MURA-479
UC-28
TID-4500 (15th Edition)

MIDWESTERN UNIVERSITIES RESEARCH ASSOCIATION*

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UTILIZATION OF VERY HIGH ENERGIES**

July 3, 1959

ABSTRACT

The physical interest in very high energy particle accelerators is discussed. The possibility of achieving such energies by means of colliding beams, and some experiments with 300 G.E.V. protons, are examined in some detail.

* AEC Research and Development Report. Research supported by the Atomic Energy Commission, Contract No. AEC AT(11-1)-384.

**This report is based on the discussions of a group which included E. L. Goldwasser, C. L. Hammer, L. W. Jones, D. B. Lichtenberg, C. Mullin, M. Sands, A. V. Tollestrup, and W. D. Walker. Sections I, II, and III of this report were prepared mainly by L. W. Jones with some assistance from D. B. Lichtenberg. Section IV was prepared by M. Sands.

I. INTRODUCTION

The Berkeley Bevatron has available 2 Bev in the center of mass and the Brookhaven AGS will have 6 Bev. Unless the trend in nuclear physics over the past 30 years is suddenly reversed, there will develop an increasing need for experiments at even higher energies. While some remarkable experiments have been done with the primary cosmic rays, that method of investigation is fundamentally limited. Below we summarize some of the cosmic ray data and speculate on the possible processes that might be observed. We then demonstrate that colliding beam devices for exploring these energies and single, very high energy accelerators of similar available center-or-mass energies will be experimentally useful with straightforward extensions of existing techniques.

II. PHYSICAL INTEREST

A. Available Information from Cosmic Rays

Cosmic ray physicists flying emulsion stacks in balloons have observed over 100 events corresponding to energies in the vicinity of 80 Bev center of mass. In reporting events he had analysed in some detail, Schein outlines general features of such interactions which are very briefly summarized below:

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 Bev. Single π^0-mesons have also been found which carry away 21% of the total available primary energy.

2. No more that 15% to 20% of the secondaries are particles other than pions.

3. The transverse momentum $p_\perp$ of secondaries is apparently between 0.2 Bev/c and 0.8 Bev/c, independent of their total energy or the bombarding energy. The average value of $p_\perp$ is $\langle p_\perp \rangle = 0.03 \pm 0.04$ Bev.

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 (at about 80 Bev C.M.) are on the average only 40% inelastic i.e. 40% of the available energy goes into producing secondary particles. As an educated guess, they might be 50-60% inelastic at 20-30 Bev C.M.

6. The total π multiplicities are low (20-25). It should be strongly emphasized that these conclusions refer to the class of events studied by the cosmic ray emulsion groups; it is not unlikely that other classes of events, perhaps those of greatest interest, are not studied by present scanning procedures either due to their infrequent occurrence or inherent experimental bias. Similarly, the reported distributions are characteristic chiefly of pions; the angular and energy distributions of heavy mesons, hyperons, and antiparticles are not necessarily similar.

7. In a study of electromagnetic cascades accompanying nuclear collisions, Schein and his group observed somewhat over 100 ultra high energies of $E > 10^{12}$ e.v. in one cubic foot of emulsion. These events average 80 Bev energy in the center-of-mass system.

For the unusual events of energy $> 10^{14}$ e.v., magnifying glass scanning is sufficient and scanning time is negligible. However, for

more frequent lower energy events, microscope scanning is necessary. The 100 nuclear collisions reported by Schein were located in a 24 liter nuclear emulsion stack exposed for 13 hours at 18,000 feet. Six full-time scanners worked between 30 to 40 hours a week for a period of eight months to accomplish this job. Thus about 60 man-hours were required for each nuclear collision reported. It is planned to extend balloon flights up to 80 hours; the event density will be increased so that one scanner would be able to find about one event of $E > 10^{12}$ e.v. per day. Automatic electronic scanning techniques would make great contributions in this field.

These events suffer from several disadvantages:

1. In most cases the incident energy is uncertain to within a factor of about 2.
2. Incident direction is unpredictable.
3. Point of interaction is unpredictable within 1 cubic foot.
4. Distance available for analysis of secondary products is only about 1 foot.
5. Interactions are in emulsion (rather than pure hydrogen).
6. Neutral particles not close to the shower axis frequently are not seen, and most large-angle charged particles are not followed for long distances.

These factors make it very difficult to identify all the secondary products. Since one of the main interests in higher energies lies in the possibility for exploration of a new part of the particle mass spectrum, this characteristic of the cosmic ray data is the most important one.

While good energy balance has been obtained for a few events thoroughly analyzed so far, complete analysis of all secondaries is possible only in the case of events parallel to the surface of the emulsion. Thus a detailed study of the properties of possible new particles would be extremely time-consuming using present cosmic ray techniques. For this information a much higher intensity is required under conditions where large spatial distributions of experimental equipment are possible. There should be the possibility for variation and control of the energy of the primary interaction and for analysis of the secondary particles.

B. Potential Physics at High Energies

It is of great interest to determine whether the particle spectrum as we know it is complete or whether more particles will be produced when higher energy interactions are readily available. It makes little sense to refer this question to the next 20% increase in energy. One might reasonably ask it about the energy interval between the present maximum and something five to ten times as large. If such an interval is explored and nothing is found, this would probably be acceptable evidence that we have exhausted the spectrum of what we mean by particles. If new particles were found, it would be hoped that a knowledge of their properties would add to our understanding of the present crop, hopefully giving us a general scheme within which all existing particles could be understood.

