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EXPERIMENTAL UTILIZATION OF COLLIDING BEAMS

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I. Introduction

Since the original suggestion by Kerst[1)] that FFAG accelerators would provide sufficient intensities to make the interaction rates between colliding beams interesting for experiments, a great deal of study has been given to the accelerator problems related to achieving such beam-beam collisions. Out of these studies have come the beam-stacking concepts[2)], the Two-Way Radial Sector FFAG[3)], various storage ring geometries[4)], and other developments. Relatively less thought has gone into the questions of experimental utilization of such interactions. To a certain extent this may be justified: the accelerator problems to be encountered are anticipated at present, while the physics at 10 to 30 Gev in the center of mass is at least one generation beyond current experience. It is thus possible that the experiments and techniques that will be of greatest interest with colliding beams have not yet been conceived. Of course this very lack of knowledge is one very strong motivation for producing colliding beams.

Below, the qualitative features of interactions at high center-of-mass energies as deduced from cosmic ray evidence are briefly reviewed,

and the characteristics of colliding beam devices together with representative working formulae are summarized. The type of experiments one might do are discussed in the light of these considerations; first, the direct observation of the colliding beam region and second, the experiments done with colliding beam reaction products.

The material in this paper should be regarded as a review rather than an original contribution; virtually all the considerations discussed have been worked out by various members of the MURA organization and its visitors. In particular, valuable contributions were made during the MURA study group in June of this year.

II. Physical Interest and Information

The most obvious motivation for going to very high center-of-mass energies with colliding beams is the search for undiscovered particles and the subsequent study of their properties. Although the primary proton-proton interaction cannot occur in the active volume of a detector, it should be pointed out that particles with very short lifetimes may be detected, as in the case of the π^0 and Σ^0, through correlations in their decay products or production kinematics. In the limit of very short lifetimes, the distinction between a resonance of a certain scattering process and the existence of a "particle" becomes unclear.

The cross sections and angular distributions of known particles may provide fundamental information about their properties and about the structure of the proton itself; while less dramatic than the discovery of new particles, this could be of more fundamental importance.

According to the concept of a nucleon consisting of a core surrounded by a meson cloud, the proton-proton collisions might fall roughly into three classes; the abundant cloud-cloud collisions (corresponding perhaps to pion-pion scattering), less frequent cloud-core collisions, and rare (but perhaps of greatest interest) core-core collisions.

Cosmic ray evidence based on a few hundred stars in emulsion stacks provides generic information on the nature of such high energy interactions. Based on proton-proton collisions of average center-of-mass energies of 80 Gev, Schein finds that: 1) The energy distribution of secondary particles in the center-of-mass is peaked at about 300 Mev and falls off with a very small tail extending beyond 10 Gev. 2) No more than 15% to 20% of the secondaries are particles other than pions. 3) The transverse momenta of secondaries are between 0.2 and 0.8 Gev/c, (average 0.30 $\pm$0.04 Gev/c) remarkably independent of their energy or of the primary energy. 4) The angular distribution in the center of mass is peaked in the forward and backward directions; the peaking being more pronounced at higher energies. 5) The events are on the average only 40% inelastic (i.e., 40% of the available energy goes into producing secondaries). As an educated guess, they might be 50% to 60% inelastic at 20 to 30 Gev. 6) The pion multiplicities are low (20 to 25) and so far cannot be satisfactorily explained by existing statistical theories.

It should be re-emphasized that these conclusions refer to the class of events studied by cosmic ray emulsion groups; it is not unlikely that

other classes of events, perhaps those of greatest interest, are not studied by virtue of their infrequent occurence or the emulsion scanning procedures.

III. Properties of Colliding Beams

A. Limitations on Stacked Beam Currents

In this and subsequent discussions, two methods of achieving colliding beams will be emphasized; the first employing a Two-Way Radial Sector FFAG accelerator for both accelerating and stacking the beams in both directions and the second employing a spiral sector FFAG accelerator to accelerate and stack a beam in one direction and then inject it into storage rings which intersect at several points as proposed by O'Neill[12)] and carry beams in opposite directions. A third alternative, injecting into storage rings from an alternating gradient synchrotron and stacking the successive beam pulses with rf in the storage rings, is not elaborated upon here.

