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RADIATION CALCULATIONS AND SHIELDING CONSIDERATIONS FOR THE DESIGN OF THE NEXT LINEAR COLLIDER

W. R. Nelson, S. H. Rokni and V. Vylet*
Radiation Physics Department MS/48
Stanford Linear Accelerator Center
PO Box 4349 Stanford, CA 94309, USA

Introduction

For over 25 years, colliding-beam machines have been used as primary instruments for studying elementary particle physics at high energies. Very important discoveries have been made at both hadron-hadron and electron-positron facilities and our ability to utilize these two different, but complementary, instruments has become essential in allowing us to work towards a better understanding of a standard model of physics. With the design, and eventual construction and use, of the Large Hadron Collider (LHC) at CERN, particle physicists from around the world expect to gain substantial insight into this evolving science. Traditionally, however, lepton machines have provided a significant complementary view of this physics and a Next Linear Collider (NLC), designed from the start to be a truly global facility, would continue this approach into the TeV center-of-mass energy regime.

The initial studies for a next-generation e^+e^- collider began in the United States, Europe and Japan during the late 1980's, leading to a series of international workshops in the years that followed. Last summer, a report entitled *Physics and Technology of the Next Linear Collider* (NLC Design/Physics Working Groups 1996b) was submitted to the Snowmass '96 conference by the major high-energy physics laboratories in the U.S.. In this document, prospects for the next generation of high-energy physics experiments with electron-positron colliding beams were presented. Just prior to this, a two-volume report was jointly issued by SLAC and the Lawrence Berkeley Laboratory, called the *Zeroth-Order Design Report for the Next Linear Collider* (NLC Design Group 1996a), which outlined in considerable detail a machine design aimed at reaching a center-of-mass energy of 1 to 1.5-TeV with luminosities of 10^{34} $cm^{-2}s^{-1}$ or better.

In the presentation to be made today, we describe some of the work that we have done as a contribution to the NLC Zeroth-Order Design Report (ZDR), with specific emphasis placed on radiation-protection issues. However, because of the very nature of this machine---namely, *extremely-small* beam spots of *high intensity*---a new approach in accelerator radiation-protection philosophy appears to be warranted.

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Accordingly, our presentation will first take a look at recent design studies directed at *protecting the machine itself*, since this has resulted in a much better understanding, on our part, of the very short exposure times involved whenever beam is lost and radiation sources are created. At the end of the paper, we suggest a Beam Containment System (BCS) that would provide an independent, redundant guarantee that exposure times are, indeed, kept very short. This, in turn, has guided us in the determination of the transverse shield thickness for the machine.

Basic Concept of the Next Linear Collider

A significant part of the NLC design is a direct result of lessons learned, and techniques developed, during years of operation of the Stanford Linear Collider (SLC). The successful development and running of the Final Focus Test Beam (FFTB) has also provided invaluable experience at producing and delivering very small beams. Supplementing this is an on-going program to develop high-power (X-band) klystrons and associated accelerator structures, soon to be fully tested in a new SLAC facility called the Next Linear Collider Test Accelerator (NLCTA).

As described in the ZDR, the NLC "consists of a set of subsystems---injectors, linacs, beam delivery, and interaction regions---that are responsible for creating intense and highly condensed beams of positrons and polarized electrons, accelerating them to high energy, focusing them to small spots, and colliding them in an environment that allows sensitive particle detectors to operate for physics". The physical footprint of the collider is approximately 30 km in length and less than 1-km wide. A schematic of the NLC, taken from the ZDR, is shown in Figure 1.

The design energies, intensities, spot sizes, etc., vary with the chosen design scenario, and are well described in the ZDR itself. For the most part, however, the current design is based on nominal center-of-mass energies of 0.5 and 1.0-TeV, referred to as NLC-I and NLC-II, respectively. For purposes of discussion in this paper, Table 1 gives the beam specifications that we have used in our calculations.

Table 1
Beam specifications used in calculations.

Parameters	NLC-I	NLC-II
Nominal CMS Energy (TeV)	0.5	1.0
Repetition Rate (Hz)	180	180
Bunch Charge (10^{10})	0.65	1.25
Bunches/RF Pulse	90	90
Maximum Beam Energy (GeV)	250	500
Beam Power (MW)	4.2	11

The NLC-I specifications were used in calculations involving, for example, the lateral shielding along the linac. On the other hand, for studies involving protection of the linac due to errant beams, we used the NLC-II parameters, together with a beam spot that was assumed to be round and having $\sigma_x = \sigma_y = 3.16$ μm (the NLC beam spot is actually designed to be an ellipse with $\sigma_x = 1$μm and $\sigma_y = 10$ μm, but assuming a round beam with the same area, greatly simplified our calculation tasks without loss in generality).

