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RADIATION PROTECTION SYSTEMS FOR THE FINAL FOCUS TEST BEAM

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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 that are necessary to achieve and measure the small spot sizes required for future generations of high-energy e^+e^- linear colliders. FFTB takes a 47 GeV/c, 1 kW electron beam at the end of the SLAC Linear Accelerator (LINAC) and transports it to the FFTB beam dump with minimal loss. A radiation protection system was designed and installed for the FFTB with the primary goal that the integrated dose equivalent outside the shielding would not exceed 10 mSv per year. This system is comprised of Shielding, Beam Containment System (BCS) and Personnel Protection System (PPS). The purpose of this paper is to present various aspects of radiation safety at SLAC that have been considered in the design of the FFTB radiation protection system. Beam tests were conducted in which the performance of various BCS devices and the shielding effectiveness were evaluated. Preliminary results from the tests are also 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 with small cross-sectional area. Small beam spot sizes are needed to produce luminosities of 10^{33} to 10^{34} cm^{-2}sec^{-1} that will be 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 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. The FFTB tunnel is composed of two sections (see Fig. 1). The first section is in the Beam Switch Yard (BSY) and the remainder of the tunnel extends beyond the BSY into an unshielded area known as the Research Yard (RSY). The BSY, located at the end of the LINAC, is a large two level structure which is shielded on the roof by more than 12.2 meters of concrete and earth. Beams from the LINAC can be steered to various beam lines (SLC, PEP, A, B and C) in the BSY. 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 BSY.

The first level of the straight ahead channel in the BSY was modified by removing the components of the old C-beam in order to house 107 meters of the FFTB beam line. A shielded structure was added that extends beyond the BSY to the East for 88 meters into the RSY to house the remainder of the beam line components (see Fig. 2). Access to the FFTB tunnel is controlled through an interlocked gate at the entrance maze which is located in the RSY.

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

1. Personnel who are working inside the FFTB tunnel should be shielded from radiation which could be generated by other beams in the BSY. This was required to allow the initial installation and the 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 RSY 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. The BCS is designed to ensure that the 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 FFTB tunnel and ensures that personnel are excluded from the tunnel during the FFTB beam operation.

MATERIALS AND METHODS

Shielding design criteria

The following design criteria have been used for shielding of the FFTB tunnel:

1. The integrated dose equivalent outside the surface of the shielding barriers must not exceed 10 mSv in a year for the normal beam operation (US DOE 1988).
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 hr^{-1}.

Radiation sources

During machine operation, particles can strike the accelerator structure and 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 BSY. 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, energy = 47 GeV, corresponding to an average beam power of $\leq$1 kW. For normal operation, a value of 1 W was considered as the amount of beam power that could be lost at any point along the beam line.

Shielding

Radiation levels outside the shielding from muons, neutrons and photons generated in showers initiated by primary electrons were estimated with both analytic calculations and Monte Carlo simulations. The thicknesses that would reduce the radiation levels in the occupied areas (inside the FFTB tunnel in the BSY, outside the tunnel in the RSY) to the limits stated above were then calculated. Photon and neutron dose rates outside thick shields were calculated using the SHIELD11 computer program (Nelson¶ 1988). 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 (1974) 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 FFTB tunnel are summarized in Table 1 and are described here. The FFTB tunnel inside the BSY is shielded from radiation generated during the beam operations with a 17 meter long iron plug on the east end (see Fig. 1), and 0.3 to 0.6 meter thick concrete roof blocks which cover the entire length of the FFTB tunnel inside the BSY. Local lead shielding and concrete roof blocks were added to the BSY beam line components to block the rays which could reach the BSY 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 RSY is constructed mainly from re-cycled concrete blocks. The

1.2 meter thick walls will reduce the dose equivalent rate outside the shield to less than 10 μSv h^{-1} for the expected 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 meter thick. In order to meet the second design criterion for an accidental loss of a 100 kW beam (see the section on BCS) in the FFTB beam line, a 2.4 meter high fence was installed around the enclosure to create an exclusion area that provides an extra distance of 3.7 meters between the radiation sources and personnel (Fig 2.).

