A 300 GeV HIGH QUALITY ELECTRON AND PION BEAM AT THE NEW GENERATION PROTON ACCELERATORS*

Z. G. T. Guiragossián and R. E. Rand

High Energy Physics Laboratory

W. W. Hansen Laboratories of Physics

Stanford University

Stanford, California 94305

Summary

It is demonstrated that high quality secondary electron beams can be made available with intensities of 10^8 e/pulse at the new generation proton accelerators. A beam design is presented with the following qualities. 1) Large beam transport acceptance [9.5 μster % Δp/p (FW), with a momentum bite of ± 2%], 2) good momentum resolution [less than ± 0.3%], 3) good angular resolution [less than ± 0.1 mrad], 4) small final spot size [less than ± 3 mm horizontally and ± 6 mm vertically]; and 5) negligible pion contamination [less than 1 pion in 10^5 electrons]. All of these qualities are achieved while preserving the valuable electron intensities at production. Using standard beam transport magnets a 300 GeV/c transport system is designed with four focussing stages, the first two of which provide a beam spot of sufficient quality for tagged photon experiments. The optics design is based on a periodic cell structure which includes correction of second order aberrations by means of four weak sextupoles. The synchrotron radiation by electron throughout the transport system is used to advantage, to remove pion contamination at the final beam spot. Pion impurity is null at energies greater than 160 GeV. This high quality transport system can also be used to deliver a high intensity pion beam [10^9 - 10^{10} π^- per 10^{13} interacting protons], up to 300 GeV/c. Thus a very versatile facility can be provided for electron and pion experiments at the same installation. A beam design specifically made for application at NAL is presented.

Introduction

A design is presented for a secondary electron beam of highest purity, suitable for the electron scattering experiments[1] proposed at the National Accelerator Laboratory. With a minor modification at the front end, a secondary pion beam of highest intensity is obtained, suitable for the pion scattering experiments[2] also proposed at NAL. In the pion mode, at 300 GeV only with this beam is it possible to provide a beam intensity of up to 5×10^9 $\pi^-/10^{13}$ incident protons, making this the highest intensity and highest energy pion beam in the world.

In the electron mode, the beam yields 10^8 e^+ or $e^-/10^{13}$ incident photons when the energy of electrons is about one half the energy of protons. Only with this type of beam design is it possible to remove entirely the pion impurity without the use of costly "chicane" high field superconducting magnets.[3] It is emphasized that synchrotron radiation by electrons in the beam transport magnets is very significant in reducing pion contamination of the final beam spot. Also, pions are readily separated from electrons because of the small value of the final spot size achieved. Thus it is shown that superconducting magnets to enhance these effects are superfluous. Pion impurity is less than 0.01% at every energy and can be made essentially null at electron energies greater than 160 GeV.

The beam is designed with four focussing stages, with the specific provision that the first two stages provide a beam spot of sufficient quality for tagged photon experiments.[4] Using standard NAL beam transport magnets the beam will operate at up to 300 GeV/c with the following properties: Acceptance 9.5 μster % Δp/p (FW), momentum bite ± 2% , momentum resolution of momentum hodoscope $\Delta p/p = \pm 0.30\%$ (HW at base), final spot size < ± 3.0 mm × ± 5.5 mm (HW at base). Hodoscopes are also included for measuring the angles at which electrons pass through the experimental target with resolutions in both planes of better than ± 0.1 mrad. These properties are achieved by a periodic beam structure which includes correction of second order aberrations by means of sextupoles. Thus, an electron beam of high purity with very fine energy and angular resolution is obtained and these qualities are achieved without degrading electron intensity at production which is a valuable commodity at NAL. Because of this careful and meticulous design, necessary for an electron beam, it is now evident that when the beam is tuned to deliver pions, the highest intensity pion beam is obtained. Therefore, it must be pointed out that such a beam line will operate equally well for secondary hadrons and electrons and will in fact constitute a very versatile facility.

