MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

L. THARP
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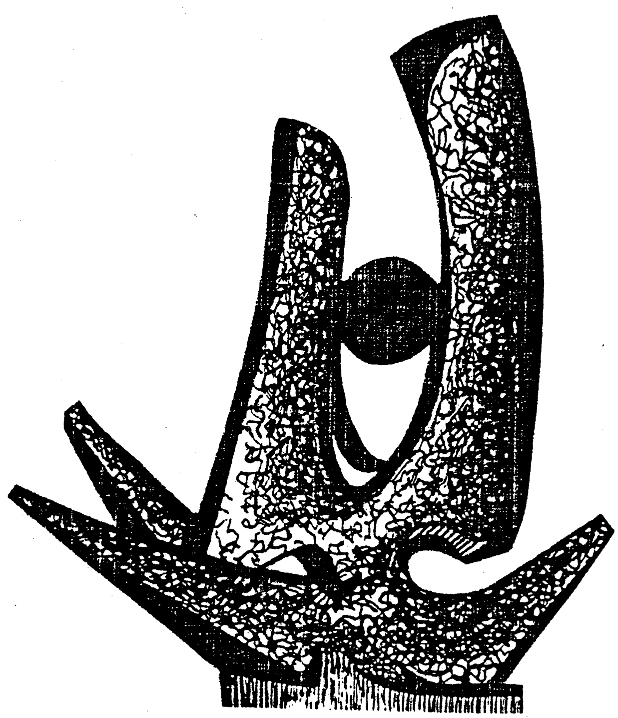
WORKSHOP ON PHASE II APPARATUS

NSCL, DECEMBER 1982



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CONTENTS

Workshop on Phase II Apparatus

Introduction

At the Workshop on Phase II devices held at NSCL on December 16 and 17, 1982, several possible types of apparatus were discussed. This report contains a description of four projects for which strong support emerged, viz. Streamer Chamber, Multiparticle Detector Array, Gamma-Ray Devices and Secondary Beams. The reports are meant to convey the scope of the discussions to prospective Users who were unable to attend the Workshop. No attempt has been made to make more final versions, since it is essential at this point to get additional User input. Other projects, eg. a Time Projection Chamber, were discussed at the Workshop, but were considered to be unfeasible. In these cases, write-ups are not included in the Report.

In addition to the above devices the Workshop identified a need for a very large Scattering Chamber and new electronics. Other Phase II Equipment, the S800 Magnetic Spectrometer, the Reaction Product Mass Separator and the Data Processing System have been discussed at previous workshops. Additions to the Data Processing Facility will be discussed at a future workshop.

The need for subnanosecond timing from the accelerator, and the desirability of multiple beams in Phase II were also stressed at the Workshop. The study of a Beam Buncher has begun, and the feasibility of beam sharing will be explored in the future. No cost estimates for these projects are available at this time.

The following table gives a tentative allocation of the Phase II funds within the total budget for Experimental Equipment and Data Processing of $4.945 Million.

		K$
Discussed Previously	Data Processing	1,095
	S800	1,940
	Reaction Product Mass Seperator	250
Discussed at Phase II Workshop	Electronics	450
	Large Walk in Vessel	100
	Secondary Beams	50
	Prototype Particle Multiplicty Modules	100
	Completed 4π Multiplicity Array	500
	Development of CCD System for Streamer Chamber (with a view to developing a full streamer chamber capability if additional money becomes available ≈500K)	60
	γ-ray Devices	150
For Future Discussion	Additions to Data Processing Facility	250
		$4,945K

Users who wish to participate in any of the above projects should inform NSCL as soon as possible. The following list gives the names of individuals who can provide more information on the projects.

Data Processing	W. Benenson	(517) 355-7432
S800 Spectrometer	J. Nolen	353-5957
Reaction Product Mass Separator	L. Harwood	355-1523
Large Walk In Chamber	G.K. Gelbke	(517) 355-4530
Secondary Beams	L. Harwood	355-1523
Charged Particle Multiplicity Array	G. Westfall	353-8727
Streamer Chamber	N. Anantaraman	353-5959
Gamma Ray Devices	D. Morrissey	355-9554
Beam Buncher	H. Blosser	355-9670
Multiple Beams	H. Blosser	355-9670

A Multi-particle Detector Array

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In recent years experiments have established the importance of measuring gamma rays, pions, neutrons, protons, light nuclear fragments (A<5), medium mass nuclear fragments (A<50), fission fragments, and projectile-like fragments resulting from the collisions of high energy nuclei. In addition it has been shown that experiments measuring one particle from each reaction suffer from integration over the unseen particles. Thus experimenters are beginning to build devices that can simultaneously detect many particles from each reaction such as the Plastic Ball/Plastic Wall of Gutbrod et. al. and HISS facility of Greiner et. al. These devices are designed to handle the reaction products observed from reactions at relatively high energies compared to the energies that will be available at NSCL. Specifically the Plastic Ball is designed to measure mainly light particles from 9 to 160 degrees with a lower energy cutoff of 35 MeV/nucleon. The Plastic Wall can handle projectile-like fragments as well as light particles, but only in the forward direction. The HISS facility handles projectile-like particles efficiently because of the kinematic focussing at high incident energies.

At NSCL energies it is important to study not only light particles and projectile-like fragments, but intermediate rapidity medium mass fragments, fission fragments, and neutrons. Therefore we have proposed here a device that is capable is simultaneously detecting most of the particles emerging from nuclear collisions occurring at energies available from the Phase II NSCL facility. The basic component of this device is the "logarithmic" detector. Its response is designed to increase logarithmically in stopping power with the range of penetration of the observed fragment. Thus fission fragments would be detected in thin front elements and highly energetic light particles would be observed using using thick range energy telescopes. This array of counters must have sufficient granularity to handle light particle multiplicities up to 50 with reasonable efficiency and slow, highly ionizing particles such as fission fragments with somewhat lower multiplicities of approximately 5.

We are proposing that this device be composed of 32 heavy fragment detectors each comprised of a Parallel Plate Avalanche Counter (PPAC) and a Bragg Curve Counter (BCC) and 180 calcium flouride-plastic scintillator telescopes covering 92% of the total solid angle. The heavy fragment detectors would be shaped as two concentric truncated icosahedrens having 20 regular hexagons and 12 regular pentagons as faces. The light particle telescopes would consist of triangular sections with six telescopes behind the hexagonal faces and five detectors backing the pentagonal faces. Each light particle telescope would contain a 2 mm thick calcium flouride delta-E detector backed by a 30 cm plastic scintillator E detector. Because the two scintillators have very different time constants, both can be read out with a single photo-multiplier tube as was done by Gutbrod et. al. in the Plastic Ball. One of the 32 modules is shown in Fig. 1. The PPAC is shown 15 cm from the target. This module is backed with six scintillator telescopes.

The BCC operates on the principle that stopping particles will have an increasing specific energy loss with increasing range until the equilibrium charge of the fragment begins to decrease causing the specific energy loss to reach a maximum at a value proportional to the atomic number of the fragment. The counter is designed such that the electric field is parallel to the direction of the fragment. The produced charge is drifted to a cathode protected by a Frisch grid as shown in Fig. 2a. The resulting charge is digitized using a flash encoder that integrates the charge in 100 nsec bins and produces the curve shown in Fig. 2b. The peak of this distribution can be related directly to the Z of the stopping fragment, the integral of the curve is the total fragment energy, and the range and plateau region provide information concerning the fragment mass number. If the fragment punches through the detector, the device functions as a simple ion chamber.

Plastic scintillator detectors have been contructed by Hasselquist et. al. in conjunction with a multi-wire proportional chamber that will serve both as a prototype for the multi-particle array as well as being used as a multi-particle jet detector for experiments at NSCL and LBL. The plastic scintillator detectors were calibrated at the Indiana University Cyclotron Facility using 150 MeV protons and a polyethylene target. Proton-proton elastic scattering coincidence measurements were used to vary the observed proton energies over a wide range for calibration. In Fig. 3 the % resolution is given for proton energies from 20 to 100 MeV. The resolution was found to range from 10% at 20 MeV to 1% at 100 MeV. A preliminary test has been carried out with the calcium flouride-plastic scintillator telescopes and the resolution was found to be adequate to resolve p,d, and t.

To get an idea of the dynamic ranges of the various particles detected by the apparatus, the energy loss for different regions of the counters, the energy loss of the particle in a given region versus the energy of the particle is given in Fig. 4. Here the energy losses are shown for the gas in the BCC and the calcium flouride. In Fig. 5 the proton energy losses are shown for higher energies with the protons penetrating the calcium flouride and the plastic scintillator. The protons punch through the entire detector system at 200 MeV. In Fig. 6 the energy losses for a 40Ca fragment are shown. The four curves correspond to losses in the windows of the PPAC, the entrance window of the BCC, and the gas of the BBC. One can see that a Ø.5 MeV/n 4ØCa fragment will just make it into the PPAC and a 1.Ø MeV/n 4ØCa fragment will just make it into the BCC.

An overall view of the multi-particle detector array is shown in Fig. 7. The array is depicted as layers beginning from the inside with PPACs, followed by BCCs, and backed by calcium flouride-plastic scintillator telescopes. The array is shown augmented with a forward particle array designed to detect projectile-like fragments. The forward angle system would consist of a superconducting dipole backed by a drift chamber array and a time-of-flight plastic scintillator wall.

Fig. 8 contains a summary of the characteristics of the array where the dynamic ranges, multiplicities, angular resolution, active area, data rate, and analysis rate are given.

In Fig. 9 estimated costs are given for all the proposed systems.

This report was prepared in collaboration with C.K. Gelbke, H. Stocker, and R. Tickle

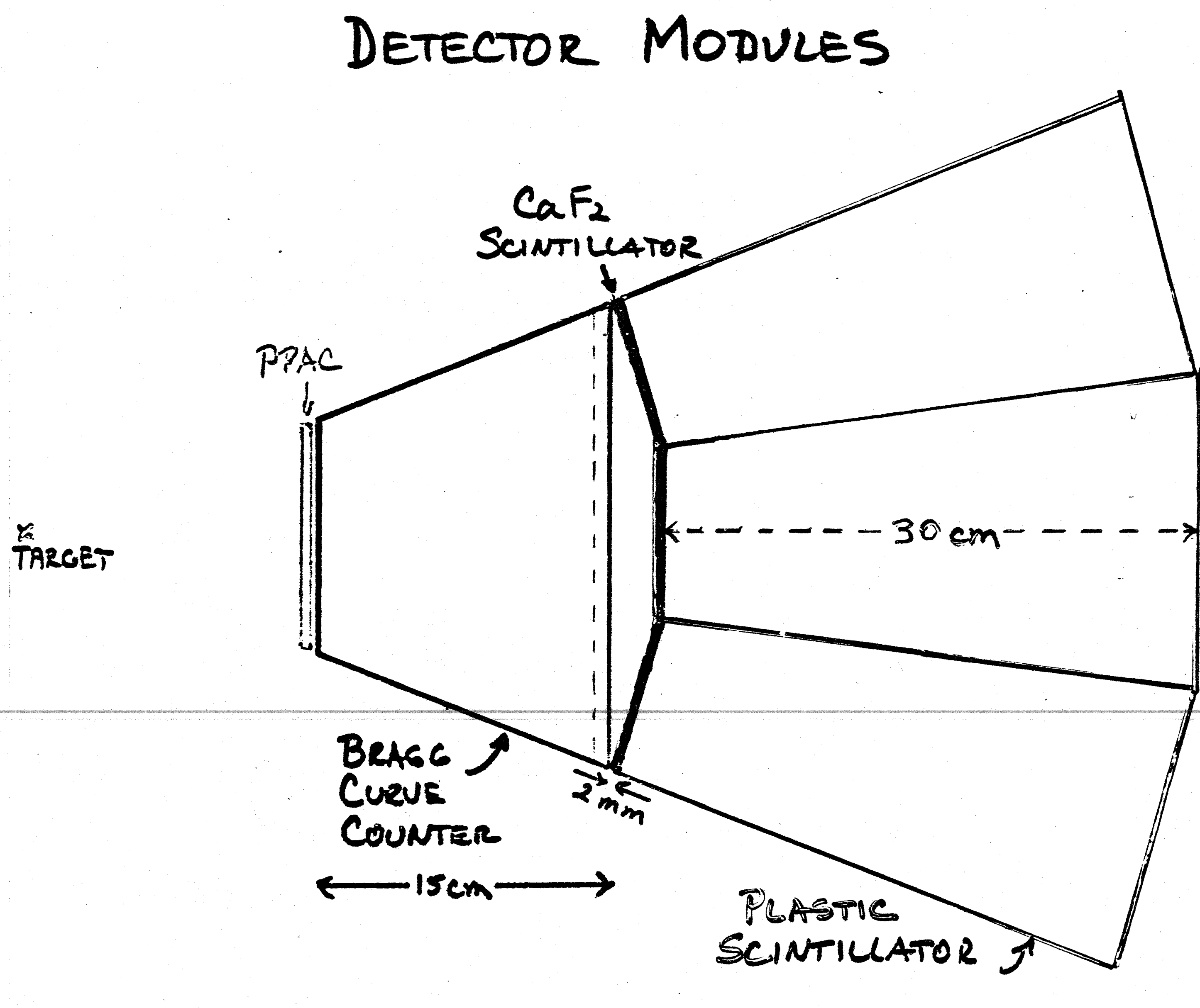
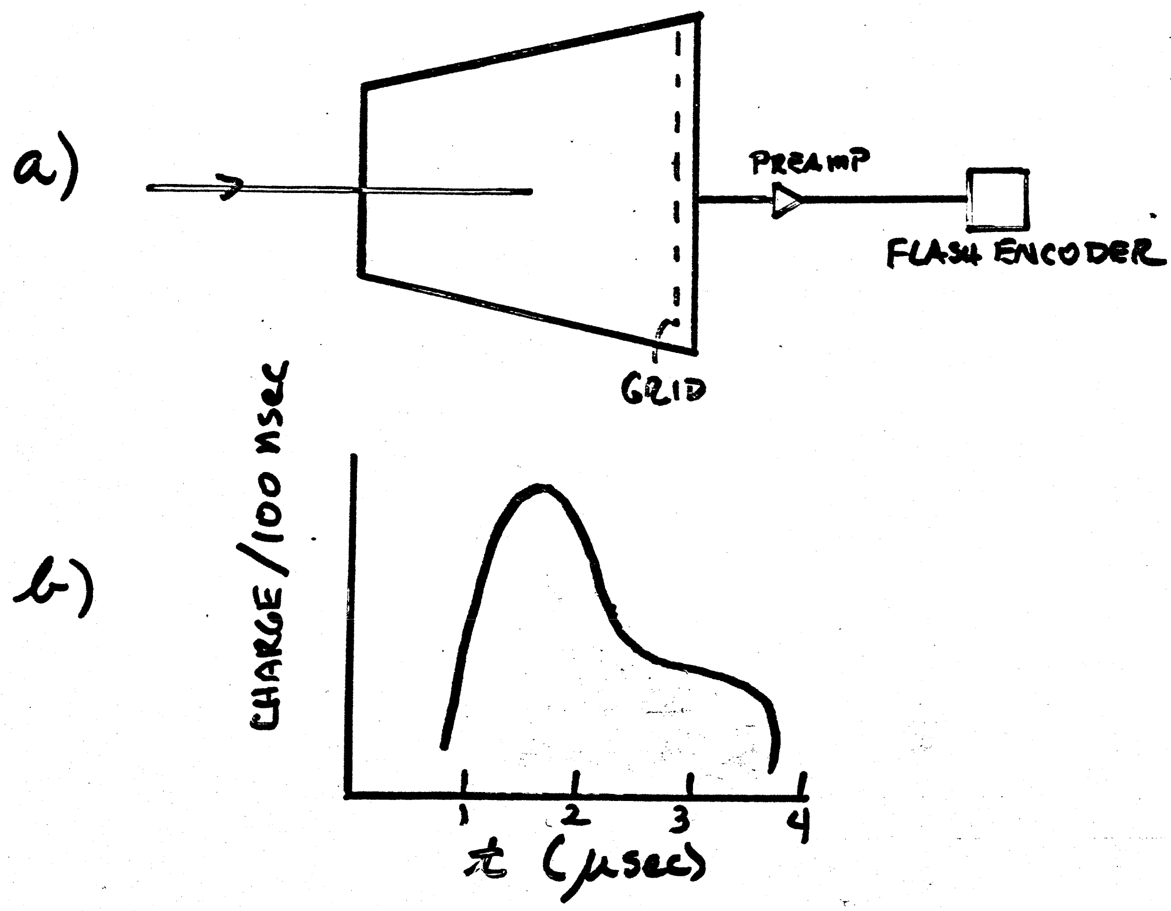