Machine Protection System (MPS)
A very serious operational issue facing any future linear collider is that of the Machine Protection System. In order to produce the luminosities required for useful physics research, the beam powers must be very high and the beam spots must be extremely small. For example, in the NLC-II design given in Table 1, the beam power is 11 MW and a single errant bunch train of 10^{12} electrons will substantially damage unprotected accelerator structures, particularly since the beam spot size near the end of the 500 GeV linac is intentionally designed to be very small ($\sigma_x = \sigma_y = 10$μm). The case of an aberrant single-beam pulse---e.g., 90 bunches, each with 1.25 x 10^{10} electrons---has been given the name 'single pulse induced failure' (SPIF). The most serious challenge in the NLC is the prevention of SPIF and the MPS strategy to accomplish this is explained as follows:

1. Provide pulses that cannot cause SPIF for tuning and diagnostics.
2. Insure that the difference between the upcoming pulse and the one that preceded it is within some limit, known as the 'maximum allowable interpulse difference' (MAID), during normal (full bunch) operation.

The case of 'average power' induced failure---i.e., full-bunch mode at full repetition rate---is component failure that occurs after a succession of pulses deposit excessive energy on a given component. This type of failure is quite familiar to what we have experienced for many years at SLAC, particularly during operation of the SLC and the FFTB, and can be controlled in a relatively straight-forward manner. Namely, using ion chambers, thermocouples, etc., to monitor (and shutoff) the beam. Towards the end of this paper we will suggest a Beam Containment System (BCS), for radiation-safety purposes, that also can be used for machine protection.

Because of the extreme energy density of the full-intensity, multi-bunch NLC beam, it is not practical to build mechanical systems that can withstand the nominal beam, except in isolated cases such as collimation regions. The strategy therefore reduces to controlling the MAID and protecting against SPIF, and the latter is possible with a mechanical system composed of relatively thin scattering foils, which we call 'spoilers'. The temperature rise for a single bunch of *N* electrons striking a thin spoiler can be calculated from a simple analytic model:

$$\Delta T = \frac{0.393N}{\pi\sigma_x\sigma_y}\frac{dE/dx_{\min}}{C_p},$$

where dE/dx_{min} is the electron stopping power and C_p is the specific heat of the material, and the 0.393 factor is the fraction of electrons within a Gaussian beam spot area of $\pi\sigma_x\sigma_y$ (cm^{-2}). This model ignores the effect of the shower buildup, the variation of specific heat with temperature and does not make use of *restricted* stopping power evaluated at the beam energy. Nevertheless, it gives reasonably useful results which we present in Table 2.

Also shown in this table is the *stress limit*, which is based on the tensile strength, the modulus of elasticity, and the coefficient of thermal expansion of the material. When a beam strikes the material, there is a sudden local temperature rise that may create local thermal stresses. If the temperature rise exceeds the stress limit, micro-fractures can develop in the material. In addition, it has been observed in experiments that if the local temperature rise exceeds four times the stress limit, the shock wave due to the thermal rise will cause the material to fail completely or "delaminate" (Walz et al. 1973; Walz 1996). Thus, the allowed temperature rise is limited either by the melting point of the material or four times the stress limit at which the material will fail catastrophically.

Table 2

Spoiler material properties and temperature rise due to a single bunch of 1.25 x 10^{10} electrons within a beam spot with $\sigma_x = \sigma_y$=3.16 μm.

	Be	C	Al	Ti	Cu	Fe
Radiation Length (cm)	35.7	21.7	9.0	3.7	1.4	1.8
dE/dx_{min} (MeV cm^{-1})	3.1	3.6	4.4	7.2	12.8	11.6
Specific Heat, C_p (J cm^{-3} $^oC^{-1}$)	3.3	1.9	2.5	2.4	3.5	3.8
Meltng Point, T_{melt} (^{o}C)	1280	3600	660	1800	1080	1530
Stress Limit, T_{stress} (^{o}C)	150	2500	140	770	180	135
Temperature Rise, ΔT (^{o}C)	2350	4740	4403	7506	9150	7637
$\Delta T / T_{melt}$	1.8	1.3	6.7	4.2	8.5	5.0
$\Delta T / 4T_{stress}$	3.9	0.36	7.9	2.4	12.7	14.1

For practical reasons Ti turns out to be the most practical choice for a spoiler. Unfortunately, the surface temperature rise due this beam is over four times the melting temperature, and over twice the temperature for delamination, so that to prevent damage to the spoilers themselves, the emittance (beam spot size) of the diagnostic beam would have to be increased significantly. However, this appears to be feasible and the task then becomes one of choosing the thickness of the spoilers and determining their locations such that an errant beam strikes them first, forcing the electrons to be substantially spread out before they strike the accelerator itself.

