# An Introduction to Ion-Optics

Series of Five Lectures
JINA, University of Notre Dame
Sept. 30 – Dec. 9, 2005

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# The Lecture Series

1st Lecture: 9/30/05, 2:00 pm: Definitions, Formalism, Examples

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

3rd Lecture: 10/14/05, 2:00 pm: Real World Ion-optical Systems

4th Lecture: 12/2/05, 2:00 pm: Separator Systems

5th Lecture: 12/9/05, 2:00 pm: Demonstration of Codes (TRANSPORT, COSY, MagNet)

# 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
- Field measurements

- Review 1st Lecture (4)
- Overview magnetic elements (5)
- Creation of magnetic B (6 - 8)
- Dipole magnets (9 -11)
- Quadrupole magnets, doublet, triplet (12 – 16)
- Wien Filter (17)
- Field measurements (18-19)
- Outlook 3rd Lecture: A beam line & spectrometer (20)
- Q & A

# Review 1st Lecture

Lorentz Force: $\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$ **(1)**

TRANSPORT of Ray $X_0$ $\boxed{X_n = R\, X_0}$ **(3)**

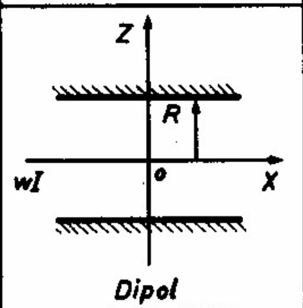
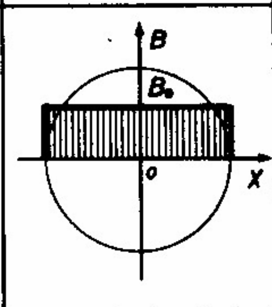
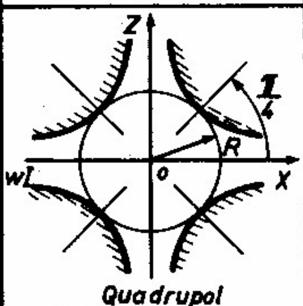
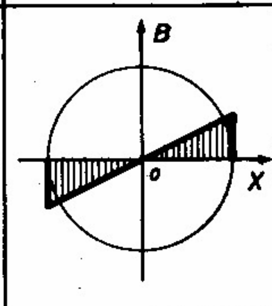
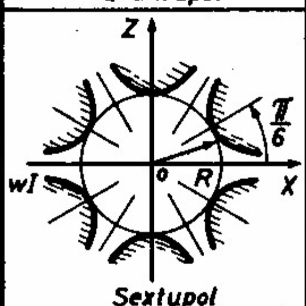
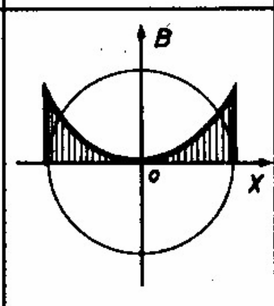
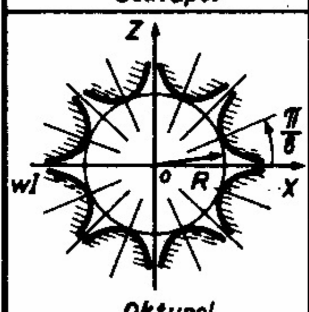
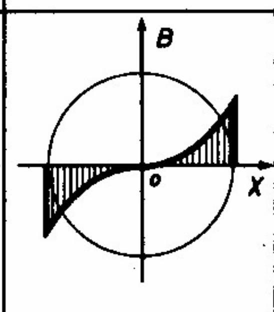
using Matrix R $\boxed{R = R_n\, R_{n-1} \ldots R_0}$ **(4)**

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, diagnostics, examples

# Schematic Overview of Magnetic Elements (Iron dominated)

| Pole shape | Field | Pole,analyt. | $B_x$ | wI |
|---|---|---|---|---|
|  |  | $z = \pm R$ | $a_1 = B_0$ | $\frac{2}{\mu_0} B_0 R$ |
|  |  | $xz = \pm \frac{R^2}{2}$ | $a_2 x = g x$ | $\frac{1}{\mu_0} g R^2$ |
|  |  | $z(x^2 - \frac{z^2}{3}) = \pm \frac{R^3}{3}$ | $a_3(x^2 - z^2)$ | $\frac{2}{3\mu_0} a_3 R^3$ |
|  |  | $xz(x^2 - z^2) = \pm \frac{R^4}{4}$ | $a_4 x(x^2 - 3z^2)$ | $\frac{1}{2\mu_0} a_4 R^4$ |

Iron dominated:

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

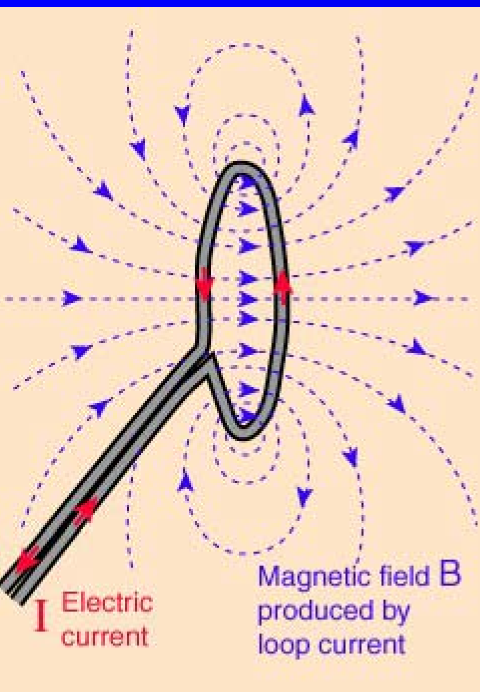
Required wI = Ampere-turns for desired magnet strength $B_0$, g, $a_3$, $a_4$ can be calculated formula in last column.

Coils are not shown in drawing in 1st column

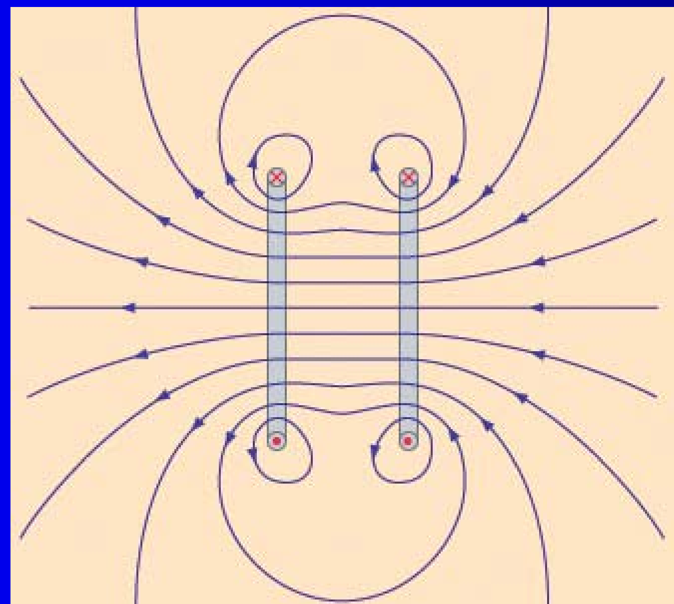
G. Schnell, Magnete, Verlag K. Thiemig, Muenchen 1973