DETECTOR MODULES
CaF2 SCINTILLATOR
PPAC
TARGET
30 cm
BRAGG CURVE COUNTER
2 mm
15cm
PLASTIC SCINTILLATOR

Fig. 1

BRAGG CURVE SPECTROMETER



PEAK → Z

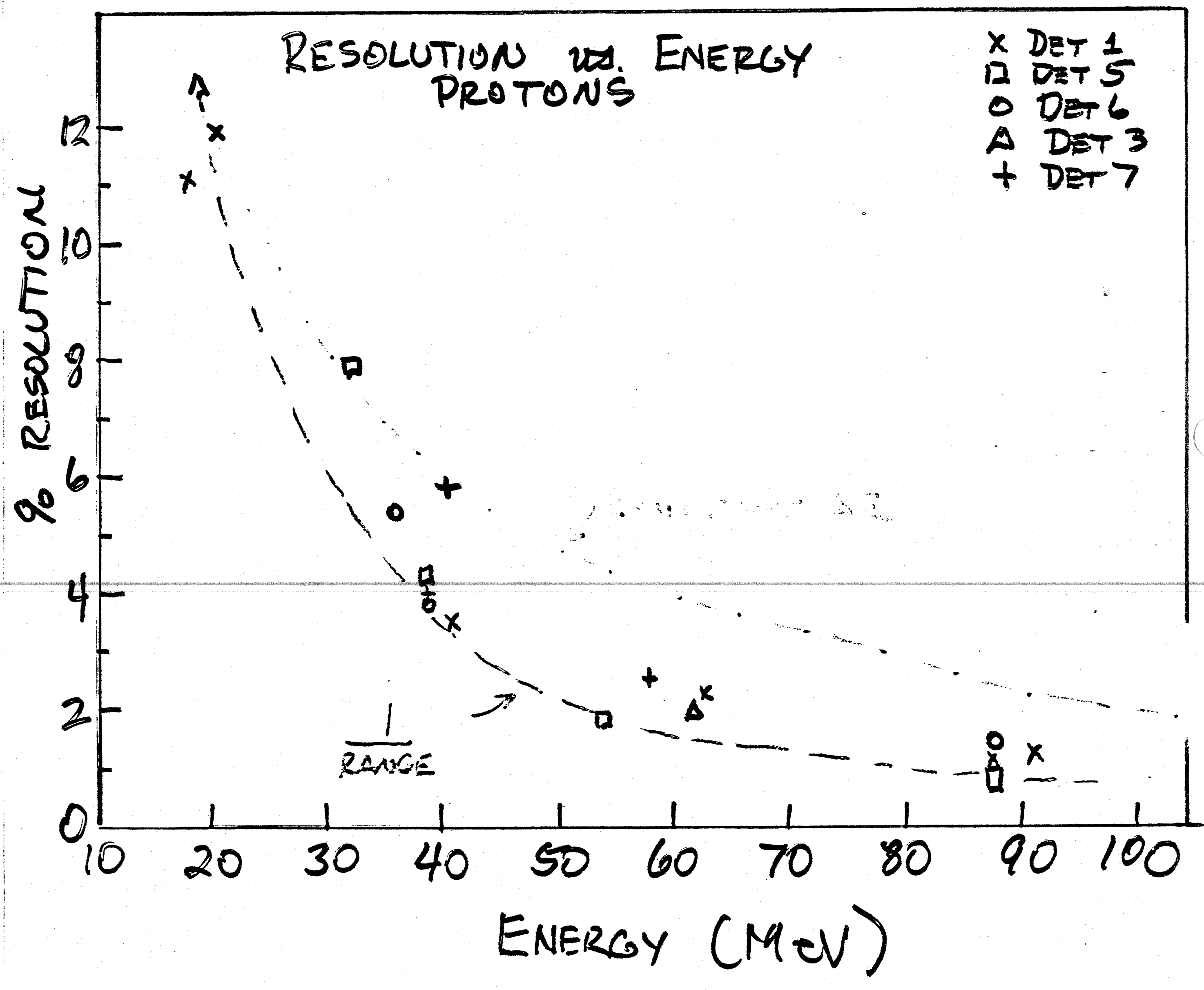
SUM → E

RANGE, PLATEAU → A

USE FLASH ENCODER TO DIVIDE UP SIGNAL INTO TIME BINS (~100 nsec)

PARTICLE PUNCHES THROUGH ⇒ ION CHAMBER

Fig. 2



HASSELQUIST et. al

Fig. 3

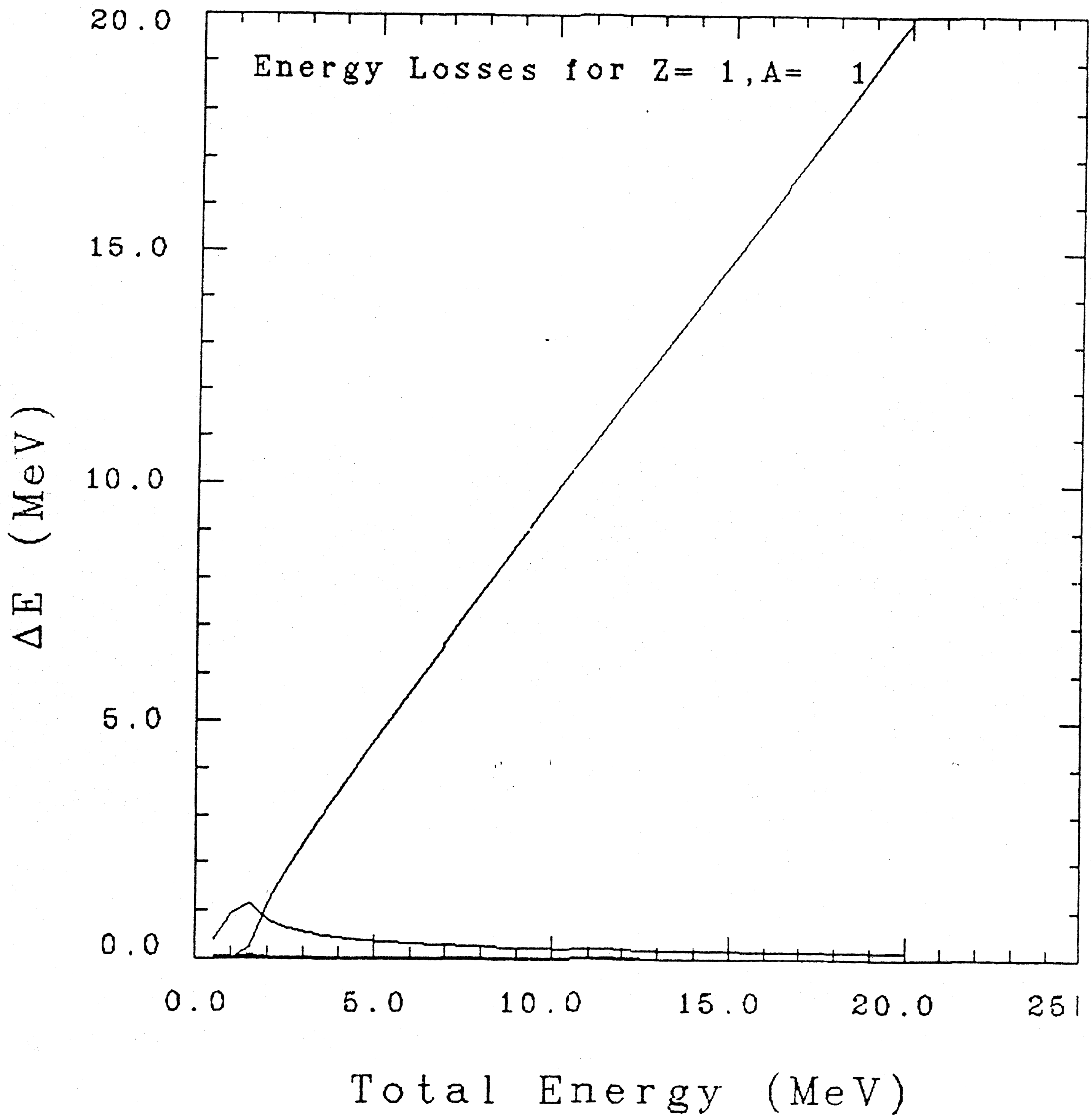
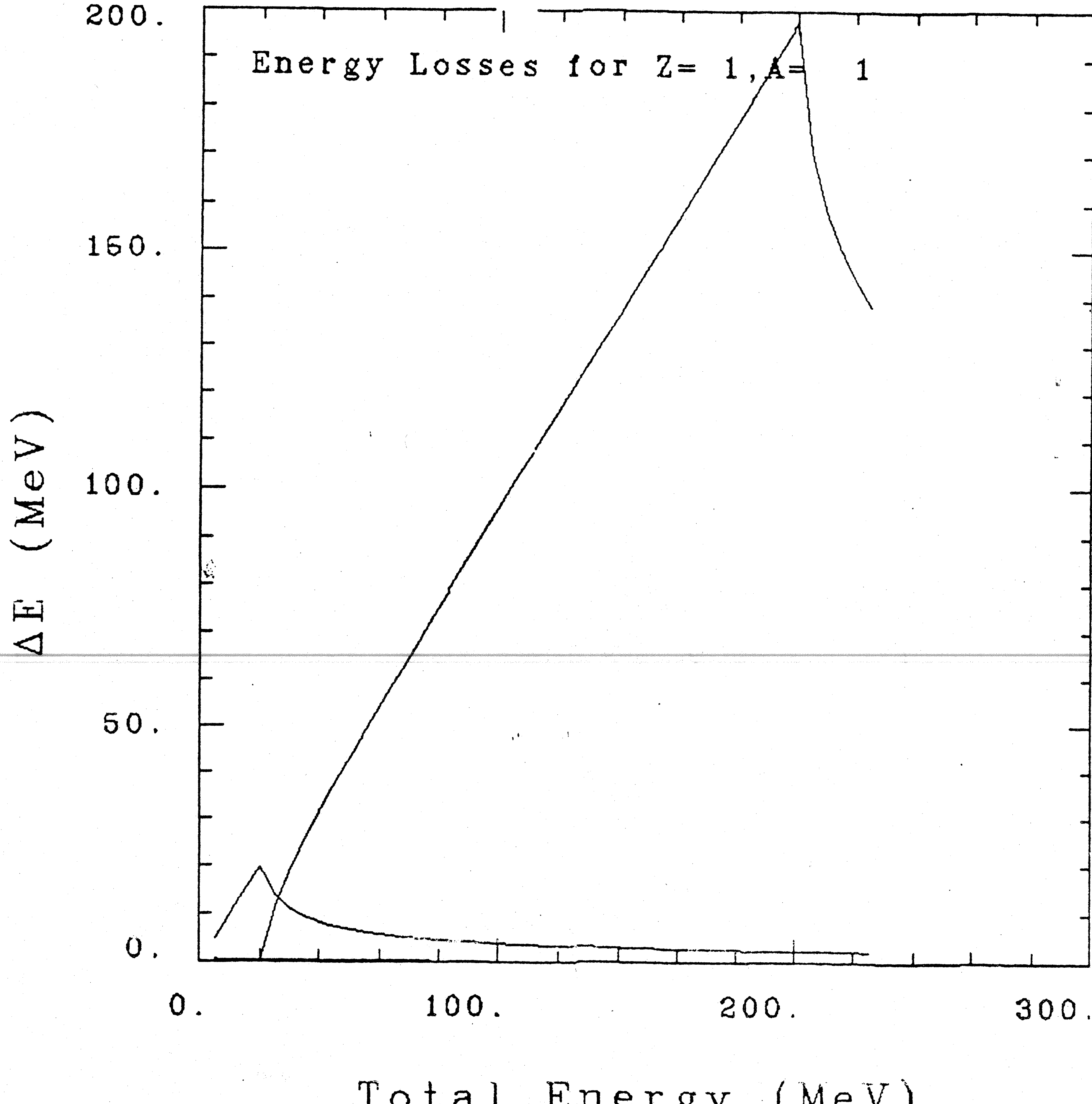

Energy Losses for Z= 1,A= 1
20.0
15.0
10.0
5.0
0.0
ΔE (MeV)
0.0
5.0
10.0
15.0
20.0
25
Total Energy (MeV)

Fig. 4



200.
150.
100.
50.
0.
ΔE (MeV)
Energy Losses for Z= 1, A= 1
0.
100.
200.
300.
Total Energy (MeV)

Fig 5

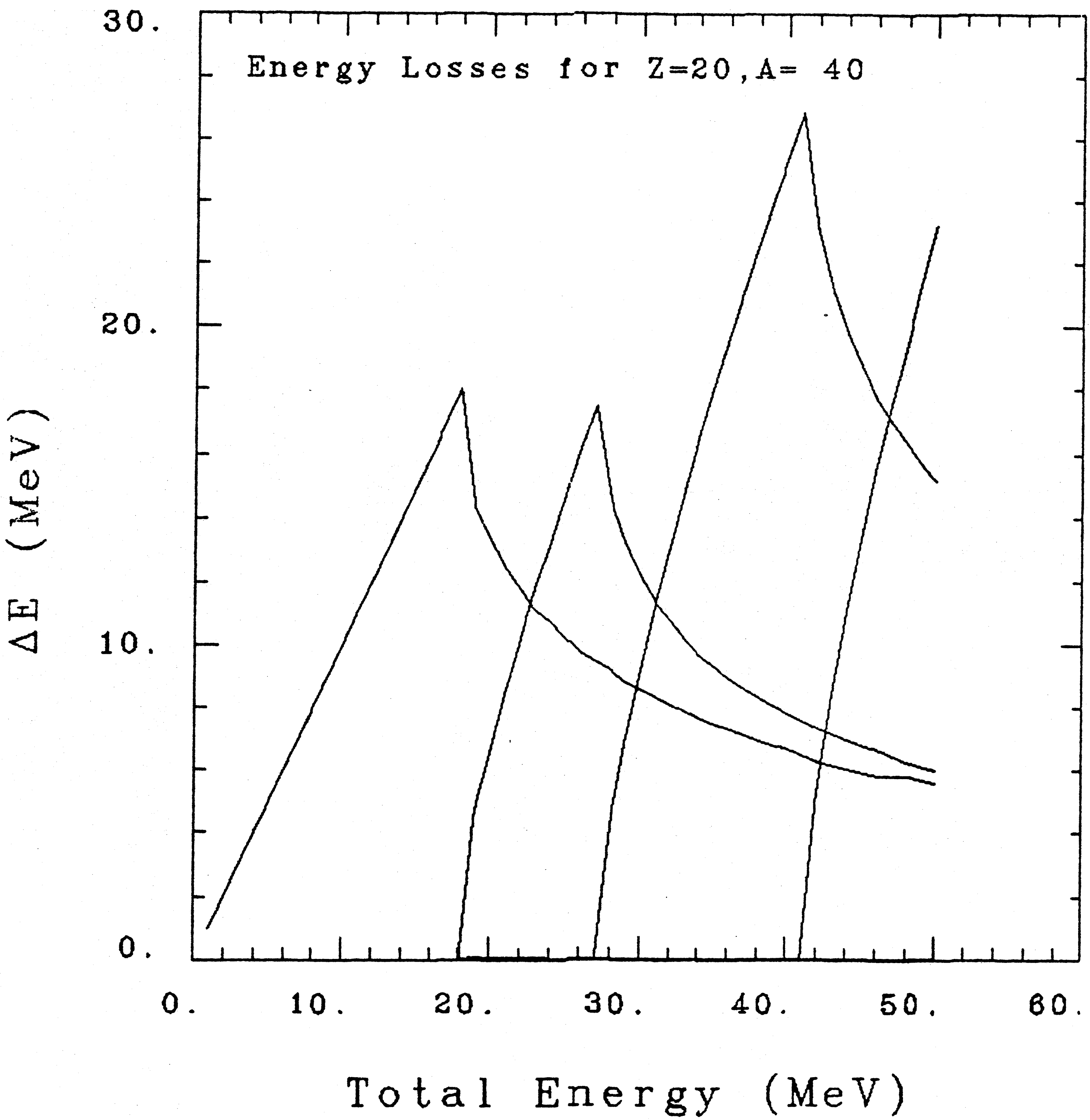

30.
Energy Losses for Z=20,A= 40
20.
ΔE (MeV)
10.
0.
0.
10.
20.
30.
40.
50.
60.
Total Energy (MeV)

Fig. 6

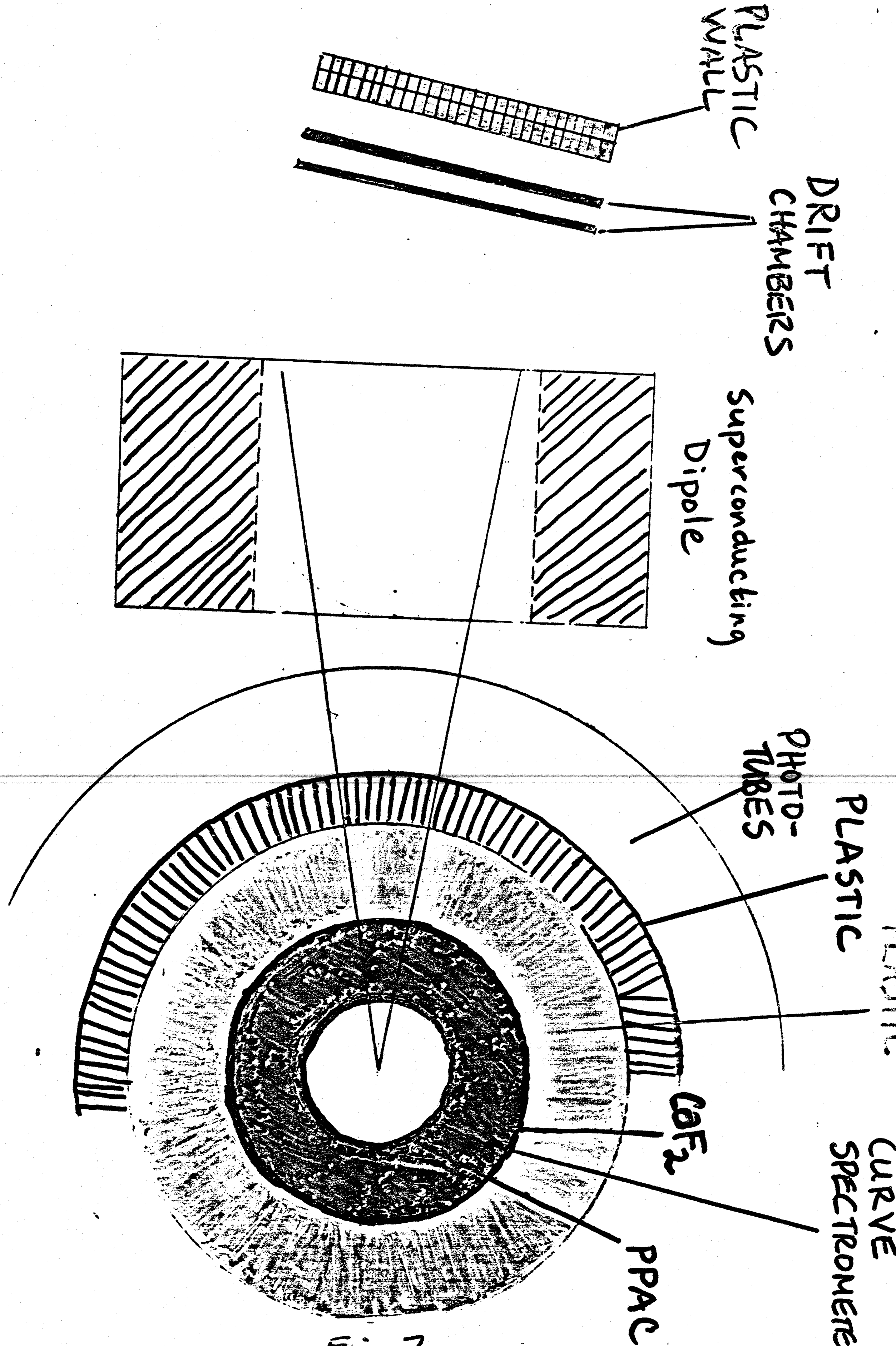

PLASTIC WALL
DRIFT CHAMBERS
Superconducting Dipole
PHOTO-TUBES
PLASTIC
PLASTIC
CaF_2
BRAGG CURVE SPECTROMETER
PPAC

