An Introduction to Ion-Optics

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

Georg P. Berg

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)

3rd Lecture

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

- Ion-optical systems: e.g. dispersive, achromatic, telescopic sections
- Spectrometers, beam lines
- Matching of phase space, dispersion matching

- Spectrometers and their properties (4 - 10)
- Achromatic system (11 - 12)
- Beam lines and their functions (13 - 18)
- Dispersion Matching (19 -22)
- Scattering Reconstruction (23 – 25)
- Effect of Dispersion Matching (26)

The Browne-Buechner, a Historic Spectrograph

built at MIT (1951-1954)

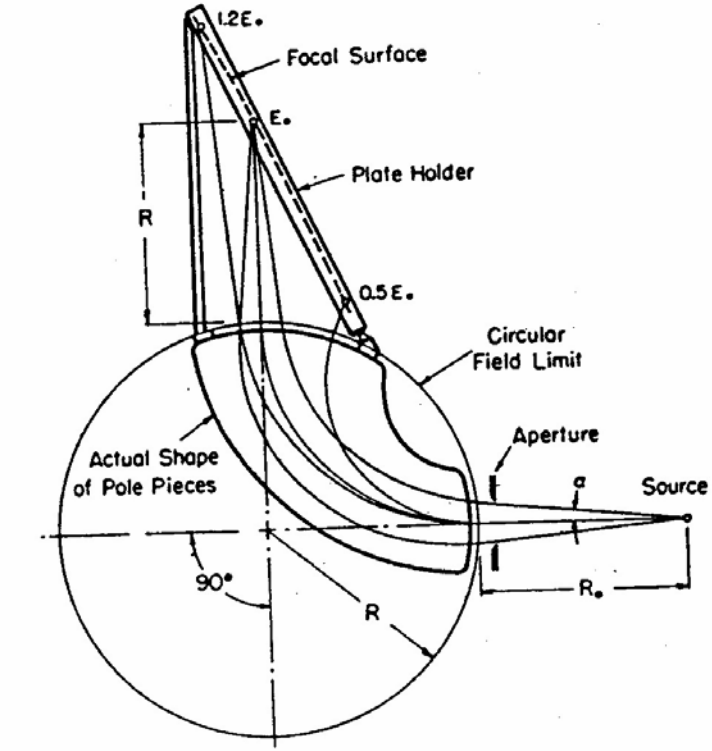


FIG. 2. Schematic drawing of spectrograph.

THE REVIEW OF SCIENTIFIC INSTRUMENTS

VOLUME 27, NUMBER 11 NOVEMBER, 1956

Broad-Range Magnetic Spectrograph*

C. P. BROWNE† AND W. W. BUECHNER
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge 39, Massachusetts

(Received August 8, 1956)

A broad-range magnetic spectrograph for precise measurement of the energies and intensities of charged particles from nuclear reactions is described. A uniform magnetic field with a circular boundary focuses particles from a source outside the field along a hyperbolic focal surface. Particles with energies varying by as much as a factor of 2.5 may be simultaneously recorded on nuclear-track plates. Under routine operating conditions, an energy resolution of better than 1000 is obtained over the length of the focal surface. The design, construction, testing, and operation of the spectrograph are described, and plots of dispersion, magnification, aberration, and calibration are given.

Spectrograph refers to an instrument with a photographic plate (historic!) in the focal plane

Spectrometer refers to an electrical detection system in the focal plane, e.g. a postions sensitive wire chamber

The present Notre Dame Spectrometer

A modified Browne-Buechner spectrometer

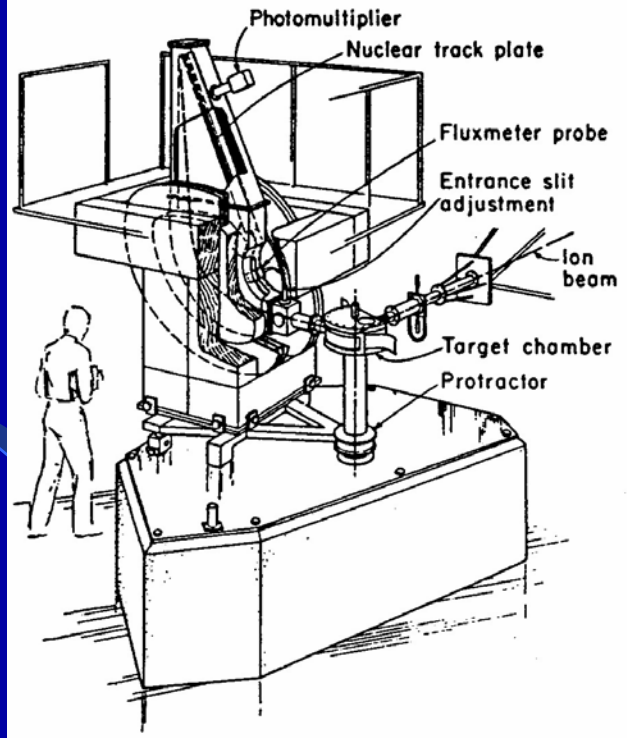


FIG. 6. Sketch of assembled spectrograph.

NUCLEAR INSTRUMENTS AND METHODS 109 (1973) 13–23; © NORTH-HOLLAND PUBLISHING CO.

DESIGN AND PERFORMANCE OF A NEW MAGNETIC SPECTROGRAPH FOR ACCURATE ENERGY MEASUREMENTS

J. D. GOSS, A. A. ROLLEFSON and C. P. BROWNE

Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, U.S.A.*

Received 16 January 1973

A large broad-range magnetic spectrograph of a new design is described. The primary requirement of accuracy is achieved with a single dipole magnet, fixed focal surface and high dispersion. A large energy range of $E_{min}/E_{max} = 3.7$, a solid angle up to 2.8 msr in the normal mode, and an energy resolution greater than 3000 over much of the range make it an excellent instrument for reaction energy measurements. The design, construction and testing are described.

Spectrometer Transfer Matrix S

Spectrometer Design

(1st Order Resolving Power)

Dispersion: $S_{16} = dx/(dp/p)$ $= D$

Magnification: $S_{11} = dx(f.p.) / dx(tgt)$ $= M$

Beam size: $2x_0$ (target, dispersive direction, monochromatic)

Resolving Power: $R_p = \frac{p}{\Delta p} = \frac{D}{M * 2x_0}$ **(22)**

Note: R_p depends on x_0, if not given here $x_0 = 1$ mm

Note: **Resolving Power** is the "best possible 1st order resolution a spectrometer can provide.

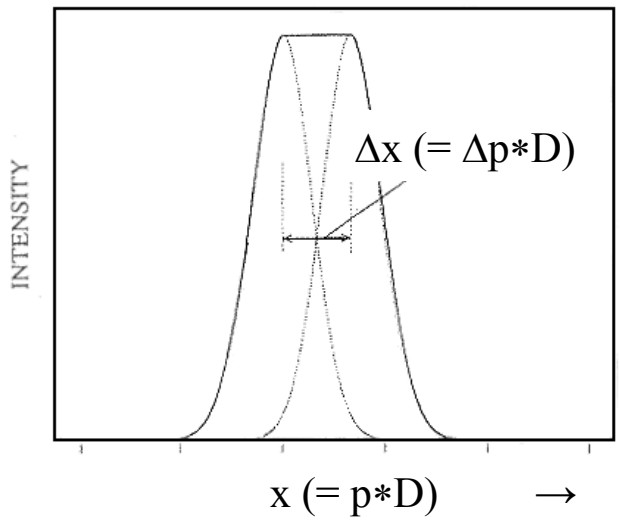
Resolution is what is measured in the Focal Plane.

Resolution is also effected (deteriorated) by:

Aberrations, target effects, detector resolution

Note: **"Resolution"** in Energy $R_E = \frac{E}{\Delta E} = 0.5 * R_p$

because $E = p^2/m$ (non-relativistic)



Peaks are "resolved" when Δx = FWHM

Specifications of the Browne- Buechner Spectrometer

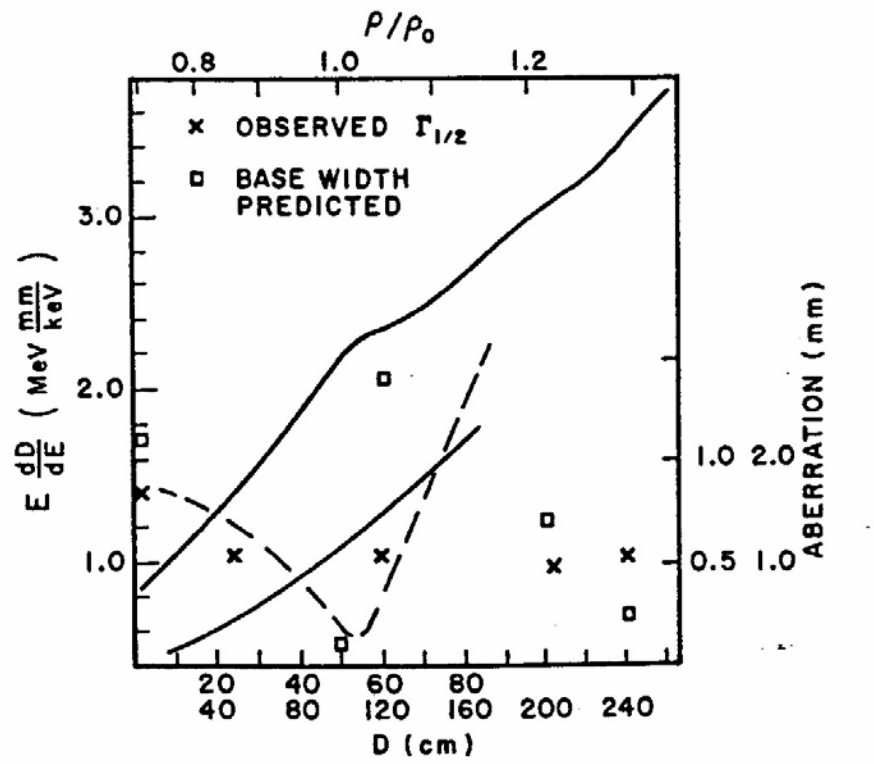


Fig. 7. Dispersion and aberration for the modified and unmodified broad-range spectrographs. The upper D-scale and inner aberration scales are for a $\rho_0 = 50$ cm broad-range; the lower D-scale and outer aberration scales are for the $\rho_0 = 100$ cm modified broad-range. Solid curves are dispersion; upper for modified and lower for unmodified. Dashed curve is aberration of unmodified broad-range. Symbols are to be read against the outer scale.

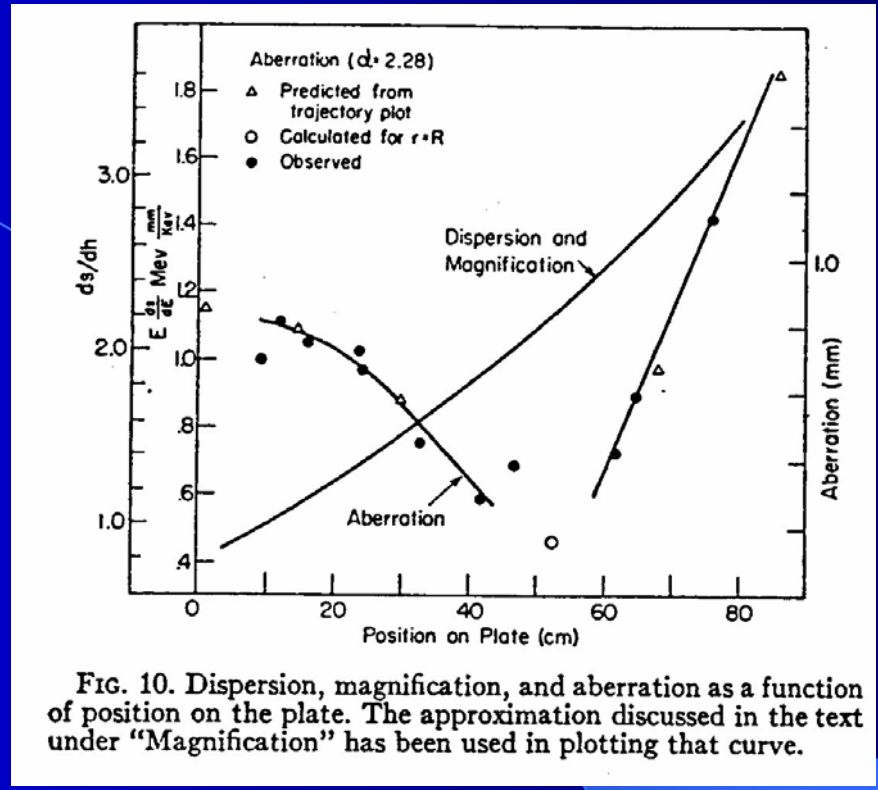


FIG. 10. Dispersion, magnification, and aberration as a function of position on the plate. The approximation discussed in the text under "Magnification" has been used in plotting that curve.

