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Machine Protection Issues in the Beam Delivery System

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Abstract: This note reports on an EGS study of the collimation and protection devices contained within the TRC version of the NLC lattice. For each fault scenario, the likelihood for damage to collimators, spoilers, absorbers or magnet apertures is arrived at by finding the maximum energy density the device must support when a full NLC bunch train is lost on it or nearby it. We find that certain devices will not survive as currently specified. Modest design changes are recommended that should permit the system to operate up at 500 GeV center of mass energy; for 1 TeV operation, certain devices are still at risk.

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Abstract

This note reports on an EGS study of the collimation and protection devices contained within the TRC version of the NLC lattice. For each fault scenario, the likelihood for damage to collimators, spoilers, absorbers or magnet apertures is arrived at by finding the maximum energy density the device must support when a full NLC bunch train is lost on it or nearby it. We find that certain devices will not survive as currently specified. Modest design changes are recommended that should permit the system to operate up at 500 GeV center of mass energy; for 1 TeV operation, certain devices are still at risk.

Introduction

The beam delivery system (BDS) consists of a linac-to-collimation matching section, a halo collimation section with five spoilers (SP1-5) and five absorbers (AB1-5), an energy collimation section with an energy spoiler (SPE), and a final focus (FF) section. Detailed studies have verified that the basic performance of the collimation system, showing that it will remove the beam tails and limit backgrounds in the detector [7]. The collimation system apertures have been specified to be $\Delta E/E < +/-1.5$ %, $\Delta x_{FD}/\sigma_x < 10$, $\Delta y_{FD}/\sigma_y < 31$ where the subscript FD denotes the final doublet phase. In addition, the energy aperture of the post-linac dump line and the beam line to the energy collimator has been specified to be $\Delta E/E < +/-20\%$. This large aperture has been specified to allow for large injection or rf phase errors that could cause large energy errors.

It has long been realized that a single missteered bunch train will damage all but low-Z, thin targets [1]. Even a single bunch of nominal emittance and intensity will damage a thick target. This study attempts to answer the following questions:

1. What magnet apertures are needed to safely handle a ±20% off energy bunch train?
2. Will a bunch train hitting the 0.6 radiation length (rl) halo collimation spoilers cause downstream absorbers and protection collimators to be damaged?
3. Will an off-energy bunch train hitting the 1.0 rl energy collimation spoiler damage the spoiler or downstream protection collimators?
4. What is the effect on the superconducting final doublet and inner detector components when a missteered bunch train hits the upbeam protection collimator?

Simulation Method

A version of the electromagnetic shower program EGS4 [2], called OBJEGS, was used to calculate the energy deposited (E_{dep}) in various beam line elements. A typical OBJEGS model used in this study is shown in Figure 1.

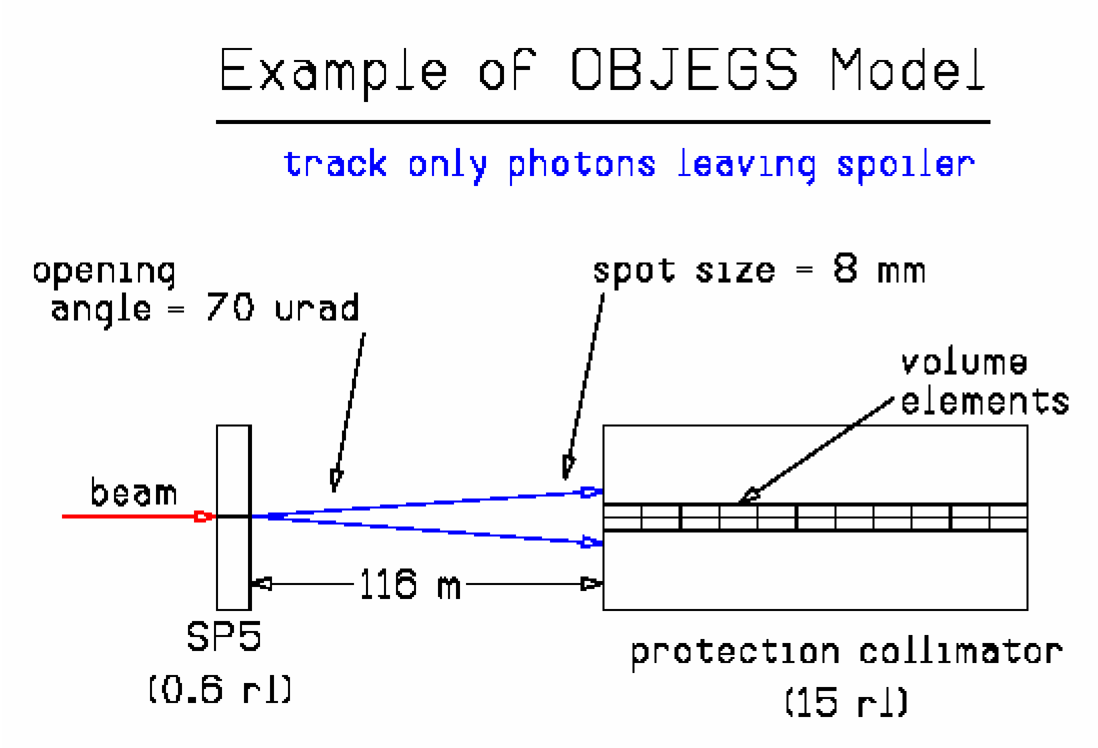

Figure 1. Example of an OBJEGS geometry model used to calculate the maximum temperature rise in a thick material from photons generated in a distant spoiler. It is important that the volume elements be smaller than the electromagnetic shower radius at the depth being sampled.