To the East, the FFTB tunnel ends in the shielding for the main dump which is a large iron and concrete structure. A 1 meter high, 1 meter wide and 22 meter long tail of iron ingots is installed directly down beam of the FFTB dump to shield against the forward directed muons generated in the beam dump. Compared with the dump shielding, the tunnel enclosure in the RSY leading to the dump is much less shielded. However, unlike the dump the full 1 kW beam will not be lost intentionally in targets inside the tunnel at any time.

Beam Containment System

SLAC's beam containment policy (SLAC 1988) requires that beam lines be designed to contain the beam, limit the incoming beam power to the beam line, and limit the beam losses 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 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 Allowed Beam Power

(1 kW): (toroid of current monitors I3, I4 and I5); devices which limit the beam loss to 1 W: (toroids I6 and I7, Long Ion Chambers); Protection Collimators (PC) 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 for the FFTB are shown in Fig. 3 and described below.

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 BCS 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 also employed in the FFTB 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 will be generated if the signal from I7 is less than 90% of the signal from I6 corresponding to a beam loss of larger than 10%.

Long ion chambers (LIONs) were designed and constructed at SLAC to sense the beam losses along the RSY section of the FFTB beam line. LIONs are 4.1 cm diameter Heliac cables pressurized with Argon to 20 psig. They are installed on both inside walls of the FFTB housing. These chambers are divided into three 30-meter-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 LIONs are connected to the modified ion chamber cards which process the signals and are interlocked with the BCS. The trip level for LIONs is set such 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 which are interlocked with the BCS. A flow switch on the water-cooled dump D2 ensures the integrity of this system.

When a fault interlock in a BCS device is generated, the beam is turned off and safety stoppers down-beam of the gun are inserted into the beam line. In accordance with the BCS requirements at SLAC, the BCS 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 is accidentally targeted on shielding walls in the RSY at small angles of incidence, large dose rates (exceeding the BCS failure limit) would 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 protection collimators were designed and installed at strategic locations in the beam line to intercept all mis-steered rays. These collimators, made of steel, are thick enough to absorb the Allowed Beam Power (1 kW) indefinitely.

To mitigate another class of failure scenarios in which high power beams could strike and burn through a collimator, the large PCs were backed up by another layer of protection, namely Burn Through Monitors (BTM). These monitors are stainless steel pressure vessels which are attached to the down beam end of each of the four PCs. In the event that an errant beam burns through a PC, it ruptures the associated BTM 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 copper collimators, PC7 (20 r.l.) and PC8 (28 r.l.), were added to the beam line to ensure that the FFTB beam enters the dump line. With installation of all the PCs, errant beams could not escape containment. In the event of complete BCS failure in which a 100 kW beam targets on a beam line component or a PC, radiation levels outside the fence in the RSY would remain below 250 $\mathrm{mSv\,h^{-1}}$.

Personnel Protection System

Another essential component of radiation safety at SLAC is the PPS. The function of the FFTB PPS is to prevent un-authorized access into an area where there exists the potential for presence of beam. The PPS for the FFTB (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 FFTB tunnel requires that three PPS stoppers (D2, ST60 and ST61) be in the "IN" state. The PPS controls entry to the FFTB tunnel and can set the tunnel to: No Access, Controlled Access, or Permitted Access states:

No Access: In this state 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: PPS stoppers are in place in the beam line; no beam is allowed in the FFTB tunnel. Entry to the tunnel is permitted under operator control only.

Permitted Access: No beam is allowed in the FFTB tunnel, the PPS stoppers are in place, and there is no restriction on entry to the FFTB tunnel.

The main entrance to the FFTB tunnel is through a maze in the RSY and is equipped with a standard access module of an outer door, inner door, keybank, access annunciator panel, door control boxes, search reset boxes, 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. An existing opening between the FFTB tunnel and the BSY housing near the west end of the FFTB tunnel was modified to provide an emergency exit into the BSY.