MIT version

Bending radius: $\rho_0 = 0.5$ m
Resolving power: $p/\Delta p = 2000$
$B_{max} = 1.2$ T
Gap = 1.27 cm
Weight = 6.5 tons (iron)
Large range: $E_{min}/E_{max} = 2.5$

ND version

ND version: $\rho_0 = 1.0$ m
Resolving power: $p/\Delta p = 6000 - 10000$
$B_{max} = 1.2$ T
Gap = 5.0 cm
Weight = 35 tons (iron)
Large range: $E_{min}/E_{max} = 3.7$

Compare weights
Gap is expensiv!

K600 Spectrometer (IUCF)

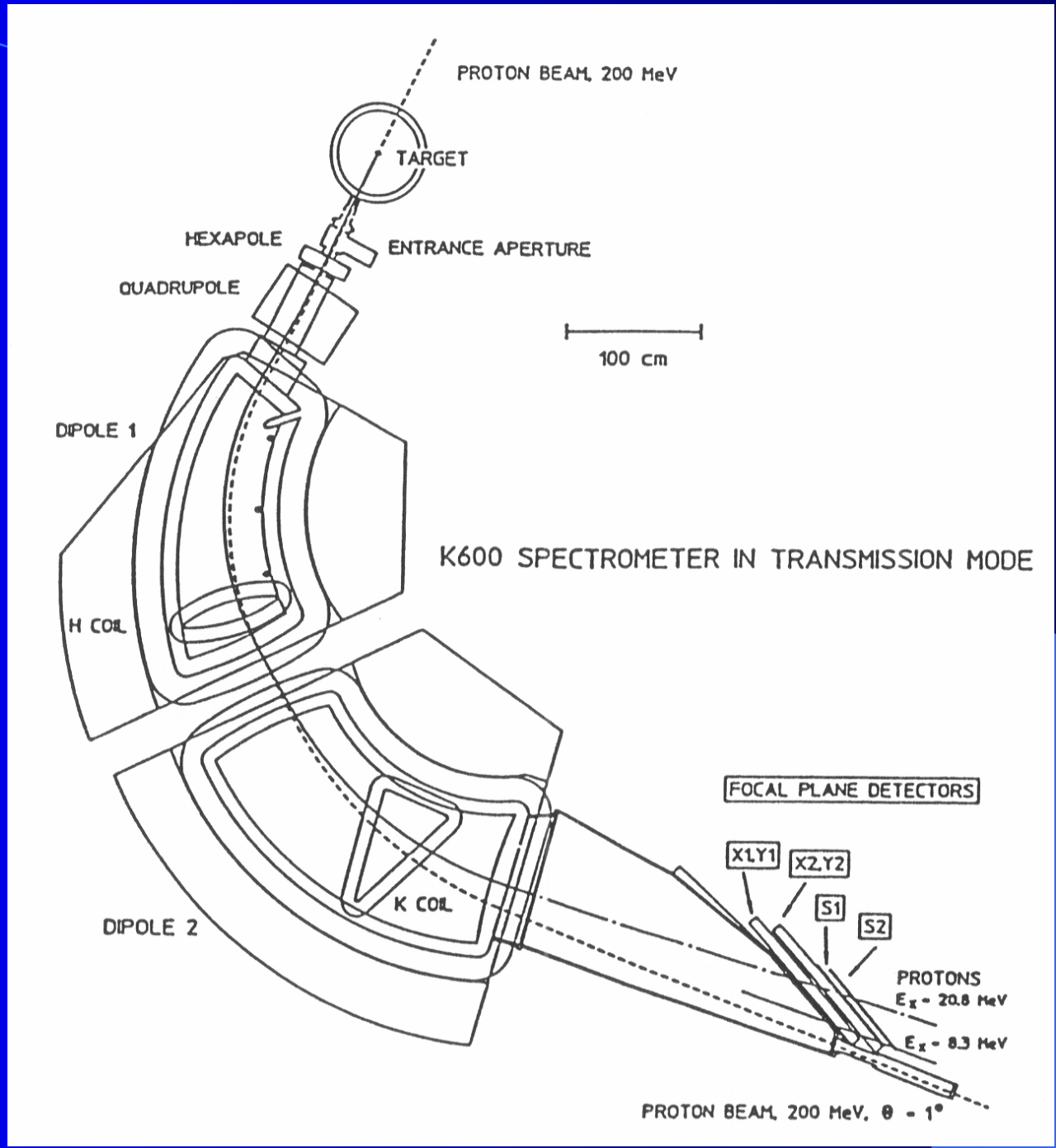
Bending radius $\rho_0 = 2.0$ m
$B_{max} = 1.7$ T
Gap = 5 cm (D 1), 6cm (D2)
Weight = ~ 30 tons (D1)
~ 45 tons (D2)

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

Kinematic correction: K coil
Hexapole correction: H coil

The K600 is shown in 0^o Transmission mode

High Dispersion Plane
B(D1) > B(D2)



BIG KARL Spectrometer (Juelich, KFZ)

Bending radius ρ_0 = 1.98 m
B_{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_{min}/E_{max} = 1.14
Solid angle: < 12.5 msr

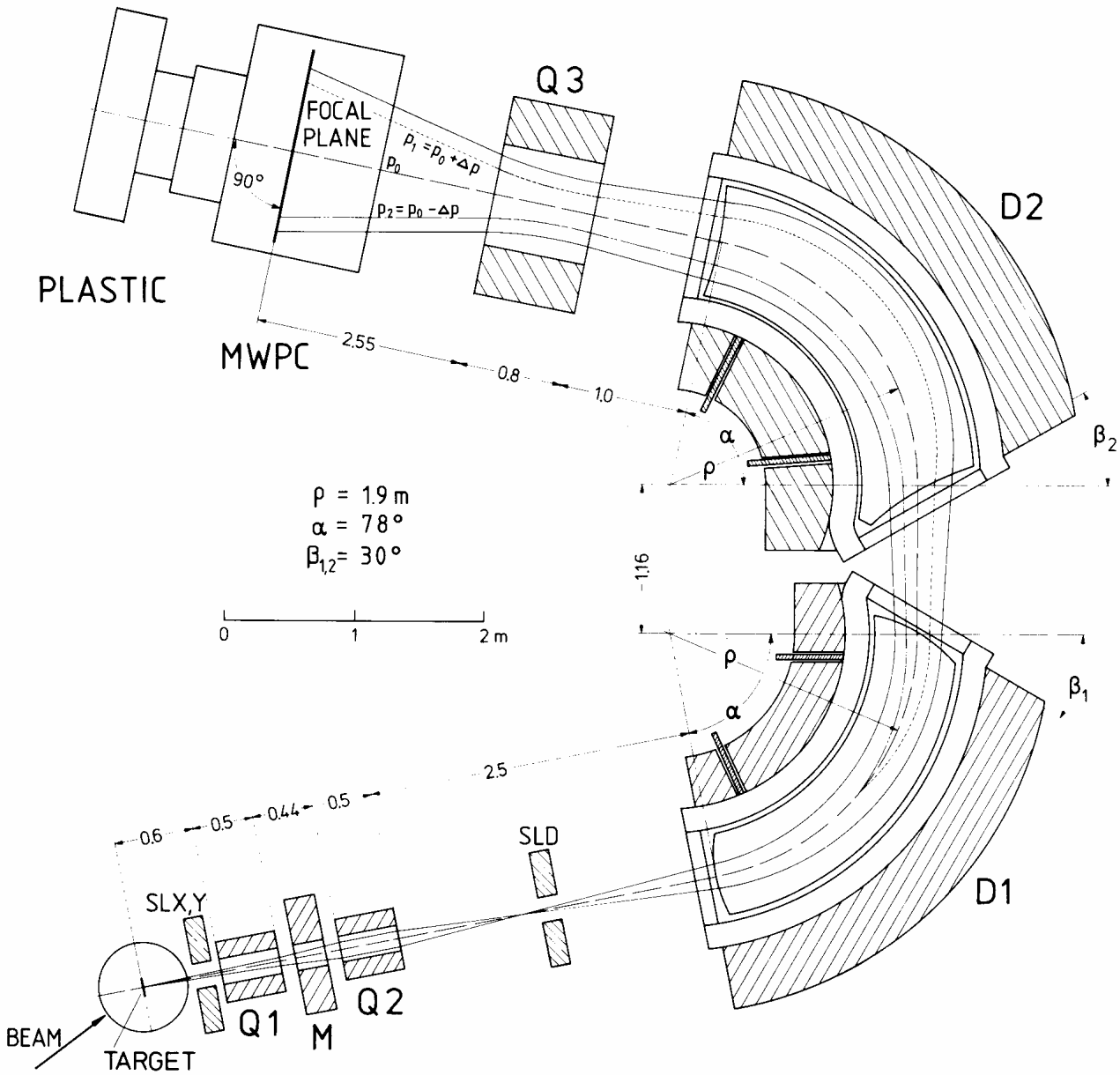


Fig. 9. Arrangement of the magnetic elements of the QQDDQ spectrometer BIG KARL. The central ray (optical axis) is shown as dashed curve. The outermost rays with the extreme radial distances are drawn as full lines. Four channels in the inner yokes allow NMR probes to be moved into the gaps of the dipoles for radial field measurements. The multipole element between Q1 and Q2 allows the correlation of vertical aberration.

BIG KARL Sample Spectra

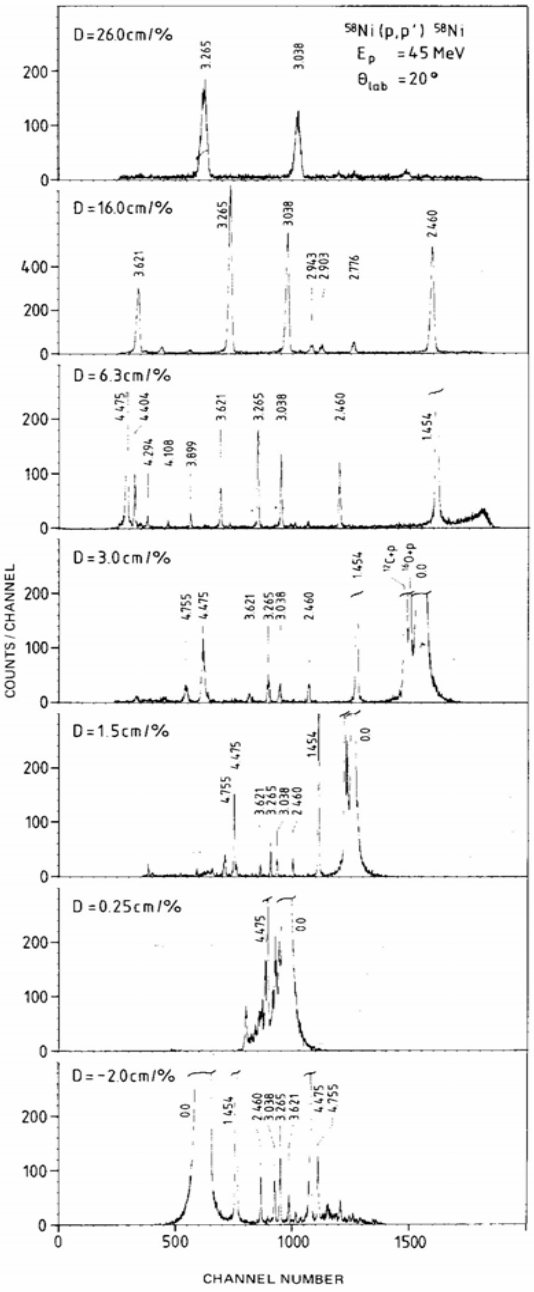


Fig. 4. Spectra of ^{58}Ni(p, p') measured for different dispersions $D = 26$, 16, 6.3, 3, 1.5, ~ 0.25 and -2 cm/%. The spectrograph was optimized for $D = 16$ cm/%.

