DESIGN, CONSTRUCTION, AND EARLY OPERATING EXPERIENCE OF THE SLAC BEAM SWITCHYARD AND EXPERIMENTAL AREAS*

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Summary

This paper gives a description of the overall design and construction of the SLAC beam switchyard and experimental areas. The electron optics and transport components of the switchyard are described. The high-intensity beams transported by this system present special problems requiring design for radiation resistance, remote-precise location, quick removal, and resistance to corrosive environments.(13) These problems and their solution are discussed. The SLAC research yard and its present experimental facilities are discussed. Finally, a design evaluation and summary of early tests and operation experience in this area are presented.

Introduction

The design of the SLAC two-mile accelerator makes it possible to run several experiments simultaneously. The beam switchyard is designed to define the momentum of beams from the accelerator, to transport beams to the experimental areas, and to control high-power beams until their dissipation in targets or beam dumps. A system of pulsed and dc magnets delivers the beam from the accelerator to the various experimental setups on a pulse-to-pulse basis. Two shielded and physically separate end-station buildings are provided for experimental setups. In addition, a large area external to the buildings is available for experimental arrangements involving bubble chamber, spark chamber, and counter experiments using primary and secondary beams. Present arrangements provide for electron, photon, positron, μ particle and K meson beams. Three spectrometers are available in end station A. Considerable flexibility has been provided by allowing space for future beams and experimental facilities. Figure 1 shows the arrangement of the structures and experimental setups and shows some of the provisions for future beams and additions. Figure 2 is an aerial view of this research area. The design of systems capable of handling the intense beam available from the accelerator and also using the accelerator's multiple beam flexibility presents numerous problems in optimum instrumentation, mechanical design and physical layout for high-energy-physics experimentation. Some of these problems have been treated in other papers at this Conference.(1,2,3,4)

The beam momentum resolution is achieved by the use of precisely machined magnets and accurately regulated power supplies controlled by a computer, which monitors a long flip-coil in one of the magnets, and precise slits. Details are given in other papers.(2,5) The positioning of magnets, slits, and other components by optical tooling and precise surveying with reference to a laser beam is also discussed.(4) We shall discuss design considerations in the development of the beam switchyard and research area facilities, describe the presently existing system, and give results of the early tests and operation of the systems.

Beam Switchyard Transport System

The beam switchyard contains the beam transport system which delivers the beam from the accelerator to the experimental areas. The arrangement of the beam transport components is shown in Fig. 3, and design criteria for the systems are presented in Table 1. The A-Beam and B-Beam transport systems are nearly identical; therefore, only a description of the A-Beam transport system is given. The beam from the accelerator is directed through the collimator C-1 by the pulsed steering magnets AP 1-4. After being defined in size and position by the collimator the beam enters the pulsed magnets PM 1-5. The doublet Q-10-11 forms a horizontal image of the center of the pulsed magnet at the symmetry quadrupole Q-12 and a vertical image of the center of the pulsed magnet at the front edge of the slit SL-10. The bending magnets B-10-13 disperse the beam for momentum resolution at the slit. The symmetry quadrupole has little effect on the beam vertically because of the small vertical size of the beam resulting from the vertical focus at the symmetry quadrupole; however, in the radial plane the symmetry quadrupole recombines the different momenta, so that after passing through the second set of bending magnets, B-14-17, the beam will be achromatic. The quadrupole doublet Q-13 produces a low-divergence beam by imaging (approximately) the slit to infinity. The final beam then drifts without appreciable spreading to the end station. A small adjustment of the final location and direction of this beam can be made using the dc horizontal and vertical steering magnets A-10-11. Essentially, the transport system up to this point has traded beam size for divergence, the phase volume being kept constant. If necessary, a doublet can be inserted in the beam prior to the target to achieve a desired spot size or to phase-match the beam to an experiment. The drift space following the doublet must be chosen in conjunction with the gradients of the doublet to give the desired spot size or the proper phase match into the experiment or auxiliary system. In the A-Beam, a target, beam dump and the associated magnets and instruments for generating a photon beam are located in the drift space following Q-13-14. The pair of doublets, Q-13-14 and Q-20-21, can be used for phase matching either the electron, or to some extent the photon-beam, to experiments. In the B-Beam, in the corresponding drift space, two magnets--bending magnet B-38 and a specially designed magnet B-36, "magnetic slit"--have been placed to distribute the beam into three beam channels.