Beam Design

Figure 1 shows a schematic layout of the beam. In the electron mode of operation, the functions[5] of the four focussing stages are as follows: (1) Electron production [protons produce π^0's in primary target of low Z material: Be or deuterium, (Be is used for practical reasons), sweeping magnets remove protons and other charged particles from neutral stage of beam; photons from π^0 decays pair-produce electrons in a high Z radiator, (Pb or U)], primary defining apertures, horizontally (x) dispersed focus (F1) to define momentum bite cleanly, vertical (y) focus (F 1/2) with slits to reduce π^- contamination. (The primary target is the virtual object of the beam optics.) (2) Magnet after F1 to clean up beam, achromatic focus at F2. This focus is used for the tagged photon beam or with a horizontal slit to further eliminate pions in the four stage beam. (3) Dispersed focus at F3 with momentum hodoscope. (4) Angle hodoscopes at first foci of last set of quadrupoles. These measure directly the angles (θ horizontal, φ vertical) at which an electron passes through the experimental target located at the achromatic focus F4.

The beam is designed for a maximum momentum of 300 GeV/c. Careful attention was paid to the desirability of using standard NAL transport magnets throughout.

* Work supported by the National Science Foundation (Grant No. GP-28299).

The design of the "front end" or electron production stage is largely dictated by necessary functions and compatibility with other beam switchyard parameters. However, a choice is made of the geometry which maximizes angular acceptance ($\Delta\Omega \simeq 2.5$ μster) and minimizes multiple scattering effects. The angle of incidence of the proton beam at the primary target can be varied to enable the use of production angles other than 0°. At the sacrifice of some intensity the final π/e ratio can be improved if at all necessary. The primary target is of a material which maximizes the ratio of π^{0} production to photon attenuation. Deuterium is the optimum choice for this condition but for practical reasons, beryllium is the most reasonable alternative. There is an optimum target thickness for which the maximum number of photons from π^{0} decays are produced. This thickness is 1.13 interaction lengths for beryllium. The n/γ ratio or equivalently the $\pi^{\pm}/e^{\pm}$ ratio, decreases monotonically with target thickness.

A knowledge of the cross section for inclusive π^{0} production from pp collisions determines precisely the electron beam intensity. Recent results from the ISR show[6] that the cross section for inclusive π^{0} production is equal to the average of the cross sections for π^{-} and π^{+} production from pp collisions. Similarly, recent measurements[7] have been made at the ISR, especially at 500 GeV/c equivalent laboratory momentum, for the cross section of inclusive π^{+} and π^{-} production at several forward angles. Empirical formulae[8] are obtained by fitting all of the measured yields of π^{+} and π^{-} production, from 1500 GeV/c down to 19.2 GeV/c laboratory proton momenta, using the latest measurements from the ISR together with those from CERN and BNL. Independently, we have used a multiperipheral model[9] of π^{+} and π^{-} production to calculate the π^{0} cross section and hence the expected electron beam intensity. The result of this calculation is shown in fig. 2. Comparison of this model dependent calculation with the three-parameter empirical formula fit of the ISR measurments shows that our NAL electron beam intensity calculations are valid and conservative by a factor of about 1.5. Therefore, it is ensured that at the fourth focus of this beam an electron beam intensity of 10^{8} electrons or positrons per pulse will be provided for experimental usage.

The electron beam intensity values are obtained in a straightforward manner. An exact energy spectrum of photons is given by integrating the above known π^{0} double differential cross sections, with an energy factor due to the isotropic decay distribution in the π^{0} center of mass. An effective target efficiency is used derived by taking to account hadronic production of π^{0}'s and electromagnetic attenuation of photons in the target. The yield of electrons is now obtained from the known pair production formula by integrating the photon energy spectrum and using the correct radiation efficiency factor. Finally, the electron beam intensity is determined by the beam transport momentum angle acceptance factor.