# Creation of magnetic fields using current

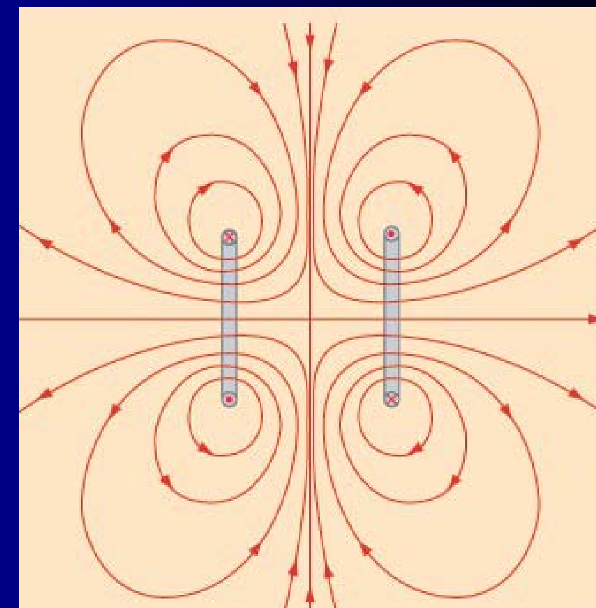
Current loop




Helmholtz coil, Dipole



Helmholtz coil, reversed current, Quadrupole

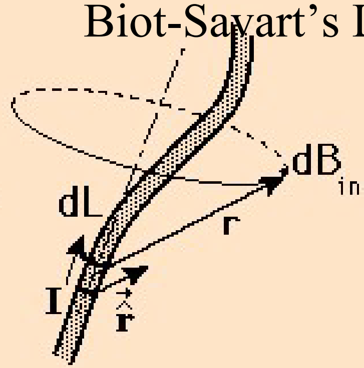


Magnetization in Ferromagnetic material:

$$B = \mu H$$

B = magn. Induction
H = magn. Field
μ = magn. permeability

Biot-Savart's Law




Magnetic field of a current element

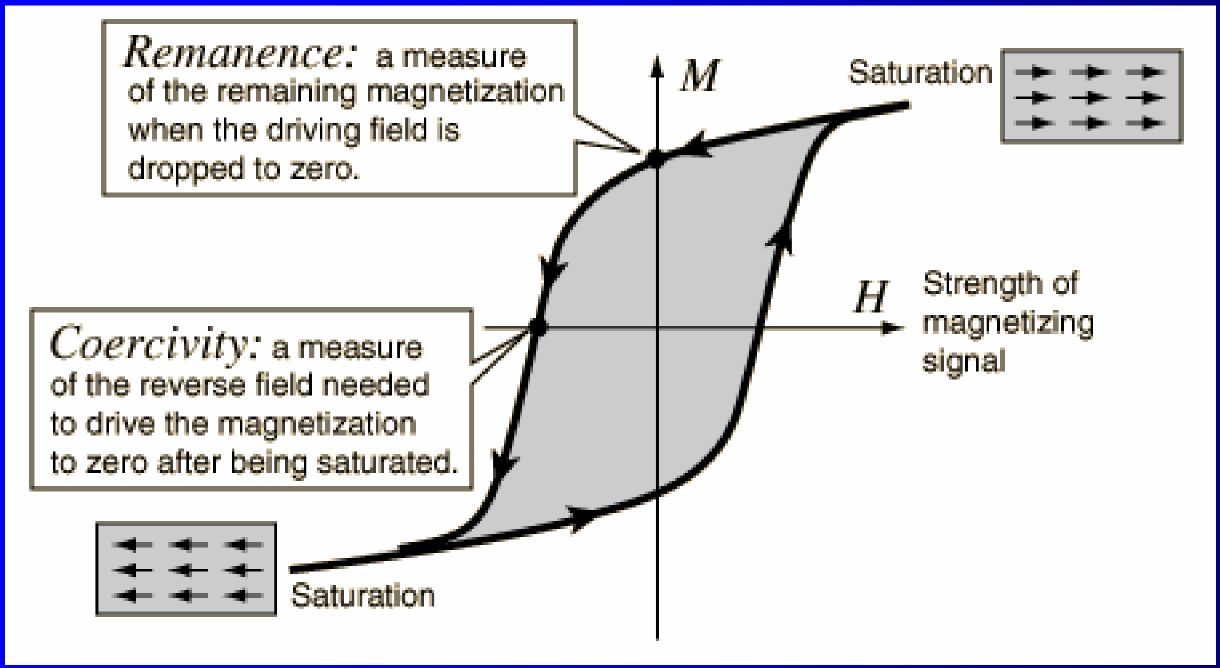
$$d\vec{B} = \frac{\mu_0 I d\vec{L} \times \hat{\vec{r}}}{4\pi r^2} \qquad (17)$$

where

$d\vec{L}$ = infinitesmal length of conductor carrying electric current $\mathbf{I}$

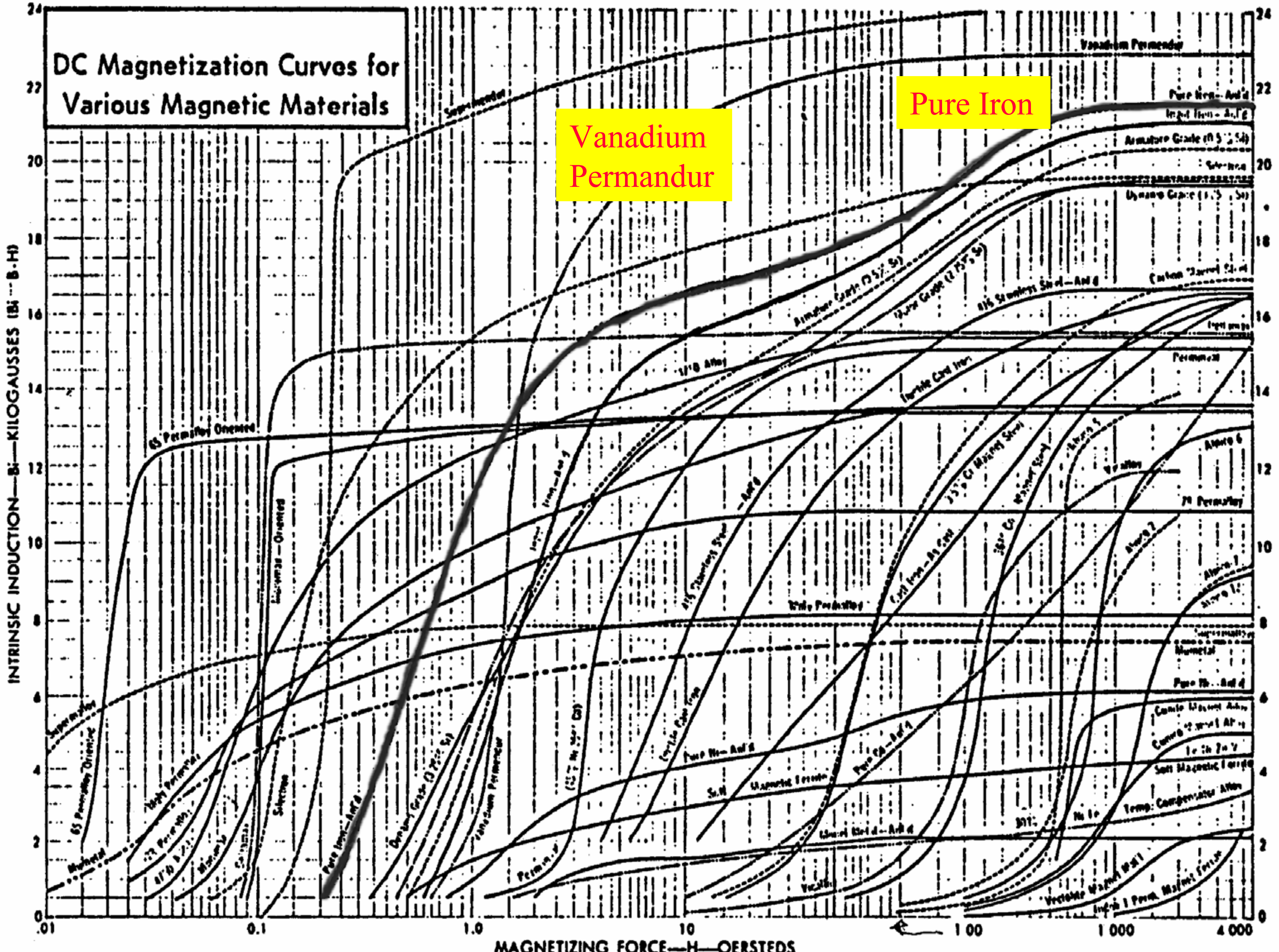
$\hat{\vec{r}}$ = unit vector to specify direction of the vector distance $\mathbf{r}$ from the current to the field point.