In order to find the maximum temperature rise, the volume elements in the model must be smaller than the electromagnetic shower radius at the depth being sampled. To get an accurate estimate of E_{dep} vs. depth in the material, the $e^{\pm}$ kinetic energy cutoff was set to 5 MeV (0.3 cm range in copper), and the photon energy cutoff was set to 0.1 MeV (0.2 cm attenuation length in copper). The temperature rise in a bunch train is calculated by,

$$\Delta T = \frac{E_{dep}}{c_p} \times 1.4 \times 10^{12}\, e^{\pm} / train$$

where,

E_{dep} = energy deposited per incident beam particle in joules/gram

c_p = specific heat in joules/gram/^{o}C

Figure 2 shows an OBJEGS schematic of the collimation system. The system consists of a halo (betatron) section, approximately 300 m long, consisting of a series of quadrupoles, spoilers, and absorbers; followed by an energy section, which is a long string of tightly packed dipoles and quadrupoles, with a single energy spoiler at the high dispersion point.

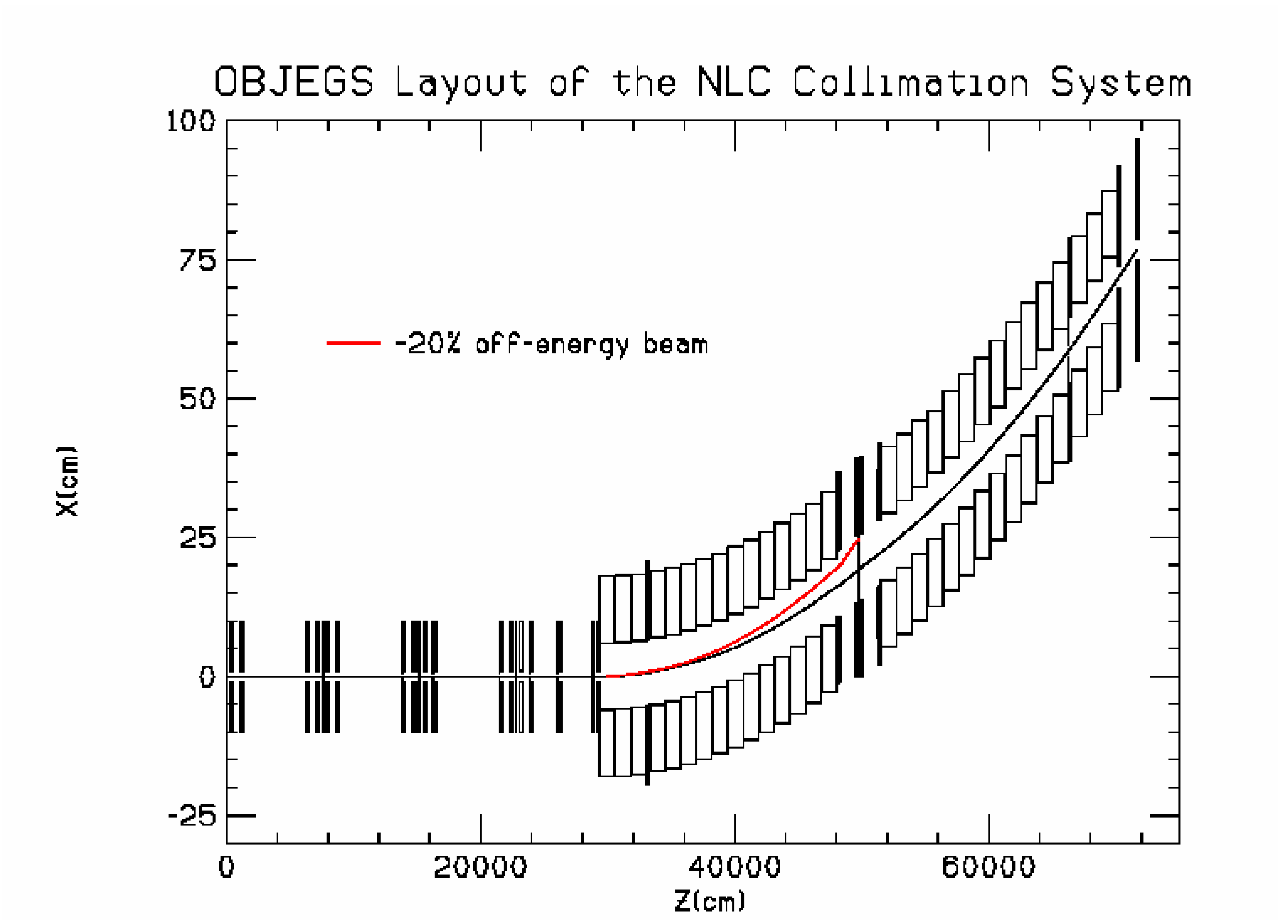

Figure 2. OBJEGS geometry model of the BDS collimation system. The red line shows the path of a -20% off-energy bunch train up to the spoiler at the high dispersion point of the energy collimation section.

Examples of Errant Beams in the BDS Collimation System

In the BDS we define two (half) aperture classes:

Small ≡ halo collimation spoilers, 200-300 μm

and

Large ≡ quadrupoles, dipoles, absorbers, protection collimators, 5,000-10,000 μm

We also define two errant beam classes according to expected frequency of occurrence, "Often" and "Rare".

The only anticipated "Often" errant beam class results in off-energy beams that strike the 1.0 rl energy spoiler, SPE. Causes include klystron misfires, rf phase errors and injection errors. The beam delivery system has been designed to let trains within ±1.5% of nominal energy pass through the IP and to the beam dump. Note that each modulator-klystron "two-pack" rf unit powers eight 60 cm structures at 45.1 MeV/m loaded-gradient, so that 1.5% energy bandpass at 250 GeV corresponds to 17 rf units simultaneously failing on the same pulse, certainly a rare event, leaving rf phase errors and injection errors as the main reasons the SPE might be struck. The energy collimation spoiler is designed to protect against beams between 80% and 98.5% of nominal. Not only must SPE survive a train hit, but downstream magnets must be protected from the dense photon shower emanating from SPE as well. Note that charged e^+, e^- secondaries are dispersed by the downstream magnets and do no damage.

