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AN ELECTRON-PHOTON FACILITY FOR THE NATIONAL ACCELERATOR LABORATORY

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INTRODUCTION

This is a proposal to install an electron-photon facility in the experimental region around the external proton beam of the National Accelerator Laboratory 200-400-GeV proton synchrotron. This facility is designed to serve as a permanent home for electron and photon physics at energies beyond those presently attainable at existing machines. An attempt was made to leave many parameters variable to a considerable extent, so as to enable physicists to incorporate the requirements of divergent experimental concepts.

The basic idea is that, barring unexpectedly quick developments in the construction of superconducting linear accelerators, specific physics problems which must be answered by means of photon experimentation at energies > 20-40 GeV will have to be investigated at the NAL and its European counterpart. Therefore, no matter what the relative difficulty of obtaining beams of respectable intensities and composition, we will have to live within the framework of what is available there. We have therefore set out to lay down the features of an adaptable facility which will yield, without much additional corrective work, photon and electron beams of various intensities and degrees of purity, and over a fairly wide range of energies.

One very important decision will be whether one favors the installation of a permanent facility, or whether it is possible to live within the framework of more-or-less changeable secondary beams emanating from the targets in the general-purpose experimental region.

Considering the low intensities and the peculiar problems of photon experimentation, we shall show that there are good reasons for suggesting a more-or-less permanent facility; a review of physics problems which are liable to occupy the schedule on this facility [1,2] will corroborate this course. Nevertheless, should this desirable scheme run into insurmountable trouble, we may try to live with a scaled-down (in cost, versatility and promise) version which we will also briefly discuss later.

The features which we will try to incorporate in a desirable facility are: particles in beam - e^+, e^-, photon. Energy of beam: ~ 40 GeV $\leq E_o \leq$ E max (where a resonable E max[1] for 200-GeV/c incident proton may be ~ 130 GeV). The (mutally exclusive) parameters of good intensity and high beam purity ought to be adaptable to individual experimental needs. Good beam optics should allow for varying momentum bites and optimum resolution for input parameters to the electron--or photon--initiated reactions.

Furthermore, the experimental area must be well shielded from random backgrounds (particularly neutrons and muons), since these are mostly low-counting-rate experiments. There are obvious needs for space for the installation of large solid-angle detection equipment, both primary and auxiliary.

It ought to be mentioned that a certain amount of photon work can and will be done using virtual photons in inelastic μ-nucleon scattering. This work, which is largely complementary to the experiments to be carried out in the facility described, can most easily be done in conjunction with other μ experiments. Muon beams will be available either as a separate facility or as a by-product of the neutrino facility. Similar information can usually be obtained from inelastic electron scattering, which will be feasible using the higher intensity version of the electron beam described here.

INPUT: NUCLEON-NUCLEON COLLISIONS AS e, γ SOURCES

Nucleon targets hit by the extracted proton beam have been shown to yield sizable photon fluxes.[3, 4] These fluxes were calculated from the expected secondary π spectrum under the assumption that (i) π^0 decay dominates as a photon source, (ii) that the angle between the π^0 and its decay photons is small and can be disregarded for practical purposes.

Figures 1 and 2 show the photon yield at forward angles, for photon energies between ~ 60 and ~ 160 GeV in the case of 200-GeV proton impinging on a nucleonic target at rest. They were calculated from the Trilling[5] semi-emperical calculation of secondaries produced in pp collisions. More recently, Hagedorn and Ranft's[6] thermodynamic model has given somewhat different estimates for the secondary spectra, with fewer empirical input parameters. A comparison[7] shows that the Hagedorn yields, which agree excellently with available accelerator data at energies < 30 GeV, have a high-energy π^+ yield too high to be compatible with existing cosmic-ray data; however, in the energy region of interest here, $E\pi$ between 60 and 150 GeV, the agreement with Trilling is reasonable. Since as of this time no results are available from the 76-GeV Serpukhov proton synchrotron, we will continue to use the fluxes shown in Figs. 1 and 2 and keep in mind that there is considerable uncertainty in these conjectured yields. However, this uncertainty is not large enough to impair the usefulness of these yields as input into our facility design.

Facts of Life with Electron and Photon Beams

The spectral features resulting from the decay $\pi^o \rightarrow 2\gamma$, from the pair production process $\gamma \rightarrow e^+ e^-$, and from bremsstrahlung emission $e \rightarrow e' \gamma$, are well-known and have been described in detail as they effect possible e, γ beams at the 200-GeV machine.[3] In particular, all these processes lead to a depopulation of the high-energy end of the spectrum, the bremsstrahlung process worse than the others. Moreover, the relative merits of extracting photons or electrons from the primary target have been studied.

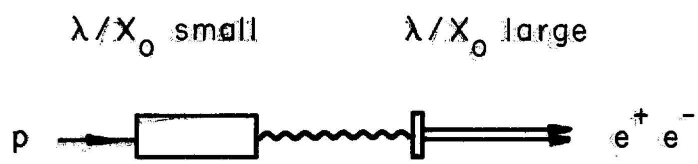
Given, e.g., that we want the external proton beam (EPB) to interact with a nuclear target of thickness $t = \lambda$ (λ is the nuclear mean free path), we can choose

(i) a low-Z target (H, Be): λ/X_o small (X_o is the radiation length): most photons will emerge without having undergone further interactions like $\gamma Z \to e^+ e^- Z$.

(ii) a high-Z target (Al, W, U): λ/X_o is large. In this case, most photons will interact in the target and a considerable fraction will generate high-energy electrons which emerge from the target. [Note, however, that for λ/X_o = large ($\approx$ 30 for Pb), $t = \lambda$ means that full-fledged showers will have developed from most initial photons, with the copious emerging electrons strongly shifted to lower energies.]

We want a decent production rate; and we want neither electrons (because of the acquisition of transverse momentum through multiple scattering) nor photons to traverse a considerable amount of material in terms of radiation lengths. A reasonable compromise will be the use of effective parameters $t \approx \lambda \approx X_o$ (to within a factor of two or three).