# Creation of magnetic fields using permanent magnets



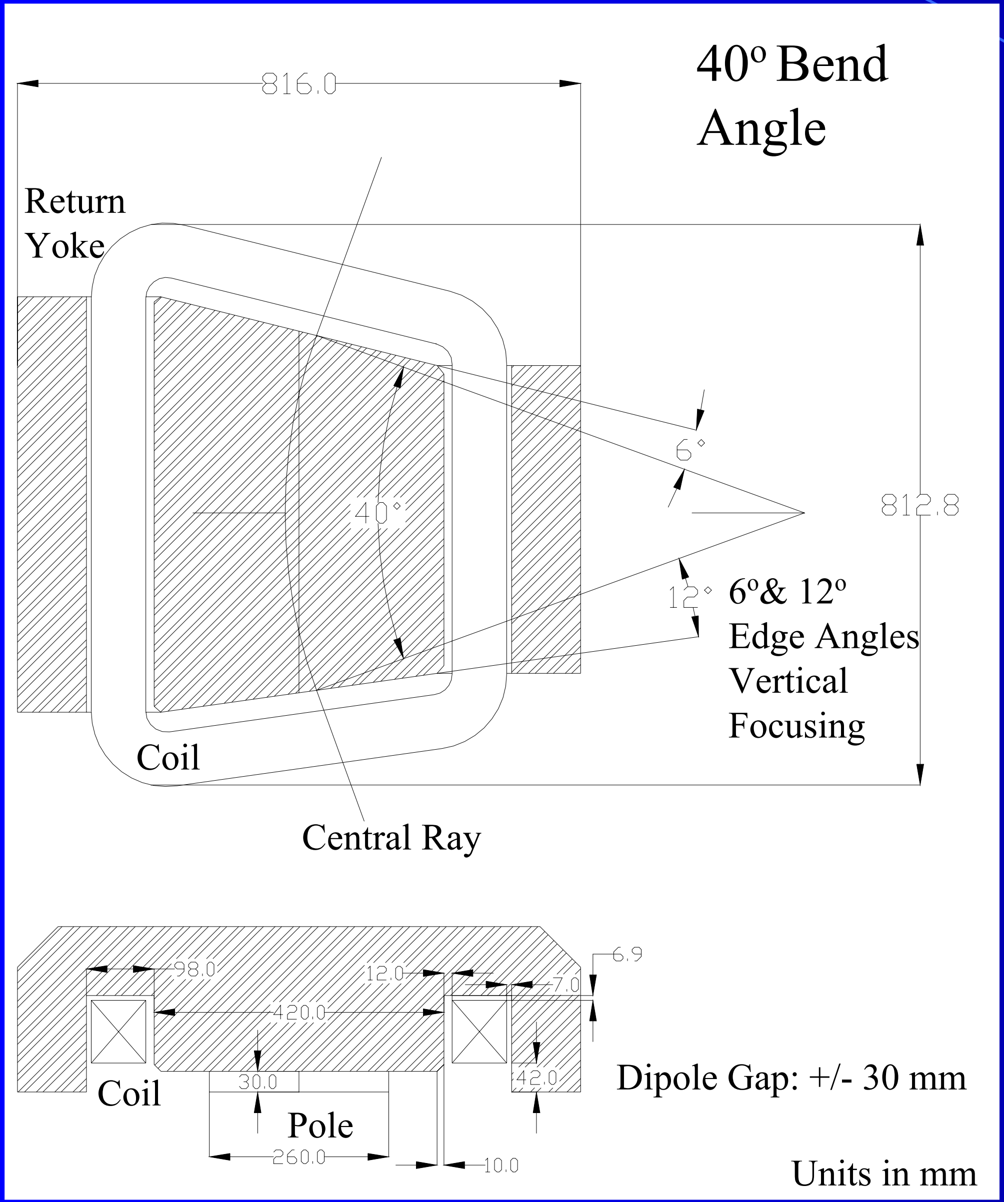

Magnet iron is **soft**: Remanence is very small when H is returned to 0
Permanent magnet material is **hard**: Large remaining magnetization B

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 echanica adjustment.


DC Magnetization Curves for Various Magnetic Materials
Vanadium Permandur
Pure Iron
INTRINSIC INDUCTION—Bi—KILOGAUSSES (Bi = B-H)
MAGNETIZING FORCE—H—OERSTEDS
.01
0.1
1.0
10
100
1 000
4 000
0
2
4
6
8
10
12
14
16
18
20
22
24

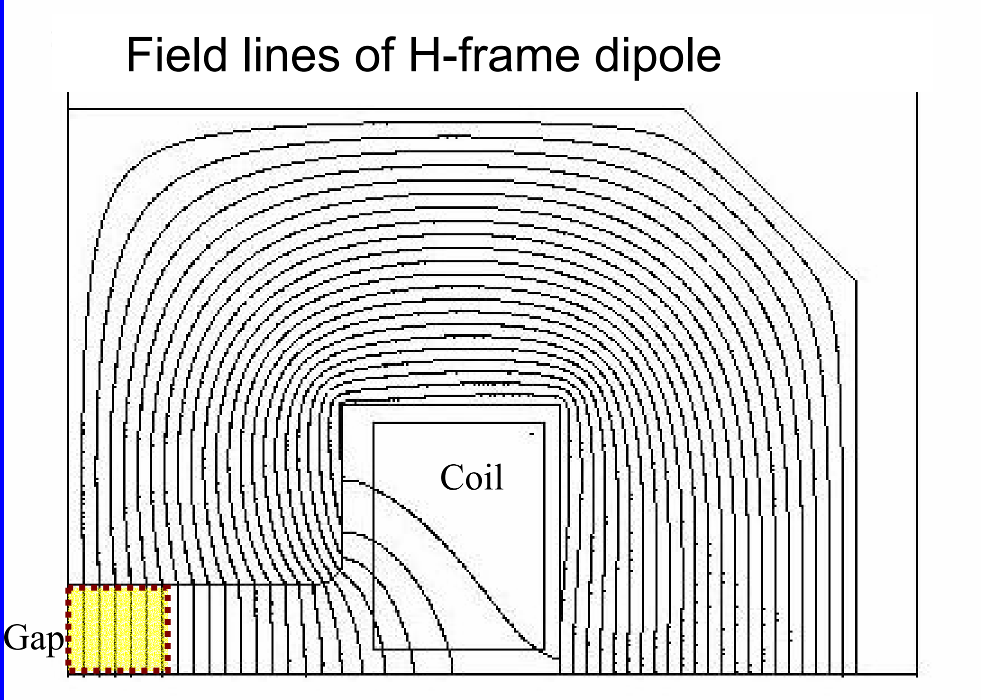
# Example: Dipole H-Magnet

Iron dominated Dipole Magnet with constant field 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