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Table 1: Parameters For
The Transport System Of The SLAC Switchyard

	System A	System B
Energy	2.5 to 25 GeV	2.5 to 25 GeV (expands easily to 40 GeV)
Acceptance		
Beam Radius	0.3 cm	0.3 cm
Ang. Divergence	$<10^{-4}$ radians	$<10^{-4}$ radians
Momentum width	2.6% total	5.2% total
Total Bend	24.5°	12.5°
"Resolution"	0.1%	0.2%
"Dispersion" at slit	0.15%/cm	0.3%/cm
Isochronicity (2856 μc rf)	$<10^{\circ}$	$<10^{\circ}$
Beam Power	0.6 MW max	0.1 MW max
Rep rate	10 - 360 PPS	10 - 360 PPS
Pulse Width	0.020-1.7μsec	0.020-1.7μsec
Achromatic	Yes	Yes

Problems Associated With Transport Of High-Intensity Beams

Equipment must be protected from direct impingement by the electron beam due to missteering and from lower-energy electrons in the spectrum from the accelerator which will be deflected into vacuum chamber walls by the transport systems magnets. For reasonable temperatures, the full beam power will heat most materials faster than they can reject heat. For example, a 600-kW, 20 GeV, 0.6-cm diameter beam resulting from 1.7 μsec long, 50-mA-peak current, electron pulses at 360 pulses/sec, will cause a rise of 50°C per pulse at the shower maximum in copper. Materials having low thermal conductivity or high atomic numbers will sustain severe damage after only a few pulses from the accelerator operating at high power. By proper design and water cooling, beam absorbers can be made for these power levels. The shower maximum at 15-20 GeV occurs at 5 to 7 radiation lengths and power absorption near the entrance is comparatively low; hence, windows of reasonable thickness--e.g., 0.060" stainless steel--can be used with water cooling. Also, if the beam strikes a chamber at sufficiently small angle the power deposition density is at reasonable levels.

Beam loss in the transport system causes intense radiation. Continuous beam losses occur at the slits, collimators, protection collimators located after magnets and, of course, in the dumps. DeStaebler(7) has estimated the integrated radiation exposure 10 feet from a shielded slit to be about 10^{10} ergs/gm in ten years. This figure was confirmed by Neet(8) whose tests also showed that radiation inside the shielding would be as high as 10^{13} ergs/gm in ten years. Preliminary measurements of radiation in the beam switchyard confirm these results. These intense radiation fields require a careful selection of radiation-resistant materials to avoid early failure of equipment due to radiation damage. In most cases the use of local electronics is prohibited.

A further complication in material selection results from nitric acid formed in the air of the switchyard as a result of the radiation. Calculations and measurements indicate that possibly 50 watts of ionizing power will be absorbed in the air of the beam switchyard when handling a 600 kV beam. This will result in the production of 80 grams of nitric acid per day and can cause serious corrosion problems in critical components.

Equipment which absorbs beam will become radioactive. DeStaebler(7) has estimated that saturation levels would be 10^5 to 10^6 mrem/hr at 5 feet from a material that has absorbed 1 MW of electron beam power over a long period. Repair and maintenance will become difficult at much lower levels. These intense residual radiation levels require that equipment be designed suitably for remote handling. Air in the switchyard housing will also become radioactive. Fortunately, most of the activity is due to isotopes with very short half-lives. It is thus possible to seal the housing in operation and to ventilate at shut-down after a short decay period. Water used to cool energy absorbers will become highly radioactive. N^{13}, O^{15}, C^{11}, and Be^7 are produced by irradiation of O^{16}. Tritium will also be produced. The N^{13}, O^{15} and C^{11} have short half-lives, but Be^7 and H^3 activity will build up to high levels. Water in which beam energy is absorbed will also be dissociated, releasing H_2 and O_2. These problems are discussed elsewhere.(1)

Description Of Beam Switchyard

The beam switchyard transport system is a permanent part of the accelerator; a serious attempt was made to solve the problems associated with the transport of intense beams discussed above. We will briefly describe the physical arrangement and some of the components and subsystems design features unique to the beam switchyard. The beam switchyard equipment is located in a 1000-foot-long concrete housing buried under 30 feet of earth. A typical housing cross section is shown in Fig. 4. An underhung crane riding on rails suspended from the ceiling has access to all equipment. Steel rails for a future shielded car are laid above the shielding ledge. All beam transport equipment is in the lower part of the housing. Shielding may be placed between the two levels to protect cable and electronics in the upper part from radiation during operation and to protect personnel from radioactivity during shutdowns. All equipment can be disconnected and removed from the upper level; all position measurements and adjustments can be made from above, through holes in the shielding.