Dalitz emphasizes that particles may exist with very short lifetimes preventing them from ever being directly observed except through correlations of their decay products. As with the $\pi^0 + \Sigma^0$, this does not preclude their interest, importance, or detectability.

Very heavy particles outside the Gell-Mann scheme may decay by strong interactions with lifetimes as short as 10^{-21} seconds or so. "Particles" with even shorter lifetimes may only be observed as resonances in certain interactions or as weaker correlations of reaction products, and in this limit the definition of what is meant by a "particle" becomes unclear.

If the naive picture of a nucleon as a core surrounded by a pion cloud is valid, one might expect three classes of nucleon-nucleon collision; (a) collisions of the pion clouds, (b) core-pion collisions, and (c) core-core collisions. Presumably the last class would be of greatest interest and least frequency. If the core-core cross section were only 1% of all nucleon-nucleon events, it is probable that so far no such event has been analyzed in the cosmic ray data.

Another area of interest, after the study of unusual particles, deals with the more statistical nature of the nucleon-nucleon interaction involving questions of secondary particle multiplicities and energy and angular distribution. Besides statistical information, such data might be useful for obtaining fundamental knowledge of the nucleon "cloud" and its core.

The above discussion is vague because so little is known of what will be found at such energies. We cannot over-emphasize that it is for this very reason that very high energies are of great interest to us.

For similar reasons of uncertainty, it is not clear what energies should be recommended. It is our concensus that a minimum goal would be three times the Brookhaven AGS center-of-mass energy or about 20 Bev, and the range 20 to 30 Bev center of mass seems like an appropriate

target. However, it is very desirable that the energy be variable down to the 6 Bev center-of-mass energy of the AGS so as to allow study of any new objects near their production threshold.

This new energy maximum can be made available in either of two ways. First, it could be realized through development of a clashing beam machine where large center-of-mass energies are made available. The velocity of the center-of-mass in the laboratory would be zero for a pair of head-on colliding beams. It would differ from zero for beams intersecting at an angle less than 180°.

The second possible machine is the ultra-high energy single beam machine. For this conventional machine, the center-of-mass of colliding particles has a large velocity in the laboratory system, as does the incident particle. The target particle is stationary in the laboratory.

As a rule, the most fruitful analysis of a new interaction can be made in an energy interval close to the threshold, for analysis is then simpler. At threshold, product particles will have no energy in the center-of-mass system. Such an interaction (somewhat above threshold) would be easily observed and analyzed in the colliding beam case. The particles would have small momenta in the laboratory. They could be observed in a bubble chamber or scintillation chamber placed in the direction of the drift of the center-of-mass.

In the single beam case, the particles would still have large energies and momenta in the laboratory at threshold and would be more difficult to identify.

For interactions far above threshold, the situation reverses. Then, if we consider secondaries to be "shaken off" from the colliding

nucleons, there is an advantage to the single beam machine for which one of the nucleons is at rest in the laboratory. Secondaries associated with that nucleon will be more easily observable than any of those coming from a similar colliding beam interaction.

III. COLLIDING BEAMS

A. Properties

The general considerations discussed in the MURA Proposal seem appropriate guides for discussion of colliding beams. With a Two-Way Ohkawa Accelerator or with storage rings and a Spiral FFAG Accelerator, current densities of 50 to 500 amperes per cm^2 of protons appear attainable including appropriate safety factors. With non-scaling orbit perturbations in the stacking region, Terwilliger has shown that these densities may be achieved with modest total currents by superposing orbits of different momenta at the colliding beam azimuths. Total circulating currents of 100 to 1000 amperes may be achieved.

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

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

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 = 25mb,

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

where J is the current density of either beam in amperes/cm^2. The total number of interactions, P, 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

$$P = \int R dv = \left(\frac{65 I^2 \cos^2 \frac{\alpha}{2}}{\Delta x^2 \Delta y^2} \right) \left(\frac{\Delta x^2 \Delta y}{\sin \alpha} \right)$$