A series of Monte Carlo calculations using the EGS4 code (Nelson 1985) have been performed in order to study the temperature rise in a system of Ti spoilers, as well as in the Cu accelerator structure downstream. In Figure 2, the maximum temperature rise is plotted for various beam sizes in each of eight linac spoilers, 0.2-radiation lengths thick and separated from one another by 1.8-m. The dotted and solid lines show the temperature in the front and back halves of the spoilers and the dashed horizontal line shows the melting temperature of Ti. The results are consistent with the simple model presented above. Also note that the temperature rise in the back half is roughly twice that in the front half due to the buildup of the electromagnetic shower. Clearly, all spoilers downstream of the first will survive a single-bunch pulse of any incoming beam size. However, the first spoiler will be damaged unless the incident beam has a size greater than $\sigma_x = \sigma_y = 10\mu m$.

The issue of trajectory scenario versus spoiler size and location is not suitable for discussion in the paper. Instead, we simply demonstrate the usefulness of the EGS-calculation approach with Figure 3, which shows the temperature rise in the Cu irises of the accelerator structure at the end of the linac due to an errant, single-bunch, pulse that has passed through eight 0.2-radiation length Ti spoilers separated by 1.8-m. The maximum temperature is observed to be much less than the T_{melt} =1080 ^{o}C, as well as the delamination temperature, $4T_{stresst}$ =720 ^{o}C, for Cu.

Shielding the NLC Linacs

The most difficult part of shielding any high-energy accelerator generally involves agreeing upon a reasonable beam-loss scenario for the normal operation of the machine. A good example is the SLAC Two-Mile Accelerator itself, where 3% of 2.4-MW was assumed to be lost uniformly (and continuously) over the 10,000-ft distance of the machine (DeStaebler 1962). This turns out to be 24 W m^{-1}.

Twenty-five years of experience has clearly demonstrated that this beam-loss scenario was far too conservative. In fact, the small radiation levels that exist inside the Klystron Gallery come primarily from the klystrons themselves (or their SLED cavities), or from radiation streaming up penetrations in the shield due to discrete losses at points along the machine (e.g., beam dumps). But, local losses generally can be shielded locally......provided we know beforehand where they will occur.

For the remainder of this paper we would like to approach the design of the transverse shield of the NLC in a different way than was done for the Two-Mile Accelerator. The following should be considered:

1. The NLC design that we will assume has two tunnels, side-by-side, located at some distance underground, with no penetrations reaching to the surface.
2. A fraction of the beam (0.25% of 4.2 MW) will be lost uniformly (and continuously) along the linac, which turns out to be 1 W m^{-1} for NLC-I. This number is much smaller than what was used in the design of the Two-Mile Accelerator, but the NLC is not a very tolerant machine when it comes to beam loss. Furthermore, we will be able to verify this number when the accelerator prototype begins to operate at the NLCTA facility next year.
3. We will use a beam energy of 250 GeV without loss of generality, since the high-energy neutron component will dominate and the radiation levels will simply scale with power.
4. For normal operation of the machine, we will use shield design tolerances established by the DOE: 10 mSv y^{-1} (1 rem y^{-1}) for radiation workers and 1 mSv y^{-1} (100 mrem y^{-1}) for the general public.

5. We assume that the machine operates 100% during the year, but that the radiation workers are in the vicinity of the shield no more than 2000 hours each year (50 weeks at 40 hours per week).
6. For the 'failure mode' we will assume that the beam is completely lost at a point. DOE order has established an exposure limit of 250 mSv (25rem) in one hour. SLAC, on the other hand, has established its own limit of 30 mSv (3 rem) integrated over the duration of the incident.

With these considerations in mind, we have used a modified version of the computer code, SHIELD11, allowing for integration along a uniformly distributed line source. SHIELD11 is a simple code developed at SLAC for performing shielding analysis around high-energy electron accelerators. It makes use of simple analytic expressions for the production of photons and neutrons by electron beams striking thick targets (e.g., beam dumps, stoppers, etc.), and for the attenuation of these photons and neutrons (DeStaebler et al. 1968; Swanson 1979; Swanson and Thomas 1990). The code uses experimental data (Jenkins 1979) and involves extrapolation (scaling) of this data based on simple physics concepts (Fasso et al. 1990). SHIELD11 has been extensively verified in many applications at SLAC during the last 25-30 years.

In Figure 4, the dose rate from a uniformly distributed line source (1W m^{-1}), produced by 250 GeV electrons, is plotted as a function of the thickness of the earth shield. The line source is located 9-ft from a 2-ft concrete ceiling upon which the earth resides. One observes that it takes less than 5-ft of earth to shield to the DOE design tolerance of 10 mSv y^{-1} (1 rem y^{-1}) for radiation workers. It would take more earth (11-ft) to shield for the general population number, 1 mSv y^{-1} (100 mrem y^{-1}), but the area immediately above the shield could be designated a controlled area in order to limit public access.

