SLAC-PUB-675
November 1969
(ACC)

BEAM SAFETY CONSIDERATIONS AT THE STANFORD LINEAR ACCELERATOR CENTER*

D. D. Busick, T. M. Jenkins, R. C. McCall, W. R. Nelson,
G. K. Svensson, and G. J. Warren

Health Physics Department
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

and

A. Baumgarten, J. L. Harris, J. J. Murray, E. J. Seppi,
R. J. Vetterlein

Research Area Department
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

(Submitted for presentation at the Second International Conference on Accelerator Dosimetry and Experience to be held at the Stanford Linear Accelerator Center, Stanford, California, November 5-7, 1969)

*Work supported by the U. S. Atomic Energy Commission.

ABSTRACT

The two-mile accelerator at SLAC is an electron linac capable of producing a beam power of 500 kW at an energy as high as 20 GeV. When a high power electron beam interacts with matter, lethal dose levels can be created in a short period of time. For example, when one kilowatt of electrons produces an electromagnetic shower in 15 radiation lengths of iron, the bremsstrahlung dose rate at one meter in the forward direction is about 10^5 rad/hr.

The Health Physics group at SLAC actively participates with the Research Area Department (RAD) in problems related to safe beam transport and shielding. The result of such planning and design is set forth in an operational document known as the Beam Authorization Sheet (BAS), which, along with the SLAC Radiation Rule Book, provides the guidelines through which the accelerator, beam switchyard, and research area safely operate.

The purpose of this paper is to describe the planning and operational phases of radiation protection at SLAC with regards to:

1. primary electron and positron beam containment;
2. control of dangerous secondary beam areas, or ones that are potentially dangerous;
3. radiation and shielding calculations;
4. beam check-out procedures and measurements;
5. routine monitoring.

Several classic examples will illustrate the ingenuity required in order to satisfy the safety criteria established at SLAC. The information that will be presented should be of particular interest to those who are planning new accelerators.

I. INTRODUCTION

The two-mile accelerator at SLAC is an electron linear accelerator capable of producing a 20-GeV electron beam with power in excess of 500 kW. The problems attendant with this accelerator are typical of those associated with other accelerators; that is, the beam must be contained within shielded areas, these areas must be inaccessible to personnel while the beam is on, radiation levels outside the shield must be measured and controlled, etc.

This accelerator, and the exploitation of the experimental beams derived from it, have generated radiation safety problems which appear more severe and less susceptible to simple solutions than those at most other high energy facilities. Some of the differences which give rise to these problems are:

(a) Many experimental detection devices, requiring human access, are located on the 0^o line relative to the primary beam, and receive neutral beams (γ, K^o, etc.).

(b) The machine is capable of extremely high average powers (for an electron energy of 20 GeV, an average power of 500 kW corresponds to a beam intensity of about 1.6×10^{14} electrons/sec) and although a particular beam arrangement may be designed for low power, prudent safety design must consider the case of accidental delivery of maximum power.

(c) The beam generates a copious flux of high energy muons which may require as much as 15 meters of iron to be completely attenuated.

(d) The extremely high specific power density capability of the machine renders the beam capable of burning through any conventional solid material (i.e., concrete, lead, sheet tungsten, etc.).

It should be pointed out here that even though the containment problem is severe due to the high powers available in the primary beam, the shielding problem itself is no more severe than that of a typical proton accelerator, and on a per-kilowatt basis, is greatly reduced. This is due to the small fraction of the electron energy which goes into nuclear interactions which in turn produce high energy secondaries. As an example, a 6.3 GeV proton will produce about 4 n/sr while a 6.3 GeV electron will produce only about 0.01 n/sr.[1] Thus, if the containment problem in an electron accelerator is solved, the radiation levels due to secondary particles from a 500 kW electron accelerator will be comparable to those due to secondary particles from a 1.4 kW proton accelerator. The important difference is the electromagnetic radiation (bremsstrahlung) which must be accounted for in the containment problem of an electron accelerator, but which is relatively minor in proton accelerators.

Beam containment is traditionally the responsibility of the machine operating groups, and this is true at SLAC. What is not so traditional, however, is the degree to which the Health Physics (HP) group at SLAC actively participates with an operating group (Research Area Department (RAD)) in problems related to safe beam transport and subsequent shielding. At SLAC all beams are scrutinized, and must be approved, by Health Physics as well as by RAD. This paper will attempt to explain the details of this relationship between the two groups in the planning and operational phases of radiation protection with regard to:

1) primary electron and positron beam containment
2) control of dangerous secondary beam areas, or potentially dangerous areas
3) radiation and shielding calculations
4) beam check-out procedures and measurements
5) routine monitoring.

Several classic examples will illustrate the ingenuity required by both groups to satisfy the safety criteria established by SLAC.

II. SLAC PHILOSOPHY

Perhaps the first question to be examined is 'why should Health Physics involve itself in an area traditionally handled only by operating groups?' There is no single answer to this, for it involves questions of policy as well as capability. Historically, the SLAC Health Physics group participated in the early shielding design for the machine. Today, rearrangements of shielding configurations for routine operation are specified or approved by Health Physics. Also, the HP Group specifies shielding for machine modification, and new machine design. Many accelerators have more-or-less static shielding configurations, whereas SLAC, with its many beam areas and multitude of simultaneous beams, is constantly changing. In accelerators throughout the world there also is a traditional separation between shielding design, and the measurement of radiation levels outside shielding. The latter is always the function of Health Physics groups, while the former is most often delegated to other groups, such as research. At SLAC where shielding calculations are performed by Health Physics, the separation does not exist. Finally, the RAD recognized early that it had a vested interest in beam transport of which safety was only one aspect, while safety is the primary concern of Health Physics. An illustration of the different outlook required of beam safety may be made by citing the usual optical alignment methods used by operating groups to place magnets, collimators and dumps, which are acceptable for beam transport but which may not be a satisfactory guarantee of safety where personnel are concerned. So, recognizing these points early in the operating history of SLAC, the Health Physics group became one additional step in the approval of any new beam system.

This additional step has both advantages and disadvantages. One obvious advantage is that the inclusion of a second group (HP) into the safety analysis of beams that are especially hazardous reduces the possibility that an oversight might occur. Another advantage not so apparent is that HP, using its measuring equipment, may locate sources of background radiation at levels that are of no concern to the safety of personnel, but which affect more sensitive research equipment, such as bubble and spark chambers. Slightly misaligned collimators have been detected in this manner.

There are also disadvantages. For Health Physics, this is a time-consuming duty. It is estimated that about 20% of the professional HP time is devoted to this function. To the Operations group, the insertion of the HP group (which is traditionally conservative) is complicating and sometimes exasperating. For the experimenter, the interrelation between RAD and Health Physics may seem confusing at times, and often laborious. However, when one examines the potential danger of the SLAC electron beam, all safety precautions seem justified. This hazard will be illustrated in the following examples.

The SLAC accelerator has high powers available (500 kW or 1.6×10^{14} e^-/sec). Also, sources are more localized than the distributed sources from a proton accelerator due to the shower development which occurs over a shorter distance. For example, about 95% of the energy of a 10 GeV electron beam is absorbed in an iron cylinder 10 inches long (15 radiation lengths). Nevertheless, the bremsstrahlung dose rate at a distance of 1 meter from this stopper would be about 1.5×10^3 rad/hr at 90° and 2×10^5 rad/hr in the forward direction for an incoming beam power of 1 kW.[2] At 500 kW, this would be 1×10^8 rad/hr in the forward direction. As the target thickness decreases (but still thicker than shower maximum, or about 6 radiation lengths) the dose rate increases approximately exponentially.[2,3]

A more practical demonstration of the hazard of this machine was made by allowing a 240-watt electron beam, under controlled conditions, to strike the 5-foot-thick concrete wall of one of the end stations, and measuring the photon dose rate at the outside of the wall. The measured dose rate of 4×10^3 rad/hr would be scaled to 8×10^6 rad/hr at full accelerator power. This was in a location outside the interlock control.

Furthermore, at SLAC there are many different types of radiation that must be considered, (n, p, γ, π, μ) and only someone versed in the shielding of these types of radiation can detect all the potential problems. For example, the muon dose rate in the 0^o direction at the outside of a 10-foot-thick iron shield struck by 1 kW of electrons with energy of 20 GeV would be about 1 rad/hr.[4]*

Because Health Physics does the shielding calculations at SLAC, their aid in beam containment was considered valuable. This becomes more apparent when one notes the many potential secondary beams at SLAC of which a few are shown in Fig. 1, and the close proximity of a multitude of buildings, most of which are occupied by experimenters or support personnel, as shown in Fig. 2.

III. ORGANIZATION

The relationship of RAD and Health Physics with the various other groups or sub-groups will be discussed by dividing the beam safety into two phases, a) planning and b) operation.

a) Planning phase: While the main exchange occurs between RAD and Health Physics, there are many other groups at SLAC that must contribute. Figure 3 shows the organizational structure relative to radiation protection in the planning phase. The main bodies of concern are Health Physics, RAD, and the Experimental groups with the other groups affecting these three indirectly. A typical beam

---

*Actually, the dose rate would be less than this due to multiple scattering in the iron shield.

