Introduction to Accelerator Physics

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Physikalisches Institut der Universität Heidelberg

Lecture 4

Lecture Dates

https://uebungen.physik.uni-heidelberg.de/vorlesung/20222/1611/lecture

Date	Topic
19.10.2022	Introduction and basic definitions
26.10.2022	Accelerating structures
02.11.2022	Accelerator Components
09.11.2022	Optics with magnets (1)
16.11.2022	Optics with magnets (2)
23.11.2022	Equations of motion
30.11.2022	Phase ellipses and magneto-optical system / Transverse beam dynamics
07.12.2022	Transverse beam dynamics, beam stability / Longitudinal beam dynamics
14.12.2023	Phase space and beam cooling (Invitation)
11.01.2023	Space charge and beam-beam dynamics
18.01.2023	Physics at Storage Rings
25.01.2023	Physics at Colliders
01.02.2023	New accelerator technologies
08.02.2023	Student seminar
15.02.2023	reserve
22.02.2023	reserve

Wednesdays, 14:15-16:00

„Leistungskontrolle“

Accelerator Physics Related Applications

- *Particle cancer therapie*
- *Cosmic rays*
- *Accelerator Mass Spectrometry*
- *Accelerator Driven System*
- *Energy recovery accelerator*
- *Superheavy elements*
- *Strongest magnetic field*
- *Tokamak*
- *Photon facility*
- *Isotopes for medicine*
- *Crystalline beams*

Summary of the last lecture

1) Accelerator types: Synchroton and Betatron

$$\boxed{\frac{\Delta E}{E}(\text{beam}) \sim 10^{-3}}$$

Synchrotron principle:

$$\boxed{\frac{\Delta\omega}{\omega} = \eta \frac{\Delta p}{p}}$$

reference particle
betatron oscillations
synchrotron oscillations

Separatix
Harmonic number
Buckets

2) Production of ion and electron beams

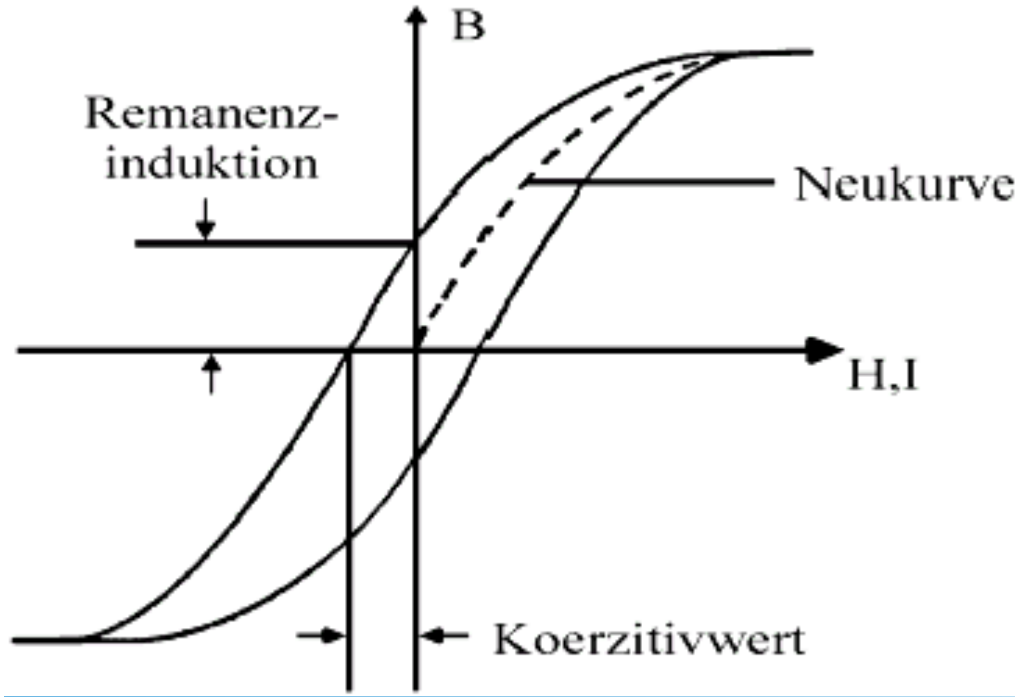
- **electron sources**
- **ionization processes**
  - **electron-impact ionization**
  - **surface ionization**
  - **resonant laser ionization**
- **production of highly charged ions**
- **production of radionuclides**
- **production of antiprotons**

Super-EBIT
GSI
ISOLDE

4 Magnets

Magnetic fields

Magnetic hysteresis



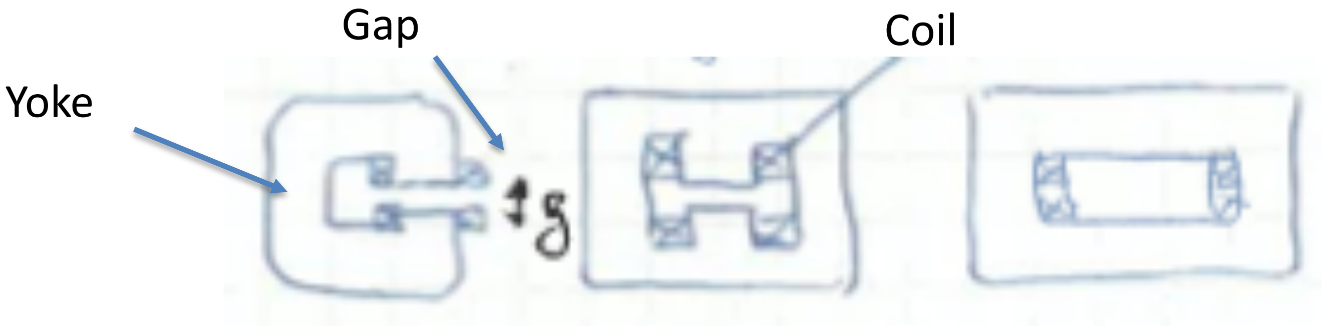
Iron (Fe):

$$B \le 2\ \mathrm{T}$$

steel with a few carbon
Small remanence
Small coercivity
Laminated (to reduce Eddy currents)
Coil:
water cooled cupper

Electromagnets (1)

1. Dipole magnets – used to bend particle trajectories



„C“

Asymmetric
Open-side =
easy access

„H“

Symmetric
Compact
Highest field
homegenity

$$\text{if } g = 4 \text{ cm}$$

$$\text{for } \frac{\Delta B}{B} \sim 10^{-4}$$

$$\frac{\Delta g}{g} \leq 4\ \mu\text{m}$$

„Window frame“

Compact
Less iron needed to achieve
fields as in “H“ magnets
+ large apertures possible
- complicated

Electromagnets (2)

1. Dipole magnets – used to bend particle trajectories

Static magnetic field

$$\vec{\nabla} \times \vec{H} = 0 \qquad \vec{\nabla} \times \vec{B} = 0 \qquad \vec{B} = \mu \vec{H}$$

field

flux

permeability

Number of windings

$$\oint H dS = H_0 g + H_{\mathrm{Fe}} l_{\mathrm{Fe}} = nI$$

$$\mu_{\mathrm{Fe}} >> 1 \Rightarrow H_{\mathrm{Fe}} << H_0$$

$$H_0 \approx \frac{nI}{g} \Rightarrow B \approx \mu_0 \frac{nI}{g}$$

$$\boxed{\mu_0 = 4\pi \cdot 10^{-7} \, \frac{\mathrm{Tm}}{\mathrm{A}}}$$

Example: $nI = 50'000A \Rightarrow B \approx 1.57 \ \mathrm{T}$

$g = 4 \ \mathrm{cm}$

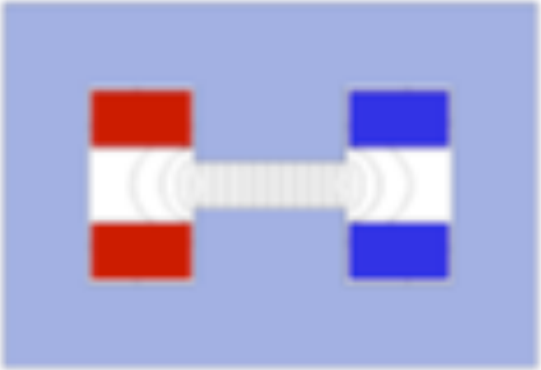
Electromagnets (3)

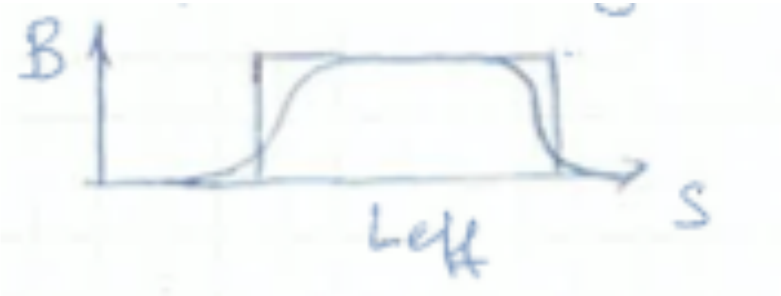
1. Dipole magnets – used to bend particle trajectories