This can be achieved either by separated functions:



or by the use of EPB target material of λ/X_o of order 2 (like carbon):

$t = 2X_o$

most photons will emerge as $e^+ e^-$ pairs.

THE PROPOSED FACILITY, OPTIMAL SOLUTION

We will now give, to be detailed in the subsequent sections, what we consider a good overall layout for the electron-proton facility. The obvious aim is to have a self-contained unit, incorporating maximum variability of parameters according to experimental needs, which is rationally integrated into the general physical setup of the experimental areas as presently planned.

The main features are shown in Figs. 3 and 4. A septum magnet is inserted into the beam-transport system of one of the branches of the EPB. We do not specify where this insertion should be done, since overall planning has not been made definite. But we will stress that the low-rate experiments to be done suggest that a position as far upstream as possible would be preferable; downstream positioning could spell trouble in terms of neutron or μ backgrounds from other sources.

The septum will divert a controllable fraction of the EPB into the γ channel, and onto a low-Z target (see below). Upstream of this target, a series of bending magnets allows the beam to be deflected and brought back to hit the target at angles between 0° and ~ 20 mrads. In this manner, a fixed slit downstream from the target can be made to accept forward beams from 0 to 20 mrads.

This fixed slit is built into a collimator C_1 immediately downstream from the target; this collimator also acts as a (partial) beam dump for the case of the slit not being at 0°.

Downstream from this slit, a sweeping magnet, M, deflects the charged particles downward and buries them in the ground. A second collimator C_2 transmits the neutral beam (γ, K^o, $\overline{K^o}$, n, ...) and lets them hit a radiator R_1. R_1 is a high-Z converter with a thickness on the order of 0.5 X_o, but, since λ/X_o is large, subtending a very small fraction of an interaction length to the K^o and n flux.

Downstream from R_1 is a beam-transport system for the charged particles produced. We will choose negative polarity so as to avoid protons in the beam (from K^o- nucleus and n - nucleus interactions in the radiators); since the pair production correlation angle in R_1 is very small, the beam optics can be worked out as though the e^+, e^- orginated in the EPB target. Typical transverse momenta imparted to the hadronic reaction products are of order 350 MeV/c, so that, as far as the hadrons are concerned, the optics will assume they were produced in a large and diffuse region around the EPB target.

The electron beam then either continues directly to the experimental area (for maximum intensity), after possibly having been purified by one of the three techniques mentioned below or it hits the radiator R_2 which reconverts it into a photon beam; R_2 has a large λ/X_o again, so that again we offer little interaction probability for the $\bar{p}$, π^-, ... still in the beam, while forcing a sizable fraction of the electrons to undergo a bremsstrahlung process.

Downstream from this radiator, the slowed-down electrons will be momentum-analyzed, so that we can tag the energy of the bremsstrahlung photons. Since this is again a process where the transverse momentum picked up in the interaction is small, we can design the beam transport system such that the beam will come to a double focus in the target in the experimental region.

The Proposed Facility, Minimal Version

Should it be impossible to obtain the scheme outlined above, one will seek to live within more restricted boundary conditions. This can be done, obviously, in a number of ways. One such possibility would be to try and locate a similar septum close to a general purpose "B" target;[8] these targets are designed to be shared by many beams, and to occur at the downstream end of the EPB or one of its legs. In principle, one could have the provisions for different angles of incidence like in the above scheme; however, backgrounds as well as the freedom to optimize the proper parameters will be vastly less advantageous.

Rather, we would conceive a minimal solution according to Fig. 4. We would use a fixed-small-angle beam-holder at ~ 2.5 mrads ; small enough to fit close to the high-flux forward region, large enough to forego the difficulties with the non-interacting beam and the forward emission of other secondaries.

As Fig. 5 shows, we could either have electrons of either sign emerge from this beam hole and be appropriately purified and focused; or we could try to play purification tricks, as in the preceding section, starting from a neutral beam. We would probably choose the electrons as the first generation in this beam; at 2.5°, the flux is considerably lower than at 0° (see Fig. 1), so that the possibility of having a magnet septum contain a larger effective solid angle around the EPB target becomes important. A general purpose target will not be a hydrogen target anyway, so that a higher degree of γ conversion within the target is to be expected.

The presence of other beams originating at the same EPB target introduces not only a restriction in primary-yield parameters, but has two more disadvantageous features: the beam path has to be made long enough to allow for sufficient physical separation of the various beams and associated experimental areas; and the stray backgrounds will inevitably be larger (see below).

DETAILED FEATURES-- CHOICE OF PARAMETERS ("OPTIMAL VERSION")

Location of Facility

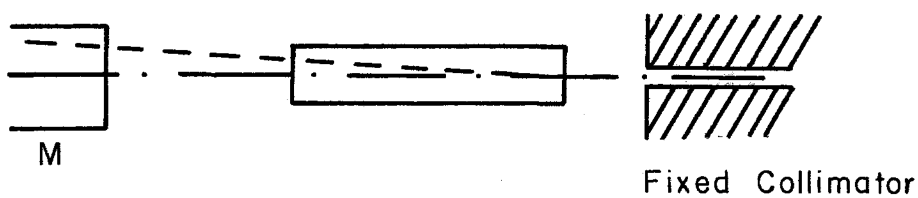
The choice of the primary-beam target in an adjustable-intensity branch of the EPB, fed by insertion of a septum magent into one of the main beam lines, is indicated for the following reasons: in this manner, we gain an independent target facility, the only coupling to the rest of the experiments being the amount of protons taken out of the main beam and diverted into the γ channel. This allows freedom to change intensities and composition of secondaries by (i) proper choice of target material and thickness; (ii) variation of the angle of incidence of the beam on the target. Both of these features are of great importance. The yield curves for photons, Figs. 1 and 2, show a very different angular characteristic when compared with the main neutral contaminant, the neutron flux (see Fig. 5). The neutron flux peaks at 0° very sharply, then falls off rapidly with increasing angle. While the γ flux also peaks forward, the decrease with angle is very much slower, and the integrated (over energies) ratio of photons/neutrals other than photon becomes much more favorable at larger angles.