The primary subsystems and components of the beam switchyard include: the vacuum system, water systems, power distribution system, magnets of various types, instrumentation and control, beam absorbers and targets, and stands of various types. The design of each of these is affected by the considerations discussed above. We will here mention some of the salient features which are not described elsewhere. The vacuum chamber system for the transport system is entirely inorganic; all chambers are aluminum or stainless weldments with the exception of the vacuum chambers for the pulsed magnet chambers which are discussed below. The remotely replaceable vacuum joints use indium gaskets in a SLAC-designed coupling. Water cooling of the vacuum chamber is provided where beam heating is expected. The vacuum pumping system consists of conventional oil diffusion pumps with refrigerated baffles and mechanical backing pumps. The accelerator vacuum system operating at 10^{-7} torr is separated from the switchyard vacuum of 10^{-4} torr by a differential pumping system including ion pumps, a refrigerated baffle and fast-vacuum valves.

Two types of water systems are required: magnet water, and radioactive water for beam energy absorbers. The magnet water system is all-copper and stainless steel. The radioactive water systems are all-stainless steel and aluminum or copper. The magnet water systems are so arranged that the piping runs inside the housing are minimized. Headers in the housing run in the upper level where they are accessible during shutdowns and shielded from excessive radiation during operation. All heat exchangers, pumps, surge tanks and instruments are outside the switchyard. The radioactive water system equipment is shielded. It is so arranged that leakage of radioactive water will drain into the switchyard housing where it can be stored until it has "cooled" and can be disposed of. No provision was made initially to handle evolved gases.(1) Magnet coils are potted in radiation-resistant alumina-loaded epoxy; insulators in the magnet water circuits are alumina. Pulse-to-pulse switching is done by laminated-core pulsed magnets. Figure 5 shows a 0.1° pulsed magnet ready for installation. A ceramic vacuum chamber is used because eddy current heating makes conducting materials unsuitable. Some apprehension was felt about internal charge buildup in ceramics, due to radiation, so attempts were made to improve the internal and surface conductivity of ceramics. Water-cooled copper protection-collimators are located throughout the transport system to protect equipment from missteered beams and low-energy electrons. Each protection collimator has an associated ionization chamber which is in the interlock chain to shut off the accelerator when a protection collimator is hit by the beam. Beam instrumentation is provided to keep track of the beam position, beam current, and energy spread.(2) The beams are monitored and directed from the "Data Assembly Building" which also houses the switchyard magnet power supplies. Most cables are run outside or in the upper level where they are shielded from the most intense radiation. Cables to the lower level are Fiberglas- or mineral-insulated. Front surface mirror optics are used with TV cameras to avoid problems with darkening of glass lenses. All beam equipment is adjustable and removable from the upper level of the switchyard housing. Water, vacuum and electrical connections can also be made from the upper level. Air actuating devices are metal-bellows sealed. Jacks for positioning of heavy equipment are lubricated with radiation-resistant grease, or in areas of intense radiation, made with low-friction bearings and run without lubricants.

Research Yard

A level paved area some 12 acres in area and surrounded by natural and manmade dikes up to 75 feet high forms the experimental area at the east end of the beam switchyard. Two major permanent buildings serve as housings for some of the major pieces of scientific apparatus. End Station A is a 25,000-square-foot shielding enclosure with three large spectrometers having maximum momentum acceptances of 20 GeV/c, 8 GeV/c and 1.6 GeV/c mounted within it on a common spindle. The spectrometers and their shielding carriages run on circular tracks and can be positioned at laboratory angles of up to 15°, 90° and 180°, respectively. Figure 6 shows the three spectrometers in the end station. The walls and roof of the end station are of concrete of thicknesses varying from 2 feet in the roof to 5 feet in the east wall. The walls up to a height of about 15 feet are made of removable blocks. The beam does not interact with other than a thin scattering target in this end station, but passes on through and crosses the yard to a water-cooled beam dump (beam dump east) in the dike.