"Rare" errant beam events result in orbit errors that cause a bunch train to hit one of the halo collimation spoilers (SP1-SP5) or one of the large aperture devices. Causes of "Rare" errant beam events include rapid unforeseen changes of a magnet mover position, a power supply value, or the sudden shorting of a coil in a quadrupole or dipole magnet. Both the mover and power supply control systems have been designed to disallow rapid changes in values. Tests of sample Cu "coupons" in an intense FFTB beam have shown that the thin 0.6 rl (8.6 mm) Cu spoiler material will melt; and as will be seen below in Table 2, a bunch train impacting SP1-5 will exceed the melting point of the material by a large factor. The halo collimation spoilers have been designed as rotating cylinders; after a catastrophic beam loss, they can be rotated by 1 mm to present a fresh surface to the beam. The cylinder diameter is set to allow approximately 1000 errant beam events before the spoiler must be replaced.

A typical missteering angle (dipole error) needed to hit a halo spoiler is ~5 μrad ⇒ 0.05 kG·m @ 250 GeV/c. A typical missteering angle needed to hit a large aperture is ~100 μrad ⇒ 1 kG·m @ 250 GeV/c. The betatron collimation quadrupoles have gradient G ≈ 2 kG/cm and length L = 2 m, and the quadrupole movers have a maximum travel of about ±1 mm; so the maximum dipole error caused by a magnet mover is about, GL = 0.8 kG·m. In addition, a shorted quadrupole coil would result in a dipole field on-axis of about $B_p/5$, which also gives GL = 0.8 kG·m. In the energy collimation section each of the 30 dipoles has GL ≈ 1 kG·m @ 250 GeV/c, so a single shorted dipole looks like a 100 μrad kick. These dipole errors are large compared to that needed to hit spoilers, and on the order of that needed to hit large apertures.

In Figure 2 the red line traces the path of a 20% off-energy beam to the energy spoiler. It is seen that transmitting a 20% off-energy beam requires that the half-aperture of the dipoles and quadrupoles in the energy section must be at least 6 cm. This is not specified in the current optics. Moreover, maintaining this 20% constraint at 1.3 TeV center of mass would imply rather large quadrupole pole tip fields of 15.6kG. The lattice may need to be changed to allow longer quadrupoles with more reasonable pole tip fields if the 20% off-energy criterion is to be respected.

Figure 3 shows two examples of errant beams hitting spoilers, and the resultant photon spray, in the halo collimation section. On the left is a bunch train with a relatively large angular kick which hits the second spoiler such that the resulting photon spray hits the nearest absorber. The numerical results of the OBJEGS runs for this case are listed in Table 2, Case#5. On the right is a bunch train with a relatively small angular kick which hits the fifth spoiler with the photon spray hitting a dipole aperture in the energy collimation section. The OBJEGS results for this case are listed in Table 2, Case#4. Despite the fact that only a small angular kick is required to produce the photon spray, the collimation system design assumes that this example would occur rarely.