Fig. 7

PARTICLE	OBSERVED ENERGY (MeV/n)	OBSERVED ANGLE	TYPE & QUALITY OF MEASUREMENT
n	.5 → 400 MeV	9°–180°	MULTIPLICITY
$\pi^{+,-}$	10–100 MeV	0°–180°	E, θ, φ, ~3%
p	3–250 MeV	0°–180°	E, θ, φ, ~3%
α	3–250 MeV/n	0°–180°	E, θ, φ, ~5%
^{12}C	2–300 MeV/n	0°–180°	E, θ, φ, ~2–10%
^{40}Ca	1–300 MeV/n	0°–180°	E, θ, φ, ~3–10%
^{120}Sn	.1–.5 MeV/n	10°–180°	θ, φ, v 10%
	.5–3 MeV/n	10°–180°	Z, M, θ, φ, E ~ 10% Z ~ 1%

MULTIPLICITIES

20 PARTICLES WITHIN 10° → 11% DOUBLE HIT PROB.

40 PARTICLES IN REST → 5% " "

ANGULAR RESOLUTION

Δθ ~ 20° 10°–140°; Δθ ~ 1° 0°–10°

ACTIVE AREA

87% 4π (θ = 0, 160°; φ = 0 – 2π; COVERAGE = 92%)

DATA RATE

UNWANTED – 5 μsec (200 KHz)
WANTED – 2 msec (500 Hz)

ANALYSIS RATE

10 msec (100 Hz)

Fig. 8

COSTS

ITEM	NUMBER	COST/UNIT (K$)	TOTAL (K$)
DETECTORS			
PPAC	32	.300	9.6
BRAGG CURVE	32	.500	16.0
CaF_2	180	.200	36.0
PLASTIC	180	.400	72.0
PM TUBE & BASE	180	.200	36.0
GAS HANDLING	2	5.00	10.0
			179.6
ELECTRONICS			
ADCs	4×180	.100	72.0
TDCs	32,180	.050	10.6
FLASH ENCODERS	32	.500	16.0
SCALERS	10	2.00	20.0
HV SUPPLIES	8	6.00	48.0
PULSER SYSTEMS	3	5.00	15.0
COMP. INTERFACE	1	50.0	50.0
			231.6
VACUUM VESSEL			
CHAMBER	1	100.0	100.0
PUMPS	2	10.0	20.0
MECHANICAL SUPPORTS	1	10.0	10.0
			130.0
MANPOWER			
FABRICATION OF DETS.	2 MY	50.0	100.0
MACHINING & MECHANICAL	4 MY	50.0	200.0
PROGRAMMING	2 MY	50.0	100.0
			400.0

Fig. 9

ITEM	NUMBER	COST/UNIT	TOTAL
FORWARD DETECTOR			
DIPOLE	1	150.0	150.0
VACUUM CHAMBER	1	25.0	25.0
DRIFT CHAMBERS	2	25.0	50.0
PLASTIC WALL	60	1.00	60.0
ADC's	60	.100	6.0
TDC's	768		38.4
			329.4
COMPUTER			
VAX 11/750 W/ DISK (.5GB) 3 MB Mem. 6250/1600/800 TAPE FPA		150.0	150.0
			150.0

SUMMARY

DETECTORS	179.6
ELECTRONICS	231.6
VACUUM VESSEL	130.0
MANPOWER	400.0
FORWARD DETECTOR	329.1
COMPUTER	150.0
	1420.3

A STREAMER CHAMBER FOR INTERMEDIATE-ENERGY HEAVY-ION COLLISIONS

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Abstract: The streamer chamber used in the avalanche mode appears to be an attractive 4π detector for NSCL Phase II experiments. It has excellent spatial, angular and momentum resolutions over a large detector volume, and very high multitrack efficiency. Its charge identification ability is adequate for light and moderately heavy reaction products and can be extended by using a charge-coupled device (CCD) instead of film. Use of a CCD will also speed up the data analysis time. The cost of constructing this facility is about $ 700 K, which is comparable to that of the proposed electronic-type 4π detector.

1. INTRODUCTION: 4π DETECTORS

In this report, we discuss the usefulness as well as the limitations of the streamer chamber as a detector with nearly 4π solid angle for experiments with the Phase II heavy-ion beams scheduled to become available at the NSCL in 1986. The types of reaction processes expected to be important in collisions involving intermediate-energy (E/A $\lesssim$ 200 MeV/A) heavy-ion beams determine the characteristics of the ideal 4π detector to be the following:

(1) Nearly 4π solid angle.

(2) Triggerability--to select the type of reaction one is interested in, e.g. central collisions.

(3) High multitrack efficiency--since the expected average

charged-particle multiplicity is $\sim$16 for Ar+U at 200 MeV/A and $\sim$25 for Xe+U at 100 MeV/A. These numbers are based on the data of Gutbrod et al. (Fig. 3 of ref. 1). The actual multiplicity observed in any particular event might be significantly higher than the average.

(4) A good precision in the momentum measurement for outgoing particle energies ranging from 3 MeV/A (which is well below the Coulomb barrier) to $\sim$400 MeV/A.

(5) A good angle resolution, to study the jet structure (nonisotropic distribution of emitted particles) predicted in some models, as well as two-particle correlations at small relative angles.

(6) Charge identification for all outgoing particles.

(7) High data acquisition rate.

(8) Fast analysis.

(9) Low cost of construction/operation.

The few types of 4π detectors that exist can be classified as follows:

4π Detectors

- Visual (Streamer Chamber)
- Electronic
  - Absorption Type (Plastic Ball)
  - Magnetic Analysis Type (Time Projection Chamber)

All three types of detectors are being discussed at this Workshop. It is a curious fact that all three had their first major application in high-energy physics measurements in one particular laboratory--the Stanford Linear Accelerator Center. Invented in the Soviet Union during the early 1960's, the streamer chamber owes much of its development to the pioneering work at SLAC.[2-3] The only streamer chamber being used in high-energy nuclear physics experiments in this country is at the Bevalac at the Lawrence Berkeley Laboratory.[4]

2. PRINCIPLE OF OPERATION OF THE STREAMER CHAMBER

The principle of operation of the streamer chamber[2-4] is illustrated in Fig. 1. The chamber is a rectangular box containing some gas, e.g. a 90%Ne-10%He mixture at a pressure of 1 A.P. After the passage of a charged particle, a trail of electrons and ions is left in the gas. An intense (15-20 kV/cm), short (∿10 nsec) pulse of voltage is applied to the chamber while free electrons are still present. In this field, the electrons initiate avalanches, which then form streamers. The high voltage pulse is terminated while the streamers are still well localized. The view parallel to the electric field is photographed via the visible light emitted by the streamers. In this view, the streamers appear as small round dots along the track of the particle.

In typical operation for nuclear physics measurements, the target is a solid located inside the chamber and made nonconducting. A magnetic field (∿10 kG) is applied parallel to the electric field for determination of the rigidity of the emitted particles. Stainless-steel wire meshes with above 80% light transmission form the electrodes through which the streamers are photographed on film. Poor light output necessitates the use of fast film (e.g. the 35-mm Kodak SO-143 film) and of small f-numbers for the camera aperture. For the sake of complete event reconstruction, 3 views are in general recorded with cameras inclined by $\sim 15^{\circ}$ with respect to the electric field. Since the chamber length is typically over 1 meter, a demagnification of ~ 50 is needed to focus the image on to the 35-mm film.

The number of streamers/cm varies with the time (t) between the passage of the particle in the chamber and the appearance of the high voltage pulse according to

$$N = N_0 \exp(-t/\Delta\tau).$$

The memory time $\Delta\tau$ is several hundred μsec for a pure inert gas, but is reduced to 1-2 μsec by the addition of a few ppm of SF_6. This shows, first, that electronegative impurities in the gas have to be controlled very carefully and, second, that the beam intensity must be limited to $\leqslant 5 \times 10^5$ particles/sec. The memory time of 1-2 μsec is long enough for an electronic detector (such as a plastic detector placed downstream of the target) to detect that an event of interest has occurred and to trigger the high voltage system. This triggerability of the streamer chamber means that interesting events can be preselected before recording. The device also has the advantage of high multitrack efficiency; events of up to 150 charged secondaries have been recorded at the Bevalac streamer chamber.[4] The response of the chamber is isotropic over almost all 4π solid angle. A small cone of about $\pm 15^{\circ}$ around the $\vec{E}$ direction is lost because there the streamers fuse with each other and form a continuous bright channel. This loss can however be determined without bias by looking at corresponding events which are at 90^{0} azimuthal angle to $\vec{E}$.

3. MEASURING ACCURACY FOR MOMENTUM

For an ion of charge z, the precision in the momentum distribution is given[5-6] by

$$\left(\frac{\Delta p}{p}\right)^2 = \frac{A}{H^2 L} \frac{1}{\beta^2} + \frac{1.4 \times 10^{-4} \varepsilon^2}{z^2 H^2 L^5} \cdot p^2 \quad (1)$$

where
H = magnetic field (kG)
L = track length (cm)
ε = setting error (microns)
p = momentum (MeV/c)
β = v/c.

The first term comes from multiple scattering in the gas and the second from the setting error, i.e. the accuracy with which the center of the streamer can be located. For the 90%Ne-10%He gas mixture, A = 0.09.

We note from eq. (1) that multiple scattering dominates at low momenta, and the setting error at high momenta. It is also clear that the accuracy is increased by having a big chamber and a high magnetic field. We choose a chamber of dimensions 100 cm x 50 cm x 50 cm and assume that the target is placed 20 cm inside it, so that L = 80 cm for particles that emerge in the forward direction and do not stop in the gas. Also, let H be 10 kG. The resulting momentum resolution is shown in Fig. 2 for pions, protons, ^{4}He and ^{12}C for two different recording devices--film and a charge-coupled device (CCD). The latter is discussed in section 8, where we show that the CCD appears to be a viable alternative to film for streamer chamber experiments at the NSCL. For the present, we note only that the setting error with commercially available CCD's is about a factor of 7 worse than with film, but that the accuracy in the momentum determination is still acceptable.

Eq. (1) is valid for a dip angle λ (the angle of the track with respect to the plane normal to the electric and magnetic fields) of zero. For $\lambda \neq 0$, it is modified to

$$\left(\frac{\Delta p}{p}\right)^2 = \frac{A}{H^2 L}\,\frac{1}{\beta^2}\,\frac{1}{\cos^2\lambda} + B\,p^2\,\frac{1}{\cos^3\lambda}\ .$$

Thus $\Delta p/p$ becomes worse by a factor of 2 at $\lambda \sim 60^{\circ}$.

To the above factors determining the precision of the momentum measurement, one must add contributions from the target (usually well below 1%), distortions in the optical system (0.1 to 0.3%), and uncertainties in the magnetic field.

4. ANGLE ACCURACY

The error in the azimuthal angle is given[5] by

$$\langle\Delta\theta\rangle^2 = \frac{0.13 \times 10^{-2}\,Lz^2}{p^2\beta^2\cos^2\lambda} + \frac{3.8 \times 10^{-6}\,\varepsilon^2}{L\cos^3\lambda}\ ,$$

where the two terms are again due to multiple scattering and the setting error, respectively. With $\varepsilon = 2000\ \mu$ (CCD), and the chamber dimensions used before, we get

E/A (MeV)	Proton	^{4}He
10.	1.0°	0.6°
200.	0.3°	0.3°

The error in the dip angle λ is similar in magnitude.

5. LOWEST MEASURABLE OUTGOING PARTICLE ENERGY

This limit is set by the stoppage of the particles in the target material, and by the requirement that they must have at least several (>8) cms of track length in the gas, since the density of tracks is too high near the interaction vertex. The limit can be lowered by decreasing the target thickness, but one may argue that the minimum thickness is set by the requirement that the number of interactions in the target be comparable to that in the remainder of the material (windows + gas) along the beam path.

The effective gas thickness t_{gas} is reduced by placing the trigger detector close to the target, say 20 cm downstream of it. Then $t_{gas} \simeq 40$ mg/cm^2 for Ne at 1 A.P. By the argument above, the target thickness must be comparable to this, say 90 mg/cm^2 of ^{90}Zr. If we assume that particles are produced at the front surface of the target, the minimum detectable energy for protons and ^{4}He would be about 6 MeV/A, since they would then have only enough energy left to traverse 9 cm of Ne. The corresponding energy for ^{12}C would be about 11 MeV/A.

To lower the energy limit further, a thinner target may be used, provided one is prepared to reject a large fraction of recorded events as corresponding to interactions in the gas rather than in the target. A series of thinner targets can also be used[7] (Fig. 3). Another solution is to use the chamber gas itself (neon) as the target. This, however, is not a general solution, and in fact it is not known whether any heavier gas will work well in streamer chambers.

Another promising way to lower the energy limit is to lower the gas pressure, so as to reduce t_{gas}. Streamer chambers have been operated at pressures as low as 1/3 A.P. The streamer brightness is found[8] to be unchanged (for a given gas) if E^3T/P^2 is kept constant (E = electric field, T = its duration, P = pressure). As the pressure is lowered, the statistical accuracy in ionization measurements does become poorer, but we do not propose operating the chamber below 0.5 A.P. The Ne-He mixture tolerates the maximum reduction in pressure (down to 100 mm of Hg) without substantial deterioration in track quality. One drawback of the lower pressure is that Bragg peak information (useful for z identification, see section 7) is lost over a wider range of particle energies.

6. COUNTING RATE/TRIGGER SELECTIVITY

Assume that the chamber operates at 0.5 A.P., so that t_{gas} is 20 mg/cm². Let the target be U of 100 mg/cm² thickness, and the beam ^{40}Ar of 100 MeV/A at an intensity of 5×10^5 pps. The reaction cross sections for Ar+U and Ar+Ne at this energy are estimated to be about 5.50 barns and 2.0 barns, respectively, so that the number of interactions per second in the target and in the gas are 700 and 600. Thus the percentage of interactions inside the target is 54%.

The maximum number of pictures that can be taken per second is about 10, being limited by the cameras and/or the charging capability of the high voltage system. (A rate of 3-5/sec is more usual.) So the optimum necessary trigger selectivity is 10/1300 or ∿1%, for full use of interactions and picture taking rate.

At the Bevalac, a central trigger is defined by accepting ΔE signals below 10% of the beam pulse height, corresponding to a selectivity of roughly 10%. This is ten times the optimum value. So it might be useful to devise more selective triggers. Alternatively, one can afford to have lower beam intensities.

7. CHARGE IDENTIFICATION

It is obviously essential to have z identification since, without it, the curvature in the magnetic field determines only the rigidity (p/z). Now, the primary ionization/cm varies as

$$I \sim \frac{z^2}{\beta^2} f(\beta^2, \text{gas}) .$$

Since one might expect appreciable production of fragments from protons to ^{12}C, with velocities from 0.1 c to 0.5 c, I will vary over a range of over 900. Because of the statistical process of streamer formation, the streamer density will not be proportional to I. However, it is evident that there will be a large dynamic range in the streamer density or brightness.

From the appearance of the tracks shown in Fig. 4, it is clear that the number of streamers or gaps per unit length can be counted to identify pions, but this becomes difficult for protons and impossible for heavy ions. A more promising method is to do a computer-assisted densitometric study of the tracks. The integrated intensity per cm provides a clean separation between p, d, t and α as shown in Fig. 5. The method even appears to be capable of separating z = 17 from z = 18 particles having a restricted range of rigidities.[9] In this method, the streamer chamber acts essentially as a continuously sensitive Bragg spectrometer. For particles that stop in the gas, the method gives information on both the momentum (from the curvature) and the energy (from the range).

A count of δ-electrons ejected by high-energy heavy ions will also help in z identification, since this number varies as z^2. However, since the electrons spiral tightly along the magnetic field, they have to be observed from the side (necessitating the use of mirrors).

The densitometric studies mentioned above have been done for streamers recorded on film. Film has a logarithmic response to brightness and a limited dynamic range (15-20). The method could be greatly improved by operating the chamber in the avalanche mode and by using a CCD instead of film, as we discuss in the next section. Attention to the performance of the high voltage system--constancy of both the peak voltage applied to the chamber and the time lapse between the passage of the charged particles and the appearance of the voltage--is also important for getting reproducible results.

8. IMPROVEMENT IN STREAMER CHAMBER PERFORMANCE

Two major ways to improve streamer chamber performance are to:

(a) Operate in the avalanche mode;[10]

(b) Use a CCD (charge-coupled device) in place of film.