In Figure 5, we show the dose rate for the 'failure case', whereby the entire 4.2 MW beam is deposited at a point. The dose rate is plotted as a function of distance from the source for various thickness' of earth shield. If 5-ft were chosen, based on normal-operation levels suggested by Figure 4, the failure-mode dose rate would be quite high: 3 Sv h^{-1} (300 rem h^{-1}). However, the duration of this event could be limited to less than 0.1 second, as we shall see in the next section (Beam Containment System), and the integrated dose would only be 80 μSv (8 mrem).

Several points should be clearly understood:

1. A Machine Protection System is mandatory for the NLC. It would be designed to prevent the 'failure case' from happening in the first place by shutting the beam off on a pulse-to-pulse basis.
2. A Beam Containment System would be designed to provide an <u>independent</u> means of limiting exposure time.
3. We have demonstrated by calculation, and this has been experienced many times at SLAC, that accelerator structures simply cannot tolerate having small, intense, electron

beams depositing their energy within them---the structures break, rendering the machine incapable of acceleration.

4. Structures that are specifically designed to accept beam, such as dumps and collimators, would be shielded locally.

It should also be observed in Figure 5 that the dose rate for the 'failure case' drops off reasonably fast with distance from the source: a factor of 10 every 2-ft. Although the results have been plotted in terms of distance along the linac, a similar trend applies to moving lateral to the beam line. This means that exposure of the general population could be effectively limited if access directly above the linac were controlled.

Beam Containment System (BCS)

The goal of the Beam Containment System for the NLC linac will be to limit the beam losses to prevent excessive radiation in shielded occupied areas. This goal is achieved by implementing a three-layer system of independent electronic and mechanical devices utilizing different technologies. For this preliminary design we have assumed that at least 2-ft of concrete plus 5-ft of earth shield separates the linac from the outside world (see Figs. 4 and 5). The maximum power in the beam is assumed to be 4.2 MW.

The primary BCS device for achieving this goal will be Long Ion Chambers (LIONs) which limit the amount of the beam loss at any point along the accelerator. These ion chambers, helical cables pressurized with argon, have been designed and constructed at SLAC to sense the beam losses along the FFTB beam line. LIONs will be installed along the entire length of the linac and serve as a distributed ion-chamber system, replacing many discrete ion chambers that otherwise would be placed on the beam line to sense beam losses at various points. Signals from LIONs will be set to generate a fault interlock when the dose rate outside the shield exceeds 30μSv h^{-1} (3 mrem h^{-1}) corresponding to 42 W of beam loss at a point along the linac. The response time for LIONs will be set to 0.1 s, limiting the integrated dose level to about 80μSv (8 mrem) for an incident involving full beam power loss.

A system of Difference Comparators (DCs) will provide the second layer of BCS protection. The difference in integrated signals from a toroid at the beginning of each 4-km section of the linac and a toroid at the end will be compared against a preset dc level. A fault interlock will be generated if the signal from the end toroid is less than 99.9% of the signal from the beginning toroid. This corresponds to a maximum beam loss of 4.2 kW at any point between the two toroids resulting in a dose rate less than 3 mSv h^{-1} (300 mrem h^{-1}) outside the shield. The response time for difference comparators will also be set for 0.1 s.

Installation of large Protection Collimators (PCs) at strategic locations in the beam line, as determined in ray-trace studies, will prevent primary beam from directly striking the ceiling, thereby providing a third BCS protection layer for those cases where large mis-steerings cannot be ruled out. These collimators, each made of 5 r.l. of stainless steel, will intercept and spoil all mis-steered beams. Burn-Through Monitors (BTMs), which are stainless-steel pressurized vessels, will be placed at the location of the shower maximum within PC. In the event that an errant, high-power, beam burns through a PC, it will rupture the associated BTM. Loss of the gas charge to below a preset level, detected with a pressure switch, will then shut off the beam. Each PC will have a power absorption capability of approximately 5 kW, the corresponding point loss resulting in a dose rate of 3.6 mSv h^{-1} (360 mrem h^{-1}) outside the shield.

The burn-through time of this PC/BTM system depends on the average power of the errant beam. At 4.2 MW, the system is expected to respond within 5 s, resulting in an integrated dose level of 4.2 mSv (420 mrem). At 5 kW, the system is expected to take a little longer (10 s), resulting in an integrated dose of less than 10 μSv (1 mrem).

When a fault interlock in one of these BCS devices is generated, the radiation hazard can be mitigated in several independent ways. Based on many years of experience with these devices at SLAC, a graded approach is recommended: beam current can be turned off, trigger permissives can be removed, safety stoppers down-beam of the gun can be inserted into the beam line, Variable-Voltage Substations (VVSs) can be shutoff, etc. (or any combination depending on which of the three BCS layers is activated). The BCS electronic devices will also need to have self-checking features (e.g., house-keeping currents).