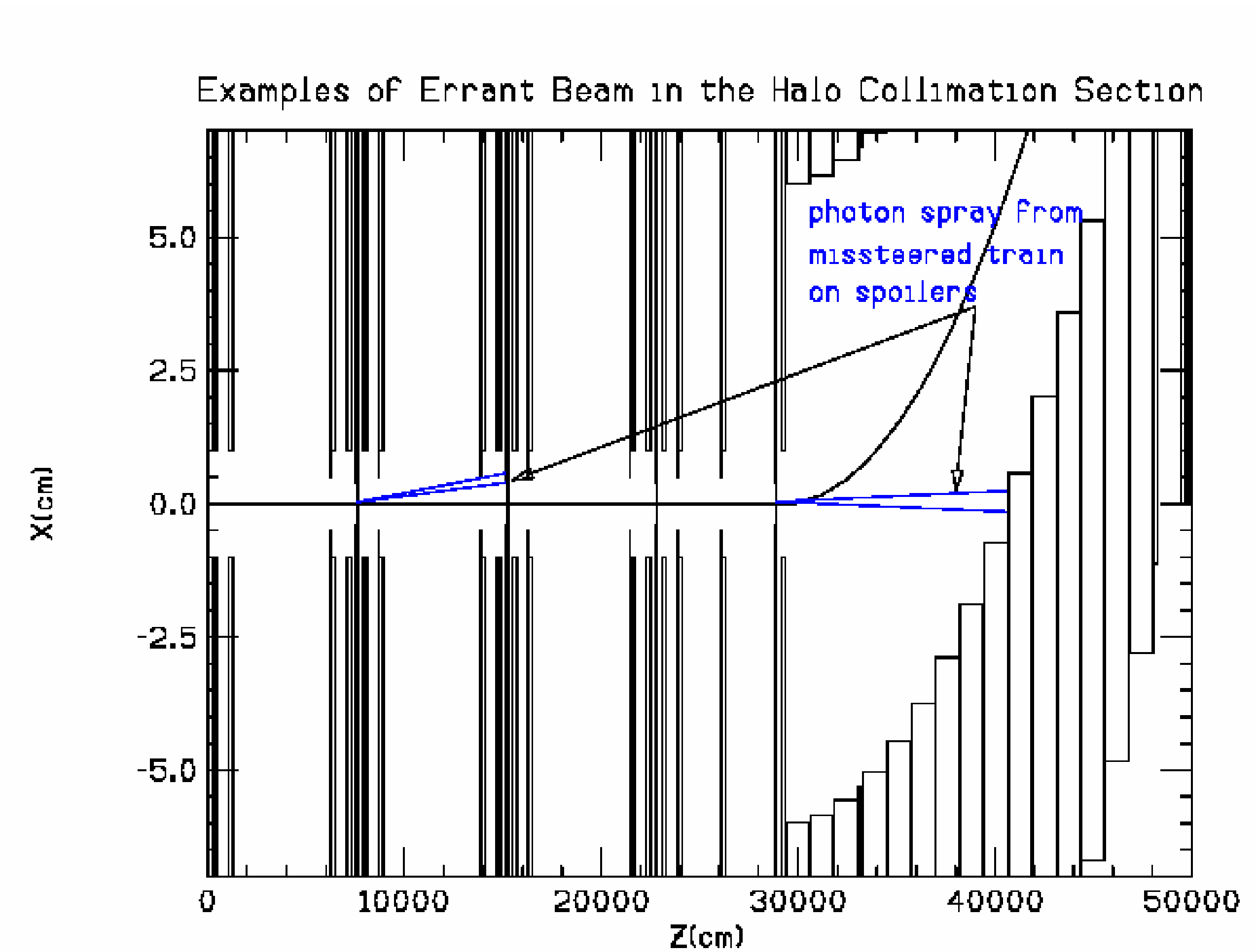

Figure 3. Two examples of errant beams hitting and damaging an azimuthal segment of the cylindrical spoilers in the halo collimation section. The Machine Protecton System (MPS) must also protect against the resultant photon spray hitting downstream beamline elements.

Figure 4 shows examples of off-energy bunch trains in the energy collimation section. The aperture of the one radiation length energy spoiler will be set to allow transmission of ±1.5% off-energy beams. It is seen that the photon spray from the -2% and -20 % off-energy bunch trains hit different dipoles, so that there will need to be several protection collimators in this region. Energy variations outside the bandpass are deemed to be events that can "often" occur. OBJEGS runs that study the survivability of the energy spoiler itself are shown in Table 2, Case#2, while the results of runs that study the requirements of the magnet protection collimators are shown in Table 2, Case#3.

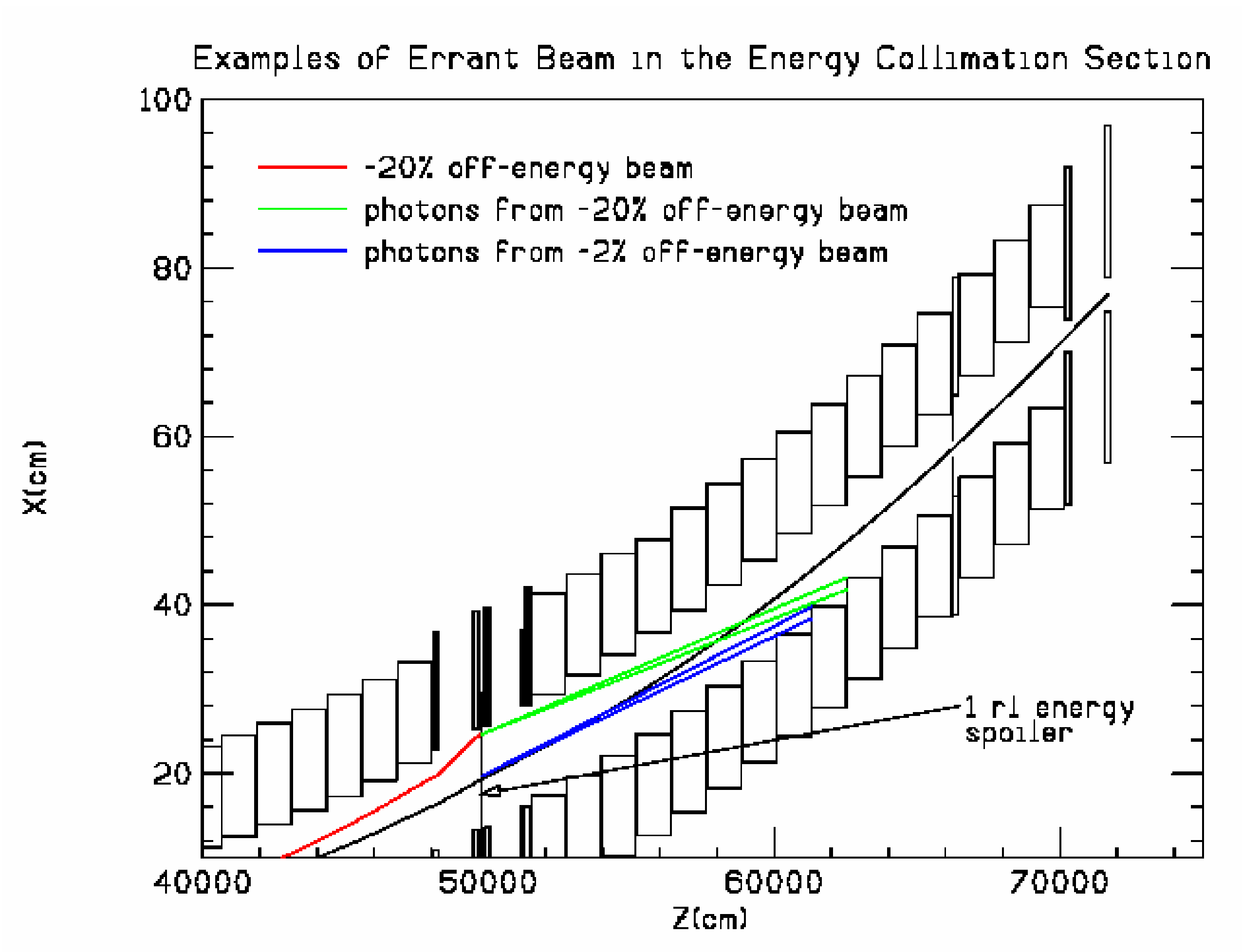

Figure 4. Examples of off-energy bunch trains in the energy collimation section hitting the energy spoiler and the direction of the resultant photons.