Problem

B(H) – saturation - complicated calculations, polynoms of high order
Hysteresis/remanence – reproducibility, stability

Effective length L_{eff} (Franging fields)





$$L_{\text{eff}} = \frac{1}{B_0} \int_{-\infty}^{\infty} B(s) ds$$

For dipole: $L_{\text{eff}} \approx L_{\text{Fe}} + 1.3g$

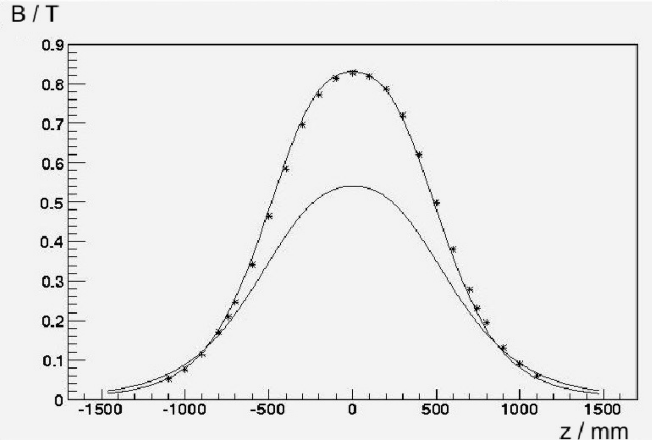
Dipole Magnets

H-magnet (BGO-OD experiment)

$$I_{max} = 1500 \text{ A}$$

$$g = (1500 \times 1500) \text{ mm}^2$$

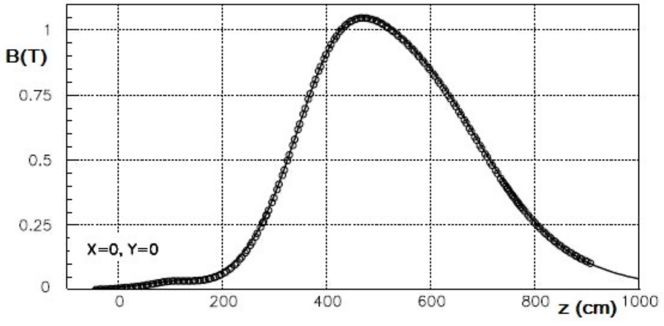
$$\int B ds = 0.9 \text{ Tm}$$

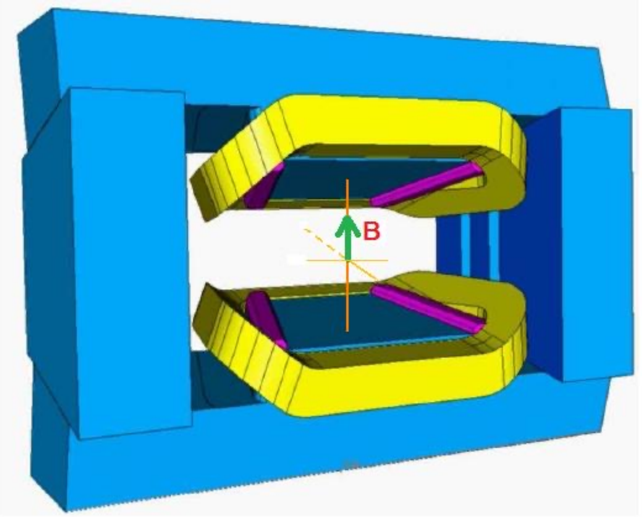


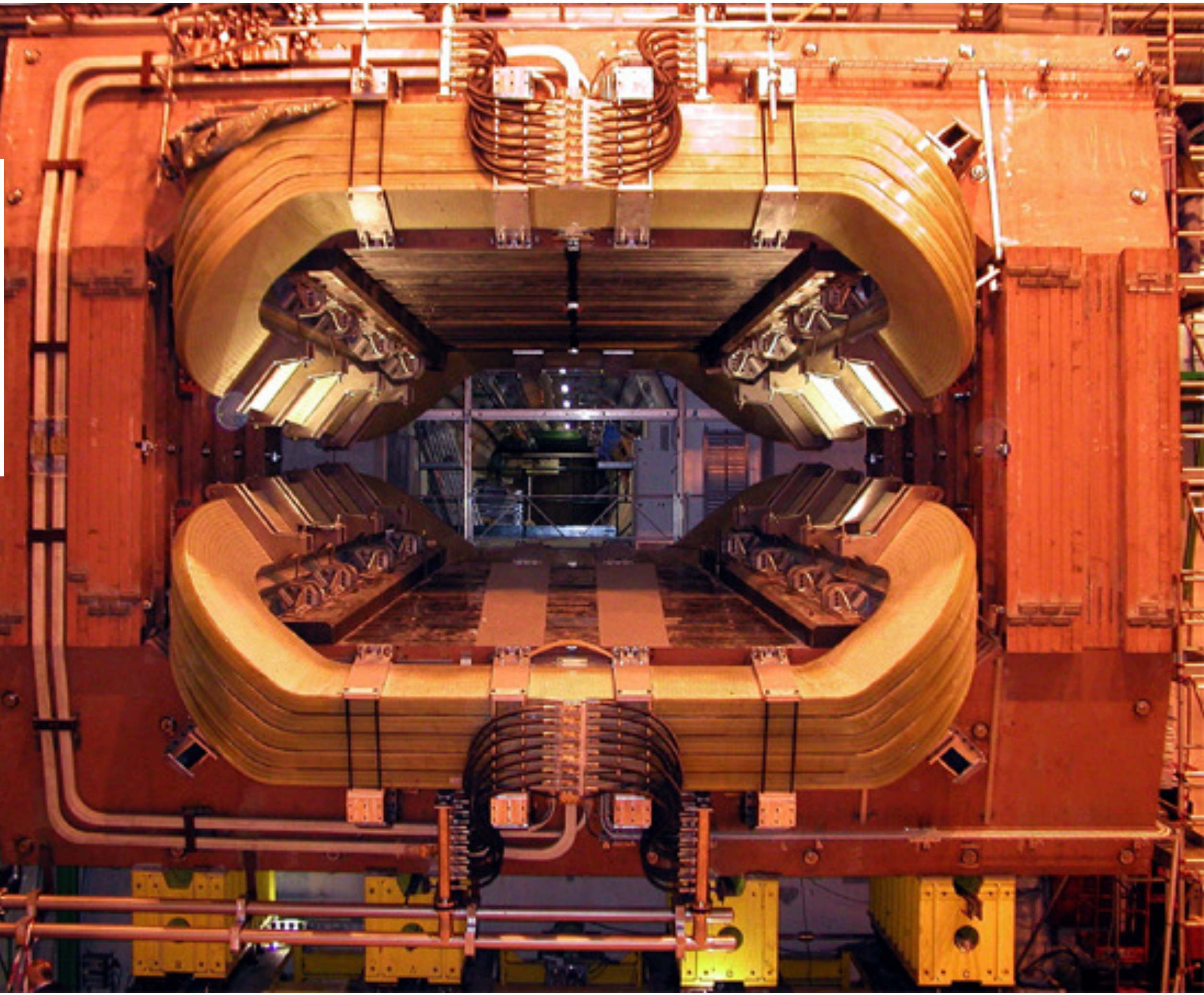
Dipole Magnets

Window frame-magnet (LHCb)