As shown in fig. 1, between the primary and secondary targets, bending magnets separate the protons and other charged particles from the neutral components of the beam. The proton beam is dumped in the vicinity of the first quadrupole, below the beam line level. The second target or radiator consists of a high Z material such as lead or uranium which has a high ratio of collision length to radiation length. Optimum thickness for the radiator is approximately 0.5 radiation lengths. The interactions of neutrons at this radiator produce the pion impurity of the electron beam. Electron purity is strongly influenced by the optical quality of the beam design, since electrons lose energy by synchrotron radiation throughout the beam transport system and thus can be separated from pions provided that the final beam spot is small and free from aberrations. Muons from pion decay and other sources are transmitted mainly through the earth shielding of the beam which is about 5 meters below ground level. The expected μ/e ratio is less than 10^{-6}.

Because the beam is 600 m long with a moderately large acceptance, it would suffer from second order chromatic aberrations of several times first order effects. Therefore, from the start the beam optics is designed to be compatible with sextupole correction of second order terms. This feature is essential to the proposed electron scattering experiments for without it, it would not be possible to achieve the necessary momentum and angular resolutions and especially the small spot size and high electron purity. The latter parameter is directly affected by the size of the electron beam envelope at F2 where a horizontal collimator is used to define a pion spot. This feature is important not only because it removes pions from the beam at F2, but because it enhances the π-e separation at F4, caused by synchrotron radiation by electrons in the beam bending magnets.

Experience has shown that sextupole magnets can only be successfully used in a beam line by locating them as optically conjugate pairs with equal strengths, i.e. the transfer matrix between the sextupoles must be identically ± unity. This ensures that even order geometrical aberrations introduced by the sextupoles cancel outside the pairs. Sextupole pairs cannot be interlaced without introducing serious third order aberrations. For each pair, the strength can be chosen to cancel only one second order chromatic aberration of the beam. The design is based on the exact correction of the main chromatic aberration term $\langle x|x'\delta\rangle$[10] in the horizontal bending plane (x) at F2 and F4. This is done in such a way that the geometric aberrations (mainly $\langle x|x'_0 x'_0\rangle$ inevitably introduced at F1 and F3 are tolerable. Worsening of the chromatic aberration in y is avoided by locating the sextupoles at y foci where they have negligible effects. A small spot size in y at each x focus (between the true y foci) is obtained by locating an angle focus waist ($\langle y|y_0\rangle = \langle y'|y'_0\rangle = 0$) at these positions. This arrangement also ensures that chromatic aberrations in y at all x foci are negligible. (There are aberrations in y' however.)

The first y focus, where pions are removed from the beam, is therefore inside the first stage (F 1/2) where chromatic aberrations are small. Location of the sextupole pairs at conjugate points requires that the beam structure be periodic from F 1/2 to F3 1/2. However, the design of the first quadrupole doublet need not form part of this structure and has been chosen to produce a magnification in the first stage of 2.4 in x and 3.0 in y. This increases the acceptance of the periodic part of the beam and enables one to use a reasonable focal length for the quadrupoles (24.4 m). It also helps to reduce the geometric aberration introduced by the first sextupole at F1 and the third at F3. Similarly the last half of the last stage (F3 1/2 - F4) does not form part of the periodic structure and is designed purely to obtain the required beam spot size and to provide suitable locations for the θ and φ hodoscopes.

Magnet positions and strengths were calculated using the computer program TRANSPORT.[10] Rays were traced through the final system using the program TURTLE[11] to evaluate the performance of the beam transport and the effect of synchrotron radiation by electrons. Calculations were performed with an effective initial electron spot size of ± 2.5 mm in both planes, the value expected at 100 GeV/c. The main effect contributing to this spot size is multiple scattering of electrons in the radiator. Pions, which are generated mostly by neutrons in the lead radiator, are produced with a much greater spread of angles than are electrons so that the effective pion spot size at the primary target is much larger than that for electrons.