The ultimate beam-beam interaction rates and interaction densities in colliding beams depend on the current and current densities stacked in each beam. Formulas for the ultimate theoretical limits on current and current densities have been given elsewhere[6)].

The current and current density achieved in practice in a colliding beam device depend on the degree to which other effects on the stacked beam may be minimized or neutralized. These are discussed at length in many MURA reports and will only be enumerated here[6, 9)].

The betatron oscillation frequencies of the stacked beam may be detuned due to space charge and self-magnetic field forces. These are particularly serious if the beam is neutralized by electrons (from ionization of the residual gas) so that the proton beam is allowed to "pinch". The slow electrons may be swept clear of the beam by electric fields parallel to the magnetic field with potentials of tens of kilovolts. Image charges and currents on the magnet poles modify the space charge forces and in the case of large stacked currents would require partial neutralization by pole-face currents[10]. Detuning of the vertical oscillations and the vertical perturbations of the equilibrium orbits may result from beam-beam interactions at the colliding beam azimuths. For a moderate number of such regions these effects are not serious below currents of hundreds of amperes. Other effects, such as longitudinal space charge forces, have been considered and have been shown to lead to no instabilities in the stacked beam for reasonable parameters.

It seems a reasonable general conclusion that circulating currents of the order of 10 amperes should be achieved with a minimum of simple compensations, currents approaching 1000 amperes require elaborate compensations (e.g., pole-face currents), and circulating currents in excess of 1000 amperes, while possible to contemplate, will surely lead to many very difficult problems.

The lifetime of a stacked 15 Gev beam at a vacuum of 10^{-9} mm Hg in a Two-Way FFAG is 8.4 hours due to multiple scattering, 50 hours due to single scattering alone, and 50 hours due to nuclear collisions. In

each case the figures refer to a 10% beam loss.

In computing estimated beam intensities in the tables below, safety factors of at least 4 have been included in the theoretical formulae based on ideal preservation of phase space density.

B. Interaction Rates

The proton-proton interaction density for both protons highly relativistic is given by

$$R = 2n^2 \sigma c \cos^2 \frac{\alpha}{2} \qquad \frac{\text{interactions}}{\text{cm}^3\text{sec}}$$

where n is the number of protons per unit volume in either beam, σ is the proton-proton cross section, α is the angle at which the beams collide, and c is the velocity of light. For σ = 25 mb,

$$R = 65J^2 \cos^2 \frac{\alpha}{2}$$

where J is the current density of either beam. The total number of interactions in a region where a beam of current I, vertical height Δy and radial width Δx intersects a similar beam at an angle α is given by

$$P = \int R dv = \left(\frac{65\, I^2 \cos^2 \frac{\alpha}{2}}{\Delta x^2\, \Delta y^2}\right)\left(\frac{\Delta x^2 \Delta y}{\sin\alpha}\right) \quad \text{(see Fig. 1)}$$

or

$$P = \frac{65\, I^2}{\Delta y \cdot 2 \tan\frac{\alpha}{2}}$$

and for small α

$$P = \frac{65\, I^2}{\alpha \Delta y}$$

The interaction density with the residual gas in the vacuum chamber is given by

$$M = \frac{J}{q}\, n\sigma \qquad \frac{\text{interactions}}{\text{cm}^3\text{sec}}$$

where n is the average density of nucleons in the gas, assuming each gas molecule has 28 nucleons and σ is 25 millibarns.

In terms of the gas pressure, p , in millimeters of mercury,

$$n \cong \frac{10^{18}}{p} ,$$

thus

$$M = 1.56 \times 10^{11} \text{ Jp.}$$

In the target region, a current density J exists in both directions so that 2M is the relevant quantity.

For a total current I, the total number of background events in a length l of vacuum chamber is given by

$$N = 1.56 \times 10^{11} \text{ I pl} \quad \frac{\text{interactions}}{\text{sec.}}$$

The ratio of beam-beam to beam-background interactions within the target volume is given by

$$\frac{R}{2M} = 2.10 \times 10^{-10} \frac{J}{p} ,$$

so that for equal beam-beam to beam-background interaction rates,

$$J \cong 5 \times 10^{9} \text{ p} .$$

For 50 amperes per cm^2, this gives a "signal to noise" ratio of unity at 10^{-8} mm Hg. Of course, background events will come from a much larger volume than beam-beam events.

