9-21-91 JS ①

SLAC-PUB--5533

DE91 012112

CALCULATION OF MUON BACKGROUND IN A 0.5 TEV LINEAR COLLIDER*

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ABSTRACT

For sources placed along a 250 GeV linac and final focus lattice, muons from Bethe–Heitler pair production are transported with a Monte Carlo ray-tracing program until they either range out or reach the collider experiment hall. For a muon source located at the entrance to the final focus, a system of toroid spoilers was designed which resulted in one muon in the detector per 3.6×10^7 electrons impinging on the source. This is a factor of 150 improvement over the case when no spoilers are present.

1. INTRODUCTION

Experience from SLC shows that tails of the beam striking collimators in the final focus can cause intolerable muon background in the experiment detector. This problem is expected to be considerably worse in a 0.5 TeV linear collider since the final focus bend angles are smaller, the linac is nearly aimed at the detector, the muon momentum spectrum is much harder, and the number of electrons/pulse is about four times larger.

The main tool for studying this problem was a Monte Carlo program written by G. Feldman for the SLC final focus. The program successfully reproduced the experimental results for the number of muons hitting the Mark II detector, both before and after iron toroid spoilers were installed in the north and south final focus tunnels. For application to the NLC, the program was modified to include variable energy primary beams and a linac with optical lattice and waveguide in front of the final focus.

2. PRODUCTION MECHANISMS

When electrons or positrons impinge on apertures in the linac or final focus, muons are produced by a variety of mechanisms: Bethe–Heitler pair production, $\gamma Z \to Z\mu^+\mu^-$; direct e^+ annihilation, $e^+e^- \to \mu^+\mu^-$; and photopion production, $\gamma A \to X\pi(\pi \to \mu\nu)$. It is estimated[1] that direct e^+ annihilation from beam e^+ and shower e^+ is less than 10% of Bethe–Heitler production in the muon momentum range allowed by kinematics of the annihilation reaction. Photopion production is comparable to Bethe–Heitler production; however, it is expected that a large fraction of the pions will interact before they decay. This initial work considers only muons from Bethe–Heitler production. More study of the other sources is required to verify that they do not contribute significantly to the background.

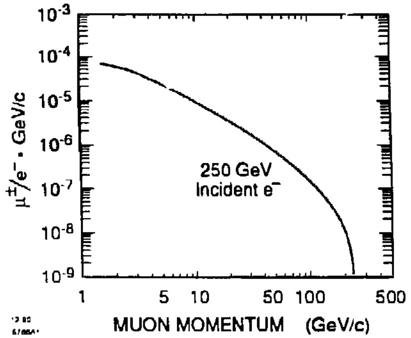

Fig. 1. Muon production via the Bethe–Heitler mechanism by a 250 GeV electron beam on a tungsten target as a function of muon momentum.

3. DESCRIPTION OF THE MONTE CARLO PROGRAM

3.1 Production

For a given photon energy, k, the differential cross section, $d\sigma/dp_\mu d\theta_\mu$, for muon pair production is evaluated for a large number of momentum-angle bins using the expressions given by Y. Tsai.[2] The total number of events in each momentum-angle bin is then given by the product of the differential cross section and the photon path length, $d\ell(k)/dk$, summed over all possible photon energies. The photon path length is calculated using the Clement-Kessler shower approximation.

$$\frac{d\ell(k)}{dk} = \frac{0.964X_o/E_{\mathrm{beam}}}{-\ell n(1-\mu^2)+0.686\mu^2-0.5\mu^4} \,,$$

where $\mu = k/E_{\mathrm{beam}}$ and X_o is the radiation length of the source material. Figure 1 shows the Bethe–Heitler yield in 1 GeV/c bins *vs.* muon momentum for 250 GeV incident electrons on a tungsten target. The program randomly selects the muon momentum and angle with the appropriate weight as calculated from the Bethe–Heitler distribution.

3.2 Sources

The source can be placed anywhere between the entrance to the linac and the IP. For source locations in the linac, where the beam has not reached final energy, the program calculates the momentum-angle distribution based upon the beam energy at that point. Once the momentum and angle have been chosen, the muon undergoes multiple coulomb scattering, assuming the source is 20 radiation

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* Work supported by Department of Energy contract DE-AC03-76SF00515.

Contributed to the DPF Summer Study on High Energy Physics: Research Directions for the Decade, Snowmass, CO, June 25–July 13, 1990.