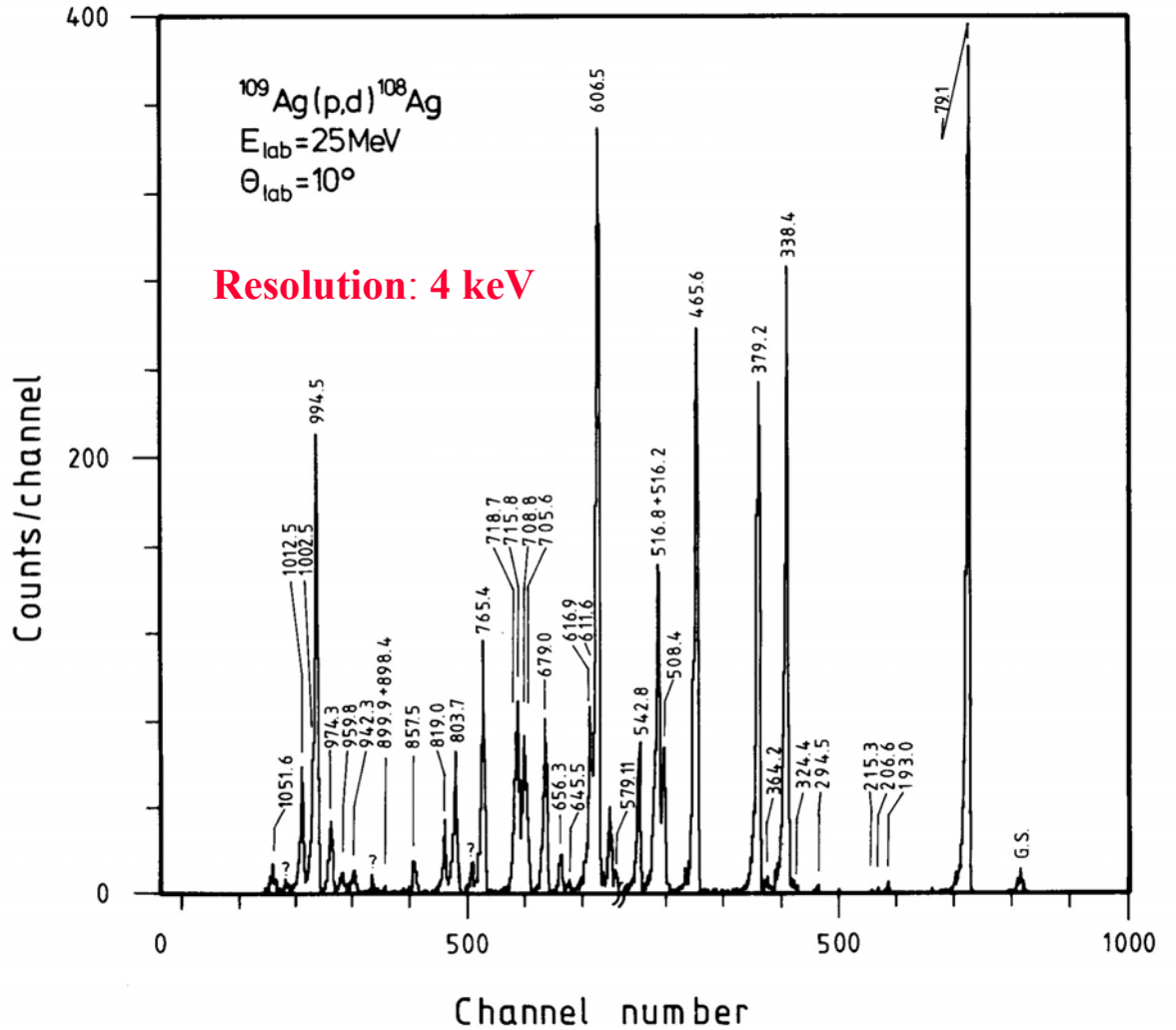


Fig. 19. High resolution spectrum of the (p, d) neutron pick up reaction on ^{109}Ag at 25 MeV incident energy and a solid angle of 1.2 msr. The resolution was 4 keV.

Schematic Layout of an Achromatic Magnet System

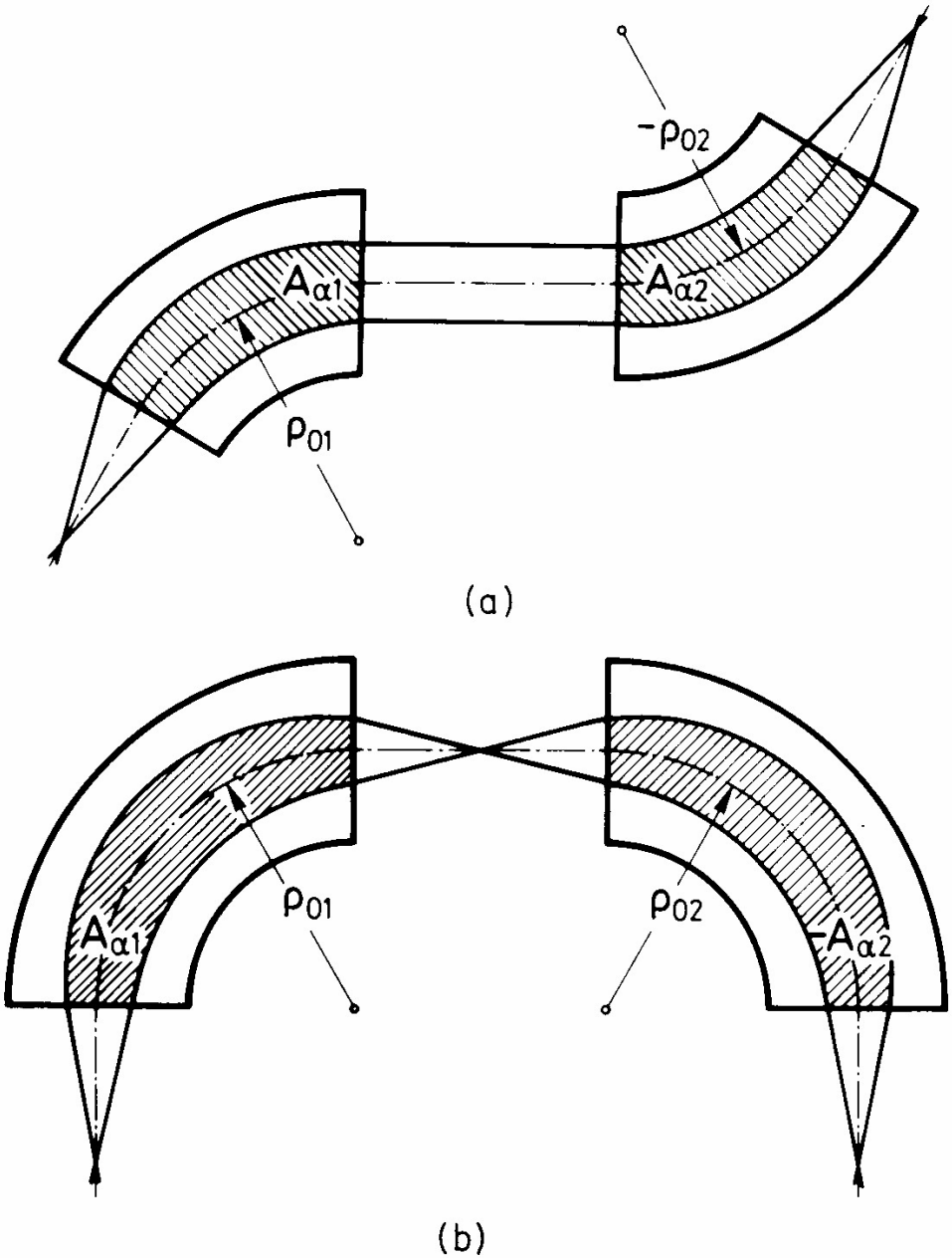
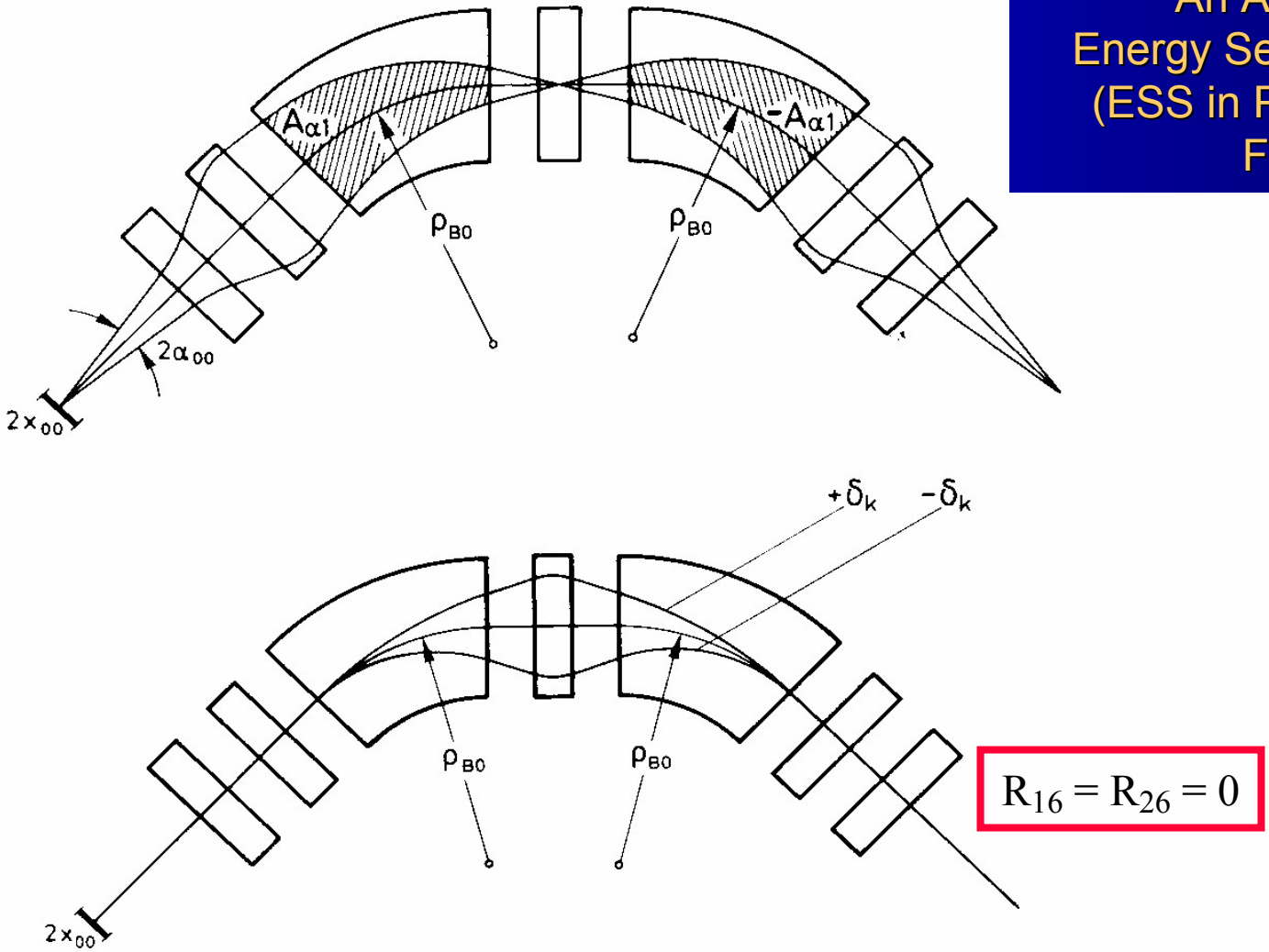


Fig. 9.6. Two double sector field arrangements that both cause achromatic beam deflections. Note that there are opposite signs for the radii of deflection in (a) and opposite signs for the area A_α in (b).

