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Radiation Protection Systems for the Final Focus Test Beam at SLAC*

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ABSTRACT

The Final Focus Test Beam (FFTB) is a new beam line at the Stanford Linear Accelerator Center (SLAC) designed to test new beam optics concepts, hardware, and techniques necessary to achieve and measure the small spot sizes required for future generations of high-energy e^+e^- linear colliders. The FFTB takes a 47 GeV/c, 1 kW electron beam at the end of the SLAC linear accelerator and transports it to the FFTB beam dump. A radiation protection system was designed and installed for the FFTB with the primary goal that the integrated dose equivalent outside the shielding resulting from beam loss would not exceed 10 mSv per year. This system is comprised of shielding, a Beam Containment System (BCS), and a Personnel Protection System (PPS). This paper presents various aspects of radiation safety at SLAC that were considered in the design of the FFTB radiation protection system. Beam tests were conducted in which the performance of various beam containment devices and the shielding effectiveness were evaluated. Preliminary results from these tests are presented.

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INTRODUCTION

The section of a linear e^+e^- collider which reduces the beam spot sizes and maintains the beams in collision is called the Final Focus. Its magnetic elements act similarly to the lenses of a fine optical telescope to collect the particles produced by the linear accelerator and focus them to a spot that has a small cross-sectional area. Small beam-spot sizes are needed to produce luminosities of 10^{33} to 10^{34} cm^{-2} sec^{-1} that are necessary to generate sufficient numbers of events at center-of-mass energies of 0.5–1.0 TeV, and cross sections of the order of 10^{-37} cm^{-2} (FFTB 1991, Balakin et al. 1994).

Other ways of increasing the luminosity (such as raising the number of particles per pulse and the incoming machine pulse rate) are limited by the available AC power and by interaction of the bunches with each other and the accelerator structure. Therefore, achieving spot sizes that are a hundred times smaller than the wavelength of visible light will be one of the main goals in the development of future generations of high-energy e^+e^- linear colliders. The objective of the FFTB is to focus a 47 GeV electron beam to a transverse vertical size of $\sigma_y = 0.06$ μm and a horizontal size of $\sigma_x = 1$ μm.

Most of the components of the FFTB beam line are installed in the FFTB tunnel, a shielded enclosure in the straight-ahead channel at the end of the linac. This tunnel is composed of two sections (see Fig. 1). The first section is in the beam switch yard and the remainder of the tunnel extends into an unshielded area known as the research yard. The beam switch yard, located at the end of the linac, is a large, two-level structure shielded on the roof by more than 12.2 m of concrete and earth. Beams from the linac can be steered to various beam lines (SLC, PEP, A, B, and C) in the beam switch yard. Part of the path for the SLC and PEP beam lines, and the entire path for beam lines A, B, and C, are located on the first or lower level of the beam switch yard.

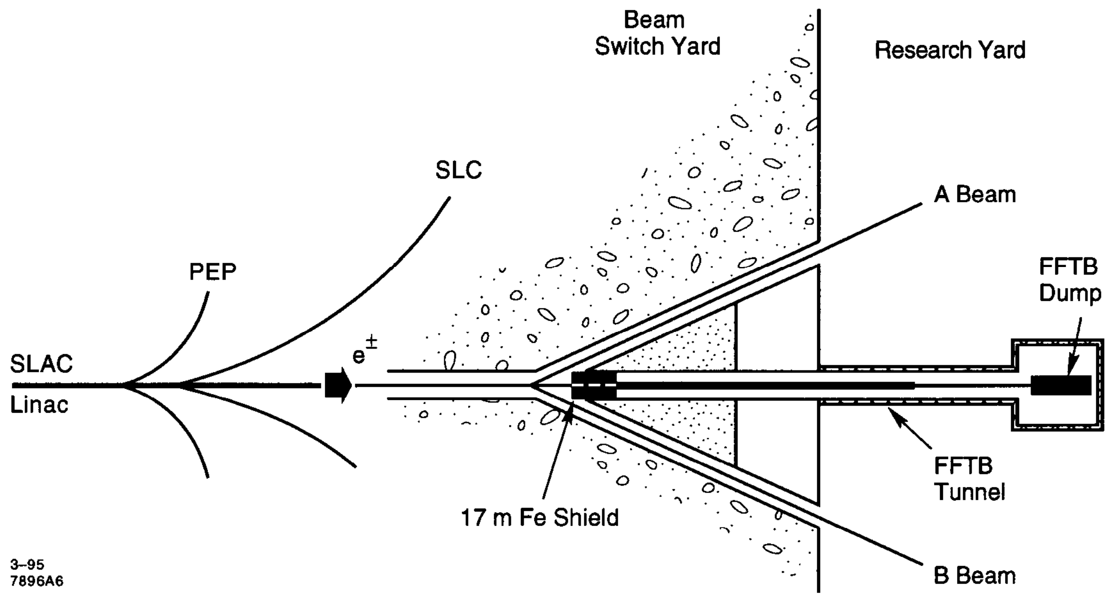

Figure 1. Location of the Final Focus Test Beam at the end of the linear accelerator at SLAC (not to scale).

The first level of the straight-ahead channel in the beam switch yard was modified by removing the components of the old C-beam in order to house 107 m of the FFTB beam line. A shielded structure was added that extends 88 m to the east beyond the beam switch yard to house the remainder of the beam line components; see Fig. 2.