Concluding Remarks

Radiation protection for the Next Linear Collider is expected to be very challenging, particularly because of its size (30 km) and because of the intrinsic nature of the beams---*small* and *intense*. In this paper we have presented arguments for a new approach to radiation-safety design, as it pertains to beam containment, and we have suggested how it can be accomplished.

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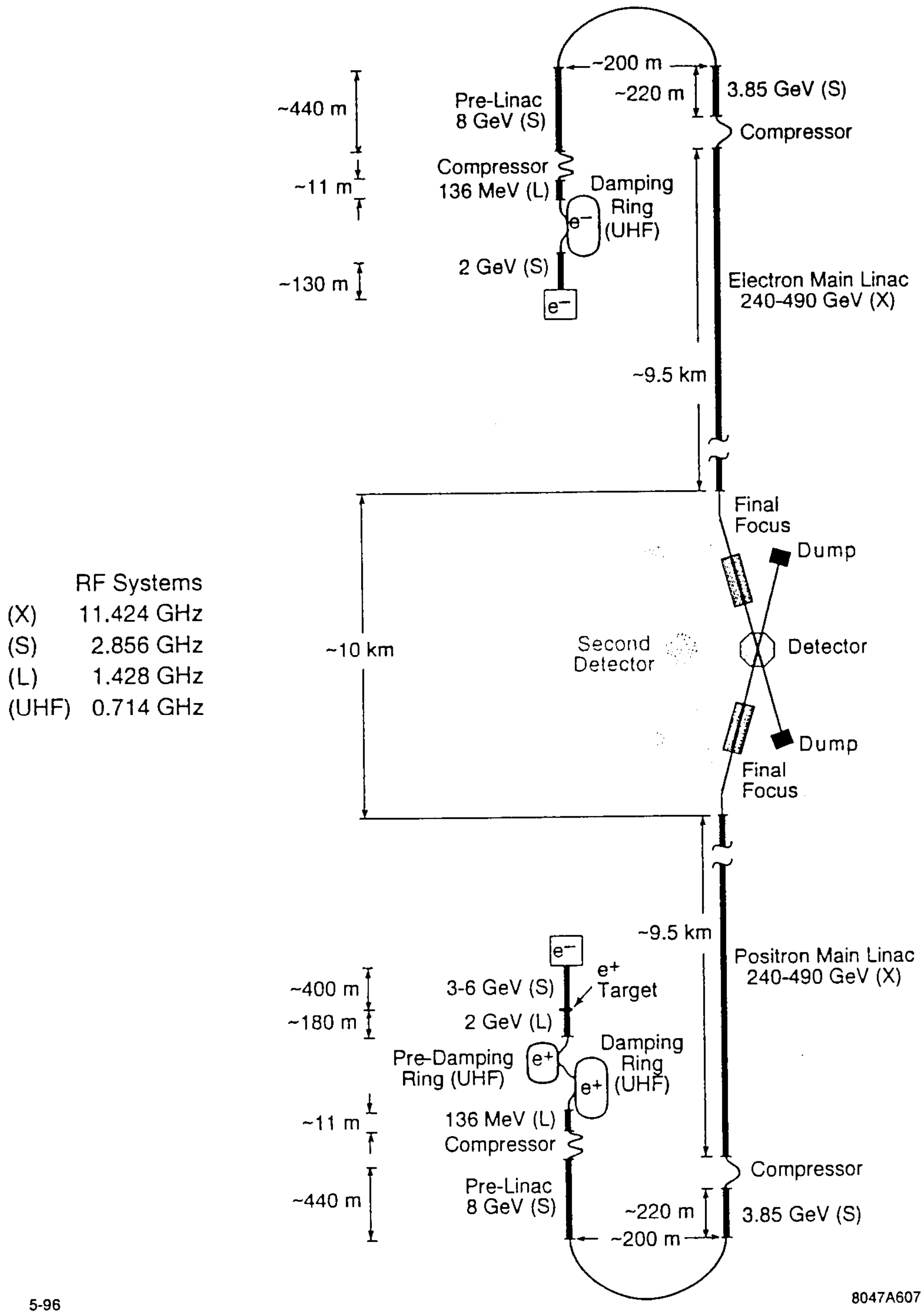