It remains for the individual experiment projects to decide on the optimal choice of these parameters. For instance, it has been pointed out[2] that γ fluxes (and electron fluxes) at somewhat lower energies (say, 50-60 GeV) are very plentiful, and are less forward-peaked than the higher-energy components. We can then, for 60-GeV experimentation, decrease the backgrounds considerably by working at larger angles, while changing nothing but the angle of incidence of the EPB on the target.

Primary Target and Shielding

The primary target is located downstream from a sequence of magnets which bring the partial EPB to impinge at angles between 0 and 20 mrads.

For most applications, it ought to have λ/X_o small; liquid hydrogen would be optimal (x = 470 cm X_o = 820 cm); photons would emerge after traversing a minimum of radiation lengths. However, at larger angles of incidence, a long target will present an extended source to the fixed



slit downstream. We will therefore probably resort to Be as a target in most cases (λ = 37.7 cm, X_o = 34.7 cm), and reserve hydrogen for use in conjunction with high-intensity photon beams at very small angles.

The primary target must, of course, be well shielded; in particular, we have to keep in mind that, for nonzero degree incidence of the EPB, the collimator downstream will also have to act as a beam dump. This is a stringent requirement, the solution of which will, however, be standard around the various end stations of the EPB.

Sweeping Magnet, Primary Radiator

Immediately downstream from the primary collimator, a low-quality high-field magnet will be used to deflect the charged component of the beam. In order to diminish background, it appears advisable to have the deflection occur vertically. A second collimator is built into a shielding wall downstream from the sweeping magnet, so that only the neutral component of the beam reaches the radiator R_1.

All neutrals will hit the radiator R_1; its thickness will be of order $0.5\ X_o$ (a compromise has to be found between a high photon conversion efficiency, indicating a thick radiator; and a small probability for a subsequent bremsstrahlung process for the e^+, e^-, which should therefore not traverse a substantial fraction of a radiation length within the high-Z radiator). If we keep the radiator reasonably thin, we not only safeguard against an undue depletion of the high-energy end of the electron spectrum, but also avoid the electrons' acquisition of a sizable transverse momentum due to multiple scattering.

Typically, the transverse momentum imparted to the electrons by multiple coulomb scattering will amount to < 15 MeV/c; this number is small enough so that the subsequent beam-transport system will essentially regard the electrons as originating in the EPB target. The characteristic angle of the pair production process itself $\approx m_{e\ell}/E$ can be disregarded with respect to the multiple scattering angle.

In addition to the photons producing e^+e^- pairs in R_1, an enormous flux of neutrons, peaked at high energies, will hit R_1, and produce sec-condaries, some of which will have the momentum and charge to be accepted by the subsequent beam-transport system.

In order to miminize this contaminant, we will make λ/X_o very large for R_1 (for Pb, $\lambda/X_o \approx 30$); this will give us strong interactions on the 1% level. In addition, cosmic-ray data indicate that typical transverse momenta imparted in these strong processes will be typically 300 to 500 MeV/c--a factor of at least 30 above that acquired by the electrons. This results in the subsequent beam optics "seeing" an apparent target which is correspondingly much larger for the strong secondaries than for the electrons. Therefore, a downstream double focus of the beam will be found to discriminate very strongly against them.[4]

Beam Optics

The electrons originating in R_1 will be used in either of several ways; in particular, we will want to have the option of using either a high-flux low-purity beam or a purified beam; of focussing it either onto an experimental target or onto a radiator R_2 where we use it to produce bremsstrahlung for the sake of obtaining a high-purity photon beam (see next section).

The beam-transport system as such is entirely conventional. We will want its parameters flexible enough so we can produce an image of the EPB target (dispersive or nondispersive), either at the location of the radiator R_2 or at the secondary target location. In addition, the beam purifying scheme to be selected for cases where high purity is indicated (see next section) may demand a wide-band momentum acceptance of the system. However, such requirements can and will be met in standard ways, and we do not forsee any problems.

Beam Purification

If we want to enrich our photon or electron beam over what comes natural in the scheme outlined here, we do this most easily in the electron phase. We can make use of the low mass of the electron in various ways in order to separate it from contaminants that carry the same charge and momentum.

1. Although it will be hard to meet all necessary conditions[9] to make such a system work, differential Cerenkov counters (DISC) can be built to separate electrons from π's at energies $\gtrsim$ 100 GeV. However, the beam divergence must be kept small, thus limiting our intensities, and the device will demand major development work.

2. Radial acceleration of high-momentum electrons causes them to radiate; higher-mass particles of equal momentum exhibit no detectable effect. We can therefore separate electrons from π, K, N contaminants by running them through enough of a magnetic field that either they lose enough energy to degrade them below the initial momentum acceptance of the beam, or have a detectable photon ("synchrotron radiation")

emerge so every electron can be tagged. Such schemes have been discussed by Luckey.[10] The relevant formulae are energy loss of the electrons and spectrum of the emitted photons passing through a 10m long magnetic field of 20 kG, the energy loss due to synchrotron radiation will amount to 0.5 GeV; however, the spectrum is strongly peaked at low energy ($k \lesssim 30$ MeV), with a slim tail extending out to 100 MeV: detection of such low-energy photons is problematic in the presence of heavy backgrounds. If, on the other hand, we want to decrease the energy of the electrons below the momentum bite of the other particles in the beam, long and expensive fields will be necessary to accomplish the job--depending on the $\Delta p/p$ of the beam. This, again, will limit the total flux available by restricting the momentum width of the beam.

3. Similarly, deceleration of electrons in the coulomb field of high-Z nuclei yields an energy loss due to bremsstrahlung emission for the electrons in the beam, without affecting higher-mass particles. Toner[4] mentions that all electrons that radiate more than the momentum resolution of the beam optical septum can be separated, in principle, from the nonradiating beam constituents. The bremsstrahlung photon spectrum is peaked in the well-known manner at low energies, so that photon tagging of the electrons may not appear promising throughout. However, for a 100-GeV electron beam, and a momentum acceptance downstream from the "purifying" device, a reasonable electron tagging efficiency can be shown to exist[11] simply because of the fact that it

is fairly trivial to detect electromagnetic showers induced by photons of energies $\gtrsim$ 2 GeV with excellent discrimination against other particles (Fig. 7).