End Station B is of similar design with thinner walls, but is preceded by a massively shielded target room where the beam interacts with thick targets and is absorbed in water-cooled dumps. Conventional beam transport elements separate and define secondary particle beams. In most cases these secondary beams leave the building, and the large pieces of detection apparatus are housed in separate structures. Among the large detectors now being readied at SLAC are: a 40" liquid hydrogen bubble chamber designed for use with tagged photon beams; a 1-meter magnet for use with large spark chamber arrays in μ-p inelastic scattering experments and a 2-meter magnet being used with streamer spark chambers in photon beams. The LRL 72" hydrogen bubble chamber, having been rebuilt to be 82", will be moved to SLAC for re-erection in a separated beam. Engineering techniques in the research yard are conventional. Standard magnet designs have been used with normal radiation 'soft' epoxy. Power supplies are universally phase-controlled SCR systems and have been built in sizes up to 5.8 MW. Wide use is made of standard portable buildings for both experimental counting rooms and for equipment shelters. Automatic hydrogen target systems have been developed which do not require constant operator attention. Beam position and intensity are derived from zinc sulfide screens, gas Cerenkov cells, current transformer toroids and other instrumentation, similar to that in the beam switchyard.

Early Operating Experience And Design Evaluation

The first electron beam was delivered through the A-Beam transport system and the End Station A to beam dump east on September 21, 1966. Since that date, numerous tests and experiments have been performed on the beam switchyard transport system. addition, several preliminary experiments(9,10,11) of a survey nature have been completed and others are in progress. In general the operation of the system has been exceedingly satisfactory. The maximum electron energy to date is 20.3 GeV. A momentum spectrum of the electron beam obtained using the beam switchyard momentum analyzing system is shown in Fig. 7. The first positron beam was delivered to End Station B on February 22, 1967. The maximum beam power which has been transported through the system is 170 kW. It is anticipated that the power level will soon be more than doubled. Multiple beams of various energies, currents, pulse lengths, and repetition rates are now routinely delivered to experimenters in the end stations. Electron beam spot sizes of one millimeter diameter have been achieved. Various early checks on the momentum calibration of the transport system have been made by comparing the A and B transport systems, by using a quantameter and Faraday cup, by comparing the end station spectrometer with the A-transport system, and by calorimeter measurements. Although much more refined tests are required, the early tests indicate that the beam switchyard system satisfies the design criteria for momentum calibration and resolution given in Table 1. Early experimental studies of beam optics and beam isochronism indicate that the transport system behaves in agreement with the predictions of the SLAC TRANSPORT(12) computer program which was used to design the system. However, optics tests indicate that the transport system solid-angle acceptance is less than expected. This effect is not clearly understood, but is probably the result of misalignment of components and certain known differences in the bending magnets of the system.(3) Since the emittance phase space of the accelerator is much smaller than the achieved acceptance of the beam switchyard transport system, there is no difficulty in delivering the beam to the experimental areas.

Operating experience to date has emphasized the need for high reliability of equipment. Problems which hamper delivery of the beam are the usual ones of getting such a system to operate--e.g., interlock faults, power supply failures, slit drive failure, browning of TV camera lenses, vacuum failure, personnel protection system failure, etc. Since the initial turn-on, equipment has been damaged by the electron beam on two occasions: (i) a spring in a vacuum quick disconnect was overheated resulting in loss of temper and a vacuum leak and (ii) a vacuum quick disconnect was overheated causing the indium seal to melt, again resulting in a vacuum leak. At the power levels run to date, usually about 1 - 10 kW, no serious radiation or radioactivity problems have been encountered. The radioactivity induced in the radioactive water systems is already sufficient to restrict system ventilation during operation.(1) Some of the cooling water becomes intensely radioactive, but most of the activity is short-lived (O^{15}, C^{11}). Be^7 is produced in the water and removed by the demineralizers. Demineralizers have been found to have about 100 microcuries of activity when depleted. Equipment close to the beam is becoming radioactive but remote operations have not yet been necessary. It is too early to evaluate the radiation resistance of special components.

Acknowledgments

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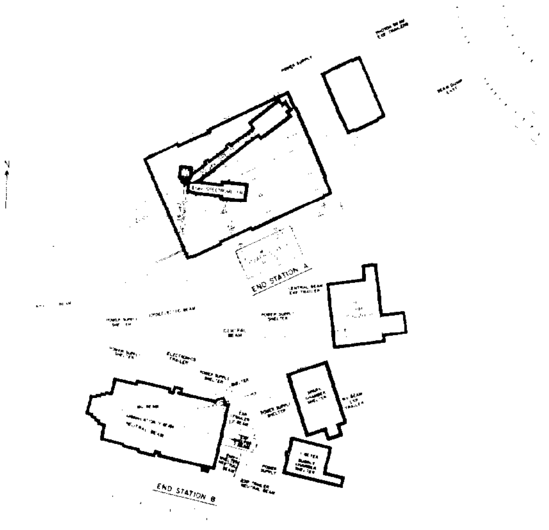

FIG. 1--Arrangement of buildings in Research Yard.

