An Introduction to the Ion-Optics of Magnet Spectrometers

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The Lecture Series

1st Lecture: 2/27/06, 10:30 am: Formalism of ion-optics and the design of a complete system

2nd Lecture: 2/27/06, 1:30 pm: Magnet design, systems and diagnostics

3rd Lecture: 2/27/06, 3:00 pm: Experiments with dispersion matched high resolution spectrometers
2nd Lecture

2nd Lecture: 10/7/05, 2:00 pm: Ion-optical elements, properties & design

- Electro-magnetic elements in ion-optical systems
  - Dipoles, Quadrupoles, Multipoles, Wien Filters
- Combining elements, ion-optics properties
- Diagnostics and field measurements

- Review 1st Lecture (4)
- Overview magnetic elements (5)
- Creation of magnetic fields B (6 - 9)
- Design and examples of dipole magnets (10 -16)
- Quadrupole magnets, doublet, triplet (17 – 20)
- Spectrometers (21 – 24)
- Wien Filter (25)
- Diagnostics considerations (26)
- Field measurements (27 - 30)
Lorentz Force: \( \vec{F} = q \vec{E} + q \vec{v} \times \vec{B} \) (1)

TRANSPORT of Ray \( X_0 \)

\[ X_n = R \cdot X_0 \] (3)

using Matrix \( R \)

\[ R = R_n \cdot R_{n-1} \cdots R_0 \] (4)

TRANSPORT of \( \sigma \) Matrix (Phase space ellipsoid)

\[ \sigma_1 = R \sigma_0 R^T \] (10)

Beam emittance:

\[ \varepsilon = \sqrt{\sigma_{11} \sigma_{22} - (\sigma_{12})^2} \] (5)

Taylor expansion, higher orders, solving the equation of motion,

phases of a separator project
Iron dominated:

B field is determined by properties & shape of iron pole pieces

Required \( wI = \text{Ampere-turns} \) for desired magnet strength
\( B_0, g, a_3, a_4 \) can be calculated

formula in last column.

Coils are not shown in drawing in 1\text{st} column

G. Schnell, Magnete, Verlag K. Thiemig, Muenchen 1973
Creation of magnetic fields using current

**Current loop**

**Helmholtz coil, Dipole**

**Helmholtz coil, reversed current, Quadrupole**

Magnetization in Ferromagnetic material:

\[ B = \mu H \]

\( B \) = magn. Induction
\( H \) = magn. Field
\( \mu \) = magn. permeability

**Biot-Savart’s Law**

\[
\frac{dB}{dl} = \frac{\mu_0 I dL \times \hat{r}}{4\pi r^2}
\]

where

\( dL \) = infinitesimal length of conductor carrying electric current \( I \)
\( \hat{r} \) = unit vector to specify direction of the vector distance \( r \) from the current to the field point.
Creation of magnetic fields using permanent magnets

Magnet iron is **soft**: Remanence is very small when $H$ is returned to 0
Permanent magnet material is **hard**: Large remaining magnetization $B$

Permanent magnets can be used to design dipole, quadrupole and other ion-optical elements. They need no current, but strength has to be changed by mechanical adjustment.
A few comments on Normal (NC), Super (SC) conducting, Permanent magnets (PM)

- Ion-optical elements can are are built with all three methods: NC, SC and PM
- Ion-optics is concerned with the fields and not how they are created.
- Magnet design is very different because of different technologies.
- Fields in NC, SC (current driven) magnets can be easily varied, PM need mechanical changes.
- Normal conducting coils are limited to typically 10 A/mm² (though 50 A/mm² is possible)
- NC conducting need a lot of electrical power, SC much less, PM none.
- Strong, current dominate SC magnets can be built (~ 5 - 10 T).
- Iron dominated magnets are limited by iron saturation (≤ 1.7 – 2.2 T).
- SC need 4.2 K cryogenic and liquid Helium cooling (note: high temp. SC improving)
Design of an iron-dominated Dipole magnet

From Ampere’s law:

\[ NI \ (\text{Ampere turns}) = \frac{B (T) \times g (m)}{4\pi \times 10^{-7} \ (m/A)} \]

Units: m = meter
T = Tesla
A = Ampere

Magnetic field \( B \) in Good-field region defined by ion-optical requirement, e.g. \( dB/B < 10^{-4} \)

For symmetry reasons only a quarter of the full dipole is calculated & shown

The Field calculation was performed Using the finite element (FE) code MagNet (Infolytica). Other programs are TOSCA or POISSON.