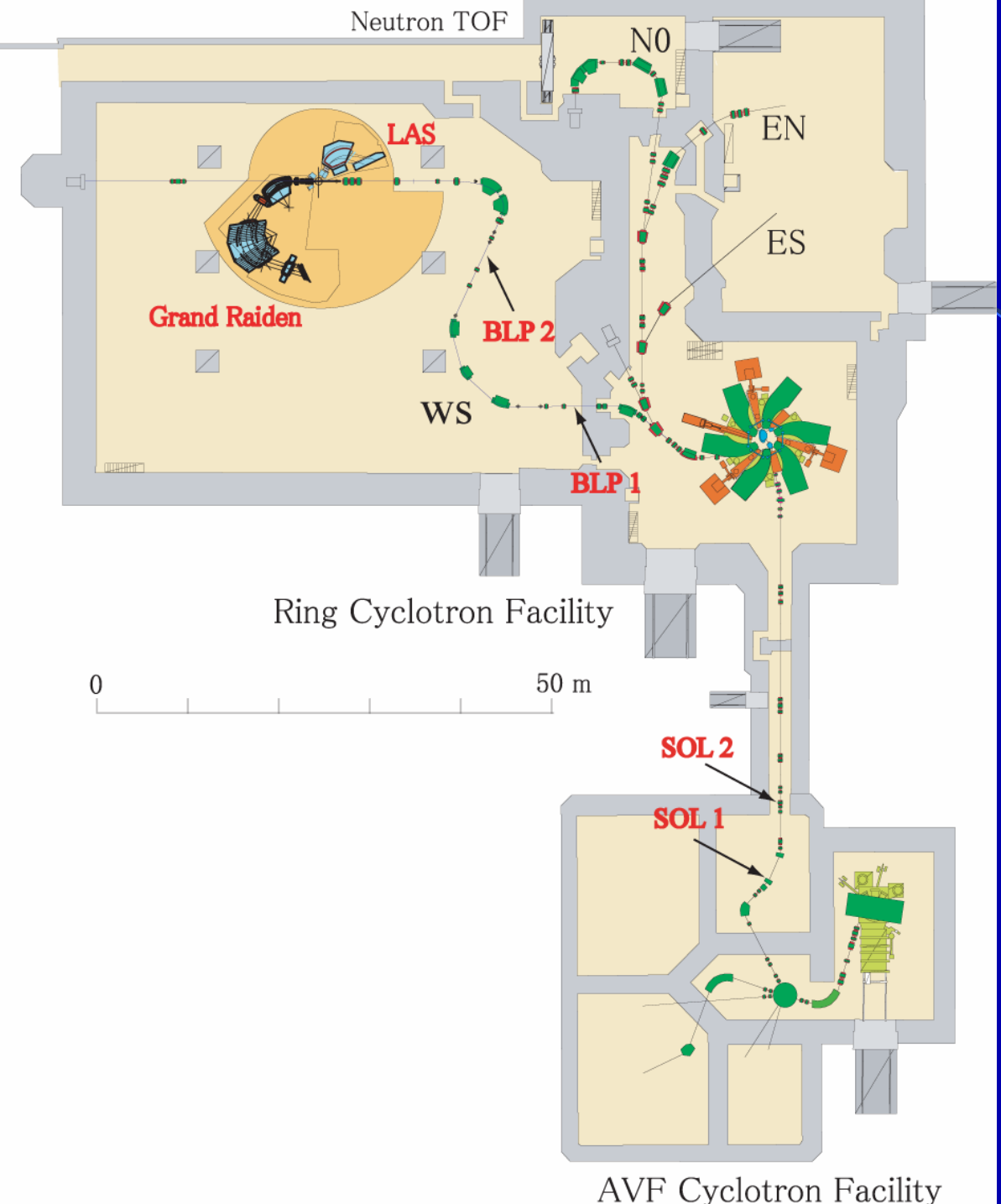
An Achromatic Energy Selection System (ESS in Proton Therapy Facility)



$$R_{16} = R_{26} = 0$$

Fig. 9.7. An achromatic beam deflector consisting of two sector fields preceded and followed by quadrupole doublets. Note that the areas $A_{\alpha 1}$ and $-A_{\alpha 1}$ are of equal size. The quadrupole in the middle between the sector fields can be adjusted so that the overall system is not only dispersion free $(x|\delta_K) = (x|\delta_m) = 0$ but achromatic $(a|\delta_K) = (a|\delta_m) = 0$; i.e., particles of different rigidities $(\delta_K \neq 0)$ are parallel in the middle of the center quadrupole and coincide at the end of the systems if they coincided at the beginning.

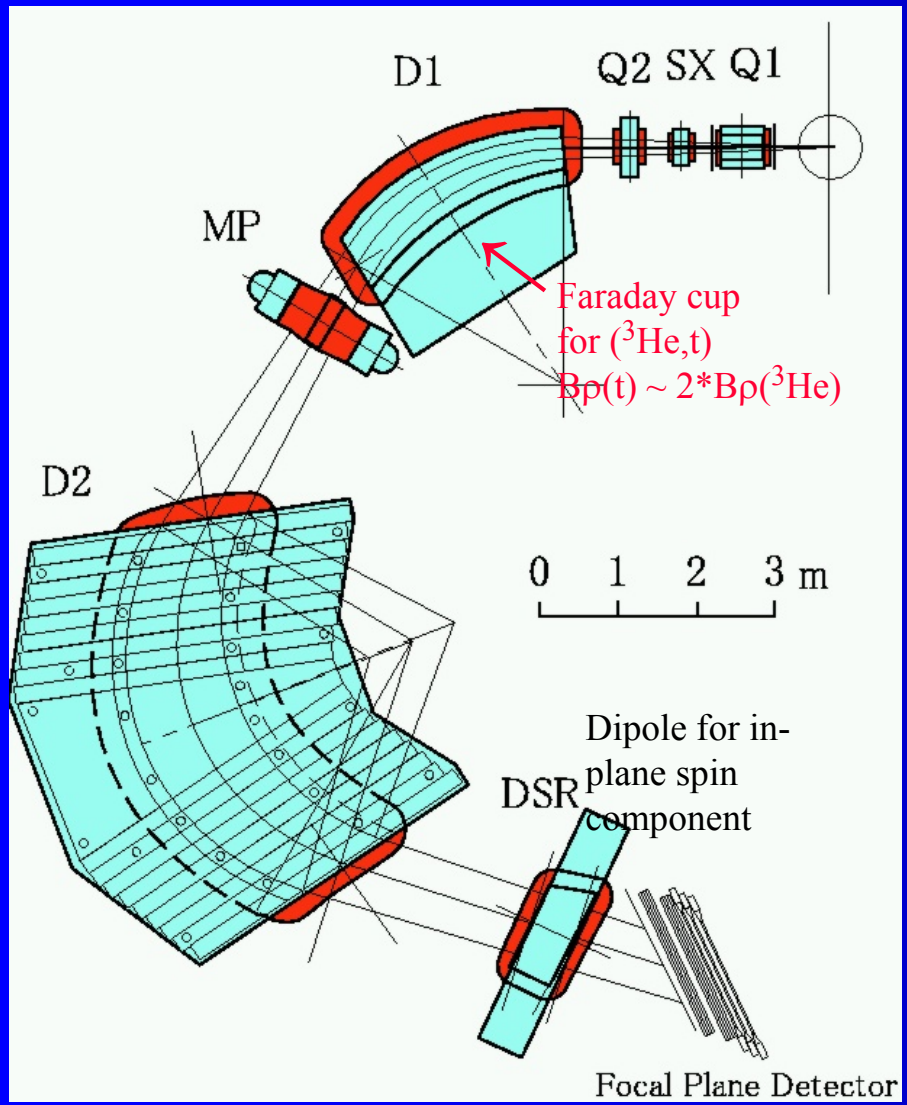
RCNP Facility Layout Osaka, Japan



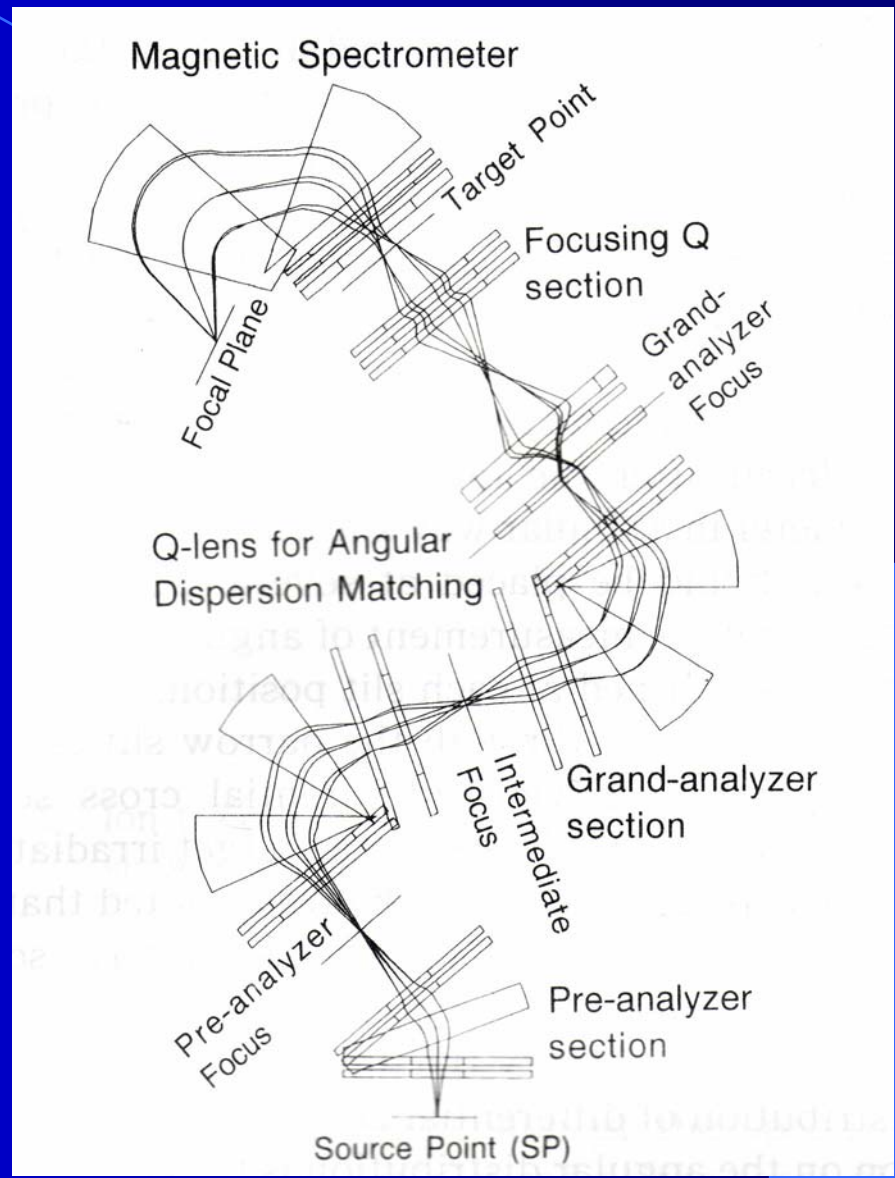
Dispersion matched beam line WS to the high resolution spectrometer Grand Raiden

Grand Raiden High Resolution Spectrometer

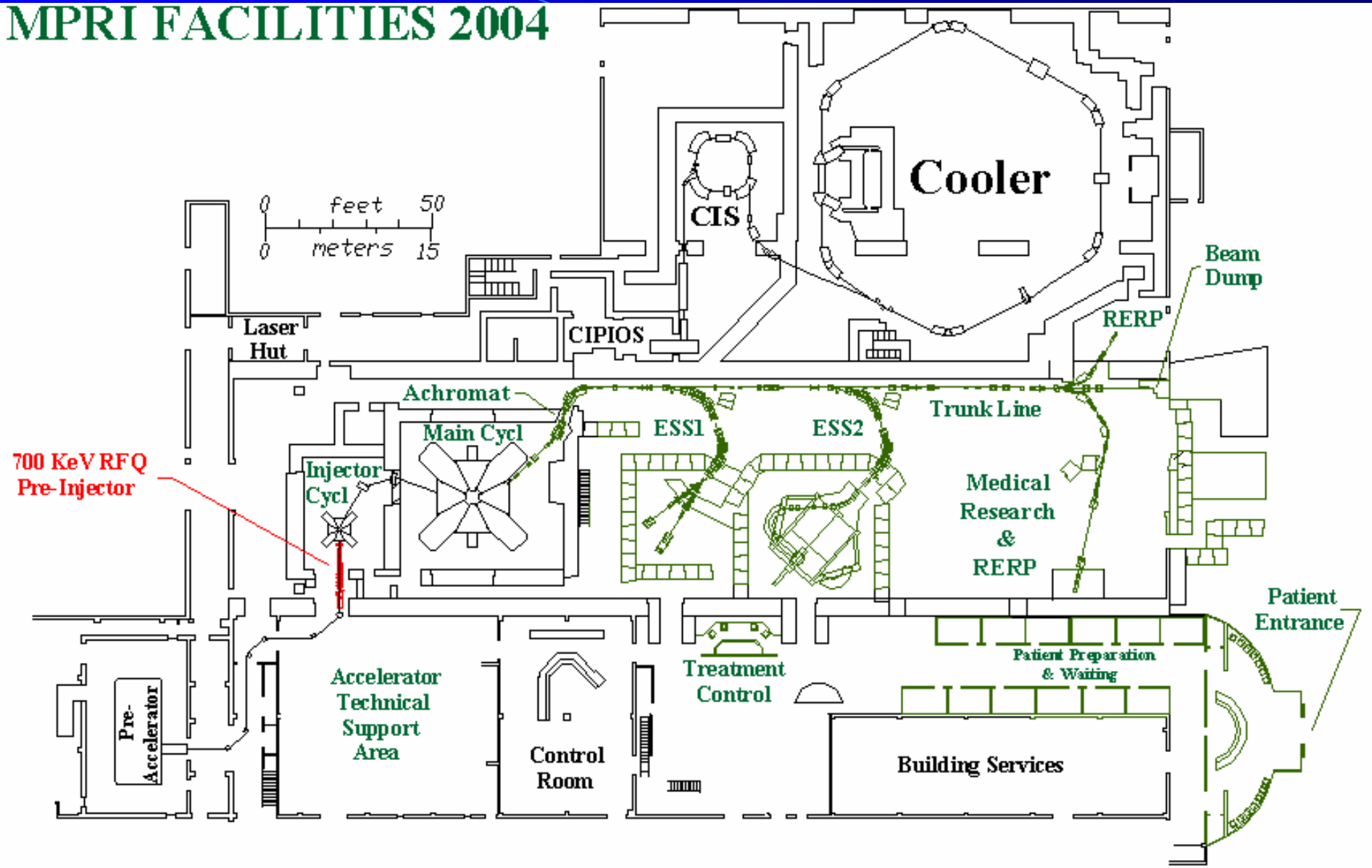
Max. Magn. Rigidity: 5.1 Tm
Bending Radius ρ_0: 3.0 m
Solid Angle: 3 msr
Resolv. Power p/dp 37000



