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

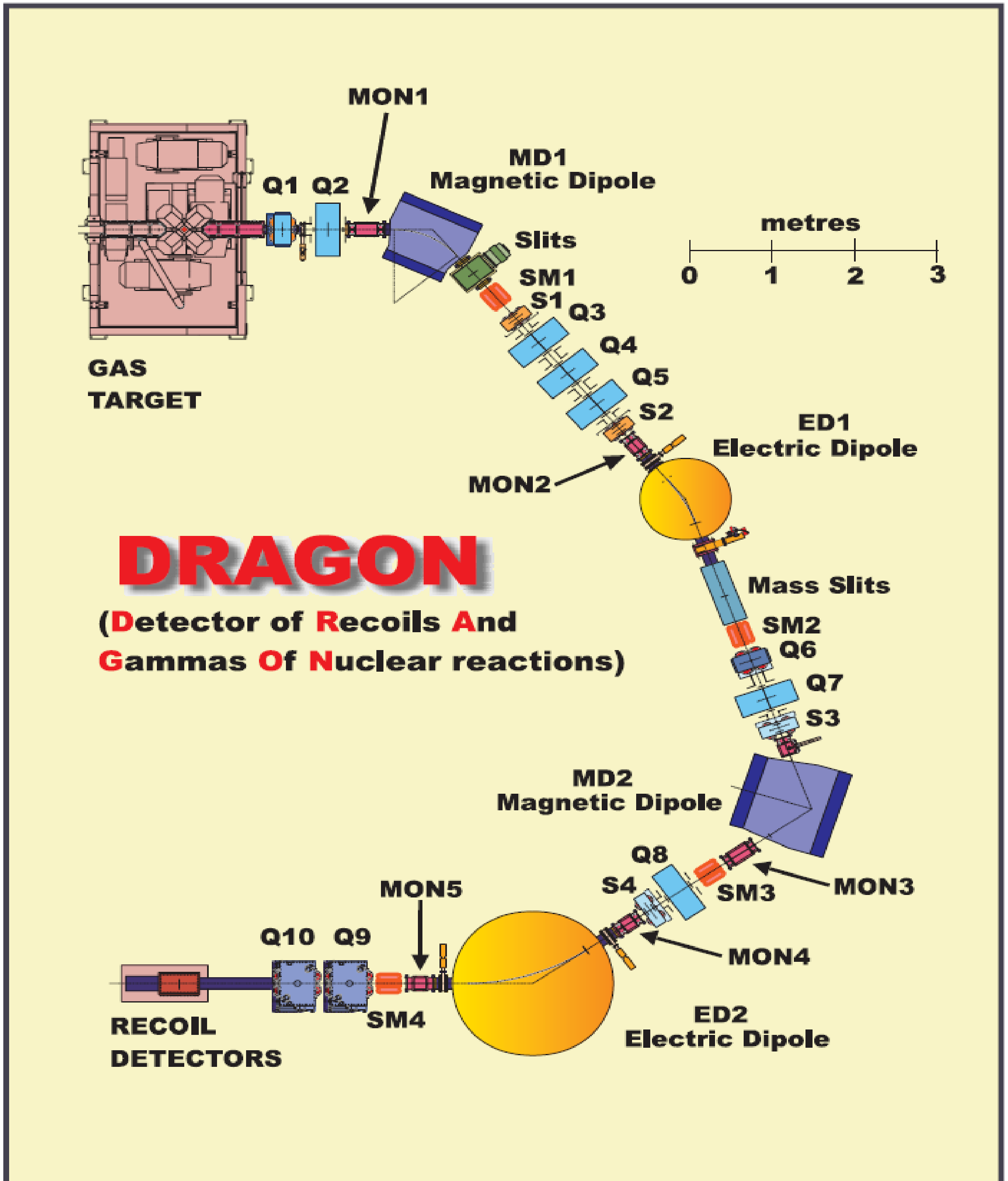
4th Lecture: 12/2/05, 2:00 pm: Separator Systems, Part 1

5th Lecture: 12/9/05, 2:00 pm: Separator Systems, Part 2

5^{th} Lecture

5^{th} Lecture: 12/2/05, 2:00 pm
Separator Systems

- Electric Dipoles in Recoil Separator Dragon & EMMA
- Wien Filter in Recoil Separators
- Recoil separators ERNA and ARES for astrophysics
- A “no-field” separation method: the Wedge
- In-flight isotope separators TRIμP and A1900
- Gas-filled separators
- Astrophysics recoil separator St. George



DRAGON

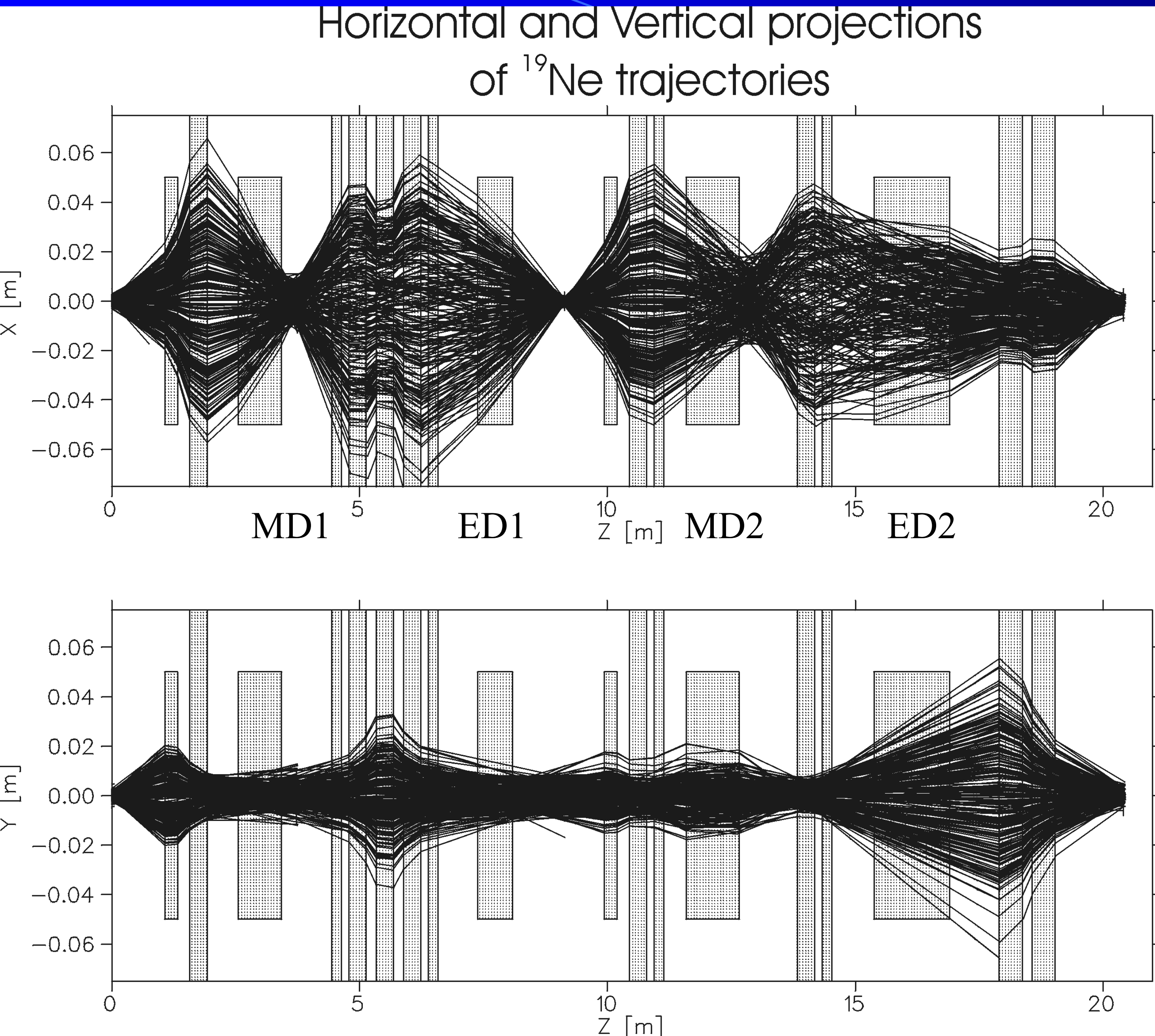
Recoil Separator with Electric Dipoles

Study of astrophyscis reactions using radioactive beams:

e.g. $^{21}Na(p,\gamma)^{22}Mg$ in inverse kinematics using a radioactiv ^{21}Na beam of 4.62 MeV to study NeNa cycle