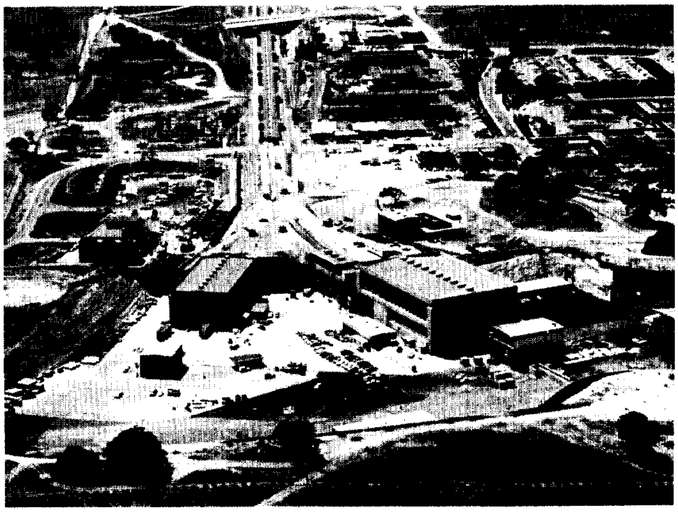

FIG. 2--Aerial view of Research Yard.

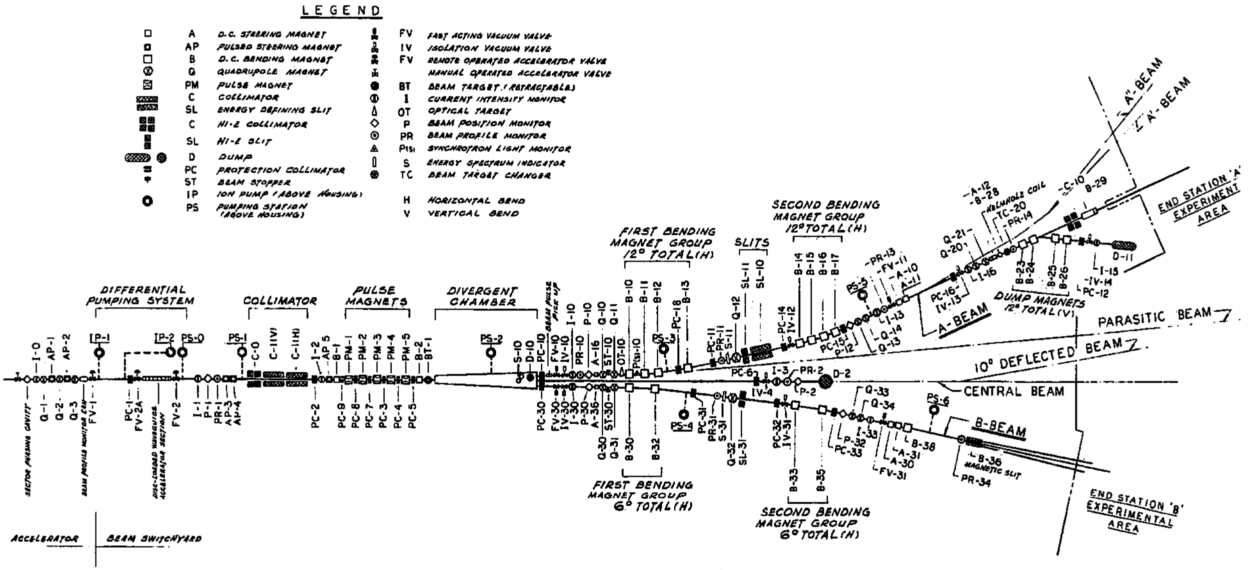

FIG. 3--Layout of beam switchyard components.