$$I_{max} = 5800 \text{ A}$$

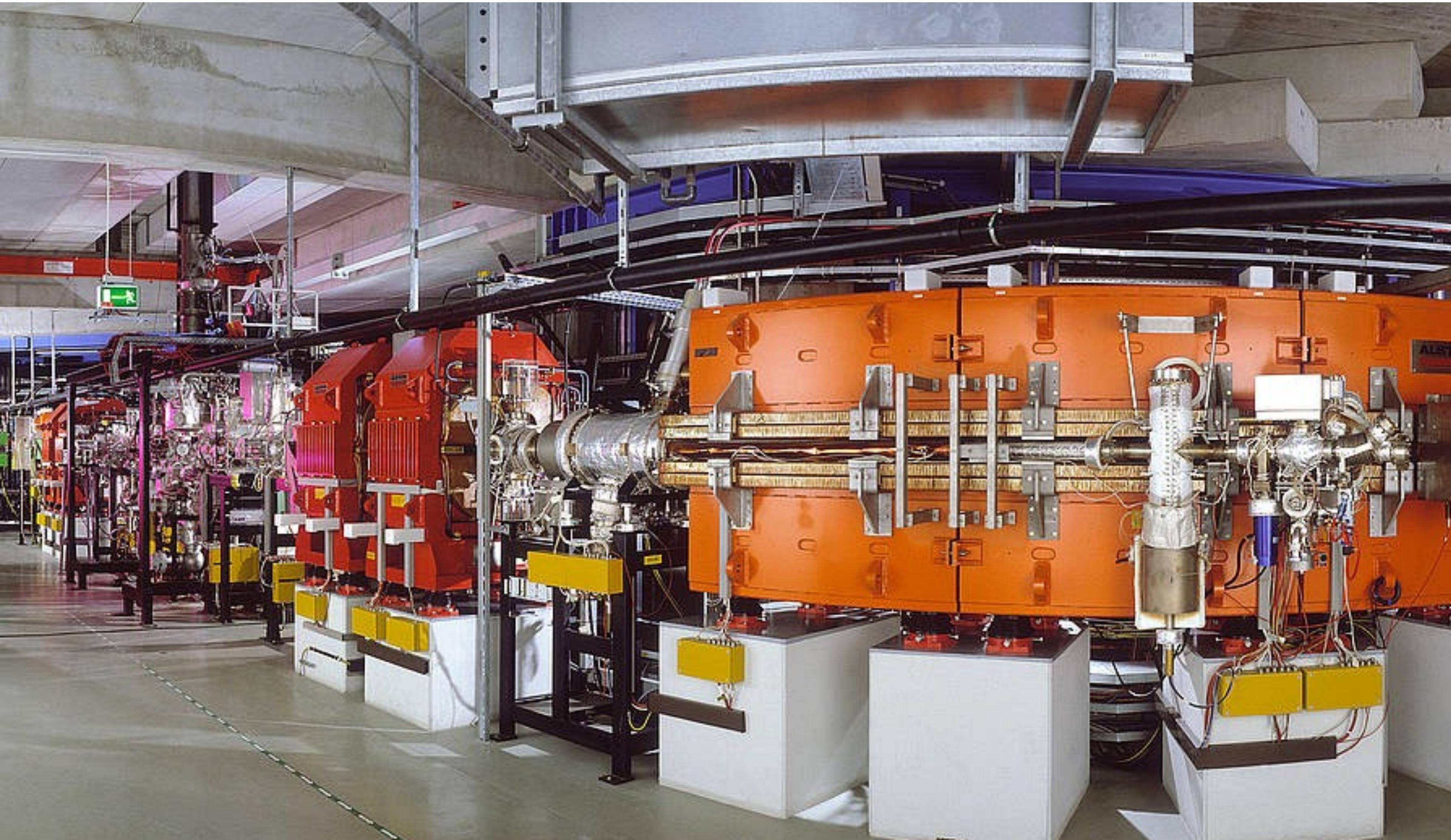






Dipole Magnets

C-magnet (ESR)



olmagnet

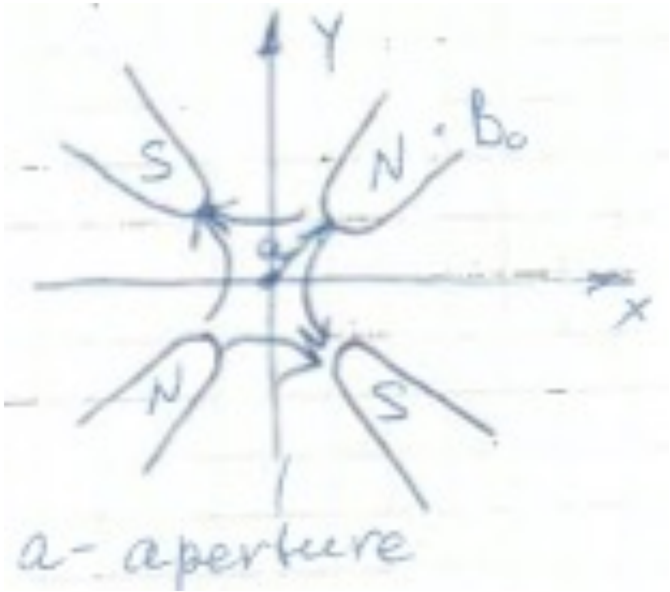
eschleunigern und Strahlführungen werden Di-
magnete dazu genutzt, den Ionenstrahl auf eine
venflugbahn zu lenken. Die Ionen fliegen durch
Strahlrohr im Inneren. Das durch die zwei Spulen
eugte Magnetfeld sorgt für eine Ablenkung der
nen senkrecht zu Flug- und Magnetfeldrichtung
orentzkraft). Das Ausstellungsstück ist ein Prototyp
r den GSI-Ringbeschleuniger SIS18. Verbaut
vurden leicht modifizierte Magnete.

Dipole magnet

ipole magnets are used in accelerators and
amlines to guide the ion beam onto a curved flight
th. The ions move through a beam tube in the
ter of the magnet. The magnetic field generated
he two coils leads to a deflection perpendicular to
ions' direction of flight and to the magnetic field
entz force). The exhibit is a prototype for the GSI
accelerator SIS18. Finally installed were magnets
slight modifications.

Electromagnets (4)

2. Quadrupole magnets– used to focus/defocus the beam



Center: $B = 0$

$$\vec{B} = -\vec{\nabla}\Phi$$

$$\Phi(x, y) = -gxy$$

scalar potential

field gradient

flux at the pole tip

$$g = \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} = \frac{B_0}{a} \approx 2\mu_0 \frac{nI}{a^2}$$

Electromagnets (5)

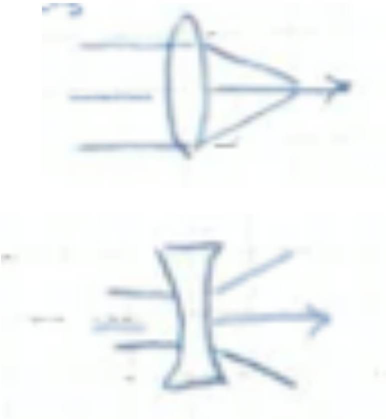
2. Quadrupole magnets– used to focus/defocus the beam

Lorentz force

$$\vec{F} = q(\vec{v} \times \vec{B})$$

$$F_x = -qgx$$ Focusing (y=0)

$$F_y = qgy$$ Defocusing (x=0)