In such a scheme, the band width of the optical system downstream from the high-Z "purifier" may be as large as 10%. In this case, purification will leave us with final intensities of $\lesssim$ 5-10% of the incident electrons, and will allow tagging efficiencies of $\lesssim$ 5%.

At this point, we do not wish to make the decision for one of these three systems; but rather keep all options open--and impose this as a condition on the optical and physical layout of the beam-transport system. In particular, we wish to await the technical advances which are certain to occur on the DISC front.

Photon Tagging Facility

Downstream from the beam-transport system, photon experimentation demands reconversion of the electrons into a photon beam. A radiator R_2 is placed upstream of the optical focus of the beam, so that we form an approximate image of the EPB target in the experimental (secondary) target. The spectrum of bremsstrahlung produced by monochromatic electrons is again well known, dk/k. However, for many experiments we will want to know the precise energy of every individual photon. We will therefore use the bremsstrahlung process occurring in R_2 to tag the photons (Fig. 8). This is a well-known technique, which has been successfully applied in many cases. The electrons emit bremsstrahlung quanta forward, into the experimental target; their (slowed down) momenta are subsequently analyzed in a different magnet and (shower) counter bank. We can then correlate the deflected electrons with individual experimental events.

Known pitfalls of this method are:

(i) Electrons may hit the magnet yokes, lose energy and thereby "fake" a bremsstrahlung event. To obviate such error, we can make R_2 out of scintillator material (i. e. Pb-doped scintillator plastic, since we want high Z for low λ / X^o!). A coincidence requirement on this counter will then exclude spurious effects;

(ii) Electrons may radiate twice; this effect can be safely calculated and demands a thin target;

(iii) Two or more photons may be emitted in the deceleration process. Such effects have been calculated approximately; they should become important on the 1 percent level.

(iv) Electron trident production may give rise to electrons' being detected in the counter bank without an accompanying photon being emitted. We can avoid trouble due to this (small) effect if we demand an anticoincidence with a veto counter between R_2 and experimental target.

Typical intensities which can be obtained in this manner are again dependent on the desired purity of the tagged beam. If we do not mind errors due to double processes in the radiator, and the tagging counter bank detects electrons that have lost > 80% of their energy, up to 10% of the incident electrons can yield useful photons. A more workable fraction is 2-5%.

Problems connected with the photon tagging method are well-known and discussed in the literature. However, a respectable fraction of the continuous bremsspectrum can be used in this fashion with good knowledge of the photon energy; other methods of monochromatizing[2] do not promise, at this time, workable intensities.

Similarly, we do not, at this time, foresee sufficient electron intensities in the parent beam to make polarized photon work possible in any one of the established techniques using real photons.[2] Instead, we can and will rely on inelastic scattering experiments using electrons and muons to yield polarization parameters.

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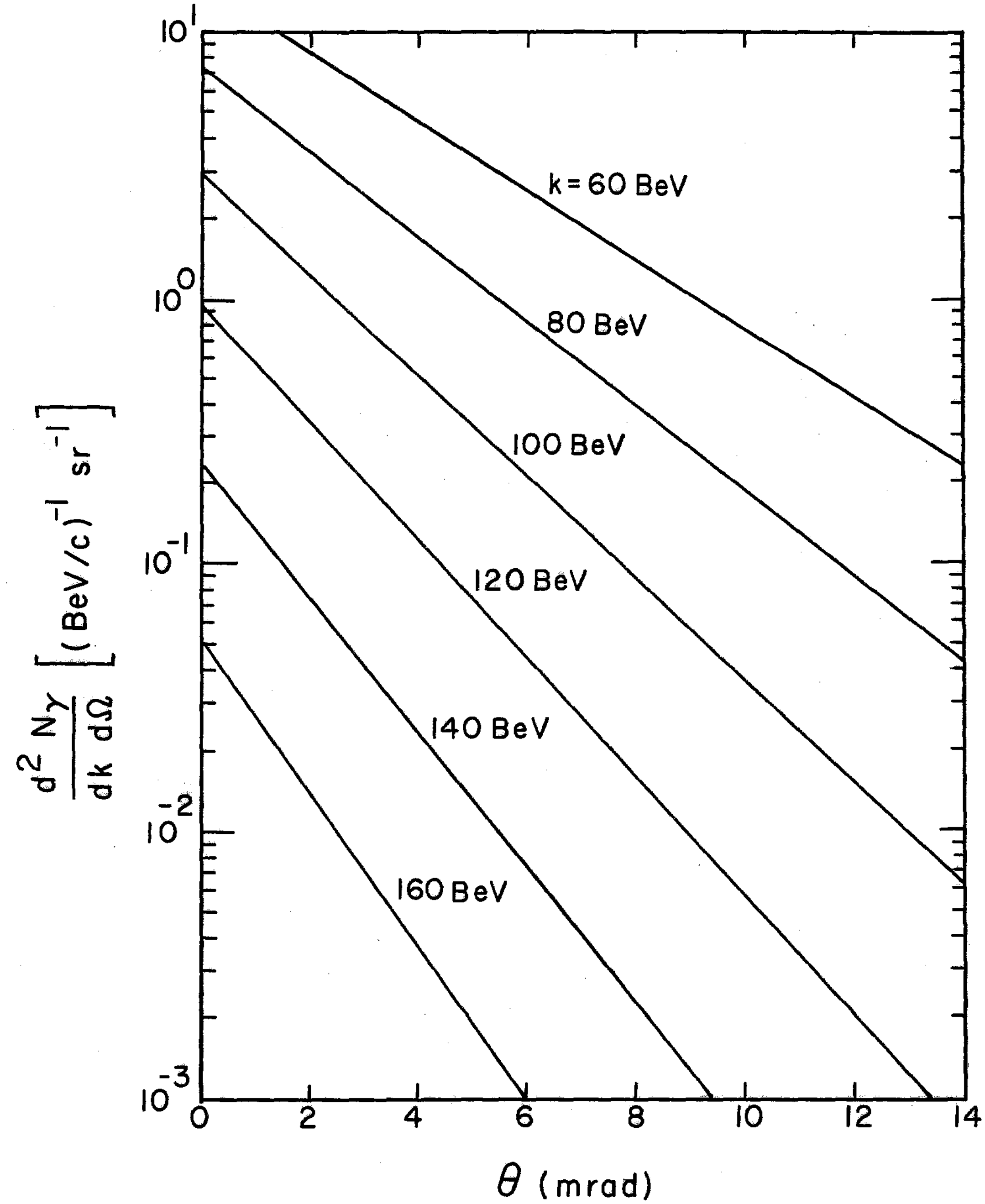