The FFTB is limited to dedicated operation for less than 1000 hours in a year. The SLC and A-beams may be running in the beam switch yard at other times (currently the B and PEP lines are not operational.) Therefore, the FFTB radiation protection system (including the shielding, BCS, and PPS) was designed to satisfy the following two separate and distinct conditions:

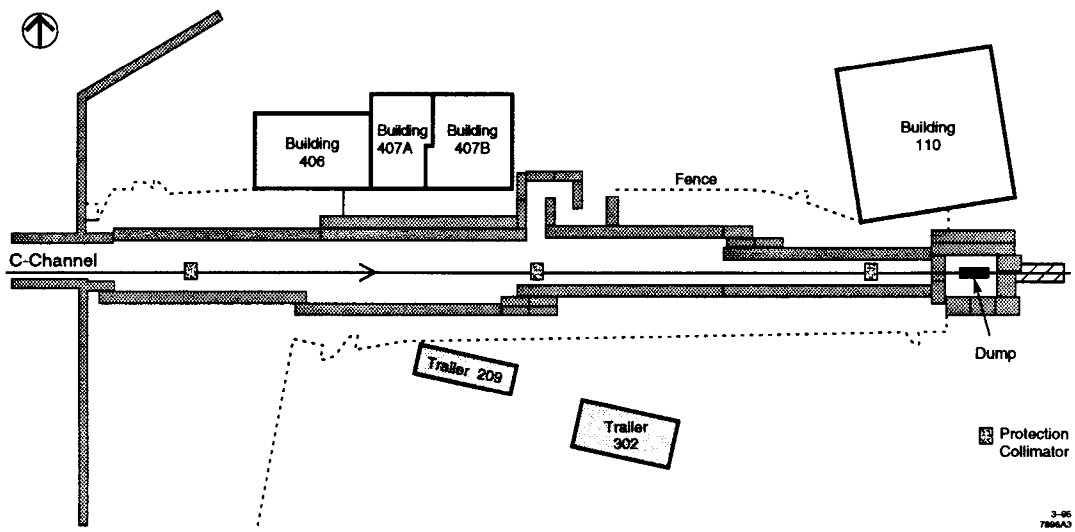

Figure 2. Layout of the Final Focus Test Beam shielded enclosure in the research yard (not to scale).

1. Personnel working inside the FFTB tunnel should be shielded from radiation which could be generated by other beams in the beam switch yard. This was necessary to allow the initial installation, and subsequent service and inspection, of the FFTB beam line components to proceed during the SLC and A-line operation.

2. Personnel working outside the FFTB enclosure in the research yard should be shielded from potential radiation generated during the FFTB operation.

The shielding is designed to ensure that the annual dose equivalent outside the FFTB tunnel is less than 10 mSv (see next section). The BCS is designed to ensure that beam parameters do not exceed the preset values, and that the beam is delivered to the main dump with minimal loss. The PPS controls entry to the tunnel, ensuring that personnel are excluded from the tunnel during the FFTB beam operation.

MATERIALS AND METHODS

Shielding design criteria

The following design criteria were used for shielding the FFTB tunnel:

1. The integrated dose equivalent outside the surface of the shielding barriers must not exceed 10 mSv in a year for normal beam operation (US DOE 1988). For 1000 hours of dedicated operation of FFTB, this limit results in an average dose-equivalent rate of 10 μSv h^{-1}.

2. The BCS policy at SLAC[‖] limits the dose equivalent-rate in the event of a complete failure of the BCS devices to less than 250 mSv h^{-1} (US DOE 1992).

Based on the first criterion, and considering occupancy factors which range from 1/8 to 1/2 for buildings around FFTB tunnel, personnel exposure are expected to remain well within SLAC's administrative control level of 15 mSv per year.[‖]

Radiation sources

During machine operation, particles can strike the accelerator structure and the beam line components, generating radiation. Possible locations for sources of radiation for the SLC and A-line were identified by beam-line designers by identifying the location of residual radiation of the beam-line components and by remote monitoring of prompt radiation in the beam switch yard. Potential sources of radiation for the FFTB were identified by beam-line physicists and engineers in extensive beam-optics and ray-trace studies.

The FFTB beam parameters are: bunch intensity $\leq 1\times 10^{10}$, pulse rate = 10 Hz, and energy = 47 GeV, corresponding to an average beam power of $\leq$1 kW. For normal operation, a value of 1 W (0.1%) was considered to be the amount of beam power lost at any point along the beam line.

Shielding

Radiation levels outside the shield (coming from muons, neutrons, and photons generated in showers initiated by primary electrons) were estimated with both analytic calculations and Monte Carlo simulations. Thicknesses were then calculated to reduce the radiation levels in the occupied areas (inside the FFTB tunnel with beam operating in the beam switch yard, and outside the tunnel in the research yard) to the above stated limits. Photon and neutron dose rates outside thick shields were calculated using the SHIELD11 computer program (Nelson and Jenkins[¶] 1990). Muon dose rates were calculated with the MUON89 computer program (Nelson and Namito[#] 1989). SHIELD11 is based on the model and measurements described by Jenkins (1979) and MUON89 is based on the experiment and calculations described by Nelson and Kase (1974) and Nelson, Kase and Svensson (1974). Muons dominate the shielding requirements at very forward angles and neutrons dominate thick lateral shielding.

