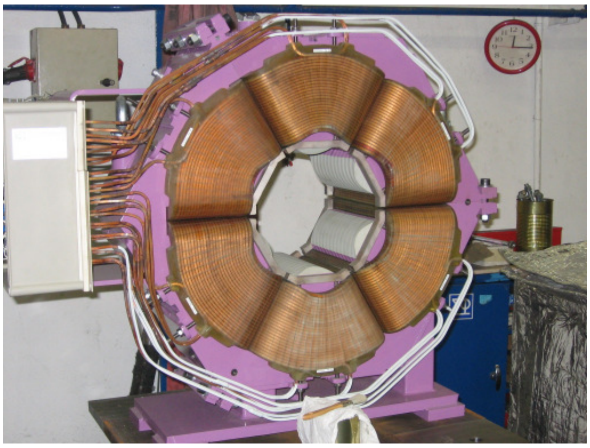
- "Figure of 8" type quadrupole
- Removable pole end pieces for field optimization and length adjustment
- 7.0T/m

Solenoid (4.1)

- 0.54T
- ~0.5t
- Diameter ~0.6m
- Length ~0.3m

Sextupol (4.2)

- Yoke 3 parts
- $d^2B/dx^2=26.7T/m^2$



Literature

- CERN Accelerator School (CAS) Magnets in Bruges https://cds.cern.ch/record/1158462
- CAS - Measurement and alignment of accelerator and detector magnets https://cds.cern.ch/record/318977
- US Particle Accelerator School, Iron Dominated Electromagnet Design, Jack Tanabe, June 2005 http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-754.pdf
- Jack T. Tanabe, Iron Dominated Electromagnets; World Scientific Publishing Co., 2005
- IEEE, Proceedings of International Conferences on Magnet Technology, every 2nd year, e.g. 24th International Conference on Magnet Technology (MT-24) : Seoul, Korea, October 18-23, 2015 published in IEEE Trans.Appl.Supercond. 26 (2016) no.4
- Heinz E. Knoepfel, 'Magnetic Fields', John Wiley and Sons, INC. , New York…., 2000
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Questions?