Ref. Dragon Recoil Separator Optics, The Recoil Group, 1/18/1999,TRIUMF

DRAGON Ion-optics



Ref. J. M. D'Auria et al.
TRIUMF

EMMA
Recoil Separator for ISAC-II at TRIUMF

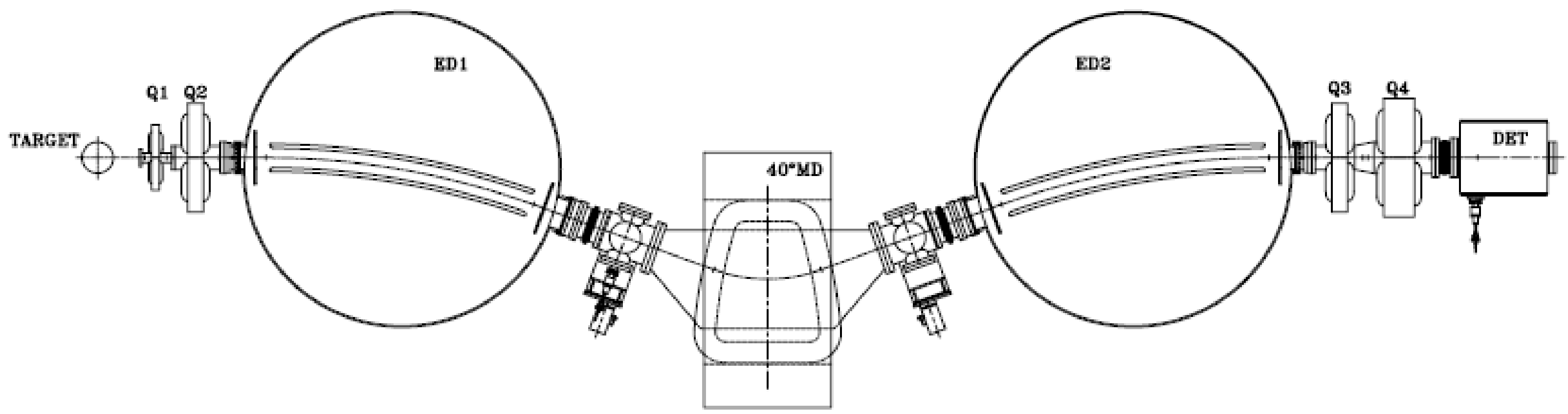


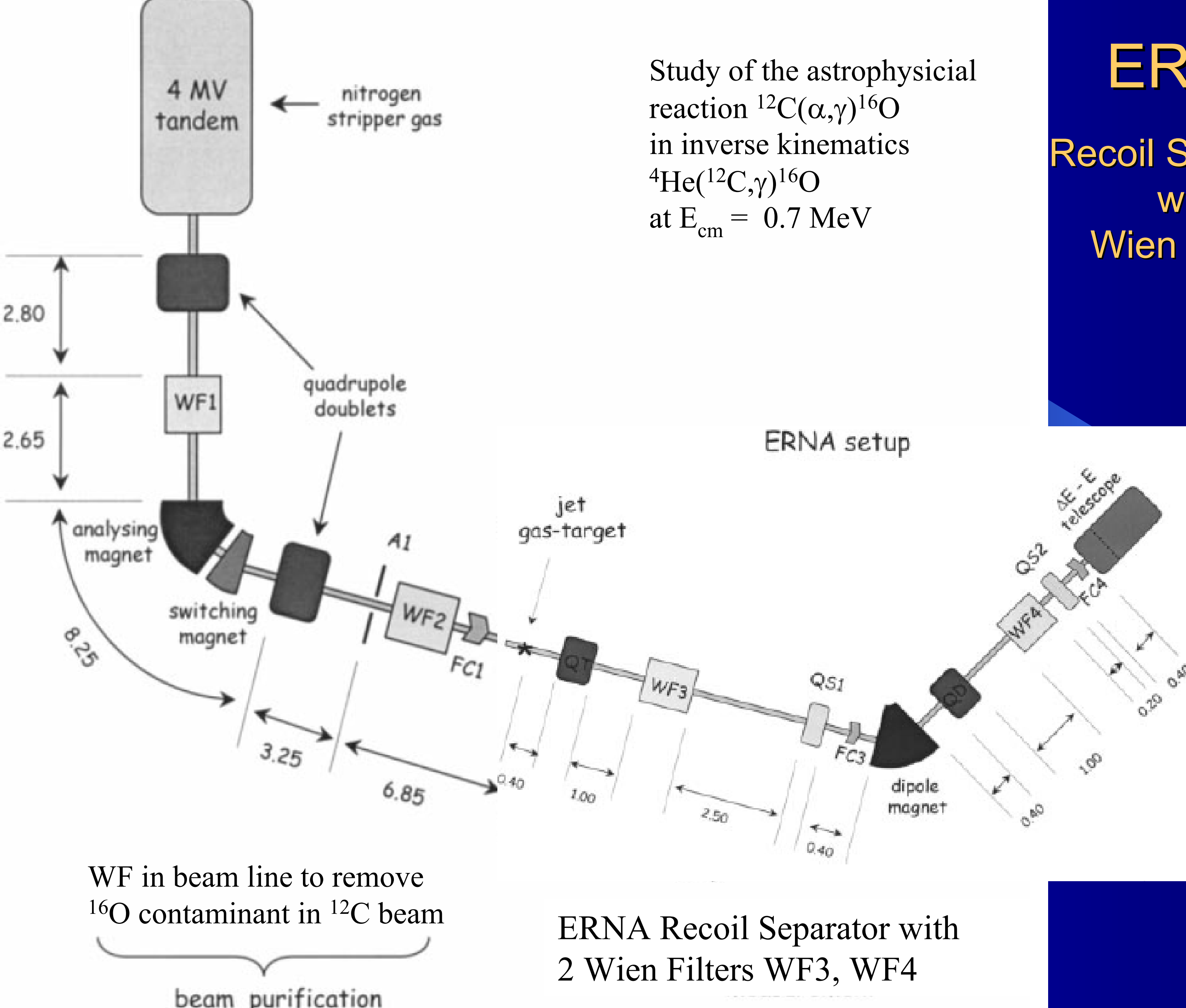
Fig. 1. Schematic view of EMMA, showing the target, quadrupole and dipole magnets, and electric dipoles. The detector box is also indicated.

B. Davids, TRIUMF &
C. Davids, ANL

ERNA

Recoil Separator with Wien Filters

Study of the astrophysicial reaction $^{12}C(\alpha,\gamma)^{16}O$ in inverse kinematics $^{4}He(^{12}C,\gamma)^{16}O$ at E_{cm} = 0.7 MeV



WF in beam line to remove ^{16}O contaminant in ^{12}C beam

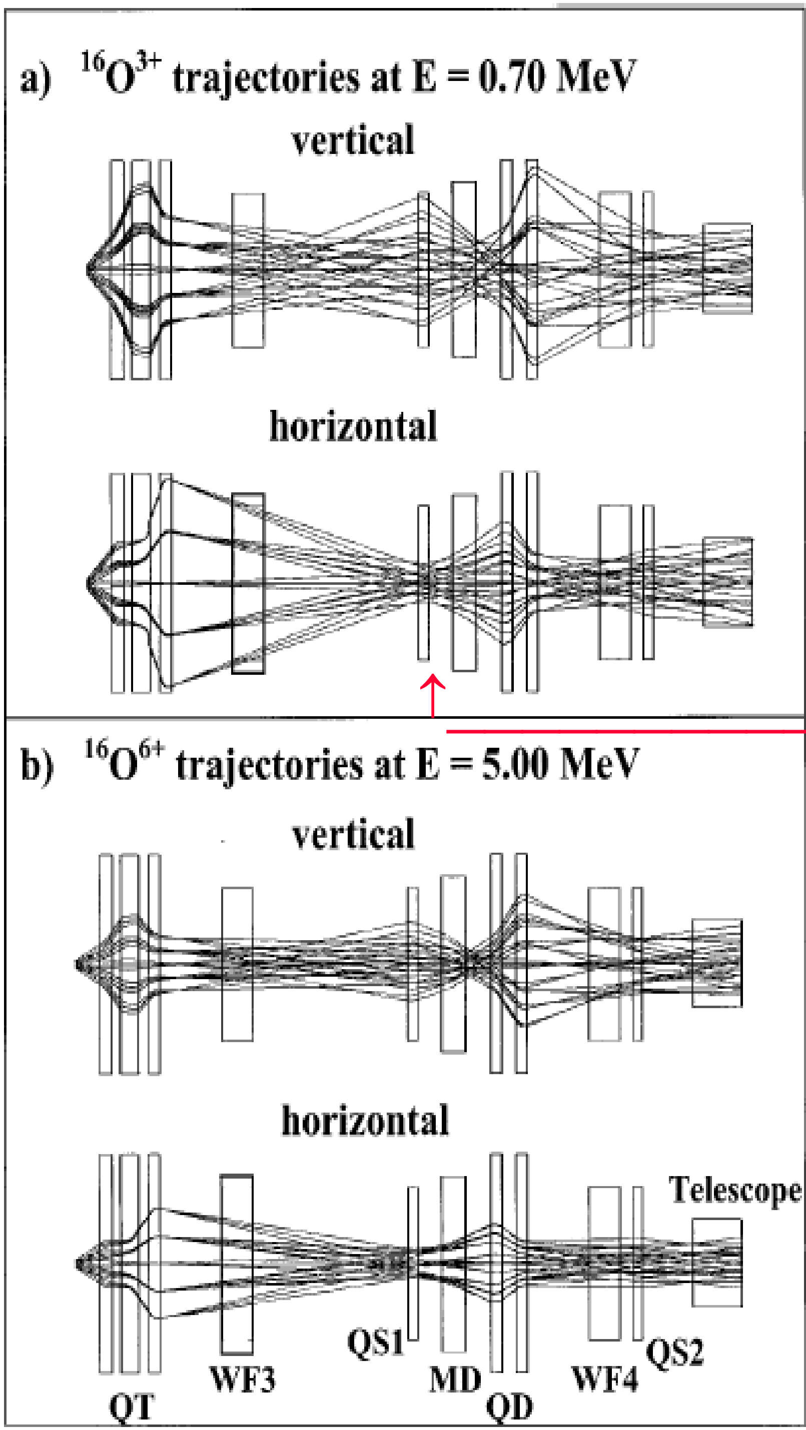
ERNA Recoil Separator with 2 Wien Filters WF3, WF4

ERNA

Recoil Separator with Wien Filters

Ion-optics of
^{16}O 3^+ and 6^+ ions

3^{rd} order calculations using
COSY Infinity



^{12}C beam mainly stopped in Faraday cup between QS1 and MD

Fig. 2. Samples of ^{16}O trajectories are shown for (a) E = 0.70 MeV ($q_0 = 3^+$, $\theta_{max} = 1.9°$, ΔE = 0.13 MeV) and (b) E = 5.0 MeV ($q_0 = 6^+$, $\theta_{max} = 1.0°$, ΔE = 0.44 MeV). The trajectories start at the jet gas-target (^4He target density = 1×10^{18} atoms/cm^2) and are followed through the filtering and focusing elements of ERNA (indicated by square boxes) up to the telescope (WF = Wien filter, QS = quadrupole singlet, QD = quadrupole doublet, QT = quadrupole triplet, MD = magnetic dipole)

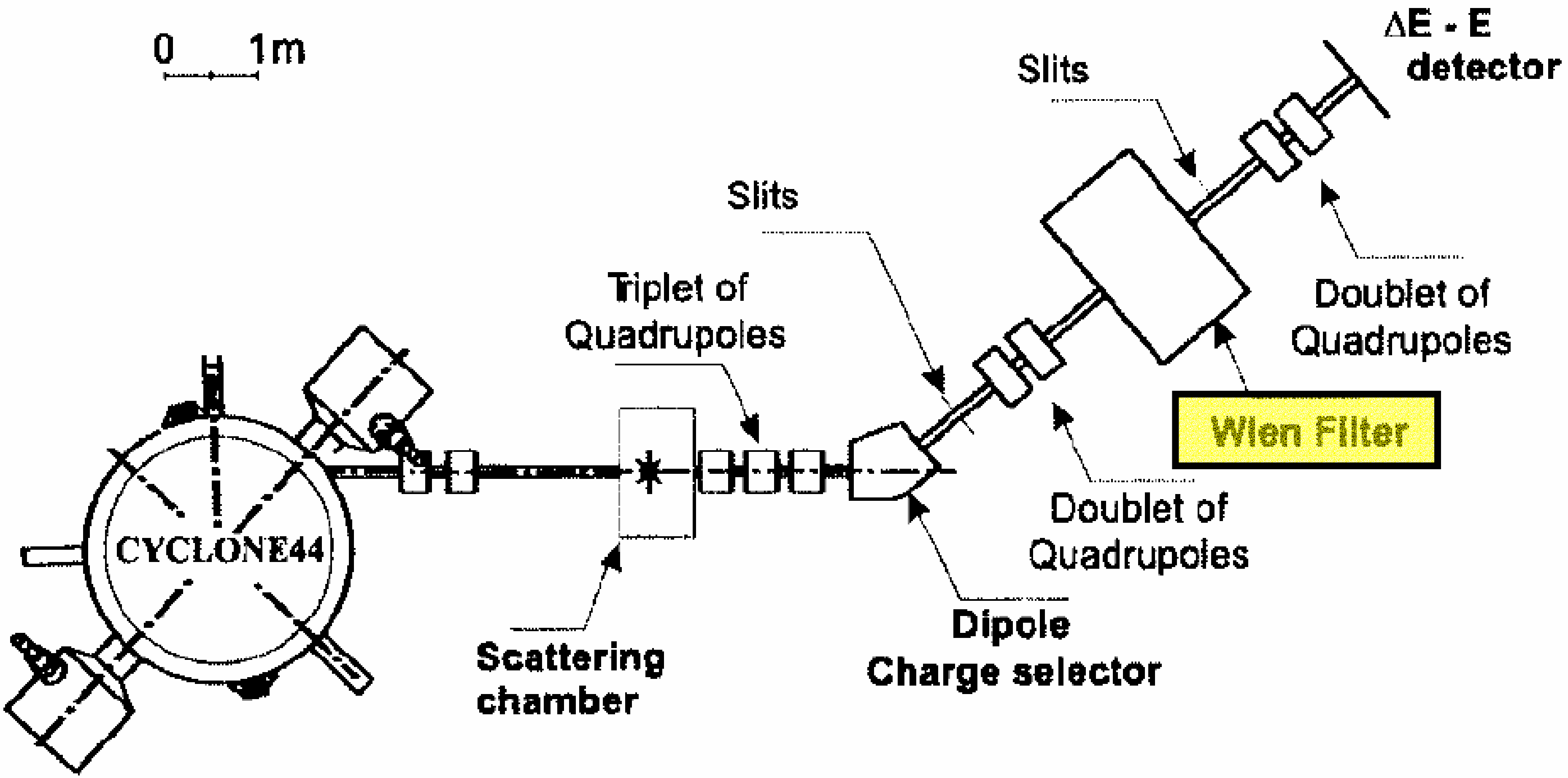
Study of astrophyscis reactions using radioctive beams.