Before the beam can be brought into the FFTB beam line, the tunnel must be searched. The Search Reset circuit for the FFTB 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 Re set box at the entrance module. The Search Reset which is located at the outer door can be set when 1)-all presets are set, 2)-the outer door and the inner gate are closed, and 3)-keybank is complete. The search can be performed only by authorized personnel who follow documented procedures and sign-off sheets to conduct the search.

Beams can be brought into the FFTB beam line only after the search is completed, the area has been set to No Access, and the audible and visual warnings are completed. There are 15 Emergency Beam Shut-off push button boxes located along the aisle way of the FFTB tunnel. When the FFTB is in No Access state, pushing any of these buttons will create a Security Fault and turns off the beam. 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, and 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.

BSOICS

Another layer of protection is provided through continuous monitoring of radiation levels outside the FFTB tunnel with seven Beam Shut-Off Ion Chambers (BSOIC) connected to the PPS. These ion chambers designed at SLAC (Neal 1968) are constructed from aluminum cans filled with a tissue equivalent gas (10 liters, 1 atmosphere). A ^{90}Sr source is incorporated in the chamber which produces a current for the system check-out. When the detected radiation level in a BSOIC exceeds the pre-set limit (usually 100 mR h^{-1}), the PPS shuts off the beam and inserts the PPS stoppers. Three other BSOICs, 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 BCS devices was evaluated

and the trip set points were determined. Extensive radiation surveys outside the FFTB tunnel in the RSY were also performed. The main purpose of these surveys was to ensure that there were no weaknesses in the shielding and 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 W to 224 W, depending on 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.

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

To check the performance of the 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.

The average current monitors I4 and I5 were set to trip at limits corresponding to average currents exceeding 20 nA. To check the bi-polar capability of these toroids, beams of electrons only, 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 the FFTB 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 a Andersson-Braun (AB) 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 AB detectors were calibrated using ^{238}PuBe and ^{252}Cf sources. The neutron spectrum outside the shield , for neutron energies below 10 MeV, was 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 have been normalized to the reading of the reference BF_3 counter for that target. The detected variations in the neutron flux in the reference counter were attributed to (un-desired) 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 BF_3 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 AB rem meter 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 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 dynamic range of the beam steering and controlling instruments, achieving such beam parameters with sufficient accuracy was not deemed feasible. The AB counts were converted to dose equivalent values using the Giant Resonance Neutrons (GRN) 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 GRN spectrum. The data measured by the Victoreen ion chamber are the exposure rates which were normalized to the reference BF_3 value and are listed as photon data. The corrected results for PC7 are reported in Fig. 5 and 6.

Uncertainties

The reported uncertainties are the results of combined random and systematic errors associated with the measurements, in which these uncertainties were added in quadrature. The statistical uncertainty for the AB measurements on PC7 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 BF_3 counter. The uncertainty of the conversion factor for the AB 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-SHIELD11

The SHIELD11 program (Nelson 1990) is a computer code for performing simple 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 1990), or expressions 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 (1976) and is given by the following equation:

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

The three terms in the above equation represent the production and attenuation of High-Energy neutrons (HEN), Mid-Energy Neutrons (MEN) and Giant Resonance Neutrons (GRN). H(neutrons) is the neutron dose equivalent in Sv per electron; E_o is the electron energy in GeV; l is the distance between the target and the shield surface, 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 cm. Z is the atomic number, and A is the atomic mass number for the target. Fluence-to-dose conversion factors of 6.7 $\times 10^{-10}$ Sv-cm^2 per neutron for HEN and 3.2×10^{-10} for GRN and MEN were used in deriving the above equation. In these calculations, the attenuation lengths in concrete (ρ=2.35 g cm^{-3}) for HEN, MEN, and GRN are λ_1=120 g cm^{-2}, λ_2=55 g cm^{-2}, and λ_3=30 g cm^{-2}, respectively. 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 and is different from that described in Jenkins (1976). 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 (Nelson et al. 1985) calculations 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.