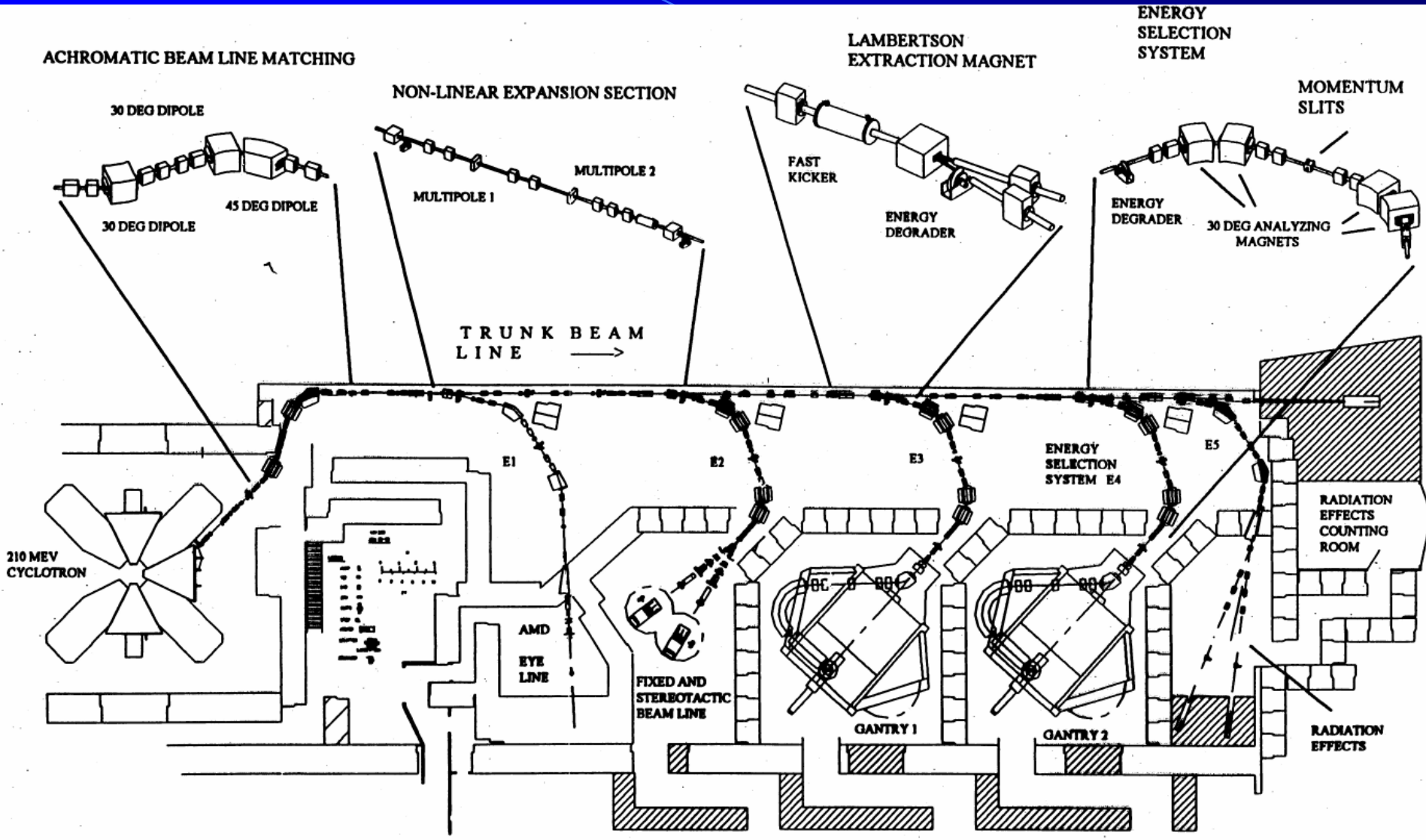
Beam Line/Spectrometer fully matched



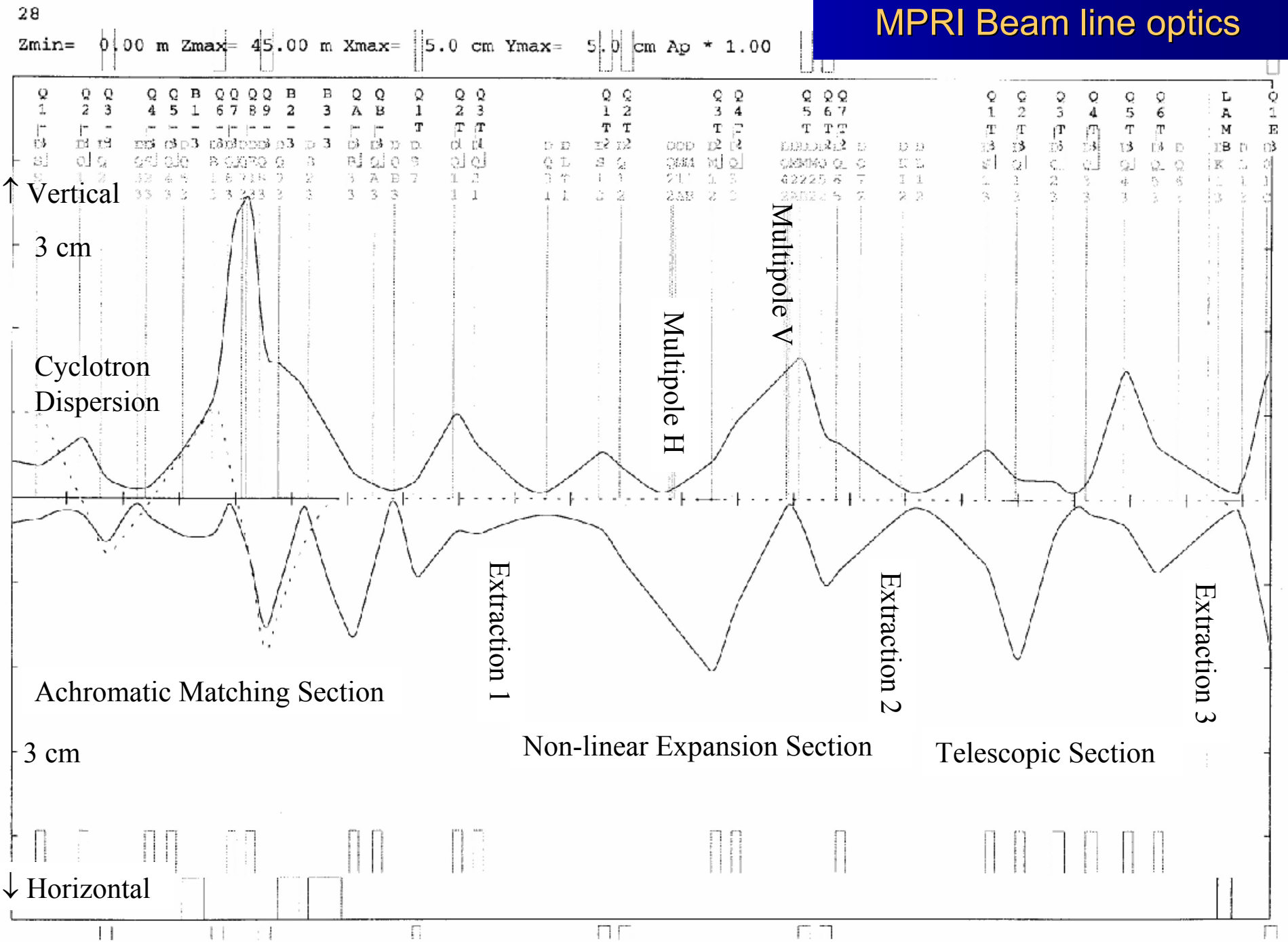
IUCF 2004, MPRI Facility



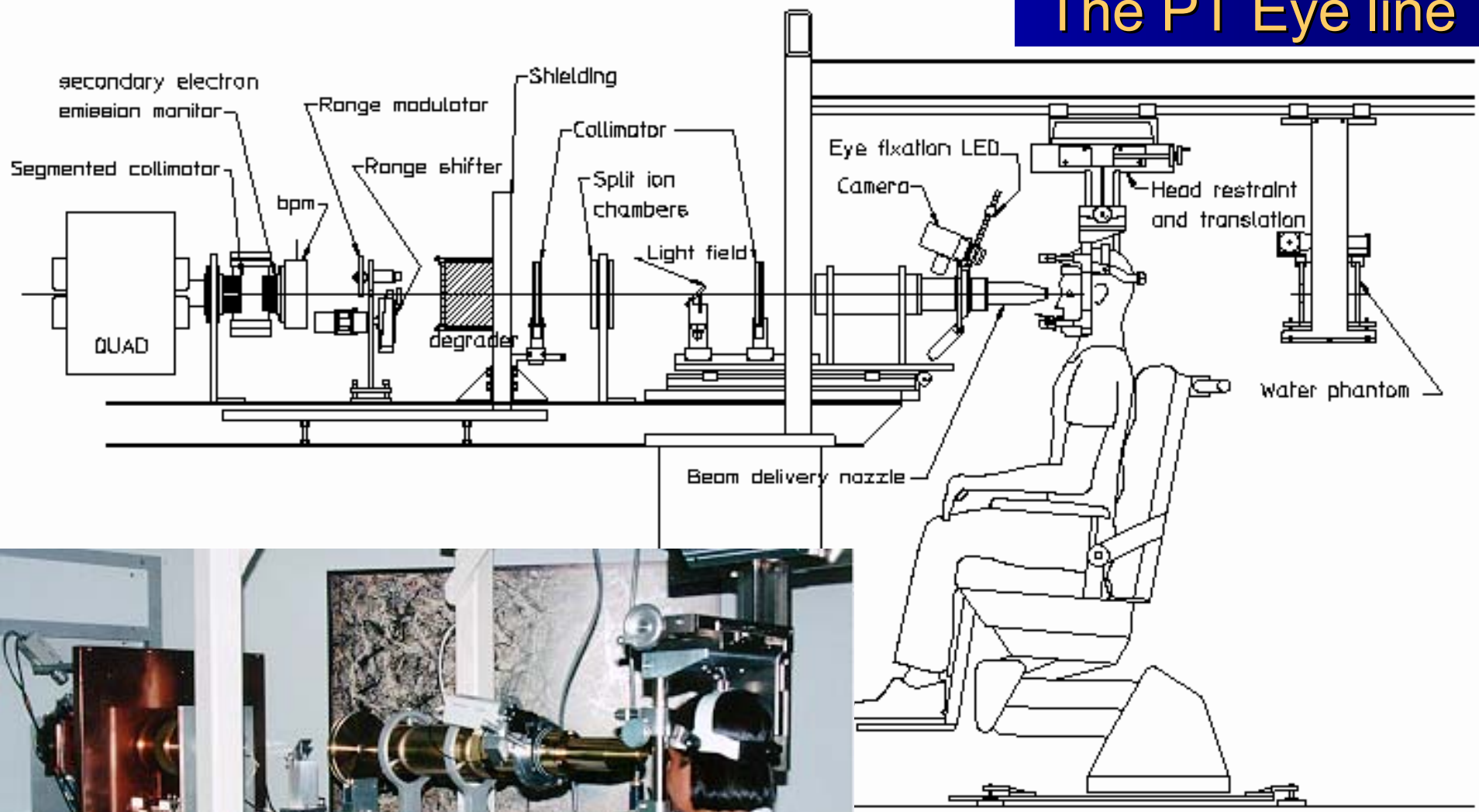
Functions of the MPRI Beam Line



MPRI Beam line optics



The PT Eye line



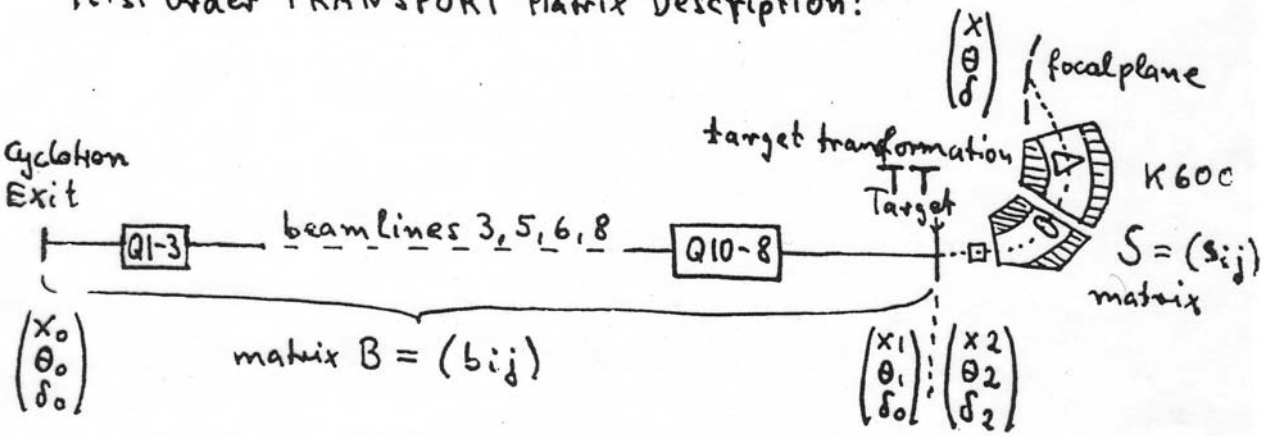
AMD Proton Therapy Beamline
Indiana University Cyclotron Facility
Sept. 1997

(AMD = Age-related Macular Degeneration)

Dispersion Matching

Matching between beam line and spectrometer

First Order TRANSPORT Matrix Description:



$$B = \begin{pmatrix} b_{11} & b_{12} & b_{16} \\ b_{21} & b_{22} & b_{26} \\ 0 & 0 & 1 \end{pmatrix} \qquad S = \begin{pmatrix} s_{11} & s_{12} & s_{16} \\ s_{21} & s_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix}$$

TT:

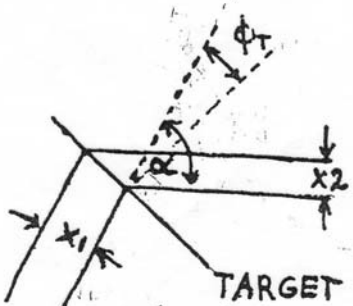
$x_2 = T\,x_1$

$\theta_2 = \theta + \theta_1$

θ_2 = random angle within acceptance of spectrom.

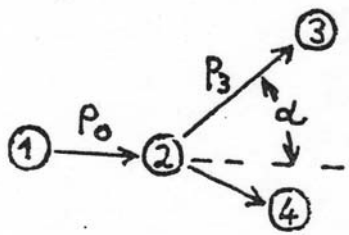
$\delta_2 = K(\theta_2 - \theta_1) + C\,\delta_0$

θ is random



$$T = \frac{\cos(\alpha - \phi_T)}{\cos\phi_T}$$

Reaction Kinematics



$P_3 = P_3(P_0, \alpha, Q)$

$$K = \frac{\partial P_3}{\partial \alpha}\,\frac{1}{P_3} \qquad C = \frac{\partial P_3}{\partial P_0}\,\frac{P_0}{P_3}$$

$$\begin{pmatrix} x \\ \theta \\ \delta \end{pmatrix} = S \cdot TT \cdot B \cdot \begin{pmatrix} x_0 \\ \theta_0 \\ \delta_0 \end{pmatrix}$$

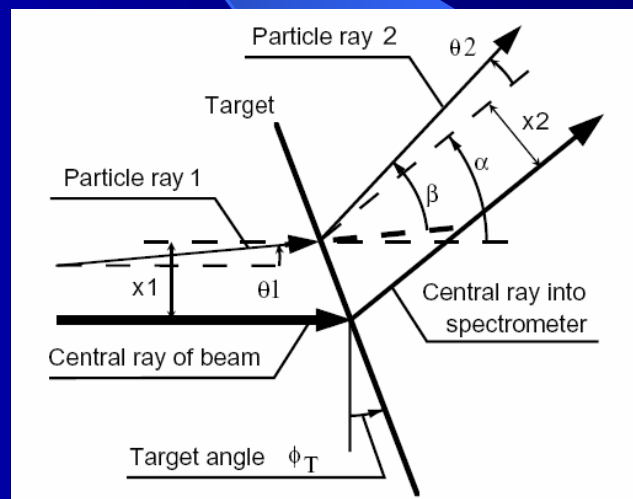


Fig. 1. Schematic layout of the incident particle 1 and the outgoing particle 2 relative to the beam and spectrometer.

Solution of first order Transport and Complete Matching