The minimum shielding requirements for various segments of the tunnel are summarized in Table 1, and are described here. The tunnel inside the beam switch yard is shielded from radiation generated during the beam operations by a 17-m-long iron plug on the west end (see Fig. 1), and by 0.3 to 0.6-m-thick concrete roof blocks that cover the entire length of the FFTB tunnel inside the beam switch yard. Local lead shielding and concrete roof blocks were added to the beam line components in the beam switch yard

Table 1. Minimum shielding requirements for the Final Focus Test Beam (FFTB) tunnel.

Shielding	Thickness (M)	Location
Beam Switch Yard		
Iron plug	16.8	West end of FFTB tunnel separating the tunnel from the rest of the Beam Switch Yard
Concrete	0.3–0.6	Roof blocks covering entire length of FFTB tunnel
Research Yard		
Concrete	1.2	North and south wall of the FFTB tunnel
Concrete	1.0	Roof of FFTB tunnel
Final Focus Test Beam Dump		
Iron, followed by concrete	1.4 1.2	East side of FFTB dump
Iron, followed by concrete	0.9 1.2	West Side of FFTB Dump
Iron, followed by concrete	0.8 1.8	North side of FFTB dump
Iron, followed by concrete	0.8 1.8	South side of FFTB dump
Iron, followed by concrete	1.0 1.8	Roof of the FFTB dump

to block the rays which could reach the ceiling, or which could pass through the penetrations reserved for the beam and laser pipes in the iron muon shield.

The FFTB enclosure in the research yard is constructed mainly of concrete blocks that were used previously in shielding of other facilities at SLAC. The 1.2-m-thick walls will reduce the dose equivalent rate outside the shield to less than 10 μSv h^{-1} for the normal FFTB beam loss of 1 W at any point along the beam line. Since there is no access to the roof during the operation, the roof blocks are only 1-m-thick. In order to meet the second design criterion for an accidental loss of a 100 kW linac beam (see the following section on the Beam Containment System) in the FFTB beam line, a 2.4-m-high fence was installed around the enclosure to create an exclusion area that provides an extra distance of 3.7 m between the radiation sources and personnel (Fig. 2.). The extra 3.7 m approximately doubles the distance from source to personnel, thus reducing the dose rate from 1 Sv h^{-1} to less than 250 mSv h^{-1}.

To the East, the FFTB tunnel ends in the shielding for the main dump, which is a large iron and concrete structure surrounding the dump on all sides. A 1-m-high, 1-m-wide and 22-m-long tail of iron ingots is installed directly down beam of the FFTB dump enclosure to shield against the forward directed muons generated in the beam dump. The shield thickness for the main dump (see Table 1.) is calculated such that radiation levels outside the dump, also meet the stated design criteria. Tunnel enclosure in the research yard leading to the dump, is much less shielded than the main dump. However, unlike the dump, the full 1 kW beam will not be lost intentionally at any time in targets inside the tunnel.

Beam Containment System

SLAC's beam containment policy requires that beam lines be designed to contain the beam, limit the incoming beam power to the beam line, and limit the beam losses in order to prevent excessive radiation in occupied areas. The containment of the beam in its channel is achieved by implementing a system of redundant, tamper-proof, and fail-safe electronic and mechanical devices that are enforced by strict operational requirements. The BCS for the FFTB is comprised of devices which limit the incoming average beam power to less than the 1 kW allowed beam power (toroid of current monitors I3, I4 and I5); devices which limit normal beam loss to 1 W (toroids I6 and I7, long ion chambers); protection collimators which ensure that errant beams do not escape containment; and devices which protect collimators, stoppers and dumps (ion chambers and flow switches). The BCS electronic devices are shown in Fig. 3 and described below.

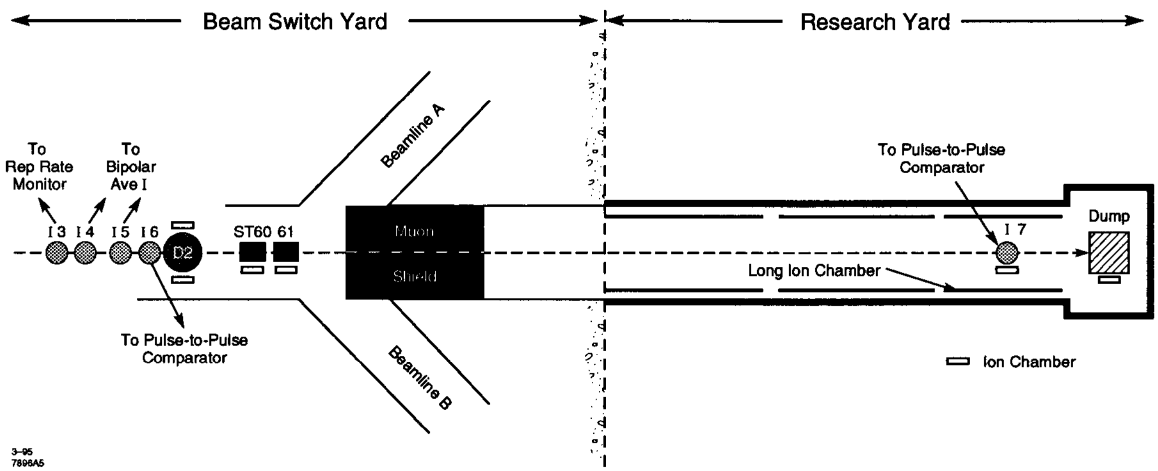

Figure 3. Layout of the Beam Containment System (not to scale).