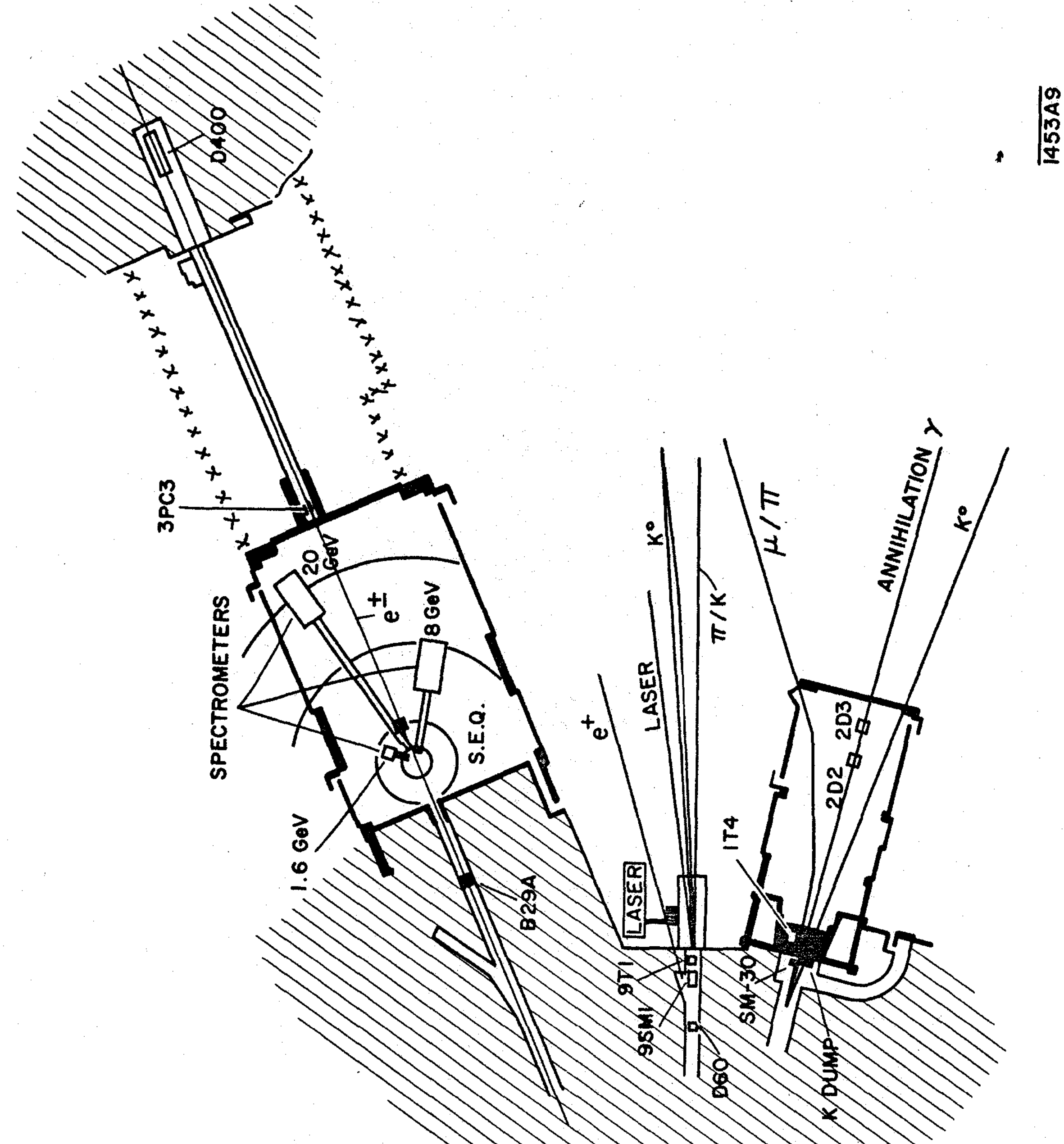
D400
3PC3
SPECTROMETERS
20 GeV
e±
8 GeV
S.E.Q.
1.6 GeV
B29A
e+
LASER
K°
π/K
μ/π
ANNIHILATION γ
K°
LASER
9T1
9SM1
D60
IT4
2D2
2D3
SM-30
K DUMP
1453A9

Fig. 1

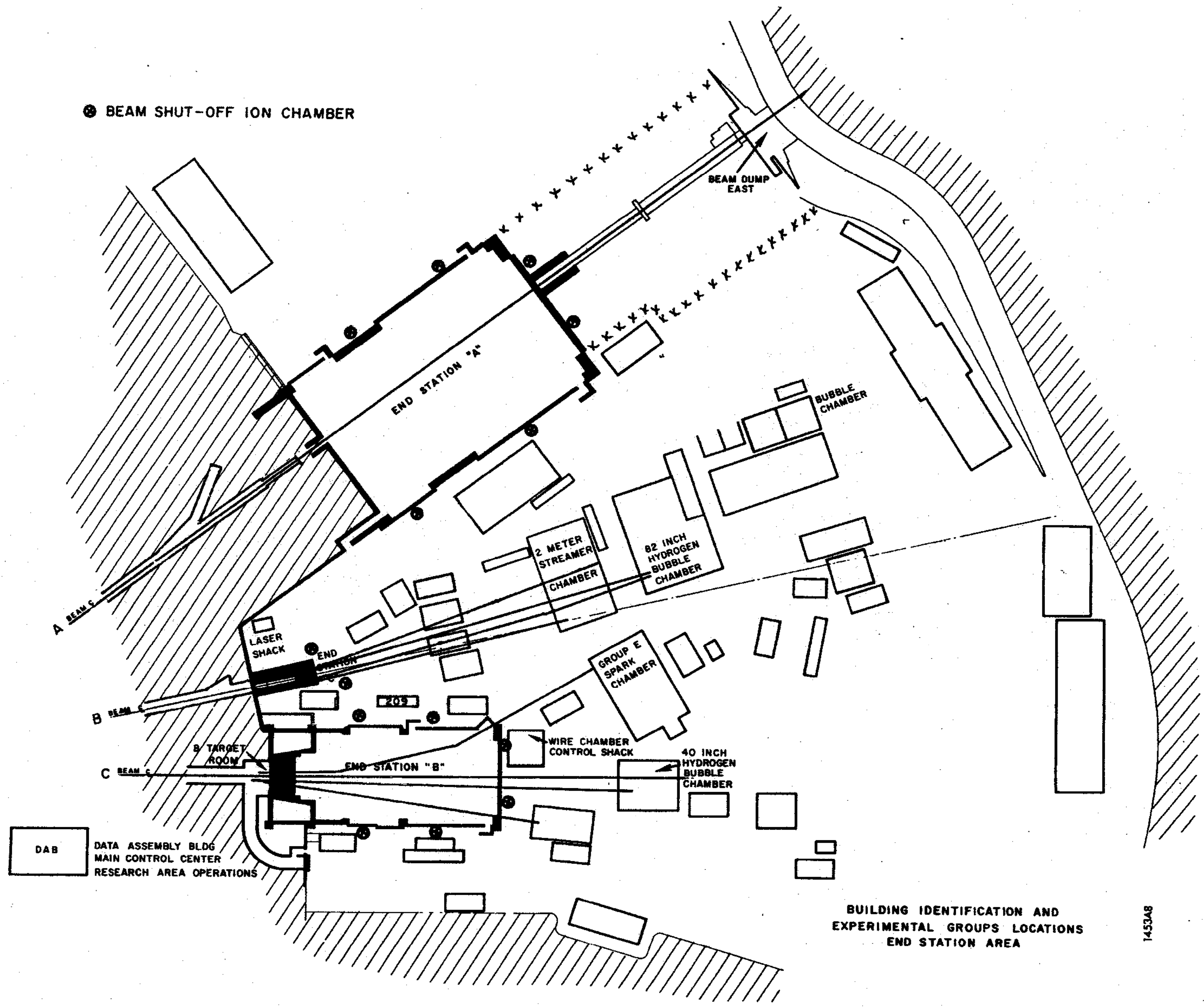

Fig. 2--Occupied buildings in the research area —proximity to secondary beams.

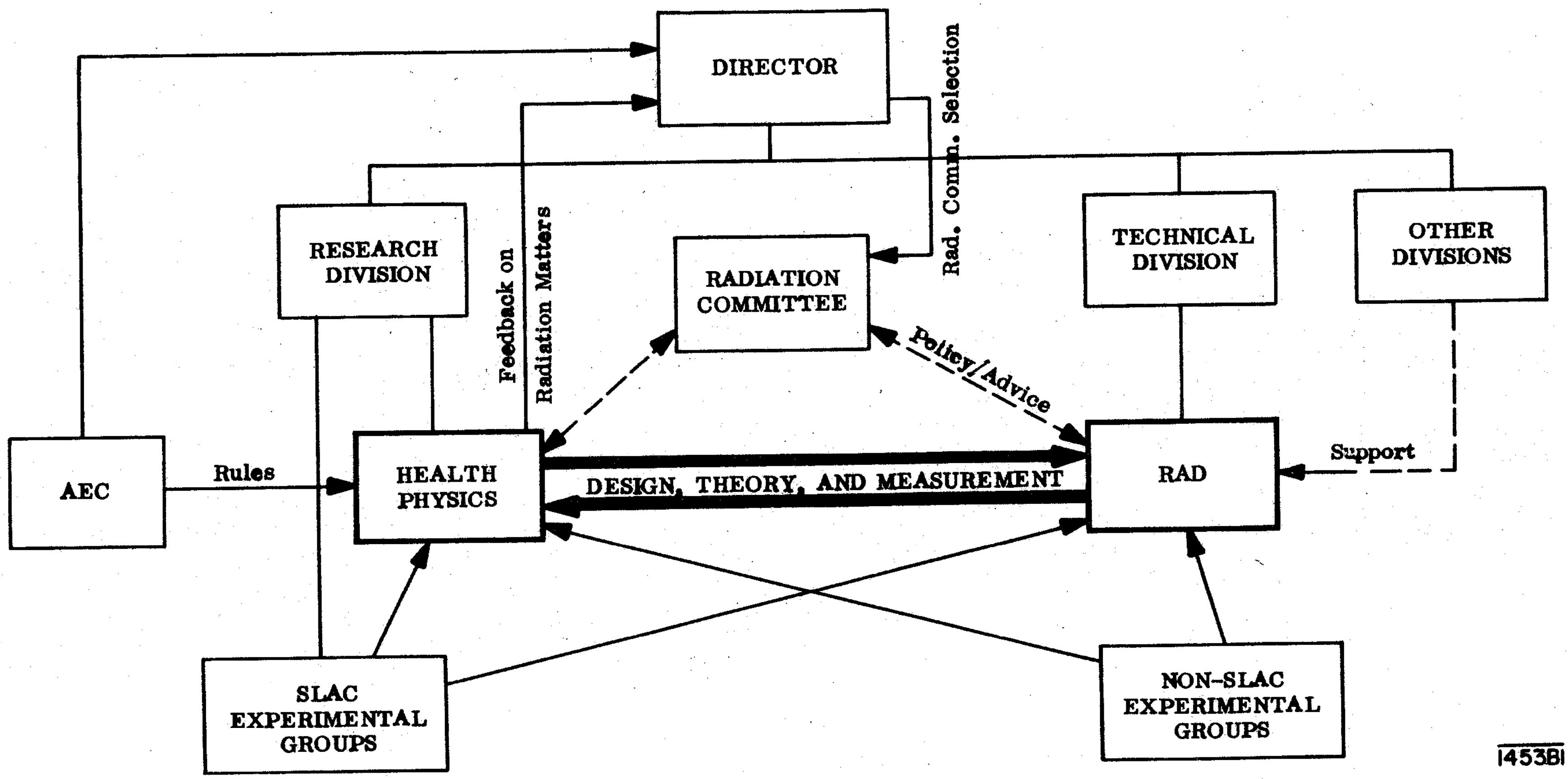

Fig. 3--SLAC organizational structure relative to radiation protection — planning phase (RAD = Research Area Department).