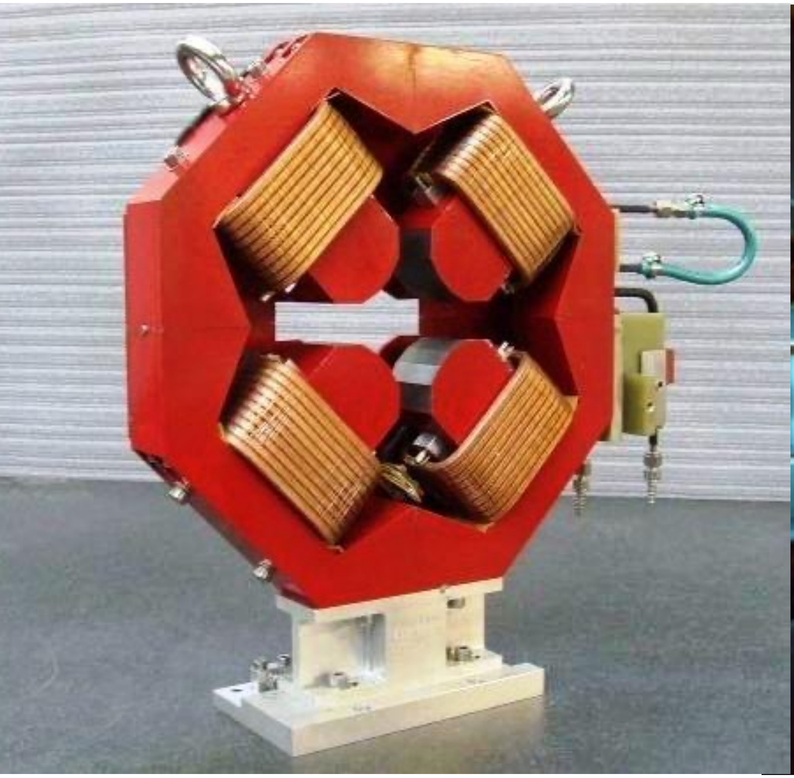
Like in optics

Effective length

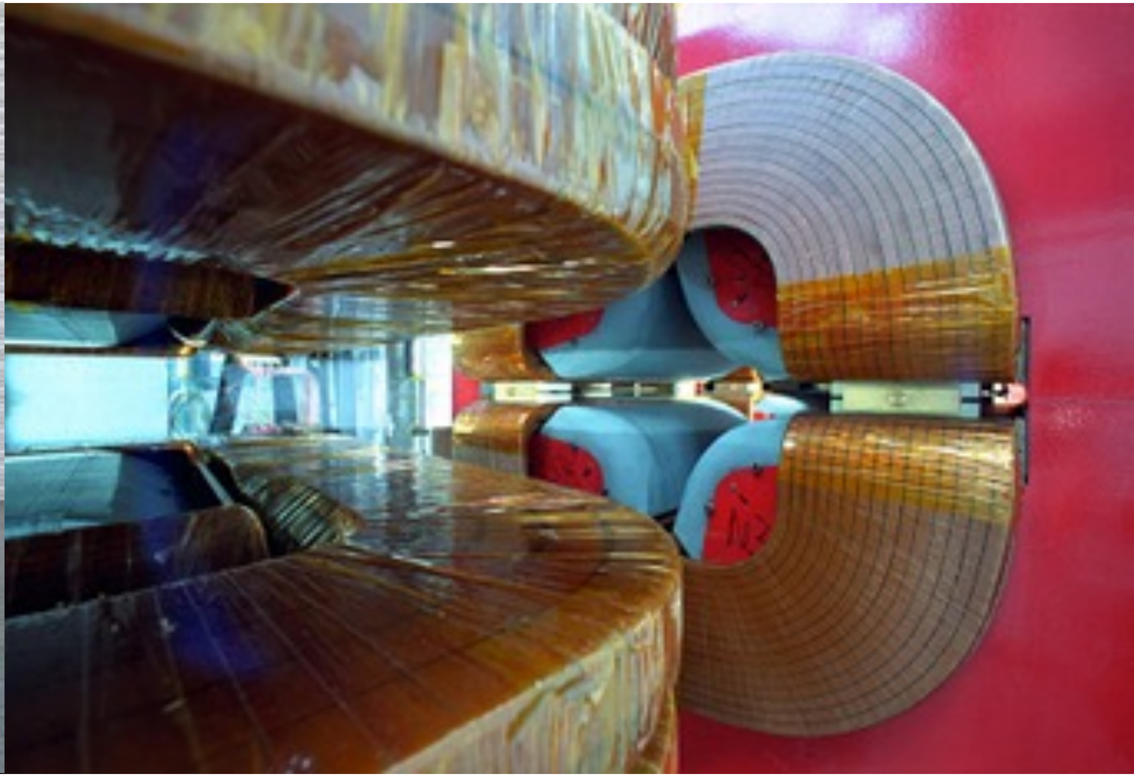
$$L_{\mathrm{eff}} \approx L_{\mathrm{Fe}} + a$$

Quadrupole Magnets

TRIUMF



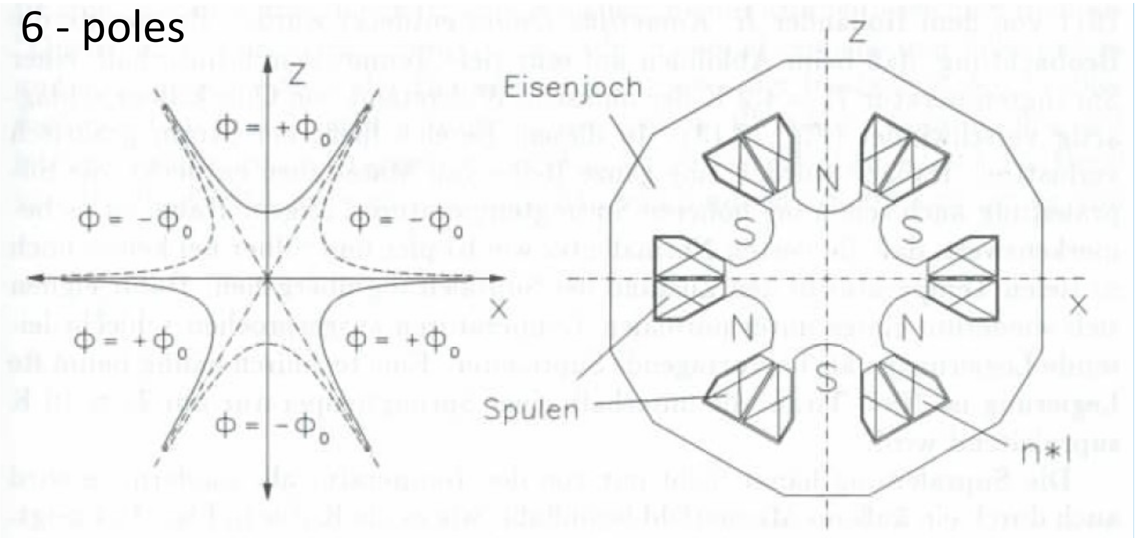
ESR

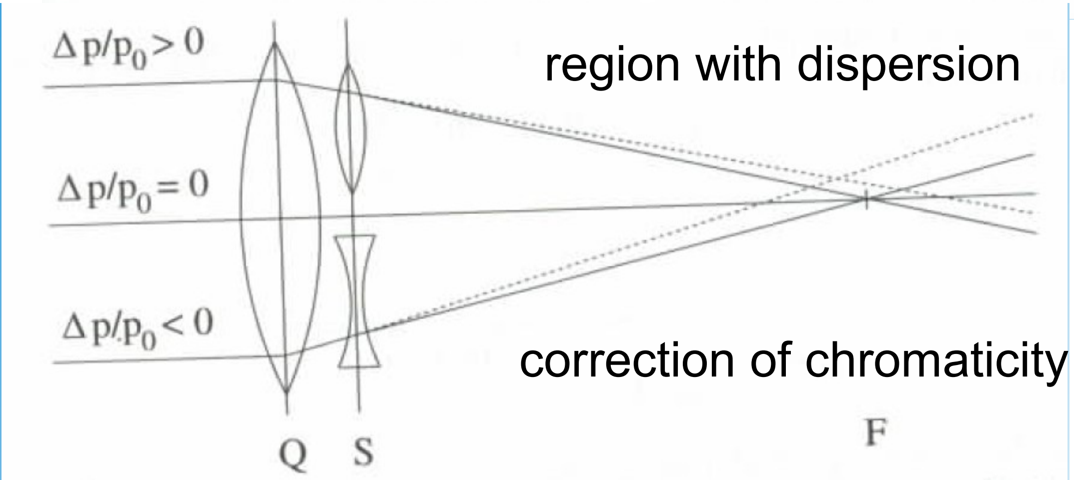


Electromagnets (6)