Imperfections in the quadrupole fields as found in actual measurements were included in the ray tracing calculations by using a higher order multipole expansion. It is interesting to note that in this type of periodic beam structure, such imperfections have virtually no effect because of cancellations at conjugate lens positions.

Figure 3 shows the electron and pion beam profiles at F4 where the experimental target will be located. The spot sizes easily satisfy the experimental requirements. The separation of the electron and pion beam spots by synchrotron radiation is discussed below.

An important property in a secondary electron beam is cleanness in momentum. That is, it should not be possible for a significant number of electrons with momenta outside the nominal limits to pass through the experimental beam spots at F2 and F4. The periodic beam structure described here performs well in this respect. Between F1 and F2, only 0.3% of the electrons are lost. Furthermore, it is impossible for electrons of momenta less than 0.865 p_o to pass through the beam spot at F2. In stage 4, losses only occur (inevitably) at the hodoscope. In each case it is possible to place a veto shower counter where it may detect photons radiated by an electron in the hodoscope elements.

Electron Beam Purity And Synchrotron Radiation

The permissible level of pion contamination of the electron beam is determined primarily by the pion rejection capability of the experimental electron detectors. A secondary consideration is that in a 25 cm liquid hydrogen target for instance, 1.4% of all interacting pions would produce electrons via π^o production followed by $\pi^o \rightarrow \gamma\gamma$ and $\gamma \rightarrow e^+e^-$. These electrons are produced mainly at low energies and do not constitute a significant background.

The electron detectors[1] under development in this laboratory consist of several large NaI(Tl) crystals interleaved with multi-wire proportional chambers. Tests with these detectors have shown that at 10 GeV, the probability of a pion being identified as an electron is $< 0.3\%$ if the momentum is known to 3% . There is reason to expect this uncertainty to drop to 0.1% at NAL energies. Now the ratio of the total cross sections for π^-p to e^-p interactions is typically 10^3. Hence the probability of confusing a hadron from a π^- interaction, with a scattered electron is conservatively 0.09% for a π/e contamination ratio of 3×10^{-4} . Such a systematic error is certainly less than other experimental errors, systematic or statistical. It is shown that a π/e ratio of 10^{-5} to 0.0 is attainable in the present beam design at the final focus F4. At F2, however, the pion contamination is unacceptable. The same would be true in a 4-stage beam not corrected for second order aberrations.

The flux of pions which remains within the electron beam spot at F4 depends on several factors, the most important of which are production mechanisms at the primary target, beam optics and synchrotron radiation. It has not been generally realized that this last effect-synchrotron radiation of electrons in the conventional beam bending magnets - is very significant.

This may be seen as follows. The fractional loss in momentum of an electron of energy E(GeV) passing through a uniform magnetic field B(kgauss) of length L (meters) is given by

$$\frac{\Delta p}{p} = 1.26 \times 10^{-8} \; E \, B^2 \, L \quad .$$

Hence for a 200 GeV electron in a field of 14 kgauss of length 3.05 m, $\Delta p/p = 0.15\%$. This is a small effect but the deviation due to this momentum loss is 4.8 μrad. Again this is a small angle but in each phase of the beam there are about 10 magnets with an average lever arm of ~ 100 m. Hence if the magnet settings are not compensated for this effect, the electron beam spot will be shifted ~ 5 mm, more than the total spot size. If however the magnet settings are "radiation compensated", the electron beam spot will be on axis with a separate pion beam spot off axis by ~ 5 mm. Thus the pion contamination can be reduced almost to zero by a suitable scraper or veto counter.