$$
\begin{aligned}
H(photons) = {} & E_{\circ} \left(\cos\beta\, l^{-1}\right)^2 \times 10^{-13} \\
& \times \left[1.26 E_{\circ} 10^6 \exp(-t\rho\mu_1) \exp(-\theta^{0.6}) \right. \\
& \left. + H(\theta > 5) 755 \ \exp(-r\rho\mu_1) \exp(-1.4\ \theta)\right] \\
& \times \exp(-d\ \rho \cos\beta^{-1}\ \mu_2)
\end{aligned}
$$

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 for the target and the shield. The values of $\lambda_\gamma = \frac{1}{\mu}$ for concrete and copper are 42.0 and 33.0 g cm^{-2}, respectively; t is the target thickness and r is the target radius in cm. $H(\theta > 5) = 1$ for $\theta > 5$ degrees and $= 0$ for $\theta \leq 5$ degrees.

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 assumed to be proportional to the HEN term with a proportionality constant of 0.27 (Jenkins 1979).

Comparison with SHIELD11

In Fig. 5 and 6 measurements which 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 meters, respectively. The calculations are corrected for attenuation at back-angles in a large PC, 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 λ_γ=42 g cm^{-2} is used. An increase of 10% in this value will increase the calculated photon dose on the PC7 roof by 90%. A change in the concrete density would 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 extra thickness of one inch in the copper target (λ_γ=33 g cm^{-2}, ρ=8.96 g cm^{-3}) is assumed, the calculated dose rate will be reduced by half. Since the attenuation lengths for HEN and the MEN have much larger values (152 g cm^{-2} in copper), the attenuation effect for neutrons is less significant and a reduction for one inch of copper 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 there was no leakage through the shielding, and the choices of target and shield geometries and thicknesses which would be needed for bench marking shielding models were very limited. Therefore, the degree of contribution of the 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, BCS and PPS. The BCS ensures that the beam parameters do not exceed their preset values and the beam remains in its channel with minimal losses. The PPS controls access to the tunnel. The shielding in conjunction with BCS ensures that the shielding design criteria are met. Beam tests were performed and the response of BCS 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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Figure Captions

Fig. 1. Location of the FFTB beam line at the end of the LINAC.

Fig. 2. Lay-out of the FFTB beam shielded enclosure in the RSY.

Fig. 3. Lay-out of the FFTB Beam Containment System.

Fig. 4. Lay-out of The FFTB Personnel Protection System.

Fig. 5. Neutron dose equivalent rate versus distance on the roof shielding for collimator PC7.

Fig. 6. Photon dose equivalent rate versus distance on the roof shielding for collimator PC7.

Footnotes

[‡] Current address: ICF Kaiser Engineering, P. O. Box 888, Richland, WA 99352.

[*] Stanford Linear Accelerator Center, P.O.Box 4349, Stanford University, Stanford, CA 94309.

[‖] SLAC Radiation Rule Book, Stanford, CA: Stanford Linear Accelerator Center; internal document, 1988.

[¶] Nelson, W. R. Computer code SHIELD11 MORTRAN. Stanford, CA: Stanford Linear Accelerator Center; SLAC Radiation Physics Department; 1990.

[#] Nelson, W. R.; Namito, Y. Computer code MUON89 MORTRAN. Stanford, CA: Stanford Linear Accelerator Center; SLAC Radiation Physics Department; 1989.