3. Sextupole magnets– used to correct for aberations/chromaticity

6 - poles





region with dispersion

correction of chromaticity

$$\Phi = -\frac{g_s}{2}\left(x^2 y - \frac{y^3}{3}\right)$$

$$B_x = g_s x y$$

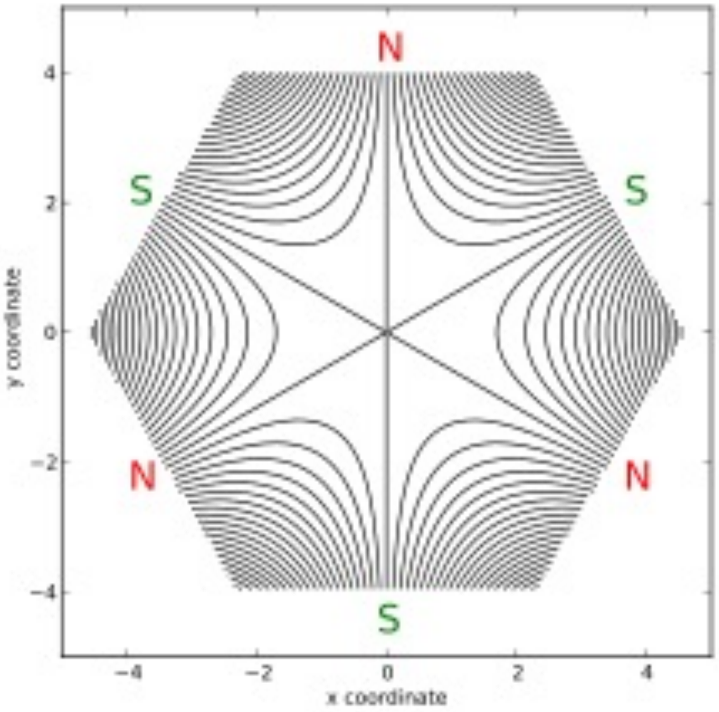
$$B_y = \frac{1}{2} g_s (x^2 - y^2)$$

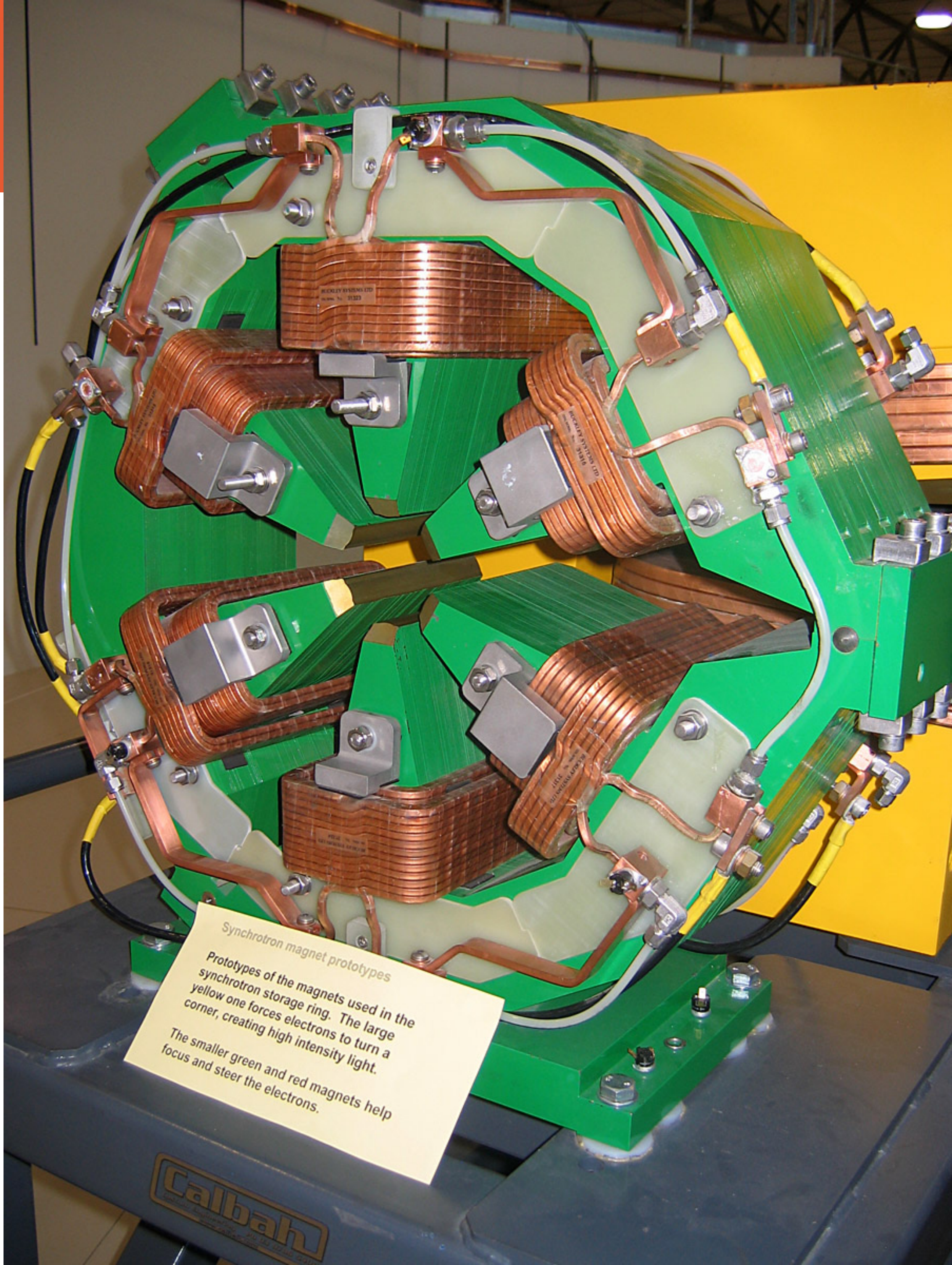
$$g_s = 6\mu_0 \frac{nI}{a^3}$$

$$L_{\mathrm{eff}} = L_{\mathrm{Fe}} + \frac{a}{2}$$

Mixes x & y planes

Sextupole magnet





Synchrotron magnet prototypes

Prototypes of the magnets used in the synchrotron storage ring. The large yellow one forces electrons to turn a corner, creating high intensity light.

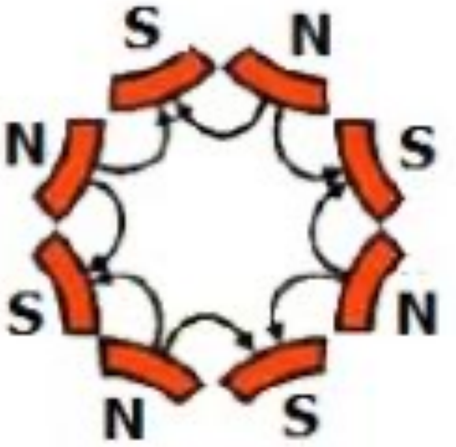
The smaller green and red magnets help focus and steer the electrons.

Further multipoles

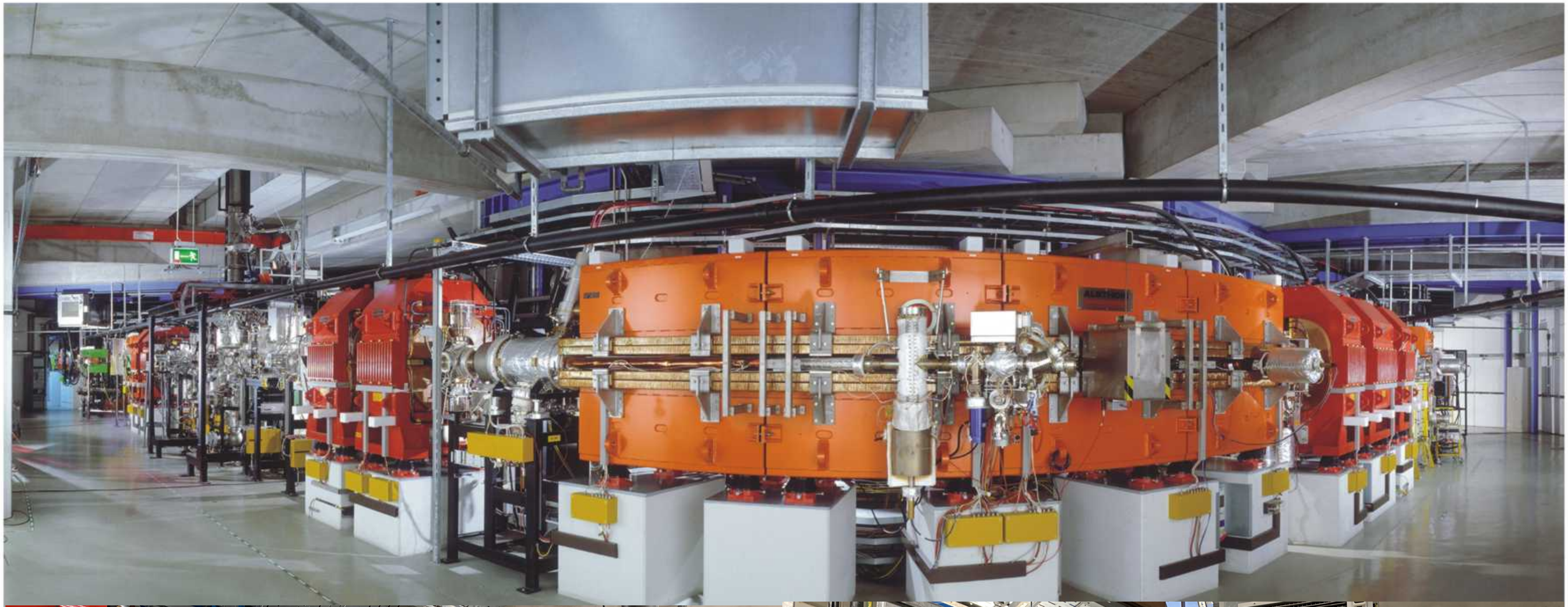
Multipole expansion – errors,

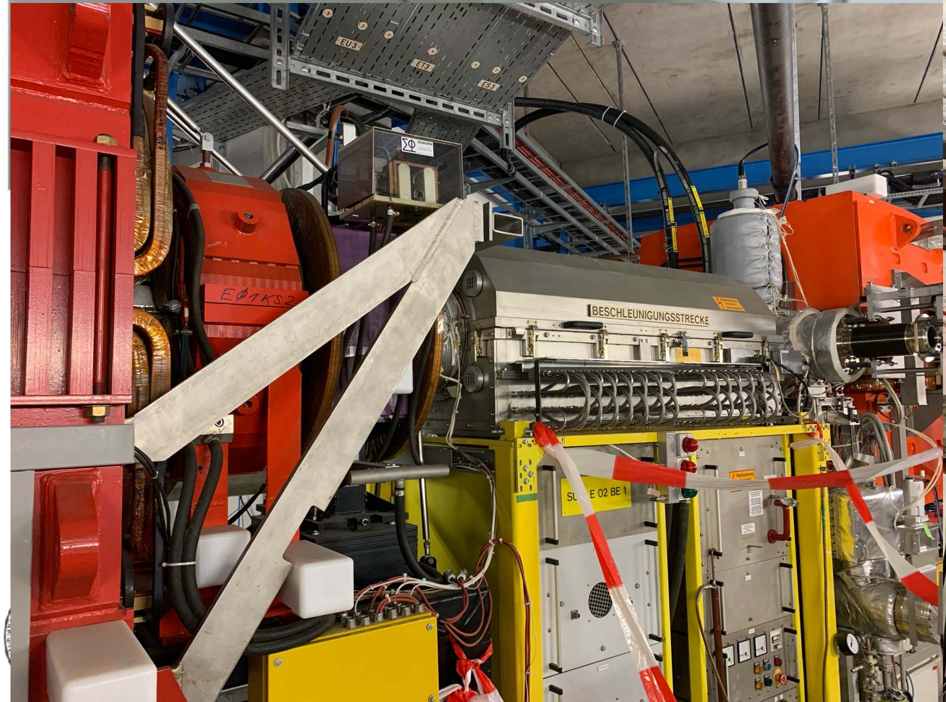
e.g., QP poles are not perfectly hyperbolic, mechanical misalignments, ...