may be planned as follows: The experimenter, with an approved and scheduled experiment, approaches RAD with a request for a particular type of beam. RAD contacts Health Physics and a three-way dialogue ensues between the three groups, with assistance available from other supporting groups, if needed. Usually at this point a beam transport configuration is arrived at that satisfies all three parties and the planning phase is finished. However, if a satisfactory transport configuration is not agreed upon, with veto power essentially lying with Health Physics and RAD, but not with the experimenter, the beam may be discussed by the Radiation Committee. This body acts as an advisory panel only, with its menbers drawn from the operations, Health Physics and Research groups. A further line of appeal exists to Health Physics or the experimental groups in their direct access to the Director. It is interesting to note that in about three years of operation, only four or five beams have been brought before the Radiation Committee, and none has required further redress. This in part may be due to the essentially conservative nature of the Radiation Committee, which tends to lean in the favor of safety in most matters brought before it. Conversely, no beams have ever been cancelled at SLAC due to safety considerations, though there have been considerable modifications on a number of beams.

b) Operational phase: After the planning phase, the operational phase begins. This phase is illustrated in Fig. 4. The operational phase essentially involves writing guidelines and disseminating information to the various operating groups that control the running of the accelerator. This phase usually begins a week or so before the beam is to turn on, and proceeds as follows:

1) Health Physics writes a beam check-out procedure, and discusses it with RAD (and various operators) to insure its feasibility. Interactions with other existent beams, correct polarities, beam monitors, etc. are discussed at this time.

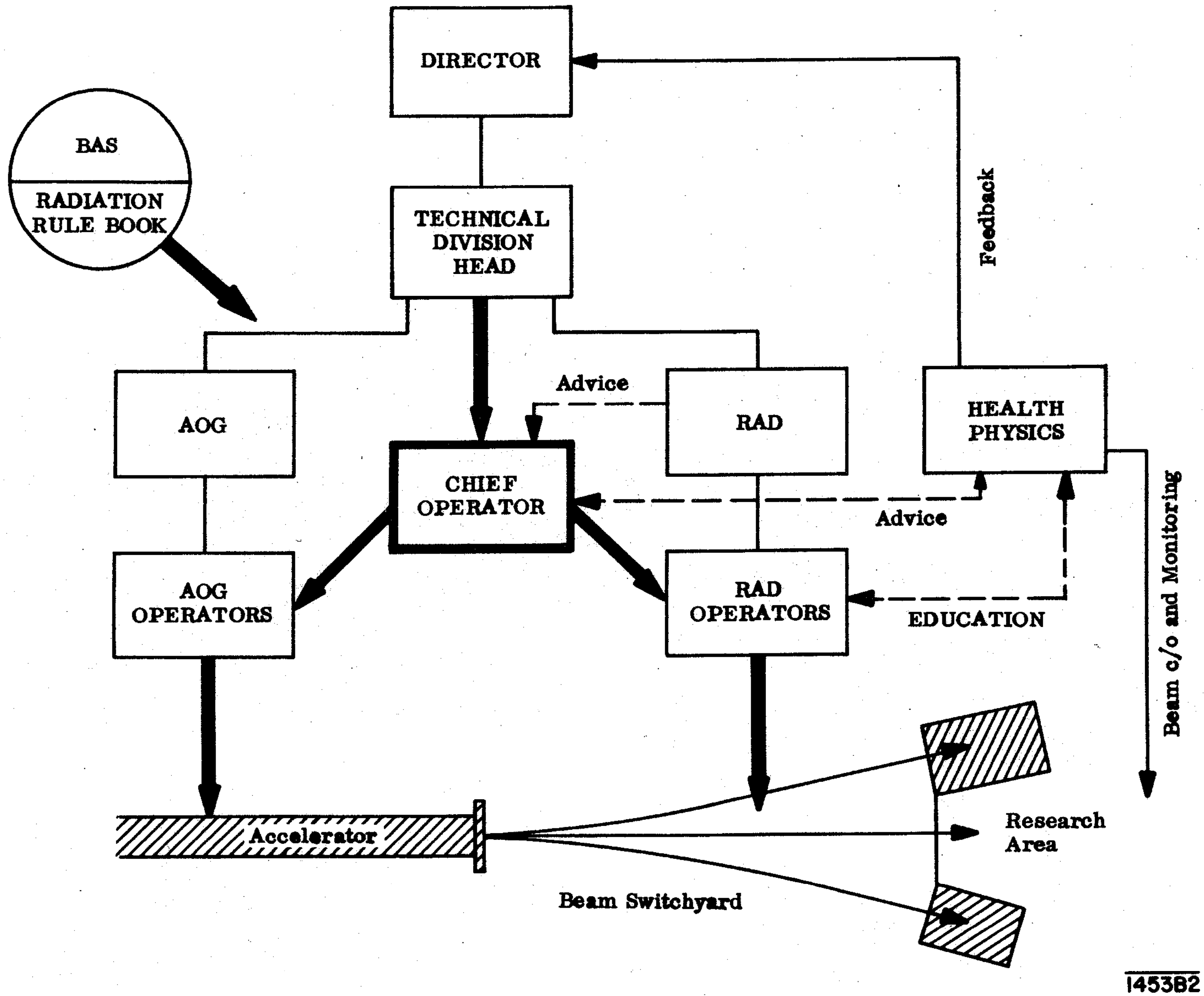

Fig. 4--SLAC organizational structure relative to radiation protection – operational phase (AOG = Accelerator Operations Group, RAD = Research Area Department).

The planning phase is considered completed when the operations group and Health Physics have agreed upon a check-out procedure. Health Physics will not be closely associated with the beam again until just prior to locking up the BSY and Research Areas involved.

2) At that time, Health Physics initiates a Beam Authorization Sheet (BAS). Two of the three sheets are shown as Fig. 5, with the third sheet being a blue-print of the beam components, including sensitive magnets, shielding, ion chambers, etc., with those items critical to safety marked in red by Health Physics. A copy of the BAS is sent to RAD where it is approved and signed by designated personnel, and it then becomes a part of the operations log. The BAS becomes the running safety manual for that beam — it cannot be violated by the operators without the approval of the proper HP and RAD personnel.

The BAS originally was conceived after a series of communication lapses between RAD, the operators, and HP. Without some form of written communication, instructions quickly become lost or distorted. Furthermore, it is easier to process instructions if a standard form is utilized, one with space for adding comments, for initialing, etc. Originally a single sheet, the BAS has evolved to its present form of two sheets with a blueprint of the beam line components as the third sheet.

The BAS is divided into 5 parts (the fifth being the third page, or blueprint). The first part is labeled "Pre-Running Conditions," and includes all items that must be checked prior to a beam being turned on. Such things as location of shielding blocks, polarity of magnets, shorting bars, etc., will be included in this section. The second section, "Initial Check-Out," includes essential items necessary in the check-out phase, but is not as elaborate as the earlier written check-out list submitted to the operations group. Included might be the requirement that certain stoppers be inserted during the check-out phase, etc. The third

BEAM AUTHORIZATION SHEET

PAGE____ OF____
FROM: HR____ DAY____ DATE____
TO: HR____ DAY____ DATE____

THIS SHEET BECOMES INVALID IF AREA CHANGES TO ACCESS PERMITTED MODE.

AREA:____
EXPERIMENT:____
SPOKESMAN:____
OFFICIAL (DAB) COPY ☐
HEALTH PHYSICS COPY ☐
ALLOWABLE BEAM TYPE____TO____
____TO____

ITEM	DATE/TIME	CKD. BY +	DAB OP. APP.	PRE- RUNNING CONDITIONS

+ANY OF RAD OPERATIONS CREW

ITEM	DATE/TIME	CKD. BY +	DAB OP. APP.	INITIAL CHECK-OUT

APPROVAL:

HEALTH PHYSICS:________ (D. BUSICK, T. JENKINS, R. MC CALL, W. NELSON, G. SVENSSON, G. WARREN)

RAD:________ (J. HARRIS, E. SEPPI)

1453B14

BEAM AUTHORIZATION SHEET

PAGE____OF____
FROM: HR____ DAY____DATE____
TO: HR____ DAY____DATE____

THIS SHEET BECOMES INVALID IF AREA CHANGES TO ACCESS PERMITTED MODE.

AREA:____
EXPERIMENT:____
SPOKESMAN:____
OFFICIAL (DAB) COPY ☐
HEALTH PHYSICS COPY ☐
ALLOWABLE BEAM TYPE____TO____
____TO____

RUNNING CONDITIONS

TIME	MON.		TUES.		WED.		THUR.		FRI.		SAT.		SUN.		MON.		TUES.		WED.		THUR.		FRI.	
0800																								
1600																								
2000																								
2400																								
	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB	CO	DAB

ITEM	DATE/TIME	CKD. BY	DAB OP. APP.	