Figures 5 and 6 show the spectra of secondaries from a 250 GeV electron bunch train interacting in a 0.6 radiation length spoiler in the halo collimation section, and from a 1.0 radiation length spoiler in the energy collimation section. Note the total energy and multiplicity of the photons, electrons, and positrons in the two cases. In both collimation sections, the electrons and positrons are dispersed by downstream magnets and do not cause damage; so that only the photons need to be considered in damage simulation

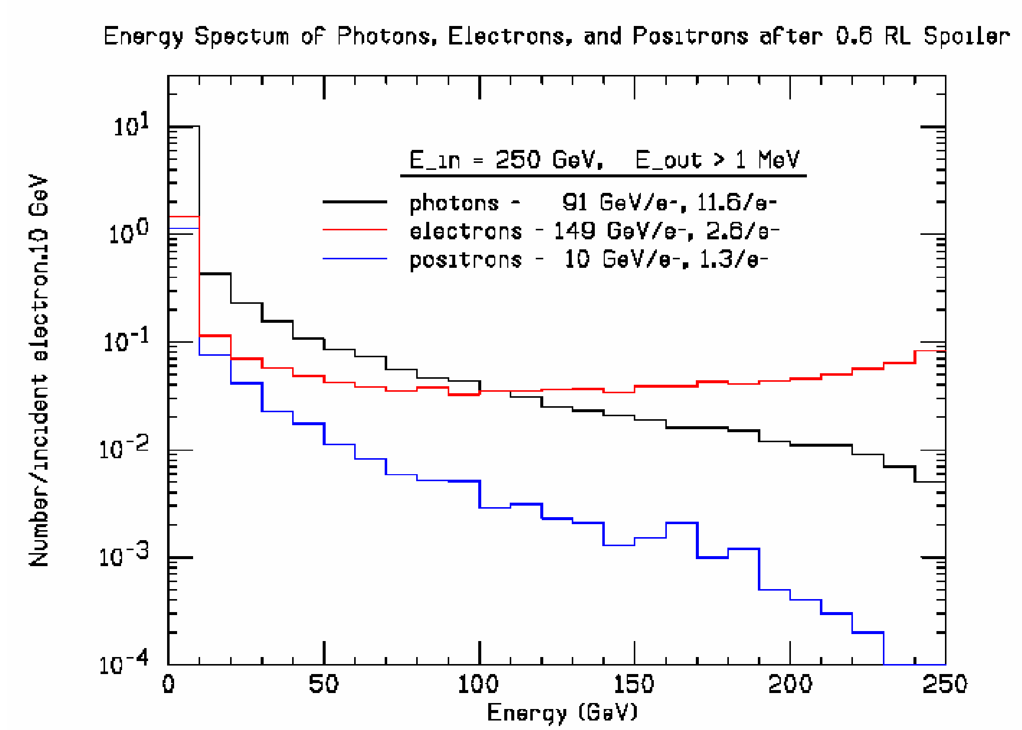

Figure 5. Energy spectra of photons, electrons, and positrons from a 250 GeV electron hitting a 0.6 radiation length spoiler in the halo collimation section.

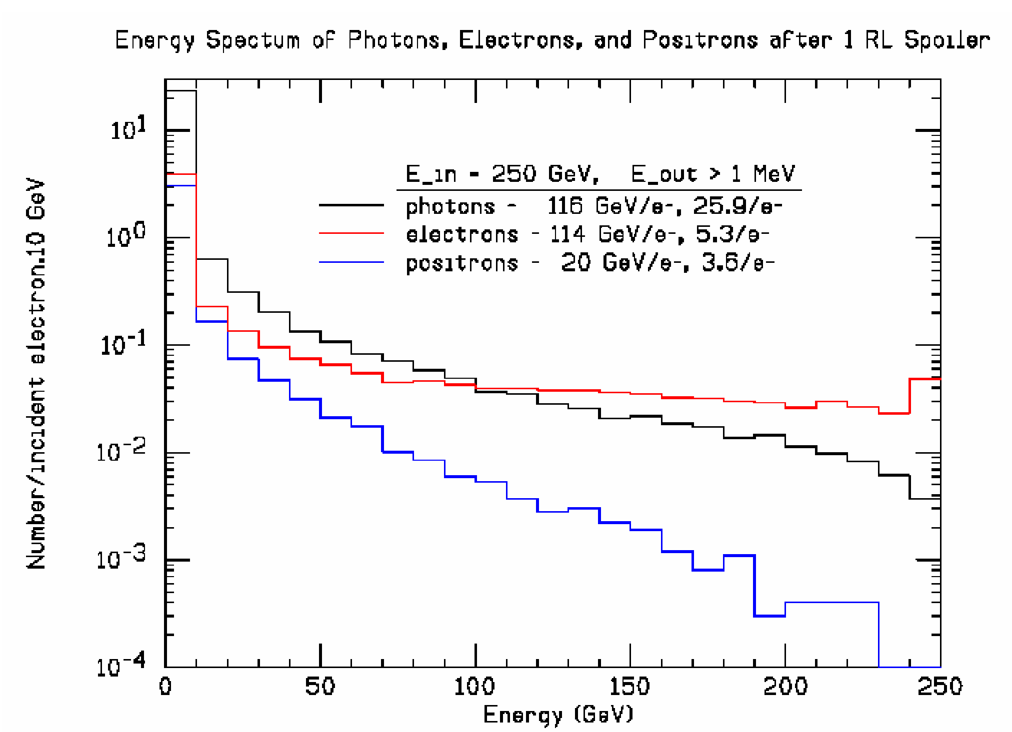

Figure 6. Energy spectra of photons, electrons, and positrons from a 250 GeV electron hitting the 1.0 radiation length spoiler in the energy collimation section.