# Field lines in an iron-dominated Dipole magnet



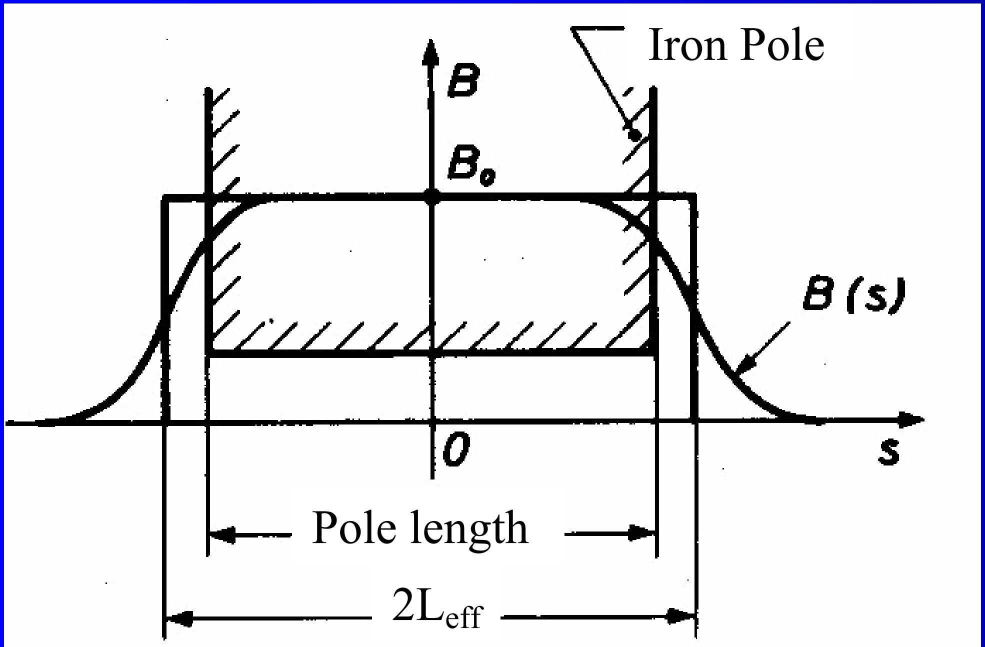

⇑ Good-field region

Defined by ion-optical requirement,
e.g. $dB/B < 10^{-4}$

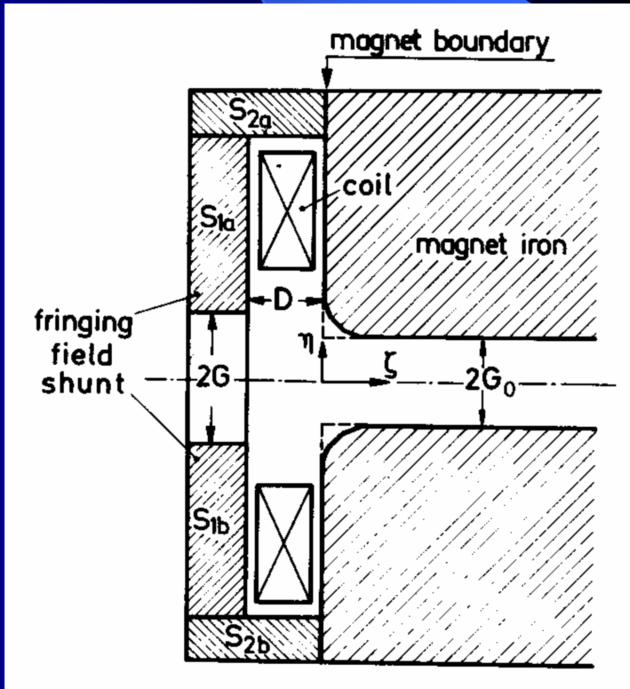
For symmetry reasons only a quarter of the full dipole is calculated & shown

The Field calculation was performed Using the finite element (FE) code MagNet (Infolytica).

# Fringe field & Effective field length $L_{eff}$

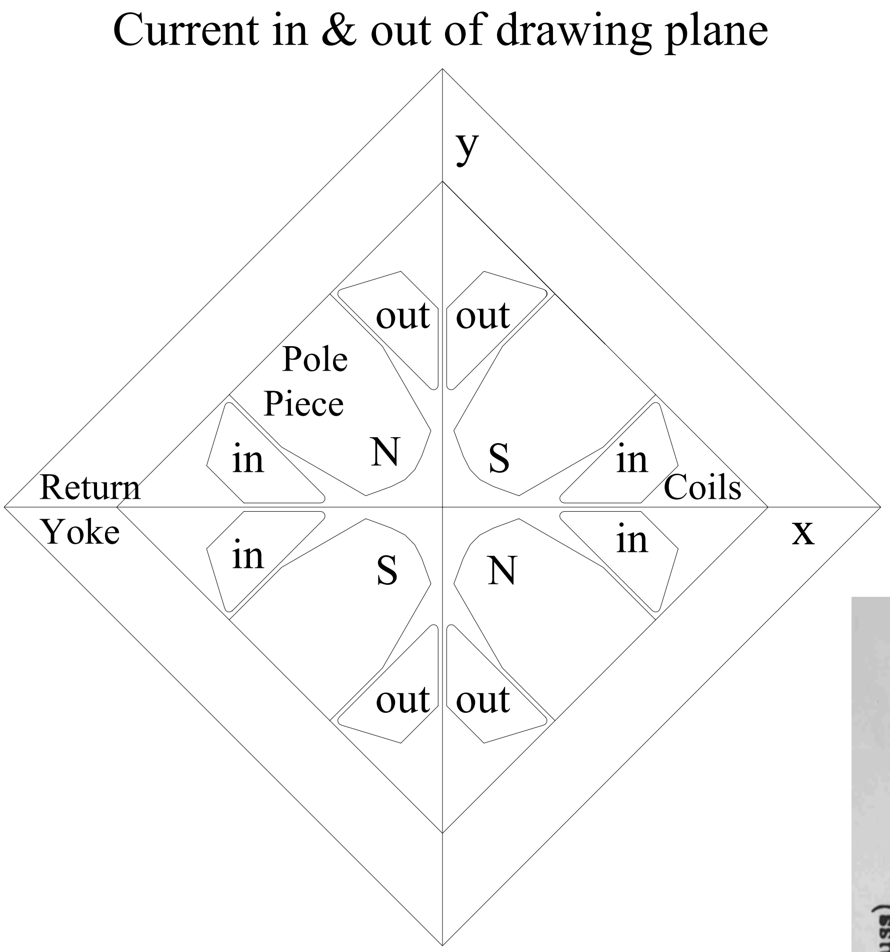



$$L_{eff} = \int_{0}^{\infty} B\, ds \,/\, B_0 \qquad \textbf{(18)}$$

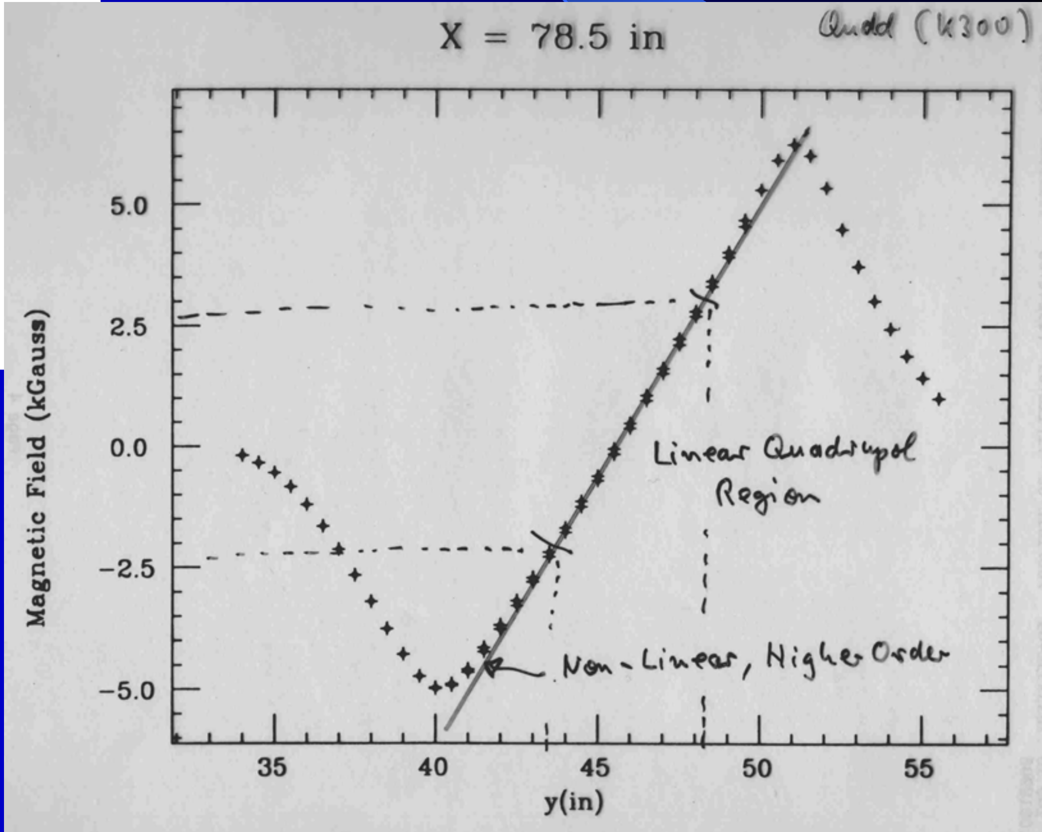



Note:

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




# Standard Quadrupole




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

# Collins Quadrupole

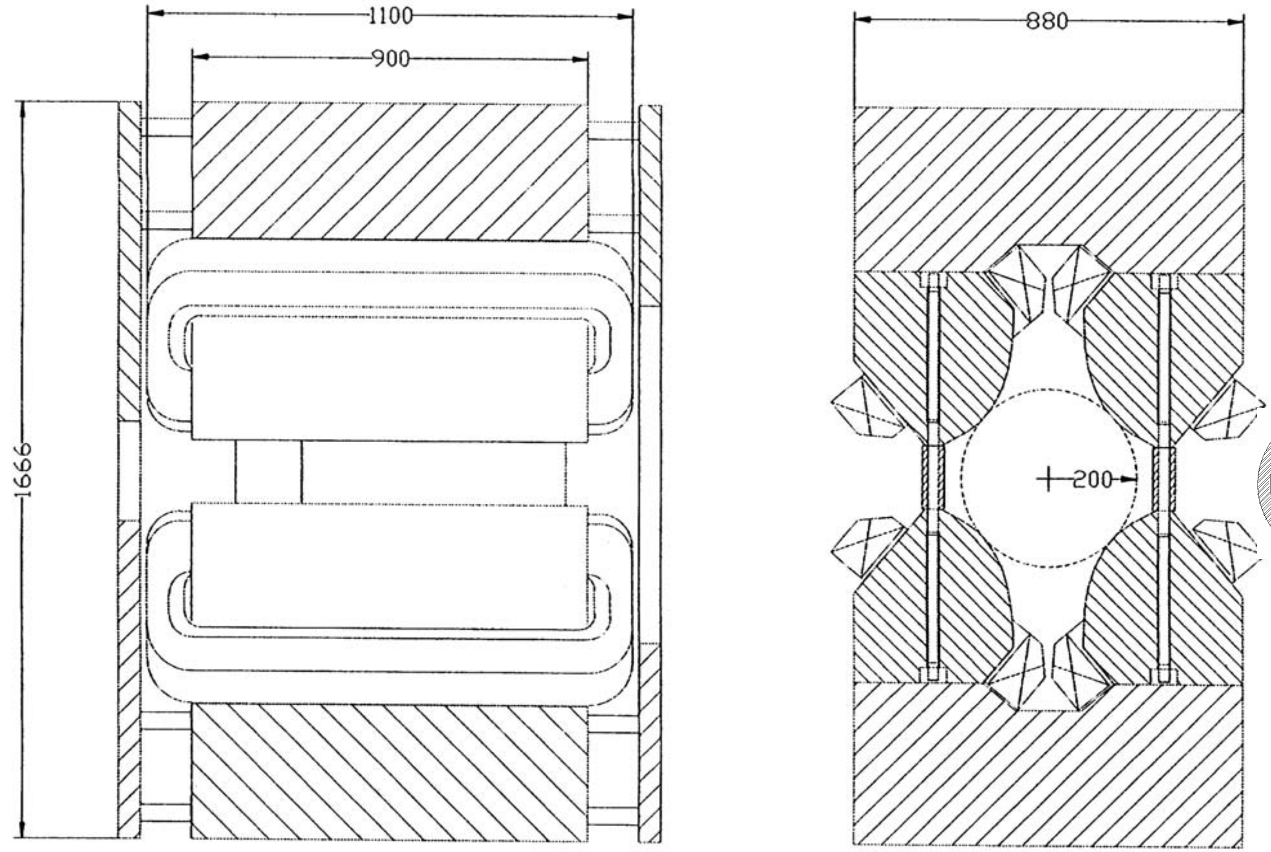
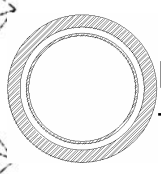



Fig. 4. Section through (right) and perpendicular to (left) the mid-plane of the quadrupole of spectrometer A. Lengths are in mm. The 50 mm thick mirror plates are mounted in a distance of 115 mm to the poles.




Ref. K.I. Blomqvist el al. NIM A403(1998)263

# Forces on ions ( quadrupole)

Quadrupole Hexapole Octopole

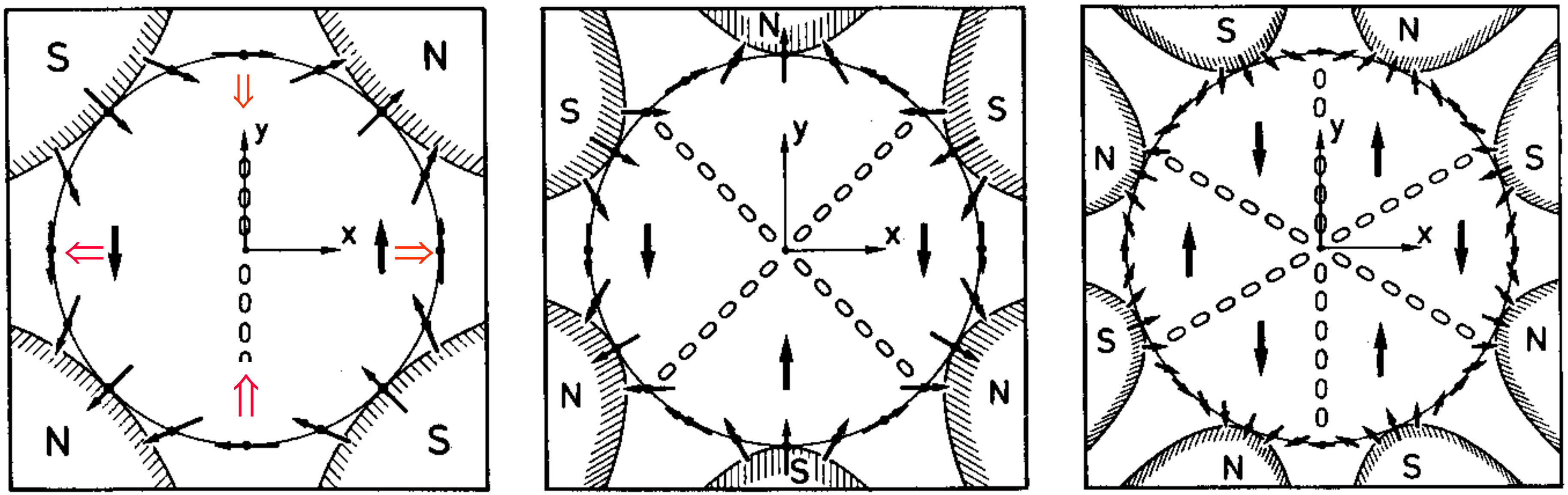
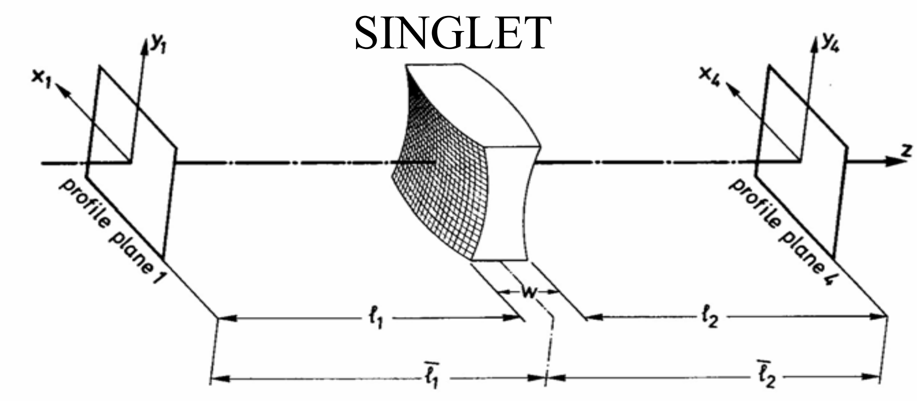