This effect is illustrated by the beam profiles in fig. 3 which are due to exact ray tracing calculations using the program TURTLE. (The momentum and deviation of each ray were suitably offset after each bending magnet.) In fig. 3 all beam profile distributions are normalized arbitrarily to have equal heights. At energies less than 300 GeV, magnet settings within each group of magnets are optional provided the integral $\int B d\ell$ is correct and B does not exceed 14 kgauss. They have been chosen as follows. For energies greater than 200 GeV, it is sufficient to use a minimum number of the available magnets with power distribution equally between them, to achieve almost complete separation of pions and electrons. At lower energies the effect of synchrotron radiation may be optimized by using all available magnets with reversed fields where necessary so that the integral $\int B^2 d\ell$ is maximized but the beam line geometry is preserved. This procedure provides a substantial reduction in pion contamination which becomes zero at about 160 GeV.

Synchrotron radiation will also be responsible for some reduction in beam quality due to the statistical fluctuations of the process. It is estimated that these effects will cause an additional beam spot spread of ~ 0.5 mm at F4 at ~ 200 GeV and a momentum spread of ~ 0.2%. Both of these figures make negligible contributions when folded quadratically with the respective geometrical values.

It has been suggested[3] that synchrotron radiation be used to enhance electron beam purity by placing a "chicane" of superconducting magnets at the intermediate focus of the beam (F2). Thus the electron momenta would be shifted by a large amount at this point and with the second phase of the beam tuned accordingly, pions could be eliminated. However it is now seen that the distributed effect of synchrotron radiation along the beam line is sufficient to reduce pion contamination to an acceptable level in the present beam design and application.

Pion Beam

It is evident that the high quality optical properties of this beam and the moderately large beam acceptance can be used profitably to provide also a beam of pions at NAL which is higher in energy and intensity than any other presently installed secondary beam at an accelerator facility. A minor modification is required to accomodate this versatility. A high quality 300 GeV pion beam is obtained by removing the first radiator and turning off the initial set of steering magnets. However, a different proton beam dump is required or the same beam dump can be used with the addition of compensating steering magnets. The yield of negative pions in this beam is high. Based on recent ISR measurements[7,8], using 500 GeV incident protons at the Be target, for 10^{13} incident protons, $(1\text{-}5) \times 10^{9}$ π's are obtained at the fourth focus within a spot size of ± 2 mm, for a pion beam tuned in the momentum range of 150-300 GeV/c. This beam will contain antiproton and negative kaon components, typically at the few percent level of pion intensities. Nevertheless, a beam of 10^{7} antiprotron and 10^{7} K^{-}'s up to 300 GeV energies can be made available to experimental usage with tagging signals from differential Cherenkov counters. Thus, this beam constitutes a very versatile facility and a powerful tool of high energy physics investigations.

The authors are especially indebted to Dr. J. J. Murray for their inspiration.Professor R. Hofstadter has provided much encouragement and guidance throughout this effort. The authors are grateful to Professor R. R. Wilson and Professor E. L. Goldwasser for their continuous interest and encouraging support.

References

* Work supported by the National Science Foundation (Grant No. GP-28299).

1. Z.G.T. Guiragossián, R. Hofstadter, R.F. Schilling, M. R. Yearian, E. V. Hungerford III, G. S. Mutchler, G. C. Phillips and B. W. Mayes, NAL Proposal No. 193 (October 1972).

2. Z.G.T. Guiragossián, R. Hofstadter, R.F. Schilling, M. R. Yearian, E. V. Hungerford III, G.S. Mutchler, G. C. Phillips and B. W. Mayes, NAL Proposal No. 192 (October 1972).

3. F.J.M. Farley, E. Picasso and L. Bracci, Nucl. Instr. and Meth. 103, 325 (1972).

4. For the requirement of a tagged photon beam facility cf: C. Halliwell, P. J. Biggs, W. Busza, M. Chen, T. Nash, F. Murphy, G. Luxton and J. D. Prentice, Nucl. Instr. and Meth. 102, 51 (1972).

5. For details of this beam design cf: Z.G.T. Guiragossián and R.E. Rand, Report No. HEPL 677 and NAL 75 (October 1972) and, Nucl. Inst. and Meth., to be published in 1973.