The pulse-rate monitor on toroid I3 at the beginning of the beam line counts the beam pulses above a preset input threshold over a 1 second time interval base, and trips the beam if the count is above 10 Hz. Average current monitors on two other toroids (I4 and I5 at the beginning of the FFTB beam line) limit the average current to 20 nA. A pulse-to-pulse comparison scheme used widely at SLAC was employed in this beam line to determine if the beam has arrived at the dump. The pulse amplitude from toroid I6 at the beginning of the beam line is compared with the pulse amplitude from toroid I7 at the end of the line. A fault interlock is generated if the signal from I7 is less than 90% of the signal from I6 corresponding to a beam loss of larger than 10%.

Especially long ion chambers were designed and constructed at SLAC to sense beam losses along the research yard section of the FFTB beam line. These ion chambers are 4.1-cm -diameter Heliac cables pressurized with argon gas to 138 kPa above atmosphere. They are installed on both inside walls of the FFTB housing. The chambers are divided into three 30-m-long segments and serve as a distributed ion chamber system, thereby replacing many discrete ion chambers that otherwise would have had to be placed on the beam line to sense beam losses at various points. Signals from these chambers are connected to modified ion chamber cards that process the signals and are interlocked with the BCS. The trip levels for the long ion chambers are set so that the dose-equivalent rate outside the fenced enclosure does not exceed 10 μSv h^{-1}.

The PPS devices, dump D2, stoppers ST60, ST61, and the main dump, as well as BCS protection collimators, are all protected against excessive deposition of beam power by ionization chambers that are interlocked with the BCS. Dump D2, made of copper, is 30-r.l.-thick with respect to the beam direction. A flow switch on this water-cooled dump ensures the integrity of the system. Stoppers, also made of copper, are 52 r.l. each. The main FFTB dump is similar to the SLC Final Focus beam dumps (Walz et al. 1989).

When a fault interlock in a BCS device is generated, beam is turned off, and safety stoppers down-beam of the gun are inserted into the beam line. In accordance with BCS requirements at SLAC, electronic devices have housekeeping currents and other self-checking features.

Failure of various layers of BCS interlocks were considered in the design. In the worst possible failure in which all the electronic interlocks fail the bunch intensity could increase by a factor of 10 and the pulse rate could raise to 120 Hz, resulting in a maximum possible beam of 100 kW. The shielding calculations predict that if such a beam were targeted accidentally on shielding walls in the research yard at small angles of incidence, large dose rates (exceeding 250 m Sv h^{-1} limit) could result. Therefore, an extensive ray-trace study was performed to identify situations which could send a beam out of containment. A beam centroid tracking computer code was generated that simulates the behavior of mis-steered beams caused by various sources of error. Based on these studies, four large collimators were designed and installed at strategic locations in the beam line to intercept all such beams. These collimators, made of iron, are at least 6-r.l.-thick, and have large transverse dimensions that prevent all mis-steered beams from striking the shielding walls.

To mitigate another class of failure scenarios in which high power beams (up to 100 kW) could strike and burn through a collimator, the collimators were backed up by another layer of protection, namely Burn Through Monitors. These monitors are stainless steel pressure vessels attached to the down-beam end of each of the four large collimators. In the event that an errant beam burns through a collimator, it ruptures the associated monitor, which is placed at the shower maximum. Loss of the gas charge to below a preset level, detected with a pressure switch, shuts off the beam. Two Protection Collimators, PC7 (20 r.l.) and PC8 (28 r.l.), both made of copper, were also added to the beam line to ensure that the FFTB beam enters the dump line. With installation of all the collimators, errant beams cannot escape containment. In the event of complete BCS failure, in which a 100 kW beam targets on a beam line component, radiation levels outside the fence in the research yard will remain below 250 mSv h^{-1}.

Personnel Protection System

Another essential component of radiation safety at SLAC is the PPS. The function of this system is to prevent unauthorized access into an area where the potential for presence of beam exists. The PPS for the FFTB (see Fig. 4) is based on a standard design at SLAC, and is composed of beam stoppers, entry module, and emergency shutoff buttons. Entry to the tunnel requires that all three PPS stoppers (D2, ST60 and ST61) be in the **IN** state.