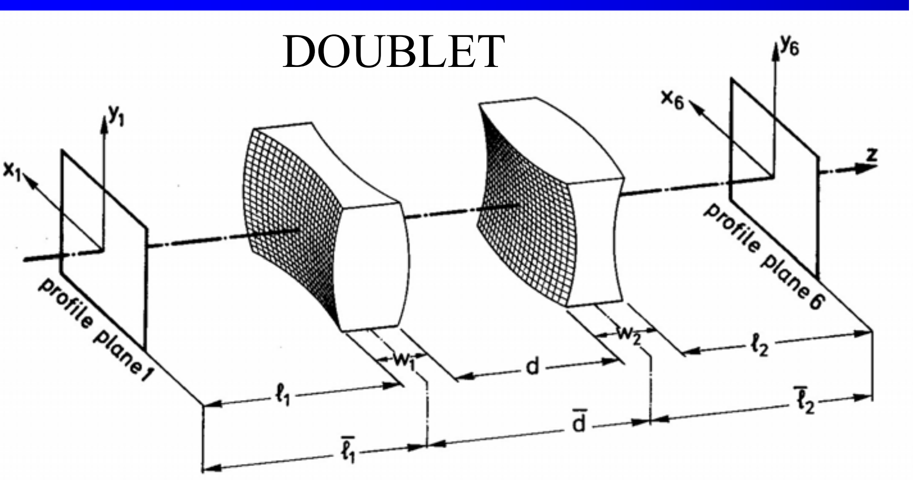

**Fig. 9.15.** Pole arrangements of magnetic quadrupoles, hexapoles, and octopoles are indicated. Also shown is a circle of radius $r_0$ along which the magnetic flux density is constant, and its direction varies as indicated. Finally, strings of zeros indicate lines along which $B_y$ the $y$ component 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 x B

A focusing quadrupole is obtained by a $90^{o}$ rotation around the z axis

# Ion optics of a quadrupole SINGLET & DOUBLET



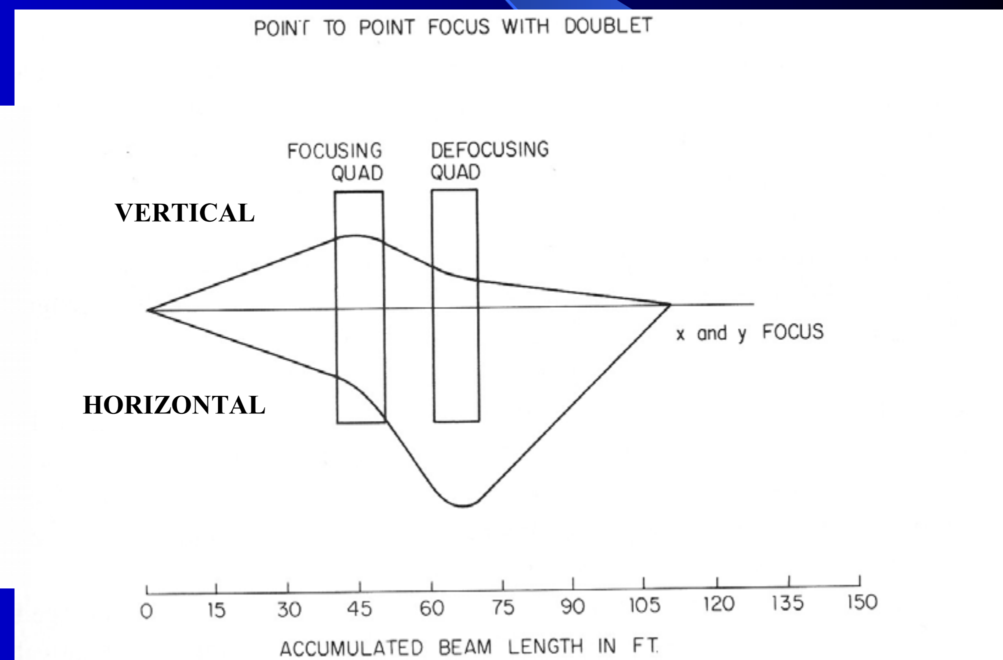
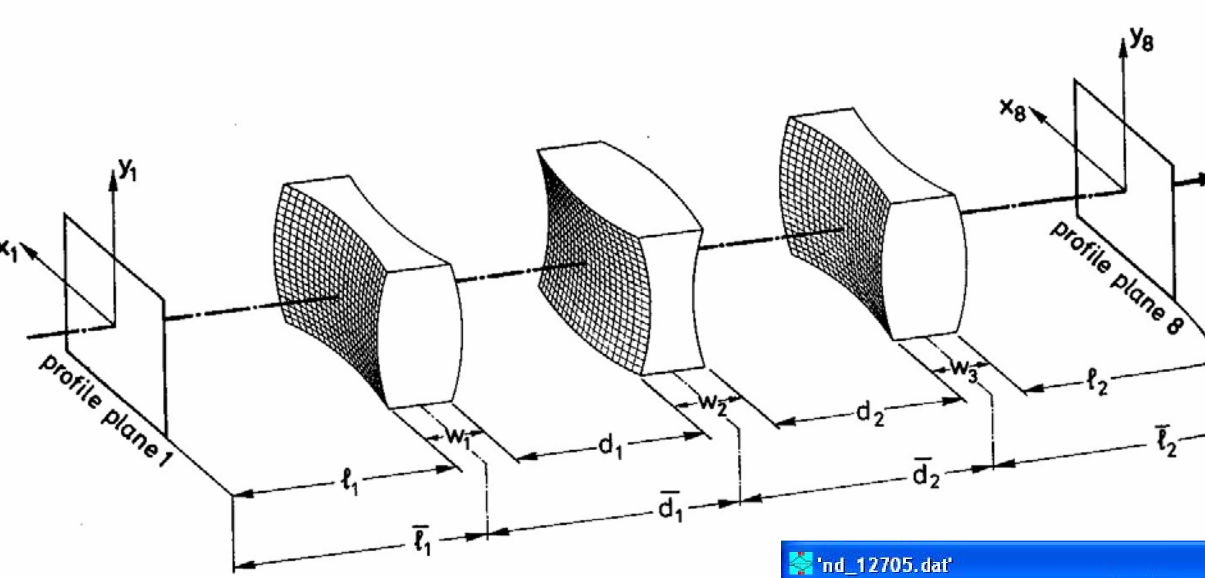
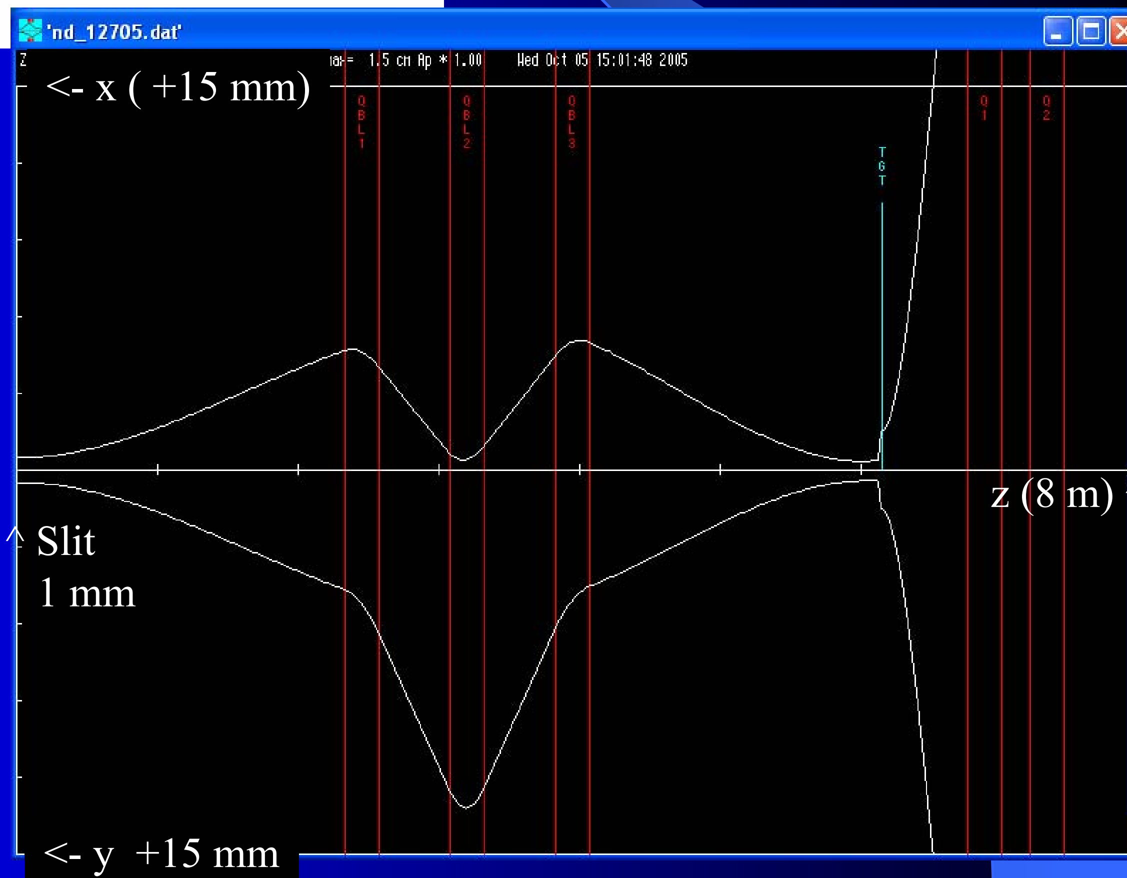




**Figure 1.9** Point-to-point focusing with a quadrupole doublet. The two trajectories shown are in the horizontal and vertical planes respectively.