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

and for small α

$$R = \frac{65 I^2}{\Delta y \cdot \alpha}.$$

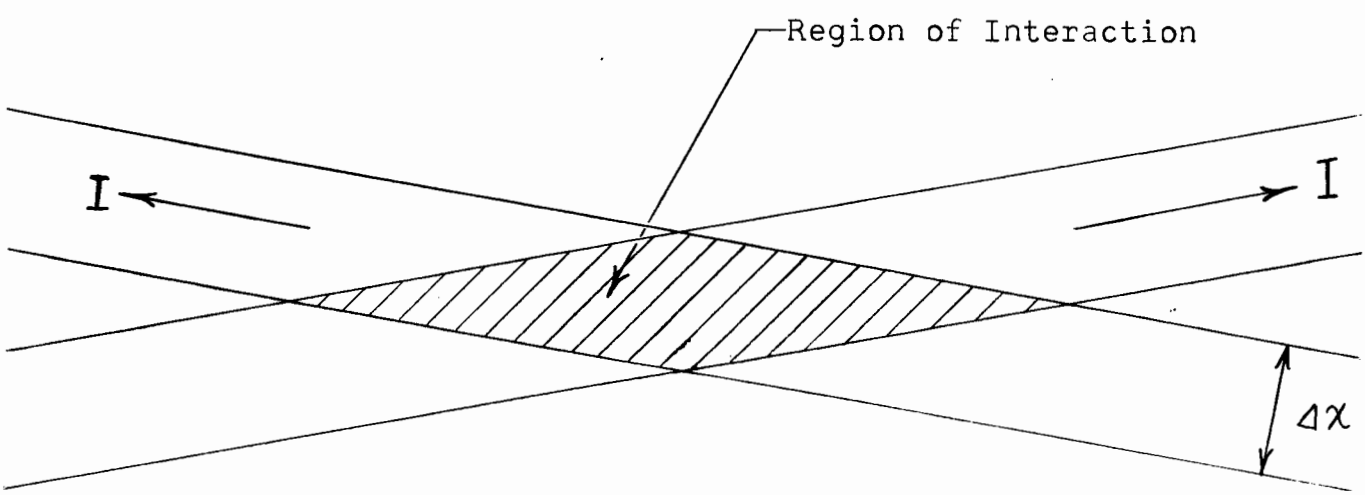


Figure 1.

Without non-scaling perturbations, the interaction density will not be uniform. If the stacked beam is built up of separately accelerated beams each having a radial betatron oscillation amplitude spread up to $\pm\ \delta x_B$ and an energy spread δE, there will be a maximum current density J_M in the stacked beam, given by

$$J_M = J_i N = J_i \left[\frac{2\delta x_B}{\delta E \left(\frac{dx}{dE}\right)} \right]$$

where J_i is the current density in each accelerated beam, N is the number of accelerated pulses stacked to achieve maximum current density, and $\frac{dx}{dE}$ is the rate of change of equilibrium orbit radial position with equilibrium orbit energy at the colliding beam azimuth. As more than N accelerated beams are stacked, the total circulating current increases but not the current density, so that a typical current density profile is given by a trapezoid:

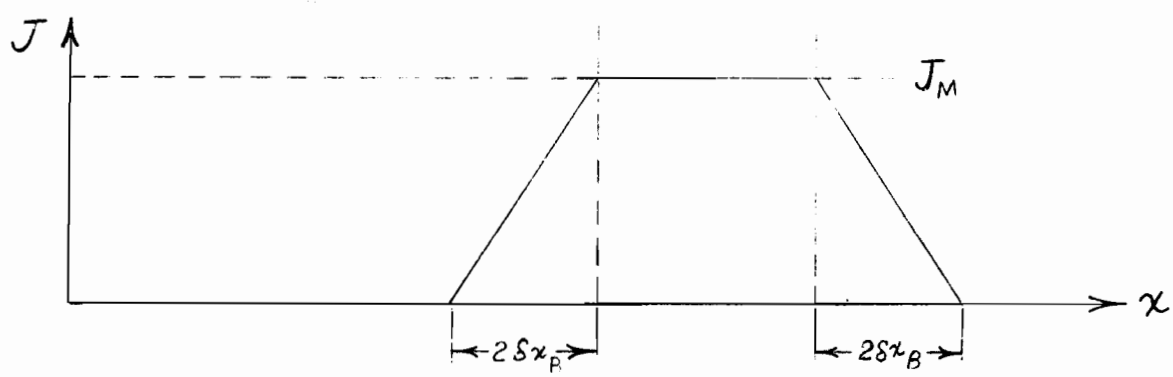


Figure 2.

For relativistic particles, $\frac{dx}{dE}$ is related simply to the momentum compaction factor α for an alternating gradient structure or to the field index k for a scaling FFAG structure by

$$\frac{dx}{dE} \cong \frac{R_o}{\alpha E} \qquad \text{A.G.}$$

$$\frac{dx}{dE} \cong \frac{R_o}{kE} \qquad \text{F.F.A.G.}$$

where R_o is the average radius of the accelerator.

It is possible to reduce dx/dE arbitarily over a small energy range at certain azimuths by a non-scaling periodic field perturbation, so that in practice (either in storage rings or FFAG accelerators) beams would be superposed for 1000-3000 accelerated bunches independent of δx_B.

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

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

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

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

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

thus

$$M = 1.56 \times 10^{11} J\rho.$$

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

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

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

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

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

$$J \cong 5 \times 10^{9} \frac{J}{\rho}.$$

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.

Two promising means of achieving colliding beams are with an Ohkawa-type Two-Way Radial Sector FFAG Accelerator and with a single FFAG Accelerator (presumably of spiral sectors) injecting previously-stacked beams into storage rings arranged to intersect at several points (Figure 3). The total cost of the two systems would be comparable (within 10% - 15%) for energies of 20 to 30 Bev in the center of mass ($100 to 200 million).