The transformation (without assuming $s_{12} = -s_{16} K$) in the bending plane from the cyclotron exit to the focal plane is given as:

$$x_{f.p.} = x_0 (s_{11} b_{11} T + s_{12} b_{21})$$

$$\theta_0 (s_{11} b_{12} T + s_{12} b_{22}) \rightarrow \text{kin. defoc.} \quad \text{equ. (1)} \qquad (23)$$

$$\delta_0 (s_{11} b_{16} T + s_{12} b_{26} + s_{16} \zeta) \rightarrow \text{disp. matching}$$

$$\theta (s_{12} + s_{16} K) \rightarrow \text{kin. correction (kin. displac.)}$$

$$\theta_{f.p.} = x_0 (s_{21} b_{11} T + s_{22} b_{21})$$

$$\theta_0 (s_{21} b_{12} T + s_{22} b_{22}) \quad \text{equ. (2)} \qquad (24)$$

$$\delta_0 (s_{21} b_{16} T + s_{22} b_{26} + s_{26} \zeta) \rightarrow \text{angular disp. matching}$$

$$\theta (s_{22} + s_{26} K)$$

$$\delta_{f.p.} = K \cdot \theta + \zeta \delta_0$$

For details see: Y. Fujita et al., NIM B 126 (1997) 274

Complete Matching

For best **Resolution** in the focal plane, minimize the coefficients of all terms in the expression of **x** f.p.

For best **Angle Resolution** Minimize Coefficients of δ_0 in expression of Y f.p.

Note: Also the beam focus b_{12} on target is important (b_{12} = 0 for kinem. k = 0)

Spacial Dispersion Matching:
D.L. Hendrie In: J. Cerny, Editor,
Nuclear Spectroscopy and Reactions, Part A,
Academic Press, New York (1974), p. 365.

Hendrie Dispersion Matching $b_{16} = \frac{D}{M} * \frac{C}{T}$ (23')

Spacial and Angular Dispersion Matching

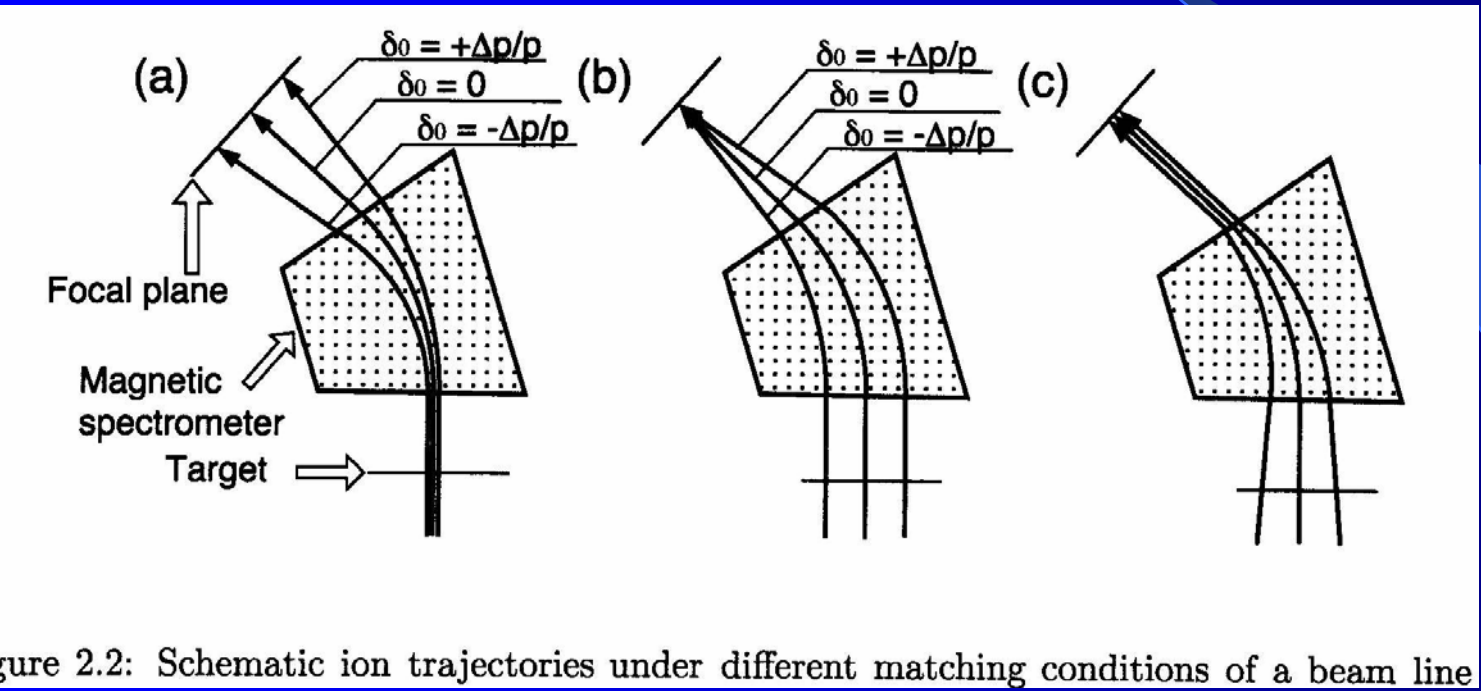
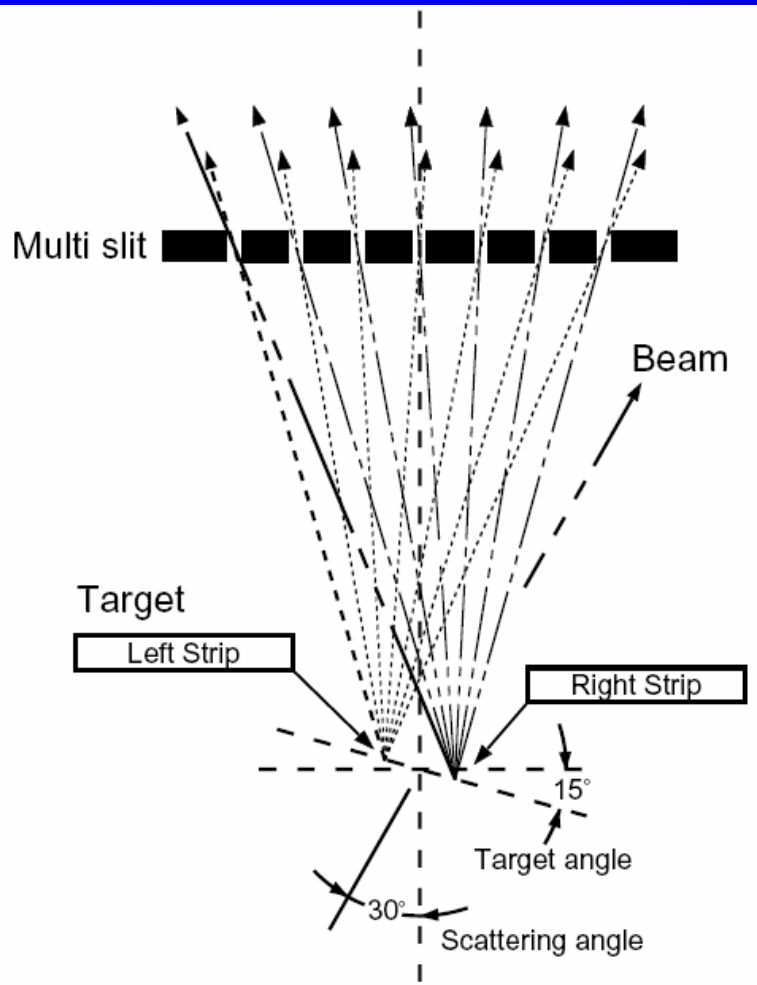
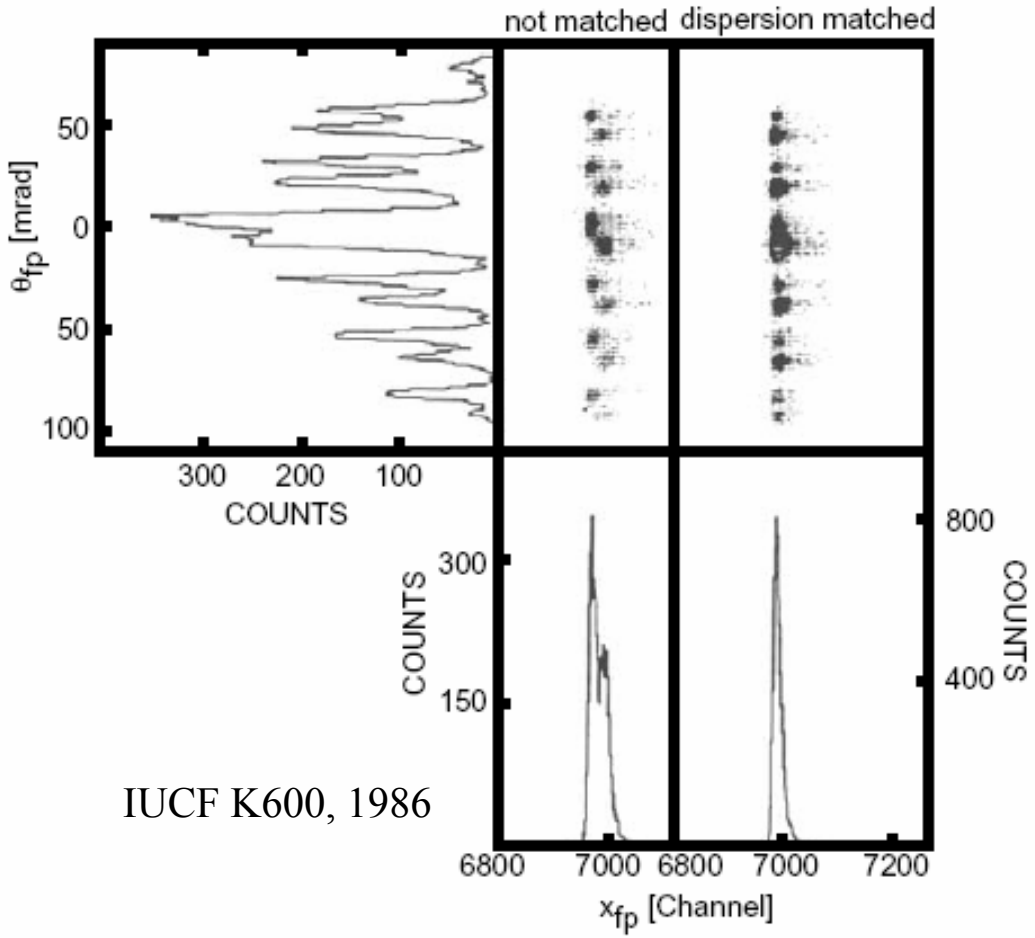