The main entrance to the FFTB tunnel is through a maze in the research yard. It is equipped with the standard access module of an outer door, an inner door, a keybank, an access annunciator panel, door control boxes, search reset boxes, a telephone, and a TV camera. The outer door has an electromagnetic lock and two door-position sensing switches used to confirm the closed status of this door. The inner door provides redundancy and has two position sensing switches as well. An existing opening between

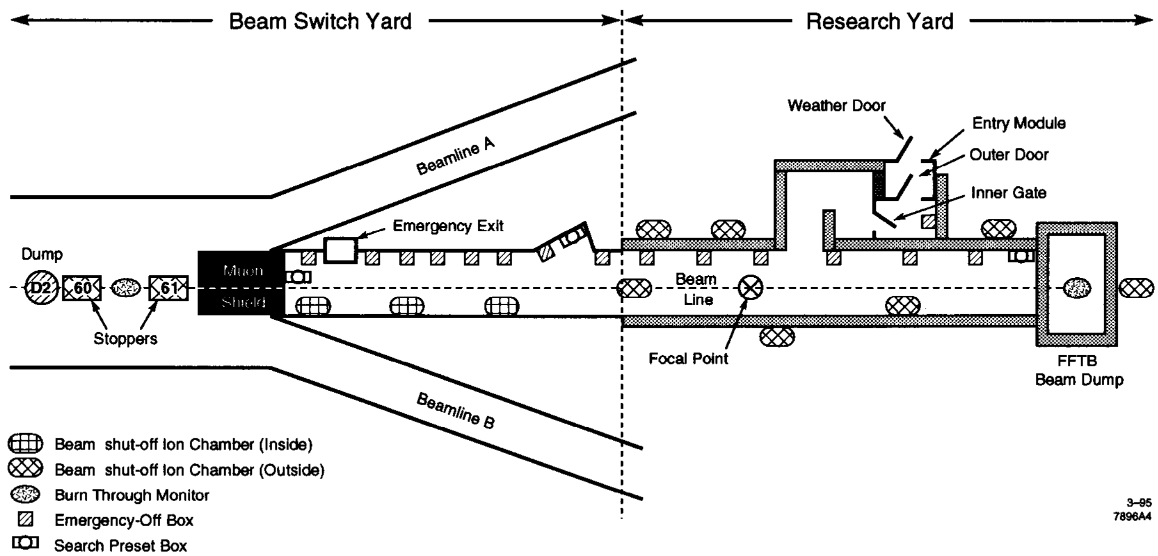

Figure 4. Layout of the Personnel Protection System (not to scale).

the FFTB tunnel and the beam switch yard housing near the west end of the tunnel was modified to provide an emergency exit into the beam switch yard.

Before the beam can be brought into the FFTB beam line, the tunnel must be searched. The search reset circuit is comprised of three search preset boxes located at the west, center, and the east end of the FFTB tunnel, as well as a search reset box at the entrance module. The search reset located at the outer door can be set only when (1)-all presets are set, (2)-the outer door and the inner gate are closed, and (3)-the keybank is complete. The search can be performed only by authorized personnel who must follow documented procedures and signoff sheets to conduct the search. The PPS controls entry to the FFTB tunnel, and sets the tunnel as indicated in Table II.

Only after the area has been set to **No Access** and the audible and visual warnings are completed, can beams be brought into the FFTB beam line. There are 15 emergency beam shutoff push-button boxes located along the aisle of the tunnel. In the **No Access** state, pushing any of these buttons will create a security fault and turn off the beam.

Table 2. PPS entry controls for the FFTB tunnel.

The PPS controls entry to the FFTB tunnel, setting the tunnel to:

No Access:	The PPS stoppers can be pulled out and the allowed beam brought into the FFTB beam line. No entry to the tunnel is allowed.
Controlled Access	The PPS stoppers are in place in the beam line; no beam is allowed in the FFTB beam line. Entry to the tunnel is permitted under operator control only. Each person entering the tunnel must get a key from the keybank. All the keys must be returned to the keybank before the area can be set to **No Access** mode. No search is required before the beam is turned on.
Permitted Access	The PPS stoppers are in place in the beam line; no beam is allowed in the FFTB beam line. There are no restrictions on entry to the tunnel. The area must be searched before beam start-up.

In the other access modes, these buttons are not active. The PPS logic was designed with fail-safe and redundant relay circuit techniques. The hardware is housed in locked racks and cabinets; wires and cables are protected in conduit, armored cable, or trays. Self-test and manual tests are provided wherever possible. SLAC's policy requires full testing of the PPS at least twice a year.

Beam shut-off ion chambers

Another layer of protection is provided through continuous monitoring of radiation levels outside the FFTB tunnel with seven beam shut-off ion chambers connected to the PPS. These ion chambers, designed at SLAC (Neal 1968), are constructed from 10-liter aluminum cans filled with a tissue-equivalent-gas at atmospheric pressure. A ^{90}Sr source is incorporated into the chamber to produce a current for the system checkout. When the detected radiation level exceeds the preset limit (set at 1 mSv h^{-1}) the PPS shuts off the beam and inserts the PPS stoppers. Three other such ion chambers installed inside the FFTB tunnel are active only when the tunnel is in access states, and are by-passed at other times.

RESULTS AND DISCUSSION

Beam tests

During the commissioning phase of the FFTB, beam tests were conducted in which the 47 GeV electron beam was targeted on collimators and dumps in the beam line. In these tests, the performance of various beam containment devices was evaluated and the trip set-points were determined.

Extensive radiation surveys outside the FFTB tunnel in the research yard were also performed. The main purpose of these surveys was to ensure that there were no weaknesses in the shielding and that the measured radiation levels were within the estimated values. The opportunity was also taken to collect more extensive data on photons and neutrons at some locations to compare the results with the calculations based on the SHIELD11 computer code, which was used extensively in the design of lateral shielding. These measurements were conducted with beam powers varying from 56 to 224 W, depending upon the thickness of the wall near the targeted collimator.