Note: FE codes solve the static of time varying Maxwell’s Equations numerically by “meshing” the geometry in triangles in 2d or “bricks” in 3d. This allows to precisely calculate the Fields \( B, E \) for any configuration of current and materials, like ferromagnetic metals.
SHARAQ Dipole D2
Iron-dominated, normal conducting Dipole Magnet with constant field in Dipole Gap (Good-field region)

- Soft magnet iron, B(H)
- Hollow copper conductor for high current density < 10 A/mm²
- Iron magnetization saturates at about 1.7 T
- For B > 2 T superconducting (current dominated or hybrid) magnets are used.
These figures show the Good-field region in the center of the magnet and the maximum field $B$ as function of the current $I$ in the conductor.

OPT-9: pole INLC, return SA08

Saturation: -3.0% (Deviation from $B(I)$ linearity)

$80 \text{cm}: 2.5 \times 10^{-4}$

$83 \text{cm}: 2.0 \times 10^{-4}$

CALCULATED $B(I)$ CURVE
compared to linear approximation

$\text{Inductance } B/I = \frac{\text{non-linear}}{\text{linear}}$
Fringe field & Effective field length $L_{\text{eff}}$

Note:
1) The fringe field is important even in 1st order ion-optical calculations.
2) Rogowski profile to make $L_{\text{eff}} = \text{Pole length}$.
3) The fringe field region can be modified with field clamp or shunt.

\[
L_{\text{eff}} = \int_{0}^{\infty} \frac{B}{B_0} \, ds
\]  

(18)
SHARAQ Dipole D2

Iron-dominated, normal conducting Dipole Magnet with constant field in Dipole Gap (Good-field region)

- Soft magnet iron, $B(H)$
- Hollow copper conductor for high current density < 10 A/mm$^2$
- Iron magnetization saturates at about 1.7 T
- For $B > 2$ T superconducting (current dominated or hybrid) magnets are used.
SHARAQ Dipole D2 specifications and Coil design

Max. Rigidity: 6.80 Tm
Bending Radius: 4400 mm
Total gap: 200 mm
Pole width: 1400 mm
Bend angle: 60 deg
Central ray length: 4607.7 mm
Iron weight: 255 tons
Weight of 2 coils: 7.4 tons
Bmax: 1.55 T
DC/Power: 310 kW
DC/Current, no saturation: 1980 A
DC, including saturation: 2050 A
Max. allowed current: 2130 A
DC/Voltage: 150 V
Conductor: 26x26/16mm
Pancakes/coil: 4
Turns/pancake: 16
Total turns/magnet: 128
Pressure drop: 5 atm
Temp. rise: 30 deg C
Water flow, magnet: 150 l/min
Current density: 4.3 A/mm²
Resistance/magnet: 73.2 mOhm
Inductance: 618 mH
L/R: 8.6 s
Ramp time: 15 s
Dynam. Power: 480 kW
Excess Voltage to ramp: 85 V
Stored Energy: 1320 kJ

Units in mm

Thumb rule: Water cooling has to dissipate the complete magnet power IR²

This figure shows the coil with hollow copper conductor for water cooling (4.3 A/mm²)
Dipole H-Magnet for St. George a new recoil separator at Notre Dame University for astrophysics.

Iron-dominated Dipole Magnet with constant field $B_{\text{max}} = 0.6 \, \text{T}$ in dipole gap (Good-field region).