The avalanche mode (in which the electron gain is about 10^8) is achieved by terminating the high voltage pulse before the avalanches have time to form streamers (see Fig. 1). In this mode, a better proportionality of the track brightness to the primary ionization is obtained, thus aiding z identification. Also the problem of flaring (the occurrence of very bright channels) is reduced. However, the light intensity is then insufficient for the tracks to be photographed directly, necessitating the use of an image intensifier. This worsens the resolution somewhat and causes some image distortion, which can be corrected for by having a set of fiducial marks. One needs a fast-decaying phosphor for the image intensifier in order that bright tracks from one event do not get superposed on tracks from a subsequent event. Image intensifiers, both electrostatic and magnetic, have been successfully used in streamer chambers for high-energy physics measurements.

The CCD is a solid-state image sensor with a two-dimensional array of electron-collecting zones. The light falling on these zones is trapped as electrons. The zones are moved about within the device to an output amplifier by changing the voltage on the electrodes in a systematic manner. CCD's of adequate resolution and large dynamic range are commercially available. For example, a Texas Instruments model provides a 390 x 584 array when used in what is called the full-frame mode; and it has a dynamic range of typically 925. Its picture elements are 22.4 microns square.

The advantages of the CCD over film are its linear response and the large dynamic range. It is also more sensitive than film, perhaps by an order of magnitude. Further, the slow, expensive process of film developing and scanning is avoided. One drawback of the CCD is that, unlike film, the image blooms if the light intensity is above saturation level, but the TI model has anti-blooming circuitry.

The output of the CCD is in analogue form. The best way to handle it is not clear. Compact storage is provided by video tapes, but these have a dynamic range of only about 50 (which is however larger than that for film). Digitizing the output and storing it on digital tape would preserve the dynamic range, but only about 240 events (with three views each) can be recorded on a standard high-density digital tape. Suppressing the dark channels would increase this number, but it is not clear whether much more than a factor of 3 or 4 increase can be achieved.

It is possible that higher density tapes will become available in the future; their technical feasibility is already established.

9. OPTICS/TWO-TRACK RESOLUTION

The choice of the optical system is determined by the conflicting requirements of light sensitivity and space resolution. The conflict arises because a large lens aperture is needed to maximize the amount of light striking the film (or CCD) but a small aperture is needed to increase the depth of field. The proportion of photons reaching film is given by $\eta = 1/[16F^2(M+1)^2] = 10^{-3}$ for an f-number (focal length/lens diameter) of 8 and a demagnification (M) of 50. We note that a typical avalanche has a reconstructed diameter of 1 mm and emits about 10^8 photons, and that a density of the order of 10^8 photons/mm^2 is necessary to make emulsion grains developable for a standard film. Thus an image intensifier system with a gain of 10^3 is needed, for a setup where the intensifier output is directly coupled to the film or CCD.

The size D of an object when reconstructed in space from its image on film or CCD is given by

$$D^2 = D_A^2 + \frac{\Delta x^2}{F^2(M+1)^2} + [\lambda F(M+1)]^2 + M^2\left(\frac{1}{R_\ell^2} + \frac{1}{R_i^2} + \frac{1}{R_f^2}\right).$$

The different terms show the effects of the size of the avalanche and distortions due to the depth of field, diffraction, and the resolutions of the lens, intensifier and film (or CCD).

D_A = size of avalanche (1 mm)

Δx = half width of chamber (25 cm)

λ = wavelength of emitted light (6000 Å)

R_ℓ = lens resolution (100 line pairs/mm)

R_i = image intensifier resolution (50 line pairs/mm)

R_f = film/CCD resolution $\begin{cases} 100 \text{ lp/mm (film)} \\ 25 \text{ lp/mm (CCD)} \end{cases}$

Thus $D = (1.0 + 0.39 + 0.06 + 0.25 + 1.0 + 0.25)^{\frac{1}{2}} = 1.7$ mm (film)

$= (1.0 + 0.39 + 0.06 + 0.25 + 1.0 + 4.0)^{\frac{1}{2}} = 2.6$ mm (CCD)

This D defines the two-track resolution of the system, viz the minimum distance between streamers which can be identified as belonging to two different tracks. We note that the two-track resolution is not appreciably worsened by use of the CCD and in fact it is much better than is readily possible with other 4π devices.

10. HIGH VOLTAGE SYSTEM

The design of the high voltage system is the most critical part of the streamer chamber setup, since the requirements of nano-second widths and megavolt pulses are not easy to reconcile. The standard practice is to have a Marx generator and a Blumlein pulse shaping network, capable of delivering typically 500 kV voltage to the chamber with a rise time of 2 nsec and an amplitude stability of better than 1%. We shall not discuss these in detail, since their technology is well developed. The Marx generator can be ordered commercially, but it is best to design the Blumlein on site, since its impedance has to be matched to that of the chamber.

Of the two possible designs, a single gap and a double gap geometry, we prefer the latter. In this design, the high voltage electrode is in the central plane, and there are two ground plates at the top and bottom of the chamber. Its advantages over the single gap design are the following: (1) The required high voltage is halved for a given useful volume. (2) It is easier to shield from the severe rf radiation emitted when the chamber is pulsed. A disadvantage is that there will be interactions of the beam or emitted fragments with the central electrode, but the resulting interruption in sensitivity can be kept below 1 cm.

12. DESIGN CONSIDERATIONS/ CONSTRUCTION COST

As stated above, we envisage a double-gap chamber of dimensions 100 cm x 50 cm x 50 cm in a 10 kG magnetic field. (Since the rigidity of a fully stripped beam from the K-800 machine will be 4 Tesla-meters, the 10 kG field will be weak enough to allow beam particles to reach the target located ∿20 cm inside the chamber.)

To get a realistic estimate of the cost of building the magnet, which is the most expensive part of the system, we made a preliminary design of a solenoidal magnet with the help of A. Zeller. This is shown in Fig. 6. A field nonuniformity of ∿10% was allowed. Superconducting coils were chosen since, for large-gap magnets, they are cheaper to build as well as operate compared to conventional copper coils.[11] The weight of the magnet is about 14 tons. The design allows a 16-cm wide gap in the median plane essentially all around. This will let external detectors view the chamber. We are keeping open the question of whether the axis of the magnet should be horizontal or vertical; there are merits to both options.

A rough estimate of the cost of the total project is as follows:

Magnet	250 K
Marx Generator	75 K
Blumlein	25 K
High Voltage Power Supply	30 K
Chamber/ Gas Handling System	50 K
CCD's (3)	9 K
Image Intensifiers (gain=100)	15 K
Cameras (3)	6 K
Image Processing System	40 K
Dedicated Vax 750 Computer	110 K
24 man-months of labor	50 K
TOTAL	660 K

The magnet cost estimate was made independently by J. Nolen and A. Zeller and includes the cost of one man-year for assembly. The cost of a film handling facility (in case the decision is made to have film as a backup to CCD) is not included above. A film processing trailer is available for free from SLAC, but a scanning table and digitizer will have to be purchased. Also not included is the cost of the monitoring system needed to optimize the performance of the high voltage system.

13. FINAL REFLECTIONS

We have seen that the streamer chamber meets many of the characteristics of the ideal 4π detector listed in section 1. For charged particles, it has excellent angle, momentum and two-track resolutions over a large detector volume, and very high multitrack efficiency. The ability to detect neutral particles (mainly neutrons), which might account for half the total multiplicity in a central heavy-ion collision, is not intrinsic to the streamer chamber, but can be added on by putting liquid scintillator detectors in the median plane.

The charge identification capability of the device via the computer digitization of photographic information on ionization density has been demonstrated for both light and moderately heavy collision products. The technique can be improved by the use of the charge coupled device in place of film as the recording device and by operating the chamber in the avalanche mode. Such improvement is necessary to encompass the full range of particle species and energies expected in intermediate-energy collisions. The use of CCD's will also remove another area of concern--the slow, expensive processing of photographic information due to manual scanning. One open question is whether to keep film as backup or dispense with it altogether. In deciding this, we should note that none of the existing streamer chamber facilities has made the latter choice. The best way of storing the huge information flow from the CCD output remains to be worked out.

The streamer chamber can only handle an event rate of 3-5 per second and a beam intensity of $\leq 5 \times 10^5$ pps. This might seem a drawback in view of the high-intensity beams that the NSCL machine will be capable of delivering, but it is a drawback that the streamer chamber shares with other 4π detectors. Moreover, this can be turned into an advantage by choosing the low-intensity high-mass beams (e.g. 100 MeV/A beams of A = 180, estimated to have a maximum intensity of 10^6 pps at the exit of the machine) for experiments.

Finally, the cost of constructing the chamber--which we propose be called the Avalanche Chamber in view of the preferred mode of operation--is comparable to that of the proposed absorption-type electronic 4π detector.

The authors are indebted to several people for valuable discussions/correspondence concerning the material presented above: J. Brannigan, M. Maier, A. Sandoval and L.S. Schroeder of the Bevalac streamer chamber group; P. Cooper of Yale; R. Mozley of SLAC; F. Rohrbach of CERN; G. A. Smith of Michigan State University; J.M. Watson of Los Alamos National Laboratory (formerly associated with the Argonne streamer chamber); and K. Wolf of Texas A&M University.

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8. F. Rohrbach, J.J. Bonnet and M. Cathenoz, Nucl. Inst. and Meth. 111 (1973) 485.
9. K. Wolf, private communication (1982).
1Ø. M. Basile et al., Physica Scripta 23 (1981) 743.
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FIGURE CAPTIONS

Fig. 1 (Top) Schematic representation of a track in a streamer chamber, (a) viewed normal to the E field; (b) viewed parallel to the E field.

(Bottom) The transition from the avalanche mode to the streamer mode and finally to the spark discharge mode with increasing duration of the high voltage.

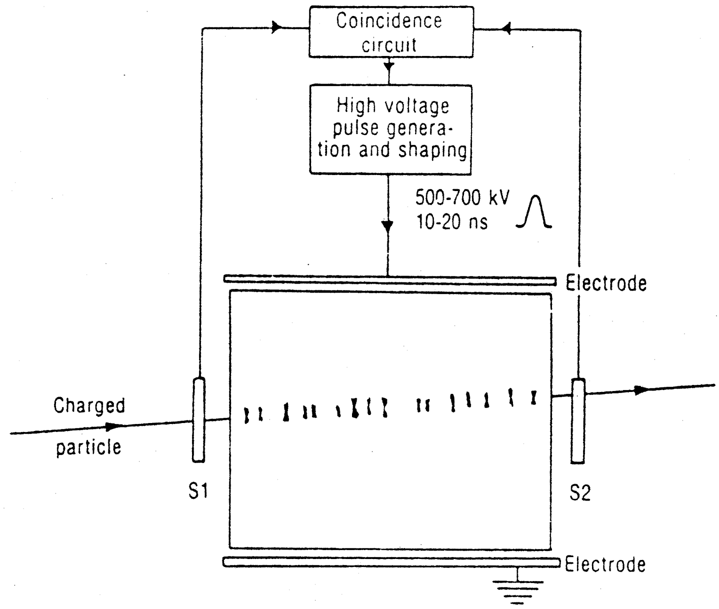
Fig. 2 Precision in momentum measurement with film (dashed lines) and the charge-coupled device (solid lines). The momentum scale shown at the bottom does not apply for pions.

Fig. 3 A schematic of the Bevalac streamer chamber set up for intermediate-energy heavy ion experiments. The trigger detector (P-counter) is a 1/16 plastic scintillator coupled via a 6 light guide to a photomultiplier outside of the H- and E-fields.

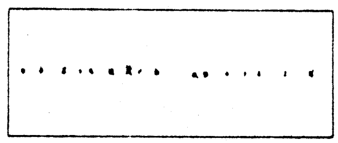
Fig. 4 Sketch of the streamer formation along the track for different particles: (a) 600 MeV/c pion; (b) 600 MeV/c proton; and (c) a relativistic heavy ion. Note the electrons in the view normal to the E field in the last case.

Fig. 5 Particle identification spectrum for the reaction products of C induced reactions at 150 MeV/A (from ref. 7)

Fig. 6 Sketch of a solenoidal magnet design proposed for the streamer chamber facility.


Coincidence circuit
High voltage pulse genera-tion and shaping
500-700 kV
10-20 ns
Electrode
Charged particle
S1
S2
Electrode

a



b

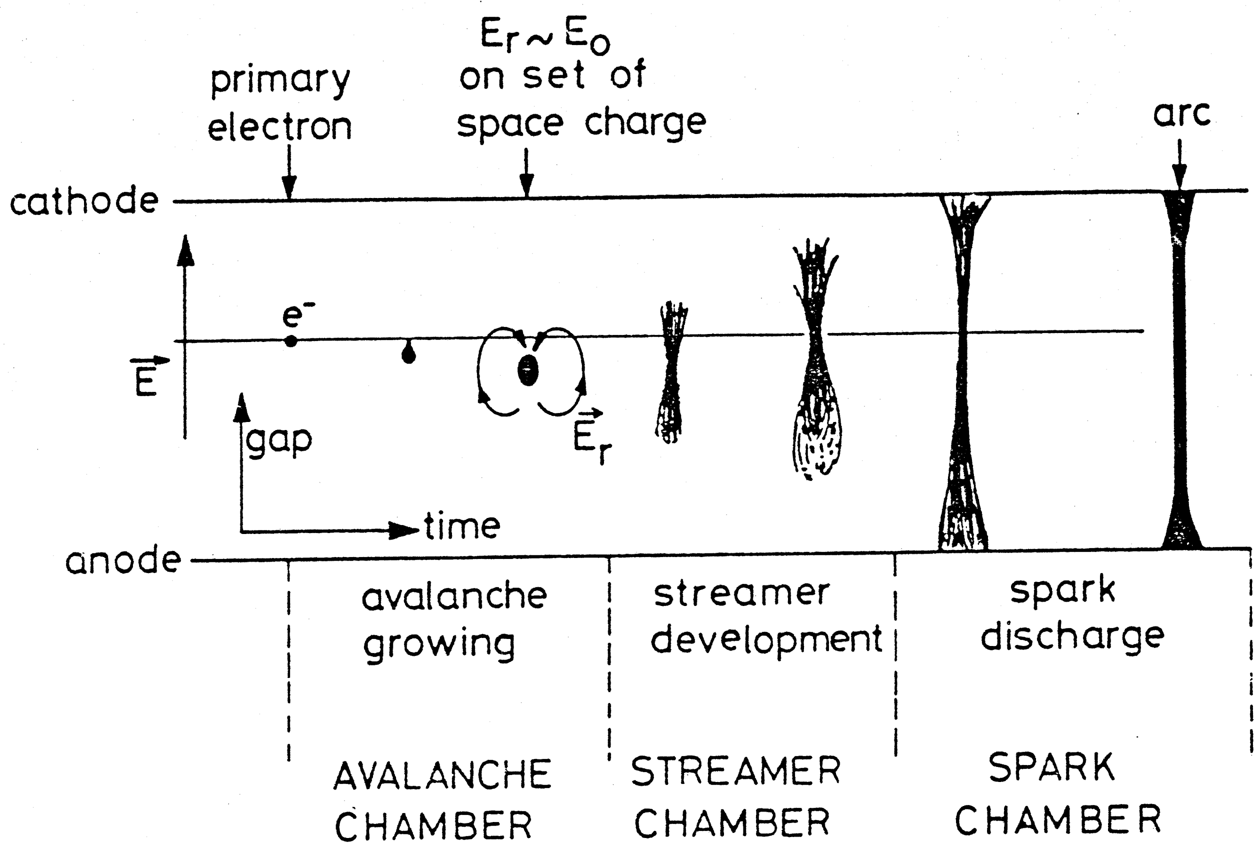

primary electron
Er ~ Eo on set of space charge
arc
cathode
e⁻
E
gap
Er
time
anode
avalanche growing
streamer development
spark discharge
AVALANCHE CHAMBER
STREAMER CHAMBER
SPARK CHAMBER

Fig. 1

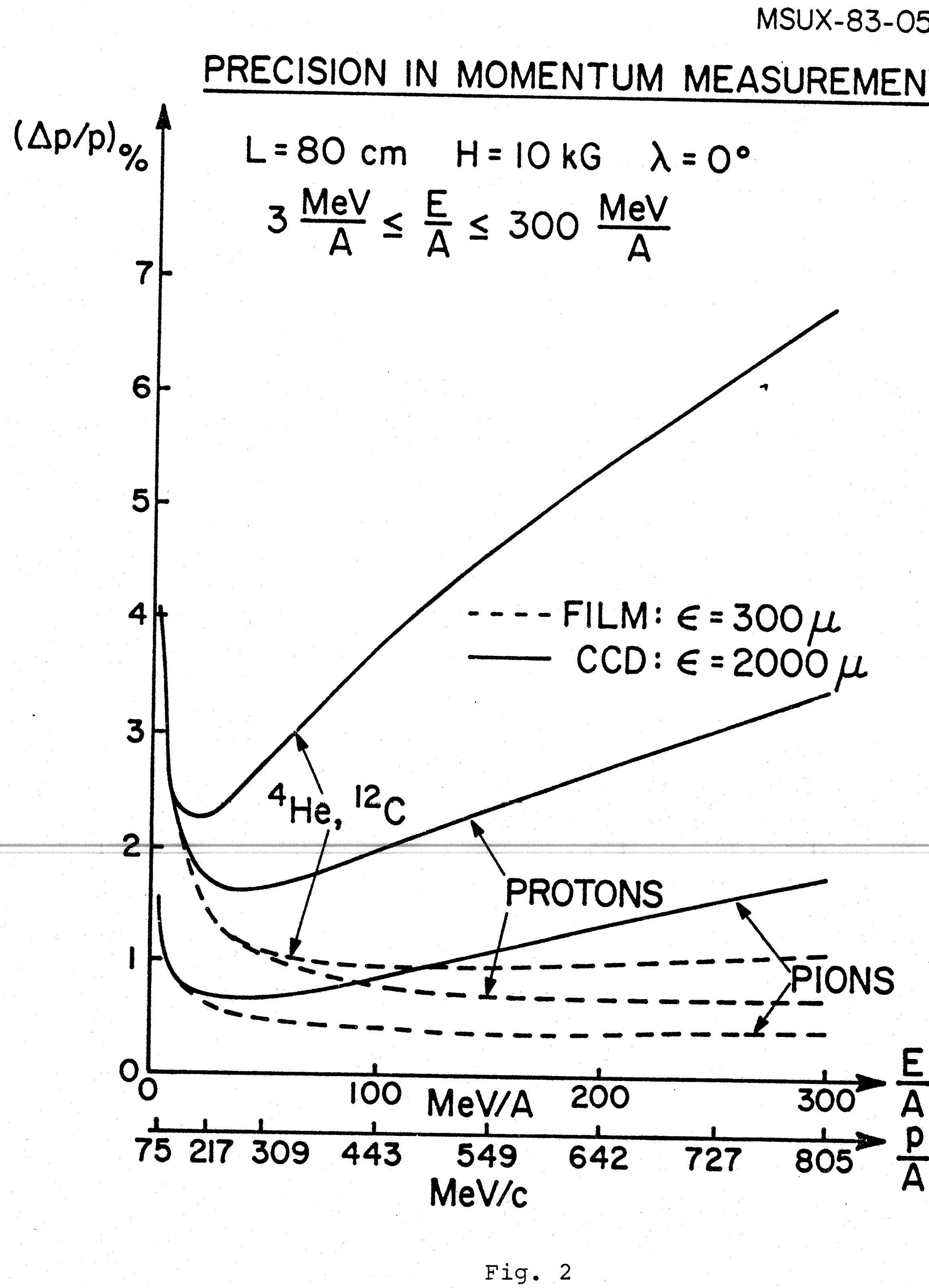

MSUX-83-055
PRECISION IN MOMENTUM MEASUREMENT
(Δp/p)%
L = 80 cm H = 10 kG λ = 0°
3 MeV/A ≤ E/A ≤ 300 MeV/A
7
6
5
4
3
2
1
0
FILM: ∈ = 300 μ
CCD: ∈ = 2000 μ
4He, 12C
PROTONS
PIONS
0
100
MeV/A
200
300
E/A
75 217 309 443 549 642 727 805
MeV/c
p/A