ARES

Recoil Separator with a Wien Filter

Example: Hot CNO breakout reaction $^{19}Ne(p,\gamma)^{20}Na$ in inverse kinematics using a radioactive ^{19}Ne beam of 10.1 MeV

Ref. M. Couder, PhD Thesis July 2004, Louvain-La-Neuve



Achromatic magnet separator

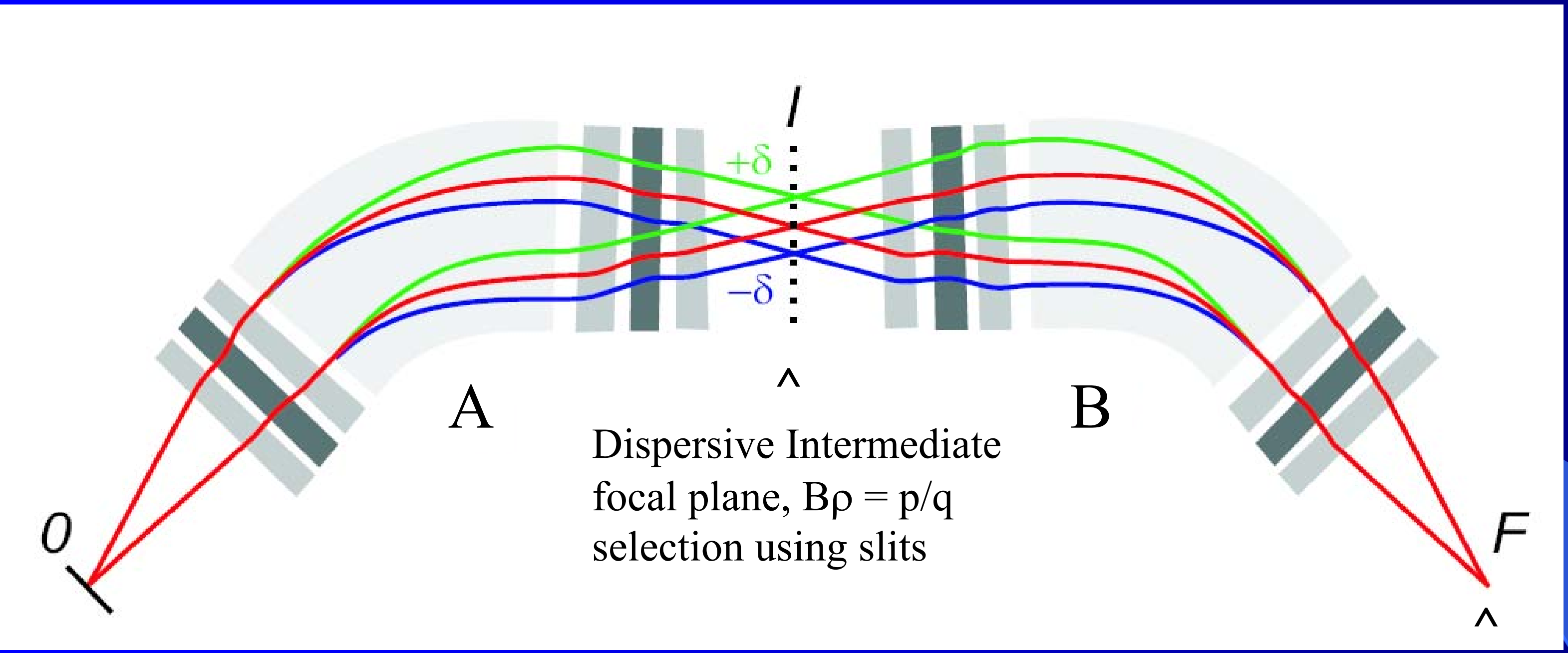


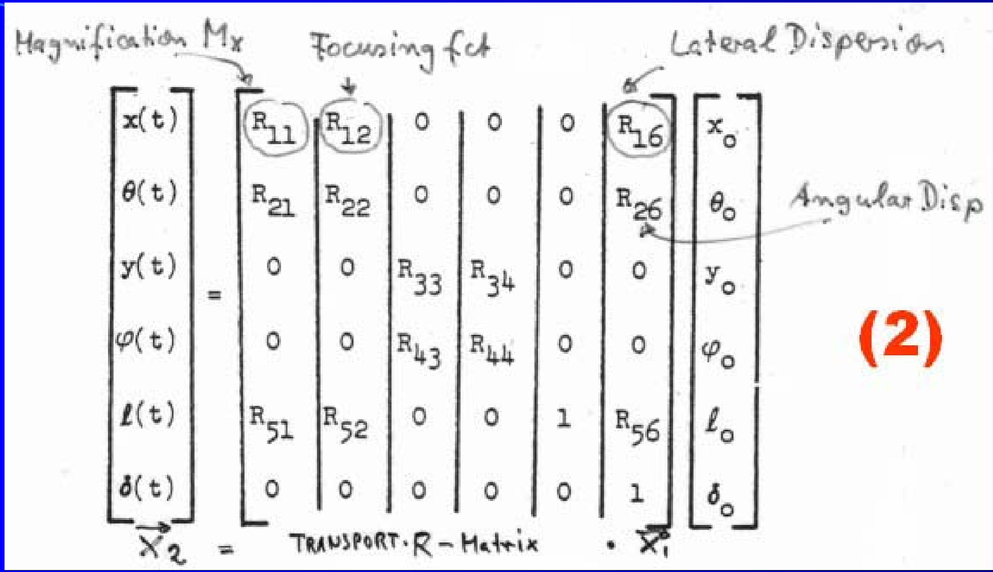
Figure from Experimental Techniques at NSCL, MSU, Th. Baumann, 8/2/2002

Achromatic Final focal plane, small beam spot e.g. for detector system

Exercise 4:

Assume foci at I & F, i.e. $A_{12} = B_{12} = 0$. Derive the first order achromatic condition of the system 0 → F and compare with the dispersion matching condition.

First order TRANSPORT Matrix $R_{\mu\nu}$



(2)

Solution of Exercise 4

$$x_I = A_{11}\, x_0 + A_{12}\, \theta_0 + A_{16}\, \delta_0 \qquad | \, A_{12} = 0$$

$$= A_{11}\, x_0 + A_{16}\, \delta_0 \qquad \textbf{(33)}$$

$$x_F = B_{11}\, x_I + B_{12}\, \theta_I + B_{16}\, \delta_0 \qquad | \, B_{12} = 0$$

$$= B_{11}\, x_I + B_{16}\, \delta_0 \qquad | \text{ substitute } x_I \text{ using } \textbf{(33)}$$

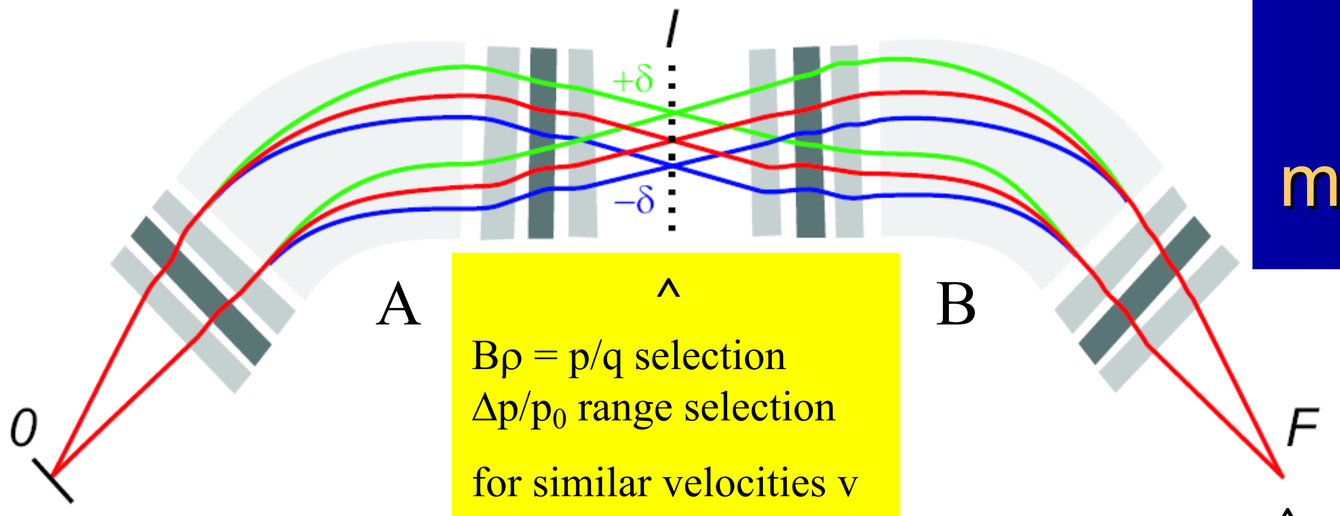
$$= B_{11}\, (A_{11}\, x_0 + A_{16}\, \delta_0) + B_{16}\, \delta_0$$