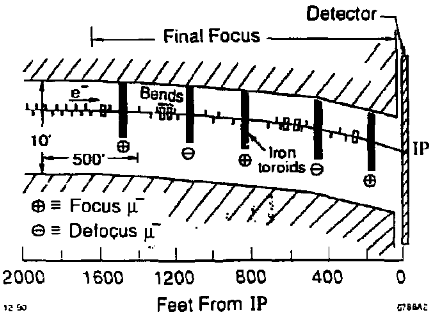

Fig. 2. Schematic of the final focus beam line used for this study. Note the different scale in the transverse and longitudinal directions.

lengths (rl) thick. Most of the muons are produced within a few units of the critical angle, $\theta_c = m_\mu/E_\mu$; so that for a given muon momentum and a 20 rl source, the ratio of production angle to scattering angle is $\theta_c/\theta_{\rm MCS} \approx 1.6$.

3.3 Final Focus Beam Line and Linac

Figure 2 shows a schematic of the final focus beam line and tunnel. Note the different scale in the transverse and longitudinal directions. The final focus layout is based on a design[3] which was available at the time of the 1990 Snowmass Summer Study. It is 1632′ long (*vs.* 477′ in SLC) and has a total chromatic correction bend of 4.2 mrad (*vs.* 73.1 mrad in SLC). The model includes tunnel walls, concrete support girders, and all bends and quadrupoles (including return flux in the iron and pole tips). The cross section of the detector is assumed to be a 20′ square, centered on the IP. For reasons discussed below there are five iron toroids of alternating polarity shown distributed through the final focus. Each toroid is a 30′ long iron donut with an inner hole radius of 1″ and outer radius of 35″. Inside the inner hole and extending the length of the donut is the 1/2″ radius beam pipe, a soft iron magnetic flux shield with a 1/4″ wall, followed by copper windings which fill the radial space between 0.75″ and 1.0″. Each toroid weighs 200 T and would cost ~$1M installed. For an iron toroid with a field of 16 KG, the ratio of bend angle to scattering angle is $\theta_{\rm bend}/\theta_{\rm MCS} \approx 3\sqrt{L}$, where L is the length of the toroid in meters.

The linac lattice is an FODO design[4] in which the quadrupole strengths and spacing scales as $E^{1/2}$ between the beginning and end of the linac. The linac model includes the 11.4 GHz waveguide, support girder, FODO lattice quadrupoles, and tunnel walls. There is also a 400′ FODO section between the linac and the start of the final focus which reserves space for a dedicated collimation section.

After the muon exits the source, the Monte Carlo program swims it in small steps thru the tunnel. When material is encountered, the muon scatters, loses energy, and bends (if magnetic field is present). The trajectory of each muon is followed until the muon either stops or reaches the IP. A muon reaching the IP within the 20′ square is counted as a detector hit. A large variety of one- and two-dimensional histograms of the muon coordinates, direction, and momentum at any longitudinal point in the tunnel can be generated. A particularly useful feature for understanding how muons manage to reach the IP is a listing of individual trajectories.

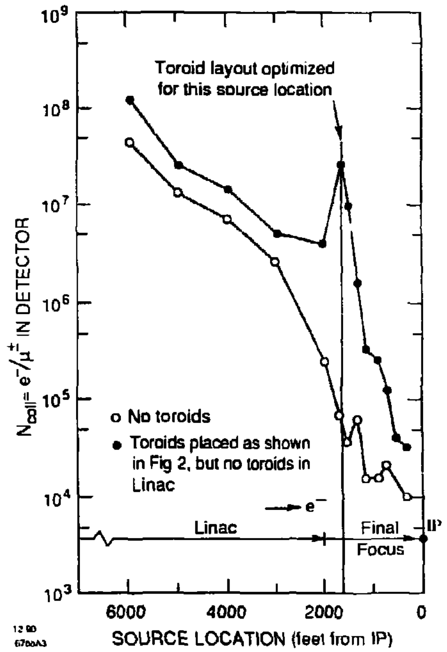

Fig. 3. Number of electrons impinging on a collimator which yield one muon in the detector ($N_{\rm coll}$) as a function of source location in the linac and final focus.