Fig. 2

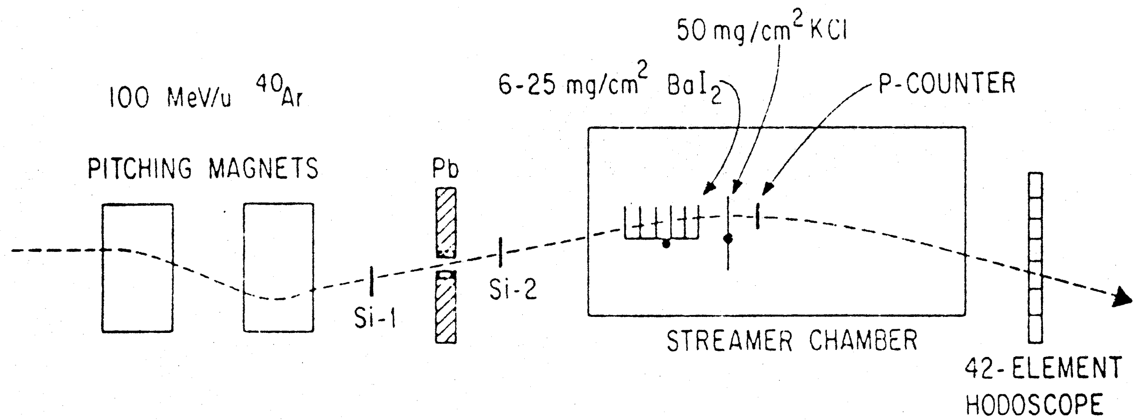

50 mg/cm² KCl
6-25 mg/cm² BaI₂
P-COUNTER
100 MeV/u ⁴⁰Ar
PITCHING MAGNETS
Pb
Si-1
Si-2
STREAMER CHAMBER
42-ELEMENT
HODOSCOPE

Fig. 3

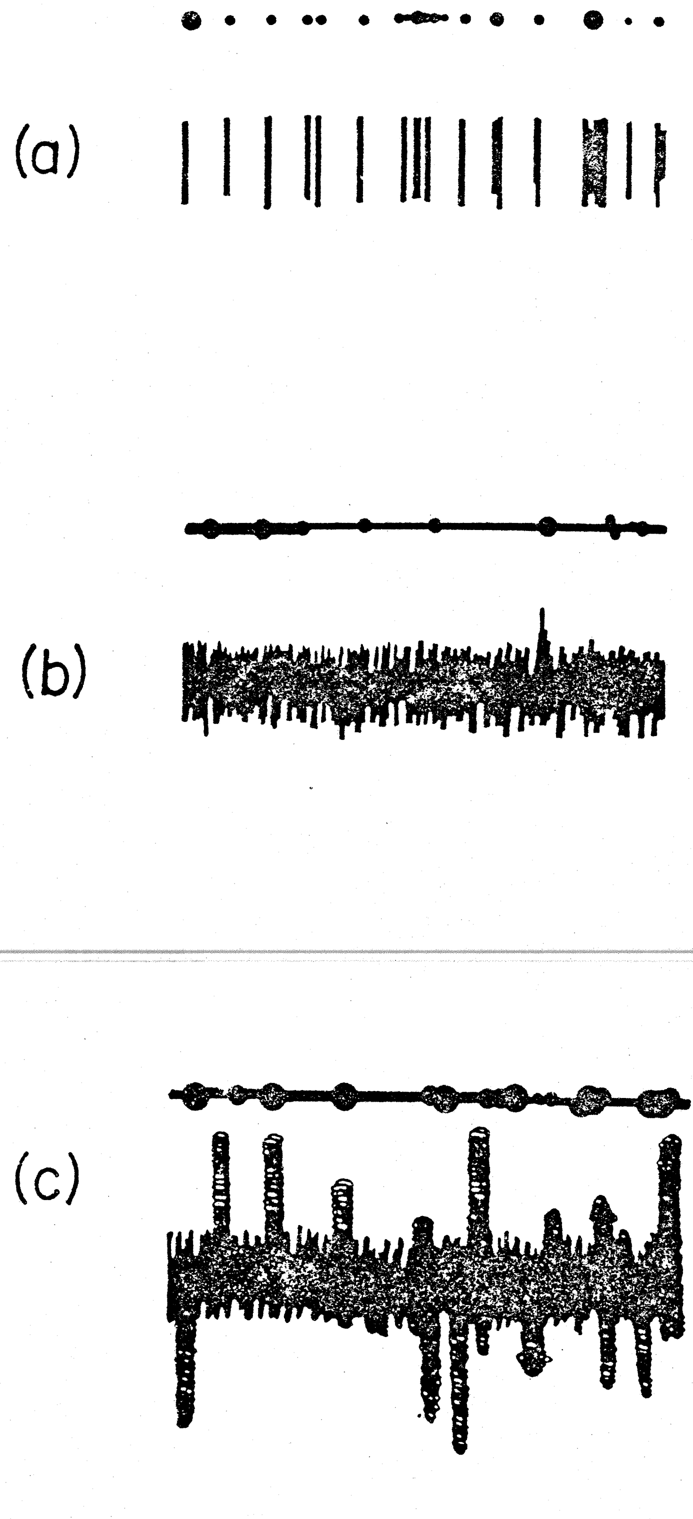
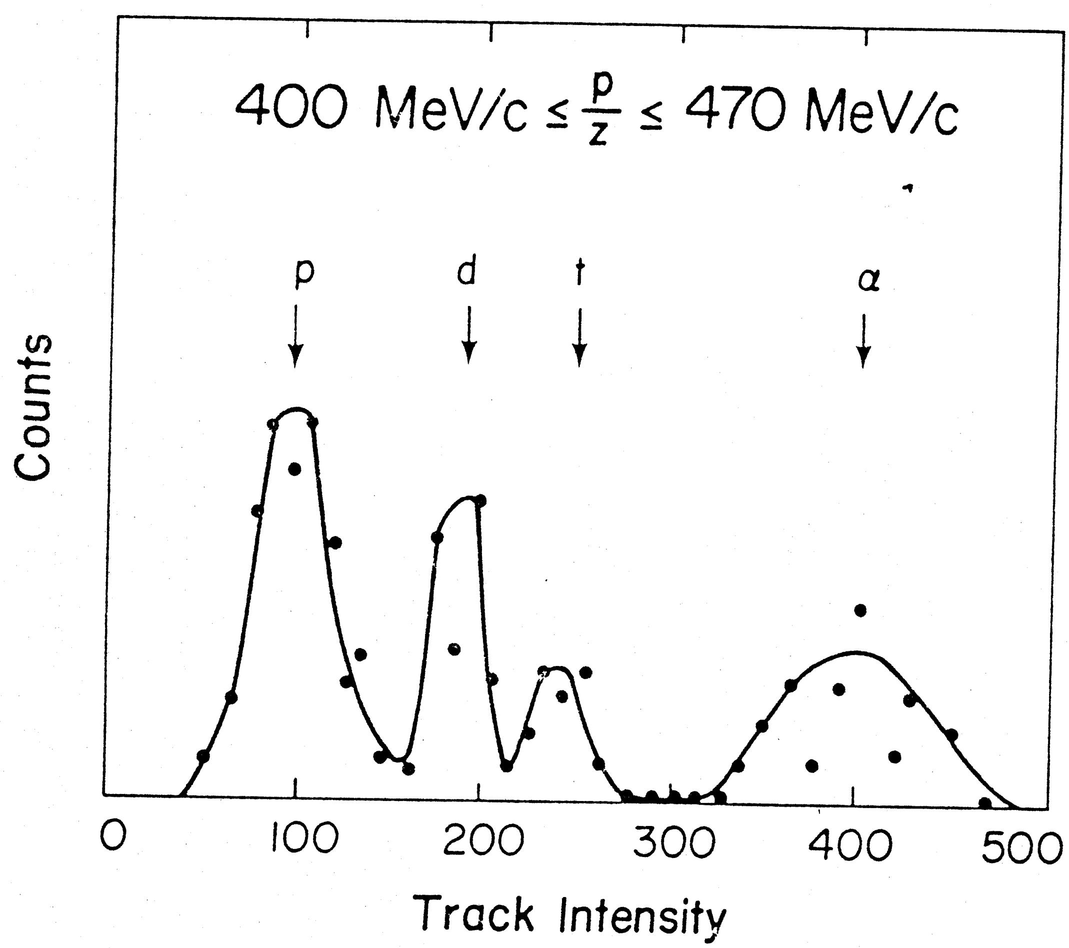


Fig. 4



XBL817-1055

Fig. 5

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STREAMER CHAMBER SOLENOID DESIGN

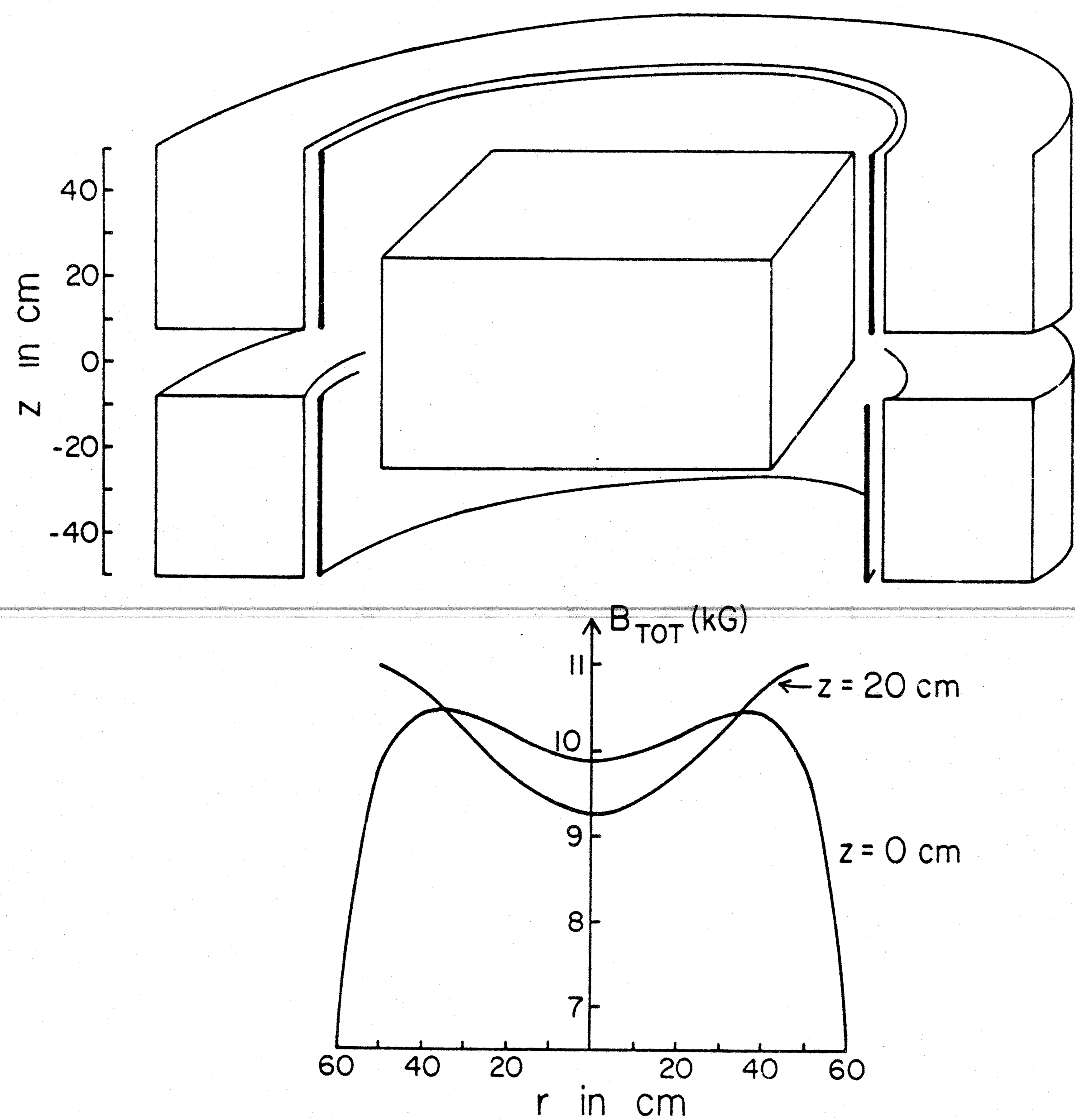
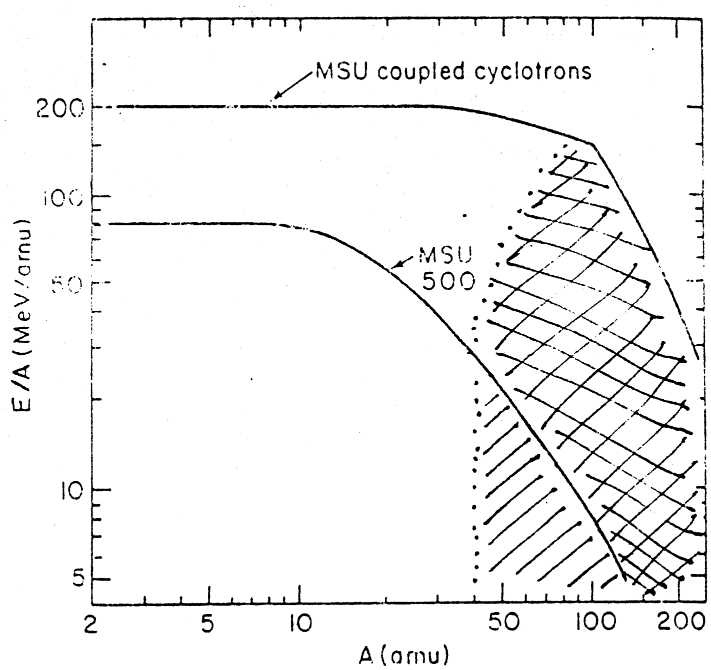


Fig. 6

Phase II Gamma-ray Devices

It is useful to review the equipment that will be available for gamma-ray studies in Phase I in order to set the stage for our discussion of Phase II equipment. There are two major items essentially in-house and a third has been proposed (to NSF externally): (a) a gamma-ray goniometer system for gamma-gamma correlation studies exists. (b) A 20" diameter scattering chamber with a thin Al lid for particle-gamma coincidence studies is under construction. (c) J. Saladin (Univ. of Pittsburg) has submitted a proposal for a Compton suppressed spectrometer system to the NSF. This is a three-quarter million dollar device designed to facilitate gamma-gamma correlation measurements that could be easily adapted to other measurements. The proposed device would be used for spectroscopic studies primarily at the NSCL. In addition various gamma-ray detectors are available, notably a new pair of 16 % gamma-X detectors and a set of 4 3" x 3" Bismuth Germanate (BGO) detectors.

We envision that the Phase I gamma-ray physics will be traditional spectroscopy or nuclear reaction mechanism studies that will rely on the highest mass beams that the cyclotron can produce. Gamma-ray studies are sensitive to angular momentum, of course, and high mass beams are used to



bring the maximum orbital angular momentum into the reaction. Figure 1 shows the nominal energy and mass capablities of the NSCL. Note that a log-log plot such as this emphasizes the few low mass beams that will be available to the highest energies. The region of the diagram that will be important to gamma-ray physics is shown by the hatched area. In Phase II we expect that the fact that gamma-ray studies will continue to concentrate on angular momenta will force such studies to concentrate on the highest mass beams. This is also indicated in figure 1 by the cross-hatched area. Even though the spectroscopic studies may concentrate on the lower energies, nuclear reaction mechanism work will certainly extend over the whole range of the capabilities of the accelerator complex. New areas that will open up in Phase II are the spectroscopic study of exotic nuclei produced in fragmentation reactions, and measurements of π_0 production in heavy-ion reactions (the π_0 decays into a pair of high energy gamma-rays). We can readily identify two areas that need the developement of new gamma-ray equipment for Phase II experiments: detectors for high energy gamma-rays, and a high solid angle modular multiplicity array. I will present some of our reasoning and the suggestions that we have come up that would enable these measurements to go forward.