$$= B_{11}\, A_{11}\, x_0 + (B_{11}\, A_{16} + B_{16}\,)\, \delta_0$$

Condition for achromaticity: $A_{16} = - B_{16} / B_{11}$

Note: This is the Dispersion Matching condition for C = T = 1

Achromatic magnet separator

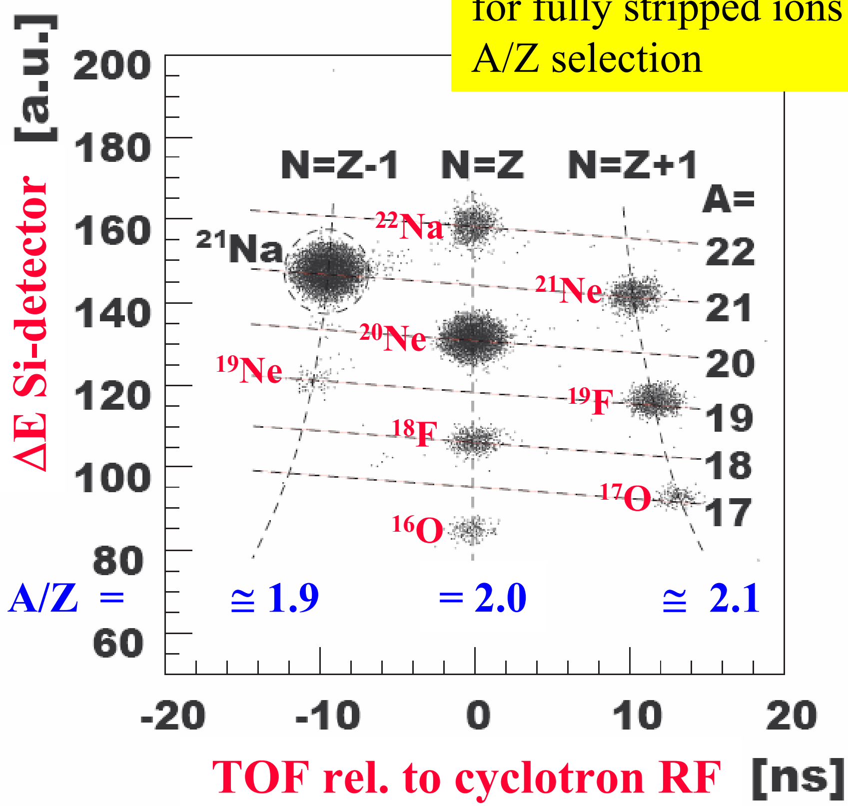


Bρ = p/q selection
$\Delta p/p_0$ range selection

for similar velocities v
m/q selection,

for fully stripped ions
A/Z selection

0.1 mm **ΔE Si-detector**
20 mm diameter



Example: Production of ^{21}Na via H(^{21}Ne,n)^{21}Na with ^{21}Ne^{7+} beam at 43MeV/nucleon using the TRIμP Separator, KVI Groningen
Ions after target fully stripped e.g. ^{21}Ne^{10+} !

^{21}Ne beam with ≅ 10^{10} ions/s with Bρ(^{21}Ne)/ Bρ(^{21}Na) ≅ 1.09 is all but eliminated by a slit (SH2) in front of plane I

Note:

Ions with A/Z ~ 2 are not separated !

Achromatic magnet separator with Wedge

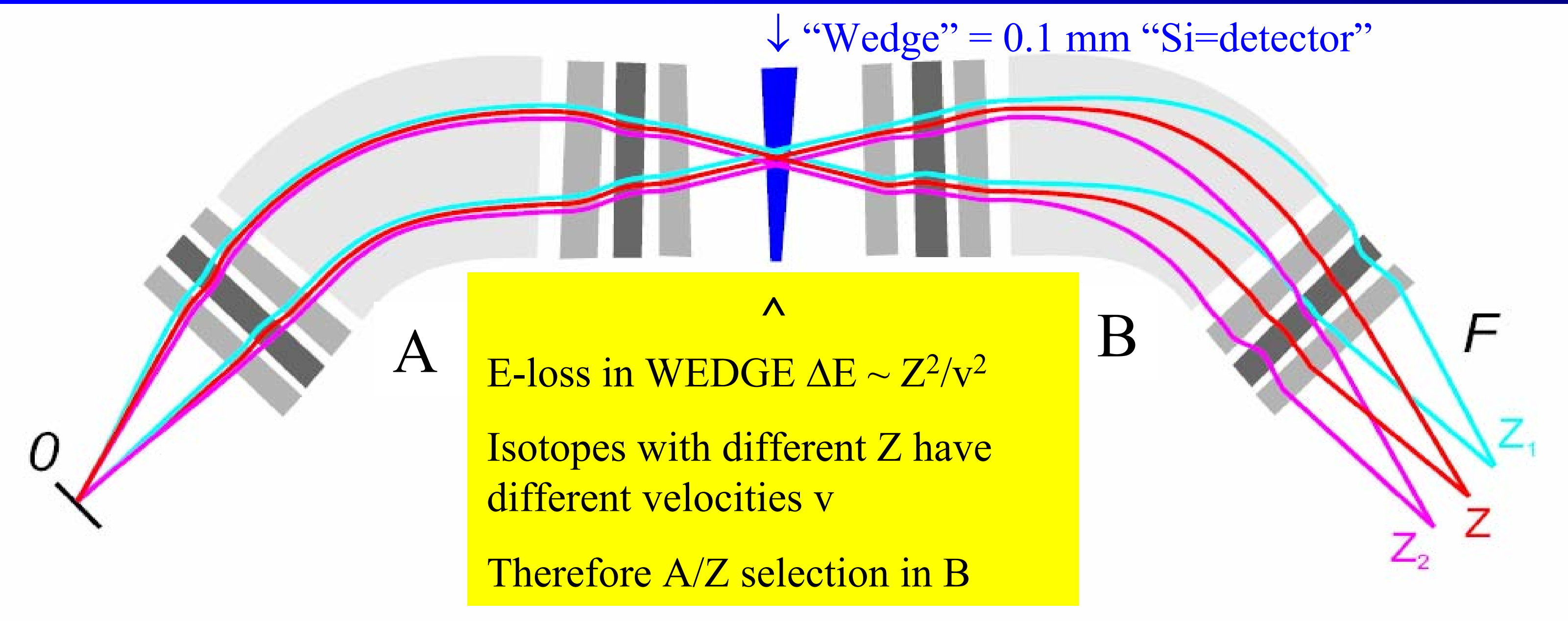
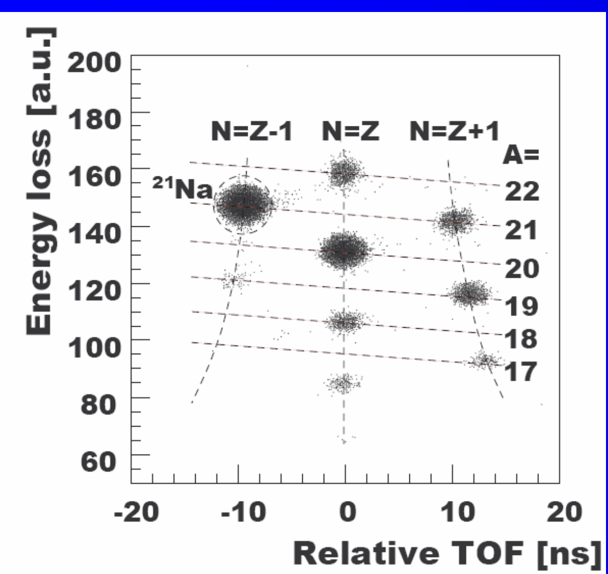


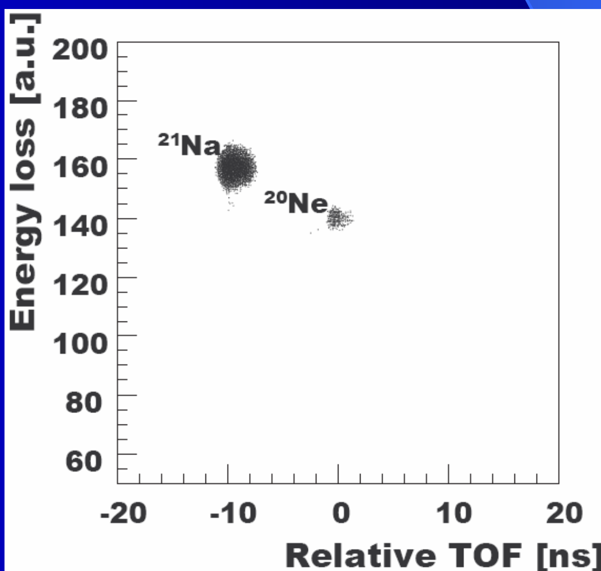
Figure from Experimental Techniques at NSCL, MSU, Th. Baumann, 8/2/2002



Effect of "Wedge" ⇒

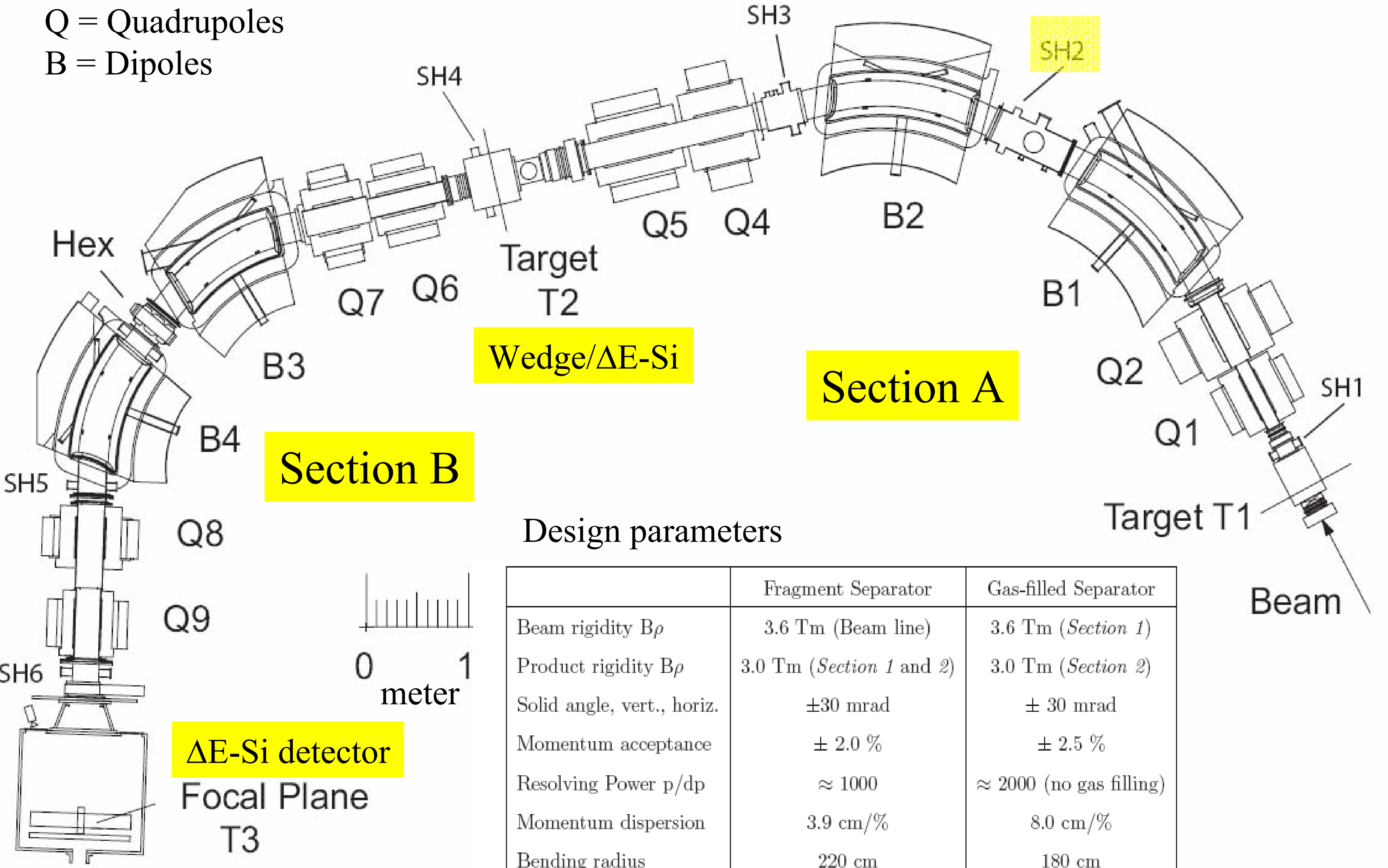
Note:

For large dp/p) the degrader should be Wedge-shaped to restore achromaticity effected by degrader with constant thickness



TRIμP an achromatic secondary beam separator

SH = Slits
Q = Quadrupoles
B = Dipoles



Design parameters

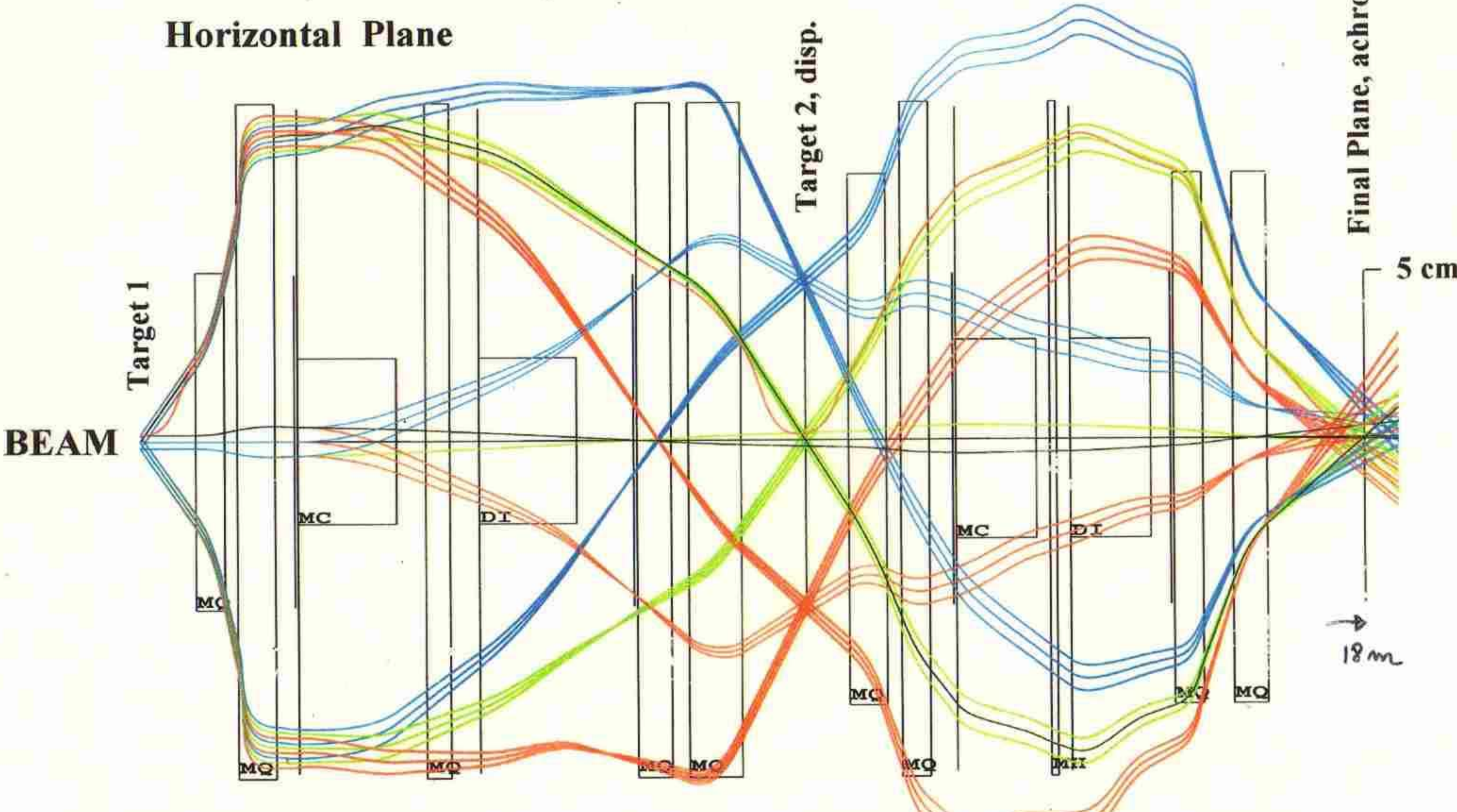
	Fragment Separator	Gas-filled Separator
Beam rigidity $B\rho$	3.6 Tm (Beam line)	3.6 Tm (*Section 1*)
Product rigidity $B\rho$	3.0 Tm (*Section 1* and *2*)	3.0 Tm (*Section 2*)
Solid angle, vert., horiz.	±30 mrad	± 30 mrad
Momentum acceptance	± 2.0 %	± 2.5 %
Resolving Power p/dp	≈ 1000	≈ 2000 (no gas filling)
Momentum dispersion	3.9 cm/%	8.0 cm/%
Bending radius	220 cm	180 cm