Results of Simulations in the Collimation System

Table 1 lists the properties of commonly used materials in absorbers and collimators in electron accelerators. Depending on the required application, each material has its own advantages and disadvantages. At the beginning of this study it was assumed that all spoilers, absorbers, and protection collimators were made of copper. However, as discussed below, it is recommended that some of the spoilers and collimators be changed to titanium.

Table 1. Spoiler and Absorber Materials

Material	Specific Heat (J/gm°C)	Melting Temperature (°C)	αE (psi/°C)	Ultimate Tensile Strength Limit	
				(psi)	(°C)
Be	1.78	1278	540	80000	150
Ti	0.54	1800	130	100000	770
Cu	0.385	1080	280	50000	180
W	0.134	3100	220	150000	680

Table 2 gives the results of the OBJEGS simulation of various errant beams in the collimation system. Cases #2 and #3, involving the energy spoiler are assumed to occur "often"; Cases #1, #4 and #5 which involve the halo spoilers being hit are assumed to be "rare" events. The simulations were done for two single beam energies, 250 GeV (listed as 500 GeV CM) and 500 GeV (listed as 1000 GeV CM). If the resulting temperatures exceed the fracture or melting temperatures of the material listed in Table 1 the case is so marked; when the expected temperature rise is below the fracture limit, the case is marked as "OK." The beam sizes shown for Cases #1 and #2 were used for 500 GeV CM calculations. For 1000 GeV CM calculations the beam sigmas were reduced by $1/\sqrt{2}$ except for σ_x at SPE, where the horizontal beam size is almost entirely due to the beam energy spread.

As mentioned earlier, the halo collimation spoilers, SP1-5, are designed to rotate [3]; i.e. each time they are damaged by a full bunch train, they can be remotely rotated so that the beam halo sees a fresh, undamaged surface. Case #1 shows, for completeness, that the energy density on the spoilers is indeed large enough to raise their temperature well above all damage thresholds. However, even if SP1-5 are struck by a full bunch train, all downstream absorbers and protection collimators are supposed to survive without damage. Case #4 shows that the photon protection collimators downstream of the halo spoilers cannot be made of copper, as currently specified. The low emittance photon spray, unlike the charge particle debris which is dispersed by the field of the intervening magnets, can damage them. Note that this has implications if even tighter emittances were ever achievable at the linear collider. Making the protection collimators of titanium keeps the calculated temperature below the fracture limit up to 1000 GeV CM. Case #5 studies the effect of photons on the absorber downstream of SP5. While switching the absorber material here from copper to titanium alleviates the danger of damage at 500 GeV CM, the absorber is still in danger at 1000 GeV CM. If SP5 is frequently hit (recall that only a small angular kick is required) we should look into segmenting it into a pre-radiator and main radiator, as proposed (below) for SPE. It would also be prudent to use titanium absorbers in the halo collimation section, even though hitting them with a photon shower should be a rare occurrence.

The energy collimation spoiler, SPE, is supposed to take a full bunch train without damage. Case #2a and #2b show that an off-energy bunch train will either melt or fracture a 1.0 R.L. piece of titanium or beryllium (SPE). Case #2c-1 and #2c-2 show that if SPE is segmented into a 0.15 RL pre-radiator and a 0.85 RL body, separated by a 10 m drift, then it can survive a 250 GeV bunch train. After the energy is upgraded to 1 TeV CM, SPE may need to be replaced by segmented beryllium pieces. Note that if the beam energy spread is ever decreased from 0.25% rms while maintaining bunch charge and emittance, the energy spoiler as modeled here may not survive. To accommodate such an eventuality, the energy collimation system should be redesigned with a larger dispersion and a larger vertical beta function. Case #3 shows that, as in the case of the halo spoiler protection collimators, the photon protection collimators in the energy collimation section must be made of titanium to survive the relatively frequent hits on SPE.

Table 2. RESULTS of SIMULATIONS of a SINGLE ERRANT BUNCH TRAIN in the COLLIMATION SYSTEM

Case #	Steering Condition	Maximum Temperature Damage	
		500 GeV CM	1000 GeV CM
1a	Hit 0.6 rl Copper SP1 or SP3, σ_x=16μ, σ_y =0.8μ	460000 °C Melts	1000000 °C Melts
1b	Hit 0.6 rl Copper SP2 or SP4, σ_x=28μ, σ_y =6.5μ	32000 °C Melts	70000 °C Melts
2a	Hit 1.0 rl Titanium SPE (design), σ_x=529μ, σ_y =29μ	2430 °C Melts	4150 °C Melts
2b	Hit 1.0 rl Beryllium SPE, σ_x=529μ, σ_y =29μ	415 °C Fractures	680 °C Fractures
2c-1	Hit 0.15 rl Titanium SPE pre-radiator, σ_x=529μ, σ_y =29μ	630 °C OK	960 °C Fractures
2c-2	Hit 0.85 rl Titanium SPE absorber placed 10m away	470 °C OK	880 °C Fractures
3a	Photons from train hitting 1.0 rl Ti SPE strike Copper Protection Collimator of Dipole BS26, 116m downstream	370 °C Fractures	1550 °C Melts
3b	Photons from train hitting 1.0 rl Ti SPE strike Titanium Protection Collimator of Dipole BS26, 116m downstream	153 °C OK	600 °C OK
4a	Photons from train hitting 0.6 rl Cu SP5 strike Copper Protection Collimator of Dipole BS10, 116m downstream	415 °C Fractures	1880 °C Melts
4b	Photons from train hitting 0.6 rl Cu SP5 strike Titanium Protection Collimator of Dipole BS10, 116m downstream	155 °C OK	610 °C OK
5a	Photons from train hitting 0.6 rl Cu SP1 strike Copper Absorber, 76m downstream	665 °C Fractures	2910 °C Melts
5b	Photons from train hitting 0.6 rl Cu SP1 strike Titanium Absorber, 76m downstream	265 °C OK	1000 °C Fractures