ITEM	DATE/TIME	CKD. BY	CH. OP. APP.	PER. HP/RAD	CHANGES OR ADDITIONS *

*ITEM CHANGED MUST BE ENTIRELY REWRITTEN AND SINGLE LINE DRAWN THROUGH ITEM CHANGED.

APPROVAL:
HEALTH PHYSICS:________ (D. BUSICK, T. JENKINS, R. MC CALL, W. NELSON, G. SVENSSON, G. WARREN)

RAD:________ (J. HARRIS, E. SEPPI)

1453B15

Fig. 5

section, "Running Conditions," assumes the check-out has proceeded satisfactorily and any limits on running such as maximum beam power, etc., are included here. The fourth section is for additions made during a running cycle.

The BAS is initialed by each chief operator and each RAD operator as he comes on shift.*

3) The actual check-out is done by Health Physics with the assistance of the RAD operators.. Details of the check-outs, and descriptions of sensitive components will be discussed in greater detail in the next section.

In many cases, initial check-out is followed by a release of the beam to the experimenter with few, if any, limiting provisions. In some cases, it is followed by a new set of restrictions, which might include beam interlocked doors or padlocks on sensitive areas, frequent monitoring by Health Physics technicians, roping off of certain areas in the research yard, etc. At this time, a beam may still be brought before the Radiation Committee if the experimenter wishes, and in fact, one beam was discussed before the Committee, with the Health Physics requirements being approved for that beam.

Often a beam needs to be checked out once; after that, many different experimenters may utilize it before it is dismantled in favor of a new beam. However, there are some beams whose components are so critically aligned that a few millimeters could be dangerous. These beams are routinely re-checked by Health Physics at the beginning of each running cycle, to insure that nothing has changed during shutdown.

*SLAC has three types of operators — the Central Control Room (CCR) operator (also known as the AOG operator) controls the two-mile acceleration of the beam, the RAD operator (also called DAB operator) controls the beam in the BSY and the various research areas, and the chief operator oversees the entire operation of the accelerator and research areas.

IV. DESCRIPTION OF BEAMS AT SLAC

Specific examples of beam loss and beam containment will be discussed to illustrate some of the complexity of the problems at SLAC, starting with the more typical problem of beam loss and the resultant radiation as illustrated by End Station A. In analyzing beams, the following beam line components will be discussed:

1) Collimators — both conventional and unique design[5]
2) Magnets — permanent and electro
3) Beam stoppers — unique design[5]
4) Beam dumps[6,7,8]
5) Beam Shut-Off Ion Chambers (BSOIC)[9]

A. Beam Loss (End Station A (ESA))

This experimental area is devoted primarily to high energy electron scattering, and to physics utilizing a high intensity bremsstrahlung beam.

For electron scattering, the electron beam is brought into the end station where it passes through a thin target before continuing to a beam dump buried in a hillside about 425 feet downstream. Secondary particles are analyzed by one of three large spectrometers inside ESA. The end station walls vary in thickness between 2 and 5 feet; they are adequate for beam power losses of approximately 100 W inside the end station, unless additional radiation shielding is employed around localized radiation sources. Unfortunately, the movement of the large spectrometers precludes almost any additional shielding inside the end station. Consequently, the fraction of beam power that may be absorbed inside the end station must be kept very low.

Radiation will come primarily from the scattering of the electron beam in the thin targets used by the experimenter, with the scattered electron beam striking components of the beam transport line inside ESA, or in the tunnel beyond ESA.

To predict this scattering adequately, one must use a more rigorous treatment than to describe it simply as Gaussian in angle, which is adequate only to small angles where the fraction of electrons that scatter out of a given solid angle is greater than 2×10^{-2}.[10] The expression in the Gaussian treatment for the 1/e point is given by $\theta = 21.2 \sqrt{t}/E_0$, where t is the thickness in radiation lengths. This completely neglects the large angle single-scattering tail, and is workable only at small reduced angles. A more rigorous treatment, such as given by Molière,[11] and modified by Nigam, Sundaresan and Wu,[12] must be used to describe multiple scattering. However, even Molière scattering is inadequate if some knowledge of the incoming beam shape is not available, because the theory is good only for an infinitely small and parallel beam. The beams at SLAC, have been bent, focused, collimated, etc., resulting in a finite shape as well as divergence. This must be considered in the scattering solution. Figure 6 shows the effect of folding a finite beam shape[10] into Molière scattering.

A knowledge of where the beam will strike, and the fraction of power absorbed, may be derived from a rigorous treatment of electron scattering, as in Fig. 6. Shielding types, locations and thicknesses may then be specified. For the case of ESA, where shielding is difficult to add inside the building, other solutions had to be found. Figure 7 illustrates the shielding problems in ESA. A beam entering ESA will strike a target about 180 feet from the end station wall. In order to reduce the fraction of beam power that is absorbed in the transport pipe inside ESA, the beam pipe diameter was increased to 36 inches. This moves the pipe away from the scattered beam, solving the problem of radiation coming from inside ESA for this type of experiment (and reducing the experimenter's background significantly at the same time), but does not solve the problem of radiation beyond ESA. The beam dump, D400, is located an additional 250 feet downstream

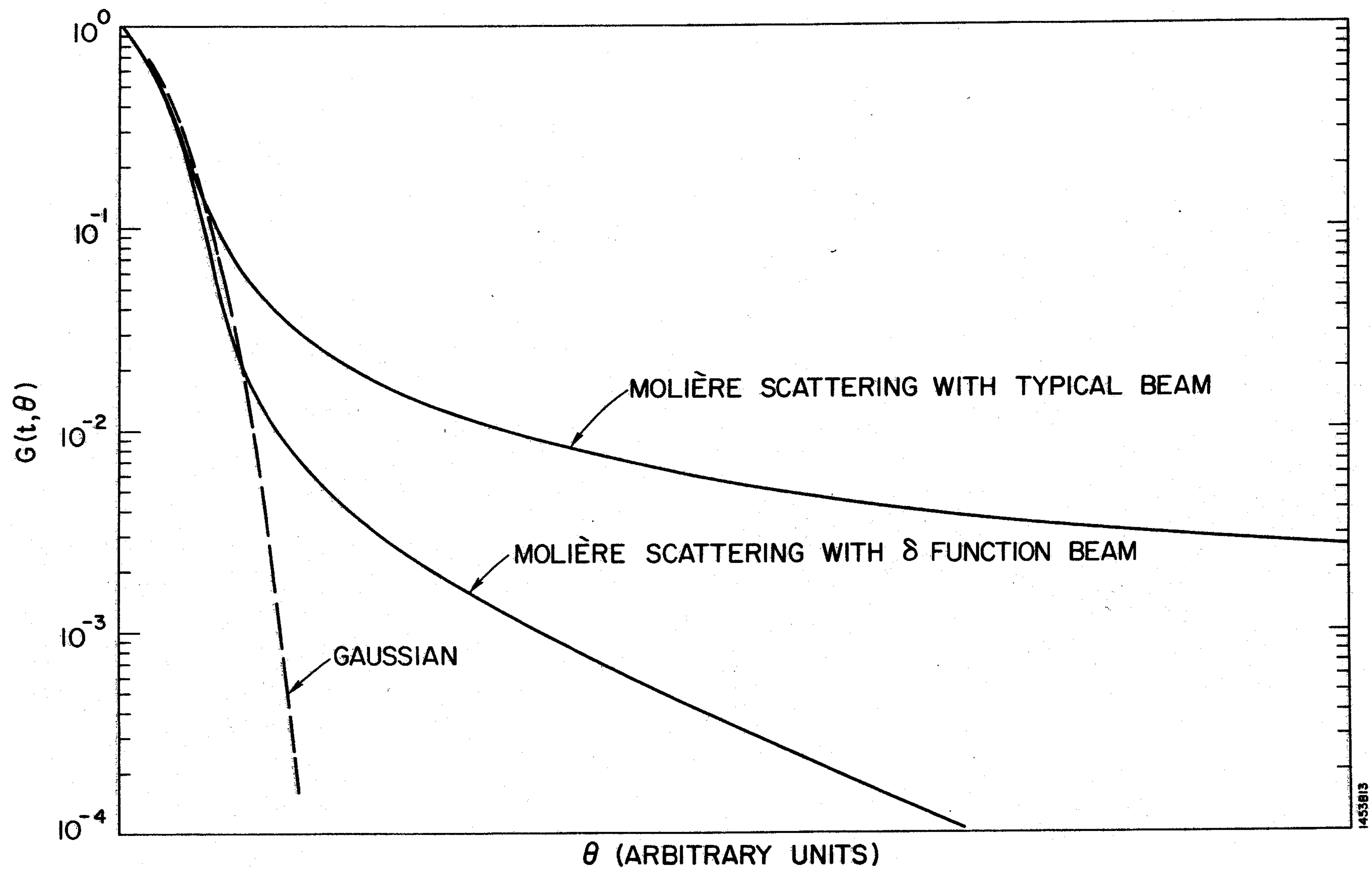

Fig. 6--The fractions of electrons, $G(t, \theta)$ that get out of a given cone of half-angle θ. Shown are a Gaussian distribution, a Molière scattering distribution with a δ-function input, and a Molière scattering distribution with a typical SLAC finite beam input.