TRIμP ion-optics

TRIμP Fragment Separator

3rd order COSY Infinity Calculation

Horizontal Plane



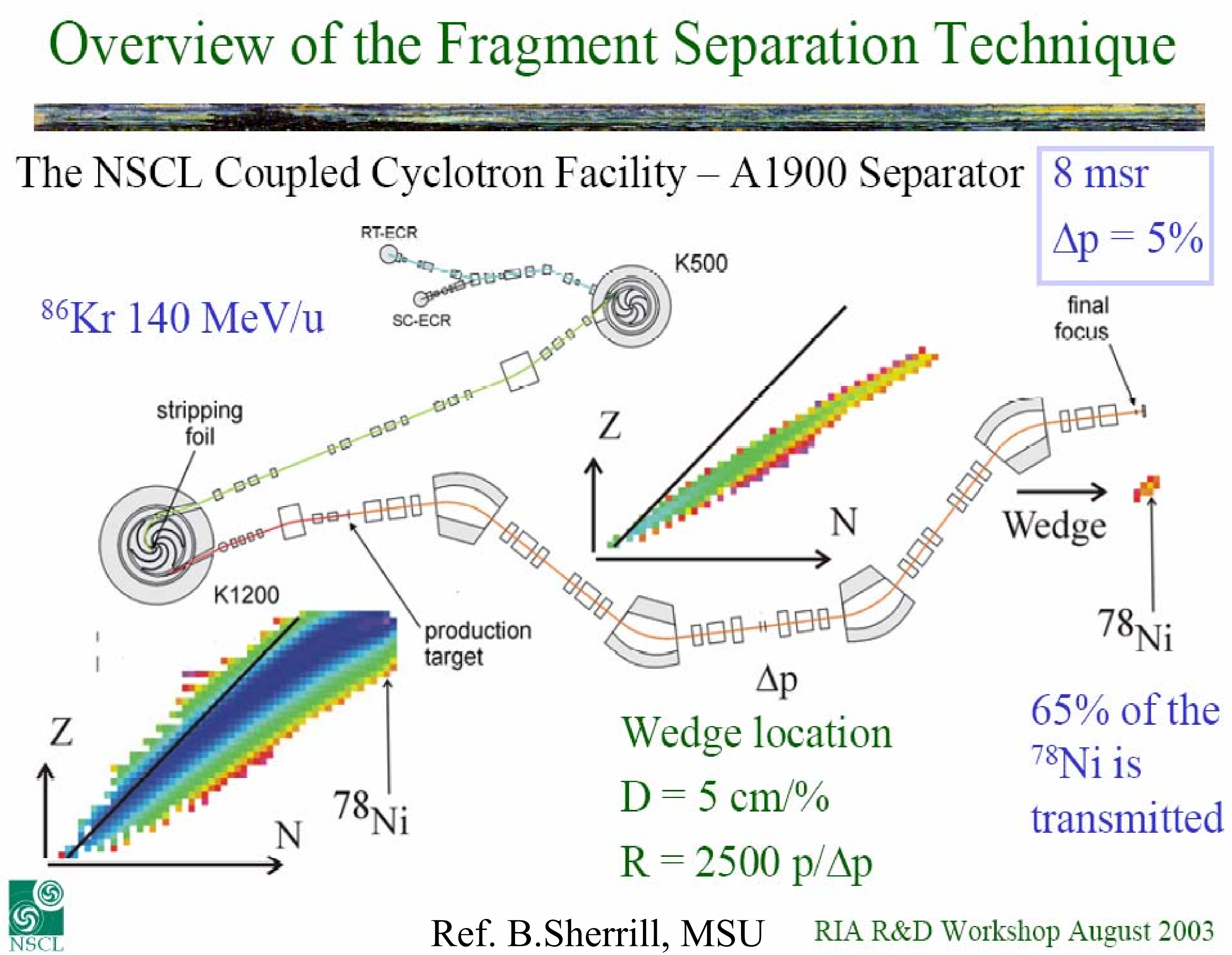
Ray Definitions at Target

x = +/- 2 mm

θ = +/- 30 mrad

dp = +/- 2.5 %

A1900 MSU/NSCL Fragment Separator

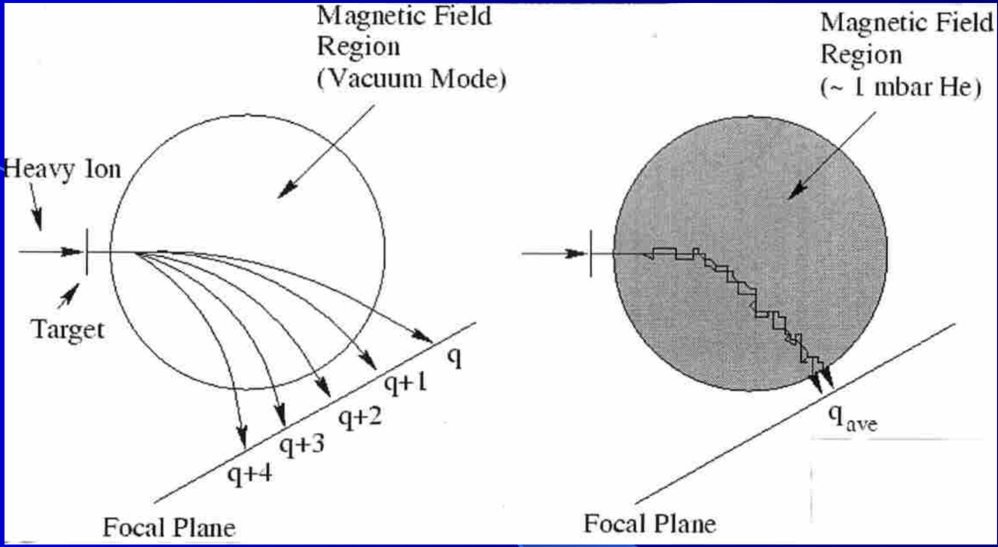


Ref. B.Sherrill, MSU

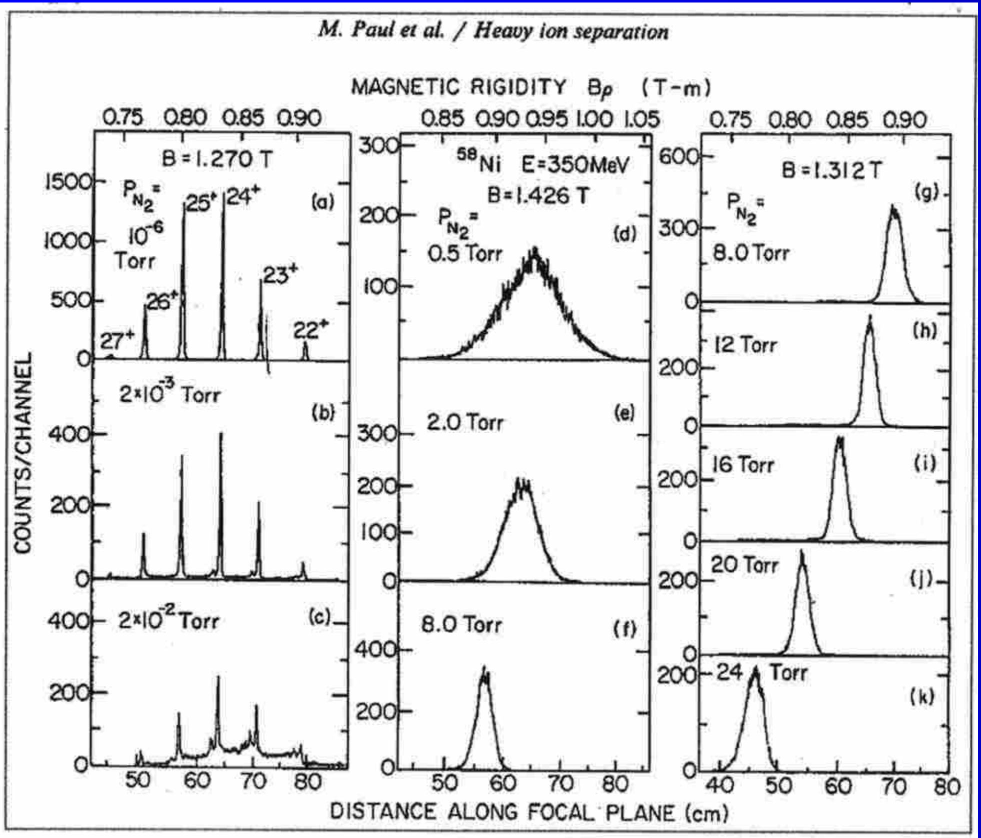
Gas-filled separators Concept

PROBLEM: After target, a distribution of several charge states q exists for low E or large Z, with Bρ range typically larger than acceptance causing transmission losses.

REMEDY: gas-filled separator



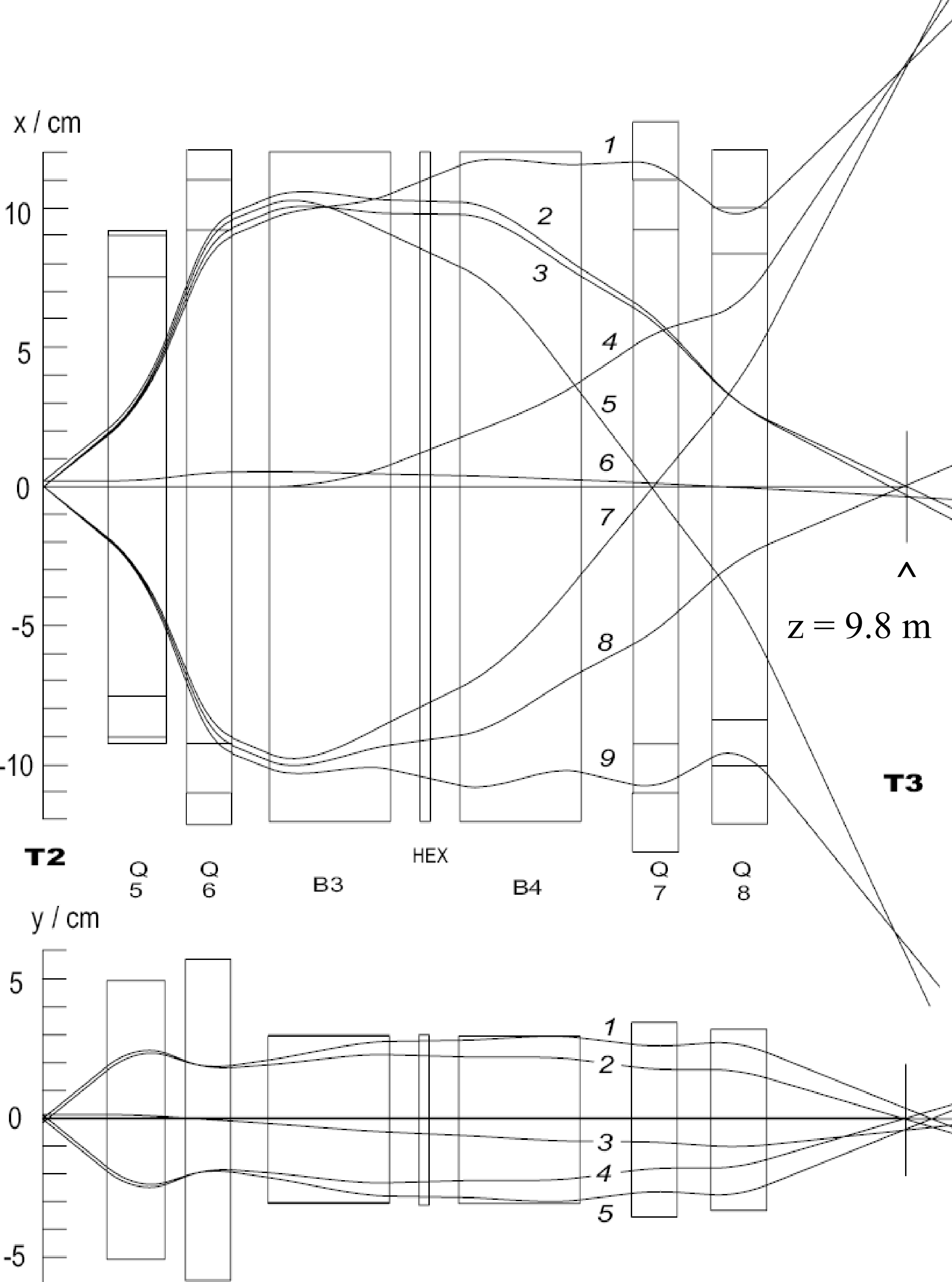
Rays in a magn. dipole field without and with gas-filling



Measured spectra as function of gas pressure (e.g. He, Ar)

M. Paul et al. NIM A 277 (1989) 418

TRIμP ion-optics Section B



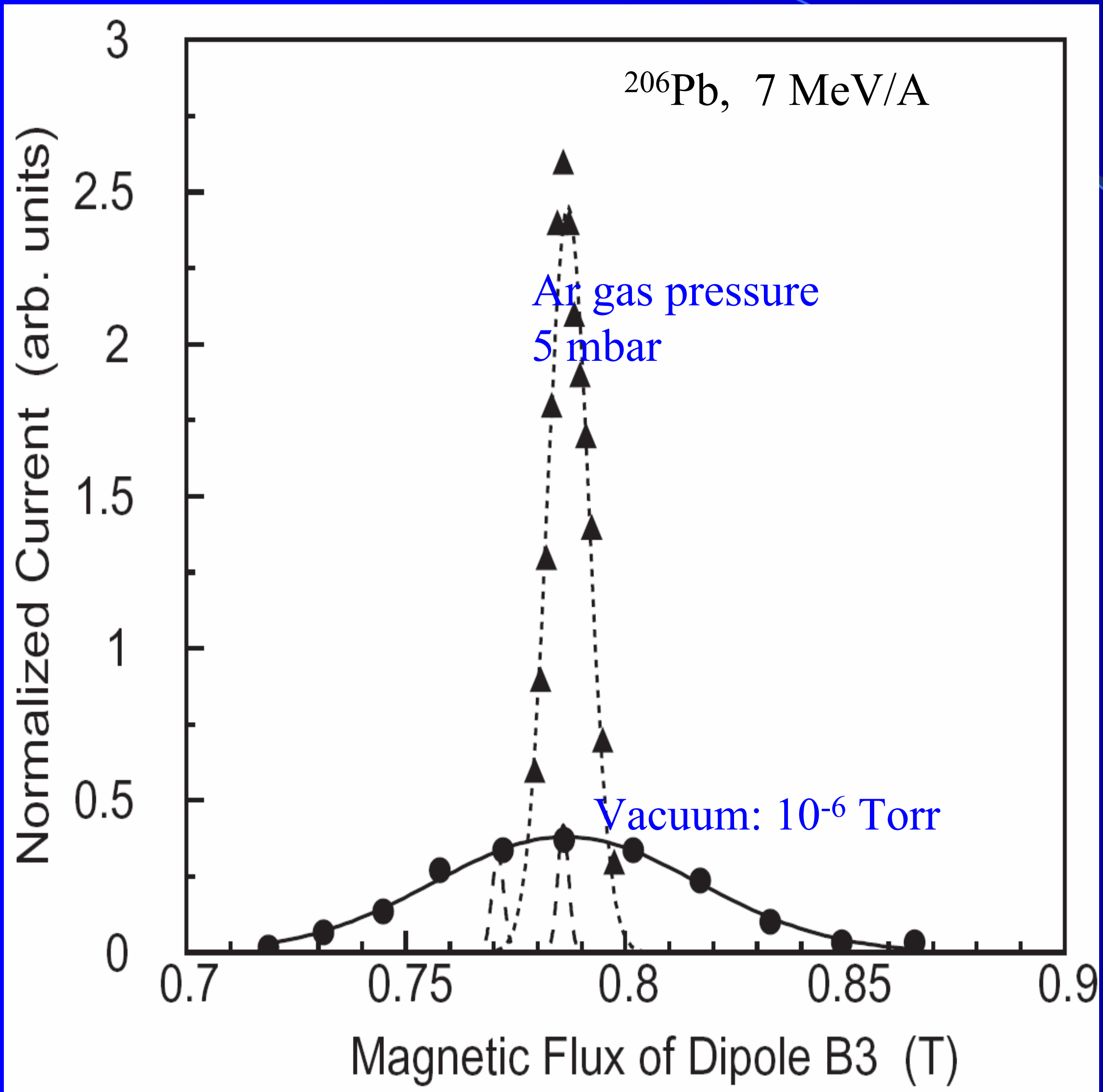
A "long" achromatic separator system is not suitable for a gas-filled separator that should be "short" to reduce statistical E spread and have "large dispersion"

ray	x [mm]	Θ [mrad]	ΔE/E [%]	y [mm]	Φ [mrad]
1	0	30	4.0	-1.5	30
2	2	30	0	0	30
3	0	30	0	1.5	0
4	0	0	4.0	0	-30
5	0	30	-4.0	1.5	-30
6	2	0	0		
7	0	-30	4.0		
8	0	-30	0		
9	0	-30	-4.0		

Therefore:

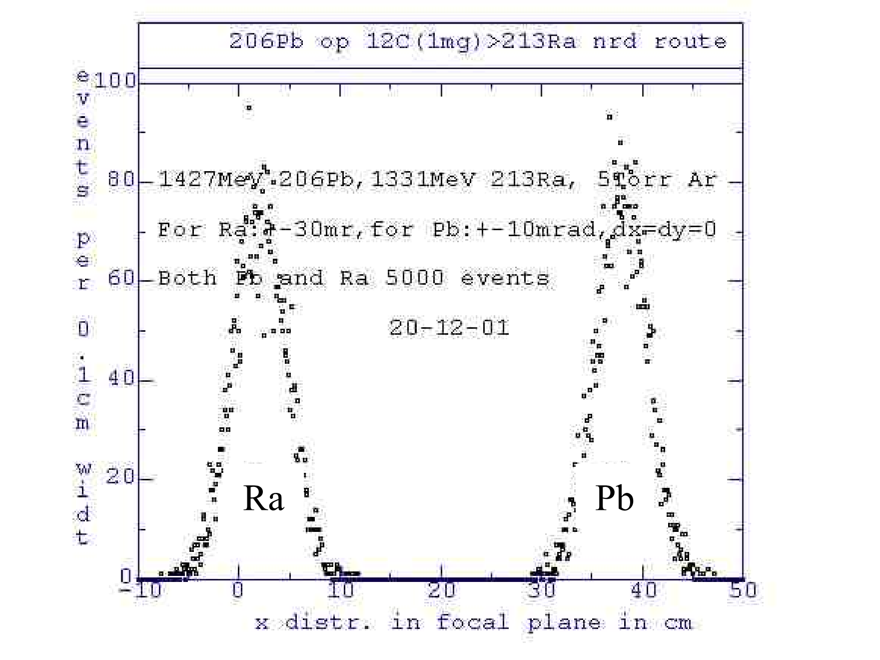
The TRIμP separator was Designed to be able operate with Section A as beam line & Section B as short gas-filled separator with large dispersion

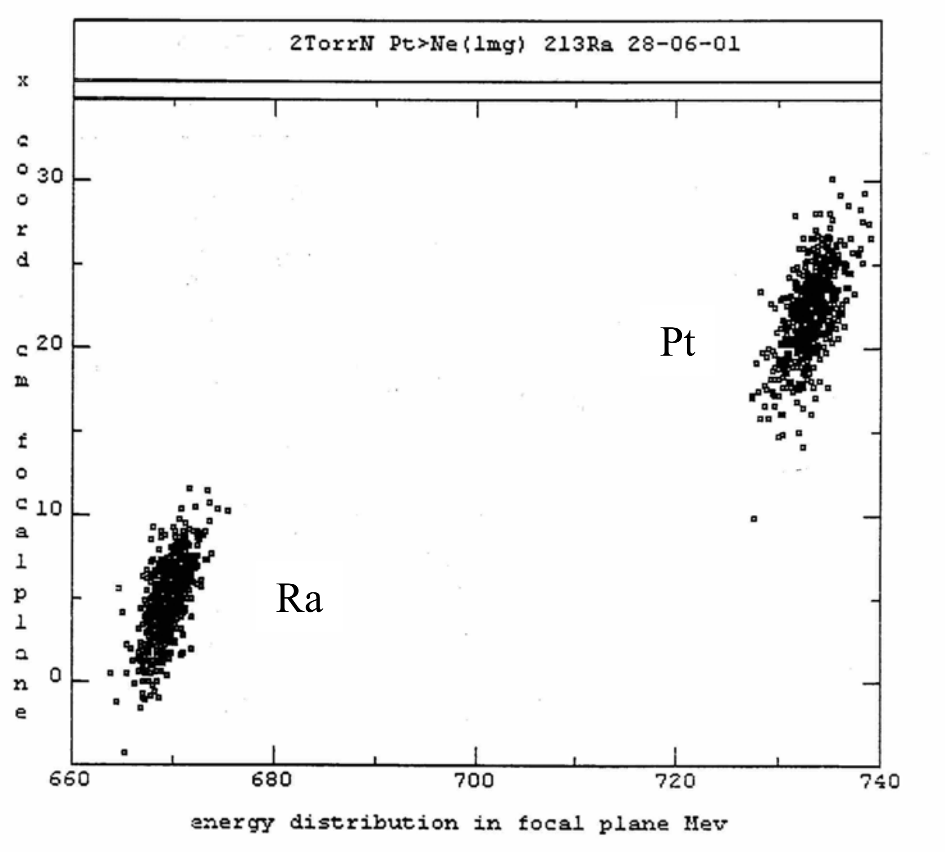
Charge state distribution in TRIμP separator with gas-filling



RAYTRACE
with gas-filling

Modified RAYTRACE code used to calculate the separation of beam to demonstrate particle and beam separation in the TRIµP separator in Gas-Filled Mode





Recoil Separator St. George

Study of (α,γ) and (p, γ) of astrophysics importance,
for A < ≈ 40 targets,
emphasis on low energies, i.e. very small cross sections,
max. energy given by KN

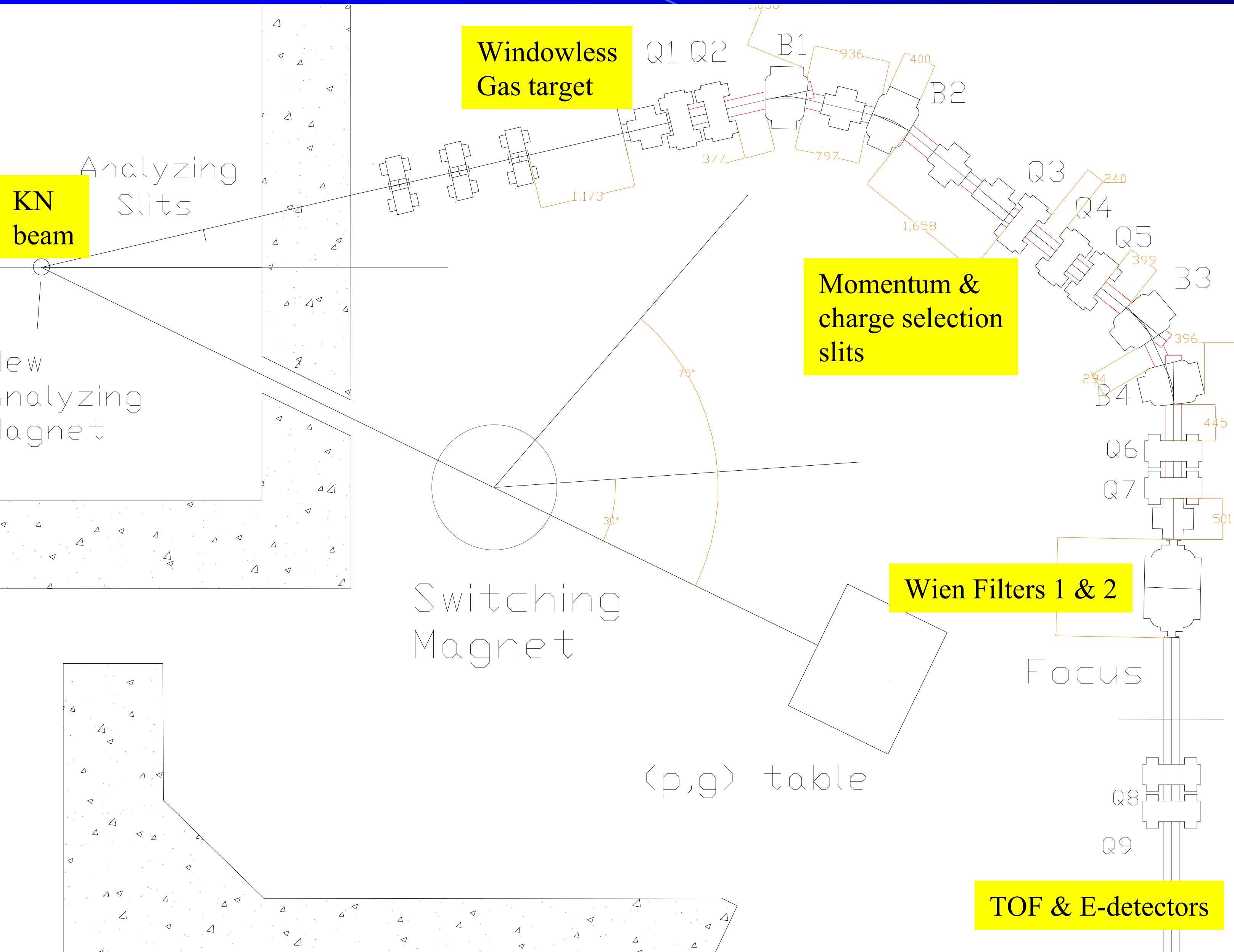
An overview of reaction result in the following
DESIGN PARAMETERS

Maximum magnetic rigidity Bρ:	0.45 Tm
Minimum magnetic rigidity Bρ:	0.10 Tm
Momentum acceptance dp:	+/- 3.7 %
Angle acceptance, horiz & vert.:	+/- 40 mrad

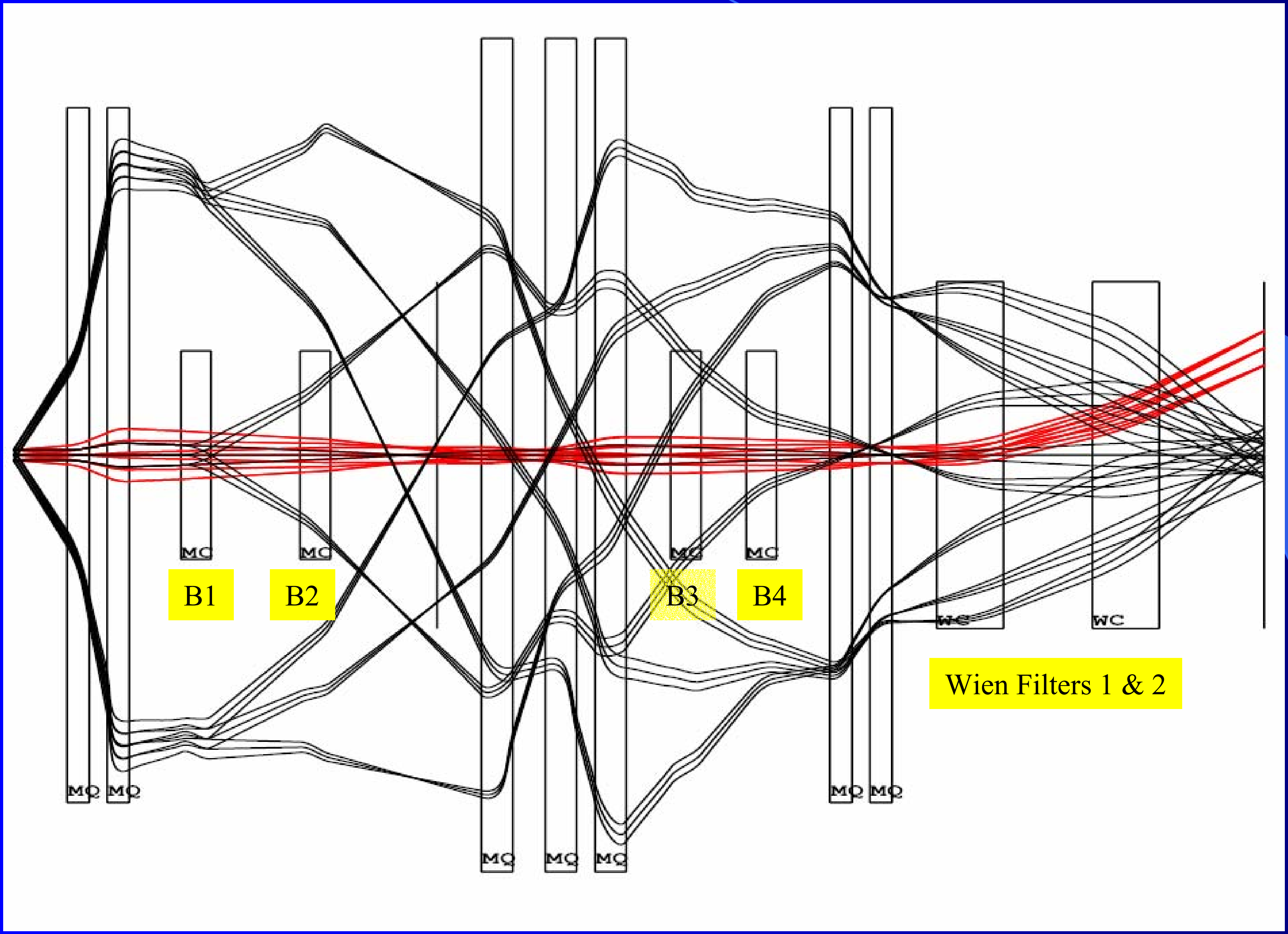
Further design considerations:
- Two phase construction
- Charge selection by Bρ analysis (typical: 50% Transmission)
- High mass resolution (Δm/m ≅ 200, 1st phase with 2 Wien Filters)
- Higher mass resolution (Δm/m ≅ 600) 2nd phase
- Wien Filters for mass resolution (energy too low for "Wedge" method