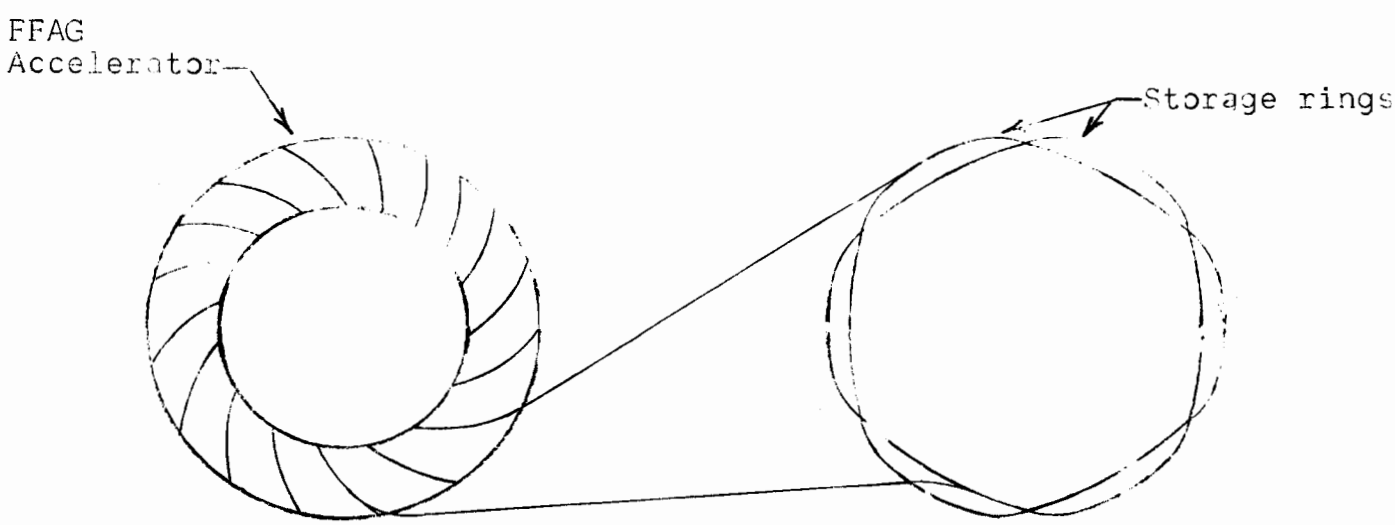


Figure 3.

The stacked currents, current densities, and other relevant parameters are summarized in Table I for 10 Bev colliding beam devices.

The numbers are based on accelerators as summarized in MURA-460, the Spiral FFAG Accelerator assumed to inject into a storage ring pair having approximately the same ν_x, ν_z and R. A safety factor of four in rf phase space density is included for the maximum current densities, where it is assumed that the space charge limit is reached at injection (including an azimuthal bunching effect) from a 50 Bev Linac. Greater current densities could be achieved using a higher injection energy. The maximum circulating currents require clearing fields and compensatory currents to prevent beam detuning due to beam charge neutralization and image effects. Lower total currents are also included representing cases where these effects require simpler compensation. While it is possible to discuss currents in excess of 1000 amperes and see through solutions to all known problems that they would entail, our discussion is limited to currents of 1000 amperes and below. It might be noted that a 1000 ampere, 10 Bev proton circulating current in a 125 meter radius accelerator 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 in liquid hydrogen would produce 5×10^5 interactions per cm^3 sec. 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.

Table 1

CHARACTERISTICS OF 20 BEV CENTER OF MASS COLLIDING BEAM DEVICES

		Two-Way Radial Sector FFAG			Storage Rings Injected Into By Spiral Sector FFAG		
J	$\frac{\text{amps}}{\text{cm}^2}$	190	190	50	470	470	100
I	Total amperes each way	800	200	1	1000	250	1
α	Beam crossing angle (radians)	0.2	0.2	0.2	0.1	0.1	0.1
R	$\frac{\text{Beam-Beam interaction}}{\text{cm}^3 \text{ sec. } (\sigma=25\text{mb})}$	2.3×10^6	2.3×10^6	1.6×10^5	1.4×10^7	1.4×10^7	6.5×10^5
Δy	(centimeters)	2	1	~ 0.1	2	1	~ 0.1
P	$\frac{\text{Beam-Beam interactions}}{\text{straight section sec.}}$	10^8	1.5×10^7	3.1×10^3	3.2×10^8	4×10^7	6.4×10^3
	Length of Interaction region	20	10	1	40	20	2
2M	$p = 10^{-7}$ mm Hg background interactions	6×10^6	6×10^6	1.5×10^6	1.5×10^7	1.5×10^7	3.1×10^6
	$\text{cm}^3 \cdot \text{sec}$ $p - 10^{-9}$ mm Hg	6×10^4	6×10^4	1.5×10^4	1.5×10^5	1.5×10^5	3.1×10^4
l	Straight section length (meters)	5	5	5	10	10	10
2Ml	$p = 10^{-7}$ mm Hg background interactions	1.2×10^{10}	3×10^9	1.5×10^7	3×10^7	8×10^9	3×10^7
	Straight section $p = 10^{-9}$ mm Hg	1.2×10^8	3×10^7	1.5×10^5	3×10^8	8×10^7	3×10^5

The choice between a two-way radial sector machine and a spiral machine with storage rings rests in balancing the more favorable geometry and ultimate current density of the storage ring geometry with the complexities of beam transfer and the ease of energy variation with the two-way design. In either case the cost of providing colliding beams would appear to add about 20% to 30% to the cost of a single, high intensity Spiral Sector FFAG Accelerator.

B. Possible Experimental Geometries

(1) Direct Observation of P-P Interaction Volume.

The primary interaction between two protons will occur within the vacuum chamber and thus will not be directly observed in any detecting device. Normally a chamber could be placed no closer than 5 or 10 centimeters from the beam axis. For direct observation of short-lived particles, a re-entrant, thin window area could be incorporated into the vacuum chamber directly over the collision region and a luminescent chamber inserted to within a centimeter of the primary interaction.