Fig. 1. Photon yield per interacting proton from 200-GeV p-p collisions.

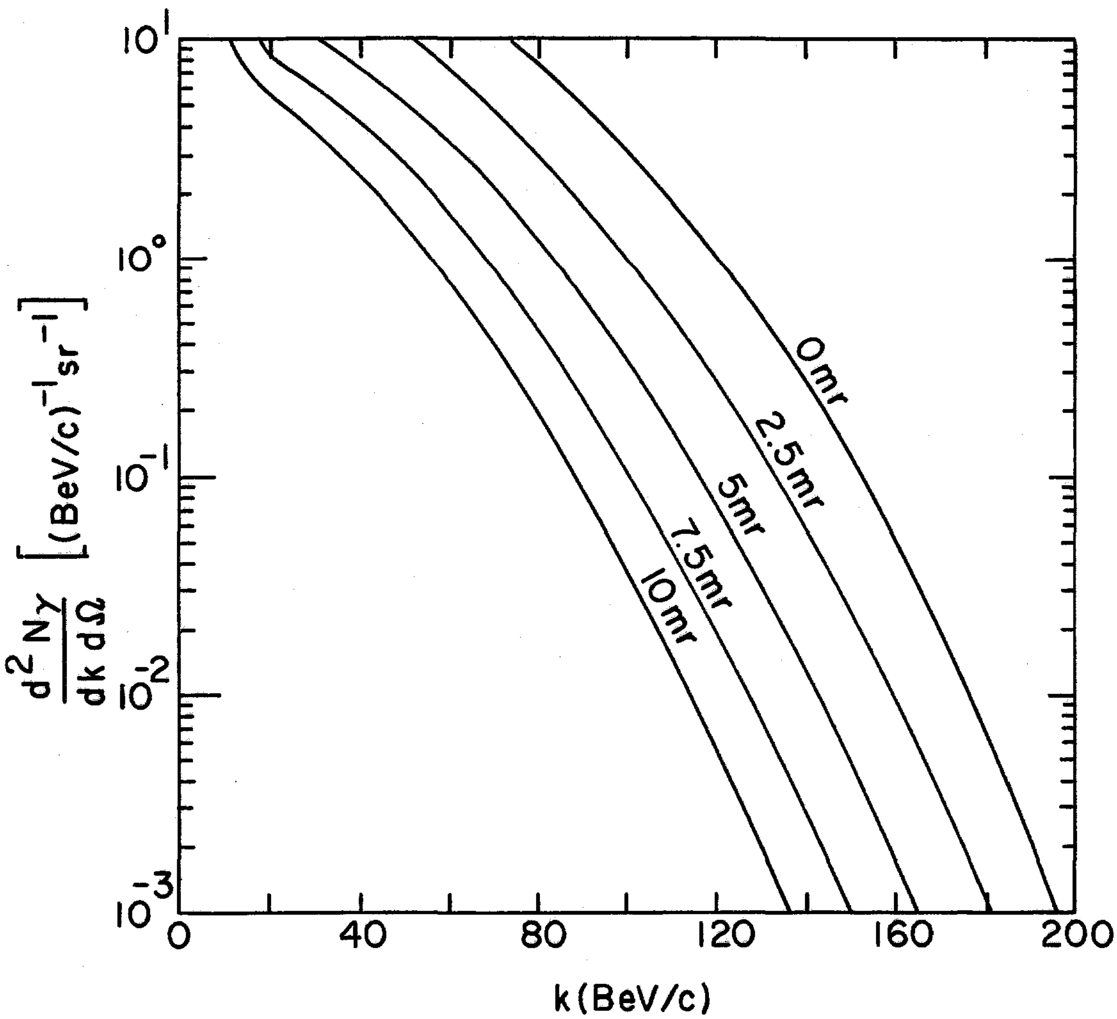

Fig. 2. Energy dependence of photon yield per interacting proton, from 200-GeV p-p collisions, as a function of production angle.