Figure 2.2: Schematic ion trajectories under different matching conditions of a beam line

Diagnostic of Dispersion Matching

of beam line & spectrometer using
a double strip target & multi slit





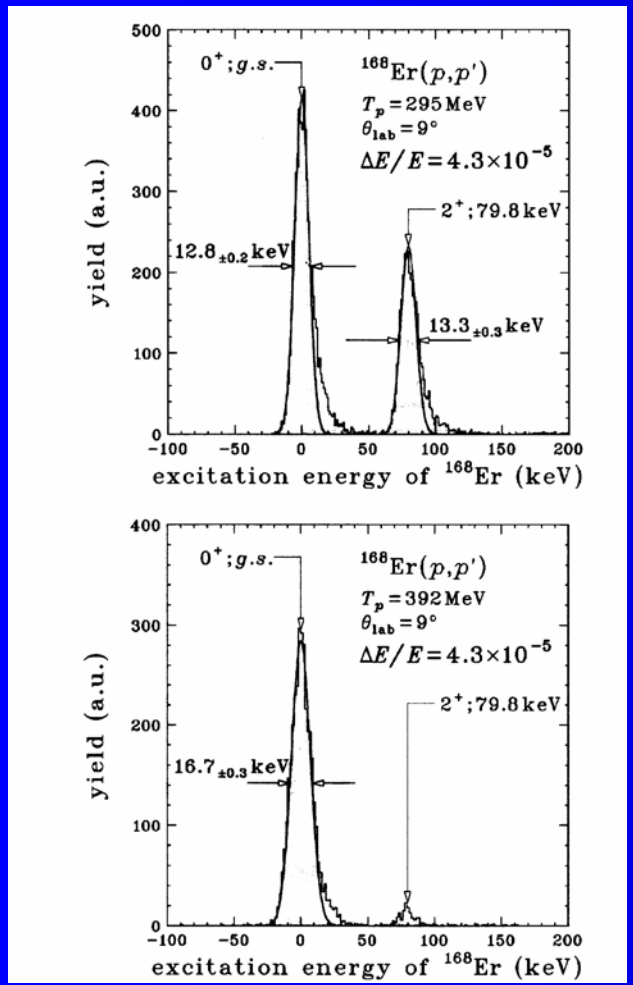
IUCF K600, 1986

Fig. 4. Scatterplots of horizontal position x_{fp} versus angle θ_{fp} and projections measured in the focal plane of the K600 using the "multi-slit system". For details, see text.

Momentum and Angular Resolution

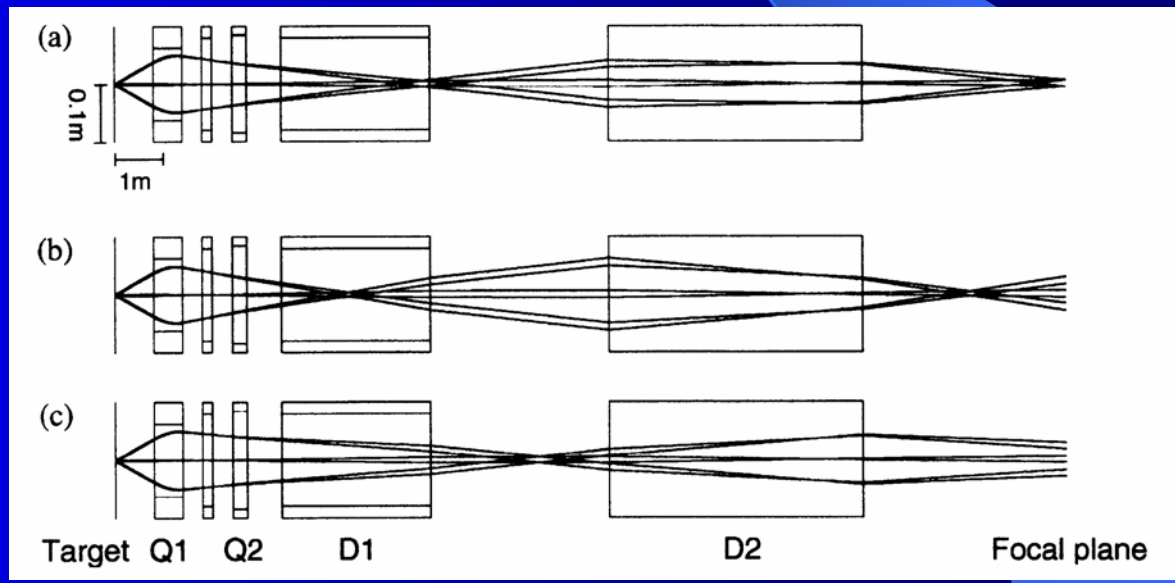
Spacial & Angular Dispersion Matching & Focus Condition allows

Energy Resolution: $\Delta E/E = 4.3 * 10^{-5}$, $\Delta p/p = 2.5*10^{-5}$, despite beam spread: $\Delta E = 4–6*10^{-4}$



Angular resolution: $\Delta Y_{scatt} = SQRT(\Delta Y^2_{hor} + \Delta\Phi^2) = 4 - 8$ msr

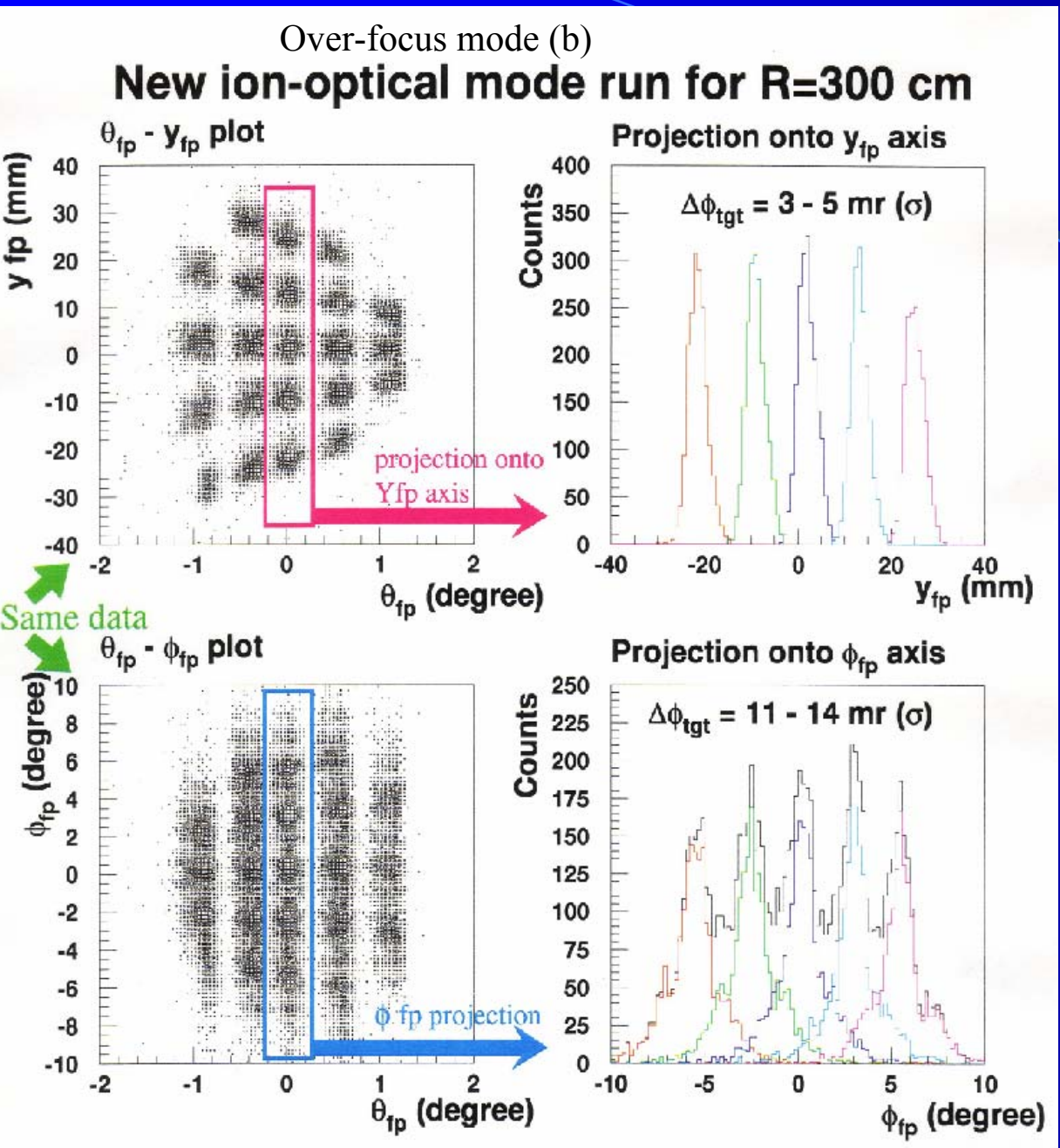
At angles close to beam (e.g. 0 deg) vert. angle component is needed → Overfocus mode, small target dimension, because (y|y) is large,
Limitation: multiple scattering in detector