1.0 HIGH ENERGY GAMMA-RAYS

Several areas of nuclear physics would require the ability to detect high energy gamma-rays, an ability that is presently lacking at the NSCL. I have already mentioned one branch, measurement of π_0 production. We already know that a large effort will go into the measurement of charged pions, and one proposal has been made by an outside user group to measure π_0's in Phase I. If we are going to instrument such measurements then we will need at least a pair of detectors that are sensitive to gamma-rays in the region of 80 MeV. Another area that has recently come into vogue is the study of nuclear deexcitation via giant E1 transitions. The existence of the transitions is reasonalbly well established, however the nature of the transitions is not well established. These transitions occur in the region of 15-20 MeV and require a detector that is more similar to a π_0 detector than a low energy gamma-ray detector. Several options are possible which would provide varying abilitites to cover this range of gamma-ray energies.

1.1 Lead Glass

If we are willing to confine our measurements to π_0 production then we should consider using a lead glass hodoscope. Moverover, there are existing hodoscopes at nearby institutions (e.g. Univ. of Indiana, Notre Dame Univ.). Such detectors could be avilable through collaboration. In view of the fact that no heavy-ion induced π_0 mesurements have been made this looks like an attractive option.

1.2 Large Volume NaI(Tl)

The traditional method for spanning the 10-100 MeV gamma-ray energy range uses large volume (10" x 15") NaI(Tl) detectors with large anticoincidence shields. These detectors are more versatile than Pb-glass in that they are sensitive to lower energy gamma-rays, such as the giant E1's. These detectors can be obtained "off-the-shelf" for of the order of 60 k$ each, or once again through collaborations using existing devices.

1.3 BGO Mosaic

A new technique for the detection of high energy gamma-rays employs a mosaic structure built up from discrete (e.g. 1" x 1" x 8" blocks) BGO detectors. The capabilities of such devices are being explored by high energy physists as electron detectors. The BGO detectors are more or less routinely available for a cost that would be similar to that of the large volume NaI(Tl) detectors just discussed. Such a detector would be even more versatile than the former detector because it is modular. We note that the device proposed by Saladin will have 14 hexagonal BGO detectors acting as the total gamma-ray energy filter. If the Saladin device is funded by the NSF then we would have the opportunity to try detecting high energy gamma-rays in the BGO mosaic.

1.4 Shielded 3" X 3" BGO

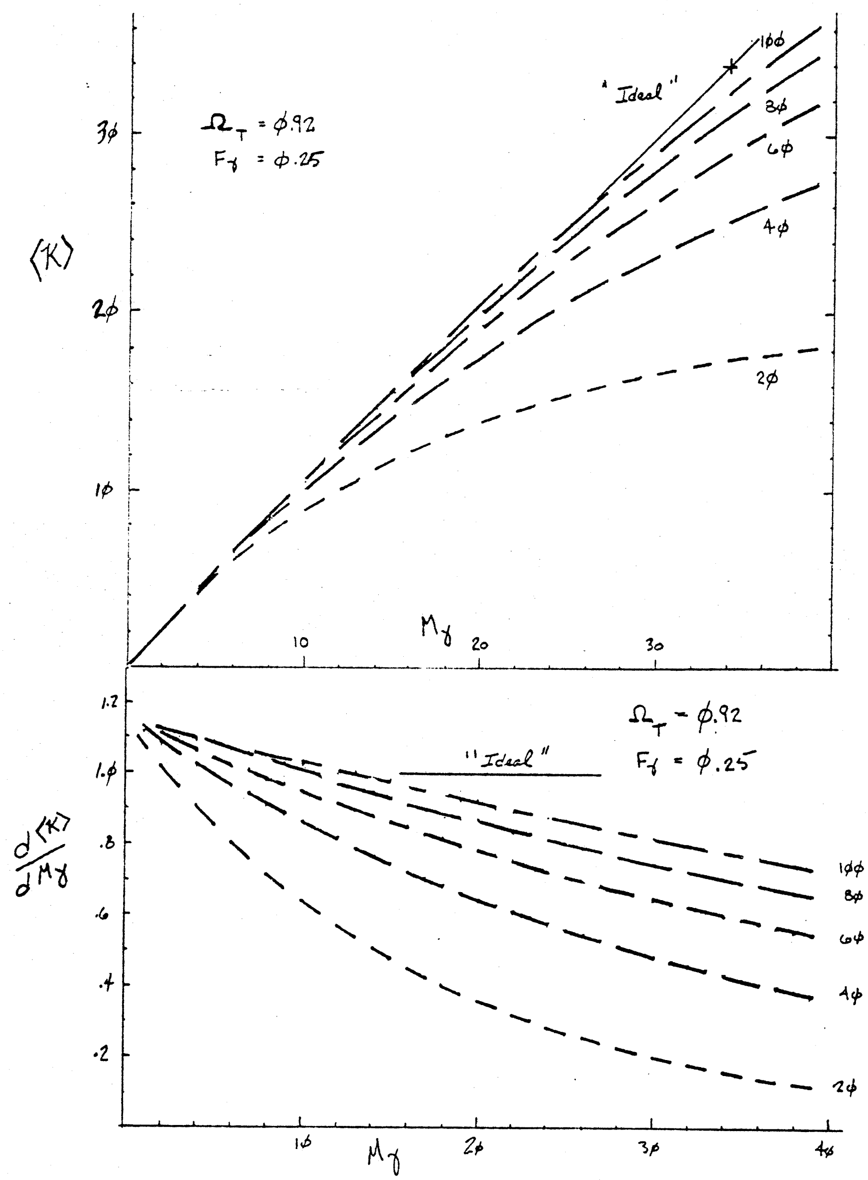
Finally, if we are willing to confine the range of gamma-ray energies of interest to the low end where the giant E1 transitions occur, then another relatively inexpensive option becomes available. The 3" x 3" BGO detectors that are in-house have a higher stopping power than the 5" x 6" NaI(Tl) detectors that were used in the initial experiments of Newton et al. (PRL 46 (1981) 1383) that identified the giant E1 transitions. We can improve the performace of the BGO by surrounding it with an anticoincidence shield. This shield is relatively compact because is surrounds a compact BGO crystal. Such a shielded detector is a novel device costing at least a factor of 5 less than a shielded large volume NaI(Tl) with a comparable stopping power.

On review, four options for detecting high energy gamma-rays are open for little or no cost. Three options which rely on existing or proposed equipment appear to be the most promising. We suggest that the interested experimenters pursue collaborative routes to the necessary detectors. However, we note that a modest R and D investment of approximately 5 k$ should be used to build an anticoincidence shield for a 3" x 3" BGO. Such shields could extend the usefulness fo the in-house BGO detectors by a large amount.

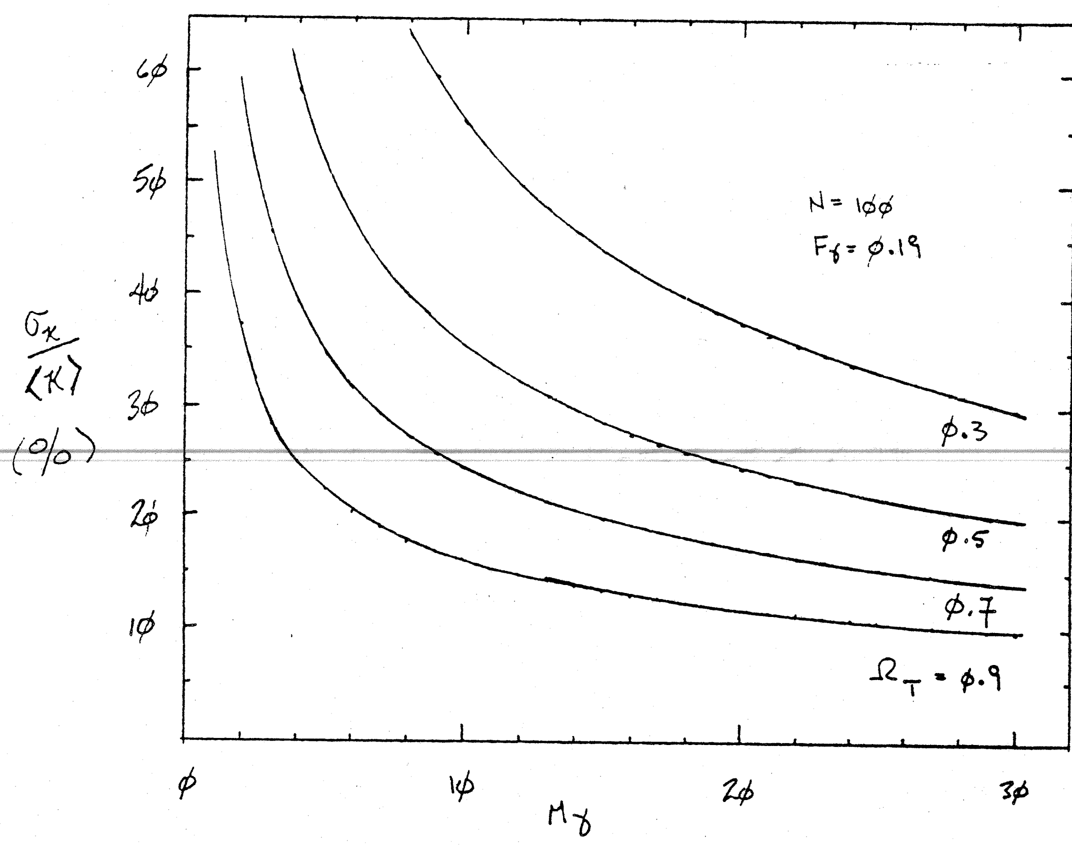
2.Ø EVENT-BY-EVENT GAMMA-RAY MULTIPLICITY ARRAY

Nuclear reaction mechanism studies and nuclear spectroscopy in Phase II experiments would be greatly enhanced if a triggerable high solid angle gamma-ray device was available. During Phase I the reaction mechanism studies will use a small number of discrete detectors to measure the average gamma-ray multiplicities and angular distributions. Initial spectroscopic studies will also have to use discrete detectors as a high spin trigger. When the Saladin device becomes available late in Phase I, nuclear spectroscopists will be able to select events by their total gamma-ray energy and only crudely by multiplicity (the sum energy part of the proposed detector system has 14 discrete elements, see later discussion). There have been two approaches to the identification of the spins of nuclear reaction products; on the one hand, the total gamma-ray energy can be measured in a relatively simple large solid angle detector nominally a sum crystal. These measurements can be complicated by the sensitivity of the detector to coincident neutrons. There are numerous examples of such devices being used in compound nuclear reactions where the ratio of gamma-rays to neutrons is 4 to 5. The other approach is to use a large solid angle multidetector array that separates neutrons by time-of-flight. The high cost of many detector elements and associated electronics is the obvious drawback to such devices. There are only two such devices in existence, the Oak Ridge Spin Spectrometer and the Heidleberg-Darmstadt Crystal Ball.

In order to create a device that is useful to both spectroscopic and reaction mechanism studies then I suggest that the device measure the multiplicity and angular distributions of the gamma-rays and relax (or perhaps eliminate) measurements of the gamma-ray total energy. The device should have a reasonably high solid angle and a large number of elements that report the passage of a gamma-ray through a given detector element, a gamma-ray "hit" array. If we use BGO for the detector material then the elements can be quite thin (2" of BGO is comparable to 5" of NaI(Tl)). The device can be designed so that the total gamma-ray energy could be obtained by simply adding the necessary electronics at a later time.

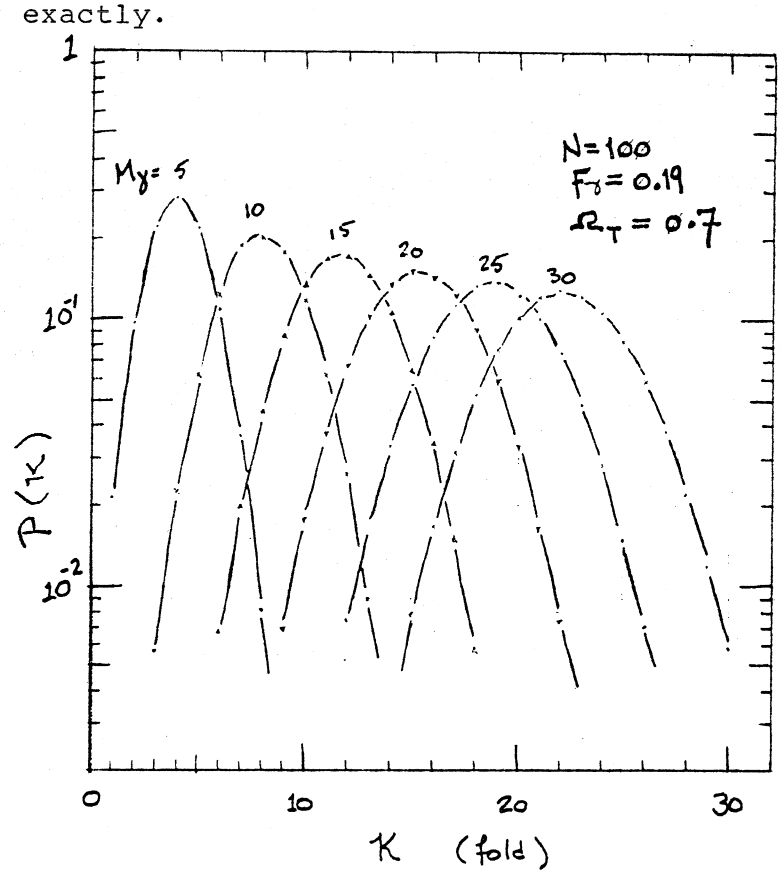

"Ideal"
10φ
8φ
6φ
4φ
2φ
$\Omega_T = \phi.92$
$F_\gamma = \phi.25$
⟨K⟩
3φ
2φ
1φ
10
M_γ
20
30
1.2
1.φ
.8
.6
.4
.2
$\frac{d\langle K\rangle}{dM_\gamma}$
"Ideal"
$\Omega_T = \phi.92$
$F_\gamma = \phi.25$
10φ
8φ
6φ
4φ
2φ
1φ
M_γ
2φ
3φ
4φ

The two parameters of the device we need to determine are the solid angle and number of elements. We can use the statistical description of such devices by Sarantities et al. (NIM 171 (1980) 503) to estimate the dependence of the response of the device on these two variables. In figures 2A and B the variation of the mean fold, <K>, (or number of detectors that fire) and its derivative are shown as a function of the true multiplicity. The independent parameters in the calculation are the number of elements in the array, the total solid angle, Ω_T , and the fraction of gamma-rays that scatter out of a given detector, F_γ. The fraction of gamma-rays that scatter out of a detector is dependent on the detector material and shape. Typical values for NaI(Tl) are in the range of 0.2 - 0.4 at about 1 MeV. If we make the elements BGO then the scattering fraction drops below 0.2, a conservative estimate is 0.19. We assume the detection efficiency is independent of gamma-ray energy.



A device with an infinite number of detectors which completely absorbed any incident gamma radiation would exhibit the behavior shown by the curves labeled "ideal" in figure 2. When, as always, we have a finite number of detectors then the mean fold must be less than or equal to that number of detectors, no matter how many gamma-rays pass through the device. The multiplicities that occur in heavy-ion reactions can range up to 5Ø or so, but we would not expect significantly higher values. A device with approximately (or of order) 1ØØ detector elements maintains a nearly linear response (+/- 2Ø%) up to a true multiplicity of 4Ø which should be sufficient for our experiments.

The multiplicity resolution of the device depends on both the number of elements and the total solid angle, but more strongly on the latter. The reduced width of the response of the device is shown as a function of gamma-ray multiplicity for several solid angles in figure 3. The reduced width varies slowly with detector number; devices with various numbers of elements but with a single solid angle describe a family of curves that would be closely spaced in figure 3. The significant fact that should be recognized in this figure is that the resolution is not degraded very much as one drops down from Ø.9 to say Ø.7 of 4π. The fold response that one would expect from such a device is shown in figure 4. A large advantage in a smaller solid angle is that the detector elements do not have to fit together exactly.



A large part of the cost of the existing 4π devices was the fabrication of specially tapered closefitting detector elements. The design of the proposed device would use the smaller solid angle in order to incorporate close packed cylindrical detectors rather than shaped detectors. An added advantage of such a design would be significantly lower cross-talk between elements, using BGO with its higher stopping power would also lower the cross-talk. In the initial configuration the electronics for the device would be only those necessary to set a discriminator when a gamma passed through a detector element plus the logic necessary to pack the discriminator bits into a small number of words.

The device we are considering is a gamma-ray multiplicity "hit" array. The device should have approximately 100 elements and cover at least 70 percent of 4π. In the initial configuration we would get only the triggering of a discrimintator. From this we can pack the multiplicity and angular distribution into a small number of words per event. If the detector elements are designed to be thick enough to stop the gamma-rays then we could expand the electronics to incorporate total energy measurements at some later time.

3.0 COST ESTIMATE FOR HIT ARRAY

3.1 Detectors

BGO / PMT / BASE ($500 / element)	$ 50 k	
Mechanical support	$ 20 k	
Subtotal		$ 70 k

3.2 Electronics

Constant fractions	$ 30 k	
Logic	$ 20 k	
High Voltage (LeCroy System 1440)	$ 20 k	
Subtotal		$ 70 k
Contingency (10 %)	$ 15 k	
Total		$ 155 k

This report was prepared by D.J. Morrissey based on the Working Group Study by D.J. Morrissey, W.C. McHarris and R.M. Ronningen.