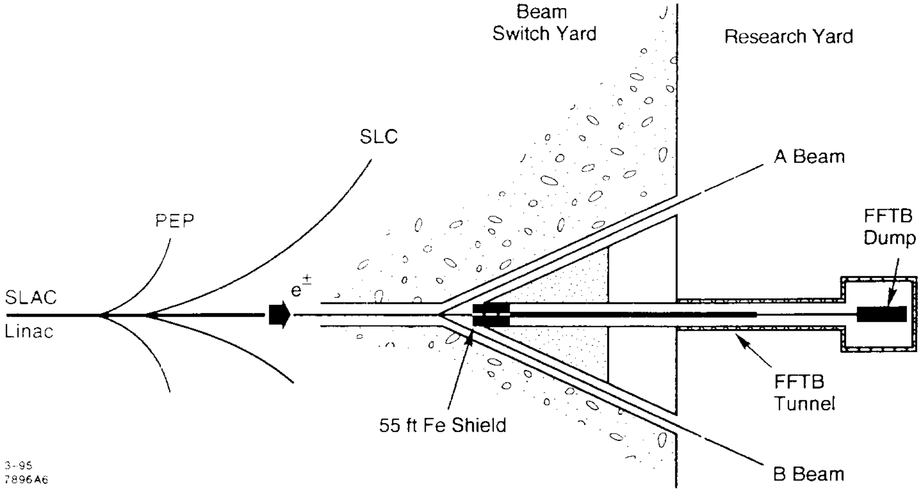
[†] Eberline, P.O. Box 2108, Santa Fe, NM 87501

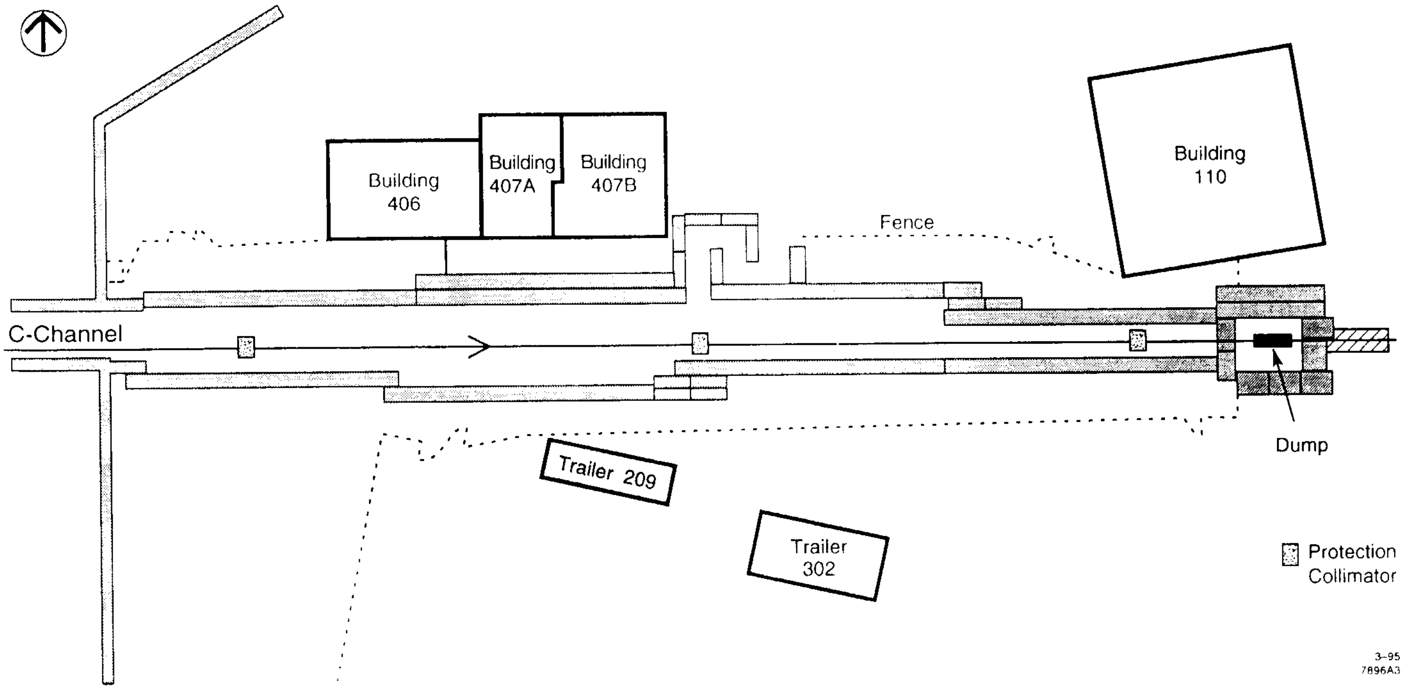
[§] VICTOREEN, INC. 6000 Cochran Road, Cleveland, OH 44139