Fig. 1 Schematic of NLC

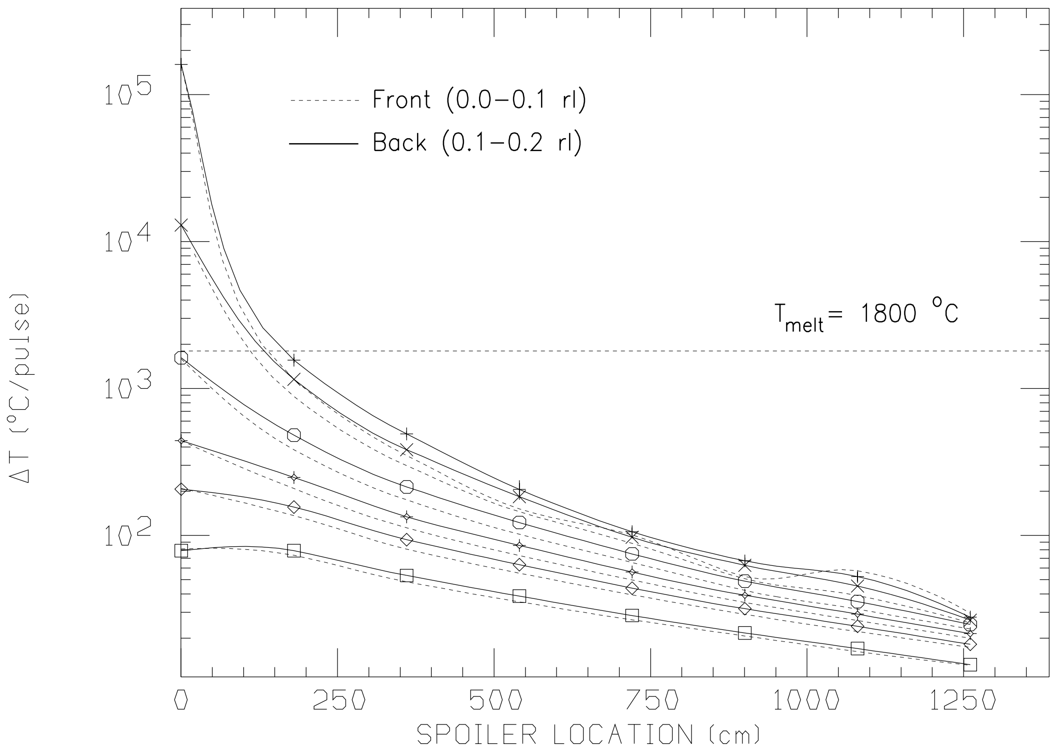


Fig. 2 EGS4 simulations of temperature rise in 0.2 rl long Ti spoilers with a single bunch of 1.25 x 10^{10} electrons at 500 GeV; the dotted and solid lines show the temperature rise in the front and back halves of the spoilers for six different incoming beam sizes (0,3.1,10,20,30,50 μm).