Protecting the Final Doublet and Detector

There is a small probability that a bunch train will be given a large enough angular kick anywhere in the linac or BDS to cause severe damage to a beam line element. It is considered impractical to attempt to guard against all such possible missteerings. We assume that for the (hopefully) rare occurrence when a bunch train damages the vacuum pipe and/or a beam line element, that the damaged component can be replaced in a relatively short time at small expense. An exception to this philosophy is the superconducting final doublet (FD) and the inner detector components. These are very expensive, one-of-a-kind pieces of equipment which need special consideration. The goal is to design a protection collimator such that any possible missteered bunch train will hit (and damage) the protection collimator instead of the FD and detector. Figure 7 shows a schematic of the FD and IP region. Using Program TRANSPORT [4] the half-gaps in the upbeam protection collimator were set so all bunch trains in the horizontal and vertical plane which pass through the collimator cannot impact any elements in the IP region. It is seen in Figure 7 that the extreme trajectories in both planes satisfy this condition.

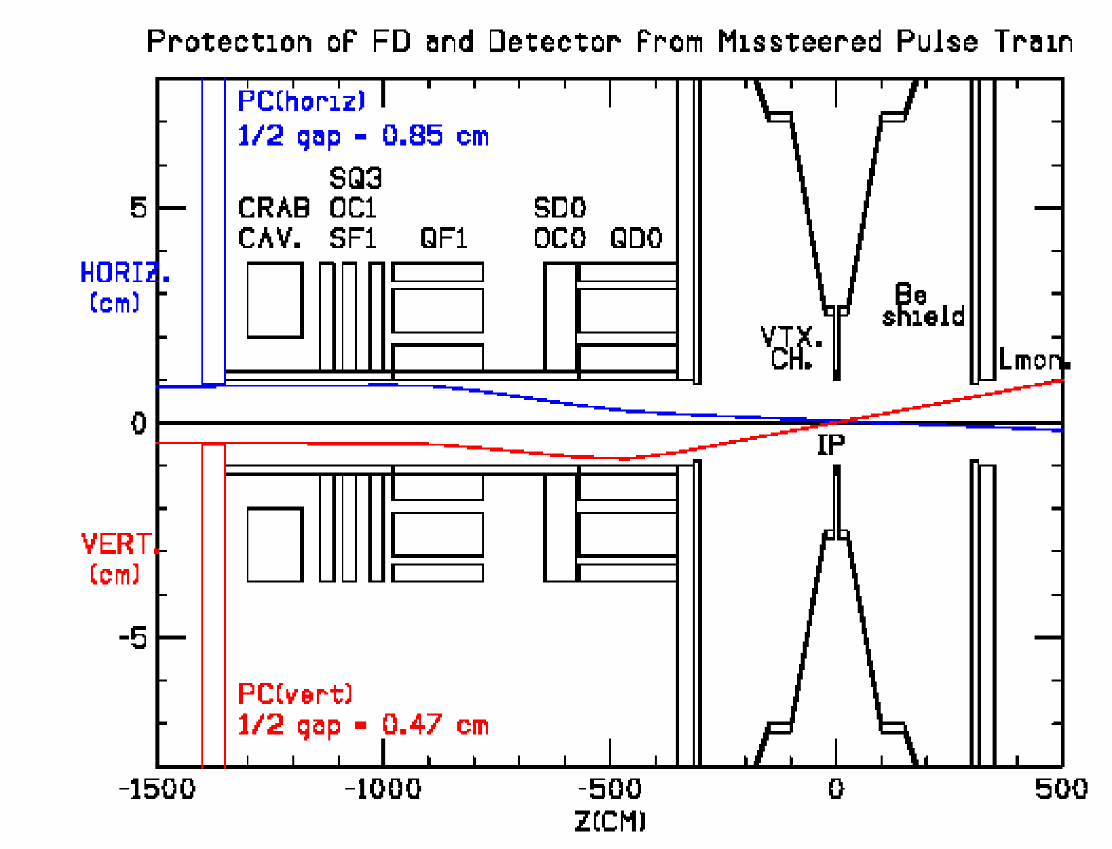

Figure 7. Schematic of the FD and interaction region (IR) of the BDS showing the extreme rays in both planes which just pass through the FD protection collimator (PC).

One of the easiest ways to produce an angular kick which will impact the FD protection collimator is to misset any of the three long dipole strings, B1, B2, or B5, in the FF section of the BDS. Figure 8 shows of percentage error of each of these dipole strings which will produce a trajectory in the horizontal plane that just passes through the FD protection collimator. The MPS must not allow setting errors greater than this magnitude in the FF dipole strings.