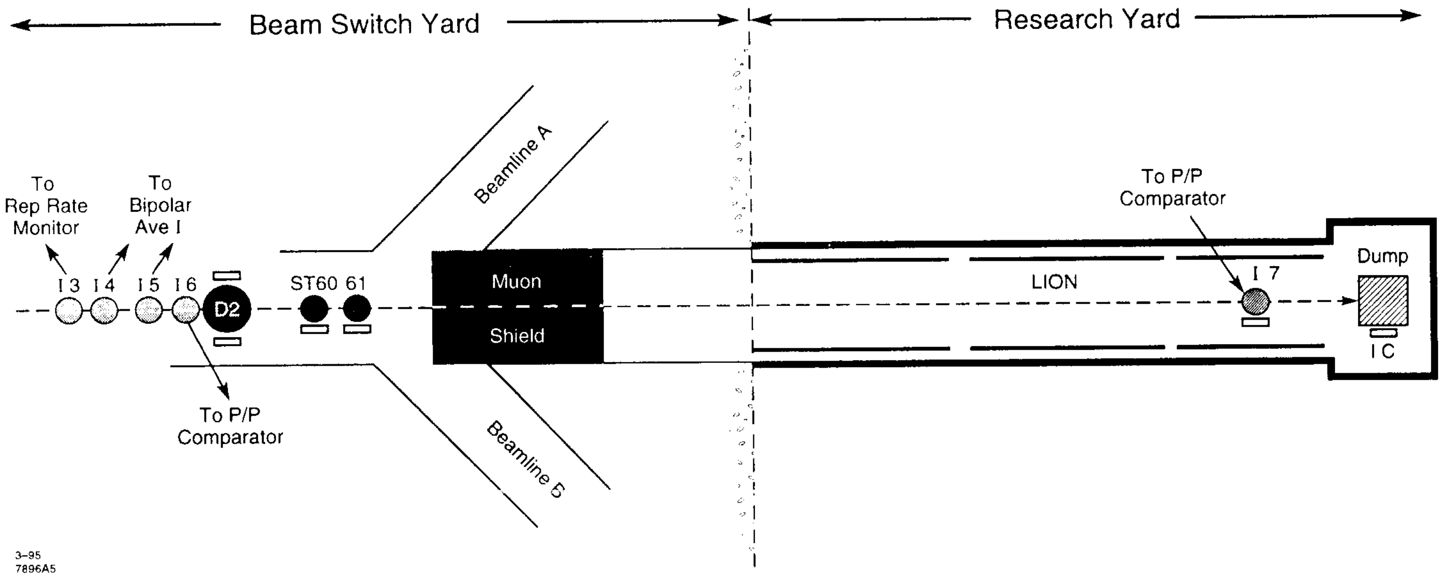
Table 1. Minimum shielding requirements for the FFTB tunnel