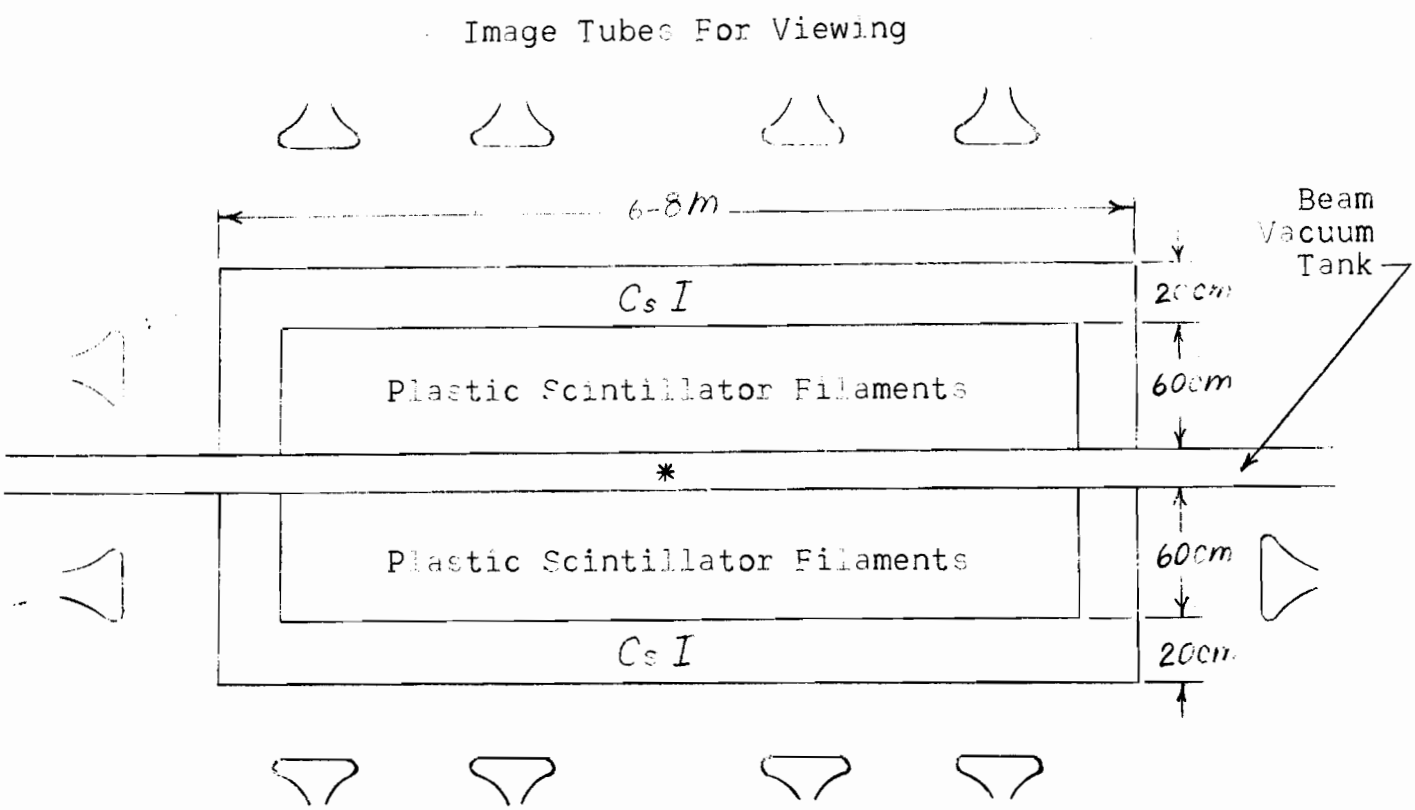
The luminescent or scintillation chamber is thought of as a prime tool for exploratory investigation of the primary interaction. Its fast time resolution together with its ability to be triggered by an event of interest make it well suited to this purpose. Fast counter arrays will be very useful for 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 this country. 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 reasonable that entirely satisfactory image tubes will be available well ahead of colliding beams.

We believe it will be practical to use large dimension scintillation chambers viewed by a battery of image tube-camera systems. Thus, it is possible to envisage a luminescent chamber consisting of 60 cm. of plastic scintillator above and below the colliding beam region extending 2 to 4 meters in either direction along the beam and one meter perpendicular to it. This chamber 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 interact (or decay) in the active volume. The spatial resolution throughout the volume would be about one millimeter and the time resolution one microsecond.

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 the

preceding table, 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 simulated pulse of appreciable ($>$ 3 Bev) energy released in 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 μsecond 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 necessary 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 combined with magnetic tape storage or direct processing of data with high speed computers could make analysis of pictures possible at higher rates. 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, if it is possible to analyze pictures containing several events, or if shorter gating times become feasible.



*Target Region

Figure 4.

Plastic filaments oriented horizontally, alternated at 45° to plane of drawing, viewed by image tubes looking inward and outward at 45° to the plane.

Known particles would be identified by their characteristic endings: $\pi - \mu$ decays, $K-\pi$ and $K-\mu$ decays, neutron and protron stars, anti-particle energetic stars, etc. 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, modifications might be desirable for certain experiments. For example it would be desirable to have access to

secondary particles close to initial beam direction. Thus, in the rather extreme case of a 9 Bev/c secondary with 0.3 Bev/c transverse momentum, access to secondary products within .03 radians of the beam direction will be important. A luminescent chamber 2 meters long, 10 centimeters from the beam axis, placed three meters from the colliding beam region, could effectively study such particles (Figure 5).