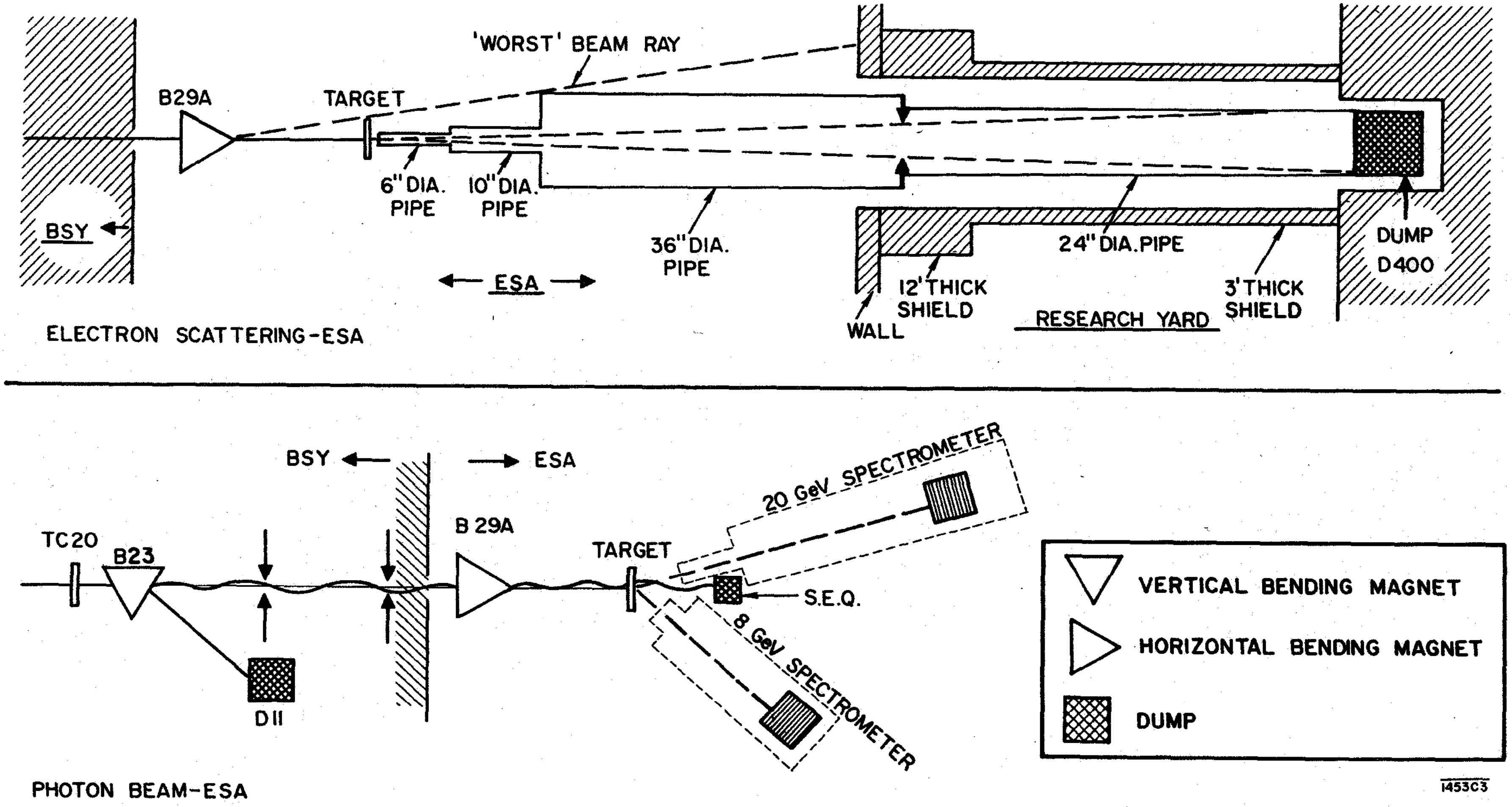

Fig. 7--Beams in End Station A. Top —typical electron beam used in electron scattering experiments. Bottom — typical arrangement for a photon beam.

of the end station wall. The transport tunnel leading to D400 is shielded by 3 feet of concrete. Consequently the same small fraction of beam power may be allowed to strike the beam pipe as in ESA. This pipe would become prohibitively large if the method of minimizing the scattered electrons from striking the beam pipe were to increase its diameter. Instead, a collimator, 3PC3, is inserted just downstream of the ESA wall at a location that may be shielded adequately. This collimator shadows the ensuing beam pipe (which has a diameter of 24 inches) and cuts down shielding requirements beyond this region.

The area to a distance of at least 40' from the transport tunnel is fenced off to prevent personnel from being in the vicinity of 3PC3 or of any mis-steered beam which could target in the wall near 3PC3. The worst mis-steered beam would strike the end station wall where the shielding for 3PC3 is located, and would be contained within this shield.

Also shown in Fig. 7 is the beam arrangement for bringing a photon beam into ESA. The beam strikes a target, TC20, and is then steered down into a beam dump inside the BSY. The resulting bremsstrahlung beam is collimated (for the experimenter, not for safety) and brought out into ESA where it is dumped into a Secondary Emission Quantameter (SEQ). Again, the movement of the large spectrometers precludes all but small amounts of local shielding around the SEQ. In the above case, it is possible to produce an equivalent beam power in excess of 3 kW; radiation levels outside ESA are usually too high at this level and require that the beam current be reduced such that the equivalent beam power entering ESA be less than 1 kW. The beam current is controlled by the operator, who receives his information on radiation levels from the HP technicians, and by reading the various BSOIC's placed around the end stations. When power must be limited due to radiation levels outside the end stations, instructions are given to the operator via the BAS in the section labeled CHANGES OR ADDITIONS.

B. Beam Containment (End Stations B and C)

Unlike the electron scattering experiments in ESA, End Station B (ESB) is used primarily for secondary beams that are produced either inside the end station or in the BSY. There are three secondary beams in ESB which typify the containment problems that have been encountered to date at SLAC.

1) zero degree bremsstrahlung beam

2) annihilation photon beam

3) pi beam

1. Zero Degree Bremsstrahlung Beam

The essential beam line components are illustrated in Fig. 8. The primary electron beam strikes a very thin target upstream of the B-switching magnets inside the BSY, and the surviving electron beam is deflected into either the muon dump or the K^O dump. The photon beam is collimated by 2PCO inside the B-Target Room (BTR), and by 2C1 inside ESB, before it enters a small building where it is stopped by 18 inches of lead. Two basic problems must be solved: first, the primary electron beam must be contained in the BTR; and second, personnel must be kept out of the bremsstrahlung beam itself. Safety magnet, SM-30, (a permanent magnet) is the primary means by which an electron (or positron) beam is kept from the zero degree direction. It is backed up, as a matter of conservative policy, by electromagnet, 2D2. Should the B-switching magnets (which work on a pulse-to-pulse basis) fail, a primary beam heading down the zero degree direction will be bent vertically by SM-30, dumping in a tungsten collimator, 2PCO. Collimator PC-40 is added to protect SM-30 from damage by the primary beam.

If, for some reason, SM-30 does not function, electromagnet 2D2 will still contain the primary beam inside ESB. This magnet has an electrical interlock that drops in beam stopper, ST-36, whenever there is a disagreement between

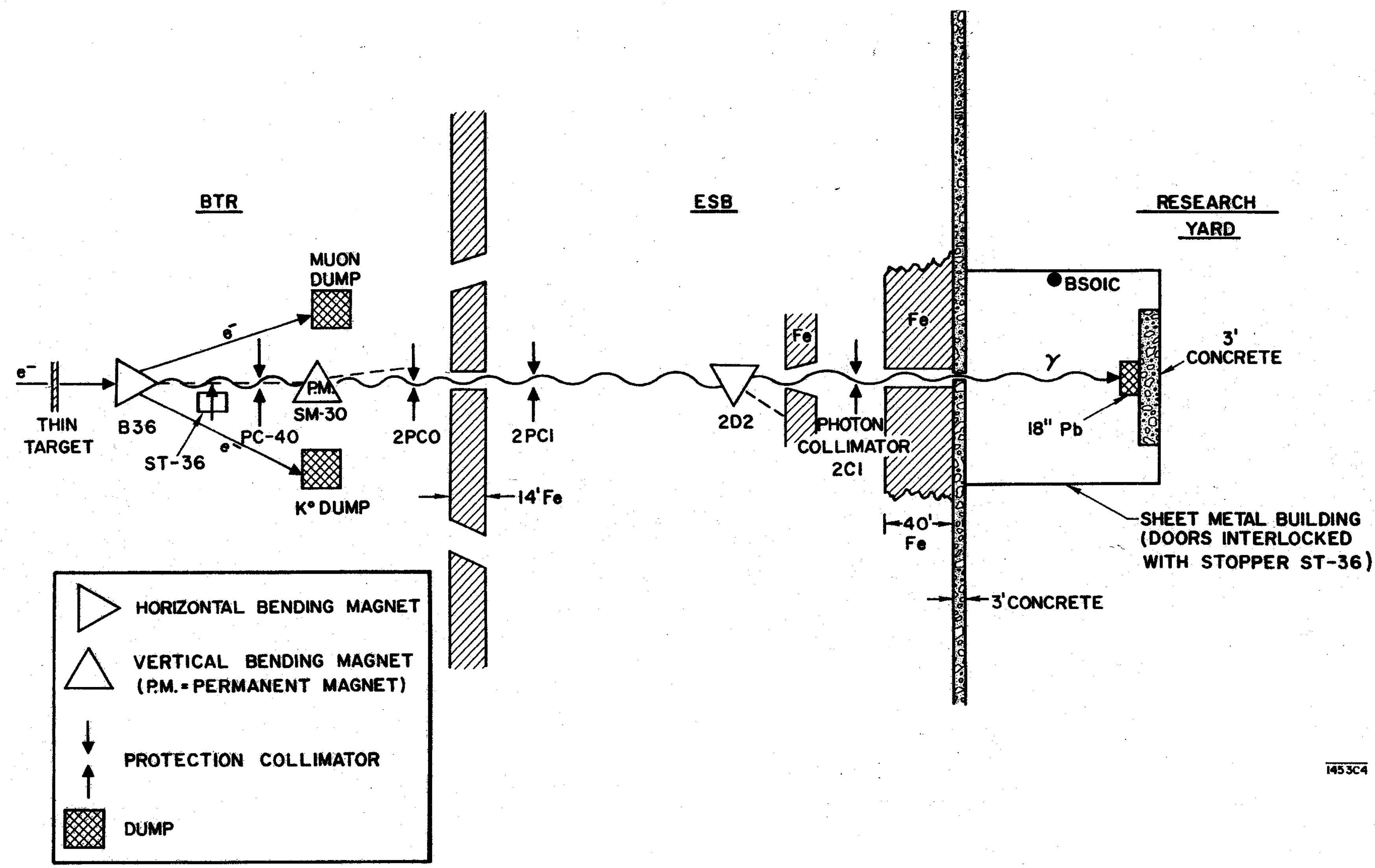

Fig. 8--Essential components in the zero degree bremsstrahlung beam.

the polarity and/or the magnet current (momentum) relationship of 2D2 to the entire B-bend magnet system.