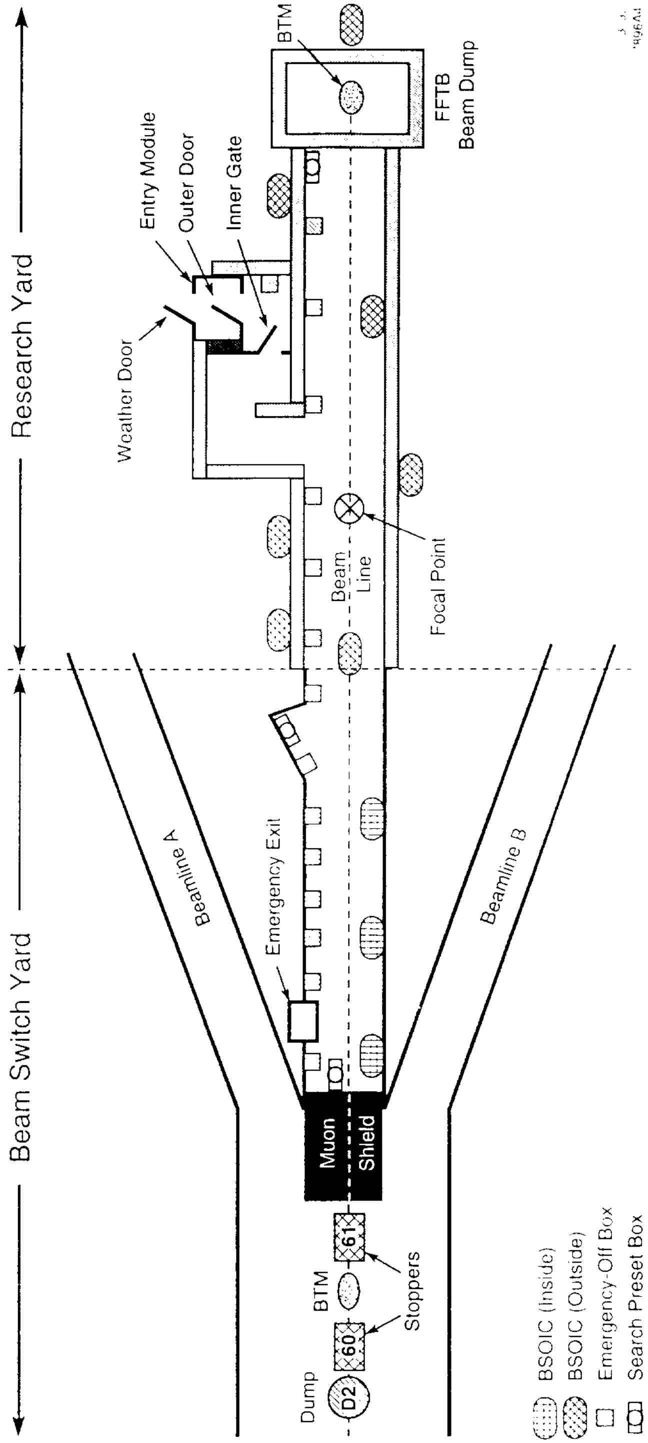
Shielding	Thickness (meters)	Location
	BSY	
Iron Plug	16.8	West end of FFTB tunnel separating the tunnel from the rest of the BSY.
Concrete	0.3-0.6	Roof blocks convering the entire length of FFTB tunnel.
	RSY	
Concrete	1.2	North wall of the FFTB tunnel
Concrete	1.2	South wall of the FFTB tunnel
Concrete	1.0	Roof of the FFTB tunnel.
	FFTB DUMP	
Iron (followed by) Concrete	1.4 1.2	East side
Iron (followed by) Concrete	0.9 1.2	West side
Iron (followed by) Concrete	0.8 1.8	North side
Iron (followed by) Concrete	0.8 1.8	South
Iron (followed by) Concrete	1.0 1.8	Roof