C. Numerical Examples

As a result of the considerations above, representative currents, current densities, interaction rates, and background rates for 10 Gev colliding beam devices are given in Table II for the two alternatives of

Table I. It may be noted that a 1000 ampere, 10 Gev proton circulating current in an accelerator of 125 meter radius represents a stored energy of 20 megajoules.

As a comparison, in a single high energy proton beam of 10^{10} protons per pulse, one pulse every 5 seconds, 2 x 2 cm in cross section passing through liquid hydrogen would produce 5×10^5 interactions per cm^3 second. The same beam incident on a dense target might produce one nuclear interaction for every 5 primary protons, or 4×10^8 interactions per second.

The choice between a Two-Way Radial Sector machine and a Spiral FFAG with storage rings rests in balancing the more favorable geometry and ultimate current density of the storage rings with the complexities of beam transfer and the ease of variability of colliding beam energy with the Two-Way FFAG. In either case the cost of providing colliding beams would appear to add about 20% to 30% over the cost of a single high intensity Spiral Sector FFAG accelerator installation. A general property of colliding beam devices is the reduction in current density and interaction rate at less than maximum energy. This is of course due to the adiabatic damping of the beam dimensions and the radial width occupied by a given momentum interval. For example, in the case of a scaled Two-Way FFAG ring, the current density is proportional to the stacking energy squared, and the interaction density to the stacking energy to the fourth power.

D. Background

For reasons of beam life and especially of source "purity", the attainment of vacuums of 10^{-8} mm Hg or better has been assumed necessary for a useful colliding beam structure. In discussing possible experiments it is of interest to know what background fluxes of various particles might be expected in the neighborhood of the interaction volume due to collisions up-stream and down-stream from the target straight section between the circulating beams and the residual gas. An approximate calculation has been made by Lichtenberg[11)] assuming a simplified angular distribution of secondaries approximately representative of the cosmic ray data and a multiplicity in each collision equal to the average multiplicity. The geometry is assumed to be a ten meter colliding-beam straight section with iron magnets extending to infinity at either end. Since shielding could be erected to fill the accelerator or storage ring tunnel around the magnets near interaction region, the straight section is assumed bounded by plane walls of material equivalent to iron. Table IV summarizes the results of this calculation for one set of parameters. p is the radial distance from the beam axis and s is the azimuthal distance from the center of the straight section to the volume element through which the flux is tabulated.

IV. Experiments with Colliding Beams

In general, the luminescent or scintillation chamber is thought of as an important tool for exploratory investigation of the primary interaction. Its fast time resolution together with its ability to be triggered

by an event of interest make it well suited to this purpose. Fast scintillation and Cerenkov counter arrays will be very useful for systematic studies of known types of interactions and products allowing use of higher currents and interaction rates than luminescent chambers. While the luminescent chamber has not yet been used in high energy physics research, particle tracks in scintillators have been photographed by Zavoskii in the U. S. S. R. and within the past year by four groups (Michigan, Pennsylvania, Princeton, and M. I. T.) in the United States. As a result of these successes and associated measurements, there is no reason to question the essential practicality of chambers made either of plastic scintillator filaments or of inorganic (NaI or CsI) solid crystals or filaments. The major inhibition to the more rapid development and use of luminescent chambers is the limited commercial availability of high quality image intensifier tubes. In view of the recent progress in image tubes, it is altogether reasonable that entirely satisfactory tubes will be available well ahead of colliding beams.

It is possible to envisage a luminescent chamber consisting of 60 cm. of plastic scintillator filaments above and below the colliding beam region extending 2 to 4 meters in either direction along the beam and one meter perpendicular to it, as in Fig. 2. This could be backed up on two or three sides by a dense scintillator (NaI or CsI) 20 cm. thick for efficient conversion of γ rays. Since the combination is more than a nucleon mean-free path in most directions from the target, the majority of all

baryons, π or K mesons, or γ rays would be observed to interact (or decay) in the active volume. The spatial resolution throughout the volume would be about one millimeter and the time resolution one microsecond. Such a chamber would subtend a solid angle from the target region into which 60% to 80% of the reaction products would go on the average.