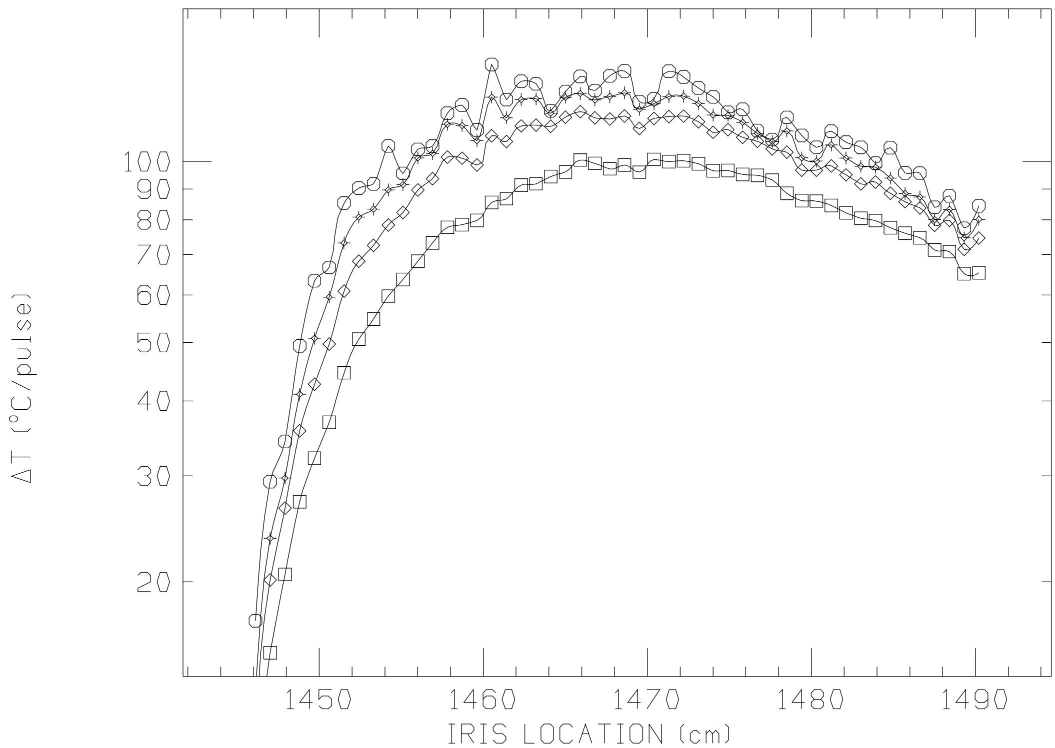
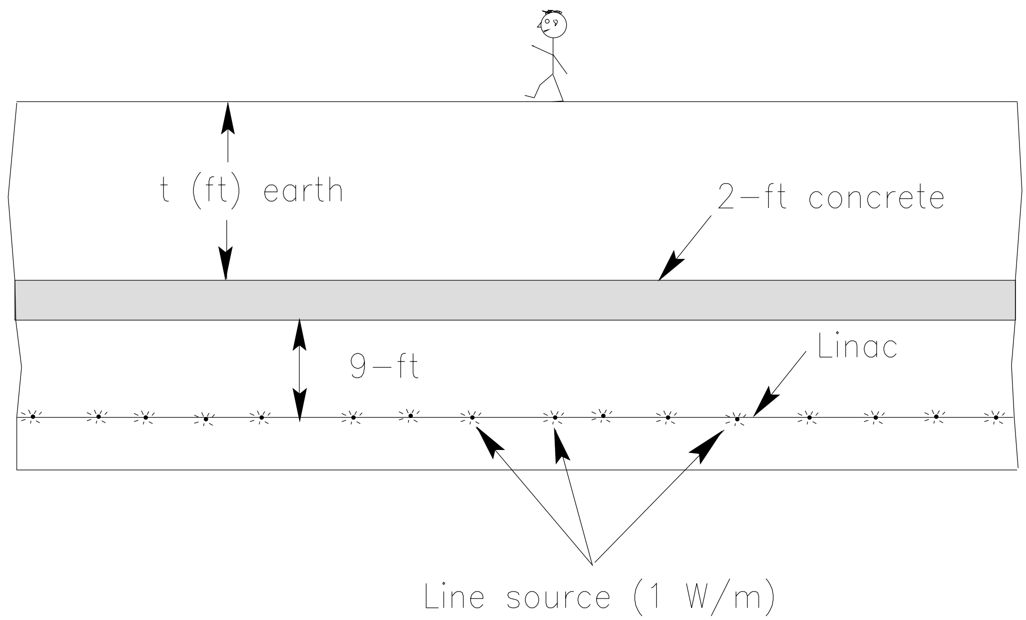


Fig.3 EGS4 simulations of temperature rise in the accelerator irises (Cu) at the end of the 500 GeV linac due to a single bunch of 1.25 x 10^{10} electrons that has passed through eight (0.2–rl) Ti spoilers separated by 1.8–m; the four curves correspond to initial beam sizes of 10,20,30 and 50μm.