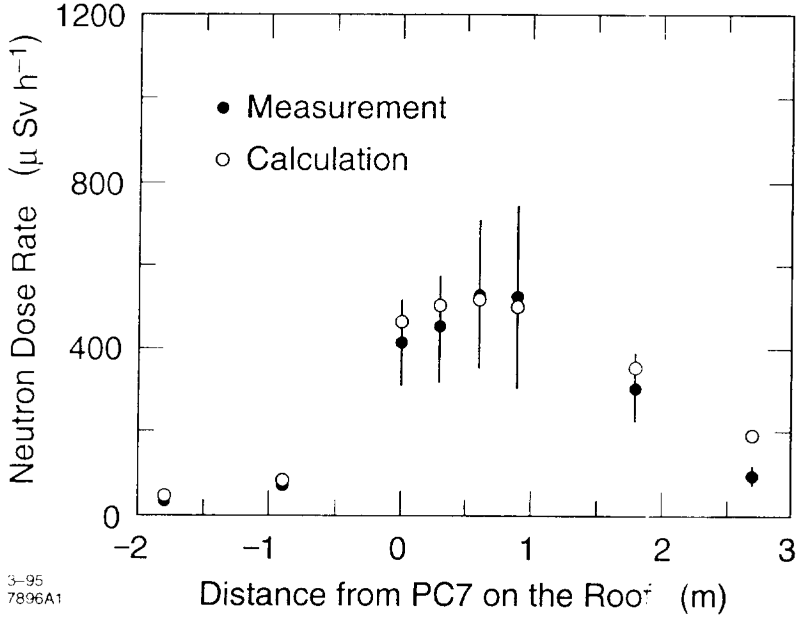
5-95

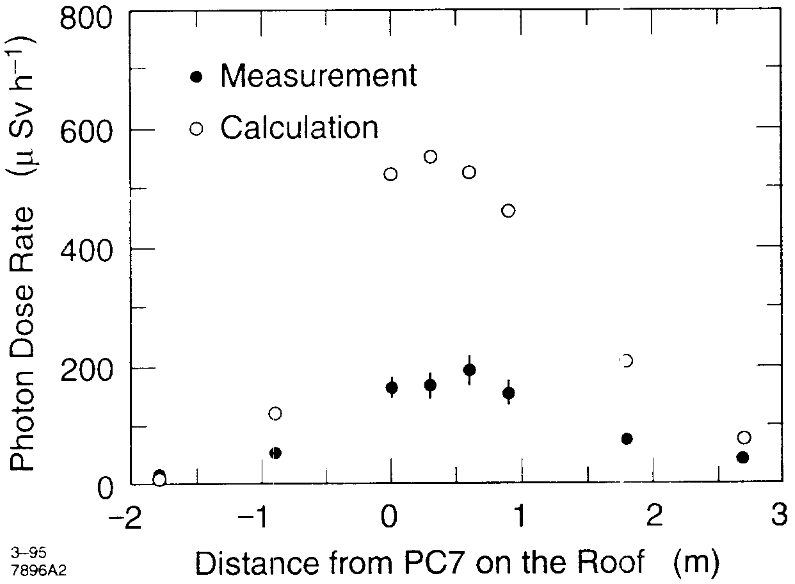



Building 406
Building 407A
Building 407B
Building 110
Fence
C-Channel
Dump
Trailer 209
Trailer 302
Protection Collimator
3-95
7896A3


Beam Switch Yard
Research Yard
To Rep Rate Monitor
To Bipolar Ave I
I 3
I 4
I 5
I 6
D2
ST60
61
Beamline A
Beamline 5
Muon
Shield
To P/P Comparator
LION
To P/P Comparator
I 7
Dump
I C
3-95
7896A5


Beam Switch Yard
Research Yard
Weather Door
Entry Module
Outer Door
Inner Gate
BTM
FFTB Beam Dump
Focal Point
Beam Line
Beamline A
Beamline B
Emergency Exit
Muon Shield
Dump
D2
60
BTM
61
Stoppers
BSOIC (Inside)
BSOIC (Outside)
Emergency-Off Box
Search Preset Box


Neutron Dose Rate (μ Sv h^{-1})
1200
800
400
0
● Measurement
○ Calculation
−2
−1
0
1
2
3
Distance from PC7 on the Roof (m)
3–95
7896A1


800
600
400
200
0
Photon Dose Rate (μ Sv h^{-1})
● Measurement
○ Calculation
−2
−1
0
1
2
3
Distance from PC7 on the Roof (m)

3–95
7896A2