With such a chamber the following procedure would be used: The beams would be turned down to about one ampere circulating current while maintaining a moderately high current density. Referring to Table III, a storage ring pair carrying 1 ampere at 100 amperes per cm^2 each direction would produce about 6×10^3 beam-beam interactions per second in one straight section and 3×10^5 beam-background events per 10 meter straight section at a vacuum of 10^{-9} mm Hg. The chamber cameras would be triggered so as to record only beam-beam collisions by demanding a simultaneous appreciable ($>$ 3 Gev) energy released in the scintillators both upstream and downstream from the target region. At a vacuum of 10^{-9} mm Hg only one picture in 3 would also contain a beam-background event with a one microsecond gate. Since background interactions would be more numerous than beam-beam interactions at this reduced current, by a factor of 100 or so, this method of triggering would be convenient to eliminate scanning of many photographs for beam-beam events. From such photographs, searches for new particles and for interesting properties of the interaction could be made. Electronic scanning or direct handling of the picture information

utilizing television systems could make possible analysis of pictures containing several events, in which case the beam could be turned up to a higher "signal-to-noise" (beam-beam to beam-gas interaction) ratio for accumulation of statistics on particular rare events. Ionization information would be available from scintillation tracks, but the resolution will be too low for good multiple scattering measurements.

While the above brute force, straightforward luminescent chamber would be generally useful, some modifications might be desirable in certain colliding-beam regions.

It would be desirable to have access to secondary particles close to initial beam direction. Thus, in the rather extreme case of a 9 Gev/c secondary with 0.3 Gev/c transverse momentum, access to secondary products within .03 radians of the beam direction will be important. A luminescent chamber 2 meters long, 10 centimenters from the beam axis placed three meters from the colliding beam region could effectively study such particles (Fig. 3). A magnetic field could be placed through the luminescent chamber and intersecting beam region horizontally as proposed by the Princeton group in such a way as to produce no net perturbation on the circulating beams (Fig. 4)[12].

While this configuration is particularly appropriate for storage rings, it is also feasible with the FFAG two-way accelerator.

Cryogenic pumping by surrounding the target region with liquid hydrogen or helium has frequently been suggested, and calculations by the Princeton-Pennsylvania group indicate it would effect a significant

reduction in background from the target region. They propose incorporating a liquid hydrogen bubble chamber around the intersecting beam region both as a detection device and as a vacuum tank refrigerator.

The time resolution of the luminescent chamber is ultimately limited only by the transit time of light and particles back and forth across the chamber volume. For a one meter chamber, this time is of the order of 10^{-8} seconds. The spatial resolution is limited ultimately by scintillator filament diameters equal to the cutoff diameter for visible light transmission. In practice, the diameter is limited by fabrication techniques and by problems of surface defects limiting total internal reflection. These are technical problems which will yield to continuing effort.

More systematic analysis of colliding beam events could be made with counter arrays observing the interaction region. Experiments are being run at the Bevatron using hundreds of photomultipliers. The fast time resolution (5×10^{-9} seconds) plus the developing ability to handle rapidly the information from many separate counters makes their utilization in this case very feasible. With complex counter arrays, the beam intensities could be increased above those useful for luminescent chambers (100 amperes circulating each way). If only one p-p collision in 10^3 produces an event of interest and if the solid angle subtended by each counter is 10^{-4} steradians, it would be possible to collect several events per minute. Time-of-flight counter arrangements designed to detect specific particles are useful with present accelerators (e. g. K

detectors, $\overline{P}$ detectors, $\pi-\mu$ detectors, etc.) and would be included in the arrays referred to above. In view of the moderate average energy of secondaries they could be used in much the same way that they are currently.

Combinations of counters and luminescent chambers are of course possible and would add to the general flexibility of experimental facilities.

A. Observation of Secondary Particles from Colliding Beams.

Conventional techniques (counters, bubble chambers, etc.) would be useful in the usual way to analyze beams of secondary particles from the colliding beam region. Quadrupoles, shielding, and electromagnetic separators would be arranged about the target region to direct analyzed beams into detectors. The primary purpose of such experiments would be to study new, long-lived particles produced at high center-of-mass energies. For particles produced close to threshold, with relatively low energy in the lab, the most favorable viewing direction is in the direction of the center of mass "drift" motion (due to the finite beam collision angle).