6. G. R. Charlton and G. H. Thomas, Physics Letters 40B, 378 (1972).

7. A. Bertin, P. Capiluppi, M. D'Agostini-Bruno, R. J. Ellis, G. Giacomelli, A. M. Rossi, G. Vannini, A. Bussière and R. T. Poe, Physics Letters 42B, 493 (1972) see also 38B, 260 (1972) and 41B, 201 (1972).

8. C. L. Wang, BNL Report No. 17218 (1972) to be published in Physical Review.

9. L. Caneschi and A. Pignotti, Phys. Rev. Lett. 22, 1219 (1969).

10. K. L. Brown and S. K. Howry, TRANSPORT, SLAC-91 (1970).

11. D. Carey, TURTLE, NAL-64 (1971); see also paper G-20 submitted to this conference.

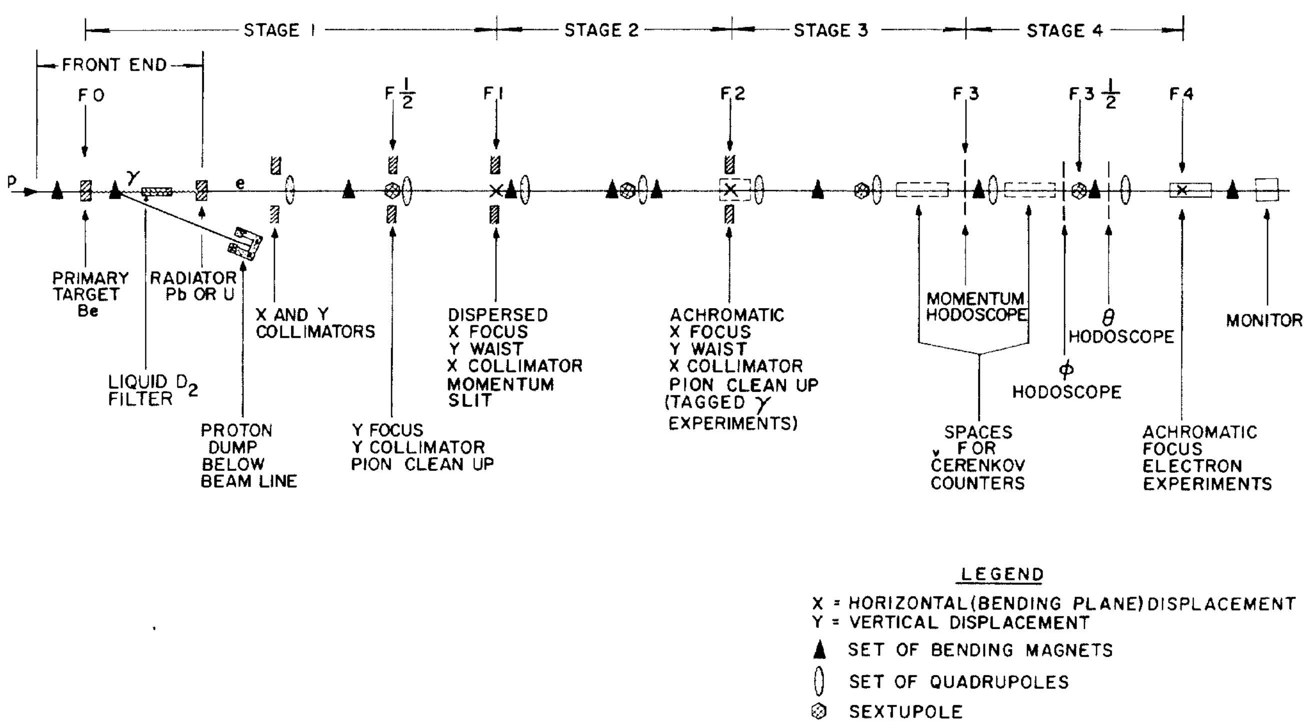

Fig. 1. Schematic layout of electron beam.