Performance of BCS

In order to set the trip levels of the ion chambers on collimators PC7 and PC8, a known fraction of the FFTB beam power was targeted on these collimators. The trip points on their associated ion chambers were set at a safe level, below their respective power absorption limits. The trip points for ion chambers on D2 and the main FFTB dumps were set when the 1 kW FFTB beam was deposited on them.

To calibrate the long ion chambers, with the beam targeted on collimators in the research Yard section of the beam line, radiation levels outside the tunnel and the current generated by the ion chambers were measured. The trip points were then set at a level corresponding to 10 μSv h^{-1} (photons + neutrons) outside the fenced enclosure.

To check the performance of pulse-rate monitor I3, the unit was set to trip at 9 Hz, a level less than the allowed limit of 10 Hz; when the FFTB beam at 10 Hz passed through I3 the BCS turned off the beam in one pulse. The minimum detection limit for I3 was determined to be 2×10^8 electrons per pulse.

Average current monitors I4 and I5 were set to trip at limits corresponding to average currents exceeding 20 nA. To check the bipolar capability of these toroids, beams of only electrons, and beams of both electrons and positrons separated by 60 ns in time, were targeted onto D2. In each case, when the average current exceeded 20 nA, BCS interlocks turned off the beam.

Toroids I6 and I7 were set to read the same value when beam was being steered to the main FFTB dump at no apparent loss. A movable collimator located between the two toroids was used to reduce the beam intensity at I7. The pulse-to-pulse comparator was set to trip the beam when the amplitude of I6 was 90% of I7. Calibrated toroids and other beam monitoring devices in the linac were used as references in determining the incoming beam current in the FFTB beam line.

Radiation measurements

The exposure rates for photons and muons were measured with a 450P Victoreen[†] ion-chamber survey meter. The neutron dose-equivalent rates were measured with an Andersson-Braun rem meter and a portable Eberline[††] (model NRD) rem meter. The Victoreen ion chamber was calibrated against a NIST calibrated ion chamber using ^{60}Co and ^{137}Cs sources. For the photon results described below, an equivalence of exposure, absorbed dose, and dose equivalent has been assumed.

The portable Eberline rem meter was used mainly for the measurements on the roof and the south side of the tunnel, which were not as accessible as the north side. A moderated BF_3 detector was kept at a fixed location during the measurements on each target and used as a reference counter. The moderated BF_3 and Andersson-Braun detectors were calibrated using ^{238}PuBe and ^{252}Cf sources. The neutron spectrum outside the shield (for neutron energies below 10 MeV) is assumed to be similar to that of the ^{252}Cf source. The relative responses of the detectors were checked frequently with a ^{238}PuBe source. A detailed discussion of the neutron detectors used at SLAC is given in Liu et al. (1991).

Results

Radiation surveys around the tunnel showed that there were no unexpectedly large stray radiation fields outside the shielding walls, thus confirming that adequate shielding had been installed with no gaps or weaknesses.

The measured radiation levels for each target were normalized to the reading of the reference counter for that target. The detected variations in the neutron flux in the reference counter were attributed to undesired changes in the incoming beam power, or to the changing beam spot location on the target during the measurements. The average value of the readings of the reference counter over all the measurements for each target was used for normalization purposes. The measured neutron results were divided by a factor 0.6 to account for the dose contribution from neutrons with energies greater than 10 MeV, where there is no appreciable response from the neutron counters (McCaslin et al. 1976, Hirayama and Ban 1989). The Andersson-Braun data were corrected for dead time due to the extremely low (less than 3×10^{-12}) accelerator duty factor, based on procedures described in Ash et al. (1977). The dead time correction factors for the data taken on PC7 with the beam vary from 1.03 to 1.52. The beam measurements were conducted at average beam powers well below the nominal FFTB power (56 W compared to 1 kW). Use of even lower power beams (and longer-pulse lengths) would have resulted in smaller dead time in the neutron counters. However, due to limits on the dynamic range of the beam steering and controlling instruments, achieving such beam parameters with sufficient accuracy was not deemed feasible.

The Andersson-Braun counts were converted to dose-equivalent values using the giant resonance neutrons conversion value of 190 cps $mSv^{-1}hr^{-1}$ (Liu et al. 1991). This is based on the assumption that the neutron spectrum outside a thick shield is mainly due to evaporation neutrons generated by high-energy neutrons traversing the thick concrete shielding walls, and is similar to a giant resonance spectrum. The photon exposure rates measured by the Victoreen ion chamber were normalized to the reference counter. The corrected results for PC7 are reported in Figs. 5 and 6.