Schematic Floorplan St. George

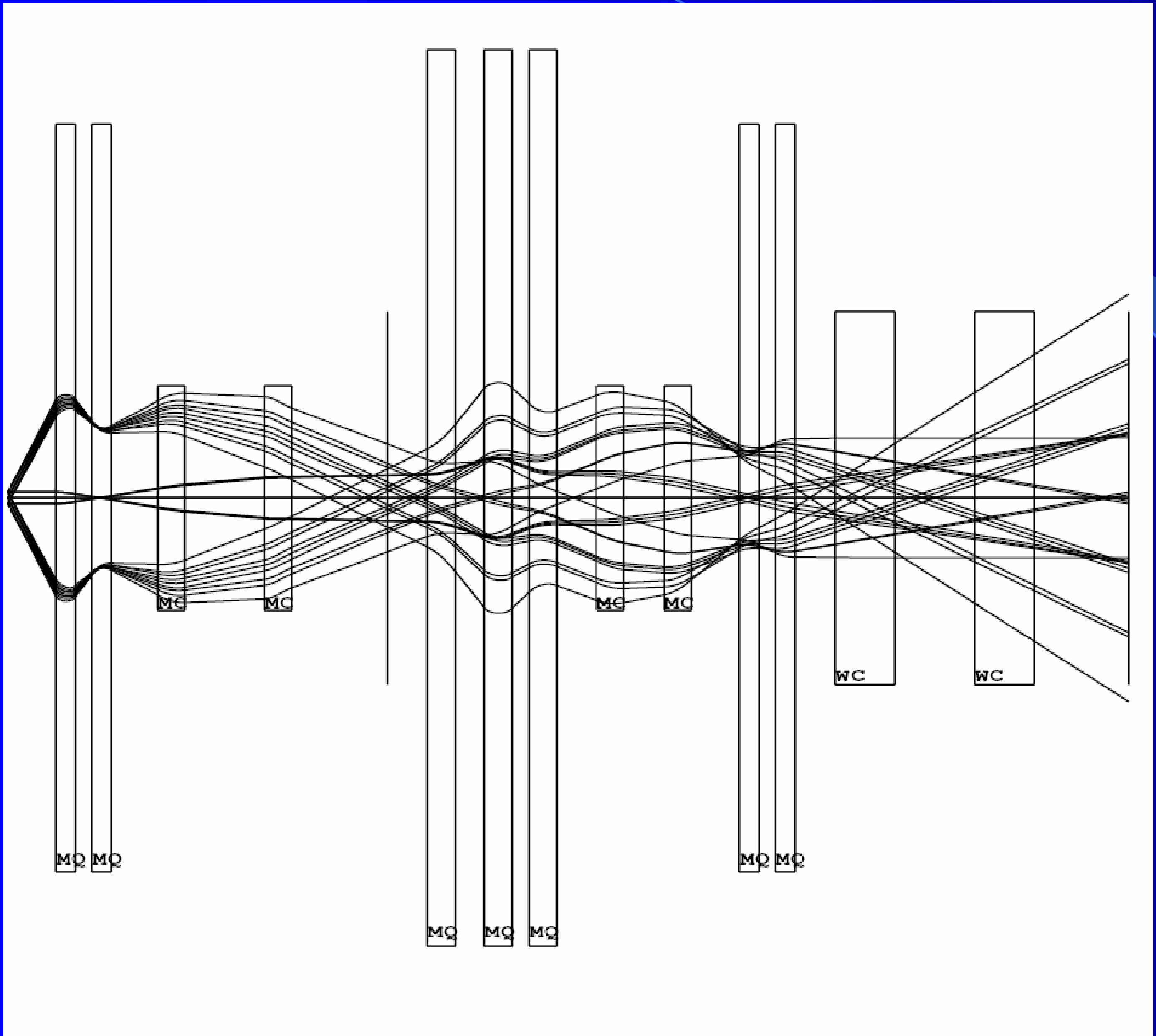
Phase 1



Horizontal ion-optics St. George

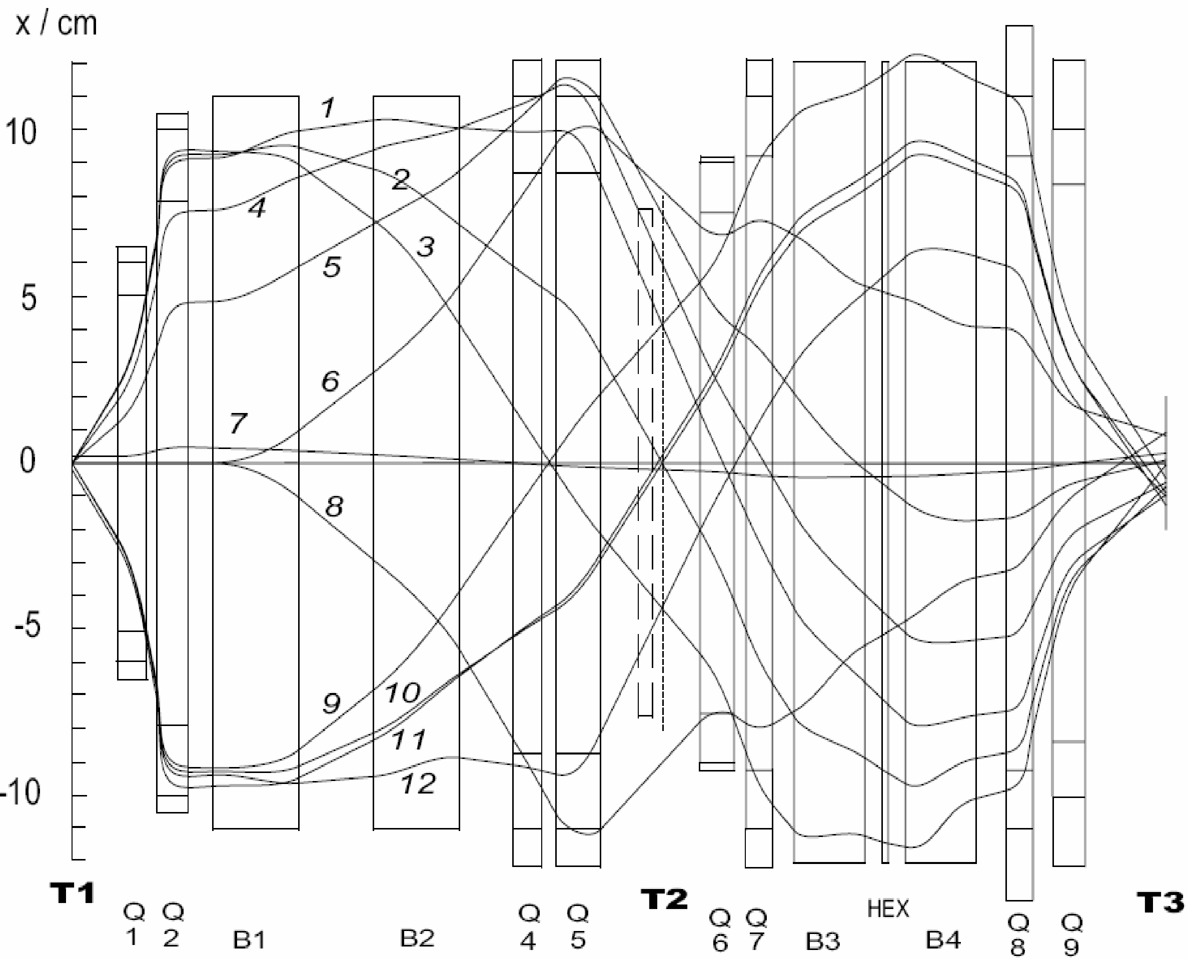


Vertical ion-optics St. George

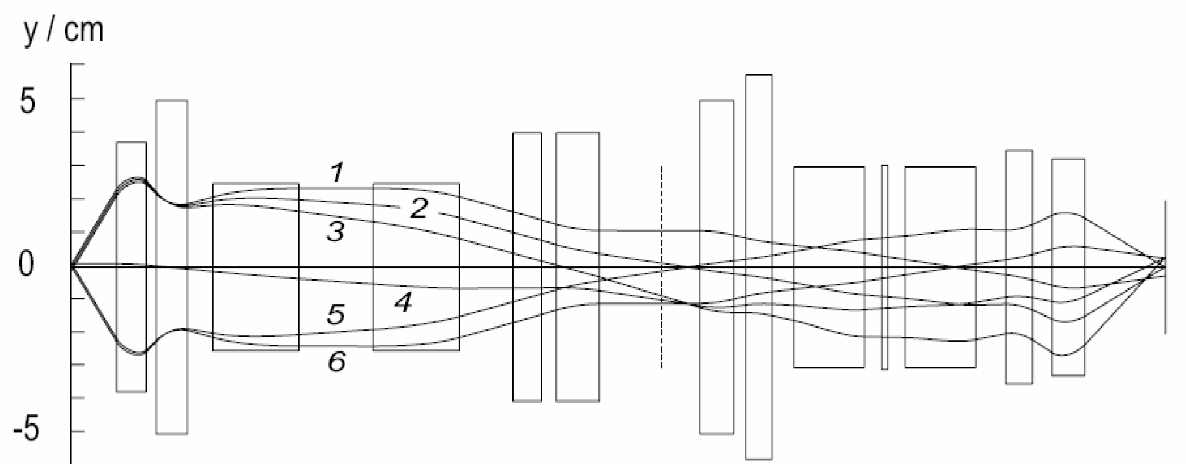


End Lecture 5

TRIμP ion-optics 1st & 2nd Section



ray	x [mm]	Θ [mrad]	ΔE/E [%]
1	0	30	2.2
2	0	30	0
3	0	30	-2.2
4	0	25	3.2
5	0	16	4.0
6	0	0	4.4
7	2	0	0
8	0	0	-4.4
9	0	-30	2.2
10	0	-30	0
11	-2	-30	0
12	0	-30	-2.2



y [mm]	Φ [mrad]
-1	30
0	30
1	30
1	0
0	-30
1	-30