Cosmic ray evidence indicates the greatest flux of particles will be in the direction of either incident proton-proton beam for secondaries of appreciable energies. Thus, it would be desirable to make available beams of particles of either sign centered within 0.1 radian of the initial beam direction with momenta up to 1 Gev/c less than the initial protons. Such a requirement seems reasonable for the colliding beam geometries considered. For such experiments the maximum beam-beam interaction

density would be used to produce the highest possible particle flux in a given momentum and solid angle interval.

It would also be highly desirable to be able to vary the colliding beam energy from a maximum down to energies of single accelerators (6 to 8 Gev center of mass). If a new particle is found, its production section close to threshold would probably be important.

V. Conclusion

It appears technically feasible to reach center-of-mass energies of 20 to 30 Gev using colliding beams either in an FFAG accelerator or storage rings. Making use of the luminescent chamber and fast counting techniques, direct observation of the particles from the primary proton-proton interaction seems reasonable. Secondary beams may be prepared as with conventional accelerators, and optimum performance figures for colliding beam machines give estimates for production rates comparable to those from a conventional accelerator operating at 10^{10} protons per pulse.

It is probable that entirely new detectors and techniques will evolve to make fullest use of colliding beams. Unless the trend in physics over the past thirty years is suddenly reversed, an increasing interest in the physics at energies made accessible through colliding beams may be expected in the future.

TABLE I

Machine Parameters

	10 Gev Mark I Two-Way	10 Gev Mark V One-Way	10 Gev Storage Ring Pair
Radius (meters)	124	50	50
Circumference factor	6.0	2.0	2.0
B max on Eq. orbit (gauss)	17,500	14,400	14,400
N (no. sectors)	62	30	32
	k = 212	k = 53	n = 302
tan γ (spiral angle with circle)	-	.1	-
λ_r (radial spacing of spiral)	-	1.05 meter	-
ν_x	24.75	8.4	8.4
ν_z	4.3	7.2	7.3

TABLE II

Characteristics of Colliding Beams In
A 10 Gev Two-Way Radial Sector FFAG

J $\frac{\text{amps}}{\text{cm}^2}$	190	190	50
I Total amperes each way	800	200	1
R Beam-beam interaction per cm^3 sec.	2.3×10^6	2.3×10^6	1.6×10^5
Δy (centimeters)	2	1	~ 0.1
P Beam-beam interactions per straight section sec.	10^8	1.5×10^7	3.2×10^3
ℓ Length of interaction region (centimeters)	20	10	1
2M Background interactions per cm^3 sec $p = 10^{-9}$ mm Hg	6×10^4	6×10^4	1.5×10^4
$2M\ell$ Background interactions per straight section $p = 10^{-9}$ mm Hg	1.2×10^9	3×10^7	1.5×10^5

Beam-Crossing Angle 0.2 Radians

Straight Section Length 5 Meters

TABLE III

Characteristics of Colliding Beams In
10 Gev Storage Rings Injected Into By
A 10 Gev Spiral Sector FFAG

J $\frac{\text{amps}}{\text{cm}^2}$	470	470	100
I Total amperes each way	1000	250	1
R Beam-beam interaction per cm^3 sec	1.4×10^7	1.4×10^7	6.5×10^5
Δy (centimeters)	2	1	~ 0.1
P Beam-beam interactions per straight section sec.	3.2×10^8	4×10^7	6.4×10^3
ℓ Length of interaction region (centimeters)	40	20	2
2M Background interactions per cm^3 sec $p = 10^{-9}$ mm Hg.	1.5×10^5	1.5×10^5	3.1×10^4
$2M\ell$ Background interactions per straight section $p = 10^{-9}$ mm Hg.	3×10^8	8×10^7	3×10^5

Beam-Crossing Angle 0.2 Radians

Straight Section Length 5 Meters

TABLE IV

Number of particles entering a small volume per square centimeter per second at (p, s). The coordinates are measured from the center of a 10 meter straight section. A circulating current of 10 amperes in each direction and a vacuum of 10^{-8} mm Hg. are assumed.

p cm	10	10	50	50	200
s cm	0	250	0	250	0
charged pions + protons + neutrons*	2300	2400	450	470	90
photons + electrons**	1000	1000	180	190	30
Total	3300	3400	630	660	120

*Of these, ~40% are pions, ~30% are protons and ~30% are neutrons.