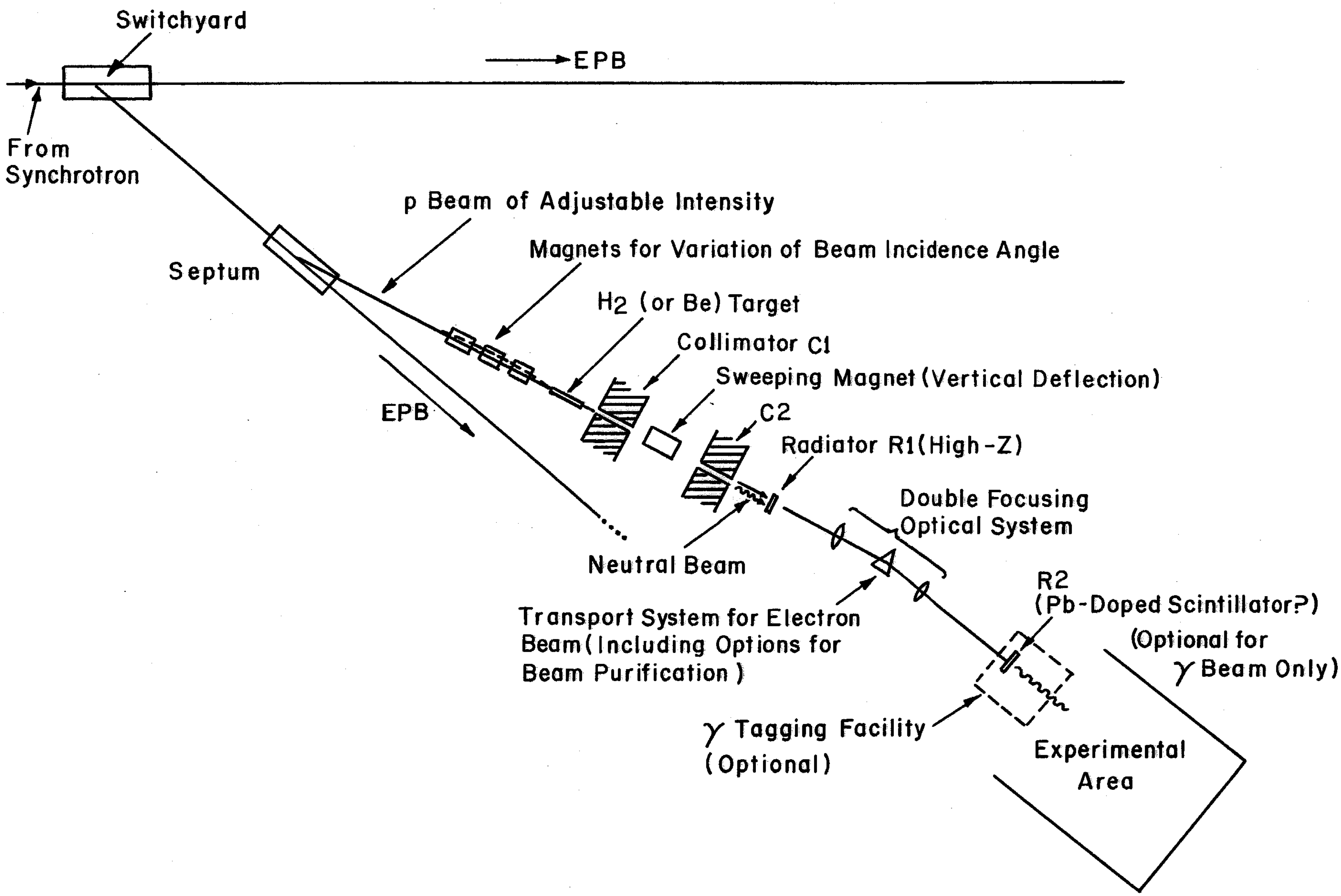

Fig. 3. Schematic layout of electron-photon facility, "optimal version."

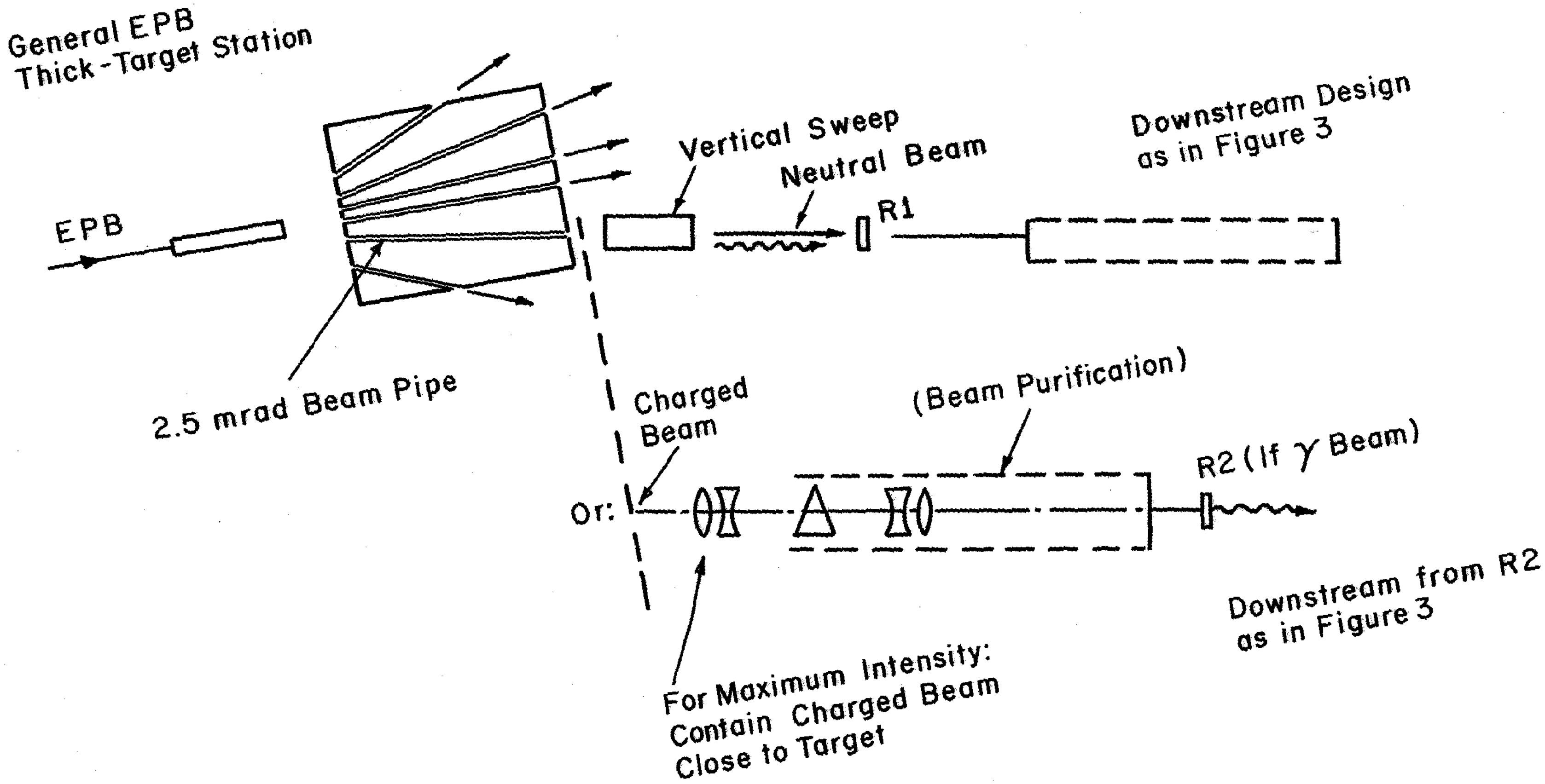

Fig. 4. Schematic layout of electron-photon facility, alternate layouts.