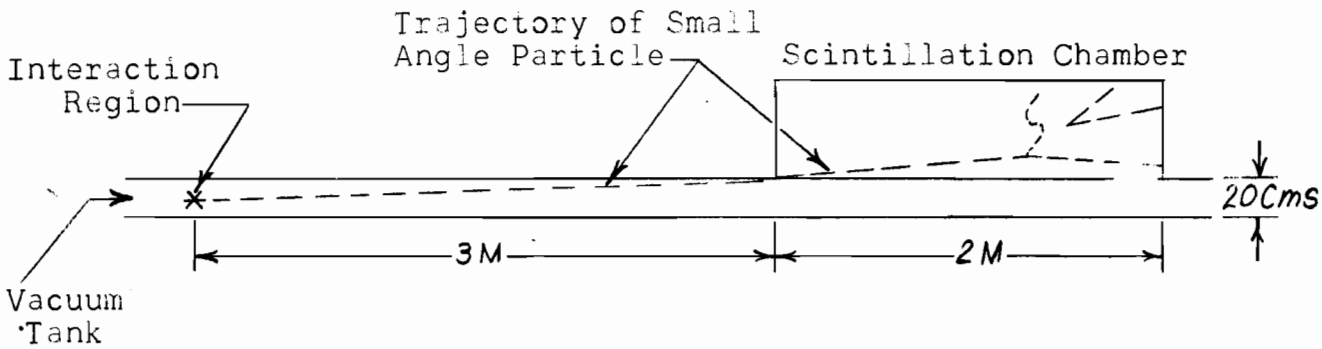


Figure 5.

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 (Figure 6).

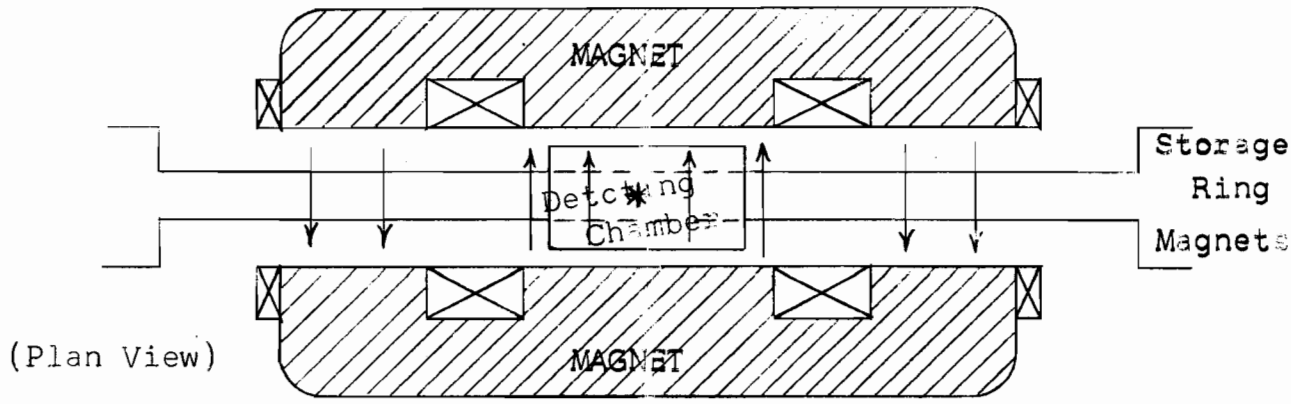


Figure 6.

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 about 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 current diameter is limited by fabrication techniques and by problems of surface defects limiting total internal reflection. These are technical problems which should yield to continuing effort.

More systematic analysis of colliding beam events could be made with counter arrays observing the interaction region. Experiments are being constructed for the Bevatron using over 200 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. Counter arrangements designed to detect specific particles are useful with present accelerators (e.g. K detectors, $\bar{P}$ detectors, π-μ 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 used currently.

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

(2) 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 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 α.)

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 Bev/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.

Once again, the uncertainty as to what will be found at these energies is at the same time responsible for the vague description of projected experiments and for the interest in exploring these energies. It should be pointed out, however, that a secondary use of colliding beams would be the production of known unusual heavy particles (e.g. anti-baryons) at an energy where their flux relative to pion fluxes will possibly be most favorable on the basis of phase space, and yet with laboratory momenta which would allow use of conventional particle separation techniques. Thus, colliding beams might prove the best source for beams of certain particles in spite of low absolute source strength, although this is speculative until information can be obtained from the 25 Bev accelerators.

It would be almost essential to provide several simultaneously available experimental areas around the colliding beam ring; some set up with dense shielding for secondary beams, and others with particularly open access to the collision regions for observation of the primary interaction (e.g. with luminescent chambers).

IV. EXPERIMENTS WITH 300 GEV PROTONS?

It has been suggested* that a 300 Gev proton accelerator could be constructed if warranted by its research utility. Protons of 300 Gev interacting with protons at rest would provide the same energy in the CM as two colliding 12 Gev protons. The possibility of

*MURA Report No. 465; M. Sands

experimentation with such high energy protons is considered briefly here. The general conclusion appears to be that experimentation at ultra-high energies can be done using existing techniques.

For the purposes of orientation we consider first some of the relevant parameters of the known particles likely to be emitted from the high-energy interactions. We take as two illustrative special cases, those particles produced in the C-M frame of the primary interactions, $\gamma_{CM} = 12$ $(= 1/\sqrt{1-\beta^2})$, and those produced in the frame of the primary proton, $\gamma_o = 300$. The limiting case of particles of the maximum possible energy (nearly that of the incoming particle) is also considered. The case of $\gamma = \gamma_{CM}$ is of special interest. Because of the symmetry of the p-p interactions, a study of products with $\gamma \leq \gamma_{CM}$ can give nearly complete information about the reaction.