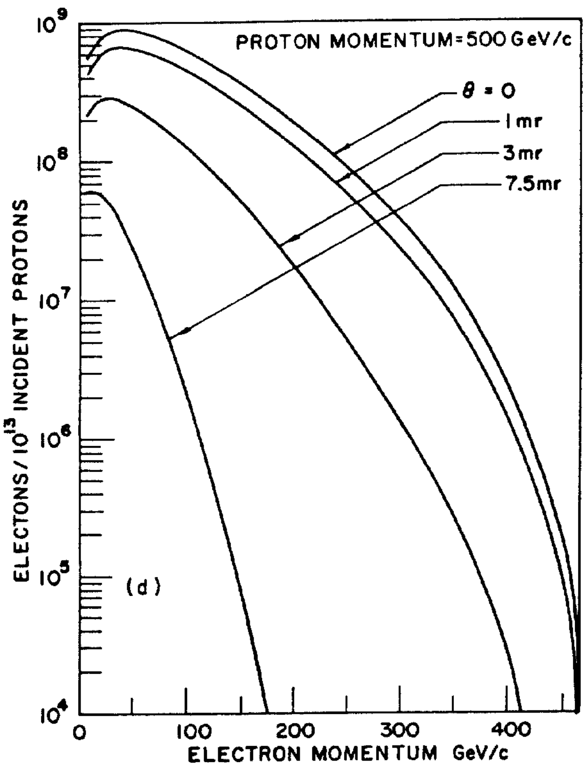

Fig. 2. Electron yields calculated from a multiperipheral model[9] for the present beam line ($\Delta p/p$) $\Delta\Omega = 9.5$ μster % $\Delta p/p$, Beryllium target 40.3 cm, 0.5 rad length lead radiator. Number of electrons/ 10^{13} incident protons at various production angles θ and 500 GeV/c momentum.

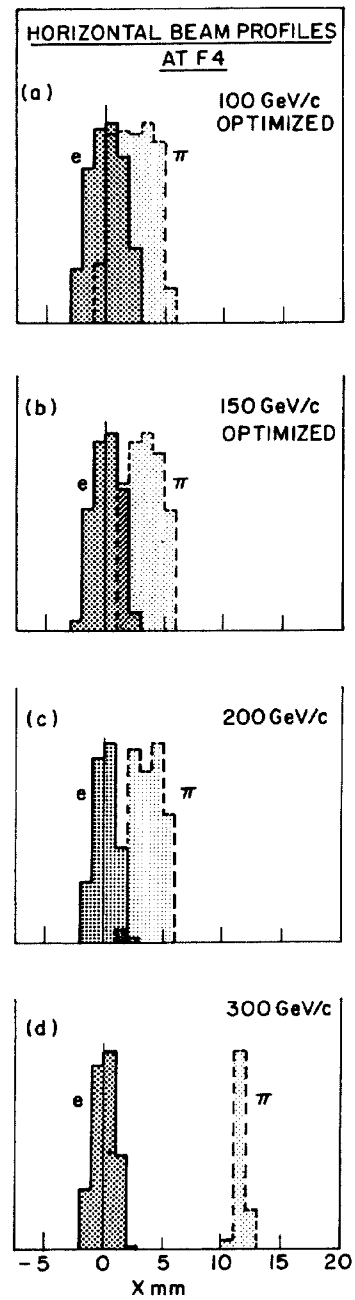

Fig. 3. Electron and pion horizontal beam profiles at F4 showing the effect of synchrotron radiation in a radiation compensated beam.
(a) 100 GeV/c, (b) 150 GeV/c. At these two momenta all the magnets in the beam line are used, some with reversed polarity, to maximize ΣB^2 and enhance the e, π separation, (c) 200 GeV/c, (d) 300 GeV/c. At these higher momenta, only the necessary number of bending magnets consistent with $B \leq 14$ kgauss are used.