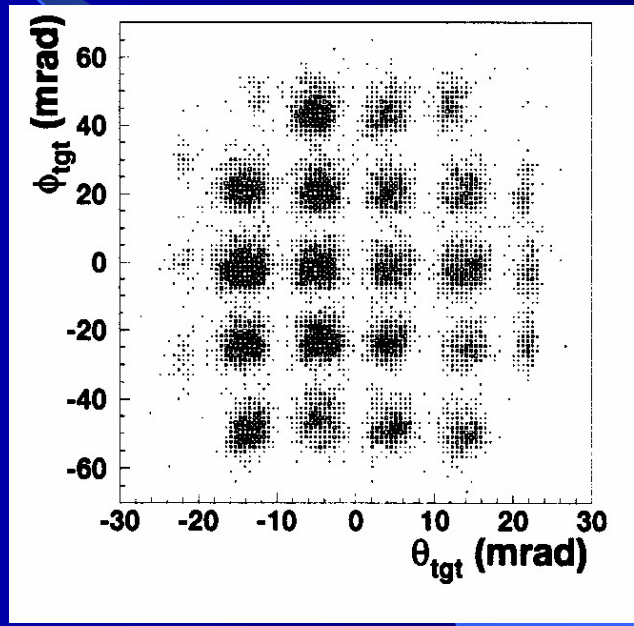
Refs.: Y.Fujita et al, NIM B126(1997)274, H.Fujita et al. NIM A 469(2001)55, T.Wakasa et al, NIM A482(2002)79

Grand Raiden Angle Calibration

Data suggest: Use y_{fp} not Φ_{fp} to calibrate angle!

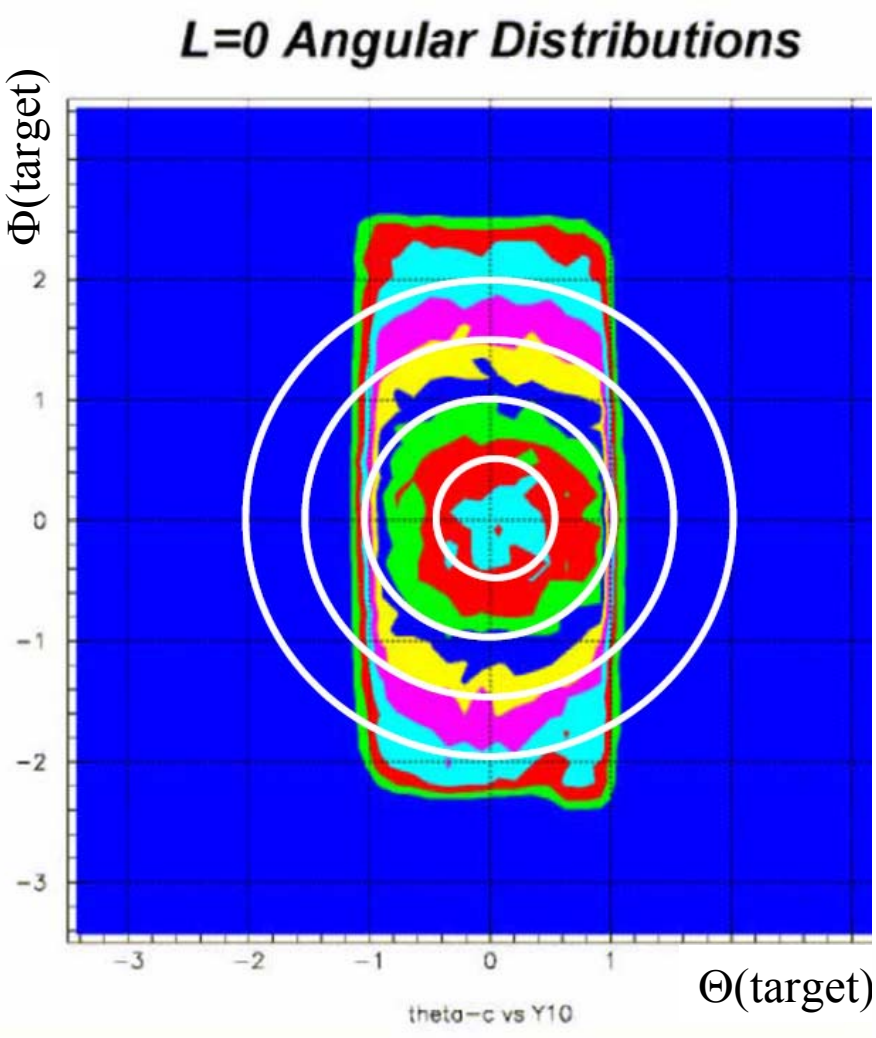


Calibrated!



Scattering Angle

reconstructed from focal plane measurements using complete dispersion matching techniques



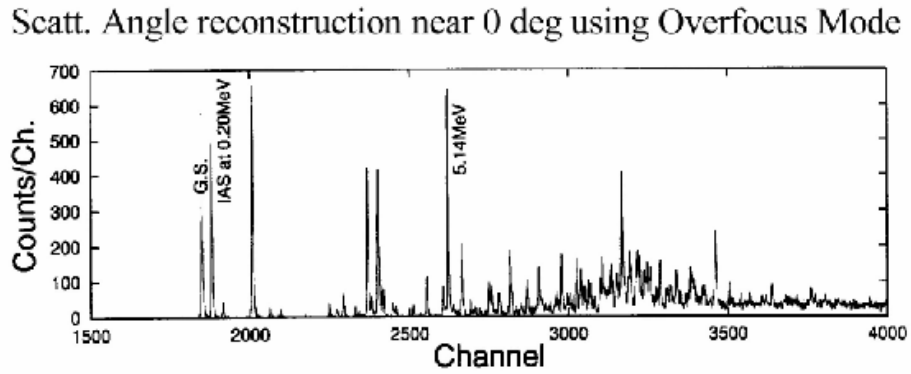


Figure 4.4: Spectrum of ^{58}Ni(^{3}He,t) reaction. The *lateral* and *angular dispersion matching* technique and *over-focus mode* were applied in this experiment for high energy and scattering angle resolution. Energy resolution of about 30 keV (FWHM) was realized.

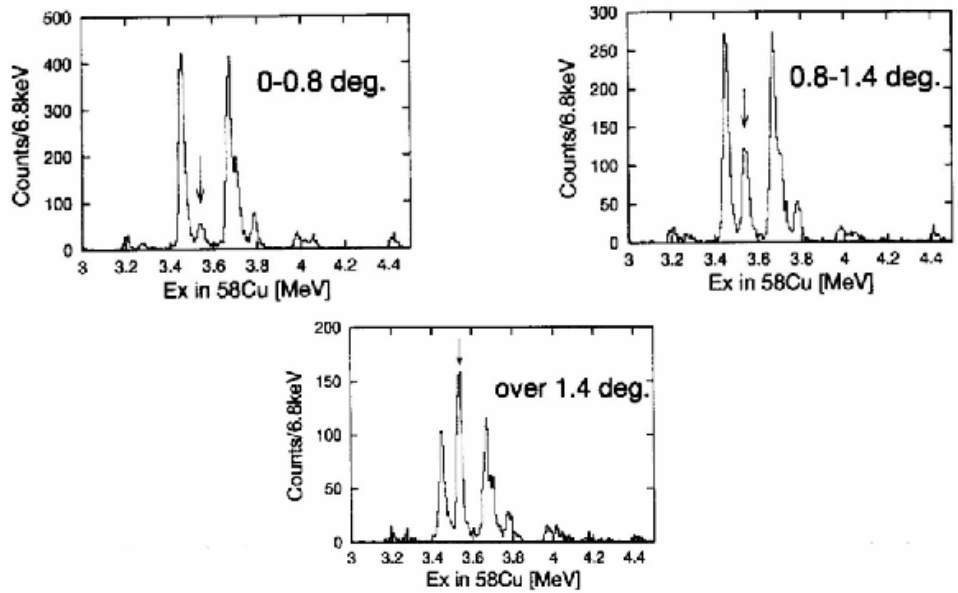


Figure 4.5: Example of angle dependence in the ^{58}Ni(^{3}He,t) spectra near 0°. Three spectra are shown for the angle ranges 0-0.8° (left), 0.8-1.4° (middle) and over 1.4° (right), respectively. The 3.54 MeV state show clearly different angular distribution from the adjacent 1^+ states which are dominated at forward angle.

Study of Gamow-Teller Resonances

$^{58}Ni(p,n)^{58}Cu$

E_p=160MeV at θ_{lab}=0°

ΔE ~ 400 keV

J.Rapaport et al.,
Nucl.Phys. A410 (1983) 371

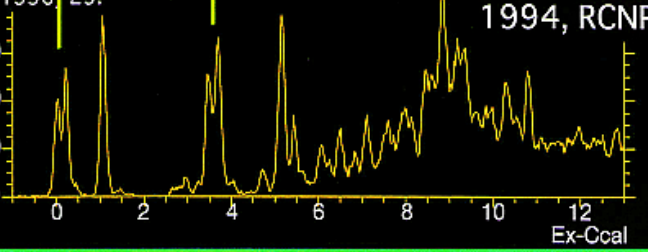
(p,n) → (^{3}He,t)

$^{58}Ni(^3He,t)^{58}Cu$

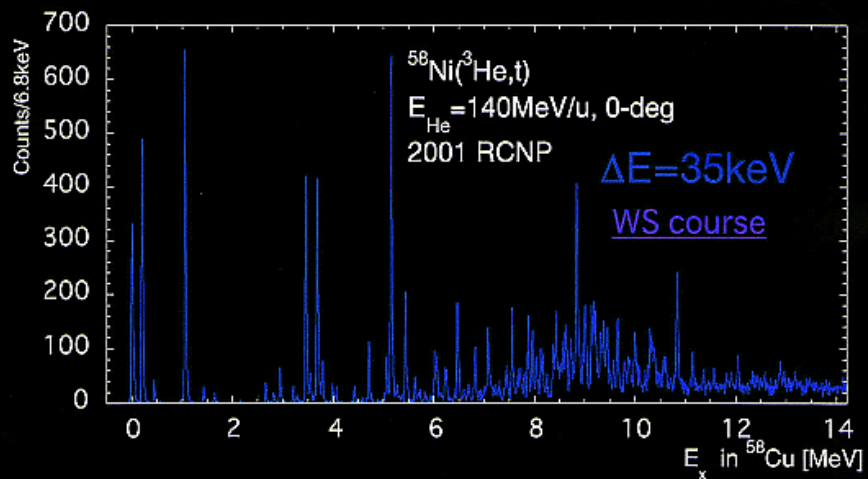
E_{He}=150MeV/u at θ_{lab}=0°

Y.Fujita et al.,
Phys. Lett. B365 (1996) 29.

ΔE=140keV
WN course
1994, RCNP

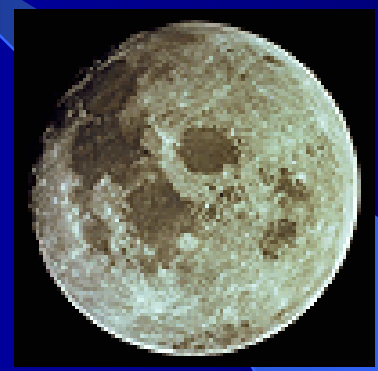


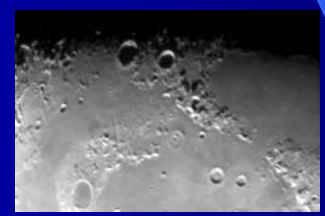
Development of Dispersion matching



Effect of Dispersion Matching

(Optical Resolution compared)





Where is the limit?

End Lecture 3