# Focusing with a quadrupole TRIPLET




Screen shot of TRANSPORT design calculation of **Quadrupole Triplet** upstream of St. George target. Shown are the horiz. (x) and vert. (y) envelops of the phase ellipse.

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

This symmetical triplet 1/2F-D-1/2F corresponds to an optical lens.

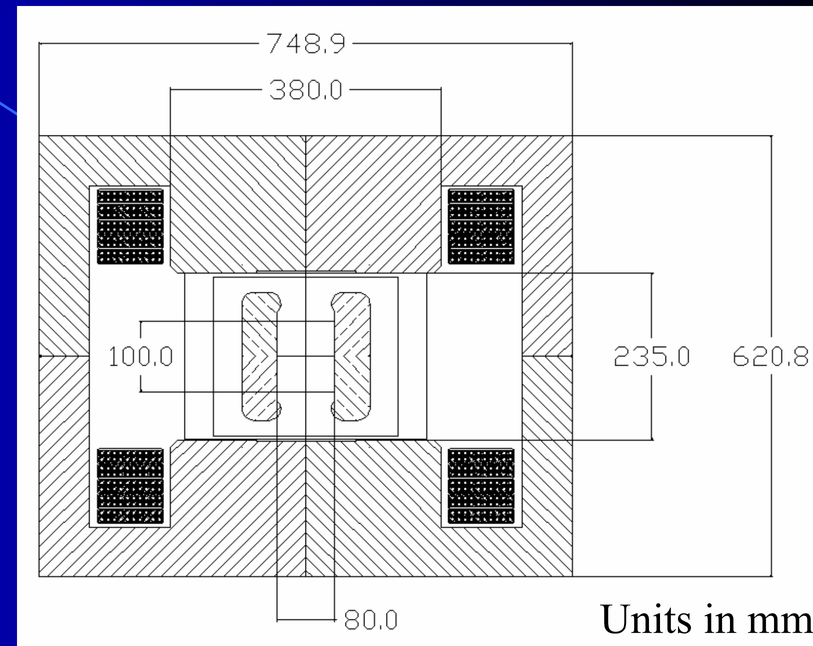
# The Wien Filter

$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}} \qquad \textbf{(1)}$$

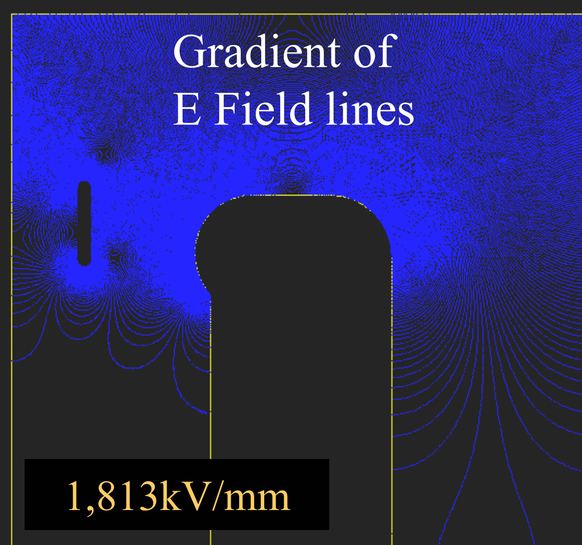
F = 0 when qE = qv x B with E ⊥ B

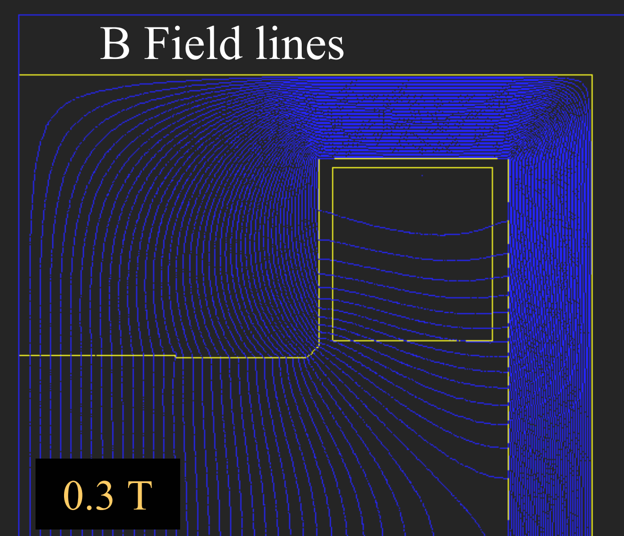
v = E/B with E ⊥ B **(19)**

Design study of Wien Filter for St. George

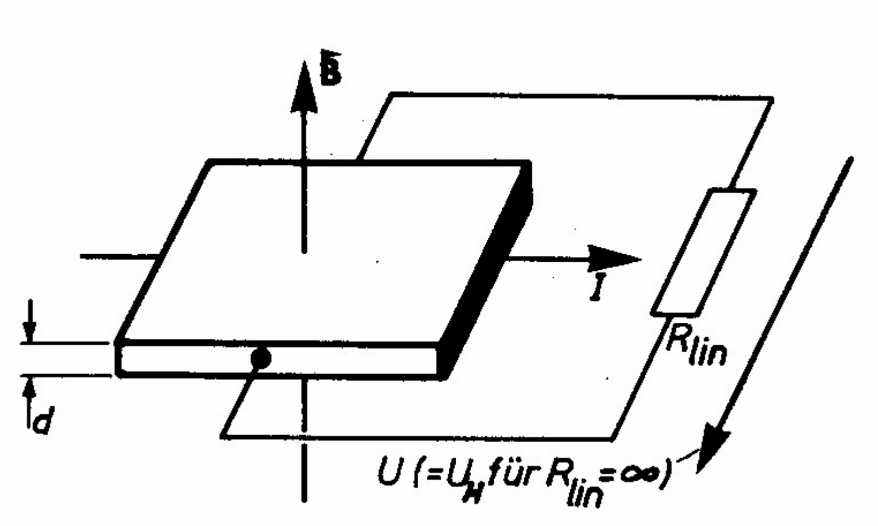



Electrostatic system of Danfysik Wien Filter



# Hall Probe




Hall Effect: $U_H = \dfrac{R_H}{d} BI$ **(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 ~ $2\ 10^{-4}$
- Needs temperature calibration
- Probe area down to 1 mm by 1 mm
- Average signal in gradient field (good for quadrupole and fringe field measurement)

# NMR Probe

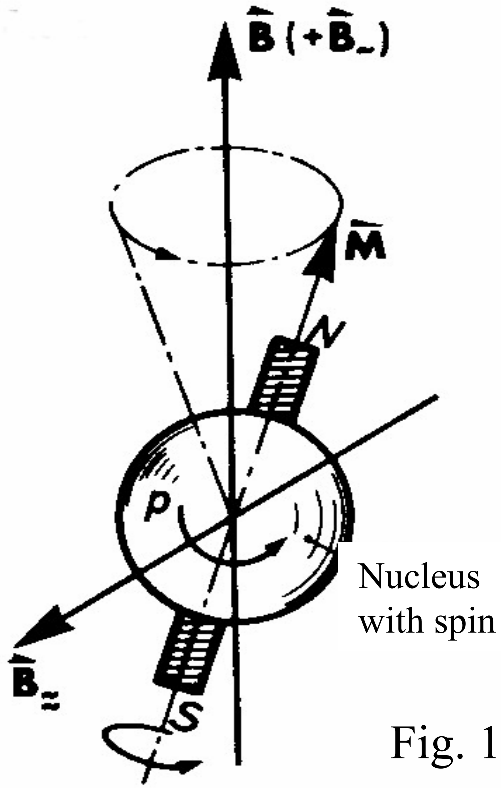



Fig. 1

Nuclear spin precesses
in external field B
With Larmor frequency

$$f_L = \frac{2\mu}{h} B \qquad \mathbf{(21)}$$

$\mu$ = p, d magn. Moment
h = 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 $B_{\approx}$ (Fig. 1) with frequency $f_t$ , observe Larmor resonance on Oscilloscope (Fig. 2). When signal a & b coincide the tuneable frequence $f_t = f_L$

- Precision ~ $10^{-5}$
- Temperature independent
- Needs constant B in probe ( 5 x 5 mm) to see signal!