- Soft magnet iron, B(H)
- Hollow copper conductor for high current density
- Iron magnetization saturates at about 1.7 T, small returns

Units in mm

Dipole Gap: +/- 30 mm
Note: Magnet is Iron/Current configuration with field as needed in ion-optical design. 2d/3d finite elements codes solving POISSON equation are well established.
Forces on ions (quadrupole)

**Fig. 9.15.** Pole arrangements of magnetic quadrupoles, hexapoles, and octopoles are indicated. Also shown is a circle of radius \( r_0 \) along which the magnetic flux density is constant, and its direction varies as indicated. Finally, strings of zeros indicate lines along which \( B_y \) the \( y \) component of the magnetic flux density vanishes. These lines separate regions in which \( B_y \) is parallel or antiparallel to the \( y \) axis.

Horizontally defocusing quadrupole for ions along \(-z\) axis into the drawing plane. See Forces \( \uparrow \leftarrow \downarrow \Rightarrow \) in direction \( v \times B \)

A focusing quadrupole is obtained by a 90° rotation around the \( z \) axis.
Figure 1.9 Point-to-point focusing with a quadrupole doublet. The two trajectories shown are in the horizontal and vertical planes respectively.
Screen shot of TRANSPORT design calculation of Quadrupole Triplet upstream of St. George target. Shown are the horiz. (x) and vert. (y) envelopes of the phase ellipse.

Note beam at Slit has +/- 2 mrad and at target TGT +/- 45 mrad angle opening.

This symmetrical triplet 1/2F-D-1/2F corresponds to an optical lens.
**K600 Spectrometer**

Bending radius $\rho_0 = 2.0$ m  
$B_{\text{max}} = 1.7$ T  
Gap = 5 cm (D1), 6cm (D2)  
Weight = $\sim$ 30 tons (D1) 
$\sim$ 45 tons (D2)

Medium Dispersion: $B(D1) = B(D2)$  
Resolving power: $p/\Delta p = 20000$  
Dispersion = 12 cm/%  
Magnification $M_x = 0.41$  
Large range: $E_{\text{min}}/E_{\text{max}} = 1.14$

Kinematic correction: K coil  
Hexapole correction: H coil

The K600 is shown in $0^\circ$ Transmission mode  
High Dispersion Plane  
$B(D1) > B(D2)$

IUCF K600, decommissioned  
In 1999, now in WS line RCNP  
iThemba Labs K600, South Africa in use
**BIG KARL Spectrometer (Juelich, KFZ)**

Bending radius $\rho_0 = 1.98$ m  
$B_{\text{max}} = 1.7$ T  
Gap = 6cm  
Weight = ~50 tons (D1)  
~~70 tons (D2)

Resolv. power: $p/\Delta p = 0 - 20600$  
Dispersion = -2.0 to 26 cm/%  
Magnification $M_x = 0.63 - 1.26$  
Magnification $M_y = 25.4 - 1.94$  
Large range: $E_{\text{min}}/E_{\text{max}} = 1.14$  
Solid angle: < 12.5 msr

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Fig. 9. Arrangement of the magnetic elements of the QQDDO spectrometer BIG KARL. The central ray (optical axis) is shown as dashed curve. The outermost rays with the extreme radial distances are drawn as full lines. Four channels in the inner yokes allow NMR probes to be moved into the gaps of the dipoles for radial field measurements. The multipole element between Q1 and Q2 allows the correlation of vertical aberration.
Fig. 4. Spectra of $^{109}$Ag(p, p') measured for different dispersions $D = 26, 16, 6.3, 3, 1.5, 0.25$ and $-2$ cm/%. The spectrograph was optimized for $D = 16$ cm/%.