Sextupole



Octupole




EU3
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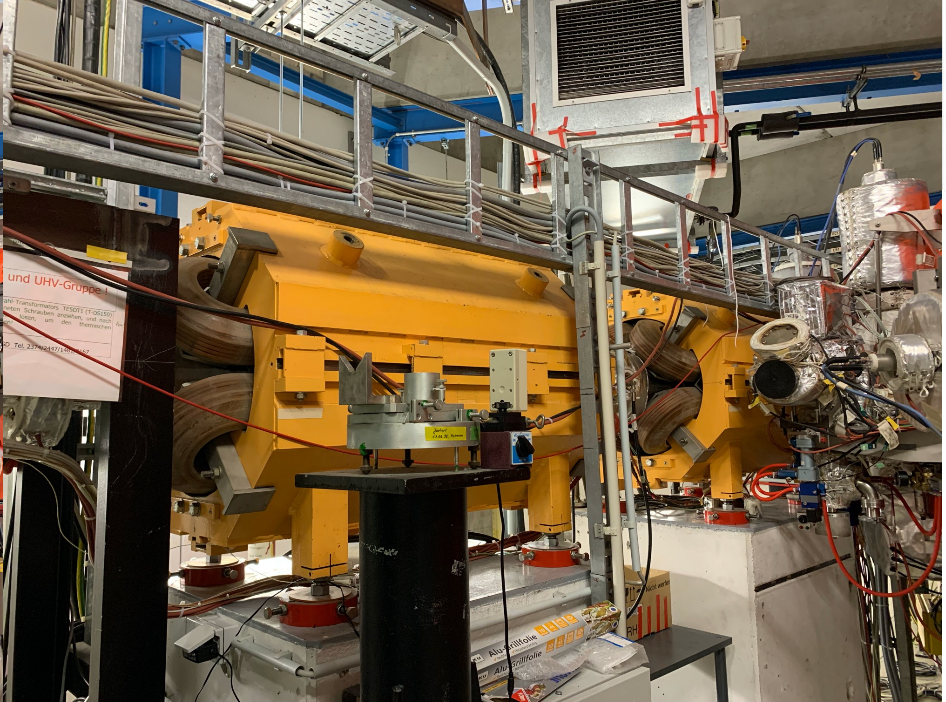
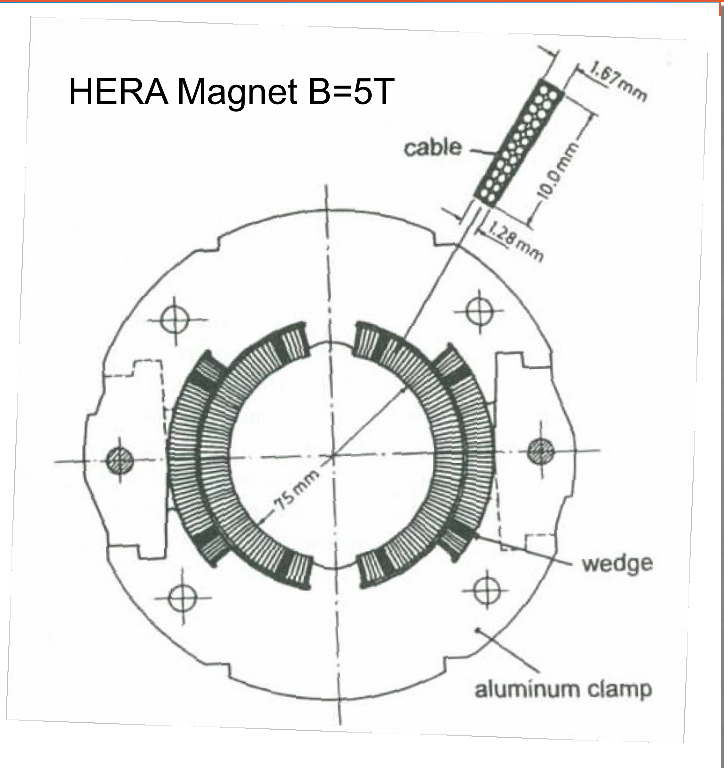
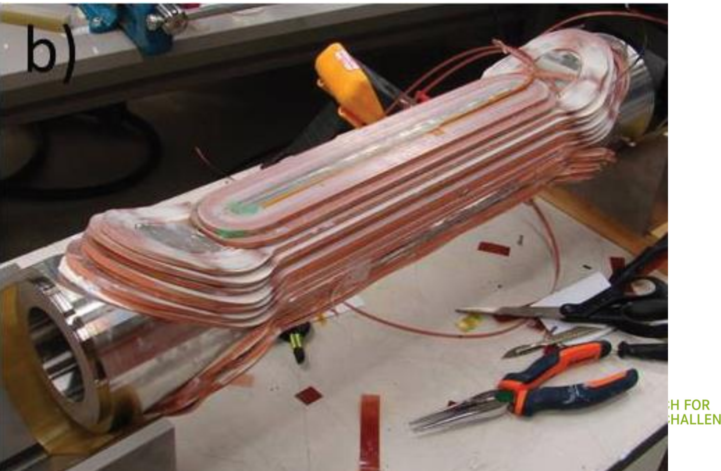
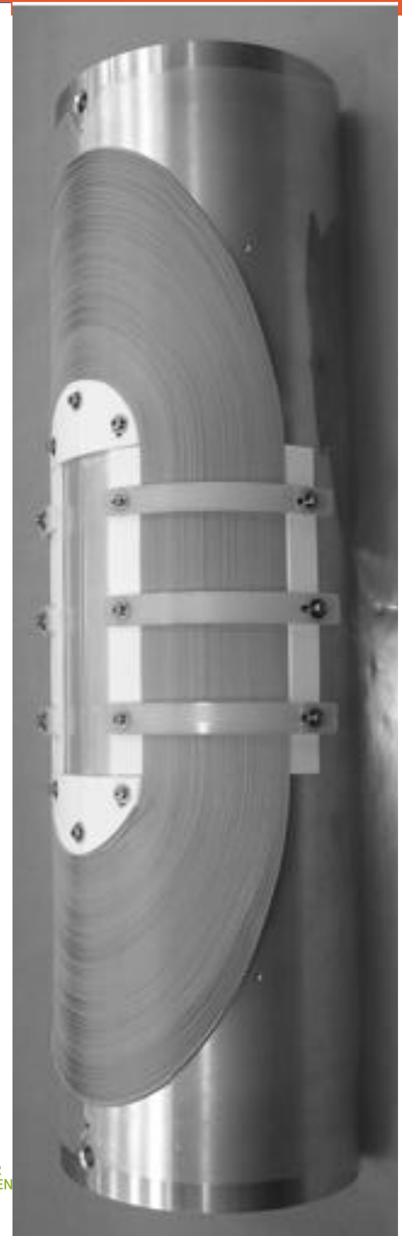

und UHV-Gruppe
Alu-Grillfolie

Superconducting magnets



HERA Magnet B=5T





14 um Nb-Ti wires (< 4 K) embedded in Cu matrix

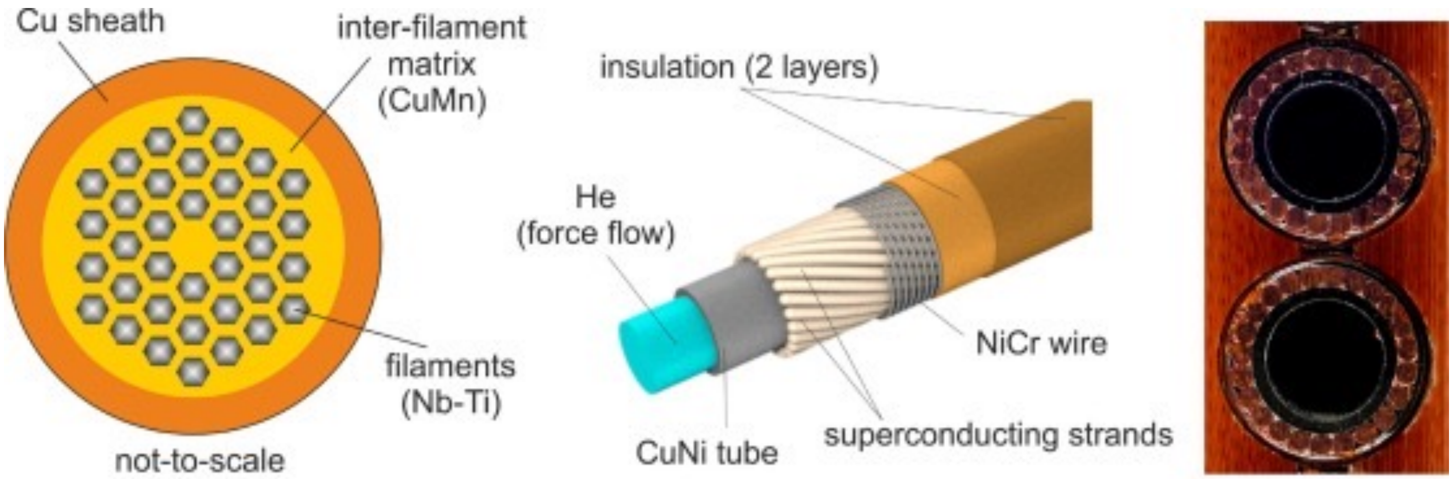
Magnetic fields a factor of ~5 stronger than normal-conducting magnets