The small building at the downstream end of ESB contains a nominal amount of shielding (18 inches of lead followed by 3 feet of concrete) which has a dual function. It acts as a stopper for an errant primary beam if all systems described above were to fail. A specifically located BSOIC will detect such a situation and shut off the accelerator. This shielding also serves to attenuate the secondary photon beam. Radiation levels in the photon beam, which has a diameter of about 1 mm, vary between 300 and 10^4 rad/hr/kW depending on degree of collimation and on detection methods (ion chamber type and size). Radiation levels outside this building are less than 1 mrem/hr.

2. Annihilation Photon Beam

A positron beam is used to produce annihilation photons for experiments using the 40" hydrogen bubble chamber. Figure 9 shows the essential features of this beam. Because the photon intensity is so low, the only problem is one of primary positron beam containment. Simply stated, the collimated positron beam enters ESB, strikes a thin target, and the remaining beam is deflected into a dump. The photon beam, which consists of an annihilation peak superimposed upon a bremsstrahlung spectrum, is observed along the 8.2 mradian line. The essential question is whether the beam will enter or come too close to the edge of the 8.2 mradian hole if 2D2 were to fail. If there were no horizontal bending magnets after PC-39, the containment problem would be simple, for the horizontal position is limited by PC-39 and 2PC-1. However, the experimenter uses a horizontal bending magnet, 2D1, to vary his production angle (rather than moving the hole in the 40-foot iron shield!) To counteract the influence of 2D2, a permanent magnet, 2SM2, has been added to bend all

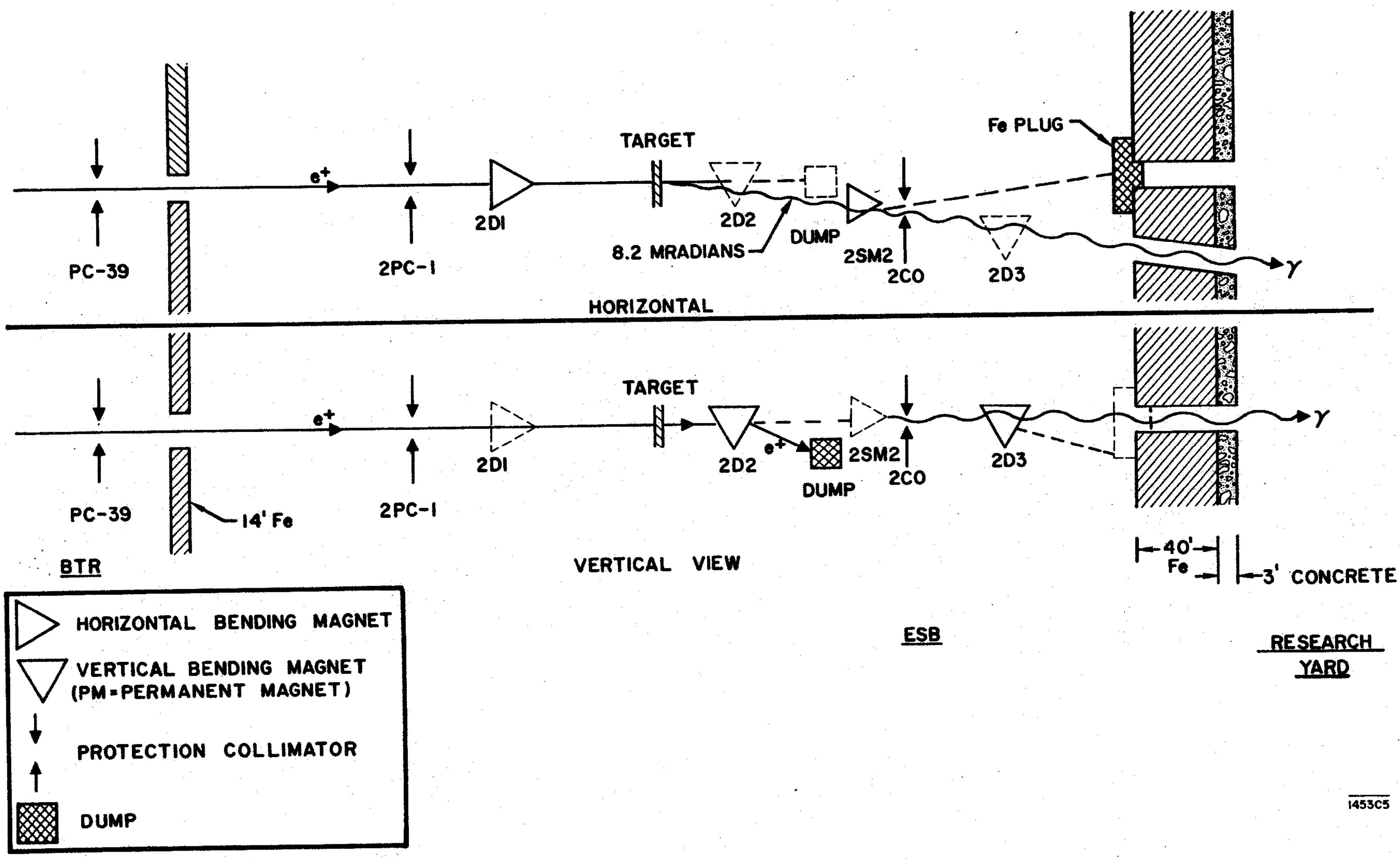

Fig. 9--Components in the annihilation photon beam. Top — horizontal view. Bottom — vertical view.

positrons away from the 8.2 mradian hole. However, this magnet is not sufficient by itself. With 2D1 at full strength, and with low energies ($\leq$ 2 GeV), 2SM2 still does not prevent the beam from escaping. Another collimator, 2CO, is positioned downstream from 2SM2 to intercept these low energy beams at the same time without interfering with the photon beam.* Vertical magnet, 2D3, is used by the experimenter to 'clean-up' the photon beam of unwanted charged particles. To be compatible with the safety system thus described, 2D3 must not bend horizontally.

3) Pi-Beam

The containment problem for this beam is very difficult due to the small angles involved. Figure 10 lists the essential components of this beam. All components exist within the BTR. The problem is to let the experimenter view a π beam produced at an angle of $0.9 - 1.5^{\circ}$, while at the same time insuring that the primary electron beam cannot escape. This is essentially done by placing two vertical bending magnets, B37 & B39, into the beam line, along with beam defining collimators to get the $0.9 - 1.5^{\circ}$ beam offset. The beam is first collimated by PC-34 or PC-39 before entering B-36, which sends the beam down the beam channel and into the first vertical bending magnet, B37. The deflected beam is collimated by 1SC2 before entering B39 where it is bent down through another collimator, 1SC3, striking the target, and continuing into the dump. The worst ray, as shown on Fig. 10, is that ray which goes through the top of the opening of PC-39, the bottom of 1SC2 and the top of 1SC3. A guarantee must be made that this worst ray cannot miss the top of the dump and escape. The only

* It should be noted that low energy beams ($\leq$ 2 GeV) have not been used in ESB (the lowest energy has been 6.0 (GeV). The act of establishing a 2 GeV beam is not only difficult, and deliberate, but it would be contrary to specifications of the BAS.