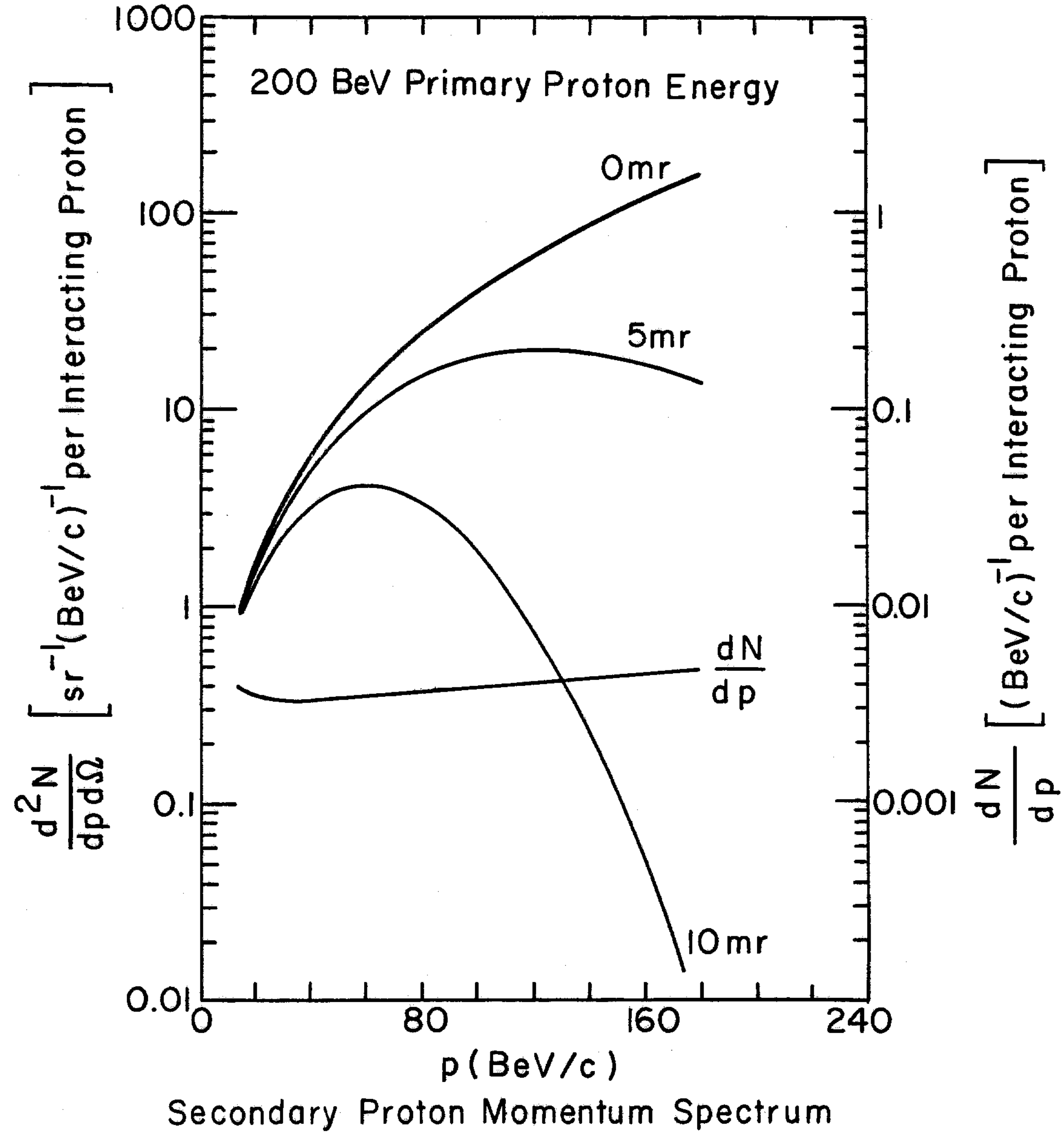

Fig. 5. Trilling's estimate of secondary proton spectrum. Neutrons show similar behavior, with somewhat smaller yields.