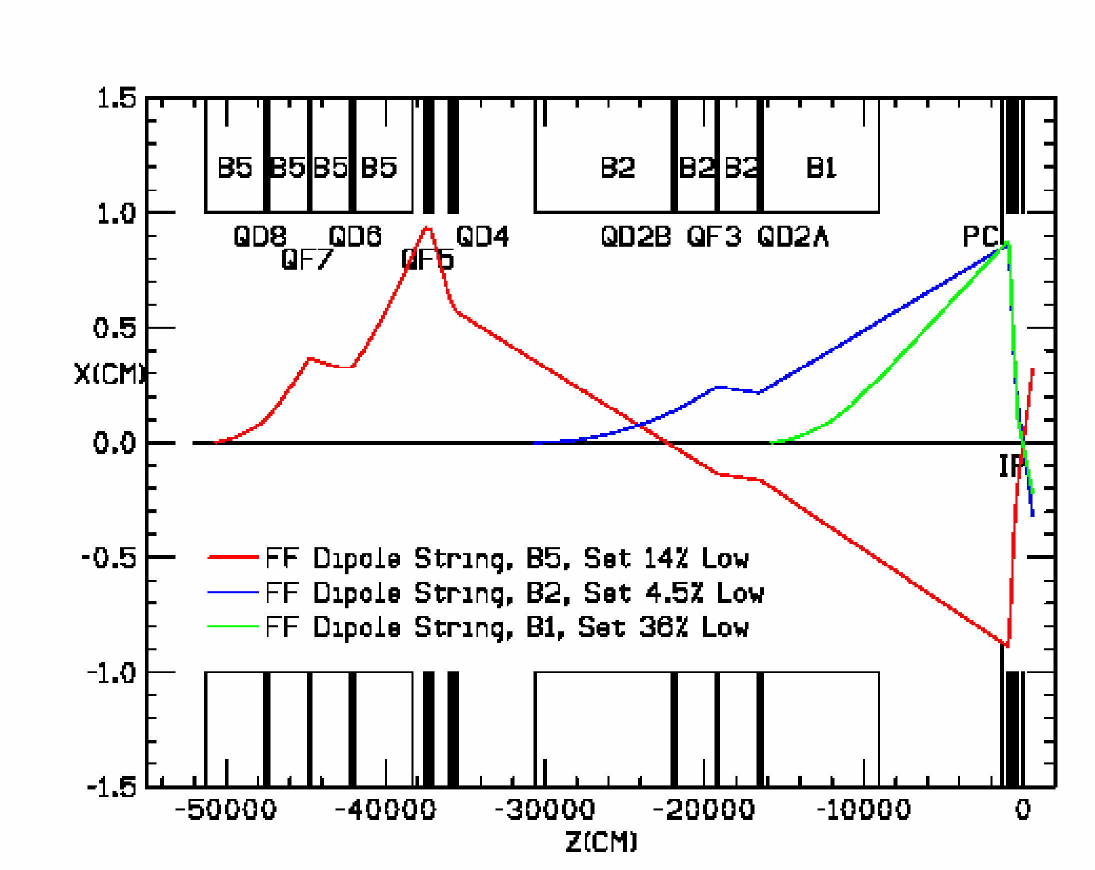

Figure 8. Trajectories which just pass through the FD protection collimator, caused by missetting of any one of the three FF dipole strings.

Using an OBJEGS model of the FD magnet string including the superconducting quadrupole coils [5], the energy deposition in the superconducting coils was estimated for bunch trains hitting the FD protection collimator. At the entrance to the FD the beam size is σ_x = 629µm and σ_y = 66µm., and the maximum angular kicks (from B1 misset) which just reach the inner edge of the FD protection collimator are x′ = 76 µrad and y′ = 31 µrad. It was found that if the entire train hits the front face of the collimator, the temperature rise along the inner edge of the QF1 coil is <0.1 °C , not enough to cause a quench. The worst case scenario occurs when the errant beam just scrapes the inner edge of the PC. However, because of the relatively large beam size and small angular kick, it is not possible for the entire beam to impact the inner edge of the PC. Even so, there is a 0.3 °C maximum temperature rise when the beam scrapes the bottom or top inner edge of the PC. This is probably not enough to quench QF1.

Finally, we need to estimate the muon flux hitting the FD and detector when an entire bunch train hits the FD protection collimator. Using program MUCARLO [6], we find there is a maximum of about 8 x 10^7 muons/cm^2 in the QF1 coil and 5 x 10^6 muons/cm^2 in the vertex detector. Neither of these hit densities are enough to cause damage.

Conclusions

The following are the conclusions and recommended design changes to the BDS from this study:

1. Horizontal apertures in the energy collimation section must be ≈12 cm full width to safely contain ±20% off-energy bunch trains. Above 1 TeV CM_the quadrupoles in this section may have to be longer, i.e. B_{pole} ≈ 12 kG @ 12 cm bore.

2. A pre-radiator and a 10 m drift are needed to keep an off-energy bunch train from melting the energy spoiler.

3. Titanium absorbers are needed in the energy collimation section to avoid edge fractures from photon showers when a bunch train hits SP5 or SPE. This means the drifts between the dipoles must increase from 30 cm to 60 cm to accommodate the titanium absorbers. This change adds ≈10 m to the total length of the BDS.

4. The energy collimation system is designed to work with a nominal beam with a minimum energy spread of 0.25%. If it is desired to operate with beams having smaller energy spreads, the system should be redesigned to have a larger vertical beta function and a larger horizontal dispersion function.

5. An errant 500 GeV beam, missteered by ~100 μrad, and hitting any spoiler in the halo collimation section will damage copper absorbers and PC's.

6. A 50 cm long copper protection collimator, foreseen as a synchrotron radiation mask, with horizontal (vertical) half-gap of 0.87 (0.47) cm will protect the final doublet and detector from errant beams near the IP.

References

1. The NLC Design Group, *Zeroth-Order Design Report for the Next Linear Collider,* SLAC Report 474(1996), p. 880.
2. W. Nelson, et.al., *The EGS4 Code System*, SLAC Report 265(1985).
3. E. Doyle, *Design of the NLC BDS Collimators,* in preparation.
4. K. Brown, et.al., *TRANSPORT – A Computer Program for Designing Charged Particle Beam Transport Systems*, SLAC Report 95(1980).
5. B. Parker, *Design of Superconducting Final Doublet for the NLC, http://www-project.slac.stanford.edu/lc/local/MAC/NOV2002/mac_Parker_1107.pdf*
6. L. Keller, *Program MUCARLO*, SLAC-Pub. 6385 (1993).
7. A. Drozdhin, et al., "Comparison of the TESLA, NLC, and CLIC Collimation System Performance," SLAC LCC-0111; Fermilab TM-2200; TESLA Report 2003-02 (2003).