EXOTIC BEAMS AT NSCL

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Introduction:

The NSCL coupled cyclotron facility will, for the first time, provide intense (10^{12} part./sec) heavy-ion beams with E/A up to 200 MeV. Such beams will be of immediate importance in answering many nuclear physics questions. They could also provide the laboratory with the ability to produce exotic beams (beams of unstable nuclei for nuclear physics experiments and/or one or two electron heavy atoms for atomic physics experiments) with useable intensities. The purpose of the following discussion is to investigate this possibility. Various methods of making the "pure" exotic beams as well as various classes of experiments will be addressed as to their apparatus needs for usefulness and their concommitant costs. Cost/benefit will be discussed for each approach. Emphasis will be placed on beams for nuclear physics use, but atomics physics needs will always be kept in mind.

Physics with exotic beams:

Before one invests the funds which would be needed to make useable exotic beams (be they great or small), the types of experiments for which they would be useful should be enumerated. They break down into two basic classes: 1) experiments in which an exotic beam would increase the cross section and 2) experiments which are impossible without them. Some reacion mechanisms would have different examples which would fit into both classes. These will be described first.

Some fusion-evaporation experiments would fit into the first class along with exotic transfer reactions. A much-coveted nucleus is 100Sn. Many attempts have been made to observe this doubly-closed nucleus, and all have failed. The mass and structure of this nucleus would provide important tests of existing nuclear structure theories which have been developed by comparison with the available data for nuclei near the valley of stbility. It has even been suggested that ^{100}Sn will never be observed in an experiment with a stable beam and stable target. This is supported by cross-section predictions (1) with the code ALICE. This same code also predicts that a (^{36}Ar,α-xn) reaction leading to ^{100}Sn might have a cross-section in the 1 microbarn range. Other fusion-evaporation experiments would fit into the second class. Gamma spectroscopy of several rare-earth nuclei would be possible for the first time with a proton-rich projectile. Very neutron-rich projectiles would make it possible to do gamma-spectroscopy on neutron-rich rare earth nuclei which were heretofore inaccessible by (HI,xn-yp-zα) reactions and would open these nuclei to study with the great range of experimental techniques which have been developed with stable beams producing neutron-deficient nuclei.

Exotic transfer reactions could have their cross-sections increased enormously. With a high quality beam direct-transfer of four, five, or even six protons or neutrons would be possible with reasonable cross-sections. Systematics indicate that the (^{20}O,^{16}O) reaction could have differential cross-sections as high as 1 mb/sr. Such reactions would be invaluable for spectroscopy of previously unreachable nuclei since multi-nucleon transfer reactions with stable beams typically have prohibitively small cross-sections. The (^{22}O,^{16}O) reaction could have a cross-section as high as 1 nb/sr, a small but not unuseable value provided there is sufficient integrated beam intensity. Again if the beam were of sufficient quality, this reaction could provide ground state masses and level schemes of previously inaccessible nuclei. The exotic beams could be used to do more straight-forward spectroscopy in a reverse kinematics mode as well. For example, the single particle structure of many nuclei was determined long ago with the (d,p) reaction on stable targets. Obviously it is not possible to get the single particle structure of ^{25}Ne with this reaction using a deuteron beam because ^{24}Ne targets are somewhat hard to come by. If a ^{24}Ne beam were available then the reaction could, in principle, be run as d(^{24}Ne,^{25}Ne)p.

Deeply inelastic transfer and fragmentation reaction mechanism systematics could be greatly expanded with exotic beams. The effects on both of the neutron number of the projectile could be investigated explicitly; at present there are few cases where one can study these reactions with more than one isotope of a given element. A logical part of the fragmentation studies would be a measurement of the effect of the neutron number of an isotope on its momentum distribution by measuring the longitudinal and tranverse momentum distributions after the reactions.

Atomic physicists desire one- or two-electron atoms for their work. Their experiments are greatly improved as the Z of the atom increases; so a 91+ U ion would be very attractive. To strip U to such a high charge state with reasonable intensity one needs to have an initial beam with E/A of several tens of Mev. The NSCL 40 Mev/u U beam would be quite good. If the exotic beam facility could separate different charge states of this beam (after going through a stripper) then atomic physics work of high quality could be done much more easily than with the much lower Z ions that are presently available.

This is certainly not an exhaustive list of the reactions and physics which would benefit from the availablity of high quality exotic beams. Essentially any reaction that one can imagine doing with a stable beam would provide new information if these beams were available. Production of the beams and the actual feasibility of truly useful experiments is another matter. These will be addressed below.

Production of Secondary Beams:

Experiments at the Bevalac (2) have shown that heavy-ion fragmentation reactions have large cross-sections for producing nuclei far from stability. These cross-sections were of the order of several millibarns for nuclei two or three mass units from the stable isotope of a given element. If one calculates the intensity of a given isotope using the predicted primary beam intensities of NSCL and a thick Be production target, then it is not unreasonable that secondary beams of 10^7 part./sec ($2x10^{-6}$ part. µA) would be available. This number would, of course, vary with the cross-section of the isotope desired and could easily vary by an order of magnitude up or down. Nevertheless, this production mechanism is quite attractive because not only are the cross-sections large but the reaction products occupy a small volume of phase space, i.e. the secondary beam would have a relatively small emittance (compared to other production mechanisms). The emittance is small enough that the beam could be passed through a separator of some type to remove the undesired particles from the secondary beam and leave a pure beam of one isotope. There are a variety of ways to design this separator, each having its advantages and disadvantages; several of the most logical designs are described below.

A Reaction Product Mass Separator (RPMS) (Fig. 1) designed to operate up to 200 MeV/u will be built at NSCL. The prototype is presently under construction and will be useful up to 30 Mev/u. This device combines a Wien filter (which disperses according to velocity) and a magnetic dipole (which disperses according to momentum) with appropriate magnetic quadrupole magnets to achieve a system which has a focal plane where the position of the particle depends solely on its mass-to-charge ratio (m/q). It will have unit mass resolution and would therefore appear to be the most logical way of getting a clean secondary beam and would have the lowest incremental cost. It does have several problems, however. Firstly, the beam would not truly be pure as it exits the RPMS since particles with the same (or nearly the same) m/q , eg. ^{23}Ne and ^{25}Mg, would not be separated; thus an additional clean-up would have to be done. Secondly, the location and direction of the beam as it exits the RPMS would be rather inconvenient for using the secondary beams. Furthermore, for mechanical reasons the Wien filter disperses vertically. The dipole must therefore deflect vertically also, resulting in an exitting beam which is no longer in the horizontal plane. A third difficulty comes from the the fact that to maintain maximum resolution of the system, the dipole bend angle must vary with particle velocity, thereby changing the vertical position of the focal plane and the direction of the beam. Finally, it is necessary to have a large space available downstream for the secondary beam separator in order that the apparatus for the experiment of interest can be set up. The present full-scale RPMS has essentially no space available at the exit (see Fig. 2). There are ways to address each of these problems. The beam direction problem can possibly be overcome by changing the mechanical design of the Wien filter, and the varying dipole deflection can be eliminated by always running with the same dispersion. To remove the m/q ambiguity, the beam exitting the RPMS can be run through a degrader and then a relatively low resolution magnetic spectrometer (LRS) as shown in Fig. 3. The particles exitting the RPMS also have the same momentum-to-charge (p/q) ratio since the Wien filter requires them to have the same velocity. Combined with the m/q ambiguity, there is then a p/q ambiguity. Since, by and large, the m/q ambiguities are between different elements, the different particles will have sufficiently large differences in energy loss in the degrader to remove the p/q ambiguity; the LRS could then easily separate them and give a monoiosotopic beam and also serve to limit the energy spread of the separated beam. The LRS could also be used to put the beam back into the horizontal plane if the dispersion is still vertical. Providing a useful amount of space for experimental apparatus would not be so easy and is, in fact, the most serious problem. Even a substitution of a design of approximately the same size as the prototype would not leave a great deal of room.

The present RPMS design is a compromize to allow us to exploit heavy-ion reaction mechanisms from 4 to 200 MeV/u and is, therefore, not optimized for fragmentation. Fragmentation products are fairly localized in velocity-space ($\Delta V/V < 5\%$), thus $p/q = m/q$. At these energies the particles are typically predominantly fully stripped; therefore, $p/q = m/z$. Thus, it is possible to do surprisingly good beam selection with only momentum selection with an LRS; the products would be be spread out over the device's focal plane, however. A dedicated "fragmentation RPMS", as shown in Fig. 4, could be designed to take advantage of the momentum-mass correlation and do an initial clean-up (i.e. remove the primary beam) before the reaction products enter the Wien filter. A system consisting of a LRS (to remove the primary beam) followed by another LRS (to bring the beam back to the horizontal plane and do additional clean-up) and finally the Wien filter (with appropriate multipole magnets to define the optical mode) would be quite effective for fragmentation product separation. Of course, this design still has the m/q and p/q ambiguities of the earlier design but would provide a cleaner radiation environment at the exit of the system; in all likelihood, it would not be any better for producing secondary beams than the earlier design, however, and would be more expensive.

The best design for producing isotopically pure secondary beams (and exotic beams for atomis physics) is the "fragmentation separator," which is illustrated in Fig. 4. It consists of: 1)an LRS, 2) a degrader, 3) a dispersion matching section, and 4) another LRS. This design incorporates all the ideas used above to enhance the RPMS options and would be cheaper, basically since the total number of elements is smaller. Conceptually, the sections would serve to: 1) separate the particles according to p/q, 2) use the differential degrading trick to remove the p/q ambiguity, 3) match the dispersion of the secondary particles after going through the degrader to the dispersion of the final LRS, and 4) remove the unwanted particles and form a dispersionless final focus on the target. It could also be run with a position sensitive counter in place of or following the degrader to measure the particle momentum and allow higher resolution experiments to be done with the beam, keeping in mind that the velocity spread of a given isotope would be about 5%, without throwing away beam. Obviously each of the above options would cost different amounts of money to build. Conservative estimates are given in Table I.

Experimental apparatus:

Once the isotopic beam is produced it is possible to do experiments with it. These experiments obviously need apparatus on which to be carried out. The requirements on the apparatus are somewhat different from experiments with primary beams since the emittance of the secondary beam is so much larger than that of a primary beam. An apparatus like a scattering chamber would not be any different for these experiments than for any other. If one wished to use a magnetic spectrograh there would be a price to pay. To use a "standard size" spectrograph, the emittance of the beam must be decreased, and this can only be done by throwing beam away with an accompanying increase in running time. In order to use the entire beam, a large acceptance spectrograph (LAS) would have to be constructed (Fig. 5). A precedent for this exists at the Los Alamos National Laboratory and is known as the EPICS spectrometer; this device takes the secondary pion beams, momentum disperses them on target, and the spectrograph runs in the energy-loss mode, requiring very large aperture magnets which are consequently quite expensive. EPICS cost approximately 2.5M eight years ago. Such a device would be a necessity for the high-resolution transfer reactions.

Feasibility:

Construction of any large project finally depends on a cost-benefit decision. One must decide whether the money needed to make the experiments with the secondary beams is worth the possibly large sums of money estimated earlier. Below is a discussion of the equipment needed to do a given class of experiment and the anticipated running times. The basic count rate equation is:

$$\text{rate (cnts/sec)} = \text{target thickness } (g/cm^2)$$
$$\times \text{ cross section (mb)}$$
$$\times\ 10^4 \text{ (for a beam intensity of } 10^7 \text{ part/sec)}$$
$$\times\ A^{-1}_{target}$$

Transfer reactions need a net energy resolution of <200 keV typically. Without the LAS, one must reduce the beam intensity to $<10^6$ part/sec to allow a direct measurement of the beam particles' momenta, assuming the optics of the secondary beam production allows this, otherwise large quantities of the beam must be discarded to decrease the energy spread of the beam even if the initial intensity is low. The example of the $(^{22}O, ^{16}O)$ reaction given above would be a worst case situation; the total beam intensity probably would be about 10^3 to 10^4 part/sec and the target thickness would be a few hundred micrograms. The estimated cross section is a few nanobarns/sr; thus the count rate would be less than 10^{-9} cps. The $d(^{24}Ne, ^{25}Ne)p$ example would be better with an approximate rate of about 1 cps if an LAS were available or 10^{-3} if it it were not. The fusion-evaporation experiments must have an isotopic beam and can only utilize about a 4MeV bite of it. Since the cross sections peak near the Coulomb barrier (~5 Mev/u) the 100 Mev/u beam must be degraded down to this energy with a resulting useful beam of 10^{-3} of the initial secondary beam intensity. The large cross-section (100 mb) experiments, eg. gamma spectroscopy in the rare earth region, typically rely on Ge(Li) detectors which have a low efficiency (~10^{-3}), thus negating their large cross section advantage. Also, lower efficiency gamma-gamma coincidence experiments are necessary. The targets can be 1 or 2 mg/cm^2, so the net detection rate is of the order of 10^{-6}, which is not very promising. The small cross section experiments would have even lower rates.

Deeply inelastic transfer reaction typically have differential cross sections of a few hundred microbarn/sr-Mev. Detectors are usually of the order of 0.1 msr, and targets can be a few milligrams thick. Thus, the counting rate would be about 0.1 cps/MeV. These experiments need thousands of counts/MeV, so running times would be tens of thousands of seconds (10^4 sec ~ 3 hr), which is not unreasonable. This number is correct if all of the secondary beam could be used; unfortunately it could not. The DIT reactions are not germaine at 100 MeV/u, where all the beam intensity is available, but rather at 5-15 Mev/u; the beam would therefore have to be degraded to that velocity range with the accompanying enormous increase in the beam's energy spread due to straggling. The beam should have only a few MeV of energy spread if possible. Therefore, the useful beam intensity is reduced by about 10^3 with a corresponding increase in running time. DIT reactions with secondary beams consequently seem unfeasible.

Fragmentation reactions seem to be a mechanism which could use the secondary beams. The large differential cross-sections for the reactions make them well suited for low beam intensities. They are also done at the energies at which the secondary beams are produced (remembering that the beams would be made with fragmentation reactions). Bevalac experiments have been done with 10^6 part./sec; this is the best supporting datum for the feasibility of fragmentation studies with secondary beams.

Conclusions:

A variety of techniques for producing isotopically pure secondary beams has been discussed along with possible interesting physics for which they could be used and the special hardware needed to do them. The feasibility of doing any class of experiment was also addressed, and it was found that few experiments would actually be practical. The large cost (1M or more) is thus probably not justified at this time.

A relatively inexpensive alternative can be found by examination of the beamline which exits the K800 cyclotron. A production target could be placed at the exit of the cyclotron; an appropriate redesign of the beamline would result in a configuration that resembles the "fragmentation separator." The modifications needed to get a system of moderate capability would not be large; this beamline-separator would also be well suited to providing the atomic physics beams. Such a system would also make the exotic beams available to any experimental area since the beamline-separator is before the main switch-yard magnet. The price to be paid is intensity of the secondary beams. The beamline elements are not sufficient to transmit the entire phase space of the secondary beams; to make them such would be enormously expensive (> 1M). With this scheme one could begin to make and use secondary beams before investing large sums of money into special,dedicated equipment. Also, the atomic physics option is made available rather easily. This is the recommended course of action for NSCL as regards exotic beams.

References:

(1) D. Morrissey, private communication.

(2) G.D. Westfall, et al., PRL 43 (1979) 1859, and references therein.

Table 1

Cost Estimates for Exotic Beam Hardware*[1]	
Fragmentation RPMS	$ 650K
Low Resolution Spectrometer (LRS)	300K
Fragmentation Separator	900K
Large Acceptance Spectrometer (LAS)	1800K
LAS - EPICS Mode	1700K
Modified K800 Extraction - Beamline[2]	50K

1) *These estimates are approximate and conservative.

2) *The modified-beamline option assumes that standard aperture magnets are used, with a resulting loss in transmitted beam but much reduced cost.