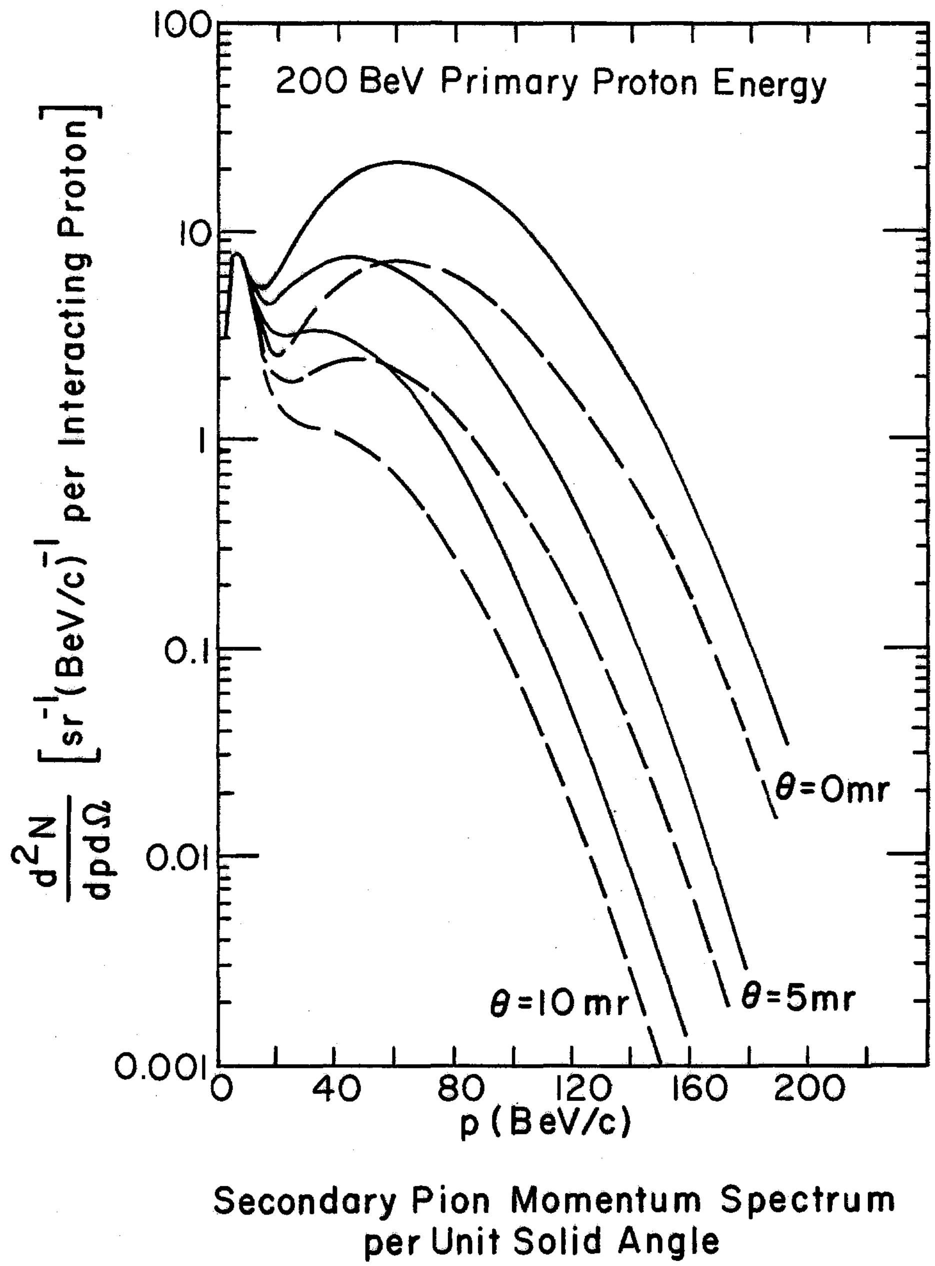

Fig. 6. Trilling's estimate of secondary pion spectra. Full line - +; dotted line, -.

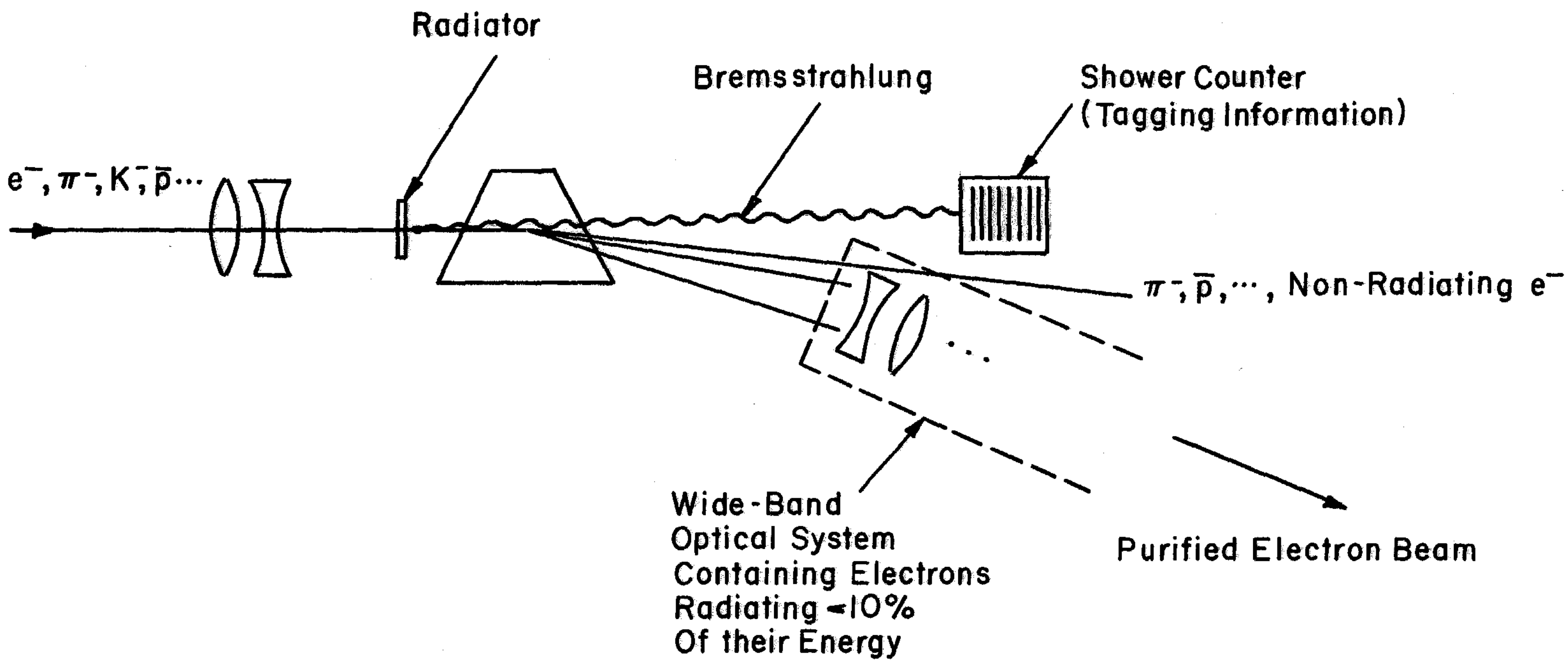

Fig. 7. Schematic of electron tagging facility.