$$B \leq 10\ \mathrm{T} \qquad \text{vs} \qquad B \leq 2\ \mathrm{T}$$

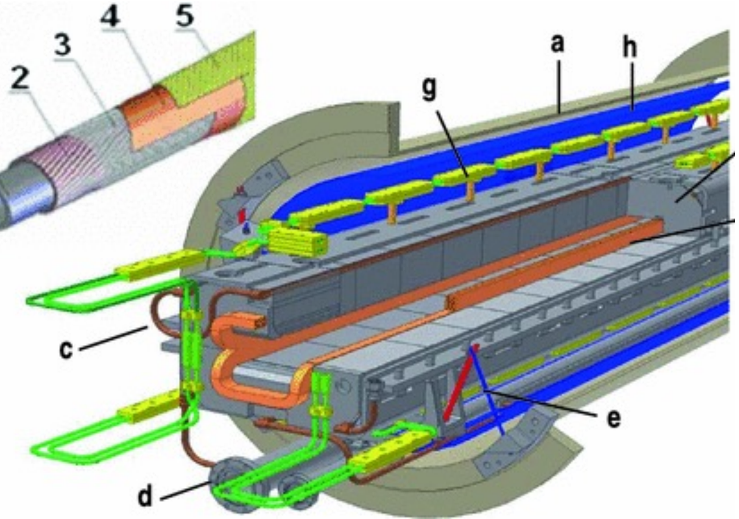
$$g \leq 100\ \frac{\mathrm{T}}{\mathrm{m}} \qquad\qquad g \leq 20\ \frac{\mathrm{T}}{\mathrm{m}}$$

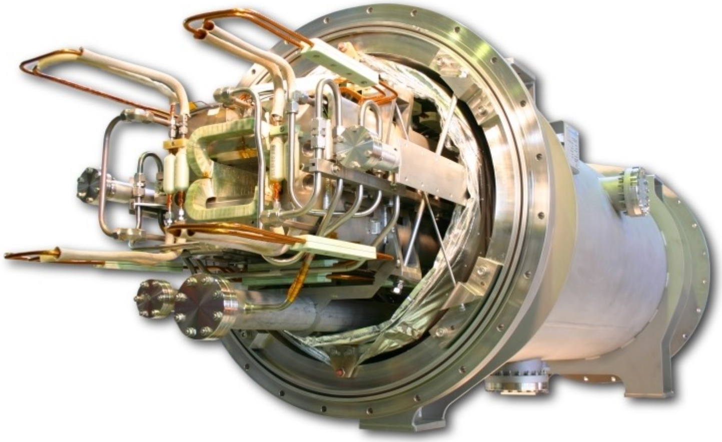
From: C. Lorin, EuCARD, 2nd Annual Meeting

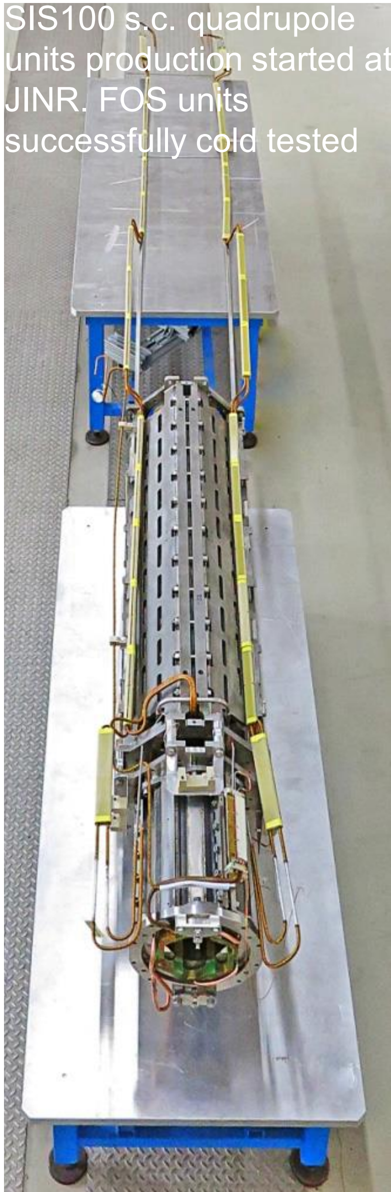
Superconducting magnets



(a) (b) (c)

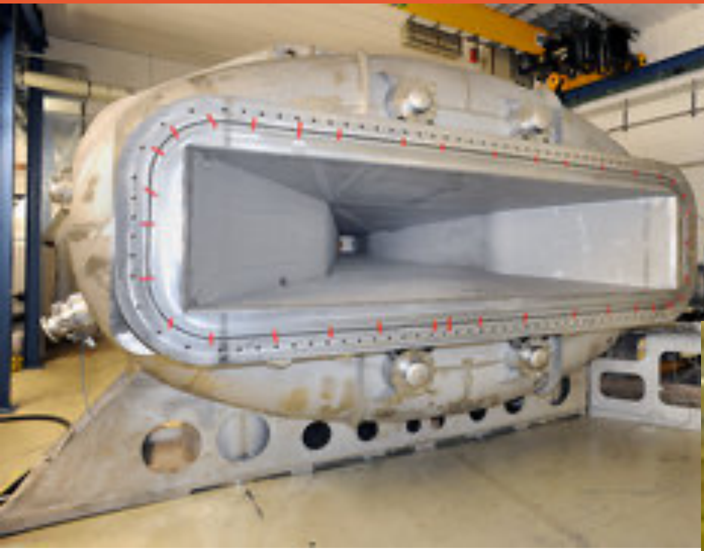






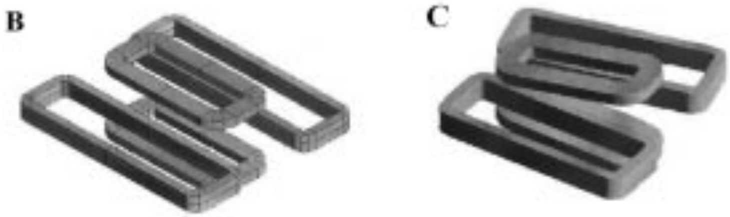
SIS100 s.c. quadrupole units production started at JINR. FOS units successfully cold tested