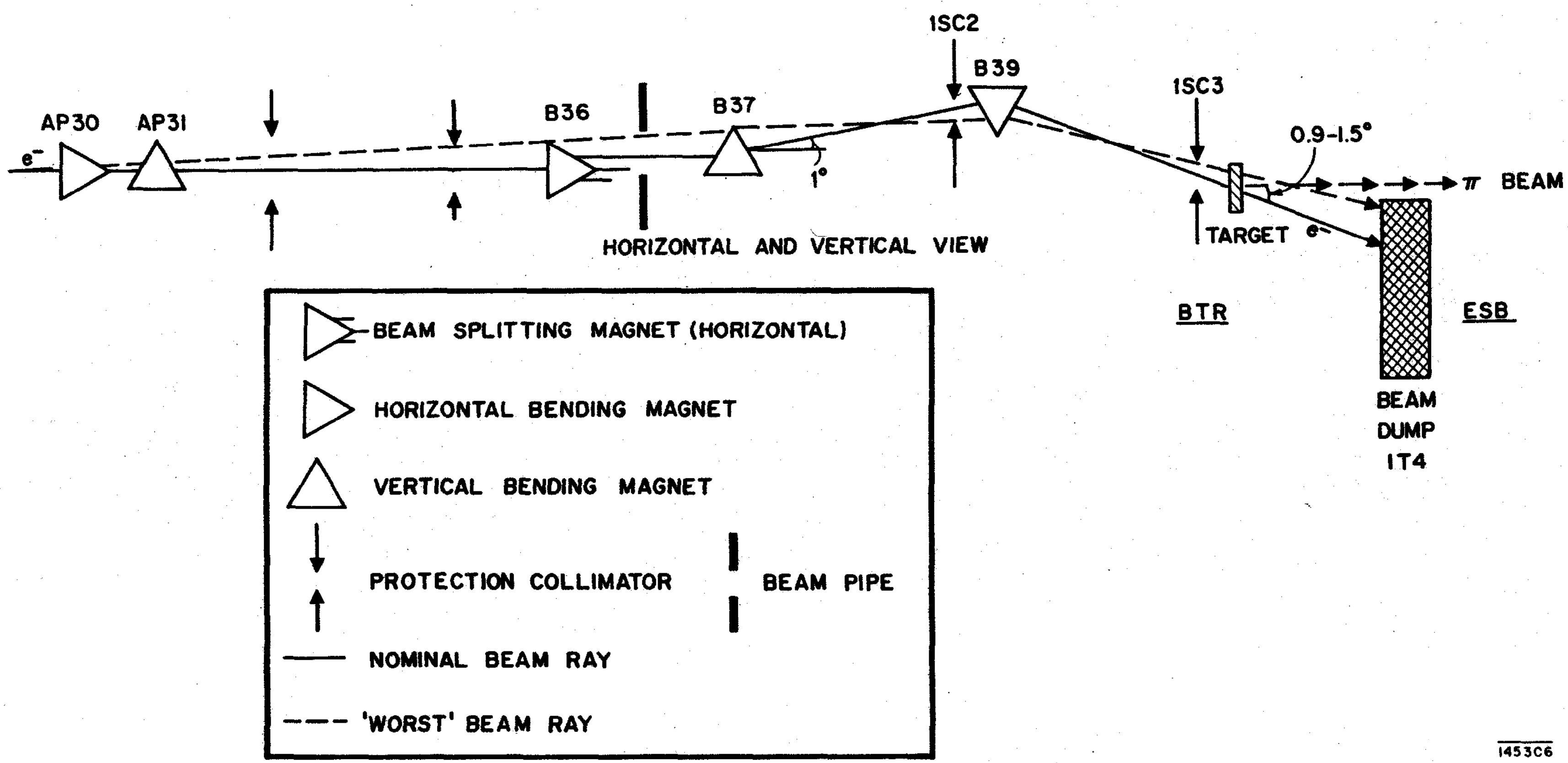

Fig. 10--Components in the π beam line of ESB.

way to insure that this cannot occur is to turn the beam on, and using appropriate ZnS screens, Cerenkov cells and ion chambers, actually define the outlines of the protection collimators in question, and set up this worst ray, observing where it targets before releasing the beam as 'safe.'

A second consideration of this beam comes from multiple scattering in the target, with scattered electrons coming down the pi-beam port. The same arguments concerning multiple scattering noted earlier in the section on ESA hold here. Knowing the pi-beam port aperture, the fraction of electrons (or power) that will enter this port after striking a 16-inch beryllium target (1.13 radiation lengths) is about 1×10^{-5}; or for a beam power of 100 kW, this would be about 1 W of electrons. While all these electrons will enter the aperture, not all of them will be of the right energy to be transported down the secondary particle line. However, if only 10% of these electrons strike an unshielded stopper (for example, a 10-inch iron block) the dose rate 1 meter away in the forward direction would be 20 rad/hr. These electrons may be removed by adding a radiation length or so of material in the beam line right after the dump, 1T4. The actual radiation level in the pi-beam must be determined by measurement before the beam may be released.

End Station C: End Station C (ESC) is perhaps the most complex beam channel at SLAC due to the interaction of one beam with another. In the C-line, there are potentially 6 beams available. Four of these beams are shown in Fig. 11 along with components of the C-line. The electron-laser interaction beam (and co-incidentally the π/K beam) will be discussed to typify the problems of this beam line. The essential components are shown in Fig. 12. The electron beam, bent up the C-line and through the muon shield, is contained by PC-63 and bent into the laser line by magnet B61. Two collimators, 9SC1 and 9SC2 (the latter located

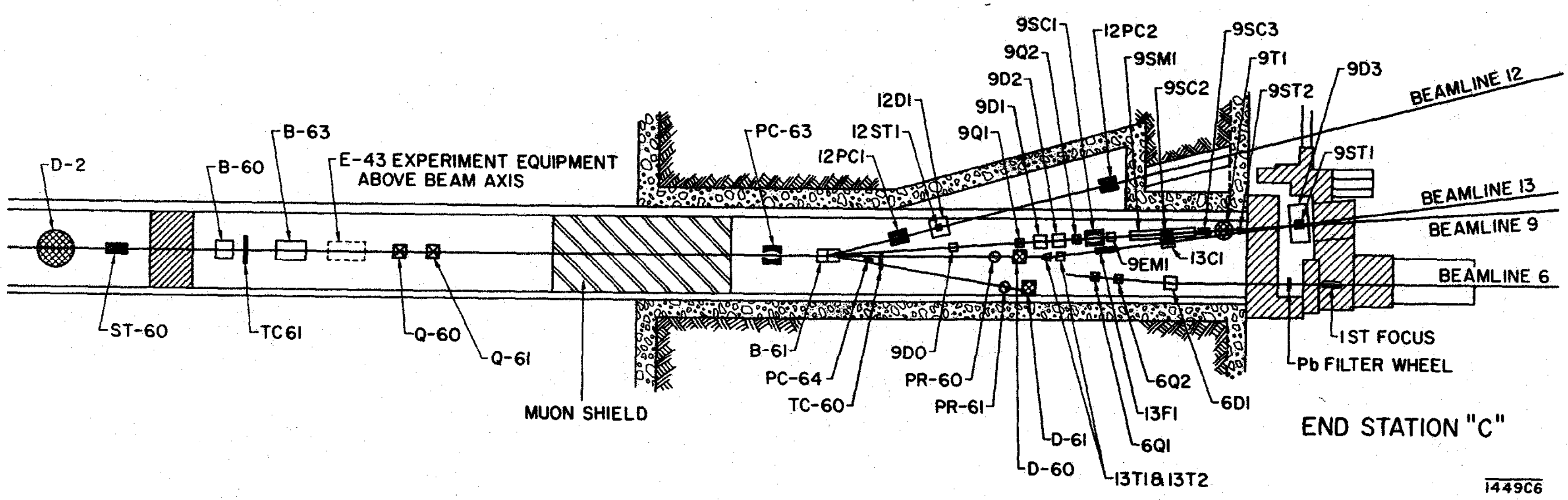

Fig. 11--General lay-out of the central beam line showing essential safety components.

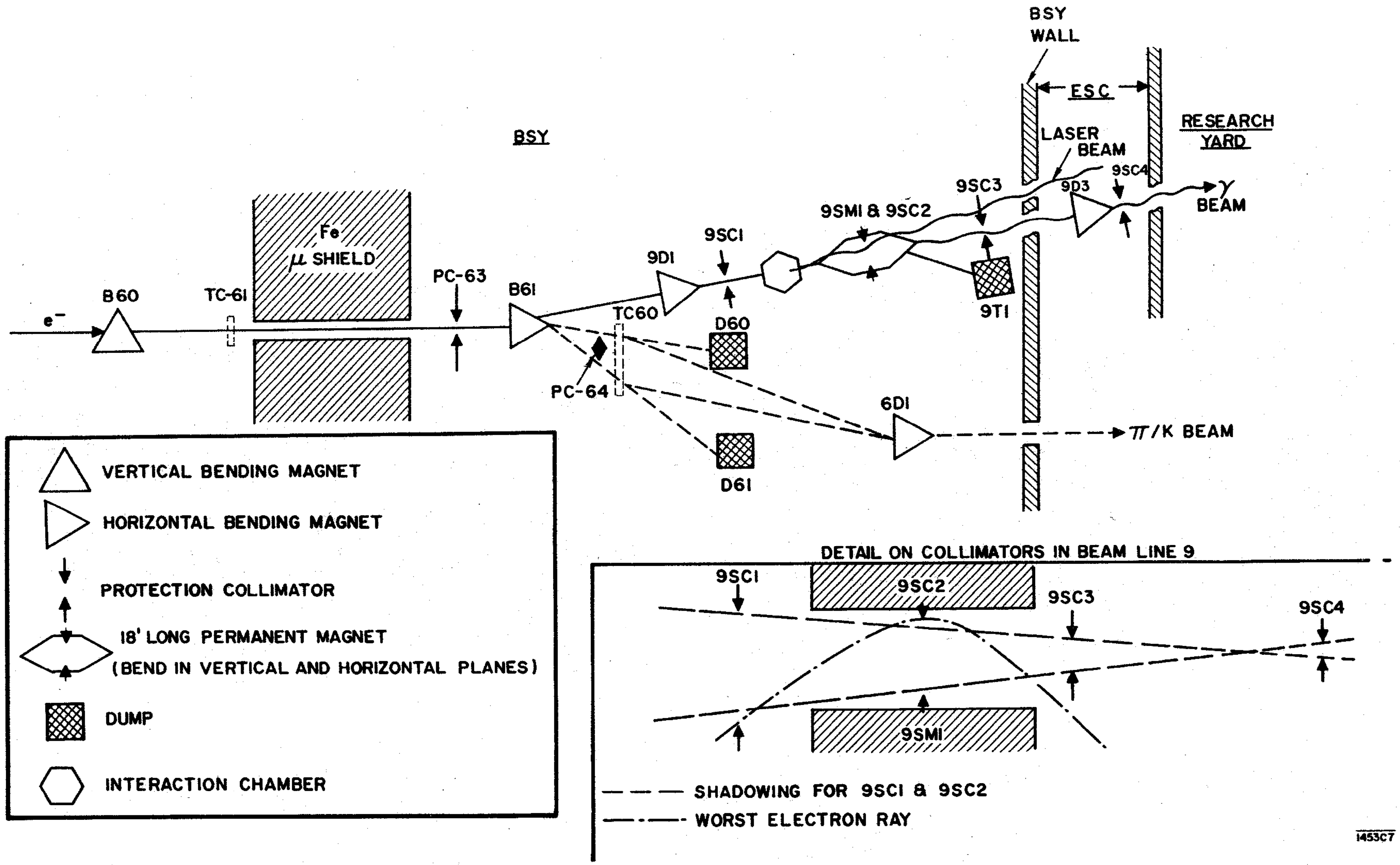

Fig. 12--Components used to guarantee containment of the beam in the electron-laser interaction beam.

inside a permanent magnet 18' long) define a 'worst' ray that cannot escape. The permanent magnet, 9SM1, is rotated 45^{o} such that it bends in both the vertical and horizontal planes. Collimators 9SC3 and 9SC4 are added to shadow 9SC1 and 9SC2 such that any bremsstrahlung produced in these latter collimators cannot get out.