Fig. 19. High resolution spectrum of the (p, d) neutron pick up reaction on $^{109}$Ag at 25 MeV incident energy and a solid angle of 1.2 mrad. The resolution was 4 keV.
Grand Raiden High Resolution Spectrometer

Max. Magn. Rigidity: 5.1 Tm
Bending Radius: 3.0 m
Solid Angle: 3 msr

Beam Line/Spectrometer fully matched

Magnetic Spectrometer

Target Point
Focusing Q section
Grand-analyzer Focus
Grand-analyzer section
Q-lens for Angular Dispersion Matching
Pre-analyzer Focus
Intermediate
Pre-analyzer section
Source Point (SP)
\[ F = qE + qv \times B \]

(1)

\[ F = 0 \quad \text{when} \quad qE = qv \times B \quad \text{with} \quad E \perp B \]

\[ v = E/B \quad \text{with} \quad E \perp B \quad \text{(19)} \]

Design study of Wien Filter for St. George

Electrostatic system of Danfysik Wien Filter

Units in mm

Gradient of E Field lines

1,813kV/mm

B Field lines

0.3 T
Discussion of Diagnostic Elements

Some problems:

• Range \(< 1 \text{ to } > 10^{12}\) particles/s
• Secondary beam intensities typically up to \(10^6\) part./s
• Interference with beam, notably at low energies
• Cost can be very high
• Signal may not represent beam properties (e.g. blind viewer spot)

Some solutions:

• Viewers, scintillators, quartz with CCD readout
• Slits (movable) Faraday cups (current readout)
• Harps, electronic readout, semi-transparent
• Film (permanent record, dosimetry, e.g. in Proton Therapy)
• Wire chambers (Spectrometer, secondary beams)
• Faint beam \(10^{12} \rightarrow 10^3\) (Cyclotrons: MSU, RCNP, iThemba)
Hall Effect: \[ U_H = \frac{R_H}{d} BI \]  \textbf{(20)}

Lorentz force \( ev \times B \) on electrons with velocity \( v \) that constitute the current \( I \)

\( R_H = \) Hall constant, material property

Remarks:
- Precision down to \( \sim 2 \times 10^{-4} \)
- Needs temperature calibration
- Probe area down to 1 mm by 1 mm
- Average signal in gradient field (good for quadrupole and fringe field measurement)
Nuclear spin precesses in external field $B$
With Larmor frequency

$$f_L = \frac{2\mu}{\hbar} B \quad (21)$$

$\mu = p, d$ magn. Moment
$\hbar =$ Planck constant

$f_L$ (proton)/$B = 42.58$ MHz/T
$f_L$ (deuteron)/$B = 6.538$ MHz/T

Principle of measurement:
Small (e.g. water probe), low frequency wobble coil $B + B_\sim$, tuneable HF field $B_\sim$ (Fig. 1) with frequency $f_t$, observe Larmor resonance on Oscilloscope (Fig. 2). When signal $a$ & $b$ coincide the tuneable frequency $f_t = f_L$

- Precision $\sim 10^{-5}$
- Temperature independent
- Needs constant $B$ in probe ($5 \times 5$ mm) to see signal!
Search Coil used in field map of S800, MSU

Induced Voltage in search coil
\[ U = -\frac{dB}{dt} \]

Coil is moved from outside \[ B = 0 \text{ T} \] to inside \[ B_{\text{max}} \]
(calibrated with NMR probe)
B at location \((x,y)\) is obtained by intergration

\( \text{Ref: J. A. Caggiano, Dissertation, NSCL MSU, 1999, Spectroscopy of Exotic Nuclei with the S800 Spectrometer} \)

Figure 3.3: Schematic of the mapper showing the coordinate system used. The thick black lines are the magnet steel, the thin lines are the mapper plate. The gray box represents the cart that moves up and down along the plate. The three cylindrical coordinates are shown originating from a typical coil position on the cart (z is out of the page).
Field map of D2 of S800, MSU

Figure 3.12: A D2 field map at 0.28 Tesla, plotted above 99% of the field strength. The contours are separated by one Gauss, indicating a very flat central field.

Figure 3.13: Field measurements for D2 at 1.6 Tesla. All contours are separated by 5 Gauss. In sharp contrast to Figure 3.12, the field exhibits a bowing behavior characteristic of saturation effects.

Ref: J. A. Caggiano, Dissertation, NSCL MSU, 1999, Spectroscopy of Exotic Nuclei with the S800 Spectrometer
End Lecture 2