The energies of particles for the selected γ's are given in the first rows of Table II. For comparison we may take for a "measurable" momentum one for which a particle is deflected from a straight path by a distance of at least 0.1 cm in passing through 100 cm of a magnetic field of 10^4 gauss. Such curvatures should be measurable in a two meter bubble chamber, or in two chambers separated by a magnetic field. Energies less than 150 Gev satisfy this criterion.

For the characteristic angles in the second part of Table I we take those angles which correspond to a transverse momentum of $m_\pi c$. One would expect that typical angles ought to be at least this large, and the data of Schein show angles, in general, somewhat larger. For comparison we remark that an angle of 10^{-3} can be measured in a

large bubble chamber. (Corresponding to a 0.1 cm separation along a 1 meter path).

With regard to the resolution of 0.1 cm assumed above for measurements of momenta and angles, we recall that typical bubble diameters are 0.01 cm, and bubble positions can be measured to about 1/10 of their diameter. It is also relevant that one may expect to make displacement measurements with respect to neighboring high-energy tracks, so that the effects of distortions are a minimum.

The last lines of Table II give the mean decay lengths for particles whose mean life at rest is 2×10^{-8} sec (ℓ_π) and for particles whose mean life is 10^{-10} sec. (ℓ_Λ). For pions and K-mesons the decay lengths are, of course, long on a laboratory scale. The hyperon decay lengths for $\gamma = \gamma_{CM}$ are short enough to appear in a bubble chamber, but are sufficiently long so that even with the small angles expected, the decay points will be separated appreciably from other forward going particles. The angles between the decay fragments are typically those of Table II so that hyperon decays will, in general, be observable.

We consider next the possibility of the identification and/or separation of the high-energy secondary particles. For particles of intermediate energy $\gamma \leq 30$, it appears possible to identify or separate pions, K-mesons and nucleons. Electronic counting techniques and microwave separators should be capable of distinguishing particles whose flight times through the apparatus differ by at least 10^{-11} sec. The flight path, L, necessary to separate a particle with an energy γMC^2 from a lighter particle of this same <u>momentum</u> is approximately

$$L = 2\gamma^2 C \Delta t,$$

where Δt is the time separation required.* The flight lengths required if $\Delta t = 10^{-11}$ sec. are:

γ =	10	30	100	300
L =	1m	10m	100m	1000m.

It appears possible to identify particles by this method if their γ is as large as 30, but not those of the maximum possible energies.

TABLE II

		$\gamma = \gamma_{CM} = 12$	$\gamma = \gamma_o = 300$	γ_{max}
Energies	E_π	2 Gev	45 Gev	$\approx$ 300 Gev
	E_K	6	150	
	E_N	12	300	
Angles	θ_π	10^{-1}	3×10^{-3}	5×10^{-4}
	θ_K	2×10^{-2}	10^{-3}	
	θ_N	10^{-2}	5×10^{-4}	
Decay Lengths	ℓ_π	72 m	1800 m	
	ℓ_Λ	0.36 m	10 m	

*For a given ρ and L, Δt is then proporational to M^2.

For the most energetic particles one can hope to distinguish members of different species by their characteristic interactions with nucleons or nuclei. It is known, for example, that in interactions with heavy nuclei 5 Gev pions produce typically 3 pions and one nucleon, while K-mesons of the same energy produce typically 2 pions and one hyperon.

Presuming, on the basis of the above discussions, that experimental observations are, in fact, possible at ultra-high energies, one may then consider the types of experiments which can be envisaged. Three classes of experiments immediately suggest themselves as being of interest: (1) A search for the production of new particles; (2) A study of the statistics of the production of known particles (i.e. $d\sigma/d\Omega dE$ for each particle type) in nucleon-nucleon collisions or in π-N interactions, etc. and (3) A study of correlations among the particles produced in the various interactions. All such experiments appear to be possible. An example of an experimental arrangement which would yield information on one or more of the suggested questions is shown in Figure 7.

Finally, we may make some comparisons between experiments using 300 Gev protons and those using intersecting beams with comparable interaction energies.

(1) <u>Interaction Rates.</u> It is reasonable to expect that an ultra high energy synchrotron would have an intensity comparable to that expected of the usual AGS, i.e 10^{11} or more protons per second. Beams of such an intensity would give interaction rates per unit volume in a hydrogen target about 10^3 times the interaction densities which can now be expected from intersecting beams. (Table I) The intersecting

beams have the problem of background from interactions in the residual gas, which problem does not arise in the one-way beams. For both cases the primary interaction rates are sufficiently high that special techniques (scintillation chambers, or large counter arrays) would be required for efficient observation of the primary interactions. The one-way beam would have the disadvantage of a smaller duty ratio (say $\sim$ 10 percent) than the intersecting beams (100 percent).

(2) Interaction Observation. The center-of-momentum of the interactions of colliding beams is nearly at rest in the laboratory. The interaction products emerge at all angles and with much lower energies than those from the interactions of high-energy primaries. The lower energy of the secondaries is advantageous for their identification, and the larger angles give greater separations in short distances, but give the accompanying disadvantage that the detection apparatus must cover all angles around the interaction region, and that the interaction itself is not observable. The narrow angles of divergence of the one-way interactions may have some experimental advantages.