This system would be defeated if any material were placed in the beam after B61. Critical beam steering requirements for the laser experiments make it necessary to insert a Secondary Emission Monitor (SEM) with a foil thickness of 0.1 radiation lengths into the beam just upbeam of the interaction chamber prior to actual data taking. The resultant bremsstrahlung must be prevented from escaping. This is accomplished by closing the beam port at 9D3 and at 9SC4 in the following manner. Inside 9D3 there is a stopper which is inserted electrically into the beam. Collimator, 9SC4 is constructed with the beam hole off-center, and with walls thick enough to act as a dump. This collimator, mounted on a pendulum arm, normally blocks the beam port unless it is swung aside. Thus there are two stoppers to prevent the bremsstrahlung from escaping.

The accidental insertion of the SEM is prevented by two independent means. First, the electrical switches connected to 9SC4 and the stopper inside 9D3 must register closed before electrical power is obtained which releases the air that moves the SEM into position (the SEM is normally spring-loaded in the 'out' position). Secondly, the air which operates the SEM also operates the position of 9SC4 (which is normally closed). Directing the air to 9SC4 to move it to the 'open' position removes the air from the SEM, which will return to the 'out' position.

This system has the advantage that defeating the electrical portion still will not allow the SEM into the beam line with the beam port open due to the mechanical linkage of the air system.

B61 may be set to either polarity depending upon which beam line, the laser or π/K, is being used, or whether electrons or positrons are being bent. At all times the π/K port and magnet 6D1 must be shadowed to insure that a beam cannot escape. This is accomplished by positioning dumps D60 and D61, along with collimators PC-63 and PC-64, to shadow the port as shown in Fig. 12. The positions of these critical components must be checked out in the manner described in the ESB section.

V. DESCRIPTION OF SOME COMPONENTS

Beam containment has produced some interesting designs of components at SLAC. For example, in the C-line, protection collimators PC-63, PC-64, 9SC1 and 9SC2 are critical for beam containment, as are 1SC1 and 1SC3 in the B-line pi-beam. What would happen if these collimators were to burn through? The same question could be asked of the dumps that shadow a port, or of the beam stoppers that are inserted in the beam to prevent a stray beam from being transported down a beam line. Often these components are secondary, that is, something upstream must fail before the beam can strike them, as is the case with most of the beam stoppers. In other cases, the components actually are expected to intercept the beam. One solution would be to design each component to handle the maximum conceivable beam power, but for a 500 kW machine, this becomes prohibitively expensive and cumbersome. An alternate solution, conceived by RAD, is to utilize the operating characteristics of the machine to add safety to these items. The accelerator has pressure sensors and fast-acting valves, which shut off the beam if there is any loss of vacuum. Figure 13 shows the features of

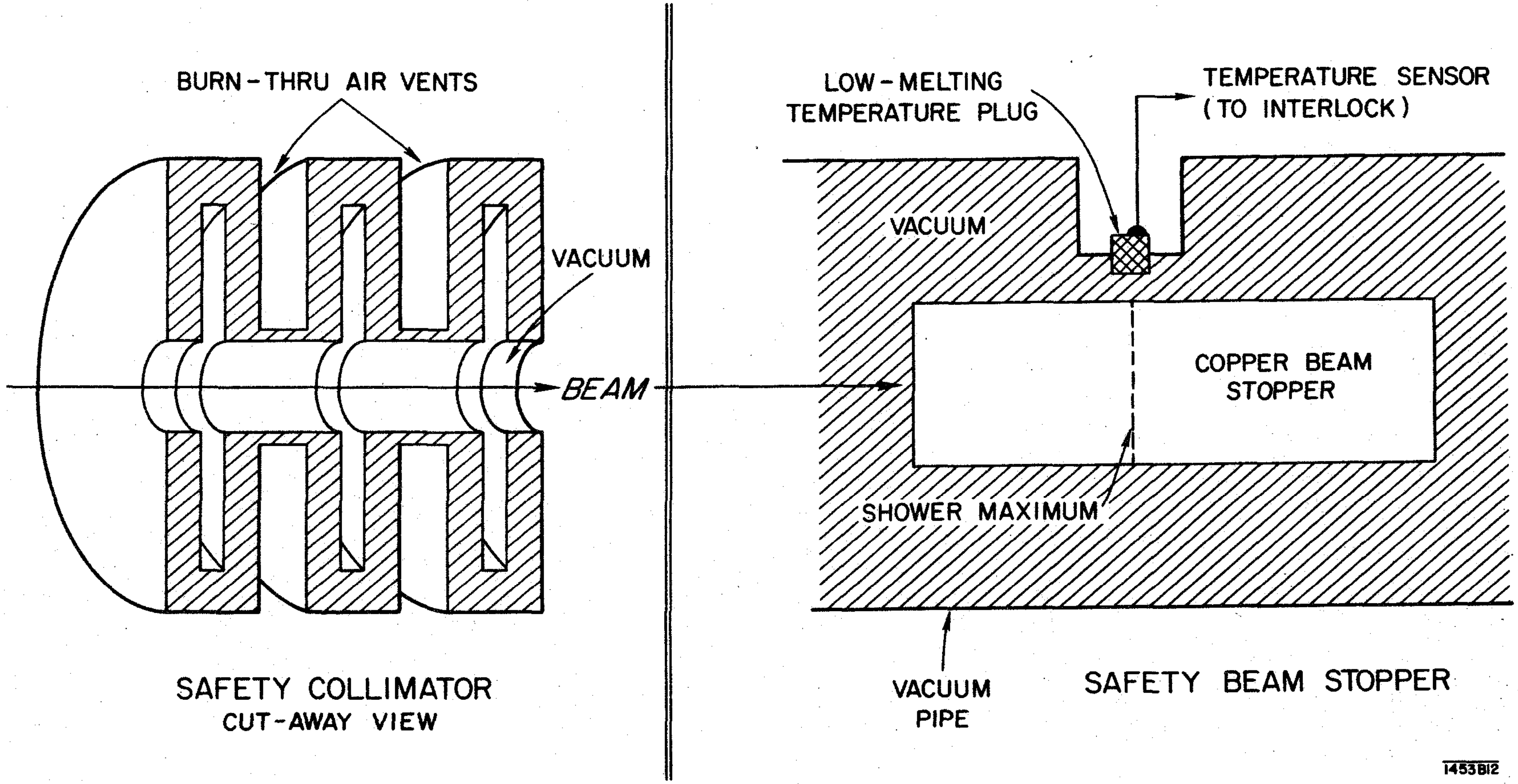

Fig. 13--Two components designed for radiation safety. Left — safety collimator. Right - safety beam stopper.

a safety collimator and a safety beam stopper each of which is designed to let the machine up to air before it completely burns through. The collimator is grooved, with the grooves open to air. The beam stopper has a cavity located at about shower maximum, with a plug in the bottom. If a beam strikes the stopper, the cavity, filled with a low-melting point metal, such as indium, melts before the copper beam stopper does, and drains out, exposing the machine to air. In locations where dumps are critical, they are being constructed such that the water from the water cooling will enter the vacuum before the dump can burn through.

VI. SUMMARY

At SLAC, the design, construction and operation of the Beam Switchyard and Research areas is delegated to the Research Area Department. Shielding calculations and subsequent radiation measurements are performed by the Health Physics group. The responsibility of beam safety, however, is shared by both groups. This responsibility is initiated in the planning phase of a beam and carries through the operating phase including, where required, a beam check-out that is usually performed by Health Physics with the aid of RAD. The beam containment problem involves ray traces, unique designs of collimators, stoppers and dumps, and, as a last line of defense, beam-shut-off ion-chambers. The latter automatically shut off the beam whenever levels outside an end station wall rise above 100 mr/hr. This working relationship has functioned smoothly for more than two years at SLAC, due, in part, to the support given to this arrangement by both the SLAC management, and also by the experimental groups themselves.

ACKNOWLEDGEMENTS

The authors are indebted to the many people, too numerous to mention, who have worked diligently in the design, construction, and operation of the SLAC research area.

REFERENCES

1. H. DeStaebler, "Similarity of shielding problems at electron and proton accelerators," Conf. 65-1109, 429 (1965).
2. R. B. Neal, (Ed.), The Stanford Two-Mile Accelerator, (W. A. Benjamin, Inc., New York, 1968); Ch. 26 by H. DeStaebler, T. Jenkins and W. R. Nelson.
3. W. R. Nelson et al., Phys. Rev. 149, 201 (1966).
4. W. R. Nelson, Nucl. Instr. & Methods 66, 293 (1968).
5. D. R. Walz, to be published.
6. D. R. Walz, "500 kW aluminum beam dump east and related changes," Technical Report No. SLAC-TN-67-31, Stanford Linear Accelerator Center, Stanford University, Stanford, California (1967).
7. D. R. Walz, "400 kW sphere beam dump," Technical Report No. SLAC-TN-68-7, Stanford Linear Accelerator Center, Stanford University, Stanford, California (1968).
8. D. R. Walz and L. R. Lucas, Nucl. Sci. NS16, 613 (1969).
9. G. J. Warren and G. Babcock, "Beam interlock radiation monitor," to be published.
10. T. M. Jenkins and W. R. Nelson, Health Physics 17, 305 (1969).
11. G. Molière, Z. Naturforsch. 2a, 133 (1947).
12. B. P. Nigam, M. K. Sundaresan, T. Y. Wu, Phys. 115, 491 (1959).