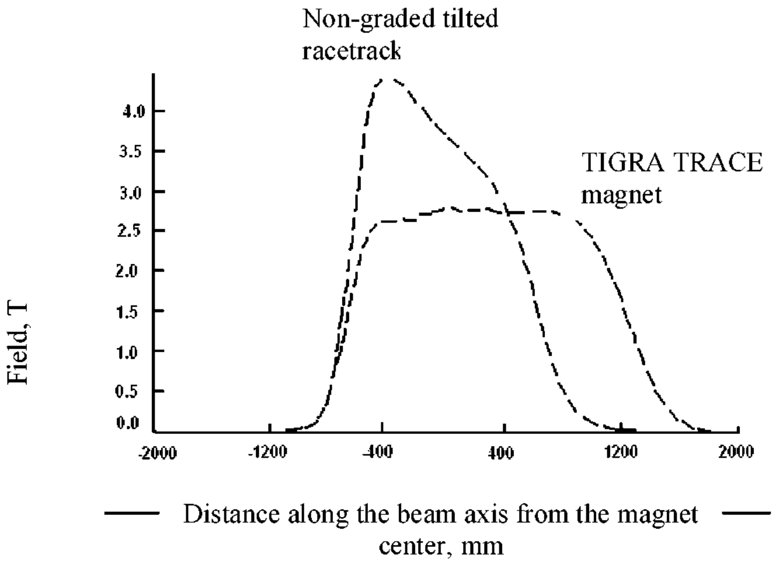
GLAD Magnet

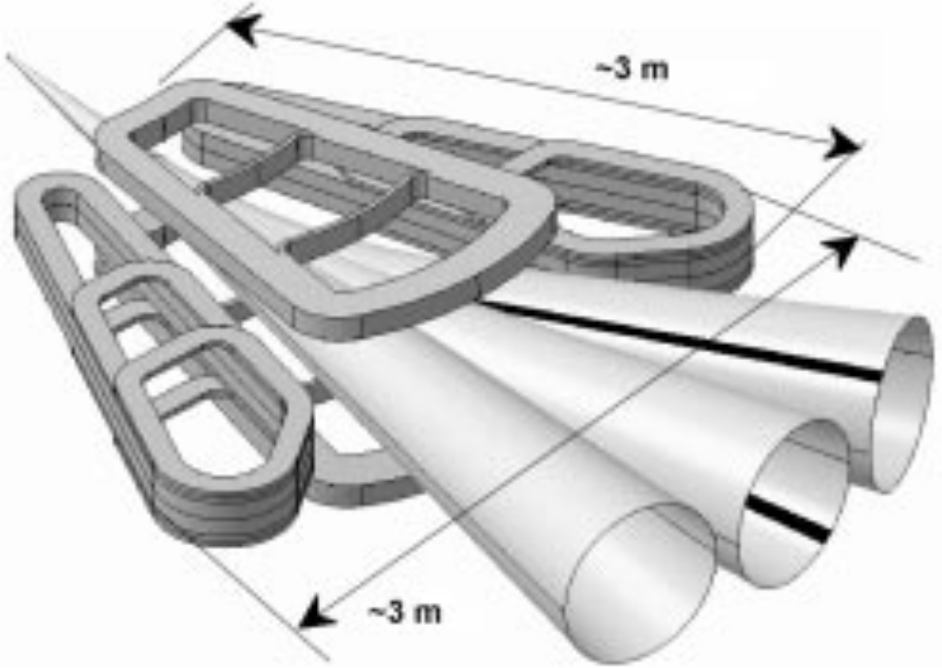


R3B Collaboration, FAIR

GLAD Magnet







A. Dael, B. Gastineau, J. E. Ducret, and V. S. Vysotsky
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 12, NO. 1, MARCH 2002

Summary of the last lecture

1) Accelerator types: Synchroton and Betatron

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reference particle
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synchrotron oscillations

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2) Production of ion and electron beams
- **electron sources**
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- **production of antiprotons**

Super-EBIT
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3) Magents
- **dipole magnets**
- **quadrupole magnets (QP)**
- **sextupole magnets**

- **superconducting magnets**

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Ion optics

Linear approximation:

x and y planes can be treated independently

This means that only drift, dipole and quadrupole magnets are considered

No aberrations, no sextupole and higher-order magnets

1. Coordinate system

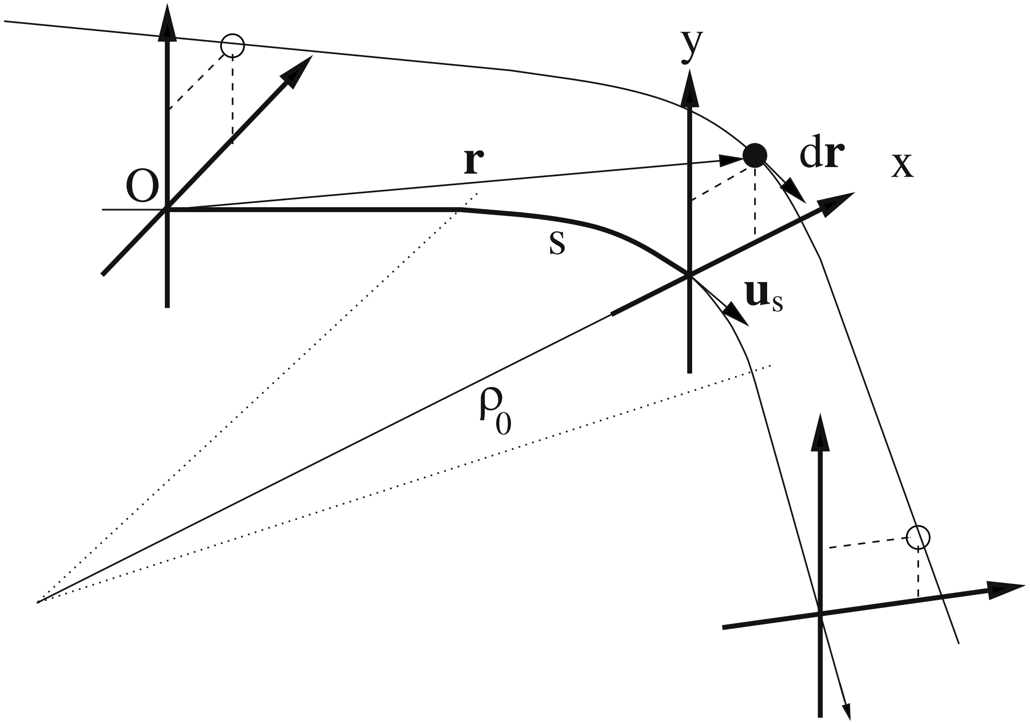
Various definitions exist ! (we adobt here the one from Hinterberger)

Curvilinear system

$\vec{s}$ - particle direction

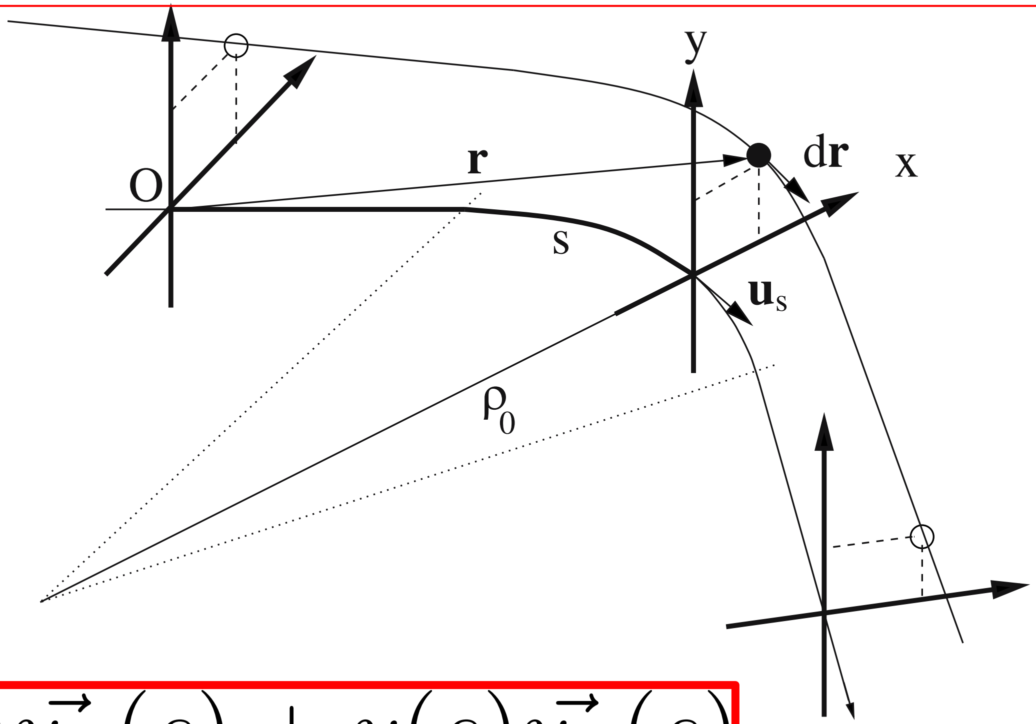
$\vec{x}$ - bending plane

$\vec{y}$ - upwards



1. Coordinate system

Coordinate system is defined on the reference/nominal/Sollbahn trajectory!



$$r(s) = \vec{r_0}(s) + x(s)\vec{u_x}(s) + y(s)\vec{u_y}(s)$$

1. Coordinate system

- metric

$$d\vec{r} = \vec{u}_x dx + \vec{u}_y dy + \vec{u}_s (1 + hx) ds$$

$$h = \frac{1}{\rho_0}$$

Curvature of nominal trajectory

Charge of reference particle

$$h(s) = \frac{1}{\rho_0(s)} = \frac{q}{p_0} B_y(x = 0,\ y = 0,\ s) = \frac{q}{p_0} B_o(s)$$

Momentum of reference particle

1. Coordinate system

- Deviation of a particle in 3 dimensions

$\Delta x,\ \Delta y,\ \Delta z$ - in space

$\Delta p_x,\ \Delta p_y,\ \Delta p_z$ - in momentum

6 parameters

$$\Delta p_x,\ \Delta p_y,\ \Delta p_z << p_0$$

$$x' = \frac{dx}{ds} = \frac{\Delta p_x}{p_0},\ y' = \frac{dy}{ds} = \frac{\Delta p_y}{p_0},\ l = -v_0(t - t_0)$$

Early particle

$t < t_0 \Rightarrow l > 0$

$$\delta = \frac{p - p_0}{p_0}$$ - momentum deviation

1. Coordinate system

- Deviation of a particle in 3 dimensions

Relative coordinates of each particle can be described with a six-dimensional vector

$$\mathbf{x}(s) = \begin{pmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{pmatrix} = \begin{pmatrix} \text{radial orbit deviation} \\ \text{radial direction deviation} \\ \text{axial orbit deviation} \\ \text{axial direction deviation} \\ \text{longitudinal deviation} \\ \text{longitudinal momentum deviation} \end{pmatrix}$$

Since $x,\ x',\ y,\ y',\ l,\ \delta l$ are small $\Longrightarrow$ units are [mm], [mrad], [promil]

$$\boxed{1\ \text{mrad} = 1\ \text{mm}/1\ \text{m}}$$