**Of these, ~ 50% are photons and 50% are electrons.

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CAPTIONS FOR FIGURES

Fig. 1. Geometry of interacting beams. Region of interaction cross-hatched.

Fig. 2. Scintillation chamber arrangement for reviewing colliding beams. Plastic filaments oriented horizontally alternated at 45° to plane of drawing viewed by image tubes looking inward and outward at 45° to the plane.

Fig. 3. Colliding beam geometry.

Fig. 4. Magnetic field for colliding beam analysis.

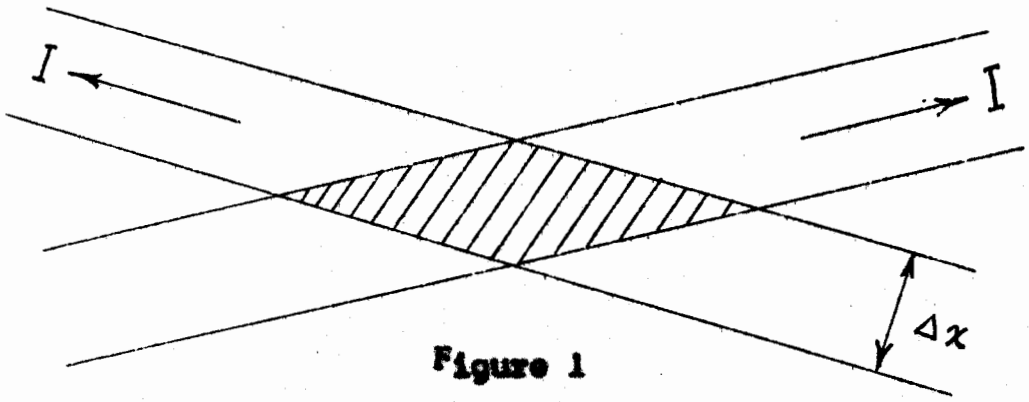

Figure 1

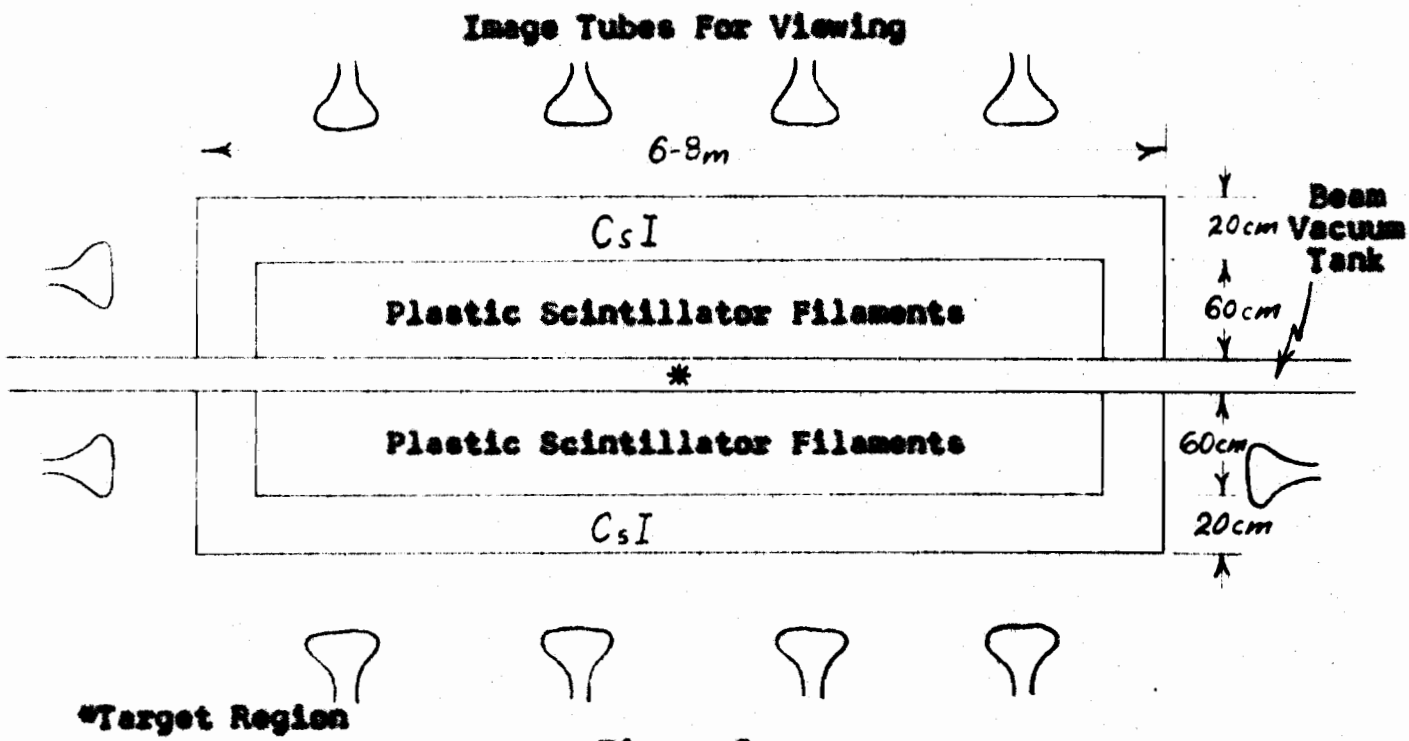

Figure 2

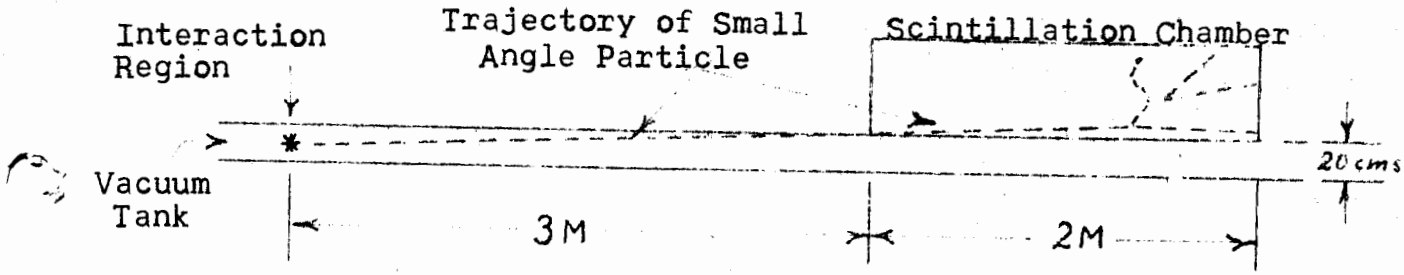

Figure 3

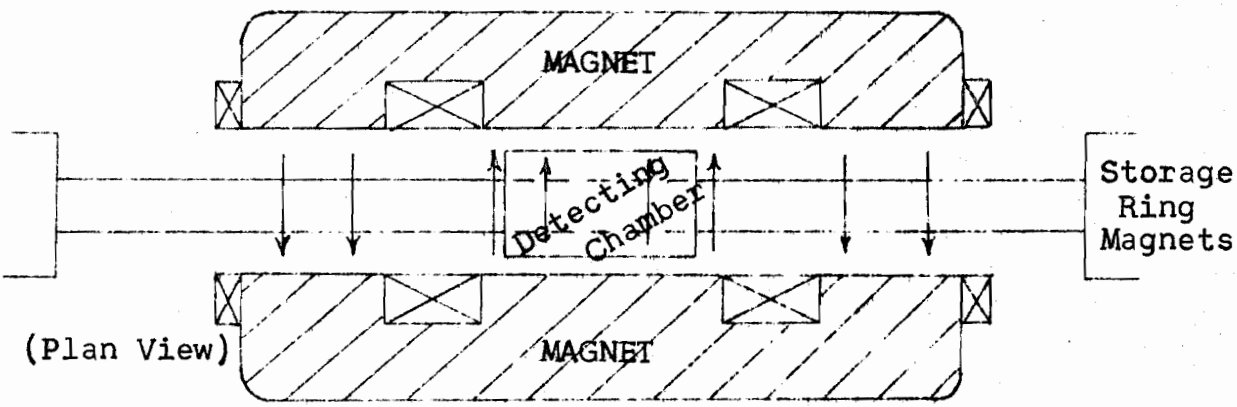

Figure 4