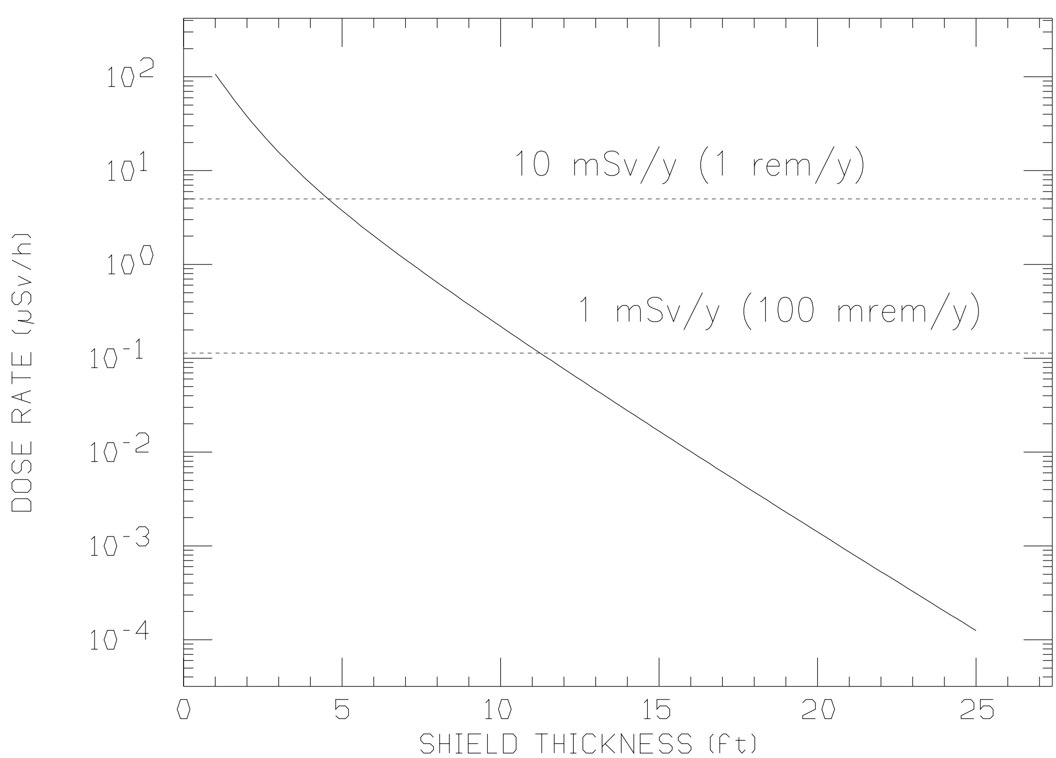


Fig.4 Radiation level vs. earth shield thickness for a 250 GeV electron beam distributed uniformly along a 10 km linac at the rate of 1 W/m.

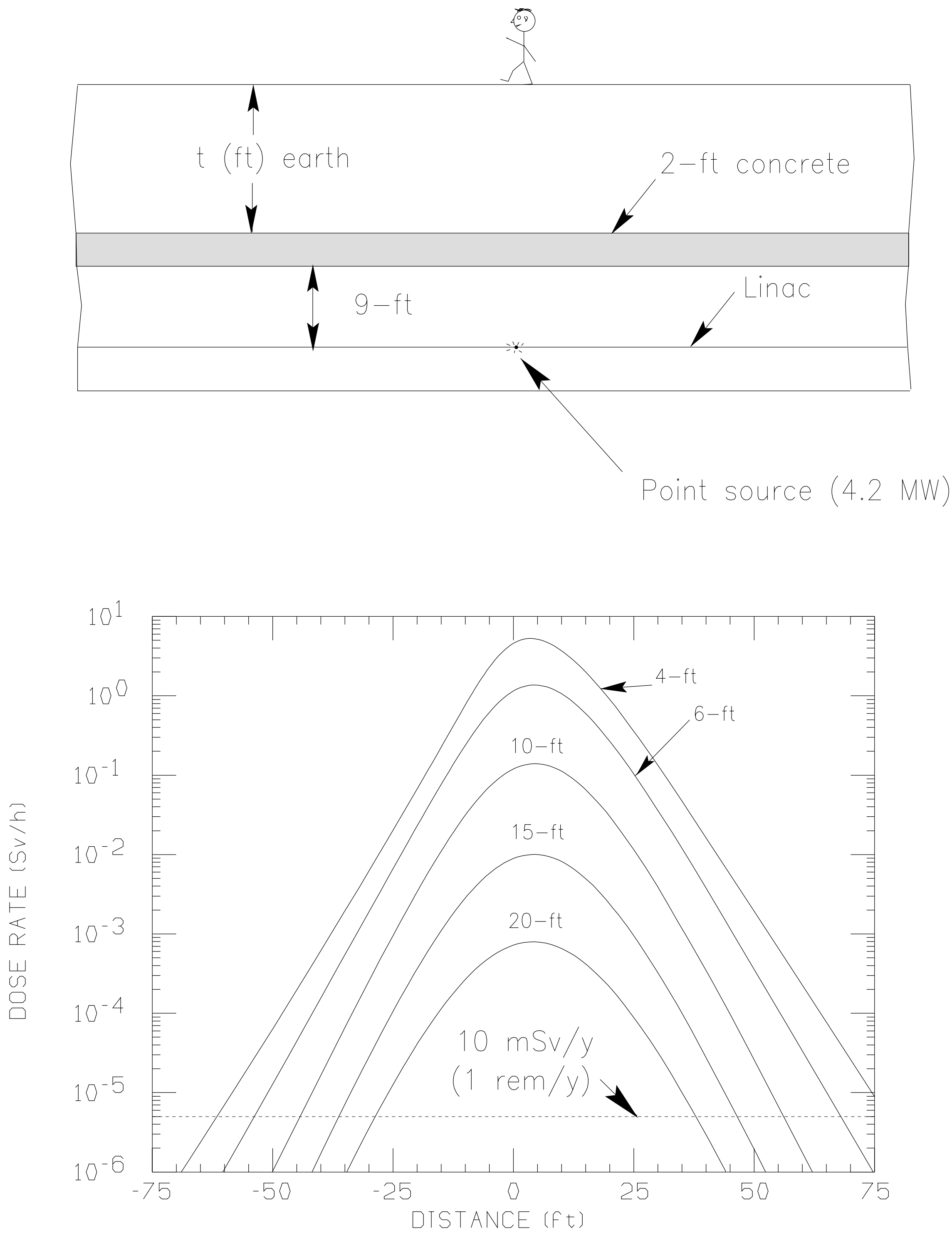


Fig.5 Radiation level vs. distance along linac from a 250 GeV electron beam lost at a point (4.2 MW).