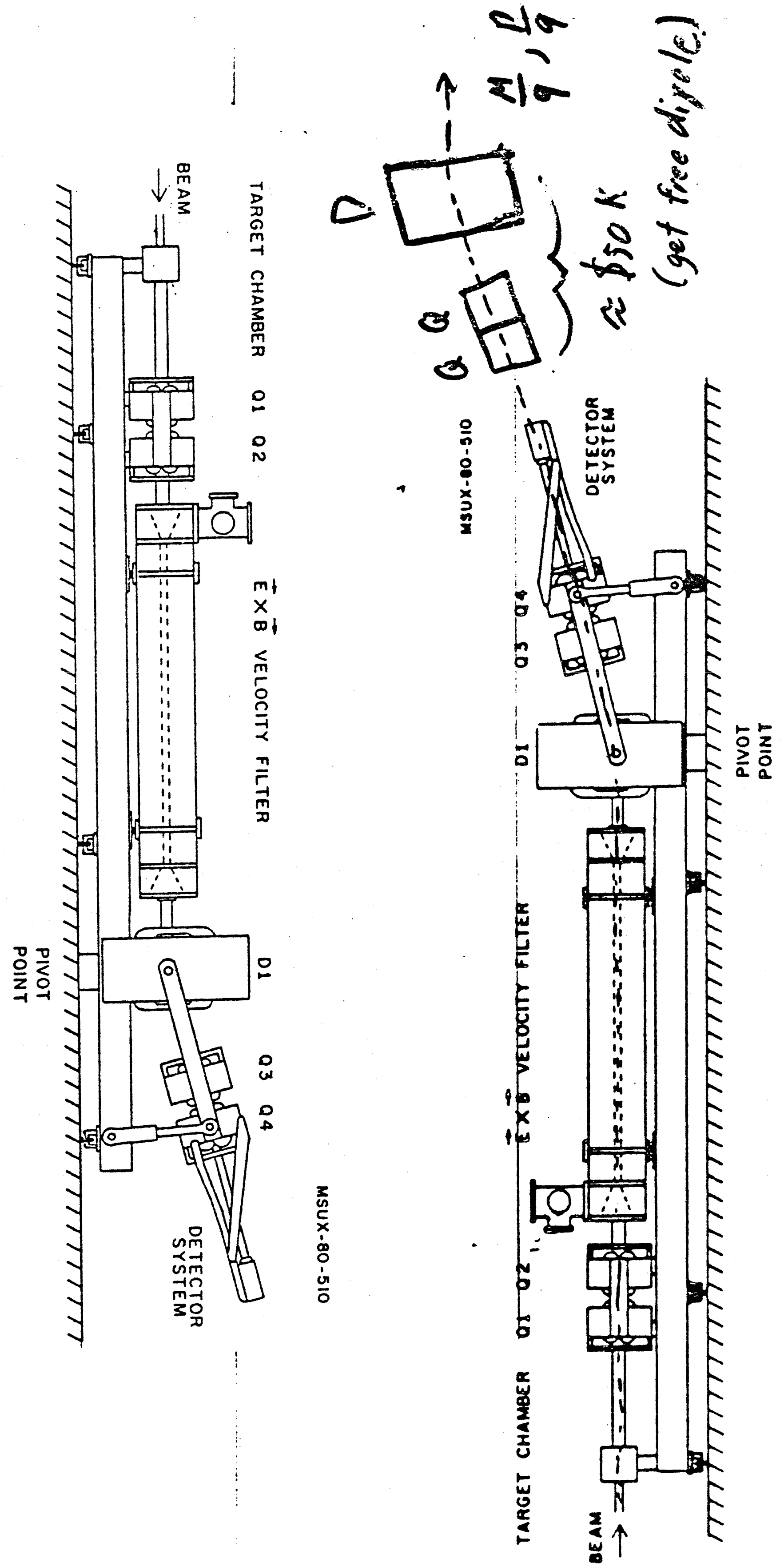

BEAM
TARGET CHAMBER
Q1 Q2
$\vec{E}\times\vec{B}$ VELOCITY FILTER
D1
PIVOT POINT
Q3 Q4
DETECTOR SYSTEM
MSUX-80-510
Q Q
D
$\frac{M}{q}, \frac{P}{q}$
≈ $50 K
(get free dipole)

Fig. 1

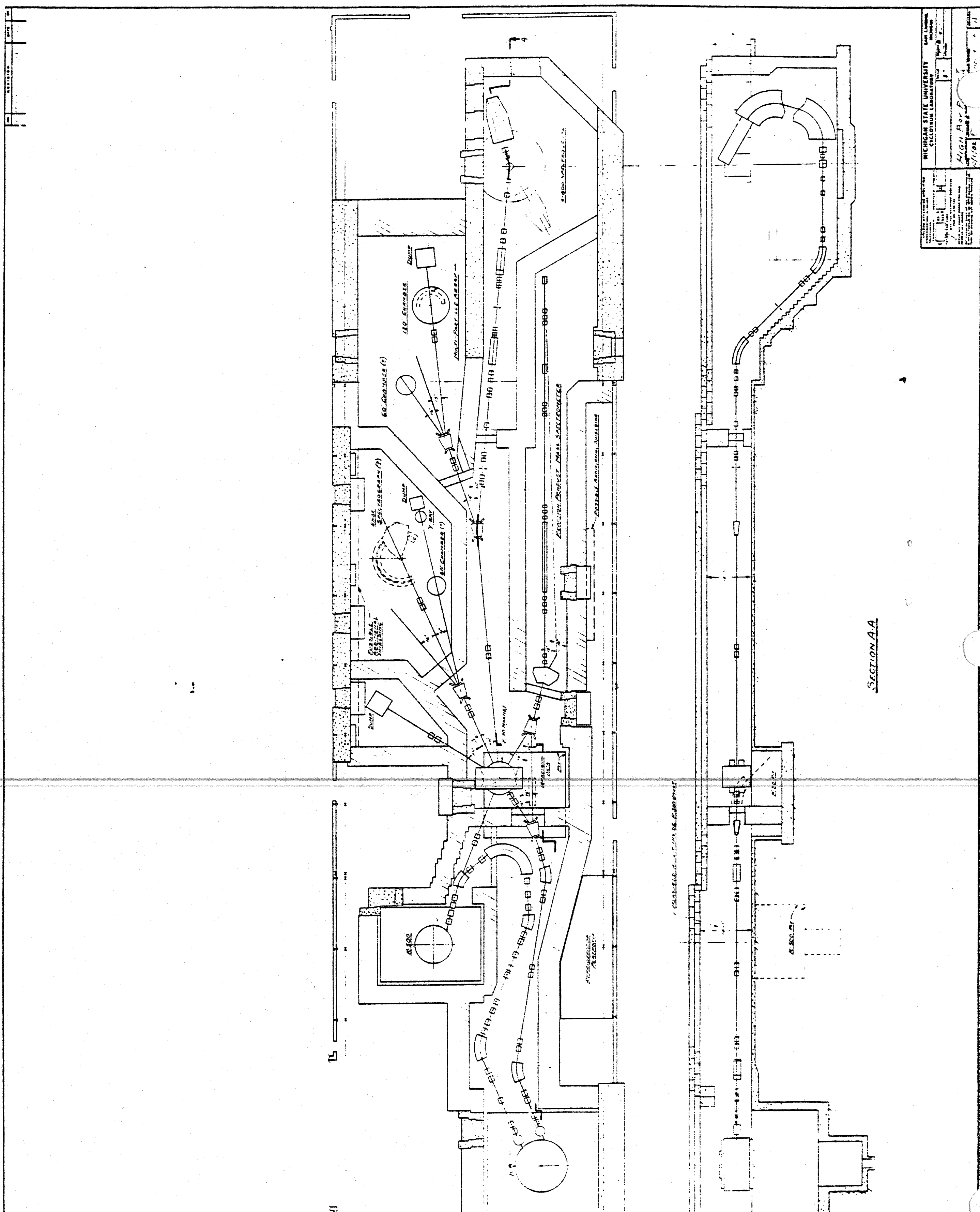
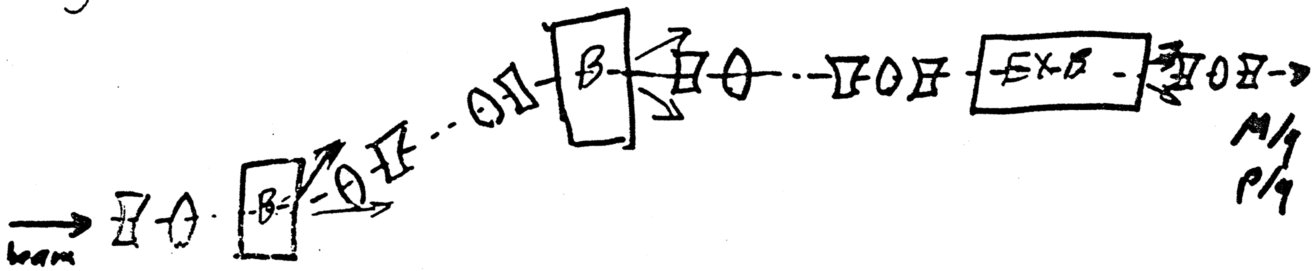

MICHIGAN STATE UNIVERSITY
CYCLOTRON LABORATORY
SECTION A-A

Fig. 2

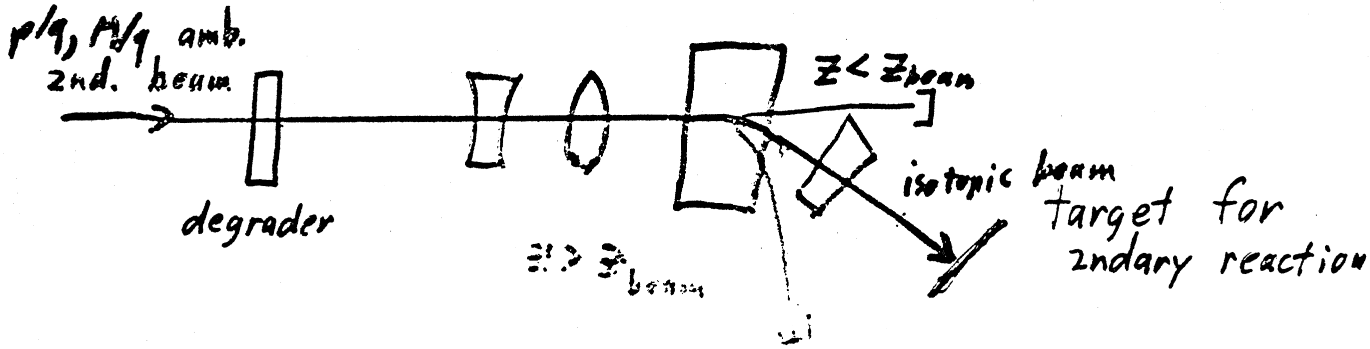
Fragmentation RPMS: fixed at 0°



Costs:

Multipoles	≈ 250K
Manpower	≈ 250K
Power supp.	≈ 50K
other	≈ 100K
	650K

Low Resolution Spect.: 1) cleans up beam energy spread; 2) removes M/q ambiguity

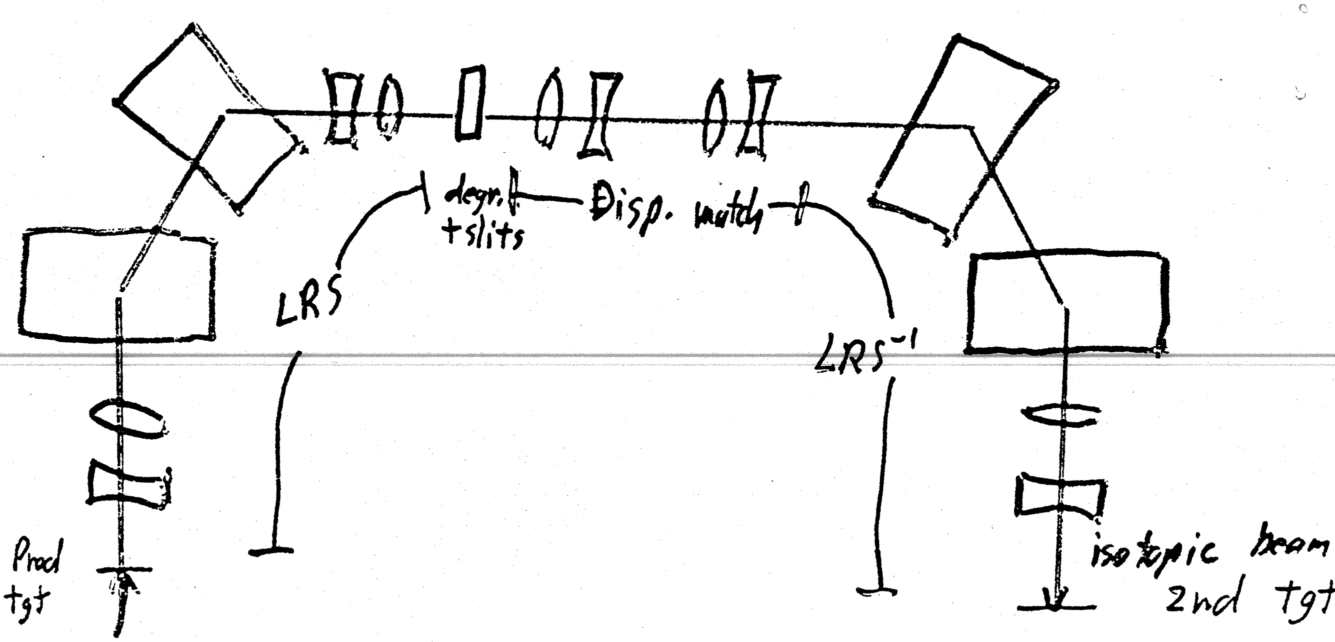


Cost: ≈ $300K

Fig. 3

Fragmentation Separator

1) Isotopic beams
2) Can clean up energy spread
3) Atomic physics beams
4) Isochromat

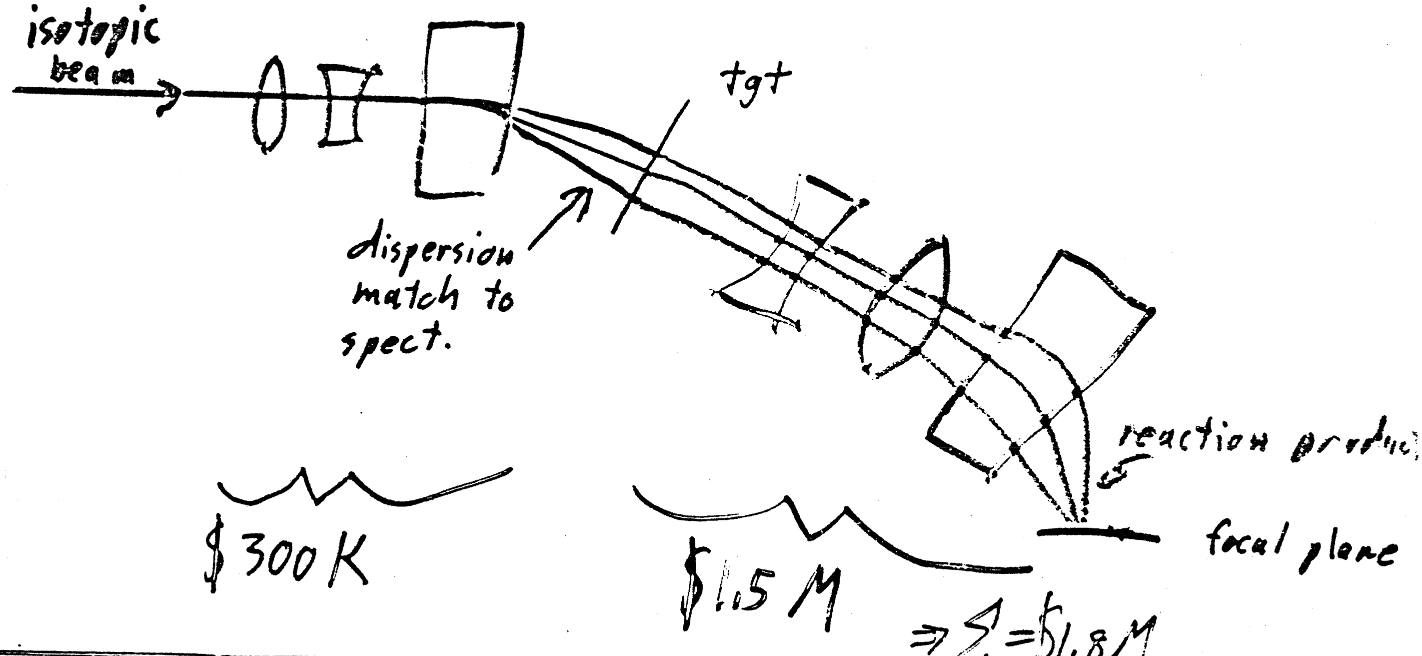


Cost: 2 × (400K) (LRS
100K D.M.
$900K

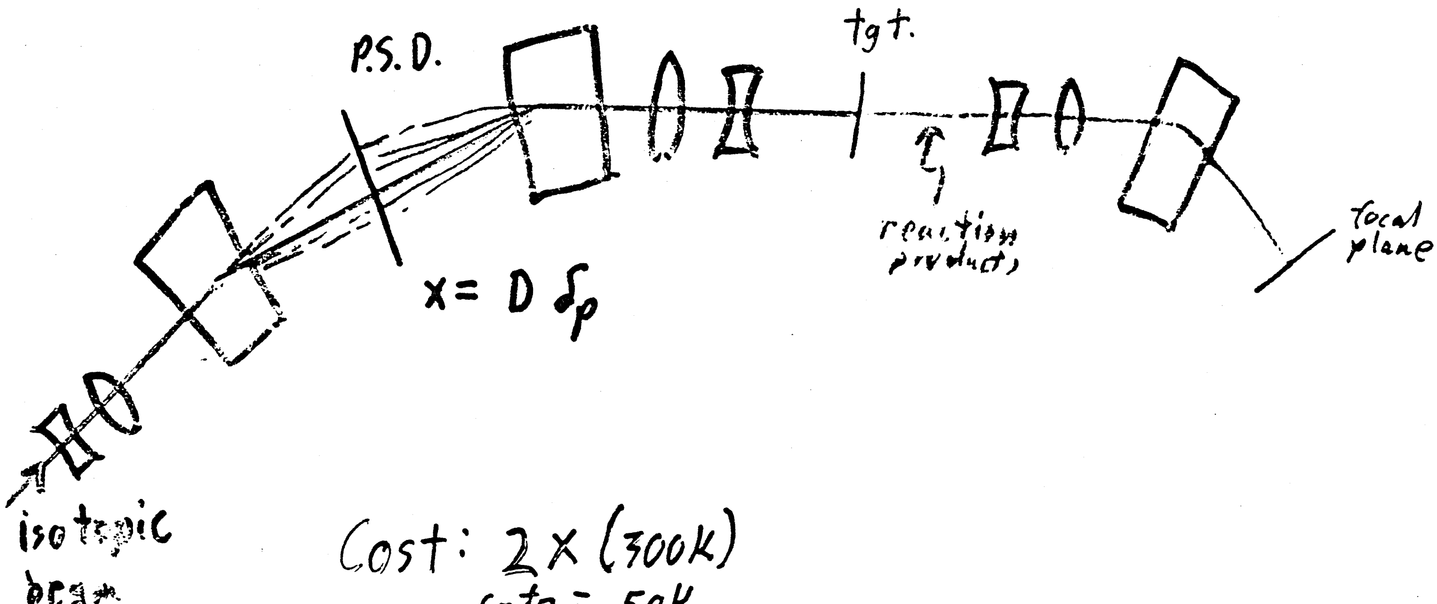
Nice features: 1) combines RPMS, tail, + LRS
2) RPMS still available
3) can be run so $\frac{\Delta p}{p}$ of secondary beam is small
4) Maybe in EPICS mode
5) Perfect for atomic beams

Fig. 4

Large acceptance spect.: uses all of beam for transfer reaction (energy-loss mode)



L.A.S. — EPICS



Cost: 2 × (300K)
cntr = 50K
spect ≈ $1 M
$1.7 M

Fig. 5