4. RESULTS

Before studying where to place toroid spoilers. it is useful to demonstrate the magnitude of the problem. Based on the Mark II experience at SLC, one muon/pulse is a marginally acceptable background. Define $N_{\rm coll}$ to be the number of electrons impinging on a collimator (the source) per muon hitting the experiment detector. Figure 3 shows $N_{\rm coll}$ as a function of collimator location in the linac and final focus. From the curve labelled "no toroids" it is seen that for sources near the entrance to the final focus, a beam loss $\gtrsim 10^5$ electrons/pulse will cause an unacceptable background, and that for sources within a few hundred feet of the IP, a beam loss $\gtrsim 10^4$ electrons/pulse is too large. This result is a factor of 10 worse than the measurements in the SLC final focus before toroids were added. In addition the design intensity of NLC is 1.7×10^{11}/pulse *vs.* 5×10^{10}/pulse in SLC. Even with the source at the point in the linac where $E = 0.6E_{\rm beam}$ (6000′ from the IP in this model), a loss of only 5×10^7 electrons/pulse will begin to be too much. Given the SLC experience of ≈ 30% beam loss on linac collimators and the energy defining slit, and ~ 0.1% beam loss on some final focus collimators: it follows that it is necessary to design a toroid system to deflect the muons away from the detector

The curve labelled "toroids" in Figure 3 shows the result of adding the five iron toroids shown in Figure 2. The toroid polarities, spacing, and position along the beam line are the result of an empirical minimization of background from a source at the entrance of the final focus ($z = 1632'$ from the *IP*). For this particular source location, adding the toroids resulted in a factor of about 150 improvement, i.e. $N_{\rm coll} = 3.6 \times 10^7$. This is still only about 2×10^{-4} of the NLC pulse intensity. Only 3% of the muons reaching the IP are within the 20′ square defined as the detector; so that the main function of the toroids is to disperse the muons, not cause them to be ranged out. Most muons hitting the detector have source momentum greater than 100 GeV/c and there is a broad peak from 140 to 200 GeV/c.

It is clear that suppression of muon background has to be considered when designing the NLC final focus and linac. There are a large number of coupled parameters which determine the number of muons reaching the detector, for example: source location, source thickness, magnet gap and bore sizes, magnet iron dimensions, total final focus bend, tunnel dimensions, and beam location in the tunnel. In addition, these parameters are coupled to the toroid parameters: location, spacing, polarity, central hole radius, outer radius, and length. While searching for the optimal toroid combination, the following observations were made:

1. In general, if the source is close to the upstream end of a dipole, it is very helpful to locate a toroid downstream from the dipole. Muons are then dispersed across the face of the toroid and deflected into the tunnel walls. If the toroid is too close to the dipole, the very high momentum muons can sneak through the central field free region. If the toroid is too far from the dipole, lower momentum muons miss the toroid altogether and scatter in the tunnel walls back toward the detector.
2. Many of the muons hitting the detector have traveled long distances in the earth outside the tunnel walls.
3. If the toroids all have the same polarity, then channeling of one muon charge occurs.
4. Channeling about the central hole of a single toroid also occurs for one of the muon charges, and reducing the central hole size to 1/4″ radius increased the number of muons hitting the detector due to this phenomenon.
5. Increasing the total final focus bend from 4.2 mrad to 12.6 mrad reduced the background by a factor of 10.

As an alternative to the system of toroids described above, the brute force technique of a full range muon shield which completely shadows the detector was tried. shield was 477′ of iron with a 20′ square cross section, centered on the beam line, and filled all available drift sections outboard of the detector. There was a 2″ square hole for the beam pipe. With the source at the same location as for the toroid study (z = 1632′ from the IP) the result was $N_{\rm coll} = 4 \times 10^8$. This is about a factor of 10 improvement over the toroid system. The muons which reach the detector start out with very high momentum and get part way through the beam pipe hole before encountering the shield. Such a shield, however, would weigh 40,000 tons and would probably cost ~$100M installed if the iron had to be purchased. It therefore seems extremely impractical.

5. SUMMARY AND CONCLUSIONS

With the source at the entrance to the final focus, the best that could be achieved with a system of toroid spoilers was 3.6×10^7 electrons on the source per muon hitting the experiment detector. This is a relatively small loss compared to the SLC experience. It is clear that muon background will be prohibitive if more than $\sim 10^{-5}$ of the electron beam scrapes apertures closer than 1000 feet from the IP. Efforts to collimate and remove tails from the beam in the damping ring transport lines or early in the linac should be pursued. Increasing the chromatic correction bends helps if emittance growth from synchrotron radiation can be tolerated.

A full range muon shield which shadows the detector is impractical, but to get dramatic improvement in the fraction of beam loss that can be tolerated may require a very substantial shielding wall in the last few hundred feet of the final focus tunnel.

ACKNOWLEDGEMENTS

I would like to thank Gary Feldman for his muon tracking program and Hobey DeStaebler and Morris Swartz for helpful discussions about muon production.

REFERENCES

1. H. DeStaebler, Private Communication.
2. Y. Tsai, *Rev. Mod. Phys.*, Vol 46, No. 4, (1974), p. 815.
3. R. Helm, TRANSPORT deck FFNO9, June 1990.
4. K. Bane, Private Communication.