Uncertainties

The reported uncertainties are the results of combined random and systematic errors associated with the measurements; these uncertainties were added in quadrature. The statistical uncertainty for the measurements on PC7 with the Andersson-Braun rem meter

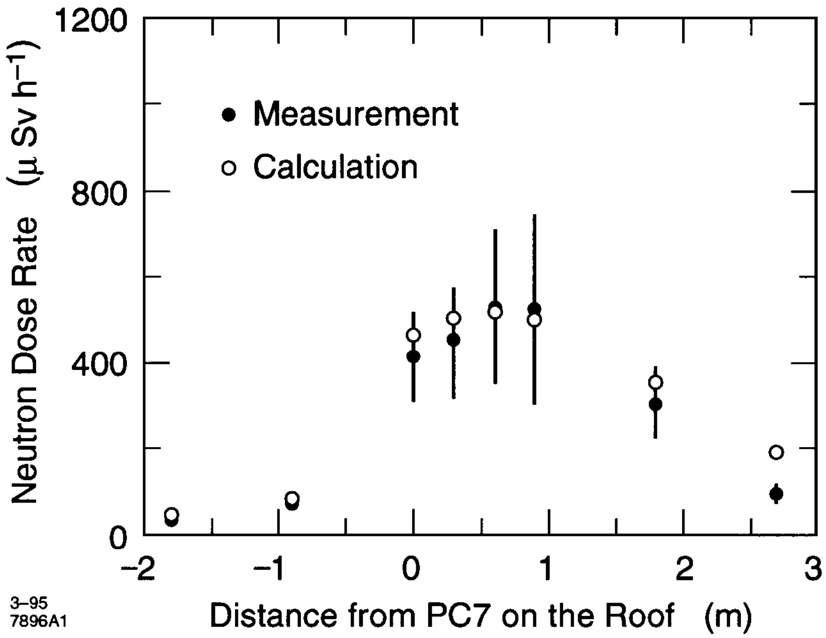

Figure 5. Neutron dose-equivalent rate versus distance on the roof shielding for collimator PC7. Calculations are based on SHIELD11.

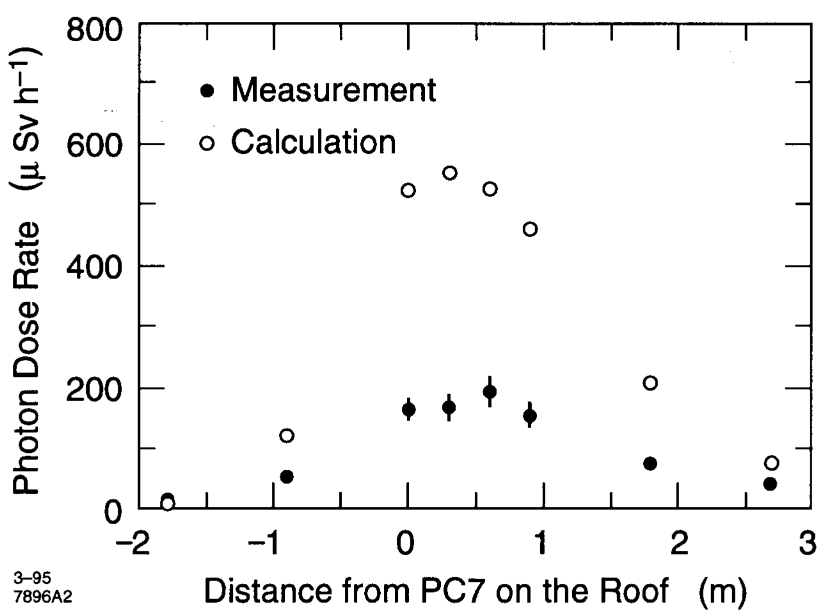

Figure 6. Photon dose-equivalent rate versus distance on the roof shielding for collimator PC7. Calculations are based on SHIELD11.

varied from 5 to 17%. The beam energy was known to better than 1%. The beam current was measured with several toroids throughout the accelerator that are calibrated to 5%. The uncertainty resulting from changing beam conditions on the target was monitored by the reference counter. The uncertainty of the conversion factor for the Andersson-Braun data was taken to be 20% (Liu et al. 1991). The uncertainty associated with the dead time correction varied from 2 to 36%. The error in the photon data reflects 10% uncertainty in the calibration of the ion chamber and the uncertainty in beam-targeting conditions.

Shielding model

The SHIELD11 program (Nelson and Jenkins[¶] 1990) is a computer code for performing calculations around high-energy electron accelerators. It makes use of simple analytical expressions for the production of photons and neutrons by electrons striking thick targets, and the attenuation of these photons and neutrons. Earlier versions of this computer code (Jenkins 1989)[§], or formulae from the code, have been used in shielding beam lines at various electron accelerators (Hirayama and Ban 1989, Ipe 1991). The neutron dose-equivalent component of this program is based on a model described by Jenkins (1979) and is given by the following equation:

$$
\begin{aligned}
H(\text{neutrons}) = {} & E_0\left(l^{-1}\ \cos\beta\right)^2 \times 10^{-13} \\
& \times \left[13.69A^{-0.65}\ \exp\left\{-\rho d(\lambda_1\ \cos\beta)^{-1}\right\}(1-0.72\ \cos\theta)^{-2}\right. \\
& +44.3\ A^{-0.37}\ \exp\left\{-\rho d(\lambda_2\ \cos\beta)^{-1}\right\}(1-0.75\ \cos\theta)^{-1} \\
& \left.+\ 4.94\ A^{-0.66}\ \exp\left\{-\rho d(\lambda_3\ \cos\beta)^{-1}\right\}\right] .
\end{aligned}
$$

The three terms in the above equation represent the production and attenuation of high-energy, mid-energy and giant-resonance neutrons. H(neutrons) is the neutron dose equivalent in Sv per electron; E_0 is the electron energy in GeV; l is the distance between the target and the outer surface of the shield, and d is the shield thickness; θ is the angle between the beam direction and the line connecting the target to the measurement point, and β is the angle between the latter line and the normal to the shield from the target. Angles are in degrees and distances are in centimeters. Z is the atomic number and A is the atomic mass for the target. Fluence-to-dose conversion factors of 6.7×10^{-10} Sv-cm^2 per neutron for high-energy neutrons and 3.2×10^{-10} for giant resonance and mid-energy neutrons were used in deriving the above equation. In these calculations, the attenuation lengths in concrete for the three terms are λ_1=120 g cm^{-2}, λ_2=55 g cm^{-2}, and λ_3=30 g cm^{-2}, respectively. The concrete density ρ, is 2.35 g cm^{-2}. Corrections with appropriate attenuation lengths were applied for the attenuation in copper targets, as well.