(3) Secondary Beams. The wide angles and low interaction rates of the colliding beam secondaries will make it difficult to obtain intense separated beams of secondaries. The narrow angles of the secondaries from high laboratory energy interactions are favorable for the geometry of separators. The maximum secondary energies of the one-way beam is very large (300 Gev), and one can expect large yields of secondaries with γ's from γ_{CM} = 12 to γ = 300 (even for anti-nucleons). The maximum likely secondary energy from 12 Gev colliding beams is near 12 Gev and the yield near this energy will

no doubt be very small. Typical γ's may be expected to be near two, or for "shake-off" particles near 12. The mass separation of beams of particles with γ much larger than 30 is probably not feasible with techniques now proposed.*

It appears that measurements with 300 Gev proton beams are practicable, and may even have advantages over colliding beams for some measurements. The cost of an ultra-high energy accelerator is much more than the cost of adding storage rings to an existing (cost) accelerator with an energy of 10 to 15 Gev. There is, as yet, little reason for a prediction that basically new processes will appear at the higher energies which would give great urgency to the achieving of these energies.

It may be possible, however, that the interactions of the fundamental particles will appear to be more tractable at C-M energies appreciably above the nucleon rest energy, say 10 Gev., than at energies of only a few Gev.

It is a pleasure to acknowledge helpful discussions with Prof. G. K. O'Neil, Prof. M. Schein and Prof. R. H. Dalitz.

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* Refer to report of discussion of beam separators.

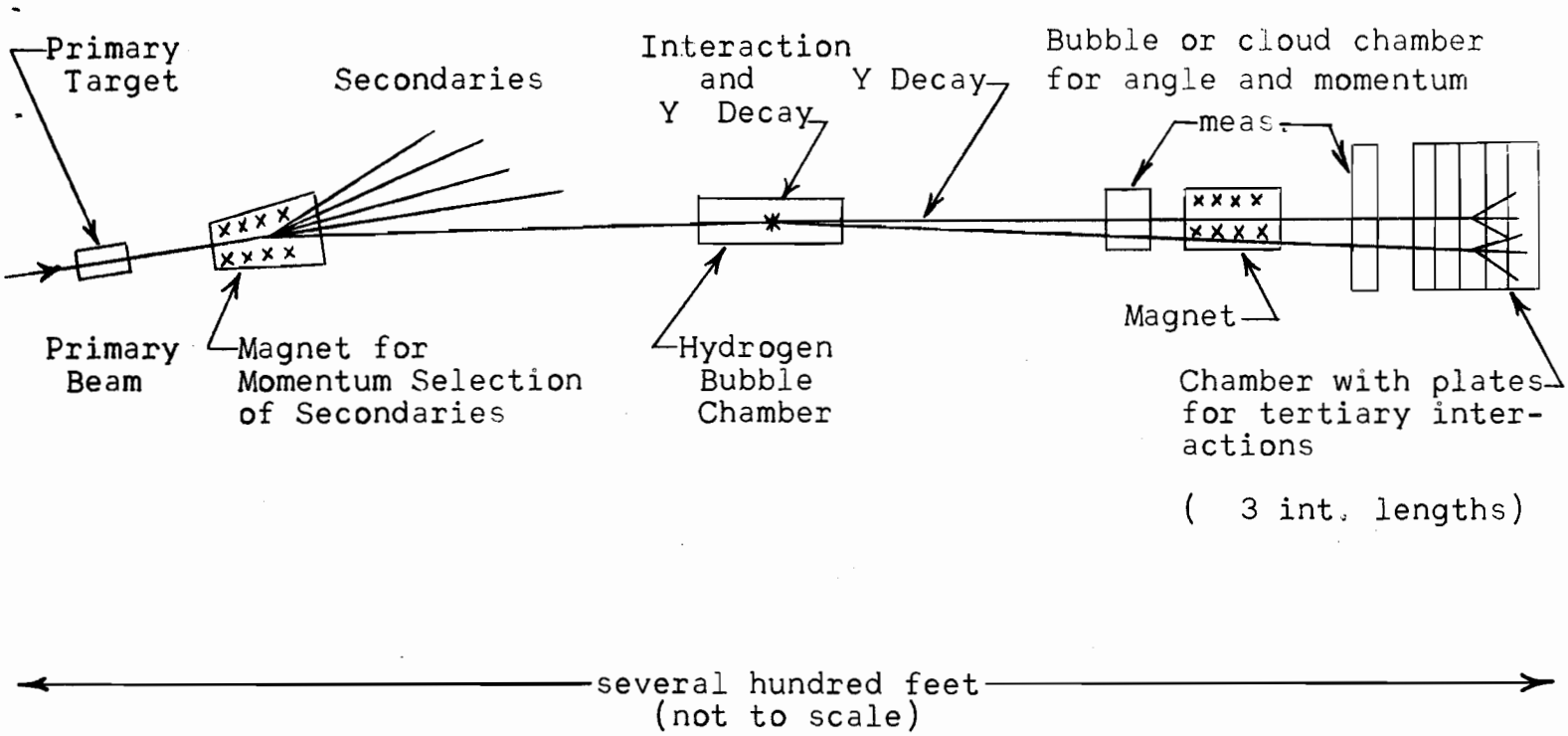

Figure 7. Possible Experimental Arrangement