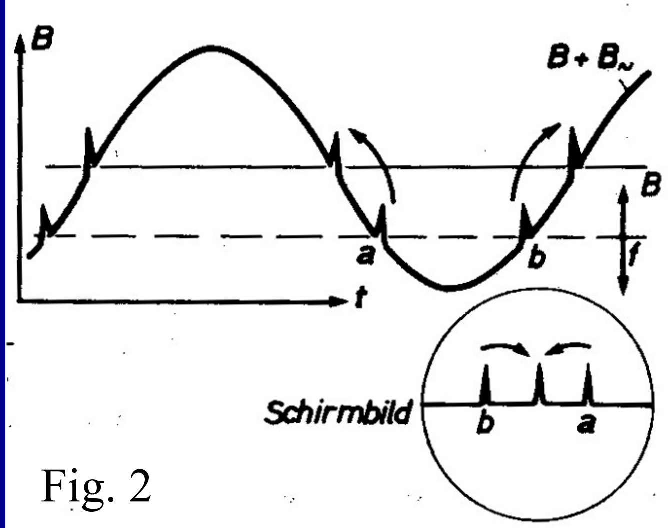
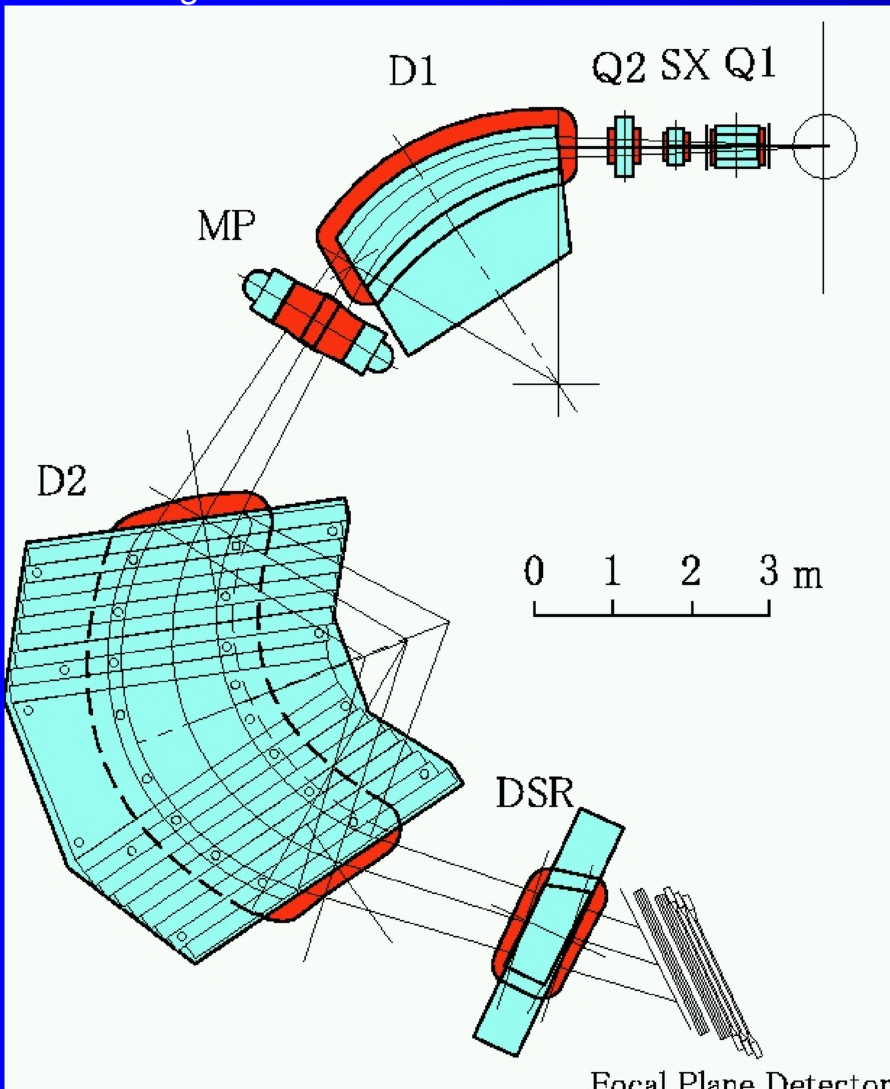


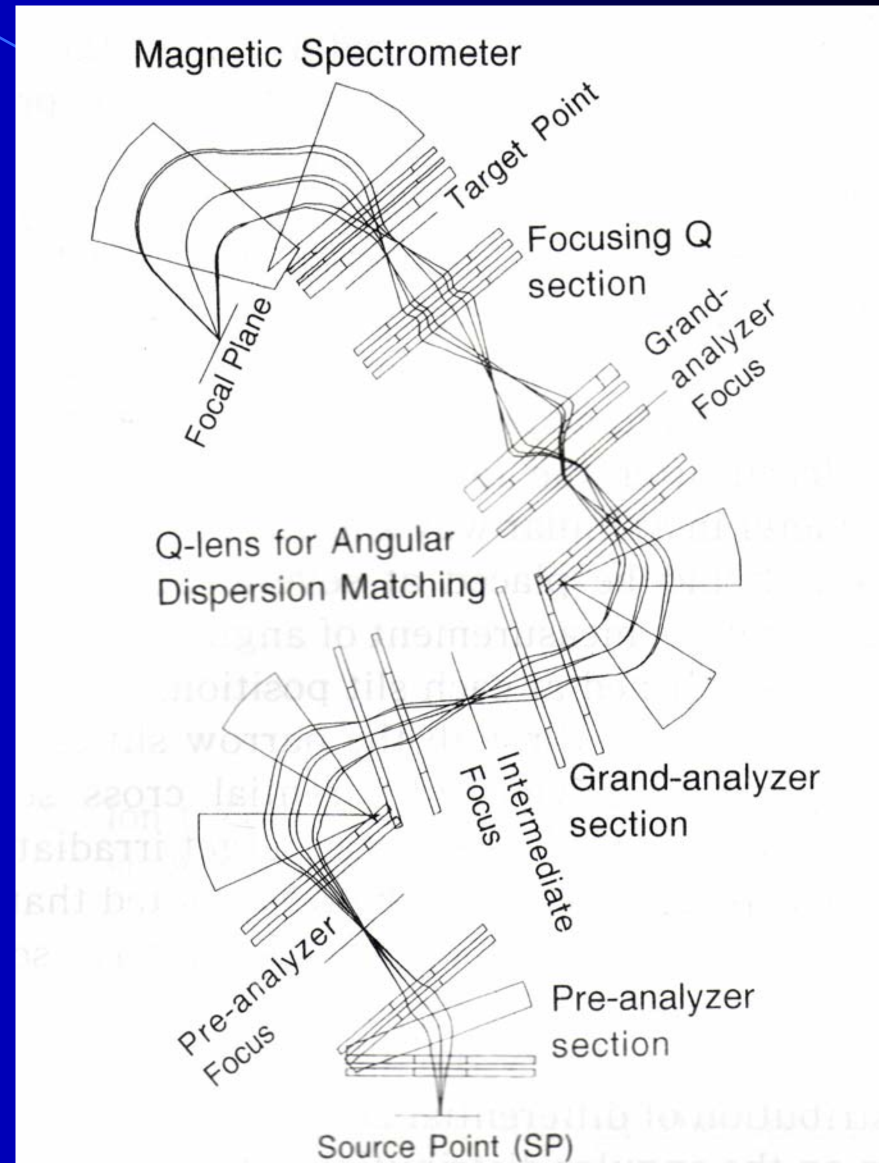

Fig. 2

# 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



# End Lecture 2