The photon component used in the SHIELD11 program is shown below; it is different from that described in Jenkins (1979). The source term (photon production) in the program is based on a two-term fit to data taken at different energies, angles, and targets (Neal 1968). EGS4 calculations (Nelson et al. 1985) were used to extend the measured data at forward angles. The first term dominates at forward angles (0–5 degrees) and the second term is valid for larger angles.

$$H(\text{photons}) = E_0\left(l^{-1}\cos\beta\right)^2 \times 10^{-13}\Big[1.26\,E_0\,10^6\exp(-\rho_1 t\mu_1)\exp\left(-\theta^{0.6}\right)$$
$$+\,\mathcal{H}\,7.55\exp(-\rho r\mu_1)\exp(-0.014\,\theta)\Big]\exp\left(-\rho_2 d\mu_2\cos\beta^{-1}\right)\Big] \;,$$

where H(photons) is the photon dose equivalent in Sv per electron, μ_1 and μ_2 are the mass attenuation coefficients at the Compton minimum, and ρ_1 and ρ_2 are the densities for the target and the shield, respectively. The values of $\lambda_\gamma=1/\mu$ for concrete and copper are 42.0 and 33.0 g cm^{-2}; t is the target thickness and r is the target radius in centimeters.

The Heavy-side function ($\mathcal{H}$) takes on two values: $\mathcal{H} = 1$ for $\Theta > 5°$ and $\mathcal{H} = 0$ for $\Theta \leq 5°$.

In the SHIELD11 program, another term is added to the photon term to account for the contribution of secondary photons, which are assumed to be generated by neutrons in the thick concrete walls. This term is proportional to the high-energy term with a proportionality constant of 0.27 (Jenkins 1979).

Comparison with SHIELD11

In Figs. 5 and 6, measurements that represent the angular distribution of radiation levels on the shielding roof for PC7 are compared with the results from SHIELD11 calculations. The distance from PC7 to the roof shield and the shield thickness are 1.5 and 1 m, respectively. These calculations are corrected for attenuation at back-angles in a large collimator, located up-beam of the target. Most neutron data agree with the calculated values within the estimated errors. However, on the average, the photon measurements are lower than the calculated values by a factor of 3. Several factors could contribute to the discrepancy in photon results. One factor is the attenuation length of photons in concrete where $\lambda_\gamma = 42$ g cm^{-2}, corresponding to the Compton minimum, is used. A decrease in this value to 35 g cm^{-2} (20% change) will decrease the calculated photon dose on the PC7 roof by a factor of 3, resulting in better agreement with the measured data. A change in the concrete density could have a similar effect.

Another factor that could influence the results is the extra self-shielding in the target. In the SHIELD11 program, the electron beam is assumed to impinge on the front face of the target at zero degrees. During the measurements, it was not possible to obtain accurate knowledge of beam location on the targeted collimator. Beam could have struck the collimator at an angle, whereby the self-shielding due to the extra target thickness would increase. If an extra thickness of one inch in the copper target ($\lambda_\gamma = 33$ g cm^{-2}, $\rho = 8.96$ g cm^{-3}) is assumed, the calculated dose rate will be reduced by half. Since the attenuation lengths for neutrons have much larger values (152 g cm^{-2} for high-energy and medium-energy neutrons in copper), the attenuation effect for neutrons is less significant. Reduction in the neutron dose rate for extra thickness of one inch in the same target will be only 16%.

It should be pointed out that there were severe difficulties in performing beam tests in the FFTB, which is a heavily instrumented beam line not designed for radiation measurement purposes. Beam tests were mainly performed to ensure that there was no leakage through the shielding. Choices of target and shield geometries and thicknesses needed for benchmarking shielding models were very limited in the FFTB. Therefore, the degree of contribution of the above factors to the discrepancy in the photon results could not be resolved further. However, the measured radiation levels are generally lower than the calculated values, thus allowing for a conservative design with the SHIELD11 program.

CONCLUSION

A radiation protection system was designed and installed for the FFTB at SLAC. The components of this system include: shielding, Beam Containment System and Personnel Protection System. The Beam Containment System ensures that the beam parameters do not exceed their preset values and that the beam remains in its channel with minimal losses. The Personnel Protection System controls access to the tunnel. Shielding, in conjunction with beam containment, ensures that the design criteria are met. Beam tests were performed and the response of beam containment devices was evaluated. Measured radiation levels outside the FFTB tunnel were compared with the models used in the shielding design.

The measured photon results were found to be a factor of 3 lower than the calculations; neutron results show better agreement with the calculations.

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