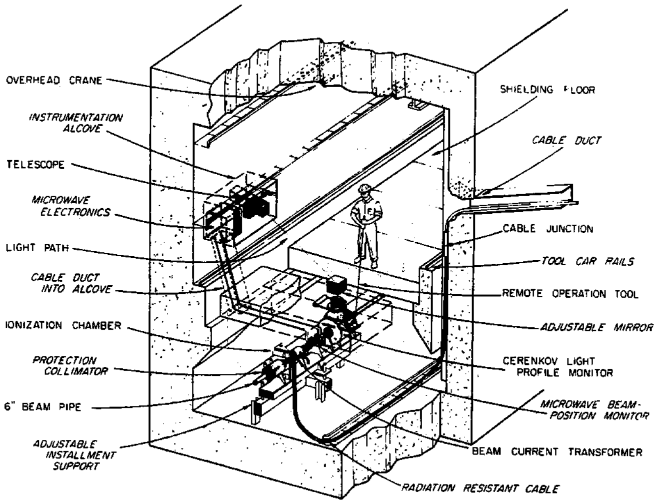

FIG. 4--Typical cross-section of switchyard housing.

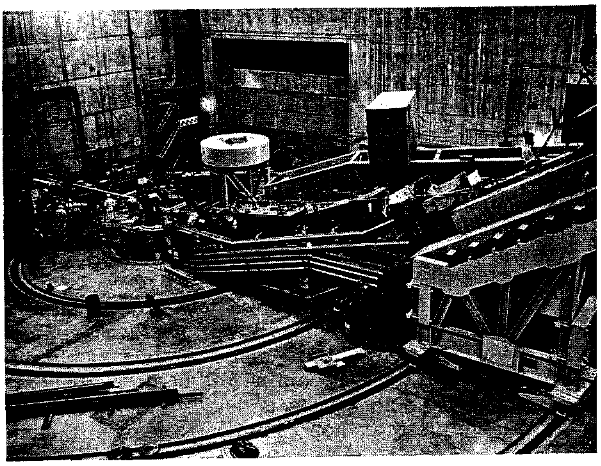

FIG. 6--8, 20, 1.6 GeV spectrometers in End Station

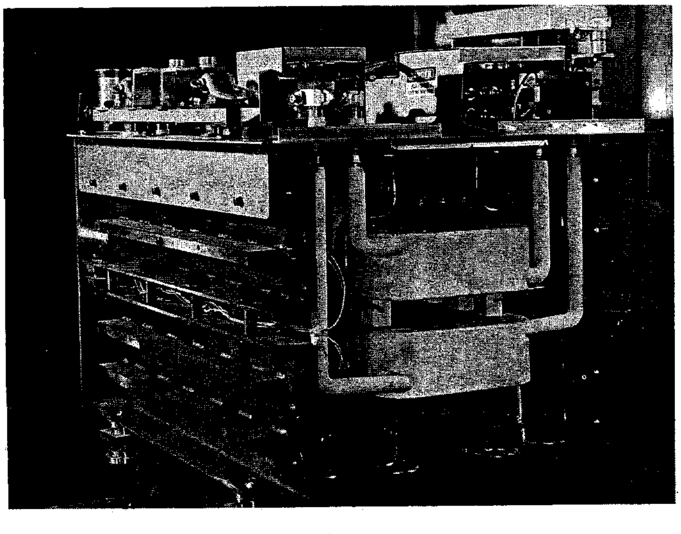

FIG. 5--0.1° pulsed magnet.

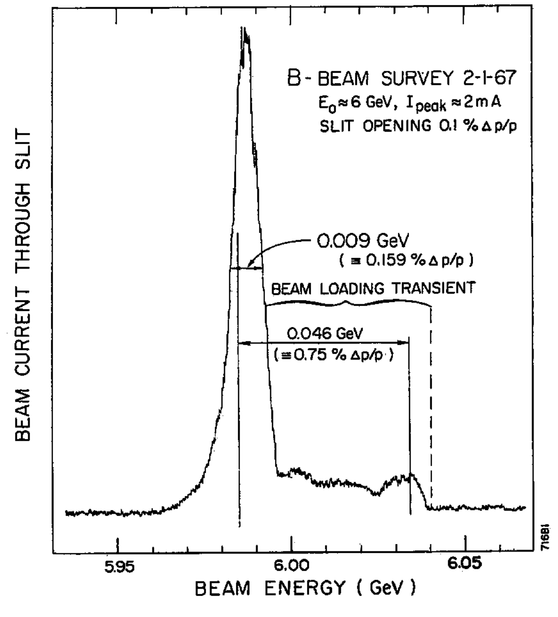

FIG. 7--Momentum spectrum of 6-GeV electron bear